IRRIGATION INSIGHTS

NUMBER THREE

GUIDELINES TO GOOD PRACTICE FOR THE

CONSTRUCTION AND REFURBISHMENT OF EARTHEN IRRIGATION CHANNEL BANKS

National Program for Irrigation Research and Development

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Improvement to the Guidelines

These Guidelines are an evolving document and it is intended from time to time to update them as more information becomes available from research of new technologies and practices. The guidelines will be maintained by Goulburn-Murray Water and they welcome suggestions for improvement to ensure the Guidelines remain comprehensive and relevant to the needs of the users.

Your comments on the format and contents of this first edition, including areas for improvement or updating are invited and can be sent to:

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They will be acknowledged and, as far as possible, taken account of in subsequent editions.

Forward

Australia's irrigation assets are ageing and improved management of this ageing infrastructure is a major challenge facing the national irrigation industry. The most significant component of these assets is earthen channels.

There are some 17,752 km of earthen irrigation channels in Australia, and at a LWRRDC workshop on Irrigation Infrastructure Refurbishment held at Tatura in 1993, the need to reduce the life cycle costs of earthen channel banks was identified as one of the irrigation industry's highest strategic priorities.

Over the next 20 years ever increasing levels of expenditure on earthen channel bank refurbishment will be required in Victoria, New South Wales and Queensland, and the seepage from inadequately constructed earthen channels can lead to water losses, rising groundwater levels, salinisation and degrading of the environment.

These Guidelines are based on LWRRDC Research Project GMW1, which was initiated in 1995 as a joint project between Goulburn-Murray Water and the Queensland Department of Natural Resources, with matching funding from the Land and Water Resources Research and Development Corporation (LWRRDC).

The aim is to provide the Australian irrigation industry with information needed to improve the understanding of earthen irrigation channel bank construction and refurbishment practices.

The Guidelines have been prepared using the accumulated knowledge and practical experience of many irrigation authorities in Australia and overseas. The research procedures consisted of a worldwide literature review, surveys of Australian irrigation authorities, specialist inputs, an investigation program and field trials.

Considerable detail is presented in sections of the Guidelines because much of this information has never before been published. Comprehensive lists of references are provided for the reader to follow up more technical information on any particular aspect. The purpose is to fill a void by providing in one document a source of comprehensive information relevant to Australian conditions on the many aspects of construction and refurbishment of earthen irrigation channel banks.

A major challenge encountered in the preparation of these Guidelines was the wide range of conditions found across Australia. The original intention was to write a *Best Practice Manual,* but as the project progressed, it became clear that such an approach was not appropriate. The diversity of conditions, circumstances and public and private schemes across Australia meant that a single best approach does not necessarily exist.

Instead these Guidelines attempt to provide an understanding of the issues, the available options and relevant decision making criteria, so that each case can be treated on its merits for the most cost-effective solution to the site-specific conditions. The title of *Guide to Good Practice* has therefore been adopted, because the Guidelines do not provide prescribed solutions, and their effective use will rely on the judgement of the reader.

These Guidelines are intended to be a practitioner's handbook, not an academic text. The *intended reader* will generally be a practising engineer or technical officer working on the design, construction or refurbishment of earthen irrigation channel banks.

During the course of this project, it became apparent that the irrigation industry is rapidly loosing knowledge and expertise in earthen channels, due to organisational changes and the generation of staff involved in channel design and construction leaving the industry. The Guidelines have therefore endeavoured to capture as much of the existing knowledge base as possible, as well as extending this through the research project.

Channel bank design, construction and refurbishment practices of some Australia irrigation authorities have not changed significantly for many years and the industry has developed some fixed views. Changes to a number of established practices and standards are proposed, and for these changes to be understood and put into practice by the industry, the reasons for the changes and supporting discussion have been incorporated in the Guidelines. It is important that practitioners keep themselves informed and retain an open mind on new ways of doing things.

Finally, critical comment from readers will be most welcome, as will the notification of errors and omissions, so that the Guidelines can be improved in subsequent editions.

Ian Moorhouse
Principal Investigator
Manager Irrigation Technical Services
Goulburn-Murray Water

Abstract

The need to reduce the life-cycle costs of earthen channel banks has been identified as one of the Australian irrigation industry's highest strategic priorities. This document provides guidelines on the construction and refurbishment of earthen irrigation channel banks, and methods to reduce seepage from irrigation channels which will lead to water savings, increased productivity, and ecologically sustainable land and water resource use.

Acknowledgments

These Guidelines represent the compilation and integration of existing and newly developed information on construction and refurbishment of earthen irrigation channel banks sourced from Australia and around the world.

This project has been undertaken with the support of many organisations and individuals within Irrigation areas of Australia, and the significant contributions made by a wide range of people needs to be acknowledged.

The primary workload of the project was undertaken by:

Principal Investigator	Ian Moorhouse	Goulburn-Murray Water, Tatura
Project Officer	Anne Noonan	Goulburn-Murray Water, Tatura

The Steering Committee and Research Team members were as follows:

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Seventeen irrigation authorities participated in surveys, interviews and site visits and are acknowledged as follows:

State	Irrigation Authority	Area
Victoria	Goulburn-Murray Water	Murray Valley Shepparton Central Goulburn Rochester-Campaspe Pyramid-Boort Torrumbarry
	Southern Rural Water	
	Wimmera-Mallee Rural Water Authority	
	First Mildura Irrigation Trust	
	Sunrasia Rural Water Authority	
Queensland	Queensland Department of Natural Resources	Burdekin River Irrigation Area Mareeba-Dimbulah Bundaberg Emerald
New South Wales	Murray Irrigation	
	Coleambally Irrigation	
	Murrumbidgee Irrigation	Griffith Leeton
	Trangie-Nevertire Irrigation Scheme	
	Nevertire Irrigation Scheme	
	Marthaguy Irrigation Scheme	
	Colly Farms Cotton Ltd	
	Namoi Valley Irrigation Area	
	Clyde Agriculture – Bourke-Brewarrina Irrigation Farms	
Western Australia	Ord Irrigation Co-Operative Ltd	
Tasmania	Rivers and Water Supply Commission of Tasmania	

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Jim Wilding	Goulburn-Murray Water, Tatura
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Laurie Jackel	Goulburn-Murray Water, Tatura
Paul Brown	Marine and Freshwater Resources Institute, Victoria
Leon Tepper	Thiess Environmental Services

Many others provided assistance to the project and preparation of these Guidelines. These are too numerous to list here, but their valuable assistance is gratefully acknowledged.

Funding

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- Land and Water Resources Research and Development Corporation
- Goulburn-Murray Rural Water Authority
- Queensland Department of Natural Resources.

Amendment List

Amendment Number	Issue Date	Description

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Book 1

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Book 2 – Specifications

1. Introduction

1.1 General

Good asset management practices can significantly increase the life of an irrigation channel and reduce its life cycle costs.

This publication provides a guide to methods of construction and refurbishment of earthen irrigation channel banks.

The Guidelines provide practical guidance for the construction and refurbishment of earthen irrigation channel banks, which, if followed, should reduce life cycle costs.

Throughout Australia the irrigation industry has been undergoing major restructuring and staff reductions, resulting in the loss of technical expertise. The wide spread loss of industry expertise in earthen channel design and construction was apparent during this research project, and the Guidelines have therefore endeavoured to capture existing industry knowledge and extend that further through the research project.

Earthen irrigation channel banks are of considerable economic importance. They form a substantial part of the initial construction and on-going costs of an irrigation system. The selection of appropriate design, construction, operation and maintenance standards will determine the life-cycle cost of the banks and in turn the life-cycle cost of an entire irrigation system.

1.2 Irrigation Industry Context

Improved knowledge of irrigation infrastructure management and the refurbishment of ageing infrastructure are major challenges facing the national irrigation industry. The most significant component of the irrigation infrastructure, both in magnitude and in replacement cost, is earthen channels.

The older channels in Australia are reaching the end of their useful lives and increasingly will require either refurbishment or replacement. Over the next twenty years high expenditure on earthen channel bank refurbishment is projected in Victoria, New South Wales and Queensland. The need to reduce the life-cycle costs of earthen channel banks has been identified as one of the industry's highest strategic priorities.

1.3 Approach and Philosophy

Australia is a very large continent with wide variations in climate and topography. Irrigation schemes are spread across the country from north Western Australia to Tasmania. Hence, standards and practices vary widely.

Therefore, it has not been possible to establish *Best Practice* procedures that cover all situations. For this reason, this publication is intended as a Guide and not a Code of Practice. It is not in any sense a *standard*.

The Guide therefore provides *Proven Practices* for various situations, from which the reader can adapt best practice for their particular circumstances.

Earthen Channel practices of proven success vary from scheme to scheme within Australia depending on the local conditions, particularly the soil formations, operational needs and desired standards of construction and maintenance.

It is therefore, inadvisable to follow the practices of another scheme regardless of the differences in the local conditions.

1.4 Target Audience

The target audience for the Guidelines is primarily the practising engineer and technical officer working on the design, construction and refurbishment of earthen irrigation channel banks. It is intended to be a teaching document. These guidelines focus on practices and procedures relevant to Australia, but the guidelines could prove useful throughout the world, provided the economic, social and environmental differences are taken into consideration.

No documented *best practice* procedures currently exist for construction and refurbishment of earthen irrigation channel banks using modern technology and techniques. Demand for this information exists in Victoria, New South Wales and Queensland, and for large scale private or group supply schemes. Consequently the primary target audience for this Guide is the irrigation authorities in Victoria, New South Wales and Queensland. However it is applicable to all irrigation authorities in Australia.

The term *irrigation authorities* describes any organisation, either public or private, regardless of the specific title, that provides the service of delivering irrigation water to agricultural lands.

1.5 Study Objectives

The objective of these Guidelines is to provide proven practice procedures for the construction and refurbishment of long life earthen irrigation channel with clay compacted banks.

The Guidelines are intended to provide the reader with a range of cost-effective options for different channel service conditions.

The specific objective of the study are listed below:

(i) identify means to reduce the rate of deterioration of earthen channel banks.

(ii) develop methods to reduce the rate of deterioration of earthen channel banks

(iii) develop design parameters and construction control criteria for use with materials exhibiting high dispersion, permeability, shrinkage, plasticity, erodability or other undesirable characteristics.

(iv) provide proven practice approaches for channel bank construction and refurbishment incorporating the latest technology and techniques, and covering:

- causes of channel bank deterioration
- measures to reduce the rate of deterioration
- material selection for bank construction
- bank design
- new bank construction
- bank refurbishment techniques
- use of low quality materials
- geomembrane liners for seepage control
- seepage control
- batter erosion control measures
- yabby and carp control techniques
- standardised contract documentation

1.6 Scope

The Guide considers the whole channel cross-section including the bed. Its primary focus is on the construction and refurbishment of channel *banks*.

Other channel design aspects such as capacity, longitudinal grade and location are not included in these guidelines.

1.7 Channel Bank Refurbishment

Over the next ten to twenty years, the irrigation industry will have to find increasing funds to refurbish ageing irrigation infrastructure. These guidelines aim by achieving gains in the cost-effectiveness of channel bank refurbishment, provide long-term savings for the industry and contribute to the development of profitable irrigation.

1.8 Channel Seepage

Percolation from inadequately constructed or inadequately maintained earthen channels can be a significant groundwater input leading to rising groundwater levels, salinisation and the degrading of the environment around irrigation areas.

Reduced seepage losses from channels through improved construction and refurbishment techniques will lead to water savings, increased productivity, and ecologically sustainable land and water resource use.

2. Background to these Guidelines

The *LWRRDC Irrigation Infrastructure Refurbishment and Water Delivery Systems* Workshop was held at Tatura in 1993 and was attended by a wide range of water agency and irrigation industry representative from all States.

At this workshop earthen channels were identified as the highest priority for infrastructure refurbishment research and development and this project was initiated to address the key outcomes required by the workshop.

A joint research project between Goulburn-Murray Water (G-MW) and the Queensland Department Natural Resources (QDNR) was proposed to bring together different knowledge and practice. QDNR has experience of construction of new channels, while Goulburn-Murray Water has experience in refurbishment of existing channels.

The project was strongly orientated to practical outcomes and the proposed methodology was based on integration, collaboration and co-ordination.

The project commenced in 1995 with the formation of a Steering Committee and Research Teams in both Victoria and Queensland. In 1996 a dedicated Research Engineer was appointed to the project by G-MW while QDNR provided an officer to work on the project part-time.

3. Research Procedure

3.1 Terms of Reference

Terms of Reference were prepared by the Steering Committee. This determined the aims and objectives of the research project and directed the Research Teams into specific areas of research.

3.2 Literature Review

A world-wide literature review was conducted by Sinclair Knight Merz. The search covered Australian and overseas databases for articles in English published in the last twenty years. This search yielded some useful information but to a great extent was of an academic rather than a practical focus.

The climatic and installation conditions of many countries are very different to Australia, and a considerable number of technical references, covering such topics as sub-artic conditions and third world countries, were not applicable to Australia.

These references have been catalogued on a *Microsoft Access* database which is available on request. References can also be found at the end of each section of the Guidelines.

It was found during the Survey of Authorities that a large amount of unpublished information was held by irrigation authorities in the form organisational communications; memos, technical manuals, project reports, plans, cost estimates, etc. These documents provided the research teams with a substantial amount of practical information on what practices and procedures are currently used in Australia. Personal communications with authority staff also yielded much useful information.

The research teams also sought product data from contractors, suppliers and manufacturers and specialist information from consultants.

Much of this information is presented in the Guidelines so that it can be shared by irrigation authorities throughout Australia.

3.3 Survey of Authorities

A review and documentation of current problems and practices of public and private irrigation schemes in Victoria, Queensland, New South Wales, South Australia and Western Australia was carried out during 1996.

The Survey of Authorities consisted of:

1. initial contact with Authorities by letter and a short questionnaire to obtain information.
2. further consultation and semi-structured interviews with irrigation schemes identified from the written responses as having new or innovative practices
3. field inspections and data collection of irrigation schemes identified as industry leaders or representing current industry best practice in a particular field

4. establishment of a network of key contact personnel in all irrigation schemes for consultation during the course of the project and dissemination of research outcomes

3.4 Investigation Program

A program of investigation and trials were then carried out to address the knowledge gaps in the following specific areas:

- causes of channel bank deterioration
- measures to reduce the rate of deterioration
- material selection for bank construction
- bank design
- new bank construction
- bank refurbishment techniques
- use of low quality materials
- geomembrane liners for seepage control
- seepage control
- batter erosion control measures
- yabby and carp control techniques
- standardised contract documentation

4. How to use these Guidelines

4.1 Who should read these Guidelines

These Guidelines are written for the technical reader, one who is required to deal with the design, construction, and refurbishment of earthen irrigation channel banks in all or part of its aspects.

4.2 Using these Guidelines

Effective use of these Guidelines will rely on the judgement of the reader.

Because of the diversity of conditions, circumstances and public and private irrigation schemes across Australia, totally prescribed solutions cannot be provided. Instead the Guidelines provide and understanding of the issues, available options and the relevant decision making criteria, so that each case can be treated on its merits for the most cost-effective solution to the site specific conditions.

The Guidelines are published in CD format so that sections can be printed if necessary, for those who require only specific sections of the Guide.

When more information on any particular aspect is needed, the reader should go to the references at the end of each chapter, to see what is available.

As feedback about the Guide is returned from the users, and as new research and development produces updated information, revised CDs will be released.

4.3 How the Guidelines are arranged

Readers are not expected to read these Guidelines from beginning to end. The order of chapters, or even sections within chapters, will not match all reader preferences or needs.

It is expected that in most cases, individual readers will refer to the Guidelines with a specific issue in mind. The Guidelines' organisation and indexing has tried to reflect this. Each chapter includes its own Table of Contents.

5. Acronyms

DNRE Department of Natural Resources and Environment (of Victoria)

G-MW Goulburn-Murray Water

LWRRDC Land and Water Resources Research & Development Corporation

QDNR Queensland Department of Natural Resources

SCADA Supervisory Control and Data Acquisition

SKM Sinclair Knight Merz

6. Units of Measurement

Quantity	Unit	Symbol
Length	metre millimetre kilometre micrometre	m mm km µm
Mass	kilogram milligram gram tonne	kg mg g t
Time	second minute hour day	s min h d
Area	square metre hectare	m^2 ha
Volume *Fluid* *Solid*	 litre megalitre cubic metre	 L ML m^3
Flow Rates	megalitre per day litre per second	ML/d L/s
Concentration/Density *Fluid* *Solid*	 milligram per litre kilogram per cubic metre	 mg/L kg/m^3
Velocity	metre per second	m/s
Acidity/Alkalinity	pH unit	pH
Grade	nil	Vertical : Horizontal
Seepage	cubic metres per square metre per day	m^3/m^2/day

6.1 References

Australian National Committee, International Commission on Irrigation and Drainage (1998), *Rural Water Industry Terminology and Units*

7. Symbols

A	area
B	bed width (m)
Ca	calcium; chemical element
CEC	cation exchange capacity
D	depth of channel at design discharge level (m)
EC	electro-conductivity: the electrolytic conductivity of a substance, normally expressed in units of Siemens per meter at 25°C
ESP	exchangeable sodium percentage
F	freeboard (m)
g	acceleration due to gravity (m/s^2)
LL	liquid limit
Mg	magnesium; chemical element
n	Manning's Roughness co-efficient
Na	sodium; chemical element
O	oxygen; chemical element
P	wetted perimeter (m)
pH	index of the concentration of the hydrogen ion in solution: a measure of acidity
PI	plasticity index
Q	discharge (ML/d)
R	hydraulic radius (m)
SAR	sodium adsorption ratio
S	slope of the water surface (m/m)
S_o	bed grade (m/m)
v	the average velocity of flow (m/s)
v_{max}	maximum permissible velocity in a reach (m/s)
v_{min}	minimum permissible velocity in a reach
Y	water depth in the canal

8. Earthen Irrigation Channels

8.1 Description

Irrigation systems require large volumes of water to be conveyed from storages to farms. Pipelines are an efficient means of water conveyance, but on economic grounds, channels supply the large irrigation systems in Australia, and most of these channels are of earthen construction.

An earthen channel is defined as an open channel excavated and shaped to the required cross-section in the natural earth or fill along a pre-determined route and of a pre-determined grade. Earthen channels are either classified as unlined or lined depending on the treatment of the wetted perimeter.

Water is often distributed within an irrigation scheme through a network of earthen channels because they can be constructed more economically than other available methods. The availability of water has been a determining influence in Australia, shaping the pattern of human settlement and economic development. Australia has large areas of land that have only been able to be used for irrigation through the construction of long lengths of earthen channels to transport and deliver water.

Main carrier channels are large channels which transport water to an irrigation area from the headworks. Distribution channels have smaller capacities and they distribute water directly to each farmer's land.

The design of earthen channel systems are based on functional requirements and the physical aspects of earthen construction. Earthen channels are generally designed with a trapezoidal cross section. This approximates the stabilised shape generally taken by natural streams and lends itself to construction and maintenance with equipment that is readily available.

If the channel bed is above the natural surface level, then the channel will be placed entirely in *fill*. When the entire excavation is below natural ground level, then the channel is in *cut*.

A typical cross-section of irrigation channel is shown in Figure 8-1 below:

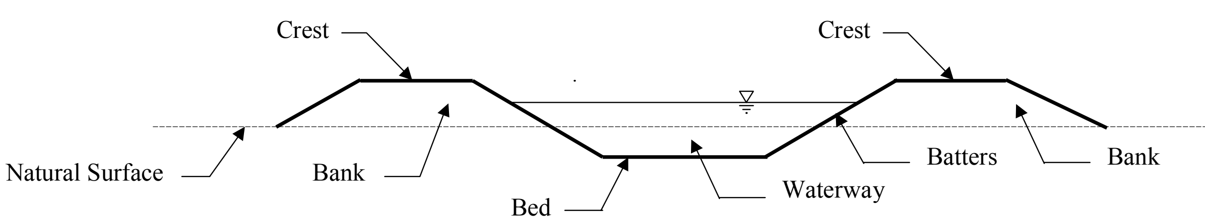

Figure 8-1 Typical Irrigation Channel Cross-Section

8.2 Length of Earthen Irrigation Channels in Australia

The length of earthen irrigation channels in Australia was surveyed during the research project for the Guidelines with an update from a more recent survey of irrigation authorities for the ANCID Seepage Project. These surveys established that there is more than 17,750 km of earthen irrigation channel in Australia. This does not include several smaller irrigation authorities and private schemes that did not respond to the surveys. The length of earthen channel per authority is given in Table 8-1.

Authority	**State**	**Length of earthen irrigation channel (km)**
Murrumbidgee Irrigation Limited	NSW	2,000
Coleambally Irrigation Limited	NSW	516
West Corurgan Private Irrigation District	NSW	565
Murray Irrigation Limited	NSW	3,800
Hay Irrigation Authority	NSW	20
Lowbidgee Flood Control & Irrigation District	NSW	50
Trangie-Nevertire Irrigation Scheme	NSW	250
Marthaguy Irrigation Scheme	NSW	60
Nevertire Irrigation Scheme	NSW	48
Colly Farms Ltd - Collymongle	NSW	200
Namoi Valley Water Users	NSW	880
Clyde Agriculture Ltd - Bourke-Brewarrina Irrigation Farms	NSW	200
Macintyre Irrigation Association	NSW	25
Eton Irrigation Area	Qld	44
St George Irrigation Area	Qld	114
Dawson Valley Irrigation Area	Qld	44
Bundaberg Irrigation Area	Qld	75
Emerald Irrigation Area	Qld	96
Mareeba-Dimbulah Irrigation Area	Qld	91
Burdekin River	Qld	305
Lower Mary River Irrigation Area	Qld	6
Pioneer Valley	Qld	35
Yambocully Water Board	Qld	3
Condamine Plains Water Board	Qld	12
Cubbie Station	Qld	70
Cressy-Longford Irrigation Scheme	Tas	155
First Mildura Irrigation Trust	Vic	4
Sunrasia Rural Water Authority	Vic	6
Werribee Irrigation District	Vic	2
Goulburn-Murray Water	Vic	6,952
Macalister Irrigation District	Vic	568
Wimmera-Mallee Water	Vic	112
Bacchus Marsh Irrigation Area	Vic	0
South West Irrigation	WA	284
Ord Irrigation Co-operative	WA	160
Loxton Irrigation Area	SA	0
	TOTAL	**17,752**

Table 8-1 Length of Earthen Irrigation Channels in Australia

8.3 References

Australian National Committee on Irrigation and Drainage (2000), *Channel Seepage Survey*

LWRRDC (1996), Project G-MW1, Construction and Refurbishment of Earthen Channel Banks, *Review of Current Practice in Victoria*

9. Channel Bank Lives

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Subject **Page No.**

9.1 Introduction

A key input to advanced life cycle asset management is the ability to predict the decay of assets and thus the estimation of asset lives and failure modes.

A channel can be considered to have two main components, the constructed banks and the excavated waterway. From a renewals perspective, the excavated waterway below natural surface can be considered to have an infinite life provided it is adequately maintained.

However, channel banks do not last indefinitely. There is a deterioration of condition with time (at varying rates), and the ageing processes mean that banks have a definite life eventually requiring renewal or replacement. This may reflect not only deterioration in physical condition, but also level service, function, capacity and safety. Figure 9.1 illustrates a typical bank deterioration process.

Channel bank life is defined as the period in years from the time of construction to the time when the channel falls below an acceptable limit or at failure. The failure modes include:

- lack of capacity (over-utilisation)
- inefficiency (costs)
- obsolescence
- level of service (reliability)
- structural integrity (condition) and
- under-utilisation (no longer required).

The useful life and mode of failure of a channel bank can be influenced or affected by many physical and environmental factors that will cause identical channel banks to fail in different ways over a variable period.

The assessment of channel bank lives can therefore be a complex process, and at best, only an estimate of average life can be made. The problem with long-lived passive assets is the ability to predict, with a high degree of confidence, the time at which failure or a sharp decline in level of service is likely to occur.

Predictions of channel bank lives can be based on:

- condition monitoring and deterioration rates
- historical records using survivor techniques
- degradation models
- accumulated experience
- engineering judgement

Goulburn-Murray Water in Victoria has some 6,700 km of irrigation channel constructed over the last 100 years. Channel construction began in the 1880's and continued until the 1960's, and from the 1970's to the present time, the emphasis has been on channel re-construction.

Goulburn-Murray Water therefore has a wide spread of channel ages, from new banks to banks constructed over a 100 years old, and this has provided a guide to how the condition of its channel banks will deteriorate with time.

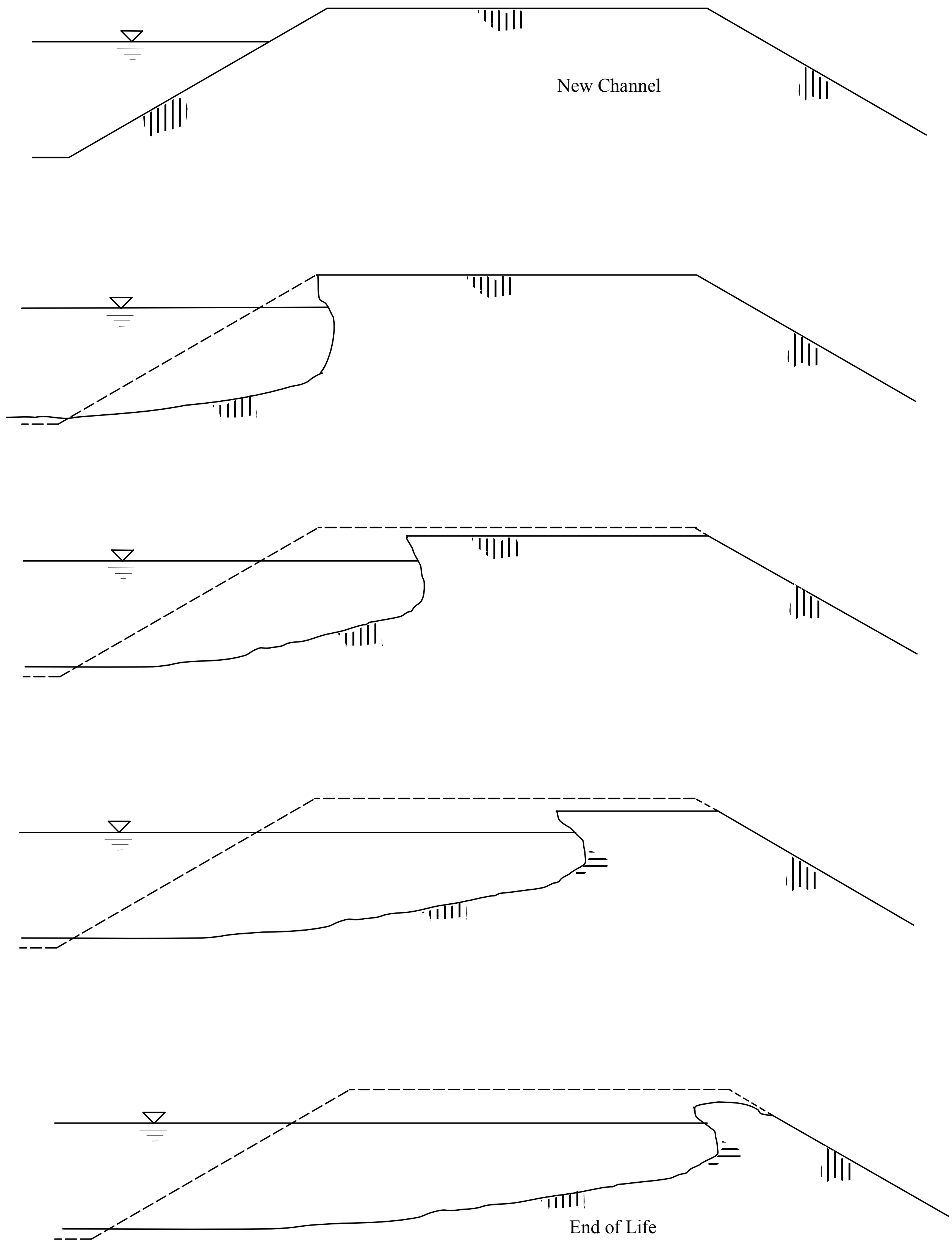

Figure 9.1 Typical Channel Bank Decay Process

Data from Goulburn-Murray Water's asset management information system, which includes the date of construction, condition rating and length of each channel, has been used to estimate the average life of channel banks.

The weighted average life of channel banks across Goulburn-Murray Water is estimated to be 90 years for the banks of smaller distribution channels and 130 years for the banks of major supply channels. Refer to Table 9-1.

Channel Name	Estimated Average Life (years)
Main Channels	
Yarrawonga Main Channel	100
East Goulburn Main Channel	100
Goulburn-Waranga Channels	150
Waranga Western Main Channel	130
Torrumbarry Bulk Carriers	100
Distribution Channels	
Shepparton Area	85
Central Goulburn Area	70
Rochester-Campaspe Area	85
Pyramid-Boort Area	100
Murray Valley Area	85
Torrumbarry Area	100

Table 9-1 Estimated Earthen Channel Bank Average Lives - Goulburn-Murray Water

The investigations by Goulburn-Murray Water to determine the lives of its channel banks highlighted the lack of understanding of the processes involved. It indicated that the rate of channel bank deterioration is not constant and more long-term research was required into channel bank useful lives.

A range of factors, as well as the interaction of these factors, affect channel bank lives and the rate of deterioration. These may include the following:

- design criteria
- size and width of bank
- velocity of flow and flow history
- age of channel
- depth of channel
- construction methods and quality control
- bank material –soil type
- usage history
- environment
- frequency and intensity of livestock access
- aquatic fish and animal activity in the channel- carp
- bank orientation relative to prevailing winds
- operating practices and running levels
- fluctuations in water level – magnitude and rate
- maintenance regimes – past and current
- extent and quality of refurbishment

- amount of vegetation and weed growth in waterway
- adjacent farming practices
- vegetation and tree growth on or adjacent to the bank

These conditions can vary widely throughout an irrigation system and the relationship between factors cannot be predicted. A variation in bank life is therefore to be expected.

With an increase in peak water demands in recent times many older channels are now subject to greater heads and velocities than they were originally designed for, resulting in more rapid deterioration and greater maintenance requirements. It is therefore questionable to predict channel bank lives solely on the basis of past records.

9.1.1 Decay curves

Decay curves map the deterioration in condition of an asset over its life.

Most channels do not decay uniformly (in a straight line), they typically deteriorate at different rates over their life cycle, and the environment in which they operate and the way in which they have been maintained and operated affects the rate of deterioration.

The deterioration processes can be quite slow, particularly initially and condition monitoring is required to detect the deterioration. A generic asset condition rating system used by Goulburn-Murray Water is set out in Table 9-2.

The use of condition assessments assists in the identification of optimal renewal (intervention) strategies and maintenance plans.

Knowing the different conditions of a channel over its life, it is possible to postulate typical decay curves for those channels operating under similar conditions. This enables asset owners to more realistically predict future performance, the life of the channel and cash flow requirements.

Figure 9.2 illustrates a life-cycle cost stream for a channel. It shows how the condition of a channel can be preserved over its service life if condition responsive maintenance and rehabilitation actions are properly timed.

Decay curves that model the deterioration rate of channel banks have been developed by Goulburn-Murray Water based on accumulated experience and observational data of its channels. The predicted decay curve for Goulburn-Murray Water's distribution channel banks is shown in Figure 9.3.

The dominant deterioration mechanism observed in Goulburn-Murray Water channels is the slumping of the waterside batters as illustrated in Figure 9.4. This can be modelled as a slip circle failure in the saturated material, which lumps into the channel. The crest of the bank is then undermined on the waterside, and subsequently a piece of the top of the bank shears vertically. The process being repeated again and again.

Following construction, it takes a period of time for the unstable waterside batter to develop, after which the deterioration continuous at a relatively constant rate. There is a slowing of the deterioration rate as a result of increased maintenance, and then acceleration in a relatively short period to the minimum acceptable level. After this point the condition is generally stable because it cannot get much worse.

General Description	1	2	3	4	5	6
Risk of Failure	None expected	Low	Medium	High	Imminent	Failed
Frequency of Concern	None expected	Very occasionally	Occasionally	Frequently	Continuously	Too late
Maintenance Emergency	None expected	Minor occasionally	Minor frequently	Major occasionally	Major frequently	Too late
Maintenance – Routine/ Preventative Required	Minimal	Relatively low frequency	Relatively medium frequency	Relatively high frequency	Effectively continuous	Too late
Maintenance Backlog Likely	None	None	Minor	Major	Too late	Too late
Restrictions on intended Service or Function	None	None	None but imminent	Minor	Major	Effectively no service or function
Overall Appearance	Near or as new	Good	Fair/mature	Poor – approaching end of serviceable life	Damaged/ near collapse but still serviceable	Collapsed/ damaged & unserviceable
Consumer Complaints about Poor Maintenance & Asset Condition, Leak, Flooding & Safety	Nil	Very occasionally	Occasionally	Frequently	Very frequently	Too late

Notes:

1. Failure means asset is effectively unable to provide it previously intended service or to perform it previously intended function.
2. Only use general description where specific condition rating descriptions are not available.

Table 9-2 Goulburn-Murray Water Asset Management – General Asset Condition Rating Description

The development of decay curves is not a straightforward process. For many long life assets complete information is usually not available and the data collection to construct the decay curve will frequently involve both objective measures (known points) and subjective measures (staff experience). Past decay rates may not be a good guide to future rates because of changed factors. Considerable data is required, as well as an understanding of the relationships between the variables influencing the deterioration process. It is an inexact science and a continuous improvement approach is needed, with decay curves refined over time, as improved information becomes available.

To better understand the long term deterioration rates of channel banks, Goulburn-Murray Water has established benchmark cross-sections on a number of channels of varying ages, and these cross-sections are being surveyed every 5 years to determine the long term rate of deterioration.

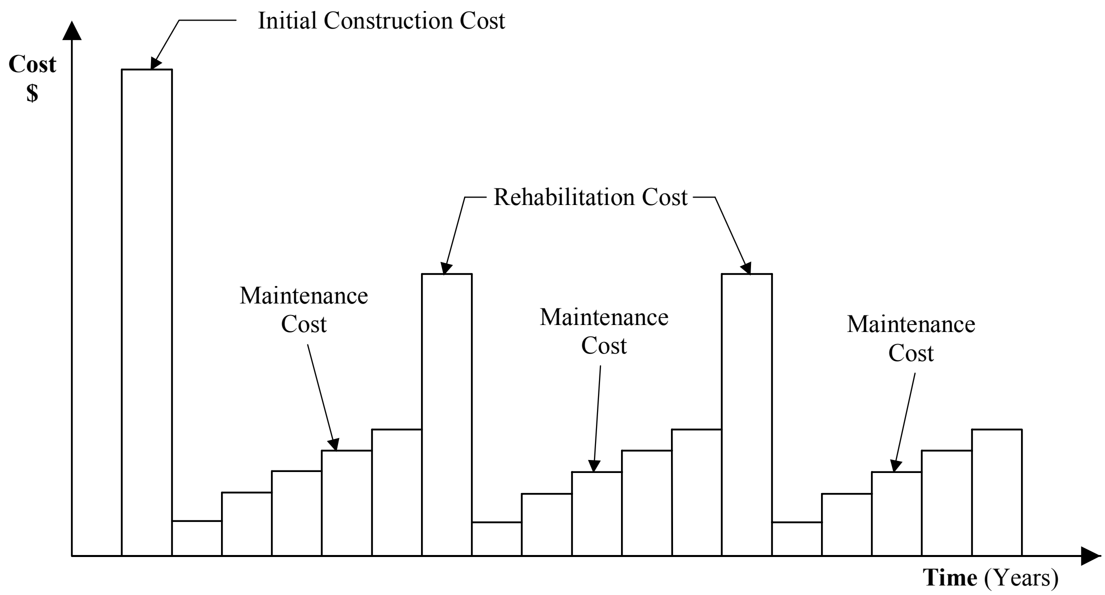

Figure 9.2 Life-cycle cost stream

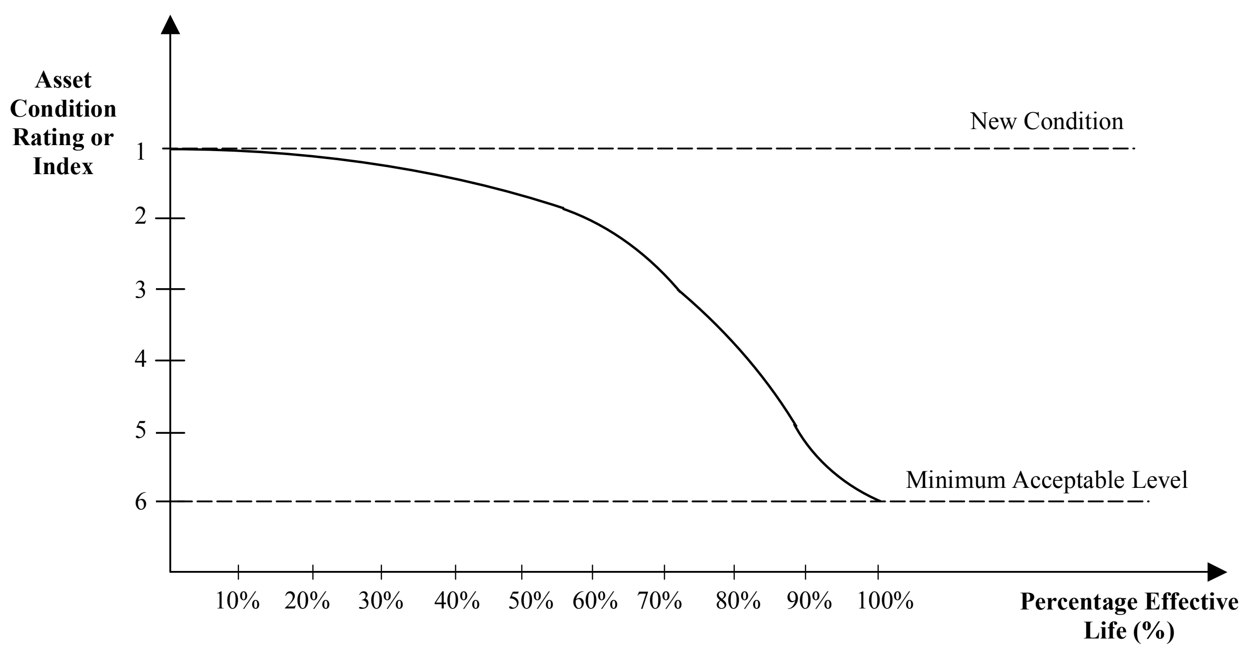

Figure 9.3 Goulburn-Murray Water Channel Decay Curve

9.1.2 Development of Optimal Intervention Strategies

A channel will pass through a number of phases during its life cycle, and these provide opportunities for intervention, which along with maintenance may include rehabilitation and replacement. There will be specific timings and costs associated with each of these actions. This is illustrated in Figure 9.5, a typical asset decay curve.

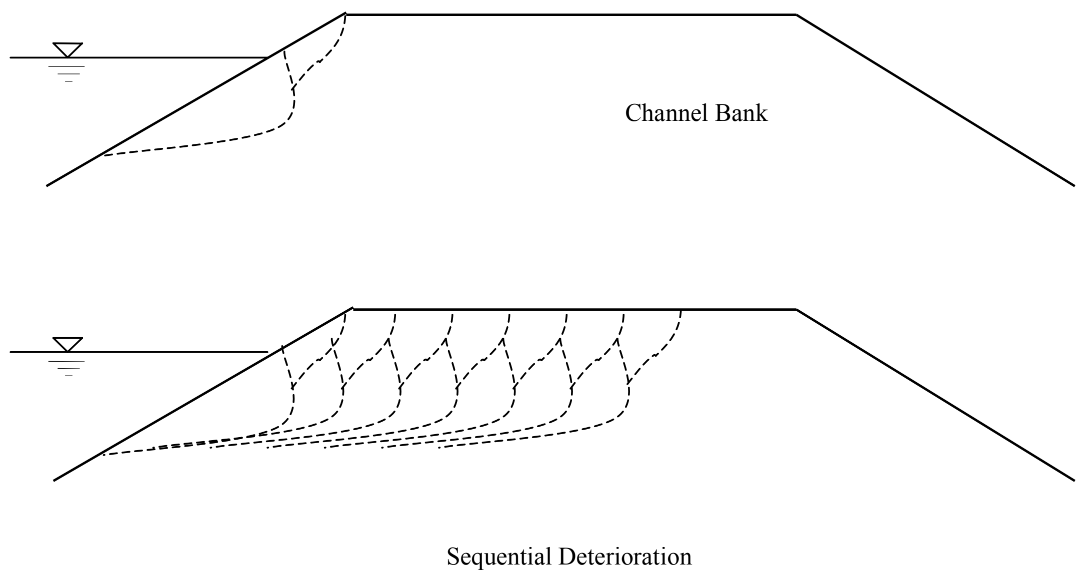

Figure 9.4 Goulburn-Murray Water Channel Deterioration Mechanism

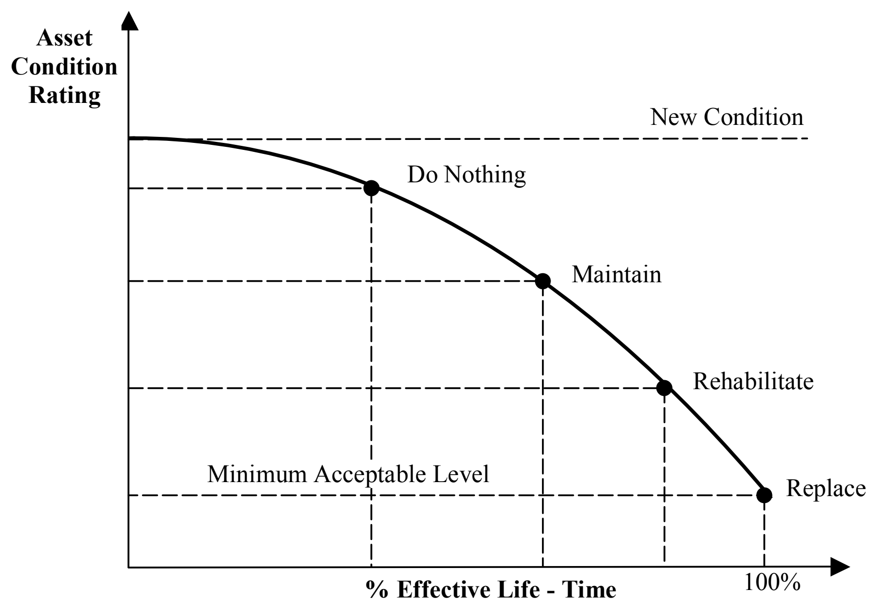

Figure 9.5 Typical Asset Decay Curve

Generally the following intervention strategies are possible:

- Do Nothing – In this phase, the channel decays only marginally, and there is nothing that the asset owner can do with current technology to significantly alter that decay curve.
- Maintain – During this phase, channel decay will include forms of distress that can be rectified by regular maintenance activities. Throughout this period maintenance costs will rise from a low to a high level.
  Different levels of preventative (planned) maintenance should be assessed during this phase

- Rehabilitate – During this phase, the channel has decayed to such an extent that maintenance cannot restore the condition or performance of the channel and rehabilitation is required.
  Various rehabilitation options should be considered to identify the optimum time and treatment.
- Replace – Once the channel has decayed into this zone, its condition or performance has deteriorated to such an extent that rehabilitation is not possible and the only effective treatment option available is to replace the channel either before failure (high consequence of failure) or after failure.

Opportunities for the most cost-effective solution may be lost if the deterioration is allowed to go too far.

Irrigation authorities need to be aware of the condition and performance of their channel assets. They need to adopt appropriate renewal and maintenance programs to achieve the lowest life cycle costs for their customers.

Applying Optimised Renewal Decision Making (ORDM) analysis, an evaluation of decay curves and life-cycle costs can lead to effective treatment or intervention strategies for maintenance, rehabilitation and replacement of channel banks. By developing strategies and identifying intervention levels, optimal maintenance and renewal programs can be developed.

Depending on factors such as the existing condition and criticality of a channel, the various treatment options that could be considered include:

1. *Utilisation options*
   - Operate differently
   - Maintain differently

2. *Non-asset solutions*
   - Demand management
   - Operator training
   - Reduce level of service

3. *Renewal options*
   - Rehabilitate
   - Replace

4. *New Work options*
   - Create new asset
   - Augment existing asset

5. *Disposal option*
   - Asset rationalisation

6. *Status Quo*
   - continue existing practices

To undertake optimised renewal analysis, considerable data is required, and all of this data may not be available. To overcome this a number of assumptions may have to be made based on interviews with experienced staff and tested in sensitivity analysis. This approach can be used to identify areas of greatest potential benefit and drive continuous improvement programs in these areas.

Refer to Section 13, Life Cycle Cost Analysis.

Life cycle asset management is outside the scope of this manual and readers should refer to the technical references for further information on the functional processes.

9.2 References

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10 Channel Bank Deterioration

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10.1 Causes of Channel Bank Deterioration

10.1.1 Introduction

This section provides a broad overview of the causes of channel bank deterioration.

The aim is to facilitate a better appreciation of the causes of deterioration, and the importance of a thorough understanding of the local deterioration processes before undertaking channel bank construction and refurbishment works.

There are many factors attributed to causing the deterioration of earthen channel banks and these factors will vary considerably across Australia. Deterioration, however mild or severe, generally will be due to a combination of factors, many of which are not amenable to modelling. However, if the deterioration mechanisms are recognised, then experience has shown that a combination of good design, construction, operation and maintenance practice, can prevent or significantly reduce their impacts.

This is an important awareness and education issue for channel operators and managers.

Channel bank deterioration factors can be grouped into the following:

- Design
- Bank Material
- Construction
- Operation
- Maintenance
- Stock & Vermin
- Adjacent Landholders
- Environment

Table 10-1 lists the deterioration causes and their specific factors, with hyperlinks to their descriptions which follow.

Causes of Deterioration	Specific factor	Causes of Deterioration	Specific factor
Channel design	• Design Standard • Shape of channel cross-section • Depth, width and capacity of channel waterway • Bank height above natural surface • Bends • Channel reach length • Orientation of channel in relation to prevailing winds • Meander formation	Maintenance	• Over-excavation and steepening of batter slopes • Core-Trenching • Vegetation and weed growth • Weed control techniques • Adjacent trees • Siltation • Inadequate Maintenance Levels
Bank material	• Soil type • Bank Cracking • Bank heaving and slumping • Piping	Stock and vermin	• Stock Access, ie. cattle • Fencing • Carp • Yabbies/fresh water crayfish • Vermin and control techniques
Construction	• Construction technique • Construction quality control • Adjacent borrow pits	Adjacent landholders	• Impact of adjacent farming practices on the bank • Farm vehicle traffic on bank
Operation	• Degree of operational supervision • Operational practices of Control Structures • Water level fluctuations • Channels running above design operating level • Overtopping of banks • High water velocities • Turbulence at structures and bends • Channel filling and drawdown • Operational vehicle traffic on top of banks	Environment	• Wind/wave action • Rainfall • Channel water quality

Table 10-1 Causes of Channel Bank Deterioration

10.1.2 Channel design

The channel design standard has a large impact on the life of channel banks. An inadequate design can allow the banks to be subject to a high rate of deterioration with a subsequent reduction in channel bank life.

10.1.2.1 Design Standard

The design standard of a channel bank will vary according to the design life of an irrigation scheme. Generally private schemes have a short design life (20-30 years) with a low capital cost but higher annual maintenance costs.

Government schemes generally have a long design life (80-100 years) with a high capital cost but low annual maintenance costs.

10.1.2.2 Shape of channel cross-section

A good design cross-section will provide:

- satisfactory bank width
- adequate waterway width and depth
- appropriate batter grades. Refer to Section 12.17.4.1 Inner Slopes.
- the required bank design life
- ease of construction
- adequate protection from vermin and environmental degradation
- take account of the structural stability of the bank-building material
- allow all operations and maintenance activities to be carried out efficiently

Any deficiency in the above can cause premature deterioration of the bank and so prevent the channel bank from attaining its required life.

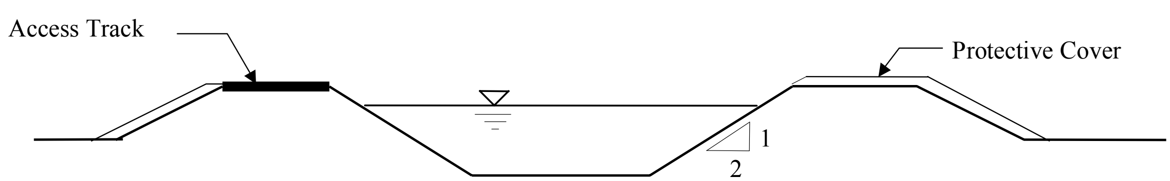

Figure 10.1 Typical irrigation channel cross-section

Typical irrigation channel

Photo 10-1 New Irrigation Channel

10.1.2.3 Depth, width and capacity of channel waterway

Design depth, width and design capacity all effect the flow pattern of water down the channel. Inadequate design can result in undercutting of banks and/or silt deposition in the bed the of channel. These may result in further erosion of banks.

10.1.2.4 Bank height above natural surface

High banks are more prone to erosion than low banks. The greater the head of water on the bank, the greater the tendency for increased leaks and seepage. Also as there is a large exposed back of bank there is more likely to be damage due to shrinkage cracking if the bank is not protected.

High banks

Photo 10-2 Channel Bank over three metres high

10.1.2.5 Bends

A bend in the channel which has too small a radius will cause the erosion of the outside bank of the channel. The outside bank of a bend can be beached or an appropriate design radius is incorporated before construction.

bend

Photo 10-3 90 degree bend in channel

10.1.2.6 Channel reach length

Wave damage can occur on long channel reaches depending upon the orientation to the prevailing winds and how open the country is.

If a long straight reach of channel is aligned in the direction of the prevailing wind, large waves can develop which can overtop banks. A greater freeboard allowance and/or rock beaching may be required to protect the bank.

10.1.2.7 Orientation of channel in relation to prevailing winds

If a channel is planned in the same direction as the prevailing wind, waves can develop which can overtop banks. This problem is exacerbated if on a long channel reach as described above.

10.1.2.8 Meander formation

Some older channels form meanders which may replicate what happens in natural streams. This is due to siltation and local erosion of banks - it is a natural process of reducing the erosivity of the channel water by reducing its hydraulic head.

10.1.3 Bank material

Selection of appropriate bank material is critical to allowing a bank to reach its design life without excess erosion. The material must perform adequately under design conditions to ensure the design life of the bank.

Channels are commonly constructed in the higher lands of an irrigation area which normally corresponds with lighter more permeable soils. In older irrigation areas, channel banks were constructed with the available material on the channel alignment, regardless of the soil quality. The resulting leakage and seepage through the banks and bed of the channel leads to bank deterioration.

10.1.3.1 Soil type

The following physical and chemical properties of a potential bank-building material all effect the integrity of the bank:

- the physical characteristics of soils; particle size distribution, clay content, tendency to disperse (in irrigation supply water and/or rainwater), plasticity, hydraulic conductivity
- whether bank material is susceptible to shrinking and cracking during hot dry weather.
- the chemical characteristics of soils; pH, EC, Sodium adsorption ratio

Also the channel water chemistry will effect how the soil on the inside batter stands up to erosion and will determine to some degree the amount of seepage through the bank.

10.1.3.2 Bank Cracking

During extended dry periods, there will be some minor cracking as a channel bank material dries out. However, some soil types are more prone to cracking than others and cracking can be a serious problem. There are three main types of cracks due to the compacted bank drying out; transverse, longitudinal and shrinkage.

Many Australian irrigation authorities report increased number of channel bank leaks and bank failures during long periods of extreme dry weather. The leaks typically occur in the top section of the bank, where cracks have opened up across the bank and extended down below the water line. The bank dries and cracks from the top down and when the cracking zone reaches the level of water in the channel, water penetrates through the bank.

Once cracking begins, it becomes a self-aggravating process. The cracks allow air to circulate deeper into the bank causing differential drying and further cracking. The problem is worsened when rainfall runs into the cracks causing accelerated erosion of the bank, particularly where the material is dispersive.

10.1.3.3 Bank heaving and slumping

Bank heaving is the process which happens particularly with highly plastic material. The material shrinks on drying, but on subsequent wetting swells and heaves - possibly resulting in slumping.

Bank slumping is the process by which a segment of bank slips into the waterway. Bank material that slumps or slips down can occur on either the inside or outside batters of a channel bank. Stability failure and slides occurs most frequently on the inside batters where the bank material is saturated and more unstable, the batter slopes are too steep, the bank insufficiently compacted or the water level in the channel is drawn down too rapidly.

Rapid filling and draining of channels can cause bank slumping.

Bank slumping.

Photo 10-4 Clod of bank material undermined and slumped into channel

10.1.3.4 Piping

Piping is a term used when seepage water creates a tunnel or pipe along a line of weakness through the bank. This is a form of internal soil erosion. The two susceptible soils are dispersive clays and pervious material.

10.1.4 Construction

The methods of construction used have a large effect on channel bank lives and the rates of deterioration.

10.1.4.1 *Construction technique*

Irrigation channels constructed up to the 1940's were largely constructed with horse and scoop teams - these banks had a rounded shape with the soil compacted in layers by horse hooves parallel to the finished surface. Material for the banks was typically obtained from borrow pits adjacent to the channels with little or no control on material quality.

Modern techniques using mechanical equipment nearly always compact in horizontal layers. Construction techniques vary with excavators, dozers and compaction rollers used to construct banks.

Construction techniques

Photo 10-5 Channel bank construction

10.1.4.2 *Construction quality control*

Any lapse in quality control will most certainly result in a reduced life for the channel banks. Careful control needs to be taken of:

- soil selection
- bank construction techniques
- moisture content and compaction during construction.
- levels to ensure bank is constructed to design height.

10.1.4.3 *Adjacent borrow pits*

The early methods of constructing channel earthworks did not lend themselves to leading material from lengths of surplus to lengths with deficiencies, or to travelling a distance to make up deficiencies from remote borrow areas. Where the volume of material excavated from the waterway was insufficient for bank construction, borrow pits were frequently formed immediately outside the banks. These borrow pits can run more or less continuously along many old channels, being the largest where channels cross low ground and bank heights are greatest.

Borrow pits immediately adjacent to channels cause the following problems:

- they are generally full with water and create additional habitats for aquatic animals which migrate between channel and borrow pit causing leaks.
- seepage, if the phreatic line from channel supply level to natural surface intersects with the borrow pit (refer Figure 10.2).

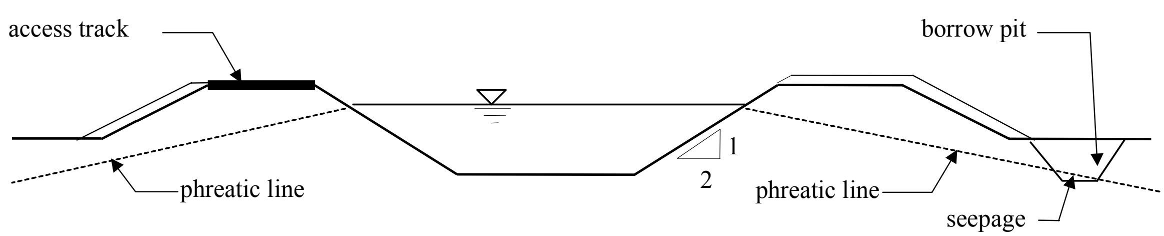

Figure 10.2 Phreatic line through channel bank

- encourages weed growth which can continually re-infest the channel.
- restricts ready access for inspection and maintenance of the channel bank.

weed growth

Photo 10-6 Weed growth in and adjacent to a leaking channel

10.1.5 Operation

Operational activities will effect the life of the channel on a day-to-day basis.

10.1.5.1 Degree of operational supervision

The number of staff employed and/or automatic monitoring and control of regulating structures needs to be considered in operating the channel in a fashion that will ensure the channel banks reach their design life.

10.1.5.2 Water level fluctuations

Normal channel operations result in some water level fluctuation. This constant wetting/drying of the bank in the fluctuation zone can prevent establishment of vegetative cover which could protect the inside batter and can also destabilise the bank material if it has weak physical or chemical characteristics. Water level fluctuations initially cause fretting at the waterline which then progresses into more serious erosion of the bank.

Rapid fluctuations of the water level speed up the bank deterioration processes considerably and can cause slumping of the saturated bank material into the channel. The steeper the batter slope, the greater the impact.

fretting at the waterline

Photo 10-7 Fretting at the waterline of a recently constructed channel bank

10.1.5.3 Channels running above design operating level

Running channels at levels higher than originally designed can lead to accelerated wear, increased scour and bank erosion, deterioration of channel capacity due to siltation from scour and erosion, and increased seepage which reduces channel bank life significantly. Refer to Figure 10.3. Excessive channel siltation and aquatic weed growth can reduce the waterway capacity and increase the channel running levels.

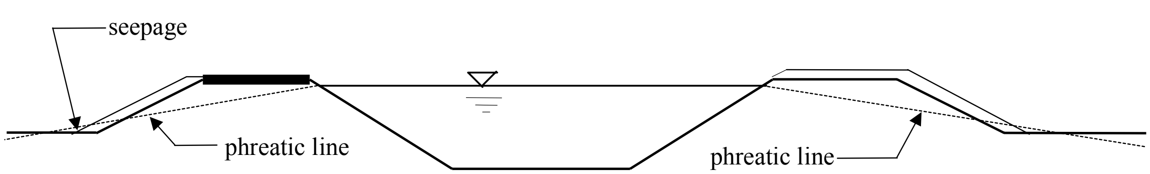

Figure 10.3 Phreatic line breached causing seepage

10.1.5.4 Overtopping of banks

In adequate freeboard is a widespread problem in channel systems, and is principally caused by erosion of channel banks.

If channels are run higher than the design operating level, the banks may be overtopped which will cause scouring of the crest and outside batter by the erosive effect of running water.

Many older channels are required to carry flows to the absolute limit of their capacity in an effort to provide irrigators with a satisfactory level of service. The limiting point is often a section of bank along the channel where no freeboard is available at maximum regulated flow. Any fluctuations that might occur above this maximum flow will cause water to spill over the banks. Resulting erosion can weaken the bank and create a serious risk of breaching.

10.1.5.5 High water velocities

Some channel operators are under increasing pressure to supply higher flow rates for shorter durations and this can require operating channels of higher velocities.

While the effects may not be immediately apparent, operating channels at velocities above design levels for extended periods of time can cause scouring of banks and bed leading to loss of bank material and reduced channel bank life. Refer to Section 12.11.3 Maximum Velocities.

scouring

Photo 10-8 Scouring of channel bank caused by high flows (structure originally flush with the bank)

The rate of bank deterioration is dependent on the characteristics of the bed and bank material and the flow velocity in the channel. Loose sandy soils free of cementing constituents are more easily eroded, where as, graded silt, sand and gravel materials containing cementing constituents are more resistant to erosion.

10.1.5.6 Turbulence at structures and bends

Channel structures such as regulators, culverts etc can cause downstream turbulence if not properly designed where substantial energy dissipation is involved. This turbulence can cause scouring downstream of structures, severely undermining and weakening banks. Typical problems are bed scour with batter collapse downstream of regulators, and batter and bank erosion caused by reverse currents downstream of culverts. In some cases this scouring stabilises to an equilibrium with a bell-shaped stilling basin being formed out of the banks and bed which reduces the erosive power of the water.

Poor channel operating practices, particularly of multi-bay regulators and offtakes can also cause scour of the bed and banks. Flows should be evenly distributed across the channel section and not concentrated in bays close to a bank.

bell shaped

Photo 10-9 Bell-shaped stilling basin eroded from banks and bed below regulator

This is primarily a structure issue rather than a channel bank issue, and designs for structures should ensure that energy dissipation is adequately controlled.

10.1.5.7 Channel filling and drawdown

Channels in temperate areas of Australia are normally not required to convey irrigation water during the winter months. Current practice in many irrigation authorities is to empty the channels which provides the advantages of:

- allowing frost to control weed growth
- reduces carp numbers in channels
- allows for construction works
- allows for maintenance activities such as de-silting and weed-spraying
- minimises accessions to watertable

However, deterioration of the channel bank can occur due to the following reasons:

- banks dry out and on re-filling channels leak and seep. Channels normally take up the extra moisture over a period of weeks and seal.
- rapid drawdown can cause slumping of saturated bank material into the bed of the channel. The steeper the batter slope the greater the impact.
- if stock have access to channel they may cause damage by walking through the empty channels.
- rapid filling of channels with dispersive soils can speed up the bank deterioration process and lead to piping failure and leakage.

Most Australian irrigation authorities do not have operating rules for the maximum rate of rise and fall of channel banks. Such operating rules would protect banks from slumping on drawdown and erosion on filling.

10.1.5.8 Operational vehicle traffic on top of banks

The use by operational staff during wet weather of dry weather access tracks constructed on top of channel banks can cause potholes and wheel ruts leading to tunnel erosion in dispersive soils and bank failure.

10.1.6 Maintenance

Adequate and timely maintenance of the channel banks and waterway appropriate to the local conditions shall allow a channel bank to reach its design life.

10.1.6.1 Over-excavation and steepening of batter slopes

The design cross-section of a channel can be severely damaged by excavators mechanically removing silt and weeds in an uncontrolled manner. The batter slopes can be increased to an unstable angle, increasing the rate of bank deterioration and siltation of the channel. The bed can be over-excavated so that the channel no longer drains out, accentuating weed problems if water lies in the bottom of the channel during the non-operational period. A channel lining can also be removed.

In the past maintenance techniques such as de-silting and mechanical weed removal using a dragline had a large impact on the inside profile of channel banks. Depending upon the skill of the operator the effect could be beneficial with the inside batter slope reinstated to a 1:2 profile curtailing the undermining/slumping of bank erosion. However de-silting could also have a detrimental effect; if not carried out carefully it could steepen batters by cutting too much bank at the toe.

Modern hydraulic excavation equipment is flexible and manoeuvrable and the integrity of the channel bank profile should be preserved while carrying out such maintenance activities.

Chemical weed spraying has reduced the need for mechanical maintenance in areas where siltation is not a big problem.

10.1.6.2 Core-Trenching

Core-trenching of banks is sometimes carried out to reduce seepage or leaks from banks. However core-trenching of channel banks with unsuitable or short-lived materials can accelerate deterioration of banks.

10.1.6.3 Vegetation and weed growth

Excessive weed growth in channels means that the water level in the channel must be higher to pass the required flow. Channels running too high increase the head on the bank and lead to increased seepage, leakage, over-topping and bank erosion.

The loss of capacity in irrigation channel through the growth of aquatic weeds is a widespread problem in Australia. A range of submerged, floating and emergent weeds can severely reduce channel capacities.

Weed growth is a problem for access but can be easily controlled by chemical means or controlled grazing. Grazing always presents the risk of erosion damage, however. A cover of grass, weeds, small shrubs etc will provide some protection to channel banks from stock damage and environmental erosion. However banks should be checked regularly to prevent any growth of trees or noxious weeds. High grass may present a problem to adjacent landowners as a habitat for vermin and be a fire hazard, as well as limiting access to operation and maintenance staff.

Weed growth

Photo 10-10 Weed growth in channel – arrowhead

10.1.6.4 Weed control techniques

If carried out carefully weed control does not cause deterioration to banks. In the past mechanical weed control often over excavated channels, steepening batters which contributed to the banks' erosion. Generally mechanical methods of vegetation and weed control are undesirable and more costly than chemical control.

10.1.6.5 Adjacent trees

Trees can have a number of benefits, including watertable control, aesthetic appeal, environmental enhancement, and provision of wind breaks, shade and timber. While trees may well provide the above benefits, trees from either intentional planting or natural seeding, immediately alongside or on channel banks can lead to a number of significant problems:

- The tree roots may cause damage to the channel banks and batters.
- Trees can fall over or drop limbs, damaging fences and structures or impeding the flow in the channel.
- The roots of some species (eg willows) can severely restrict the channel waterway.
- Access for operation and maintenance can be impeded.
- The margin of land for disposal of silt can be reduced.
- Controlled grazing for weed control may not be possible in the years it take the trees to become established.
- The trees may be in danger from channel weed control operations.

Trees send out their roots over long distances to seek food and water. When a tree dies the roots will rot and form tunnels which allow water to leak through the bank. The tunnels thus formed can lead to failure through piping erosion, and are exacerbated by the presence of dispersive clays. It is not only dying trees that cause problems. Trees that are alive and apparently vigorous can have dying roots with similar consequences. Shrubs can provide a habitat for burrowing animals and these can do serious damage to a channel bank. High winds can blow over trees and damage banks.

The intrusion of tree roots can require complete re-construction of a bank to overcome leaks.

Trees on channel banks

Photo 10-11 Trees on channel bank

10.1.6.6 Siltation

Siltation of channels reduces the waterway and increases the likelihood of dense aquatic weed growth that will cause channels to run above design levels. Periodic removal of silt is necessary to restore original design capacity and control weed growth.

Compared with other countries where more use is made of river run with high silt loads, there are relatively few channels in Australian irrigation systems in which rapid and excessive siltation is a problem. In most cases, siltation is a gradual process taking place over many years.

10.1.6.7 Inadequate Maintenance Levels

The condition of a channel bank will deteriorate with time, and a regime of maintenance, starting when the channel is new, is necessary to slow the rate of deterioration.

Maintenance is a continuing requirement. Reduced or delayed maintenance may reduce immediate costs, but it can also:

- shorten the effective life of a channel bank
- decrease levels of service
- reduce the efficiency of the channel system
- increase the risk of failures

resulting in heavy future rehabilitation costs or a degraded channel system.

In the early years of a channel bank's life, deterioration is usually slow, and the maintenance requirements are low. However, as the channel ages there can be ongoing tendency to give little priority to funding of inspections and maintenance.

Some irrigation system managers give preventative maintenance activities a lower priority because it does not show an immediate benefit. This can be false economy. Short term cost cutting can have long term cost penalties in increased maintenance and replacement costs, reduced channel bank lives and reduced system efficiency.

Adequate and regular maintenance of earthen channels is as necessary as proper design and construction, since overall expenditure will usually be minimised. The nature and extent of maintenance required, in general, will largely be dependent on the condition of a channel, and this is often linked to the age of the channel.

10.1.7 Stock and vermin

Earthen channel banks can be easily damaged, and stock can do a considerable amount of damage to channel banks in a short period of time if unchecked. Adequate protection of banks needs to be provided to reduce or prevent such damage.

10.1.7.1 Stock Access, ie. cattle

Channels should not be used for stock watering, stock feeding or the movement of stock because of the extensive damage and water pollution that this can cause. Stock on banks can cause erosion of the whole profile of the bank; crest, outside batter and inside batter. It is particularly important to keep stock off channel banks constructed from dispersive clays. Stock push bank material into the waterway while drinking, and their close-grazing habits leave banks bare and exposed to erosion by wind and rain drying and cracking. The greater the intensity of heavy stock on a channel bank, the greater the impact on channel bank deterioration. The reinstatement of channel banks damaged by stock can be costly and the deteriorated water quality, contaminants and stock disease risks which may be passed to downstream users can be just as great a concern.

Stock on banks

Photo 10-12 Cattle damage to channel

10.1.7.2 Fencing

Fencing is recommended where ever stock are concentrated on adjacent land. They may also be necessary to prevent landowners encroaching on the channel reserve for their own purposes; such as using it as extra horticultural/pasture land, stock laneways, for farm vehicles and machinery.

Many channels, particularly earlier constructed channels, are not fenced off from the holdings they pass through and are thus open to damage from farming activities.

Refer Section 23, Measures to Reduce the Rate of Deterioration.

10.1.7.3 Carp

The conditions in earthen irrigation channels are an ideal environment for carp and their erosive feeding behaviour is perceived to cause undermining and slumping of channel banks.

Carp are now found throughout the Murray-Darling Basin. Much anecdotal evidence of the erosive capacity of Carp has been recorded and there is a strongly held view by channel managers in south-eastern Australia that carp are a major contributor to bank deterioration. However this has not been scientifically quantified. Only one scientific study of the effect of Carp on Channel Banks has been carried out to date - by the CSIRO at Griffith, NSW. This study has had no conclusive results to date.

The observation in G-MW channels is that where carp are present, the channel waterway is *mumbled*- indentations where the fish vigorously suck on the silt for nutrients from plant roots and micro-organisms. These channels are often bare of vegetation on the inside batters as the carp suck on the bank material and the binding vegetation roots, eventually undermining sections of the bank and causing collapse into the waterway.

It is the view of experienced operational and maintenance staff that the rates of channel bank deterioration in Goulburn-Murray Water have increased in the last 20 years, following with the appearance of carp in the channel systems in the 1970s.

mumbled

Photo 10-13 Mumbling on channel bed and banks

Carp have been called many names. In Australia, the carp has commonly been know as the European Carp. It is recommended that the word European be dropped as Carp is among the most standardised common name in the word. It is also probable that the species had its origin not in Europe, but in Asia minor.

For further discussion on carp, refer to Section 23.5, Reduction of erosion due to Carp.

10.1.7.4 Yabbies/fresh water crayfish

Yabbies are prevalent in channels which have silty-clayey banks and beds. They are not found in sandy areas. Yabbies are an aquatic animal that burrow close to water level under the rootzone of plants. If water levels fluctuate yabby burrows can be found up and down the wetting/drying zone. These can form large holes in the bank. These can cause slumping on their own, but the observation is that slumping occurs with the combined activity of Carp feeding on bank material. If there are borrow pits or drains at the back of the bank that are normally filled with water, yabbies will also tend to migrate between channel and borrow pit causing leaks.

yabby burrows

Photo 10-14 Yabby burrows in channel bank

large holes

Photo 10-15 Detail of yabby burrows

10.1.7.5 Vermin and control techniques

Other animals that can cause problems to channel banks are rabbits, foxes and water rats which burrow into banks.

10.1.8 Adjacent landholders

10.1.8.1 Impact of adjacent farming practices on the bank

Deterioration of the channel bank can occur due to adjacent landholder activity particularly if the channel is not fenced. Landholder practices which may cause damage include:

- using the bank as an elevated farm laneway
- allowing stock onto bank to graze
- allowing stock to drink from the channel
- encroachment of crops and using the bank as a headland
- placing farm channel against channel bank
- removing material from the back of channel bank for farm use
- placing cuts in the bank to obtain unauthorised supplies of water

10.1.8.2 Farm vehicle traffic on bank

If channels are trafficked, particularly when wet, potholes and wheel ruts may form which could lead to tunnel erosion in dispersive soils. Farm traffic may also prevent operations and maintenance staff accessing the channel.

10.1.9 Environment

Environmental deterioration may happen progressively over time due to wind, channel water and rainfall erosion. Serious erosion can happen very quickly in areas subject to intense rainfall if the banks are not protected by vegetation. Rainfall can cause rilling erosion which can lead to failure of the bank.

10.1.9.1 Wind/wave action

Banks can be damaged through wind generated waves causing erosion at the waterline. This process if allowed to continue unchecked for some time, can seriously reduce the bank cross-section. It occurs mostly on wide channels in particularly those with long reaches running in the direction of prevailing winds.

10.1.9.2 Rainfall

Rainfall water is of very low salinity. If the channel bank is exposed (not grassed) and the bank material is dispersive, tunnelling may occur if the rainwater is allowed to pond on the crest. Rilling of exposed inside and outside batters can also occur.

Rilling

Photo 10-16 Rilling of outside batter caused by rainfall

Intense rainfall during the wet season which occurs in tropical areas of Australia can cause physical damage to the compacted bank causing potholes and rilling of batters. If soils are also dispersive, tunnelling failure may then occur as described in section 10.2.4.

10.1.9.3 Channel water quality

Water chemistry can interact with the wetted soil of the bank as follows:

- If soil has a low Emerson class number, water of low salinity (low cation concentration) will tend to cause erosive problems.
- If water has a high cation concentration, (particularly Ca^{++}), the soil will take up the cations from the water and form stable compounds. Over time an equilibrium will occur and these banks will no longer be subject to erosion caused by dispersion.

10.2 Understanding the Processes

Many of the causes of deterioration listed in section 10.1 do not cause bank failures in themselves. It is often the combined action of several of these factors which will cause failure over time. Some of these processes are described below:

10.2.1 Inside Batter Erosion

Inside batter erosion occurs by several different modes of failure as shown in Figure 10.4 through to Figure 10.8. Different modes may act simultaneously. Refer Section 18, Inside Batter Treatment.

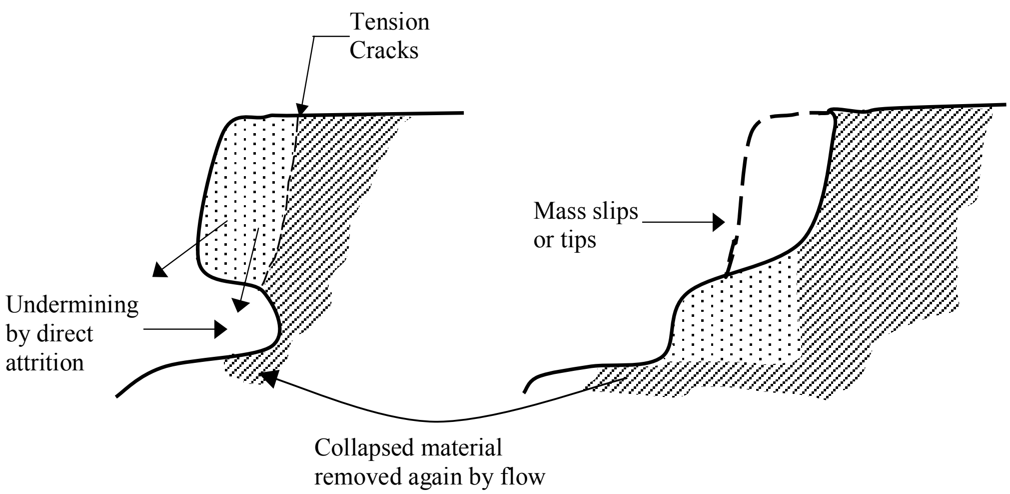

Figure 10.4 Collapse following undermining

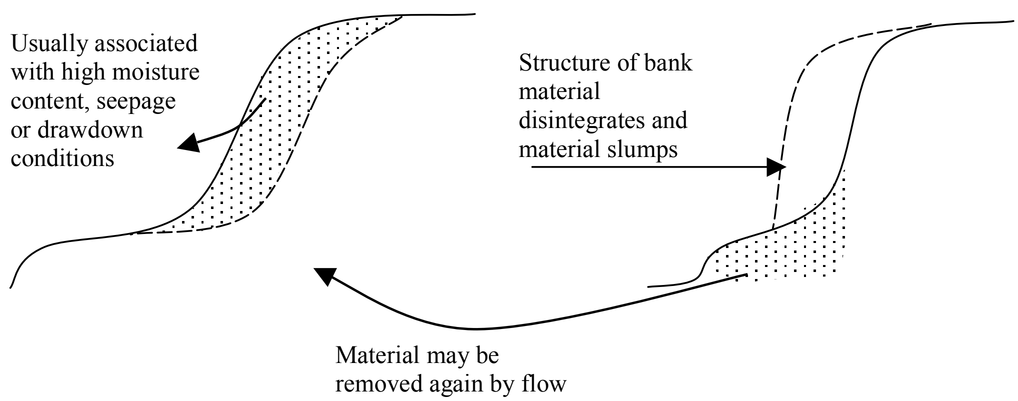

Figure 10.5 Slumping

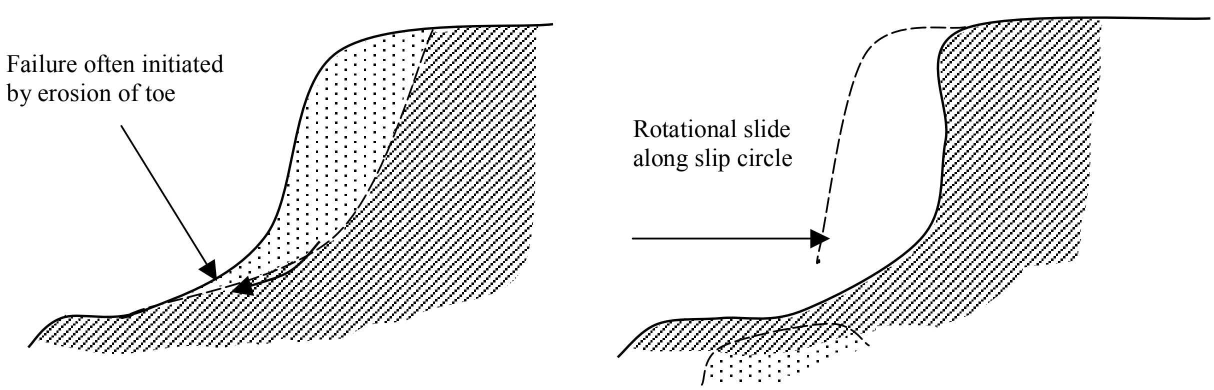

Figure 10.6 Rotational or Slip Circle Failure

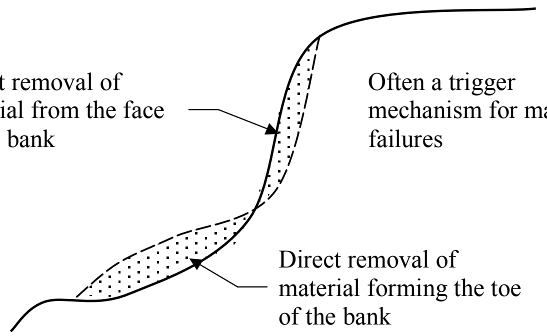

Figure 10.7 Attrition

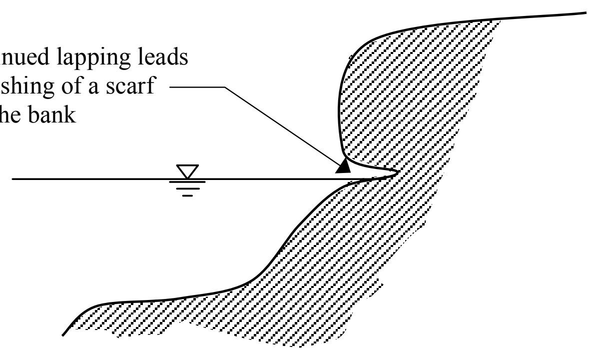

Figure 10.8 Fretting

10.2.2 Cracking

Soils prone to cracking are highly plastic, swelling when wet and shrinking on drying. The characteristics of this type of soil is described in more detail in Section 15, Material Selection and Testing. In periods of dry weather it is common for minor surface cracking of the channel bank to occur. This is a normal cyclic occurrence and these minor cracks should seal up during the next period of wet weather. However more serious cracking may occur which can lead to rapid failure of a bank.

Where banks are inadequately protected the exposed surface loses moisture and as the material dries and shrinks, surface cracks begin to open. Once cracking begins in the surface of the bank, it may become a self-aggravating process. The crack allows air to circulate deep into the soil causing differential drying and leading to further cracking at depth.

These shrinkage cracks develop in a random pattern of both transverse and longitudinal cracks. The transverse cracks running across the bank can allow seepage to begin, and lead to failure of the bank. The longitudinal cracks are not quite as serious a problem as transverse cracks. However if rainwater collects in cracks on a bank constructed of dispersive soil, tunnelling failure may occur as described in section 10.2.4.

It is important to test for shrinkage to give an indication of how a channel bank will behave in dry conditions. A high shrinkage will indicate that bank cracking could be serious problem if the bank is not adequately treated. To reduce the cracking of high shrinkage material, a protective cover is required over the outer surface of the bank.

Photos\deep cracking.jpg

Photo 10-17 Crack greater than 600mm in depth

Photos\transverse cracking.jpg

Photo 10-18 Transverse crack across channel bank

Figure 10.9 illustrates how a transverse horizontal crack can occur between the saturated and unsaturated zones in a bank. The lower saturated material settles more than the upper drier material, causing the upper soil to arch and form a horizontal crack between the two materials. This arching phenomenon is sometimes termed as *roofing*. This type of cracking will lead to rapid bank failure and is more prone to occur when the material is compacted dry of optimum moisture content.

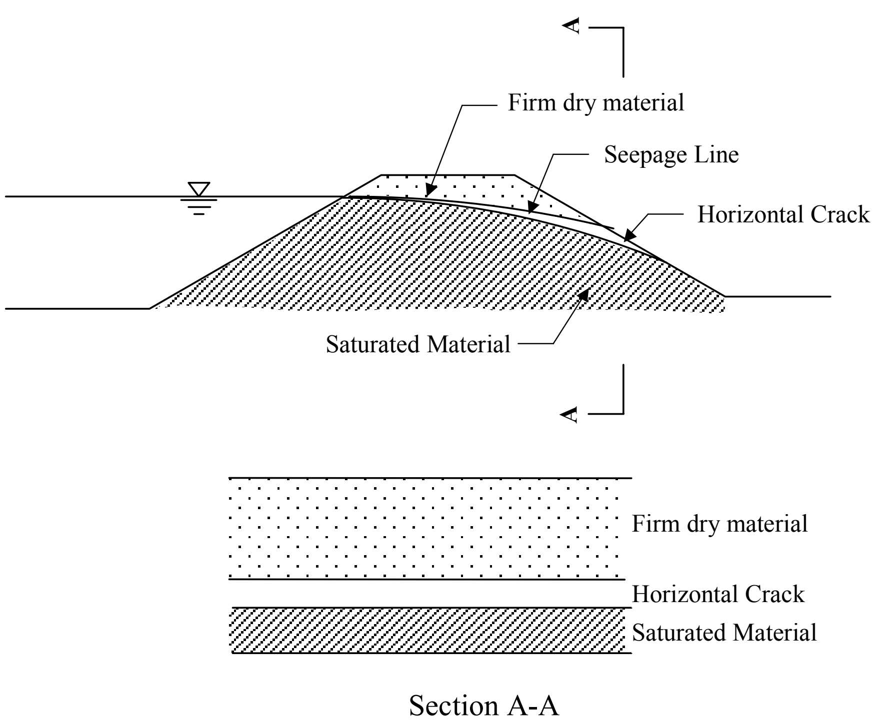

Figure 10.9 Transverse crack

Figure 10.10 shows longitudinal cracking. This may cause slumping of banks if the crack is near the top of the inside bank and contribute to inside bank erosion.

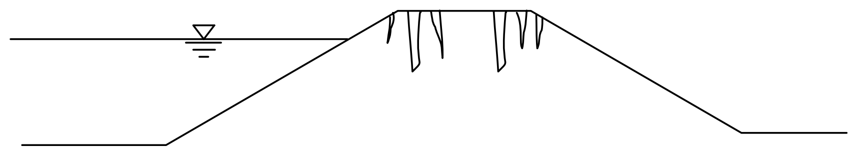

Figure 10.10 Longitudinal cracks

10.2.2.1 Case Study - Cracking

Goulburn-Murray Water has suffered several bank failures caused by cracking, particularly on new banks during dry summers.

A 400 metre length of the CG channel 2/4/8 was remodelled during the winter of 1995. In January 1997 both channel banks suffered numerous leaks caused by severe cracking.

A visual inspection was carried out and the following observations were made:

- deep cracking up to 900 mm in depth
- longitudinal and transverse cracking
- sparse vegetation cover on banks

An investigation of the top cover material was then carried out. It was found to have a high clay content with minimal organic content. It was discovered to be old bank material rather than topsoil.

After consolidation due to rainfall and vehicular traffic, no significant vegetation could establish on the bank. Two very dry Spring/Summer seasons followed construction which promoted cracking through the *top cover* which then extended into the compacted banks.

The problem was rectified by scarifying the top 200mm of the bank to loosen the clay clods and then applying a new top cover of crushed rock. No significant cracking has occurred since this treatment was applied.

10.2.3 Piping

Piping as illustrated in Figure 10.11 is a common failure mode of channel banks. Piping is generally caused by *dispersion* of the bank material. Dispersion is the tendency of a clay soil fraction to go into colloidal suspension in (or when exposed to) water. Thus the clay or colloidal fraction of the soil fails to cohere closely to or bond with other soil particles.

The tendency for dispersive erosion in a given soil depends upon such variables as the mineralogy and chemistry of the clay and the dissolved salts in the soil pore water and in the eroding water.

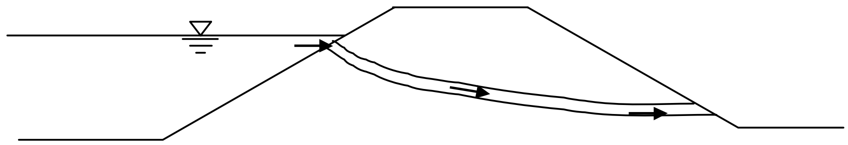

Figure 10.11 Piping through bank

The deterioration or failure of channel banks constructed from dispersive soils occurs when two thing happen simultaneously:

i) Water rapidly saturates the soil, causing the clay to break down and form a suspension of extremely fine particles.

ii) The channel bank is sufficiently permeable to allow water to seep through carrying the dispersed clay. The slow seepage increases in local areas to form a *pipe*. Enlargement of the *pipe* proceeds from the inner face with the material removed passing downwards. The *pipe* eventually emerges at the outside face, at which stage it enlarges rapidly.

Dispersive clays generally cannot be differentiated from ordinary erosion-resistant clays by visual or physical tests. The most common test performed in Australia to measure dispersion is the Emerson Class Test which numerically rates a soil according to its reaction in a beaker of water. Refer Section 15.8.3, Dispersion. Piping failure can also be caused by dispersive layers, lack of compaction, irregular compaction and lamination of layers, described below:

10.2.3.1 Dispersive layer of material in bank

Just one layer of dispersive material in an otherwise sound channel bank may cause failure as shown in Figure 10.12.

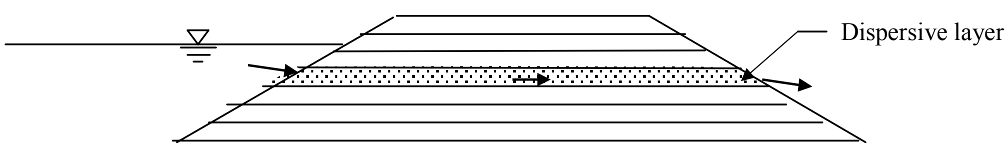

Figure 10.12 Piping failure due to dispersive layer

10.2.3.2 Lack of compaction

Figure 10.13 shows failure by a under-compacted layer. This failure is similar to that of a dispersive layer.

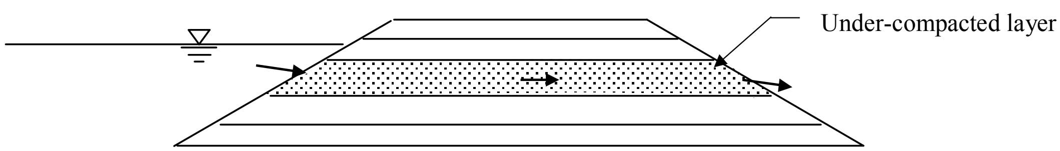

Figure 10.13 Piping failure due to lack of compaction

10.2.3.3 Irregular compaction – bridging of layer

Irregular compaction is where adjacent layers are compacted to significantly different densities. Figure 10.14 shows the case where the lower layers are compacted to a normal density, eg 95%. The upper layer is over-compacted, eg 105%. This means that the swelling and shrinkage characteristics of each layer differ. Over time the over-compacted layer, because it has a greater density and strength, may begin *bridging* when changing from a wetted state to a drier state while the lower layers remain in a similar position to when they were constructed. Therefore a gap will result between the layers which will cause a piping failure.

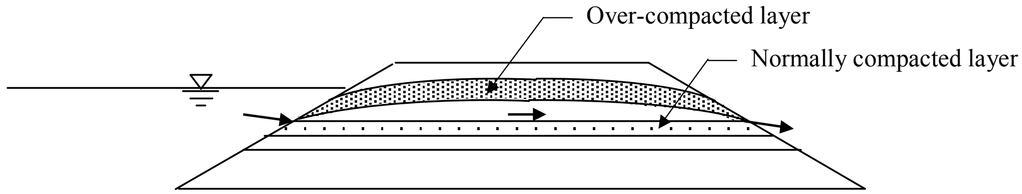

Figure 10.14 Piping failure due to irregular compaction

This failure mode can be prevented by ensuring compaction density at construction remains within construction tolerances.

10.2.3.4 Lamination of the layers

Lamination of layers is caused by two smooth layers being in contact with each other but not bonded. With wetting up and drying of the bank each layer will move independently of the other. Therefore over time, a piping pathway between the layers may form. This is prevented by good construction practice during compaction where the surface of each layer is *tined* or roughened before the next layer of material is placed on top for compaction.

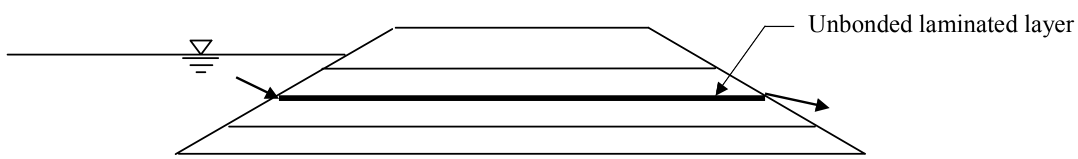

Figure 10.15 Piping failure caused by lamination of layers

10.2.3.5 Case Study - Piping

Piping failure occurred on the CG Channel 5/6 during 1995/96 season. A large leak was discovered and the channel was drained to inspect the bank. A large pipe was discovered in the base of the bank.

Piping failure

Photo 10-19 Entrance to *pipe* near bed of channel

pipe

Photo 10-20 View through *pipe* after channel was drained

An investigation found that the section which failed was constructed during wet weather. It is assumed that bank material was placed in a condition above optimum moisture content. This wet material shrank on drying and thus provided a passage for the water. This section of bank was re-constructed.

10.2.4 Tunnelling

Tunnelling failure can begin with the formation of a pothole and/or wheel rutting on top of the bank which will eventually catch water from rainfall and form gradually larger holes. A sinkhole is formed as rainwater in the pothole creates a tunnel downward through the dispersive soil. Along with cracking of the bank, serious structural failure will eventually occur.

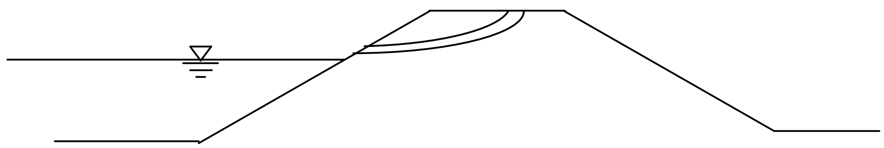

Figure 10.16 Tunnelling Failure

Tunnelling occurs as a combination of dispersive soil, potholes on crest filling with rainwater and animal burrows in the bank. When the burrows and tunnels meet inside batter protection will be washed out and expose the inside batter to erosion. This can also happen towards the back of bank. The result will be a weakened bank which may slump and erode rapidly.

Photos\deterioration\pothole4.jpg

Photo 10-21 Pothole on crest of bank caused by wheel ruts and rainfall on dispersive soil

Photos\deterioration\pothole1.jpg

Photo 10-22 Detail of pothole on crest

10.3 References

Emerson W (1996), personal communication, November 1996

Jackel LM (1996), *European Carp (Cyprinus carpio) Observations on the Impact of Carp in Irrigation Systems of Victoria*, Goulburn-Murray Water

Rural Water Commission of Victoria (1991), *Guidelines for Stabilisation of Waterways*, Standing Committee on Rivers and Catchments, Victoria, August 1991

11. Planning and Investigation

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11.1 General

The Investigation and Planning phase of the channel bank project requires the designer to give consideration to those factors which may affect the works.

Before site works are commenced, some or all of the following details may need to be taken into account:

a) *Approval* the precise terms of approval of the project by relevant authorities including local government and heritage, planning and environmental protection agencies, can influence the execution of the works

b) Services Inspections, where necessary in conjunction with the relevant authority, to locate existing and proposed public utility services, which may be affected by or affect the works. Obtain from each relevant authority its written requirements in respect to such services.

c) *Adjoining property* examination to assess whether there is a potential for damage due to vibration, excavation, filling, noise, run-off, dust or other effects of the earthworks, and liaison with the adjoining owners.

d) *Regulations* working hours on site, warning signs, fencing or security requirements and emanations from the site including dust, water, silt, noise or smoke, are controlled by regulations. These regulations are in addition to the civil rights of adjoining owners and the public.

e) *Preservation items* surveys necessary to identify and locate aboriginal or historic relics, heritage items or rare flora or fauna which may require preservation or relocation.

f) *Drainage* Temporary or permanent diversion of permanent or ephemeral watercourses prior to or during construction of the earthworks and associated works may affect the quantity or quality, or both, of the stormwater run-off. Therefore, special provisions may be necessary to minimise the effects and to protect the legal rights of adjacent and downstream landowners. Failure of such special provisions could lead to litigation and delay in completion of the earthworks project.

Approval from the relevant authorities is obtained prior to either the placement of fill on flood-prone lands or construction of drainage structures, ie culverts in natural watercourses.

g) Erosion and siltation protection of the earthworks from erosion, both during construction and after construction, needs to be taken into account. Run-off from the works, and areas affected by the works, may be subject to special provisions.

h) *Existing filled ground* existing filled ground, for which the conditions of the placement are not adequately documented, should not be assumed to be either of the standard of compaction or the composition adequate to support fill or any other loads.

Site investigations, which may include test pits, test bores, test rolling, or other methods, are necessary to assess the degree of compaction and composition of the existing filled ground. Analysis of the results obtained from these investigations will allow an assessment of the adequacy of the existing filled ground or the extent of remedial works that might be required. Such remedial works could include complete removal.

i) *Non-potable water* the suitability of non-potable water for increasing the moisture content of fill should be evaluated by field and laboratory trials. Saline waters should not be used:

- In the upper layers of fill, beneath either bitumen pavements or areas where vegetation may be established

- In fill where steel is buried.

j) *Trenches* excavations for trenches require special consideration for support. Relevant authorities place limitations on the maximum depth to which trenches may be excavated without shoring.

k) *Compaction moisture content* the optimum moisture content determined by laboratory methods is only a guide for field construction, as the optimum moisture content for compaction under field conditions will depend on the material type, equipment used and on the layer thickness and the nature of the foundation. In general, the heavier the compaction effort or the thinner the layer, the lower the optimum moisture content. Increased compaction effort may cause the soil to approach saturation and higher densities may not result.

l) *Vibration* construction activities, particularly those using equipment such as compactors or blasting, may cause vibrations which could damage nearby structures whether directly (due to the vibration transmitted to the structure), or indirectly (for example, by causing settlement of the foundations).

m) *Contamination* any known or suspected ground or groundwater contamination should be investigated. Relevant authorities have set limits on the quantity of contaminants permitted in ground, in various applications. Removal of contaminated soil from the site may require special consideration. Similarly, allowing contaminated soil to be imported or to remain on site may require approval from the relevant authority. The impact of any investigation on planned earthworks, including safety and environmental aspects, should be considered.

11.2 Documentation

Investigations for the planning of earthworks for use by the designer, the constructor and other interested parties should include the following:

a) Outline of the need for, and objectives of, the project

b) Site investigation of the project and any associated sites, in accordance with AS1726, covering the:

   i) Condition of the site(s) including:
      - Present uses, ie. buildings and vegetation; and
      - Evidence of past use, ie demolition, filling and vegetation

   ii) Foundation and subgrade materials;

   iii) Special areas due to groundwater, seepage, rock, reactive and collapsing soils;

iv) Available fill materials and, where applicable, details of the overburden;

v) Quantity and quality of the available water; and

vi) Suitability of water for the placement of the fill

c) Where applicable, an outline of other plans which have been considered in the investigation.

d) The quality assurance requirement for the project.

12. Earthen Channel Design

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12.1 Introduction

Operation and maintenance problems often stem directly from the design. While major headworks channels have generally been designed on an individual basis, a number of Australian irrigation authorities have set procedures and standards for distributary channel design and construction that they apply in nearly all situations.

Rather than following this relatively uniform approach, it is considered that each channel should be evaluated individually for the most economic solution, taking into consideration such factors as the size of the channel, required service life, local topographical and geological conditions, the criticality of the channel and total life-cycle costs.

This section provides information on the design of unlined channels in erodible material. An unlined channel is defined as an open channel excavated and shaped to the required cross-section in natural earth or fill without special treatment of the wetted surface.

Channel Lining is covered in Section 22.

Figure 12-1 is a typical section of an unlined channel.

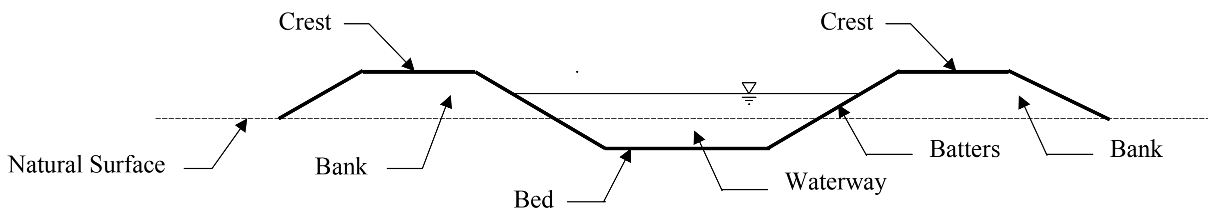


Figure 12-1 Typical section of an unlined channel

12.2 Scope

The different types and locations of conveyance systems, such as unlined and lined channels, gravity and pressure pipelines, to serve new irrigation schemes in the most efficient and economic manner, are outside the scope of this Manual.

For the purposes of this manual, the assumption is made that the final channel alignments and the fixing of water levels and capacities to supply the maximum area that is economically commanded have been established, and it is only necessary to consider the detailed design of the cross and longitudinal sections of the earthen channels in the system.

Readers will need to consult other technical references on the determination of the design capacity, the determination of commanded land levels, the adoption of supply levels and the location, type and size of channel structures.

12.3 Required Life

When an investment is made in a channel, there is an expectation that the channel will function reliably for a pre-determined period – its useful life.

There are several ways a channel can fail to provide its required level of service or reach the end of its useful life. These failure modes include:

- lack of capacity
- inefficiency
- obsolescence
- level of service (falls below acceptable levels)
- structural integrity
- redundancy

Early in the design phase, there needs to be agreement between the channel owner and the designer on the required life or durability of the channel. There is no simple or single answer to how long this period should be. It will depend on the particular circumstances, and life cycle cost analysis is a very useful decision-making tool to use. Refer to Section 13.

It should be recognised that the service requirements of a channel may change over time, and under some circumstances, the best solution may be one which permits some flexibility to address change and goes some way towards minimising life cycle costs. For example, a lower cost less durable channel where there is some uncertainty about future requirements.

The designer needs to think broadly, from concept through detail, to the quality of construction.

12.4 Life-Cycle Cost Considerations

The design of channels should include consideration of future operation, maintenance and renewal costs, as well as initial construction costs so that an overall economy is achieved. Changes in design may be desirable in order to reduce future operation and maintenance problems, even though this may require increases in initial costs.

The design service life of a channel bank should not exceed the projected economic life of the channel system or irrigation scheme. Otherwise the project will have over-capitalised in an asset which will have a physical life beyond its required service life. A lower cost, shorter life bank design may be more appropriate to match the design and service lives.

Possible combinations of design variables should be considered and the volume of earthworks, capital and maintenance costs etc worked out, with sectional dimensions and bed gradient chosen to achieve the lowest life cycle cost.

A poor channel design can lead to excessive scour, weed growth, silting and seepage losses, resulting in reduced channel life, progressive increase in maintenance costs or extensive remediation works.

Refer to Section 13, Life-Cycle Cost Analysis.

12.5 Objectives in Design

The design of channels in erodible material can be a complex process involving a range of parameters based on functional requirements and the physical aspects of earth construction.

The detailed design issues include consideration of bed width, batter slopes, depth of flow, bank sizes, and other dimensions that satisfy all the functional, hydraulic, construction, operational and maintenance requirements.

It is here that a number of factors that affect the life-cycle cost of channels, such as scour, erosion, bank failure, sedimentation, structure failure and weed growth can be reduced by careful attention to the design and soil conditions present.

The cross-sectional design that satisfies the constraints and produces the lowest life cycle cost is selected. In practice, highly theoretical approaches to channel design frequently fail to function properly under field conditions. Practical considerations, economic conditions, bank stability, and operation and maintenance practices all combine, so that considerable engineers' experience and judgement is still necessary in the design of channels.

Irrigation systems in Australia differ materially from those in other parts of the world, and these differences mean that particular rules, formulas and equations that are accepted elsewhere may not be applicable to Australian conditions. The criteria used in Australia for channel design has traditionally been strongly influenced by Unites States experience, particularly through the Water Resource Technical Publications produced by the Bureau of Reclamation.

The following sections discuss the general design of earthen channels in Australia. Much of the design approach is empirical, based on practical experience and observations of the behaviour of channels over long periods of time. The widely varying soil and hydrologic conditions encountered in Australia will require different channel designs, different methods of construction and different provisions for operation and maintenance.

12.6 Design Procedure

The design procedure for channel networks typically covers the following steps:

1. Determination of Design Requirements
    - Site inspection
    - Consultation
    - Establishment of the alignment (layout) of channels
    - Determination of the required water levels in the channel network
    - Determination of the required channel capacities
    - Engineering survey
2. Determine Physical Requirements for Channels
    - Geological investigation of channel alignments
    - Selection of channel longitudinal gradients
    - Regulator/check locations
    - Channel structures location, type and size
    - Determination of water surface profiles
    - Meter outlet locations and type
    - Assessment of the need for seepage control
    - Design of the shape and size of the channel cross-sections
    - Cross drainage/subways
    - Channel access

- Land acquisition extent and type
- Determine fencing requirements
- Identify Public Utility services requirements

3. Detailed Design

   - Prepare earthworks schedule
   - Prepare structures schedule

4. Design Documentation

   - Locality plan
   - Longitudinal sections
   - Schedule of works
   - Prepare estimate of cost
   - Prepare design report
   - Correspondence to landowners and service authorities

5. Handover

   - Design Handover

Some of the basic issues underlying the design process include:

- design capacity
- seepage limits
- minimum water levels for supply and operation of offtakes
- water level fluctuation limits
- maximum non-scouring flow velocity
- capabilities and limitations of available construction equipment
- minimum flow velocity to limit silting and aquatic plant growth
- the channel depth and bed width for economic construction
- structure costs

All these factors will, to a varying degree in different projects and areas, influence the channel design.

Earthen irrigation channels need to be designed from a comprehensive perspective. The resulting design must satisfy the requirements of proper function, acceptable hydraulic performance, satisfactory operation, reduced maintenance and construction practicality.

Experienced operation and maintenance personnel can assist by having an opportunity to review designs before a channel is constructed. In making reviews, the operations and maintenance personnel can recommend designs and construction that will require reduced operation and maintenance.

A channel should divert from a supply source at sufficient elevation (static or pumped) to reach, with proper gradient and by the most economic route, the land to be irrigated.

Channel alignment is an important feature of channel design. It should be selected with careful consideration given to all factors affecting its location, including a comparison of alternative alignments. Many factors affect the planned alignment of a channel. Alternate alignments should be considered in areas where geologic conditions present problems. An alternate alignment may locate the channel in more favourable soils.

A range of factors influence the design capacity of irrigation channels, and capacities need to be determined on a basis appropriate to each project. This detailed analysis of individual projects may include such factors as the area to be irrigated, types of crops, soil conditions, climatic factors, the quantity of water required per hectare, maximum demands, water availability, number of supply points, rates of farm supply, maximum flow changes, rainfall rejection effects, and seepage, evaporation and operational losses.

Channels are no longer designed just for *Maximum Flow Capacity*. New channel systems are being designed for *maximum rate of flow change* as well as the traditional *maximum capacity criteria* in order to provide delivery flexibility.

The determination of channel flow capacities is outside the scope of these Guidelines.

12.7 Site Survey

To enable the designer to be thoroughly familiar with the channel line and the properties to be supplied, an inspection should be carried out to ensure that the design concept is consistent with all the features affecting, or affected by, the proposed channel.

A longitudinal section of natural surface along the channel centreline should be drawn up with levels of typically 100 to 150 metre intervals depending on variability. The location of any features within 25 metres of the channel centreline which could effect design or construction should be noted; eg buildings, electricity poles or lines, farm dams, significant trees, etc.

The location and elevation of all soil investigation sites along the proposed channel alignment should be recorded.

12.8 Geotechnical Investigation

There are conditions specific to investigations for channels that cause them to differ from investigations at other types of construction sites. One significant difference is that channels may extend for many kilometres through a variety of materials.

Geotechnical studies can proceed once the longitudinal and cross-sectional profiles of the channel along the proposed alignment have been prepared, and the depths of cuts and heights of banks have been determined.

The following basic geotechnical requirements need to be met in the design of a channel:

i) the bed and side slopes should be reasonably impervious with a seepage rate within acceptable limits.
ii) the side slopes should be stable.
iii) the channel cross-section should be resistant to scour and erosion.
iv) there should be no detrimental settlement of the channel into the underlying material.

This should enable an effective and economic design to be prepared which avoids or minimises problems during construction and operation.

A surface geologic map along the proposed channel alignment should be prepared covering a strip approximately 100 metres wide. The location of rock formations and different soil types should be identified on the map.

The investigation should generally proceed in three stages:

i) research and collection of available information
ii) preliminary reconnaissance and visual inspection
iii) detailed exploration

The surface geologic studies will determine the need for and the intensity of sub-surface investigations by boring or geophysical methods.

The soil can be examined in test pits or by sinking boreholes from which samples are extracted. The number, location and depth of such pits or borings, will depend both on the nature and variability of the soil strata, and on the form of the channel works.

Where the watertable is above the proposed channel bed, its elevation should be identified in the logs of test holes and pits. A high watertable may interfere substantially with construction or affect the stability of the earthen channel after excavation.

In uniform soils, test holes may be placed 500 metres apart or more, while in erratic strata a spacing of 250 metres or less may be necessary along the channel centreline. Additional holes should be located where the geological or topographic conditions sharply change. Where the geology is well known, the frequency of test holes may be reduced. The test holes should be carried to a depth of at least one metre below the channel bed level.

Soils should be described and classified according to the Unified Soil Classification System.

The soil profile and the results of the sub-surface investigation should be plotted on longitudinal profiles of the channel centreline. Refer to Section 15, Material Selection and Testing.

Numerous soil tests are available, but only a few are generally necessary for channels. Testing of the different soil types along the channel alignment may include:

Index Tests	• classification • Liquid limit/plastic limit/plasticity index • Dispersion • Compaction (moisture-density relationship) • Natural dry unit weight and moisture content • Soluble salts • Linear Shrinkage
Engineering Properties Tests	• Permeability • Shear Strength • Settlement (compressibility)

The selection of the appropriate tests to be performed should be made on a site by site basis. Unless the channel is very large or has very high banks, soil shear and settlement tests are generally not necessary for most channel bank projects. Refer to Section 21, Channel Seepage.

Other geotechnical investigations may include determining:

a) Soft or compressible foundation soils Soft or compressible silts do not form a good foundation on which to construct a channel bank, and they may have to be excavated and backfilled with suitable subgrade material.

b) *Low density or potentially collapsing soils* Low density or potentially collapsing soils lose volume when compacted beneath a channel bank.

Calculation of quantities needs to take into account the effect of compression of the channel bank material and/or foundation.

Further detail on geologic investigations can be found in Section 2 of AS3798, items (i) to (v).

Unexpected discontinuities or variations in soil characteristics may be revealed during excavation of the channel. it should be standard procedure to examine the channel during or immediately after excavation and any variations should be brought to the attention of the project manager.

Refer also to the following sections:

Section 11, Planning and Investigation
Section 15.2, Investigation of Material
Section 21.3.1, Permeability

12.9 Estimation of Earthworks Volumes

Material volumes should be estimated and recorded on design plans for:

- volume required for channel bank construction
- volume obtained from channel excavation
- volume required from borrow pits

In calculating quantities, the following should be taken into account:

i) volume changes due to excavation, hauling and compaction
ii) compression of the foundation

When soils are excavated, hauled and compacted they undergo a sequence of changes that, unless allowed for, can lead to errors in quantity assessment. There are two changes in volume. First, when soil is excavated from its natural state it swells. Later, after being subject to compaction there is shrinkage to a volume that can be smaller than the soil's original bulk in its natural state.

Different soils and different levels of compaction result in different changes in volume. To give an example, a volume of 100 cubic metres of clay could increase after excavation to about 120 cubic metres and then, when compacted in the bank, could be reduced to about 90 cubic metres. This means that 120 cubic metres of loose soil will have to be transported to produce 90 compacted cubic metres in a bank.

Typical compaction and bulking factors for earthen channel bank quantities are:

- compacted bank: 20% compaction factor, ie 1 cubic metre of compacted bank requires 1.2 cubic metres of solid material from excavation.
- spoil bank: 25% bulking factor, ie 1 cubic metre of solid material from excavation occupies 1.25 cubic metres in the spoil bank.

- Backfill: 10% compaction factor, ie 1 cubic metre of backfill requires 1.1 cubic metres of solid material from excavation

The degree of volume changes is dependent on the type and geological origin of the material and required relative compaction. It can be assessed as part of the site investigation, using field density tests and laboratory compaction tests. It is important in earthworks calculations to convert all volumes to a common unit of measure. The natural (solid) cubic metre is commonly used for this purpose.

12.10 Hydraulic Considerations

The hydraulic issues may include consideration of types of flow, different shapes of cross section, loss of head, mean velocities, permissible velocities and effects caused by changes in direction of flow.

The following section provides an overview of some hydraulic principles, formulas and methods of analysis that are useful in designing earthen channels. For more detailed treatment of channel hydraulics, the reader should consult textbooks on the subject.

12.10.1 Types of Open Channel Flow

A flow of water is termed open channel flow when the water surface is subject to atmospheric pressure. Flow conditions in a channel are determined by the channel geometry, flow parameters and gravitational acceleration.

The criteria used to classify open channel flows are summarised in Table 12-1.

Criteria	Types of Open Channel Flow
Flow Description	1-, 2-, or 3- dimensional flow
Time	steady or unsteady flow
Space	uniform or varied flow
Reynolds Number	laminar or turbulent flow
Froude Number	subcritical, critical or supercritical flow

Table 12-1 Classifications of Open Channel Flow

Flow in a straight prismatic channel may be described as a *one-dimensional flow*.

The flow of water in open channels is of two general types, laminar, where the particulars move in parallel paths, or turbulent, where the particles are continually intermingling.

When the flow is laminar, friction losses vary as the velocity. When the flow is turbulent, fiction losses vary approximately as the square of the velocity. Practically all flows in irrigation channels are turbulent.

Turbulent flows may be *steady* or *unsteady*, depending on whether the rates of flow remain constant or vary with respect to time. In practice, steady state flow is rarely found in irrigation channels, fluctuations occur continuously as a result of operational changes and changes of inflows and outflows.

In channels, steady flow may be *uniform* or *non-uniform*, depending on whether mean velocities change at successive cross sections as the water moves downstream. Steady uniform flow occurs in a channel when the cross sections are uniform throughout its length and the bed slope is parallel to the water surface profile.

Non-uniform flow conditions apply where the cross-section or bed slope change and the flow rate remains constant or where the water surface profile is subject to downstream control. In these situations, backwater computations are required to determine the water surface profiles under the non-uniform flow conditions.

Figure 12-2 illustrates various types of open channel flow.

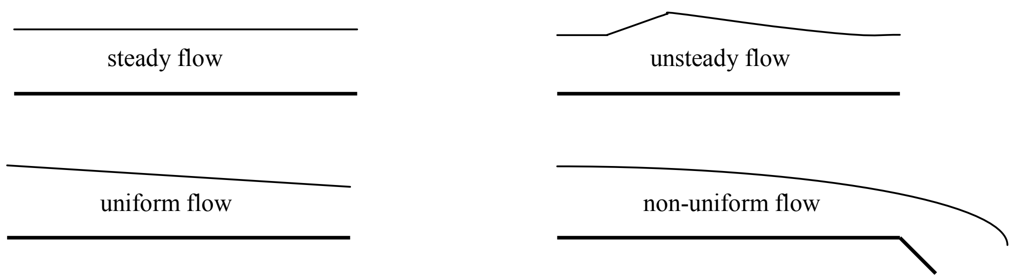


Figure 12-2 Various types of open channel flow

Conditions of turbulent flow are further classified with respect to critical velocities based on the energies of flow. Flows at velocities higher than critical are referred to as supercritical, rapid or shooting. Flows at velocities lower than critical are referred to as sub-critical, streaming or tranquil.

To avoid shock waves, air entrapment, and to facilitate control, flows in irrigation channels should be kept sub-critical.

Earthen irrigation channels should be designed to carry water at sub-critical velocities, and further discussions in this section, unless otherwise specified, apply to turbulent flows at sub-critical velocities.

12.10.2 Channel Cross Section

Generally speaking, the trapezoid is the most widely used shape for irrigation channels.

The channel sectional elements shown in Figure 12-3 and Table 12-2 are used in channel hydraulic computations.

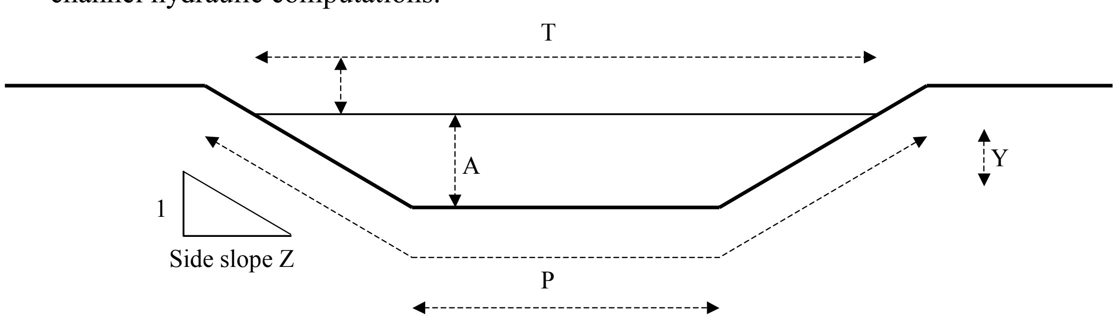


Figure 12-3 Channel Section Elements

1. *Flow Area, A,* is the cross-sectional area which conveys the flow.
2. *Flow depth, Y,* is the vertical distance from the water surface to the lowest point of the cross-section.
3. *Top width, T,* is the width of the water surface
4. *Wetted Perimeter, P,* is the length of the line intersection of the channel wetted surface.
5. *Hydraulic Radius, R,* is the ration of the flow area to the wetted perimeter.

$$R = A/P$$

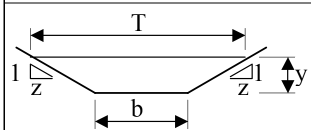
Section	Area *A*	Wetted Perimeter *P*	Hydraulic Radius *R*	Top Width *T*
 Trapezoid	$(b + zy)y$	$B + 2y\sqrt{(1 + z^2)}$	$\frac{(b+zy)y}{b+ 2y\sqrt{(1 + z^2)}}$	$b + 2zy$

Table 12-2 Cross Section Elements

12.11 Channel Velocity

A number of formulae have been developed for computing mean velocities and discharges in open channels. These velocity formulae are empirical equations that include factors for friction slope, hydraulic radius and roughness of wetted perimeter, the three principal factors that affect turbulent velocities.

The regime formulae, such as those of Kennedy and Lacey are not considered to be generally applicable to Australian conditions. The Manning formula is widely used in Australia for irrigation channel design, assuming for simplicity, steady uniform flow conditions.

The formula in metric terms is as follows:

$$\text{Manning} \quad V = \frac{1}{n} R^{2/3} S^{1/2}$$

In the above formula:

V is the mean channel velocity, in metres per second (average for flow area),
R is the hydraulic radius, in metres,
S is the slope of the energy gradient in metre, (vertical) per metre (horizontal), and is equal to longitudinal grade for uniform flow,
n is Manning’s coefficient of roughness for the wetted perimeter (no unit).

The hydraulic radius *R* is the area *A* of the water cross section divided by the wetted perimeter *P*.

$$R = A \backslash P \text{ (m)}$$

The product of the velocity and area is equal to the discharge

$$Q = 86.4 \times V \times A$$

Q is the flow rate in ML/day
A is the cross-sectional area of waterway in m^2

The Manning formula will give reasonably accurate results for open channels if the appropriate co-efficient of roughness is used and the channel slope is less than 0.10.

Table 12-3 gives ranges of *n* for earthen channels in situations most frequently encountered with irrigation systems. The tabulated values have been compiled from a number of technical references, based on experiments and observations of straight uniform earthen channels.

Wetted Perimeter	**Description**	**Co-efficient of Roughness *n***
	Unlined Channel – well-constructed straight uniform section	
Earth Formations	Large carrier channels (above 2500 ML/d) – with slick uniform section, free from aquatic growth	0.018 - 0.020
	Main supply channels (250 to 2500 ML/d)- newly constructed - bare soil	0.020 - 0.0225
	Small channels- less than 250 ML/d with some aquatic growth	0.025 - 0.030
	Channels with considerable aquatic growth	0.030 - 0.035
	Channels with very heavy aquatic growth	0.040 – 0.050

Table 12-3 Values of Manning's *n* for Open Channels

12.11.1 Manning's n – Co-efficient of Roughness

The estimation of realistic values of the roughness coefficient *n* is an important factor in channel design.

For a given channel the rate of flow is inversely proportional to the roughness of the perimeter surface. The co-efficient of roughness used in the design of channels represents an evaluation of the degree of roughness of the wetted perimeter and its net retarding effect on the flow of water.

The estimation of *n* warrants critical consideration and judgement in the evaluation of factors affecting its value.

Channel roughness does not remain constant with time or even with depth of flow. An earthen channel may have one *n* value when first put into service and another after *ageing* and weed growth. If an earthen channel is to have a reasonably constant value of *n* over its life, a continuing maintenance program will be required.

The value of Mannings *n* adopted can have significant life cycle cost implications. The lower the co-efficient, the smaller the resulting channel cross-section and the higher the need for ongoing weed control to maintain the design capacity. Alternatively, the higher the co-efficient, the larger the channel cross-section and the higher the construction cost.

An important point sometimes overlooked is that the co-efficient of roughness should not be based on the initial surface finish, but rather the surface that will exist after a few years of operation, giving consideration to the degree of maintenance that can reasonably be expected.

The co-efficient of roughness used should allow for some deterioration in the channel water way after construction, as the perimeter becomes roughened and irregular, for example, by seasonal weed and aquatic plant grow along the bed and banks, and gradual erosion and silting of the cross section.

It is important to note from Table 12-3 that the Mannings *n* values for well-vegetated channels can be twice those of bare soil channels.

As weed growth during the irrigation season can significantly increase the co-efficient, the maintenance program needs to ensure that the channel waterway is kept in a condition reasonably consistent with the co-efficient used to determine the design capacity.

To allow for loss of capacity due to weed growth and provide some margin of flexibility in the maintenance program, consideration should be given to increasing the base *n* values by 0.005. Where excessive weed growth is a problem, such as in the northern parts of Australia, the base *n* values may have to be increased by 0.01.

For example, to provide some balance between the waterway size and a practical maintenance program, Goulburn-Murray Water uses a coefficient of roughness of 0.0275 for channels with capacities less than 250 ML/day, and 0.0225 for larger channels.

In some situations, such as on steep grades, it may be necessary to consider two values of *n*. A lower *n* value, when weed growth is short or immediately after construction, will give higher velocities and should be used to design for non-eroding velocity. A higher *n* value should be used to check that the waterway capacity is sufficient when the weed growth is more severe.

The total roughness of a channel is a combination of the type of material, unevenness of the bed and batters, change in channel cross-section, bends and vegetation.

A good discussion of the various factors effecting n is included in Chow (1959). This reference also includes a set of photographs of channels with measured *n* values, which may be compared with the channel being considered to arrive at an estimate of *n*.

Table 12-4 sets out a systematic method which can be used to estimate *n* for channels, taking most of the variables into account. At best, value of *n* is based on an estimate, and the designer must use best judgement when selecting it.

<table>
<tr><td colspan="4">Steps to compute mean n:

Assume basic n
Select modifying n for roughness or degree of irregularity
Select modifying n for variation in size and shape of cross-section
Select modifying n for obstructions such as debris deposits
Select modifying n for vegetation
Select modifying n for meandering

Add items 1 through 6</td></tr>
<tr><td colspan="4" align="center">Aids in Selecting Various n Values</td></tr>
<tr><td colspan="4">Recommended basic n values for material involved</td></tr>
<tr><td>Channels in earth</td><td>0.020</td><td>Channels in fine gravel</td><td>0.024</td></tr>
<tr><td>Channels in rock</td><td>0.025</td><td>Channels in coarse gravel</td><td>0.028</td></tr>
<tr><td colspan="4">Recommended modifying n value for degree of irregularity</td></tr>
<tr><td>Smooth</td><td>0.000</td><td>Moderate</td><td>0.010</td></tr>
<tr><td>Minor</td><td>0.005</td><td>Severe</td><td>0.020</td></tr>
<tr><td colspan="4">Recommended modifying n value for changes in size and shape of cross-section</td></tr>
<tr><td>Gradual</td><td>0.000</td><td>Frequent</td><td>0.010 to 0.015</td></tr>
<tr><td>Occasional</td><td colspan="2">0.005</td><td></td></tr>
<tr><td colspan="4">Recommended modifying n value for obstruction</td></tr>
<tr><td>Negligible effect</td><td>0.000</td><td>Appreciable effect</td><td>0.030</td></tr>
<tr><td>Minor effect</td><td>0.010</td><td>Severe effect</td><td>0.060</td></tr>
<tr><td colspan="4">Recommended modifying n values for vegetation</td></tr>
<tr><td>Low effect</td><td>0.005 to 0.010</td><td>High effect</td><td>0.025 to 0.050</td></tr>
<tr><td>Medium effect</td><td>0.010 to 0.025</td><td>Very high effect</td><td>0.050 to 0.100</td></tr>
<tr><td colspan="4">Recommended modifying n value for channel meander
(L_s = Straight length of reach L_m = Meander length of reach)</td></tr>
<tr><td colspan="2" align="center">L_m/L_s</td><td colspan="2" align="center">N</td></tr>
<tr><td colspan="2" align="center">1.0-1.2</td><td colspan="2" align="center">0.000</td></tr>
<tr><td colspan="2" align="center">1.2-1.5</td><td colspan="2" align="center">0.15 times ns</td></tr>
<tr><td colspan="2" align="center">> 1.5</td><td colspan="2" align="center">0.30 times ns</td></tr>
<tr><td colspan="4" align="center">Where ns = items 1+2+3+4+5</td></tr>
</table>

Table 12-4 A method of computing mean *n* value for a channel

12.11.2 Permissible Velocities

The design of earthen channels required knowledge of the relationship between flowing water and the earth materials forming the boundary of the channel. These relationships may be the controlling factors in determining channel alignment, grade and dimensioning of the cross-section.

There are a number of methods that can be used to evaluate the stability of channels. These include permissible velocity, tractive forces, sediment transport and regime approaches. The permissible velocity approach is considered to be the most applicable and straightforward method for the design of low gradient unprotected earthen irrigation channels, where the soil boundary effectively resists the erosive efforts of the flow.

Velocities need to be carefully considered in the design of earthen channels, to prevent, as far as possible:

- scouring of the bed and erosion of the banks, and damage to structures, that must be repaired in order to maintain operational integrity.
- deposition of sediments and silts that must be removed in order to maintain adequate waterway capacity.

The term *permissible velocities*, in relation to earthen channels, refers to two considerations:

- the maximum velocity that will not cause damaging erosion
- the minimum velocity that will prevent appreciable silt deposition

The design objective is the minimisation of maintenance costs.

The term maximum velocity is used to describe the mean velocity in the channel when carrying maximum flow. Similarly, the term minimum velocity is used to describe the mean velocity when carrying minimum flow.

Permissible maximum velocities in earthen channels depend primarily on the characteristics of the material in the wetted perimeter, the shape of cross section, depth of flow, and degree of sealing with age. Permissible minimum velocities depend principally on the quantities and qualities of the sediments carried by the water.

A soil's ability to resist erosion is affected by the kinds, amount and character of clay, the amount and size distribution of coarse particles and the nature and amount of cementing assets.

12.11.3 Maximum Velocities

The size of a channel cross section needed to carry the required flow varies with mean velocity. Therefore, designing for velocities as high as can be permitted without causing damaging scouring and erosion can usually reduce construction costs. To minimise the upfront construction costs there can be a natural tendency for designers to use as small as possible channel cross-section, but this can in turn result in higher, but less immediately apparent maintenance costs. Erodible properties of materials along newly constructed channels depend principally on the size and grading of the soil particles and on the amounts of binding materials in the formations. Loose sandy soils free of cementing constituents are easily eroded, where as, graded silt, sand and gravel material containing cementing constituents are more resistant to erosion.

Higher velocities can be permissible in earthen channels when suspended loads contain colloidal materials. For a given velocity clear water may scour, while water carrying moderate to high concentrations of sediment may either replace dislodged particles or form a protective cover as the result of settling.

After a channel has been in operation for a period of time, the material in the perimeter of the channel tends to consolidate and the fine sediments in the flow can cause cementing (cohesion) of the material, increasing the resistance to erosion. This often results in an increase in the permissible non-erosion velocities. Some scour may be tolerated when the channel is totally in cut, but where the channel is extensively in fill, scour cannot be allowed. Hence judgement dictates the *safety factor* that is to be used against scour.

A new irrigation scheme will usually have an initial period of relatively low demand as the land is being developed. This period allows the scour resistance of the channel material to increase, as the channel goes through the seasoning or ageing process before full capacity will be required. On the other hand, an existing scheme may required the channel to operate at full capacity almost as soon as the channel is constructed, allowing no time for the ageing process to increase scour resistance of the channel material.

Ranges of maximum permissible velocities that limit erosion at the soil-water interface of earthen channels are given in Table 12-5. The tabulated velocities, which have been compiled from a number of technical references, are for straight channels with depths of 1 metre or less, that have been aged by service. Increases of 0.15 metres per second can be made for channel sections more than 1.5 metres deep. Clear water is defined as sediment concentrations lower than 1000 ppm by weight. Water with colloidal silts is defined as concentrations equal or greater than 20,000 ppm by weight.

Perimeter Material	**Velocity in metres per second, after ageing, in straight channels with depths of 1 metre, carrying:**		
	Clear water with no silts, sand or gravel	**Water with colloidal silts**	**Water with non-colloidal silts, sand or gravel**
Fine sand, non-colloidal	0.45	0.75	0.45
Sandy loam, non-colloidal	0.55	0.75	0.60
Silt loam, non-colloidal	0.60	0.90	0.60
Alluvial silts, non-colloidal	0.60	1.10	0.60
Firm loam	0.75	1.10	0.70
Fine gravel	0.75	1.50	1.15
Stiff clay, very colloidal	1.15	1.50	0.90
Graded loam to cobbles, non-colloidal	1.15	1.50	1.50
Alluvial silts, colloidal	1.15	1.50	0.90
Graded silt to cobbles, colloidal	1.30	1.70	1.50
Coarse gravel, non-colloidal	1.50	1.85	2.00

Table 12-5 Maximum Non-Erosion Velocities in Channels through Different Soils

These maximum velocities should be able to be used as a guide for the design of most earthen channels.

The soil formations along a channel route can vary widely, and one of the difficulties in using Table 12-5 can be the identification of the most comparable material from section to section.

The shear or *tractive force* theory is a more sophisticated method that can be used to assess maximum non-erosive velocities in earthen channels. The tractive force is the pull of the flowing water on the wetted perimeter. To prevent erosion in the channel, the tractive force (boundary shear stress) should be less than the critical value of tractive force for the material on the bottom and side slopes. There are a number of technical publications on this subject that can be referred to for further details.

Although clay stands velocities up to 1.5 m/s, in time the flow resistance may drop considerably owing to the alternate wetting and drying effects and other weathering and structural changes.

In NSW and Queensland the maximum permissible velocity for earthen channels is normally not higher than 0.5 to 0.6 metres per second. Experience has also shown that the average clay loams in Victorian channels can tolerate mean velocities of up to 0.6 metres per second without scouring, whereas the lighter sandy loams require a lower limit of around 0.45 metres per second. In some locations, where the soils are more erodible, the maximum safe velocity has been found to be 0.3 metres per second.

Because of the flat grades that are available for the majority of channels in Australia, velocities are usually kept below the erosion limits.

Some overseas literature indicates that higher earthen channel velocities, 0.8 to 1.0 m/s, can be used. However designers should be cautious when applying overseas design approaches to Australian conditions.

12.11.4 Additional Protection against Erosion

In situations where velocities are likely to cause scour and erosion, consideration should be given to bank protection or the use of check structures to reduce grades and velocities to satisfactory limits. Additional protection against localised erosion may also be required at bends and structures where velocities can be higher than the mean flow. The selection of a particular measure or combination of measures should be based on an engineering and economic assessment of each particular situation.

Structures at which considerable energy dissipation is involved, should have rock beaching or riprap included in their design. For most successful performance, a rip rap or beaching layer must be designed to:

- protect the individual rock particles from displacement by the water force
- keep the protected earth underlying the rip rap from washing out through the voids

The type of rock beaching (sized grading), its extent and shaping, depends on local conditions and the flow pattern produced at each type of structure. The local conditions include the cost of beaching, risk to structure, type of soil and velocity of water, and consideration of these issues are outside the scope of these Guidelines.

Depending on the velocities involved, the size grading of the beaching and the characteristics of the bank material, the beaching may need to be placed over a geotextile filter fabric to prevent washing out by the channel flow of the subgrade soil, and hence, the slumping and collapse of the beaching protection.

In cases, where the soils are unable to withstand the erosive forces, caused by flowing water or wave actions, a protective layer of gravel or crushed rock can be provided over the soil.

The cost of reducing the velocity with a larger section, as compared with the cost of a smaller section with its higher velocity and protection with a gravel or crushed rock cover, should be considered if suitable material is available from local deposits.

To ensure effective long-term protection, the size, grading and thickness of the gravel or crushed rock layer, as well as the slope of the batters, needs to be carefully consideration. Refer to Section 18, Inside Batter Treatment.

Open channel flow behaviour can be difficult to predict at times, and with borderline bank materials, rather than taking a conservative approach and using extensive and possibly excessive lengths of protective material, it may be more cost-effective to adopt a policy of *wait and see*. Periodic inspections of the channel will identify localised erosion sites at an early stage of development, where additional spot protection can be easily provided.

12.11.5 Minimum Velocities

Ideally a channel should have sufficient velocity at low flows to prevent silt deposition and growth of aquatic plants. Channel designs in Australia are generally based on the capacity required for short periods of peak demand. This results in channels being operated for most of the time at below design capacity. Because of this, any sediments above colloidal size in the supply water will have to be excluded at the intakes or periodically removed from the system.

Where the silt content of the water is high and the silting of channels is a significant problem, the prevention of silting during long periods of partial-capacity operation may be more important than the prevention of a limited amount of erosion during the short periods of full-capacity operation.

Generally, the silt content of water in Australian rivers and channels is comparatively low and is mainly limited to suspended clay. The silting of irrigation channels is therefore not a significant problem. There are times after heavy rain in the catchments or immediately after channels has been built, when the silt content rises considerably. However, it has been found that the thin layers of silt deposited at these times are helpful in reducing channel seepage and erosion. It is therefore not necessary in most Australian situations to adopt any particular measures to avoid silting. The low silt loads permit adoption of low velocities, and permissible maximum velocities are generally the primary design consideration.

Thus channels are usually designed to avoid erosion at maximum discharge, and provision made to remove or exclude the sediment at the intakes or periodically remove it from the channel system.

In earthen channels, sediments generally enter at the intakes, or are eroded from the bed and banks. Large particles eroded from the banks usually settle along the channel bed, where they tend to prevent bed erosion. Small particles eroded from banks are carried downstream, since scouring velocities are high enough to maintain transportation.

Fine sands and silts that can be carried in suspension are not normally as much of a problem as the heavier materials. Coarse sand and gravel should be kept out of channels as much as possible by sediment-control works, either at the intake or along the channel.

Where channels flows carry silty water, minimum velocities should be high enough, wherever practicable, to keep the silt moving. The velocities required in particular channels depends on quantities and qualities of silt transported. Velocities of 0.45 to 0.6 metres per second are usually high enough to keep small quantities of fine sand and silt in motion. Velocities of 0.8 metres per second or more are required to inhibit growth of aquatic plants. In areas where these velocities cannot be achieved, the minimum channel velocity should be kept above 0.3 metres per second when ever possible.

Where the silt content of water is significant and velocities high enough to prevent serious silting can not be maintained, silt-control works at the intakes would be required. The design of such works is outside the scope of this Manual.

12.12 Channel Control

The two basic systems of channel control are defined by the location of the controlled water surface relative to the control structure:

- upstream – supply orientated operation
- downstream – demand orientated operation

Upstream Control refers to a system where the water level being controlled or maintained constant, is immediately *upstream* of the regulating point. Most manually controlled drop board systems in Australia have been designed on this basis. Drop bars are removed or replaced, or gates opened or closed to maintain a steady level upstream of a regulating point.

The opposite mode of operation, defined as *Downstream Control*, is where the control is operated so the level on the *downstream* side of the regulating structure remains constant. Because it reacts to changes downstream, it is user-oriented. This control mode which was introduced to Australia in the 1970's, can operate automatically since demand signals can be passed up the system. If individual outlets turn on, the change in that pool level causes a change in the regulator to change the flow to re-establish the prior setpoint. A change in any pool will cause a sequence of proper compensating actions to be made in the upstream structures, all the way back to the source. A secondary benefit is the increased distribution efficiency since the system is essentially closed at the downstream end. Downstream control systems are always automated; upstream control systems may be manual or automatic.

Figure 12-4 illustrates the principals of each control system with relevant features marked showing the essential differences. The most important characteristic is the operational storage wedge, defined as the difference between the volume in a channel reach at zero flow and that at full flow. For upstream controlled systems the wedge characteristic is negative and represents a limit on the speed of propagation of changes through the system. That is, the operational storage must be made up before the flow in any reach can be increased. Flows are therefore normally adjusted in a downstream direction.

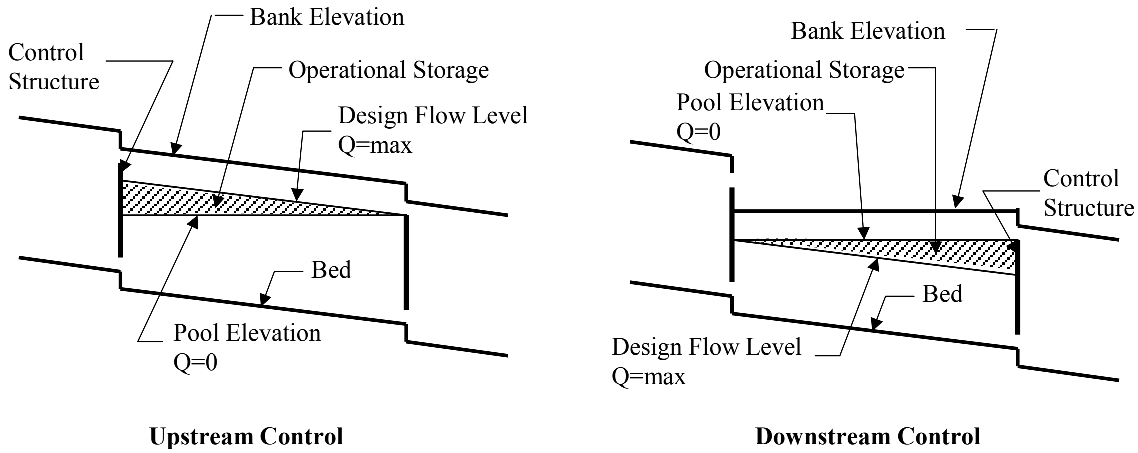


Figure 12-4 Upstream and Downstream Control

For downstream controlled systems, this wedge characteristic is positive and represents the limitation to automatic operation. If the response time of the regulations is short enough so that flow changes can be met from the operational storage volume, the system can theoretically operate automatically. That is, changes in demand will be fed back up the system progressively back to the source of supply. System responds to demand changes rather than supply changes.

This gives rise to the flat top channels in downstream controlled systems, compared to the sloping top channels in upstream controlled systems. In downstream control the channel banks and structures have the same elevation over the entire channel pool.

The decision-making criteria for upstream control mode versus downstream control mode can be complex, involving a range of technical and economic parameters. The different control methods cannot be mixed within a channel system unless a buffer storage separates the different segments. These issues are outside the scope of this manual and readers should consult other technical references on the subject.

Some of the design issues that should be considered include:

Upstream Control

- Lower cost of bank and structure construction
- More stable flow levels
- Lower distribution efficiency
- Can operate with manual and automatic channel regulators

Downstream Control

- Increased distribution efficiency and flexibility
- Higher construction cost for extra bank and structure height
- Must have automatic channel regulators
- Subject to more channel flow and level fluctuations
- Adverse impact on performance of Detheridge type meter outlets
- For stability require flat grades with substantial storage wedge
- Places heavy operation duty on automatically controlled regulators
- Must be continuous system and commence from a balancing storage

12.12.1 Upstream Control

In upstream channel control there are two methods for determining the level of the design bank. They are the Design Discharge Level and the Maximum Water Level.

12.12.1.1 Design Discharge Level

Most Australian authorities presently use Design Discharge Level in determining the bank level as shown in Figure 12-5.

Freeboard is added to the Design Discharge Level to determine the Design Bank Level. Freeboard is determined according to Section 12.13.

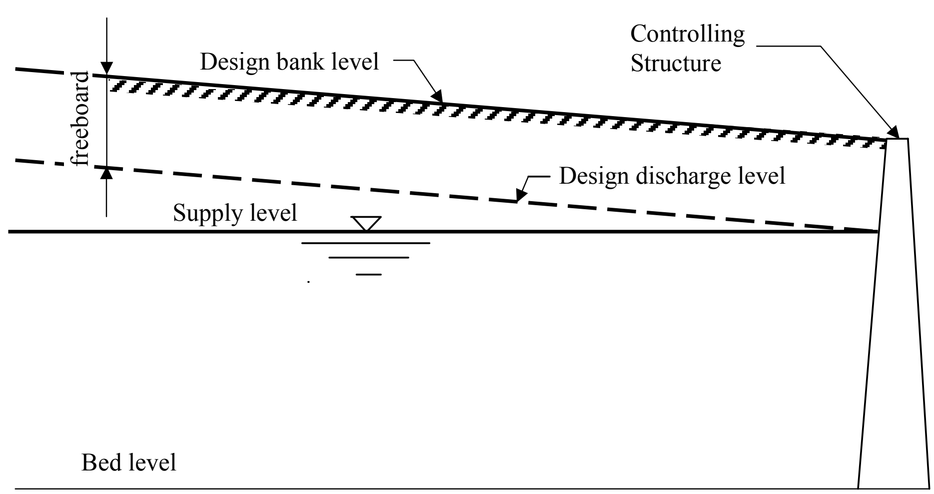


Figure 12-5 Determination of Design Discharge Level (DDL) and Design Bank Level

Where the bank level is based on the Design Discharge Level, the regulating structures have to be operated during rainfall shutdown events to allow the channel water to flow through the system to outfalls. The water in the channels is drained down and the channels have to be re-filled before irrigation can resume.

12.12.1.2 *Maximum Water Level*

The concept of Maximum Water Level was developed in the early 1970's by the then State Rivers & Water Supply Commission of Victoria to allow holding of water in the channel system during a shut-down regulation. This allows water levels to rise above the Design Discharge Level in the lower half of the channel pool and store water which would otherwise be lost to the system through outfalls. This leaves the channel system full in readiness for irrigation to be resumed. The broad aim is to convert the *wedge* of water between supply level and the design discharge level in a channel pool to an equivalent rectangle, as shown in Figure 12-6.

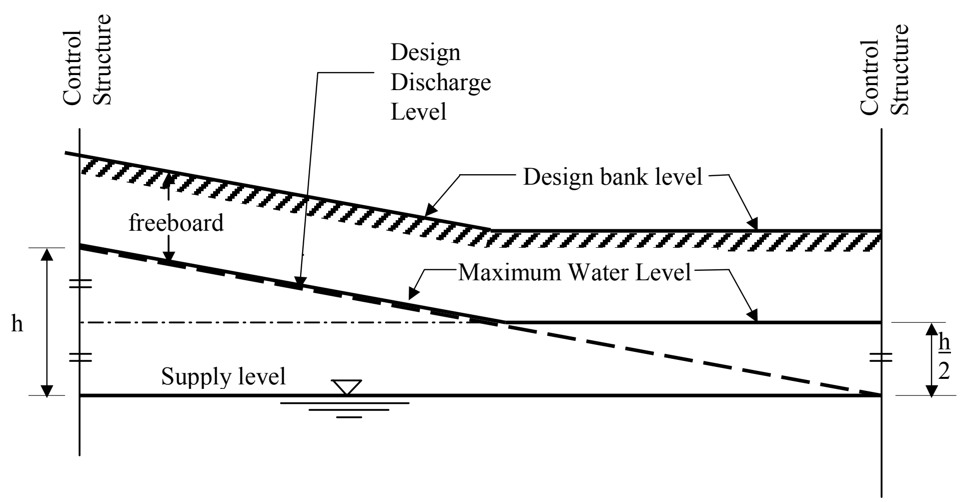


Figure 12-6 Determination of Maximum Water Level (MWL) and Design Bank Level

This means that a channel operator does not have to wait for excess water to run out before closing up regulating structures, but can proceed to shut-down the channel as quickly as possible.

The maximum rise in water level at a check, in a complete shut-down from design to zero flow, is seen to equal half the rise in the design discharge profile over the pool. The stabilised water level is thus above the design discharge level over the downstream half of the pool. The highest water levels in channel operation are thus represented by the Maximum Water Level (MWL), as seen in Figure 12-6.

The maximum water level concept also accommodates the tendency for high water levels to occur in the downstream reaches of channel pools as a result of the accumulation of errors in measurement and regulation and variations to planned meter outlet operations.

12.12.1.3 Best Practice

Either of the above methods are valid in terms of design approach for a channel system. The Maximum Water Level approach has a greater capacity for storing water in the event of a rain shutdown. However the Maximum Water Level approach requires higher channel banks than the Design Discharge Level approach, therefore earthworks costs are greater.

When deciding between the two approaches, a cost analysis should be completed between the saving of water in the channel and the cost of the extra compacted bank required. Other factors such as the environmental impacts of water outfalls with the Design Discharge Level approach may have to be considered.

12.13 Freeboard

12.13.1 Purpose and Philosophy

Channels are designed with a margin of safety between the highest water levels expected and the top of the channel bank. This difference in height is known as *freeboard*.

This section discusses freeboard provision for unlined earthen channels. It does not cover freeboard for hard surface lined channels. For earthen channels, freeboard is defined as the vertical distance between the water surface when running at maximum water level, and the top of the compacted bank. It does not include the protective cover.

Freeboard can be considered a factor of safety against any number of unforseen circumstances which might cause the water level to be higher than expected. It gives protection against damage or failure of channel banks from high water levels or overtopping, which in turn can cause flooding of adjacent lands.

Significant rises in water levels may occur at times from:

- operational fluctuations
- wind and wave action
- temporary mis-operation of channel regulators
- unauthorised interference of control structures
- obstruction of flows
- errors in regulation and flow measurement
- excess inflows after heavy rainfall
- shutdowns due to rainfall
- temporary passing of high flows than normal
- surges which accompany rapid changes in flow
- variations to planned farm deliveries

Alternate wetting and drying, shrinkage and cracking, vegetation and animals, acting on the top of a channel bank, reduces the compacted density and thus lessens the water tightness, slope stability and erosion resistance of the top section of bank. Where channels are operated well above their design level, with very little freeboard, this places increased pressure on any weaknesses in the channel bank, and increased rates of leakage, seepage and bank deterioration occur.

Settlement due to material consolidation in the subgrade and the bank will in most channels be very small, typically 2 to 3% of bank height, if the subgrade is adequately stripped and the bank is compacted correctly. From a practical point of view this can be ignored, as it will be within construction tolerances.

Freeboard allowances in earthen channel design should be based on consideration of such factors as:

- size of channel
- location of channel
- risks of damage that may result if the banks are overtopped
- velocity of water and conditions of flow
- stormwater entering the channel
- proximity to outfalls or escapes
- water level fluctuations
- operating procedures
- wind and wave action
- bank material characteristics
- channel gradient
- potential for unauthorised interference
- reliability of water level control
- availability of bank material
- cost of providing freeboard

Channel design procedures and codes of practice generally specify freeboard as a function of channel capacity. The larger the channel capacity, the greater the freeboard provision. The logic being that the consequences of failure would be proportional to channel size.

A channel bank consists of selected compacted material and is expensive to construct, particularly where the material has to be obtained from borrow at some distance from the channel. The provision of channel bank freeboard is a significant component of construction costs, and somewhat arbitrary freeboard approaches have their shortcomings.

The issues associated with construction of channels with high banks include:

- increased construction costs
- difficulty obtaining suitable bank material in sufficient quantity
- increased acquisition width required for the channel
- reduced visibility at road intersections crossed by channels

The volume required to achieve additional height in a bank of constant crest width is represented by a slice inserted at the base of the bank as shown in Figure 12-7.

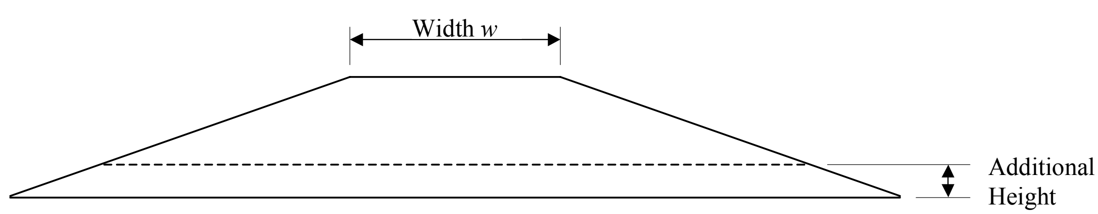


Figure 12-7 Additional Bank Volume

Assuming an average channel with water level 0.6m above natural surface, crest width 3m, inside and outside batters 1(V): 2(H); increasing the freeboard from 0.3m to 0.45m increases the volume of earthworks by 24%.

12.13.2 Channel Maintenance

Increases in water depth due to accumulation of sediment deposits decreasing waterway area or excessive weed growth increasing the roughness of the channel, are usually included, within reasonable limits, in the hydraulic analysis of design water levels and are not included in the freeboard allowance.

The value for the co-efficient of roughness in Manning's equation used in channel design should allow for deterioration in the channel waterway after construction. Refer to Section 12.11.1.

Weed growth can be a major cause of fluctuations in water levels, especially in small channels, but it would be uneconomic to provide freeboard for the most severe weed growth conditions. To overcome this situation, maintenance programs need to ensure that satisfactory levels of hydraulic efficiency are maintained and excessive water levels do not occur at design flows.

12.13.3 Past Practice

The historical approach to determining freeboard in most Australian irrigation schemes assumes that the amount of freeboard required is directly related to the channel capacity or depth. This approach assumes that the larger the capacity of the channel, the greater the consequences of failure. However this assumption is not entirely sound. For example, a single meter outlet on a small spur channel may cause a large rise in water levels, while a large channel may be in cut and run through open dry land, with less consequence from overtopping.

Other factors which are used overseas to determine freeboard are supply depth, velocity head, bed width of channel, fluctuation in water level and fetch. For earthen channels, supply depth, velocity head and bed width are almost always directly related to discharge capacity.

For irrigation authorities in NSW and Victoria, the design freeboard on banks ranges from a minimum of 0.3 metre to a maximum of 0.9 metre on the basis of channel capacity. In Western Australia, the freeboard allowance is based on the height of the bank above natural surface, and ranges from minimum of 0.3 metres to 0.5 metre for banks 3 metres high. In Queensland the freeboard ranges from a minimum of 0.38 metres to a maximum of 1.2 metres.

A more considered approach is recommended, where each channel is evaluated for the most appropriate freeboard provision. Depending on the operational conditions, this approach can achieve significant economies, particularly for larger channels.

12.13.4 Wind and Wave Action

Wind action can raise water levels and produce waves of various heights depending on the relative directions of the wind and the channel, wind speed, channel width and the length of the channel reach.

Waves in a channel can cause erosion on the inside batter by the physical action of washing away the batter material. If the waves become large enough they can overtop the bank causing erosion of the crest and outside batter.

The mechanics of wave generation are extremely complex, and the forces causing erosion during wave attach on an earth slope are both varied and complex.

One of the main environmental factors that has an impact on the amount of freeboard included in a channel design is the wind. The three effects that the wind will have upon the water level in the channel are:

Setup -	height of the wind tide
Wave Height -	height of a wave running along a channel parallel to the banks
Wave Runup -	the height a wave will reach running up a batter (eg at a bend in the channel).

12.13.4.1 Determination of the Setup (Wind tide)

The wind tide or setup is the *heaping up* of water at the downwind end of an enclosed waterway caused by the frictional force from a strong wind. Wind setup may be estimated from:

$$\mathbf{S = \frac{U^2F}{1400D}}$$

where:

S - Wind tide or setup above the still level (metre)
U - Average wind velocity (metre per second)
F - Fetch or length of water surface over which the wind blows (metre)
D - Average depth of water (metre)

The setup may result in extra freeboard being allowed at the end of a channel. For example, in Northern Victoria the prevailing wind comes from the south-west. Therefore at the north eastern end of a long section of channel that runs in a south west - north east direction a greater freeboard may be required.

12.13.4.2 Determination of Wave Height

Waves are developed on channels as a result of wind blowing across the exposed water surface. Turbulent eddies in the wind stream and the friction between the air and the water surface cause waves to form. The major factors that influence the size of a wave is:

- the length of the open water over which the wind blows, called the fetch
- the strength or velocity of the wind
- the cross sectional dimensions, width and depth of the channel
- the duration of the wind

As the fetch is lengthened the wind blowing along the water has more time to build up a wave. Also if the wind is stronger along the fetch, the wave will become larger.

Because almost all channels have a limited depth, the height that a wave can reach is limited by both the depth of the water and the width between the banks. Little information is available for the effect that banks have on the waves running along a channel. The depth of the water effects the wave in that the bed limits the height that the wave can reach, this is called a shallow wave.

Photos\Design\Definition of Wave Height.doc

Figure 12-8 Definition of Wave Height, *H*

There are various methods of determining the wave height that can be developed in a channel. Some are simplistic in their method while others are quite sophisticated.

Considerable work has been done in the past on the development of waves in the ocean, in harbours or in reservoirs where the effects of waves can be large. Little work has been done on the development of waves in channels.

The US Army Corps of Engineering *Shore Protection Manual* method is considered to be the best way to evaluate the height of a wave in a channel as it is the only method that considers the effect of the bed depth on the wave development.

However the method considers the water area to be infinitely wide, or in other words, no consideration is given to the effect the channel banks will have on wave development.

The method may therefore give excessive answers in regard to wave heights particularly for smaller channels. An example of this is a small channel would not have the same wave sizes forming in it, compared to a large channel, because of the effect of the banks and bed resistances.

12.13.4.3 Freeboard for Wave Height

Fetch (km)	Wave Height (m)	Half Wave Height (m)	Freeboard Allowance (m)
0.1	0.3	0.1	0.3
0.2	0.4	0.2	0.3
0.3	0.4	0.2	0.3
0.4	0.5	0.2	0.3
0.6	0.6	0.3	0.4
0.8	0.6	0.3	0.4
1.0	0.7	0.3	0.4
2.0	0.8	0.4	0.4
5.0	0.8	0.4	0.5
10.0	0.8	0.4	0.5
15.0	0.8	0.4	0.5

Table 12-6 Determination of Freeboard for Wave Action

Notes:

1. This table is derived from the US Army Corps Shore Protection Manual (1984).

2. This table is for a channel 1.5 metres deep and a wind blowing constantly at 120 km/hour along the channel.
3. All wave heights have been rounded up to the nearest 0.1 metre.
4. It is considered that once a channel fetch is greater than 400 metres, fetch can be considered to be long and therefore extra freeboard may have to be added to the 0.3 metres accordingly. This extra allowance is only used where the wave is running along the channel, and not likely to run up the batter.

12.13.4.4 Determination of Wave Runup

Another important factor to include in the allowance for wave actions is the distance which the waves may run up the inside batter of a channel when a wave strikes a bank full on. The waves will dissipate by running up the slope of the batter to a height above its open-water height. Depending on the relative smoothness of the material used on the inside batter of the channel bank, the run up distance varies and so does the amount and type of erosion that follows.

In the worst case situation, the wave runup, *R*, can be as much as 2.5 times the height of the wave itself for a batter slope of 1:2 with a relatively smooth surface.

Photos\Design\Wave Runup.doc

Table 12-7 Wave Runup, R

R = height of wave runup

R = 2.5H, where batter is relatively smooth (eg compacted clay)

R = H, where batter is rough (eg heavy beaching or riprap)

12.13.4.5 Methods to Reduce Wave Runup

Where wave runup is significant, there are two main methods to reduce it, and therefore reduce the required freeboard. These are:

- batter protection
- change of alignment

12.13.4.6 Batter Protection

Batter protection increases the roughness of the surface and so reduces the runup of waves. Inside batter protection methods include rock beaching, vegetation, etc. described in Section 18.

The batter protection for wave action should be located from the minimum to maximum heights that the water surface could reach. This is at least from the trough of the wave to the height of the runup of the wave. In many cases batter protection would be provided from the top to the toe of the inside bank for ease of construction.

Consideration to protecting the crest and outside batter of the bank should also be given if overtopping of the bank may occur.

12.13.4.7 Change of Alignment

The inclusion of bends in the channel alignment will reduce the fetch length. However this may increase construction costs and cause difficulties with land acquisition.

12.13.5 Minimum Freeboard Allowance

A minimum 0.3 metre compacted bank freeboard has been used for many years in Australia and overseas in the design of earthen distribution channels and has proven satisfactory under a wide range of circumstances and conditions.

In an attempt to reduce the cost of channel bank construction, the Rural Water Commission of Victoria reduced its compacted bank freeboard from 0.3 metre to 0.15 metre above the maximum water level. However this did not prove to be entirely satisfactory, as the margin of safety was too small and the number of banks being damaged and overtopped increased.

It is therefore recommended that a minimum compacted bank freeboard of 0.3 metre is used on all channels irrespective of size.

With this minimum freeboard allowance being increased if the risks dictate.

12.13.6 Risk Approach

A Risk Approach should be used when determining freeboard.

Firstly a Risk Assessment of the Channel should take place, as described in Section 14, Risk Analysis. The Risk Assessment will take into account what would happen in the event of the channel being overtopped:

a) Damage to the bank
b) Failure of the bank
c) The value of property damage that will occur
d) The effect on the security of the irrigation system

The Risk Assessment could be reduced if continuous monitoring by SCADA is implemented.

The freeboard allowance for risk is shown in Table 12-8.

Risk Assessment	Additional Freeboard allowance for Risk (m)
Low	0
Medium	0.3
High	0.6

Table 12-8 Freeboard allowance for Risk

12.13.7 Determination of Freeboard Allowance

Freeboard = minimum freeboard plus the larger of the following:

- risk allowance
- wave setup (S)
- half wave height (H/2)
- wave runup (R)

If a designer rigorously followed the above freeboard standards it would be possible to have a bank with varying freeboard along it. For ease of construction, the designer should therefore ensure that changes to freeboard occur only at structures, ie regulators or road crossings.

The designer should check whether or not wave setup (S) or wave run-up (R) required additional freeboard provision, particularly on large channels with significant fetch.

For most channel situations, wave height and run-up will not be significant freeboard factors and should be adequately accommodated within the minimum and risk freeboard allowances.

The effect of wave action is worse on very friable soils or fast slaking clays. The provision of extra freeboard will not overcome this problem. Some form of inside batter protection is required. Refer to Section 18, Inside Batter Treatment.

12.13.8 Construction Notes

It is important that the design bank level is constructed within the tolerances set out in Section 12.17.

12.13.9 Operation Notes

Limited encroachment on channel freeboards should only be planned during major system regulations or during short periods of maximum irrigation demand. Full freeboard should be maintained at all other times in order to ensure safety against damage from the unanticipated occurrences listed in 12.13.1.

12.13.10 Unauthorised interference

Unauthorised interference with control structures can cause rises in water levels. Important control structures should be fitted with locking devices or protected with security fencing in order to prevent interference.

12.14 Longitudinal Sections

The longitudinal grade of earthen channels is dictated principally by the topography along the channel alignment. The grade of each reach should be selected as far as possible to suit the ground slope and balance the earthworks.

The steepest grades are determined by the maximum permissible flow velocities as described in Section 12.11.3. If the natural falls in ground levels permit, the channel gradients should be the steepest practicable, consistent with the maximum permissible flow velocity. The longitudinal grade can be reduced, if necessary, by the use of drops, to restrict the velocity of flow to the allowable maximum.

12.15 Radius of Bends

12.15.1 Flow Around Bends

All changes in the direction of channel flow, such as curves and bends, cause disturbed flow conditions, which in effect increases the roughness and reduces the capacity.

Where sharp bends or considerable number of bends are necessary, their effects may need to be taken into consideration in the channel design.

The design of channel systems should seek to avoid an excessive number of bends, especially right-angled bends.

Disturbed conditions of flow caused by changes in direction consist principally of eddies or cross-currents that increase friction heads.

The disturbed conditions in channels can extend slightly upstream and long distances downstream from the bend, and are accompanied by differences in surface elevation, with a slight drop in surface level at the inner edge of the bend and a slight rise at the outer edge.

When water flows around bends in channels at sub-critical velocities, the differences in surface levels seldom amount to more than a few centimetres and is usually not a design consideration.

The disturbed conditions usually result in a concentration of higher velocities along the outer edge of the bend that can cause erosion along the banks of earthen channels, particularly along the outer banks in the downstream sections of the bend.

Where channels are constructed through easily erodible soils, changes in direction should be avoided, if possible. Where unavoidable, bends should be made gradually with long radii of curvature or adequate bank protection should be provided.

The use of gravel or rock beaching is an effective method of preventing erosion of channel banks at bends. Refer to Section 18, Inside Batter Protection.

12.15.2 Minimum Radius of Bends

To counteract the effect of erosive forces at curves in earthen channels, restrictions need to be placed on the radius of curvature.

The permissible minimum radius of a bend for an earthen channel depends primarily on:

- the dimensions of the cross section
- the velocity of flow
- characteristics of the soil

In general, permissible minimum radii of bends are shorter for small cross sections than for large cross sections, shorter for lower velocities than higher velocities, and shorter for tight soils than for loose soils.

Numerous criteria are used by irrigation agencies in Australia and overseas for determining the minimum radius of bends for earthen channels. Typically, they are based on the channel size, such as 10 times the water surface width, 15 times the water depth or 20 times the bed width.

An empirical equation developed by the Rural Water Commission of Victoria for the minimum radius of channel bends has proven to work satisfactorily. After many years of field observations, the only cases of scouring have been in dispersive clays, where some rock protection has been required.

The equation is based on the thesis that flowing water provides the energy that erodes beds and banks, and the radius of a bend should be related to the mass and velocity of the water. These two factors can be related to the hydraulic radius and longitudinal slope of the channel.

The radius of the bend, R_b (in metres) along the centre line of the channel is given by:

$$R_b = F \times R \times S^{0.5}$$

In the above formula:

F = empirical factor to account for the material through which the channel is constructed (refer Table 12-9.)

R = hydraulic radius for design flow, in metres

S = slope of the channel bed, in metres (vertical) per 1000 metres (horizontal)

Soil Type	F
Shale	30
Clay/Loam	45
Sand	60

Table 12-9 Factor for Minimum Bend Radius

Where feasible, smooth curves should be used rather than sharp bends in order improve the hydraulic properties and stability of the channel section. However, reasonably sharp changes in alignment are often needed to decrease the waste areas in fields and to avoid disruption to farm layouts. In these situations additional protection against erosion may be required and it becomes a matter of economics. The cost of land acquisition, severance and structures may be greater than the cost of protecting a tighter curve. Refer to section 12.11.4.

12.15.3 Bend Losses

Bend losses in open channels vary principally with radius and length of curvature, cross-section and velocity. In designing earthen channels, allowances for bend losses can generally be ignored. The bend losses in channels carrying water at low velocities are usually negligible, and in most situations the losses are less than the uncertainty commonly involved in selecting appropriate roughness co-efficients.

12.16 Channel Cross Section

The cross section selected for a channel must be able to carry the maximum design flow and satisfy the appropriate relationships between bed width, water depth, batter slopes, freeboard, bank dimensions and operation and maintenance. The cross section may, at various points along the channel, be partially or entirely in cut or fill.

Designing the cross section of a channel means determining the geometric shape for two major elements:

- the water section
- the above-water section

The components of a channel cross section are shown in Figure 12-9.

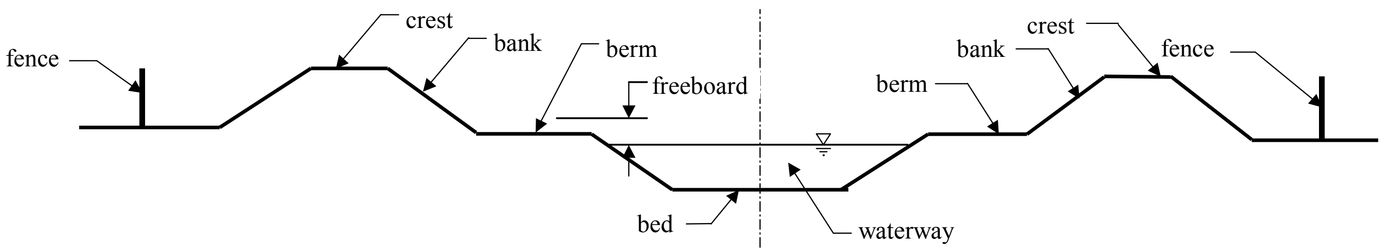


Figure 12-9 Channel Cross-Section

Many channel design methodologies are primarily concerned with the hydraulic aspects of the water section, and less attention is given to the above-water section. These optimisation methods determine a channel cross-section which minimises hydraulic resistance or alternatively, determining the least cost channel dimensions. However, they focus primarily on the water section, and do not take into consideration the practical construction, operation and maintenance requirements of the total channel cross-section.

Many of the variables related to channel geometry used in these methods, such as flow depth, channel width, channel bed slope and batter slopes, are in fact independent variables for earthen channels and are determined by the combination of the physical situation of the channel; practical considerations, economic conditions, bank stability, and operation and maintenance practices.

The definition of the best cross-section for a channel is not the one which conveys a given discharge with the minimum cross-sectional area or the least cost cross-section. Rather, the best cross-section is the one that has the lowest life cost, including construction, operation, maintenance and renewals of the *below*-water section as well as the *above*-water section of the channel.

To reduce total life cycle costs, the design approach must incorporate the above-water section as well as the water section and each channel needs to be evaluated individually for the most economic combination. Refer to Section 13, Life Cycle Cost Analysis.

Earthen irrigation channels in Australia are almost exclusively constructed with a trapezoidal cross-section.

The proportions of a channel cross section below the water level will vary considerably depending on the channel capacity, grade and the soils along the channel alignment.

The water section must be able to contain the maximum design flow below the top of the banks by the amount of freeboard.

The design of the longitudinal and cross sections of a given channel are usually carried out simultaneously because the water surface slopes are tentatively selected before the cross sections can be determined to carry the design flow.

The major design variables for the water cross section are the:

- Bed width — Section 12.16.6
- Water depth — Section 12.16.5
- Freeboard — Section 12.13
- Batter slopes — Section 12.16.4
- Bed longitudinal slope — Section 12.14

Usually, the longitudinal bed slope is selected to be equal to the required water surface slope.

Earthworks for new channel construction are usually designed as far as possible to balance cut and fill. This involves selecting a channel section that provides with reasonable lead, sufficient suitable material for compacted banks. The objective is to achieve the most cost-effective solution overall by optimising channel size and the amount of borrow. To do this, the capabilities and limitations of available construction equipment will need to be taken into consideration as part of the design process.

As far as practicable, the cross sectional shape of a channel should be based on high hydraulic efficiency. However, while the shape that has the minimum wetted perimeter provides the maximum hydraulic efficiency, achieving high hydraulic efficiency in earthen channels is usually much less important than economic considerations and certain practical construction, operational and maintenance requirements.

Channel sections based on hydraulic efficiency alone will have depths much greater than widths. These greater depths can be impractical to construct or very expensive, because the unit cost of excavation increases greatly with depth.

Because of the small width-depth ratio, the channel will experience large variations in water levels when flows are less than the full design capacity, and this can cause significant operational, service level and bank deterioration problems.

The cross section of channels should be designed so that available grades can maintain the required flows at mean velocities between the maximum and minimum permissible limits discussed in Section 12.11.

In the case of new channel construction, to produce enough bank material from the waterway excavation, most low capacity channels will need to be over-excavated, resulting in low velocities and flat water surface grades.

12.16.1 Hydraulic Design

In Australia, the Mannings flow formula is the most familiar and widely used channel design approach for steady uniform flow conditions. Refer to Section 12.11.

Mannings Formula $V = \frac{1}{n} R^{2/3} S^{1/2}$

Some irrigation authorities use one roughness coefficient (*n*) for design of all earthen channels irrespective of size. While a single figure may be adequate for a range of situations, a more careful consideration of the roughness coefficient is recommended to reduce life-cycle costs and achieve the most economic outcome.

Section 12.11.1 considers the selection of appropriate roughness coefficients.

Detailed design of channel cross sections that provide satisfactory velocities and adequate capacities are determined principally by the topographic and geologic conditions along the channel alignment. Topographic conditions determine available grades and depths of excavation, and geologic conditions determine most of the other details of design.

A careful study should be made of the materials forming the channel section order to determine the appropriate velocity for the required capacity. Section 12.11 considers the channel velocity aspects of design.

For open channels, the semicircle is theoretically the most hydraulically efficient shape, ie the maximum area for the minimum wetted perimeter, but the construction and maintenance of a semicircular earthen channel presents particular difficulties and costs. One major issue is the instability of the circular side slopes.

Close approximations to the semicircular shape can be made without sacrificing too much hydraulic efficiency, and trapezoidal cross sections are commonly used for earthen irrigation channels since they are usually the most practical shape to construct and maintain.

The proportions of the trapezoidal sections vary depending on the size of the channel, the grade, and the soils through which the channel is to be constructed.

Trapezoidal earthen channels often became naturally rounded at the bottoms as a result of gradual scouring and silting. A section constructed with rounded toes between the bed and batters is better than a strictly trapezoidal section, as it is more stable.

Deep narrow sections are desirable when feasible, since they provide higher hydraulic efficiency than wide shallow sections. However, this section is seldom practical for earthen channels because flatter batter slopes are required due to soil stability conditions.

Once the batter slopes have been determined, the trapezoidal shape with the greatest hydraulic efficiency can be determined. For batter slopes of 1:2, a bed width equal to about half the water depth is the most hydraulically efficient section.

However, economic considerations and certain practical construction, operational and maintenance requirements, usually make necessary considerable departure from the most theoretically efficient cross-section, and bed widths are generally three times the water depth for small channels and up to eight times the water depth for large channels.

The costs of construction needs to be considered, where the excavation cost of a channel may be reduced by adopting a wide shallow section instead of a more efficient deep narrow section.

Close attention needs to be paid to the design of cross sections for earthen channels on steep hillside locations, as channel seepage may cause failure of the downhill bank. Whenever feasible, water surfaces should be kept below the natural surface levels along the downhill sides. Where downhill banks are required, special design and construction precautions may be required.

The dimensions of a channel section needed to carry a specified flow depend on the types of section, roughness factor, available grades and permissible velocities.

Some typical cross-sections for channels are shown in Figure 12-10, Figure 12-11 and Figure 12-12.

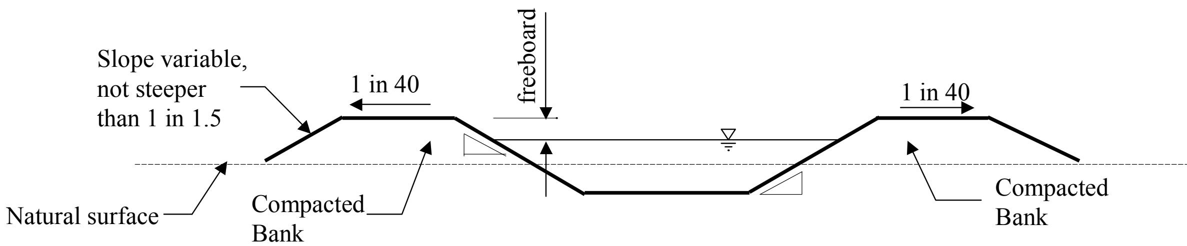


Figure 12-10 Typical Trapezoidal Section

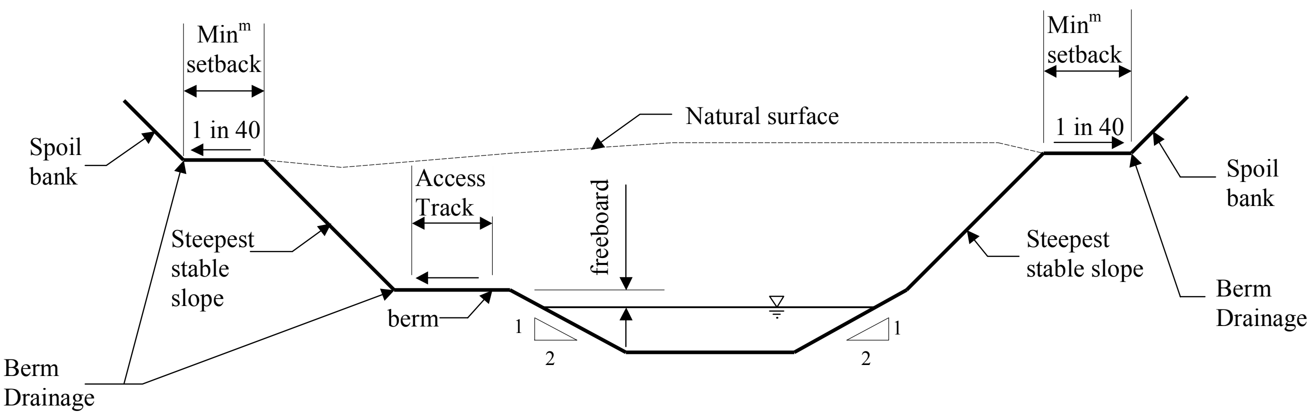


Figure 12-11 Typical Trapezoidal section in cut

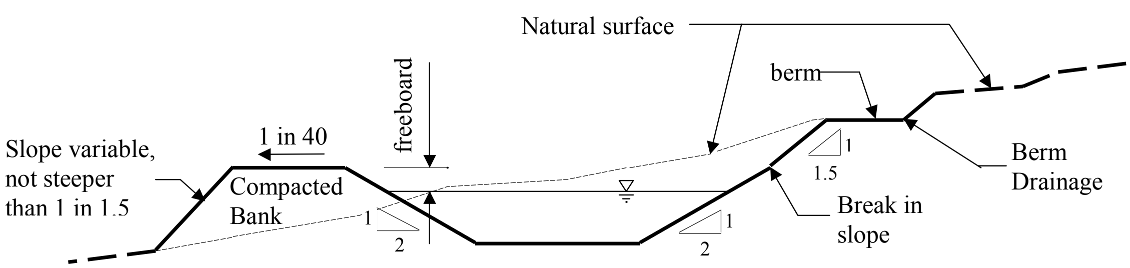


Figure 12-12 Typical trapezoidal section on hillside location

Channel cross sections have a number of components:

- depth
- bed width
- batter slopes
- banks
- berms
- earth lining
- stripping
- access track
- beaching

12.16.2 Banks

Many irrigation channels are required to carry water above ground as the basis of a gravity supply system.

The height of the bank crest must be sufficient to provide the nominated freeboard above the water level in the channel. The channel water level should be determined from the higher of the design discharge level for the adopted design capacity or the maximum water level assuming shut down of the channel from design flow to zero flow. Refer Section 12.12.

The dimensions of earthen channel banks will depend on such factors as:

- size of the channel
- height of water surface above natural ground level
- method of construction and type of plant employed
- the required service life of the channel
- amount of excavation material available for bank construction
- need for operational and maintenance access along the top of the bank

The bank width must:

- provide stability against the water pressure at the sides of the channel section
- keep the seepage gradient below ground level outside the banks
- prevent piping failure of material underneath the bank construction
- be wide enough for the types of equipment used in operation and maintenance

Greater bank heights than those needed for hydraulic reasons may be used where excess excavation exists, provided undesirable impacts on land acquisition, maintenance or structures are not introduced. The use of excessively high banks, particularly on sidehills, increases the risk of bank slumping.

Where the excess material from excavation has low cohesive strength and is susceptible to slumping, it should not be placed on top of the bank. Rather the material should be placed in spoil banks or spread on adjacent lands.

In the case of channels that run on contour around hills, the uphill bank level may be determined by the level to which stormwater runoff is expected to accumulate outside the channel. This water level will be a matter of individual assessment calculated from the cross drainage design for the particular location. The additional height required to ensure that the banks are not overtopped by stormwater flows will depend on the consequences of the stormwater entering the channel system.

Where a channel runs below natural surface, a minimum bank height of 0.3 metre is recommended to prevent drainage flows entering the channel.

12.16.3 Seepage Gradient

No earthen channel bank is completely impermeable; a small amount of seepage will occur and there will be a continuous movement of water from the waterface of the bank towards the outside face. Consequently, part of the soil making up the bank will be saturated, while the remainder will be relatively dry. The dividing line between the two is called the seepage gradient or phreatic gradient. The channel bank must contain the seepage gradient (phreatic grade) within the compacted bank section because saturated soil has little strength. If seepage were to break out on slope leading to local instability at this point, a process of gradual erosion and undermining of the channel bank may begin, which can lead to failure. The critical region is near the toe of the outside batter. This is illustrated in Figure 12-13.

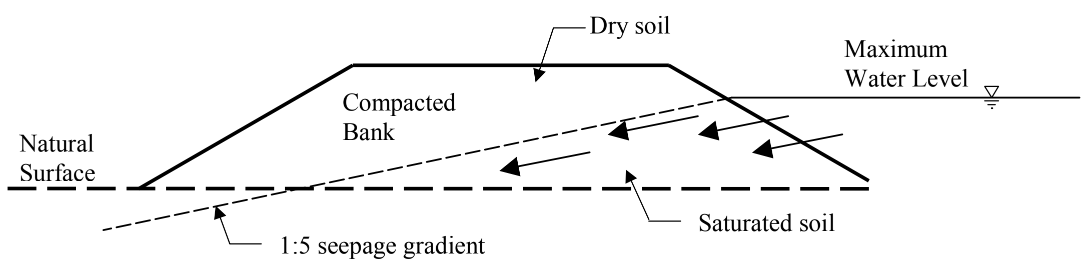


Figure 12-13 Seepage Gradient

The seepage gradient through channel banks, begins at the edge of the water level in the channel, and depends upon the permeability of soil, the amount of compaction and the location of the water table. The seepage gradient through the bank is a parabolic curve, but it can be assumed straight for the design of most channel banks.

Laboratory soil testing is required to determine the actual gradient and this should be checked, particularly for large channels with high banks. As a guide, Table 12-10 gives seepage gradient by soil type.

Soil type	Gradient
For stable relatively impervious soil	1:4
For clayey soil	1:5
For sandy soil	1:8
Porous materials	1:10

Table 12-10 Seepage Gradient by Soil type

Where the design height of bank is such that the seepage gradient intersects the outer slope above natural surface level, the bank crest should be widened or the batters made flatter to adequately contain the gradient within the bank section.

Unless the bank is very high, the seepage gradient is rarely critical to design. In practice, construction and vehicle access requirements generally dictate the width of the channel bank.

A soil having a seepage gradient of more than 1:6 would generally be unsuitable for bank construction.

12.16.4 Batter Slopes

12.16.4.1 Inner Slopes

Earthen channel batter slopes need to be stable under all anticipated conditions, and the angle of slopes should be carefully considered as part of design.

Batter slopes ranging from 1 (vertical):1.5 (horizontal) to 1 (vertical) :2.0 (horizontal) are practically standard for earthen trapezoidal cross-sections in Australia, frequently without due regard to the soil types present.

Long term channel bank performance indicates that some of the design batter slopes used in the past may have been too steep, and flatter batter slopes could increase bank life and reduce maintenance costs considerably.

Experience has shown that where the batter slopes are too steep, channel water level fluctuations can cause bank slumping and wave action can cause erosion, increasing rates of deterioration and gradually eroding the bank away.

While the standard cross-section approach may be adequate for a range of sites, more careful consideration is recommended.

Each channel should be evaluated separately, taking into consideration the operating conditions, effects of water, the type of soil, shear strength, soil shrinkage conditions, depth of cutting or height of bank, surcharge loading, ground water, and climatic conditions. A study of the soils in which the channel is to be excavated will assist in determining batter stability and this should be established by drilling bores along the line on which the channel is to be constructed.

The batter slopes of earthen channels are principally determined by the stability requirements of the material forming the channel. For some channels, the maximum batter slopes may be determined by economic methods of construction.

The batter slopes on earthen channels need to be flatter than the angle of repose of the saturated bank material at least as far up the slope as the maximum water level in the channel. Otherwise, under the less stable saturated soil conditions, the high pore water pressures in the bank can cause a shear failure and induce slumping of the batters into the channel. A similar failure can occur if the bank is made of expansive material that swells in contact with water and loses all or part of its shearing strength.

Experience has shown that these conditions speed up the bank deterioration processes considerably, with the steeper the batter slope, the greater the impact.

In serious cases, a large section of soil can slide out of the bank and the channel may have to be taken out of service for repairs.

The batter slopes of banks built in fill may have to be flatter than batter slopes entirely in excavation. With practically all types of soil the angle of repose is steeper in air than it is under water and in deep cuts, the batter slopes may be steeper above the water surface, than in the wetted sections. Table 12-11 gives a guide to maximum batter slopes for saturated bank materials.

Soil Classification	**Symbol**	**Maximum Batter slope** (vertical:horizontal)
Clayey/silty gravels and sands	GC SC GM SM	1:2
Clays and silts with low to medium liquid limit	CL ML CI	1:2 to 1:2.5
Clays and silts with high liquid limit	CH MH	1:2.5 to 1.3

Table 12-11 Guide to Maximum Batter Slopes for Saturated Bank Material

Slopes of 1 (vertical) to 2 (horizontal) are the steepest that should be considered, unless granular material is provided for bank protection.

The slopes given above should be suitable for bank heights up to about 3.0 metres where the material has been compacted to a high density. For greater bank heights, the stability of channel bank batters should be checked by determining the soil cohesive strength, the soil internal friction angle and unit weight of the saturated soil, and carrying out slip circle analysis of the proposed batter slopes, using an appropriate factor of safety. Under normal conditions, a factor of safety of at least 1.5 is recommended.

If rapid fluctuations in water level are expected, greater than 150mm in 24 hours, consideration should be given to flattening the slope by 0.5. If severe fluctuations, of more than 300mm in 24 hours are expected, a crushed rock or gravel cover on the batters can be used to reduce bank slumping.

Refer to Section 15, Material Selection and Testing on important physical properties of soils and their relative suitability for channel bank construction based on the Unified Soil Classification System.

Note that the channel bank materials make a considerable difference in the maximum batters. Quite large cost variations can therefore occur between the same size channels through different soils.

Unstable soils of very low cohesive strength, deep channels and channels subject to rapid reductions in water levels, or severe wave actions will require special consideration, and the use of flatter batters of 1 (vertical) : 3 to 3.5 (horizontal) may be advisable in these cases unless granular material is provided for bank protection. However, such channels can be expensive to construct, due to the amount of material to be excavated and the area of land occupied by the channel.

The stability of channel batters can also be identified from field observations of existing channel banks through the same soil and hydrological conditions. The flatter the batter slope the better for reducing the erosive action of waves.

Experience in Victorian irrigation areas has shown that channels through clay soils generally show long term stability with batter slopes of 1 (vertical) : 2 to 2.5 (horizontal) and in the lighter sandy loam soils batter slopes of 1 (vertical) : 2.5 to 3 (horizontal) generally perform satisfactorily.

12.16.4.2 Parabolic Cross Section

From United States and Canadian experiences, which are supported by field observations in Australia of eroded but stable channel banks, it has been found that a channel cross section which approximates a parabola, can provide stable batter slopes that minimise the top width of the channel, as well being efficient in terms of capacity.

The parabolic cross-section, which conforms to Equation 12-1 has a batter slope gradually increasing from zero at the centre to about 1 (vertical) :1.5 (horizontal) at the top of the bank. The parabolic section has been found to be no more difficult to construct than the conventional trapezoidal cross section. Refer to Figure 12-14 for details of the parabolic design and construction approach.

Some properties of a waterway with parabolic cross-section:

Cross-sectional area $A=\frac{2}{3}(td)$

Hydraulic radius $R=\frac{t^2 d}{1.5t^2 + 4d^2}$ or approximately $\frac{2}{3}$ d

For width $t = \frac{3A}{2d}$ for water depth d

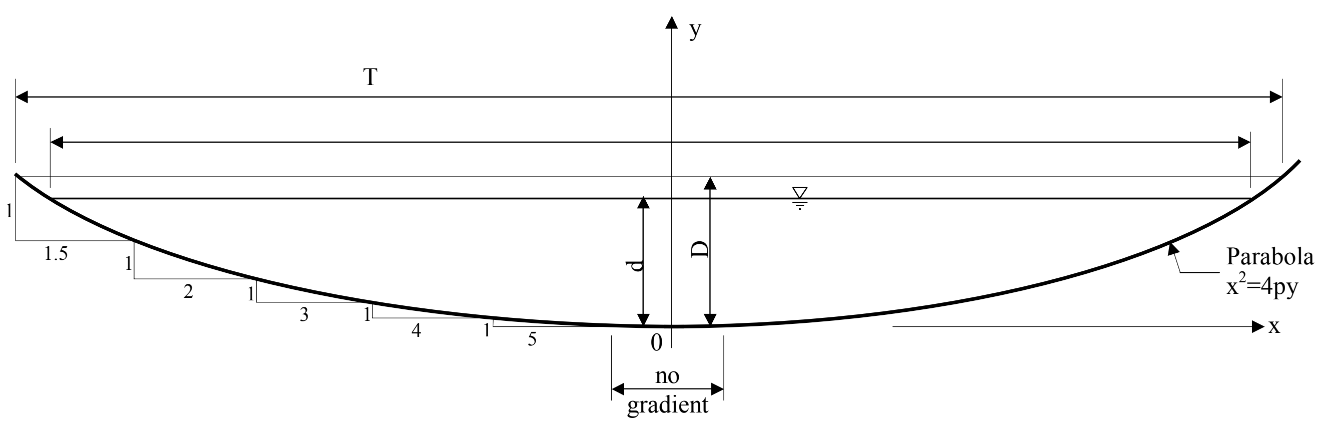


Figure 12-14 Design of parabolic cross-section

Given $t =\frac{3A}{2d}$; $T = t\left(\frac{D}{2}\right)^{½}$ when the top width T is desired for a depth D other than d

The general equation for a parabola is $\mathbf{x^2 = 4py}$, where p is a constant

Equation 12-1

Depending upon the particular conditions, use of the parabolic cross section may be an option to reduce erosive forces and stabilise channel batters without resorting to the expense of 1 (vertical) :3.5 (horizontal) batter slopes that result in excessively wide channels. For a 2 metre deep channel this can represent a reduction in top width of 6 metres.

The parabolic cross section therefore represents a compromise that should be considered, between flatter batter slopes at the expense of greater channel width, and steeper batter slopes at greater risk of bank instability.

This non-conventional parabolic cross section can also be used in the remodelling or reconstruction of deteriorated channels, as well as a batter stabilisation technique used to extend the life of a channel by improving the stability of the eroded bank.

12.16.4.3 Outer Batters

The outer batter slopes of channel banks are frequently made the same as the inner batter slopes. While this may be appropriate in many situations, a more considered approach is recommended. The outer batter slopes are seldom steeper than 1 (vertical):1.5 (horizontal), but are often flatter, depending on the type of material, amounts of excavated material and the height of the bank above natural surface.

An outer batter slope of 1 (vertical): 2 (horizontal) would generally be appropriate for most channel banks up to 1.5 metres above natural surface. For higher banks of up to 3 metres above natural surface, a slope of 1 (vertical): 3 (horizontal) may be required.

12.16.5 Depth

The minimum depth of cut for small channels is generally determined by the practicalities of construction rather than by capacity, and is about 0.5 metre. This depth produces useful volumes of material for bank construction, provides for reasonable depths of water for channel operation, and provides some buffer against the impact of weed growth. Small shallow channels let sunlight into the bed and on earth channels this aids the growth of water weeds. Deeper channels tend to reduce this effect. Less weed problems occur in deeper water, and it has been observed that carp, yabbie and water rat activity in channels are also reduced with deeper water.

When trying to balance the cut and fill of earthworks for new channels, a minimum depth of 1 metre is frequently adopted. Irrespective, the cross section of smaller channels will normally require additional fill material. When deciding on the appropriate depth to width ratio, the designer should consider the most cost-effective solution overall, including earthworks and structures. The effect of greater depth on structure costs should be considered, particularly in sections of channel with numerous structures. Wide shallow channels suit drop-bar regulators because drop bars become difficult and time consuming to manually handle for depths of water in excess of a metre.

The cost issues associated with structures include:

- longer spans or additional spans on bridges with shallow piers verses shorter or fewer spans with deeper piers.
- wider shallower headwalls verses narrower deeper headwalls.
- larger number of regulator bays of shallow depth verses fewer bays of greater depth

Geological conditions, slope stability, groundwater, limitations of construction and maintenance equipment and the dimensions of structures generally govern maximum depth of cut for channels. Deep channels are more expensive to construct because the unit cost of excavation increases significantly with depth.

In some channels, the desirable depths of flow may not be feasible because of geological conditions:

- cuts that extend through impermeable strata into porous formations are undesirable because of increased seepage losses
- cuts that extend through earthen deposits into rock strata are undesirable because of increased excavation costs
- cuts that extend below the ground water table are undesirable because of construction difficulties

A wider shallower channel provides more stable flow regulation conditions. More constant water levels can be maintained in the channel because the higher width to depth ratio means that the levels are less affected by changes in flow rates. A narrower, deeper channel will experience larger variations in water level with changes in flow, and this can cause significant operational, service level and bank deterioration problems.

12.16.5.1 Emptying of Channel

Depths and structure inverts should be designed so that the down stream slope of the channel bed enables complete emptying of the channel (excluding siphons) via one practicable route during non-operational periods, so that maintenance and replacement works can be carried out on the channel waterway and structures.

12.16.6 Bed Width

The adopted bed width is generally the most practical one for construction purposes.

A wide bed width is an advantage for earth moving equipment, and the minimum practical bed width for construction is about 1.5 to 2 metres. A bulldozer, excavator or grader can be used to construct beds of this width. While the minimum bed width for construction with a self-elevating scraper is 2.5 to 3 metres. For these reasons, a minimum bed width of 2 to 2.5 metres is frequently adopted.

In new channel construction, if the material is suitable, the earthworks are designed to balance the material required for banks, with the excavation of the channel cross section. Should insufficient spoil be available from this approach, local widening may be used in combination with deepening to achieve a balance of earthworks. Since non-uniform flow conditions are then introduced, a backwater computation must be carried out to determine the water surface profile.

Where the bed width changes along a channel, the transition rate should be at 1 metre width per 10 metre length (except through structures).

The maximum bed width for large channels is usually based on the practical limits of depth, the design flow rate and available grade.

12.16.7 Top of Bank

Practical construction, operational and maintenance requirements usually dictate the width of the bank crest. In theory, the minimum crest width for a small channel could be 2 metres if plant is available to work or trim such a narrow crest. However, to accommodate efficient construction equipment, minimum crest widths are typically 2.5 to 3 metres. The minimum crest width should also meet the hydraulic gradient (phreatic grade) requirement from the maximum channel water level to the outer toe of the bank.

Where it is a major channel and vehicle access is located on the top of the bank, the crest width may have been designed in the past to a 6 metre standard. These situations need to be looked at more closely, as the crest width is a major cost driver. The wider the crest the greater the earthworks volumes and the larger the land acquisition. Rather than a set standard, each situation needs to be evaluated for the lowest overall cost and the economics should prevail.

Where vehicle access is required along the channel for operation and maintenance, the minimum crest width needs to be about 3.5 metres to allow the passage of large plant, trucks and vehicles. If all-weather access is necessary, the crest can be covered with 75 to 100 mm of gravel.

The crest of banks should be graded away from the channel section at a slope of not flatter than 1 (vertical):40 (horizontal), so that rainfall will drain down the outer slopes, and not down the less stable inner batter slopes that are more susceptible to erosion.

12.16.8 Berms

Channels that have deep cuts through high land may need to have berms constructed on the inner batters between the water section and the top of the cut.

These berms provide access to the channel for construction and maintenance equipment, prevent sloughing of the batters caused by heavy loads too near the edge of the channel, and reduce the erosion due to rilling that can be associated with long lengths of exposed batter draining into the channel. The erosive action of water increases as the slope length increases.

Both the height above the bed and the width of the berm are selected to suit the size of the channel, the construction and maintenance equipment, and the stability of the particular type of material in which the channel is constructed.

Typically, berms are provided every 5 to 8 metres of height and are 3 to 4 metres wide to ensure stability of the channel batters. Where the bank material is susceptible to slumping, soil testing and stability analysis will be required, to ensure bank stability.

Berms will usually require some form of drainage, with disposal either into the channel or away from it. In deep cuts, the berm may have to be 5 to 6 metres wide to allow for both access and drainage.

12.16.9 Spoil Banks

Earth from excavation of a channel that is unsuitable or surplus to the requirements of the banks, can be deposited as spoil banks, formed on or behind the design banks. In some situations, it may be possible to spread the soil material on adjacent land or use the material for farm roads, rather than place it in spoil banks. This approach is recommended as it eliminates the erosion, drainage, vermin and weed problems created by high spoil banks.

The height and width of spoil banks should be selected to suit construction equipment, and the stability of the particular material. The location of the spoil should ensure that the resulting surcharge loading does not adversely effect the stability of the channel batters.

Large quantities of spoil are normally encountered only on very large channels or where channels pass through deep cuts, and would warrant special design of the spoil placement.

If the spoil material is not spread, spoil banks should be proportioned for height and width so that the areas of land occupied are not excessive and the finished banks are stable and have an overall acceptable appearance.

The side slopes of spoil banks should be trimmed to an even slope, typically not greater than 1(vertical) : 2(horizontal). Spoil banks will usually require some form of drainage. Crest are frequently sloped (1 in 40) to the outer batter to provide satisfactory drainage away from the channel.

If the soil and climatic conditions permit, top soil should be spread over the inner batter, crest and outer batter to encourage grass and minimise erosion.

12.16.10 Vehicle Access

Access for operational and maintenance purposes along many irrigation channels in Australia is limited or non-existent.

Continuous vehicle access along at least one side of a channel for operational and maintenance staff and for use by maintenance plant is highly desirable. Refer Figure 12-15 and Figure 12-16.

The side of the channel selected for access should be the most convenient for operation and require the minimum number of structures crossing it and connecting to it. Exceptions may be where there is an adjacent public road. Vehicle turning bays should be provided at operational structures and at appropriate intervals along the channel road, ie every 2 kilometres.

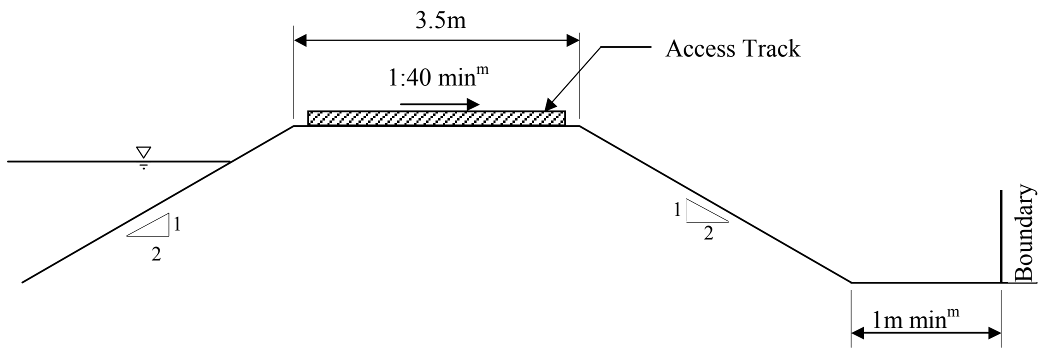


Figure 12-15 Vehicle Access – top of bank

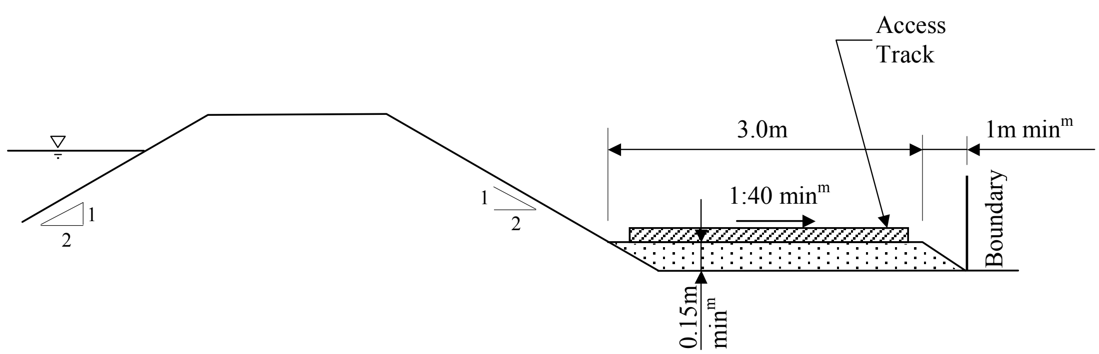


Figure 12-16 Vehicle Access – adjacent to channel

While the need for access along one bank, both banks or no access should be decided on an individual channel basis, the provision of continuous vehicle access along one side of a channel is considered to be best practice. In the United States and Canada, the provision of access roads along main irrigation channels is seen as an almost essential feature.

The reasons for providing access include:

- enables regular inspections to identify maintenance and replacement needs as they develop, leaks, damage, interference to works, water theft and contamination
- Enable operational staff to safely and efficiently travel between regulators measuring points and outfalls
- reduced travel times and increased efficiency of operational staff

- enable maintenance of the channel to be carried out efficiently particularly weed spraying, desilting and repairs to banks and structures
- enables operational staff to quickly shut-down the system in the event of heavy mid-season rain.
- enables rapid corrective action to be taken
- reduced response times and increased efficiency of maintenance plant
- wear on vehicles and mobile plant is reduced

The timeliness of maintenance is very important to prevent increases in both difficulty and cost. The detection of minor faults at an early stage when repair is simple and economic is crucial in minimising life-cycle costs. Good access provides the most effective tool for preventative maintenance.

Where dry weather only access is required, a 3 to 3.5 metre wide road can be formed by grading off the top of a sufficiently wide channel bank. If all weather vehicle access is required, the road surface can be covered with a suitable thickness of gravel, typically 75-100 mm.

All-weather access to offtakes and main control structures, particularly near the upstream end of main channels, allows operational staff to quickly regulate or shut down the channel system in times of heavy rainfall, otherwise loss of water and damage to works and private property may occur. The actuation and installation of SCADA systems on key control structures may be an alternative to the provision of all-weather operational access.

Live stock on access roads can be a problem, especially if large stock such as cattle are allowed to graze on the channel during wet weather, which results in damage to the channel banks and the access road.

12.16.11 Entrance of Side Surface Water to Channel

Side surface water should not be allowed to spill over channel banks without protection. Interception drains should be provided to control local drainage on the land side of the banks. These drains should be graded towards collection points to discharge either into the channel through appropriate inlets or into the surface drainage system if there are water quality issues.

12.17 Construction Tolerances

The tolerance of the physical dimensions of the channel cross-section(s) should be stated on the Design drawings and Specifications.

Typical construction tolerances for earthen channel banks are as follows:

Design Bank Level	- 0 to +0.1metre	
Crest Width	- 0.2metre to +0.2metre	
Moisture Content	-2% to +2% of *optimum moisture content*	(Refer to Section 16.8.1)
Bank Density	-0% to +5% of *maximum dry density*	(Refer to Section 16.8.2)

Tight specifications and construction tolerances add significantly to costs, and realistic requirements need to be established for general channel bank work. In some situations, stringent specifications have been adopted that are really more appropriate to major earth works projects, rather than the construction of channel banks that are typically not much more than one metre high. Wherever possible, the liberalisation and simplification of channel bank specification should be pursued to lower construction costs.

12.18 Seepage

All channels will seep to some extent. When the rate of seepage is unacceptably high, some form of control is required.

Earthen channel design should therefore include an assessment of likely seepage rates, limits that can be considered tolerable, and control measures that are appropriate in each particular case.

Where the costs of seepage control are high, alternatives such as a change in channel location or modification of the channel network to eliminate a high seepage section of channel should be explored.

The subject of channel seepage because of its importance is treated separately. Refer to Section 21, Channel Seepage and Section 22, Channel Lining.

12.19 Rights over Land

An irrigation authority requires legal rights to occupy lands for the purposes of constructing, operating and maintaining channel works. It requires access to those works and the rights to protect them from damages by stock, farming activities or any other cause.

Where an authority channel crosses private property, an appropriate form of land tenure will be required to adequately protect the channel works and secure access rights.

In these situations the channel, including any access track, berms or spoil banks, should be located on an adequate but not excessive width of land, over which the irrigation authority has suitable rights.

Careful consideration of land acquisition issues from the planning to construction stages can significantly expedite a project and reduce its costs. Modifications of location and alignment can ease land acquisition problems.

Some landholders argue against freehold acquisition on the grounds that it reduces the saleable area of their property title. Other landholders request freehold acquisition because they would otherwise have to pay municipal rates on lands held under easement.

The methods of land tenure over the areas occupied by channel works vary across Australia and can include:

- Reserves
- Freehold
- Easements
- Fenced easements
- Leases

- Access agreements

A description of each form of land tenure with its advantages and disadvantages is listed in Table 12-12. The question of what method of land tenure is appropriate, largely evolves around the issue to what extent fencing is required. Refer to Section 12.21, Protective Fencing.

The authority's legal rights vary for the different methods, so do the financial compensation, survey, legal and administrative costs of acquiring the different rights.

Unless there is a specific reason for doing otherwise, the channel is located in the centre of the land acquisition.

Tenure	Description	Advantages	Disadvantages
Easement	An easement is a contract which results in an interest in land being created. An easement creates a proprietary interest in the dominant landowner (the irrigation authority) over the land owned by the servient landowner. Once an easement is registered on Title it stays there in perpetuity until the relevant parties agree that it is no longer required. If the dominant landowner is in breach of the conditions of the easement, the easement cannot be terminated, but damages can be awarded.	• Easements can be registered on title and are secured for all time. • Minimal cadastral survey required. • The law relating to easements is relatively well settled. Easement wording and terminology is generally accepted through the legal profession, and less open to interpretation.	• The authority cannot enforce fencing. If fencing is required, it may be carried out only by agreement with the landowner. This can lead to problems if the property changes hands, whereby a new agreement must be drawn up or the new owner could remove the fence. • Easements do not provide exclusive use. It confers only the specific rights created by the easement, with the landholder having certain residual rights of land usage. Therefore a landowner may successfully argue to use the land for grazing etc. with the accompanying risk of damage to channels and structures. • There are survey and administrative costs involved in noting the easement on title. • Cross fences and flow hurdles can obstruct the channel and require maintenance and clearing of debris.
Lease	A lease is a contract which results in an interest in land being created, but it differs from an easement in many ways. A lease is normally only for a certain term of years and not inperpetuity. The lease is recognised by the courts as more of a contract and the terms and conditions of the lease need to be set out in the document creating it. This means that a lease can be terminated in certain circumstances by the landlord if the tenant is in breach of the conditions contained in the lease.	• Leases can be registered on title. • The costs of establishment are the least expensive. For registration on title, the costs can be substantially reduced as a licensed surveyor is not required. • Leasing provides exclusive use of the land, enabling longitudinally fencing where desirable and appropriate.	• Leasing does not secure the use of the land for all time and extra negotiations will be required on each lease as it expires. This could be time consuming and costly. • There are survey and administrative costs involved in noting the lease on title.
Freehold and Reserve	The most secure form of land tenure held. With freehold the irrigation authority purchases the land as a separate title in the name of the Authority. In developing a new irrigation scheme, the areas required for channels can be set aside as reserves under the irrigation authority's control. With land acquisition the Authority has a legal obligation to provide, replace and share in the maintenance of the fence, as the fence is then a boundary.	• Exclusive ownership of the land • Can establish complete control over use and maintenance • Provides the most secure land tenure held in perpetuity in the name of the Authority. • Can be fenced legally and form the boundary with adjoining properties	• High cost - requires extensive survey, subdivision work and compensation. • Slowness of land acquisition process • Fire, weed and vermin management is the responsibility of the landowner or manager on both public and private land. If land is acquired by the irrigation authority it is required to manage the land for pest plants and animals, in the same way as any other land manager. (In Victoria, under the Catchment and Land Protection Act, land managers are responsible for controlling pest plants and animals.)

Table 12-12 Land Tenure type

12.20 Channel Tenure Width

The channel tenure should incorporate the channel banks and adequate access for operation and maintenance purposes.

The acquisition width should allow enough space between the outside toes of the channel banks and the acquisition boundaries for access of maintenance equipment and the depositing of silt from the channel waterway.

On smaller distribution channels, the width of this space should be at least 1 metre and preferably 2 to 3 metres. On larger channels, each case needs to be assessed, but the width of the space between the bank toe and the boundary could be up to 5 to 6 metres.

The main purpose of the margin is to provide an area for:

- placement of silt removed from channel
- leak repairs
- maintenance of structures
- weed spraying
- allows for swing of an excavator without damaging the fence
- future refurbishment works

If fences are located at the toe of the bank, the fences can be damaged from soil movement in wet weather, from material from track grading or spoil from de-silting operations putting pressure on the fence and rusting the wires.

12.21 Protective Fencing

The question as to whether or not channels should be fenced has caused controversy between landowners and irrigation authorities here in Australia and overseas.

By fencing the land tenure boundary along both sides of a channel:

- the banks, berms, access track and waterway can be protected from damage from private stock and traffic
- continuous access can be provided along the channel to facilitate efficient channel operation, maintenance and supervision.
- problems arising from unsatisfactory operation of flow gates at cross-fences can be avoided.
- pollution of the water can be prevented
- hazard to the public can reduced, particularly children.

Photos\Design\trangie4.crossfence.batter erosion.jpg

Photo 12-1 Cross-fence has caused erosion of bank

Earthen channel banks can be easily damaged and where they are exposed to potential risks, it is recommended that fencing along both sides of the channel should be erected as soon as practicable after the completion of the earthworks to physically separate and protect the channel banks, berms, waterway and its associated structures and access from damage from adjacent landowners, stock and inappropriate farming practices.

However, fencing of channels tends to be a contentious issue with landholders and should not be treated lightly.

12.21.1 Reasons for Protective Fencing of Channels

It is important that the banks of a channel are protected from physical damage caused by stock, adjacent farm operations or other unauthorised access as described in section 12.21.1.1 to 12.21.1.4.

The channel waterway should also be protected against deteriorated water quality, stock diseases and contaminants which may be passed to downstream users.

12.21.1.1 Stock Damage

In Goulburn-Murray Water, livestock damage has been found to reduce channel bank life significantly. Most of the damage caused by stock on channel banks is related to stock using the channel as a drinking trough.

stock damage

Photo 12-2 Erosion of channel bank caused by stock access

Stock can cause quite extensive damage to channel banks. In the heavy stocking areas of northern Victoria, new unfenced channel banks constructed from light friable soils can be effectively destroyed by stock within a year.

Stock damage to channel banks results in material being pushed into the waterway, steepening of channel batters, erosion, damage to structures and reduced bank life which impacts on the flow capacity of the channel as well as increased maintenance costs.

Both sheep and cattle can cause damage to earth banks. Sheep trample and graze channel banks bare, exposing the bank material to rain and wind erosion. Cattle damage can be very serious, trampling and pugging up the banks and waterway, particularly where cattle use the channel bank to access water.

Cattle cause steepening of the inside batters of channels as they walk down to the water's edge, which may deteriorate further due to wind and wave action. The installation of stock watering troughs away from the channel bank will reduce the amount of damage that occurs.

Channel banks may be used as a stock laneway, wet weather stock holding area, storage of hay and for stock feeding. Where the channel bank is used as a laneway for stock, the access track requires increased maintenance. Stock using an access track in wet weather can render it impassable for operation and maintenance vehicles. The crest of the channel bank can be damaged quite badly when used for access during wet conditions as ruts and potholes can be formed. In dispersive soils this can lead to the development of sink holes and possible piping failure.

As with the damage to the inside batter, the outside batter may be eroded by stock walking up and down the bank. In time, the phreatic surface may be breached causing leaks through the bank.

Light stocking rates may be acceptable in some irrigation areas in order to reduce vegetation growth which may become a fire hazard and habitat for noxious weeds and vermin.

12.21.1.2 Damage due to adjacent land use practice

Adjacent farm operations may also increase maintenance costs and adversely effect the life of an earthen channel bank as follows:

- using the bank as a farm access track for stock and vehicles
- using bank as a headland around crops
- locating farm irrigation channels immediately adjacent to the authority's channel bank, so only one farm bank is required.
- 'borrowing' of earth from the back of bank for farm use
- storage of farming equipment or use as a rubbish dump
- encroachment of channel tenure for cropping

The phreatic surface of the bank may be breached if earth from the outside batter is removed or if a farm channel is located nearby. This will cause the bank to begin leaking which may lead to a piping failure of the channel bank.

12.21.1.3 Unauthorised public access

Unauthorised access which may impact on channel bank includes:

- Potholes and ruts on the crest and outside batters caused by vehicles
- Dumping of rubbish which may impede access for operations and maintenance

12.21.1.4 Waterway contamination

The potential adverse environmental and water quality impacts caused by stock and other unauthorised access are:

- contamination through the deposition of animal faeces directly into the waterway
- increased turbidity and nutrients (Nitrogen and Phosphorus) in the channel water
- increased possibility of toxic blue-green algae
- spread of bacterial and viral diseases; eg Johnes Disease
- spread of parasite eggs and cysts; eg Liver fluke
- dead stock in channel causing general health risks
- increased weed growth
- chemical pollutants, such as spills from farm chemicals.
- increased health risks to other farms and downstream water users

12.21.2 Advantages and Disadvantages of Protective Fencing

The asset protection and water quality benefits of fencing a channel need to be weighed up against the initial capital cost and ongoing maintenance costs.

The advantages of fencing are summarised in Table 12-13.

Advantages of Protective Fencing	
Improvement of Operation and Maintenance efficiency	- improves access for operation and maintenance staff by eliminating the need to open and close gates – more effective channel control and reduced O&M costs. - overcomes need for cross-fences and flow hurdles that catch debris, cause head loss in channel, require maintenance and periodic clearing, can cause bank erosion and channel to overflow if they become blocked with debris and generally are not entirely stock proof.
Protection of Channel Earthworks	- protects the significant capital investment of the irrigation authority - provides a clear delineation of the boundary between privately owned land and the channel tenure - maintains the channel's design integrity by minimising stock damage to channel banks, batters, access track and structures particularly in light friable soils.
Control of Stock	- encourages grass growth that protects bank - the control of stock allows rapid grassing of the banks and batters when new or remodelled, minimising batter erosion - eliminates damage by stock - allows for controlled grazing when required, controlling grass growth on top of bank. Stock can then be moved out when the task is accomplished.
Reduces potential physical damage from farm practices	Controls inappropriate use of channel banks for: - stock access tracks - buildings, ditches, structures, trees etc - stock feeding, the storage of hay bales and rolls resulting damage to the banks and restriction to access - wet weather stock holding, - disposal of fruit tree prunings. - disposal of plastic sheeting used on horticultural blocks - the removal of earth from the channel banks - prevents farm machinery from working too close to the channel, where the weight of machinery operating with wheels on the crest of the bank can initiate slumping and bank failures.
Water Quality	- reduces sediment turbidity and nutrient problems within the channel system. - improves stock health on farms – can prevent the transmission of waterborne diseases such as liver fluke and johnes disease. - impedes stock access to channels thus reducing sources of contamination (stock faecal excretions, dislodging of bank material, dead stock, spread of disease) - chemical pollutants such as spills - dead stock in channels causing blockages, general health risks and offensive odours
Public Safety	Fencing can also be used to provide a measure of safety for both the public, particularly children, and wildlife from accidental entry into the channel.
Capital and Maintenance Costs	Savings in capital and maintenance costs of cross fences, flow hurdles, gates and strainers.

Table 12-13 Advantages of Fencing

The disadvantages of fencing channels includes:

- capital cost
- loss of stock access to water
- loss of grazing area
- grass growth on the channel may become a fire hazard and habitat for vermin.

However these disadvantages can be overcome as described in Table 12-14.

Disadvantages of Fencing	Management of Disadvantages of Fencing
The additional direct cost associated with construction and maintenance of the fence.	Where longitudinal fencing is not constructed, it is often necessary to install cross-fences where property boundaries cross the channel tenure. Cross-fences require the installation of a flow hurdle across the channel waterway, which are expensive to install and maintain.
Vegetation can become a fire hazard and allow the growth of noxious weeds within the fenced channel tenure. High vegetation cover may provide a habitat for vermin which may also burrow into the bank.	To prevent vegetation growth from becoming excessive, encouraging vermin and becoming a fire risk, light stocking or other measures as described in Section 17, Protective Cover may reduce the problem. In Goulburn-Murray Water, grazing by light animals such as juvenile cows and sheep is allowed for short periods after permission is granted by the Area Manager, under strict guidelines.
Loss of stock grazing area and access to water	Landowners can provide water for their stock by stock troughs or dams on their properties.
Restricted plant access for maintenance	Provide sufficient space between bank and fence

Table 12-14 Management of Disadvantages of Fencing

12.21.3 Location of Protective Fence

Where a fence is located too close to a channel bank there can be insufficient room for effective maintenance and access by plant and equipment. Therefore the designer should delineate sufficient room for maintenance activities and plant access between the fence and bank.

The fence should be placed on the boundary of the channel tenure, with at least 1 metre from the outside toe of the channel bank. If space is available, a distance of 2 to 3 metres from the bank toe to the fence line is recommended for smaller distribution channels and up to 5 to 6 metres for larger channels.

12.21.4 Use of Stock Grids versus Gates

Stock grids are sometimes used instead of gates at access points such as cross-roads. Their main advantage is that operators do not need to open gates.

The disadvantages of stock grids are:

- stock grids are not absolutely stock proof and stock could be injured if forced over the grid
- gates would be required in any case to allow stock access for controlled grazing

- gates provide a better deterrent to unwanted public access

12.21.5 Areas where Protective Fencing may not be Required

The need for longitudinal fencing should be considered on an individual channel and farm type basis.

In some circumstances fencing along both sides of a channel may not be required; ie

- low stock numbers
- no likely problems caused by soil types
- no access track
- when the channel passes through orchards or cropping areas
- when damage is unlikely from farming practices, ie use as a headland, traffic way, rubbish dump or source of fill material

12.21.6 Proven Practice

Where significant damage to channel banks can occur, best practice is considered to be physical separation using post and wire longitudinal fencing along both sides of the channel tenure boundary. Several types of fencing are available. The two most commonly used with stock are described in Table 12-15.

The standard of fencing should be based on such factors as the existing standards of farm fencing, stocking types and rates and the availability of continual energy for electric fences.

12.21.7 Other options to Protective Fencing

Another option to fencing to prevent damage to channels from stock is to introduce a policy, such as fining farmers who damage channel banks. An awareness raising program, eg advertisements on television and local newspapers will inform landowners of the costs to the irrigation authority in repairing channels and also inform them of the material consequences to them if they continue to allow stock on channels.

A policy approach can work well as a deterrent. Goulburn-Murray Water has a policy of charging individual landowners for repairs to works damaged by stock.

12.21.8 Decision Criteria

An economic evaluation / risk assessment of fencing as compared with not fencing should be carried out.

12.21.9 Specifications and Plans

The specification used for fencing in Goulburn-Murray Water is attached.

Fence Type	Post and Wire	Electric Fence or Hot Wire
Description	Traditional post and wire construction.	Insulated steel posts are put into the ground at distances apart that will support the electrified wire. The wire is strung along the posts and connected to a pulsating power source that sends shocks through the wire at regular intervals. If livestock touch the wire, while being contact with the ground, they will be shocked and will move away from the fence.
Advantages	Can be used anywhere.	- the electric current in the wire is the deterrent, not the physical strength of the fence - lower construction cost than a post and wire configuration - ability to be moved for various reasons can be advantageous - during construction access can be still maintained, as fence can be erected at the end of each day's construction.
Disadvantages		- The need for a power supply is required to keep the wire electrified constantly. Since the fence is easily moved, theft may become an issue. - May be more expensive in terms of operation than post and wire type fences. Possible electrification of operation and maintenance staff
Limitations	Timber posts may be damaged due to fire or termite damage.	An electric fence will be a barrier for livestock only. The method is limited to the distance from a power supply.
Comments		An electric fence is usually not as permanent as a post and wire configuration, they may sometimes be combined to get the benefits of both types of fences.

Table 12-15 Protective Fencing Options

12.22 Safety

12.22.1 Risks

Open channels present a safety risk to people and animals, and plans for new channels or for refurbishment of existing channels should include measures for minimising these risks, based on an assessment of the risk exposure.

Safety measures will vary from site to site depending on the inherent danger of a particular channel and the level of exposure to people and animals.

The risk depends primarily on two factors. The first concerns the inherent danger of the particular channels. Although a channel may be inherently dangerous, unless people and animals are exposed to this danger, the risk may be low. Therefore, the second factor concerns the degree and type of exposure to the channel.

When considering exposure, factors such as the proximity to schools and housing should be taken into consideration.

Channel safety measures can be grouped into two categories:

- those which limit or deter people and animals from entering a channel
- those which are escape devices in the event a person or animal enters a channel

12.22.2 Reducing risks to people

Water has a peculiar fascination, especially to children, and drowning can be a tragic consequence.

All open channels, regardless of size, depth, flow or type of construction are a hazard to people, particularly children, and safety measures need to be taken to minimise the associated risks. Selection of the most appropriate measure is dependent on the degree of risk.

Public safety education programs, warning signs and protective fencing are safety measures, which limit or deter people from entering a channel.

Protective fencing is probably the most common and effective safety measure, particularly to deter the access of small children. It may vary from a simple 1.2 metre high rural stock fence, through to a 2.4 metre high chain wire security fence.

Escape ladders, suspended cables, float lines and siphon guards are devices, which aid people to escape from a channel.

Photos\Design\siphonguard.jpg

Photo 12-3 Manguard on entrance to siphon

Fencing, regardless of height, will not be an effective barrier to older youth and adults determined to gain access.

It is not known how many people take notice of warning signs. Warning signs are thought to do little to prevent someone from entering an area and becoming a potential drowning victim. However, suitably worded signs located at appropriate places accessible to the general public, can at least alert some of the public to the dangers that exist, and make them more careful or cautious in their behaviour.

One of the most effective means of protecting the public from the hazards of irrigation channels is the education of people to realise that hazards do exist.

12.22.3 Reducing risks to animals

Channels with earthen banks generally do not present a high risk to domestic and native animals because they can usually escape from them unassisted.

Wherever channels present a risk to animals they should be fenced, and in most cases conventional stock fencing 1.2 metre high is effective.

12.23 Design Drawings

The design drawings, which often become a part of a contract, may include:

- Locality plan
- Longitudinal drawings
- Cross-sectional drawings
- Earthworks schedules
- Structure schedules
- Land acquisition details

These drawings together form the set of plans expressing the finished design for a project in complete detail. Sufficient information, specifications, instructions and references should be given to allow construction, operation and maintenance to be carried out in accordance with the design intent.

The design drawings should be sufficiently complete to allow proper pricing and planning of the works, a constructor to unambiguously carry out the works, and a superintendent to interpret the design and administer the contract.

The criteria for material selection and compaction must be clear and unambiguous, as well as the testing to be carried out to ensure compliance with the specified criteria. The design drawings should be neat, clear and drawn according to standard drafting practice.

The longitudinal section is a key plan, which is used to note the essential features of the channel design.

The longitudinal section plan is prepared both as a summary of the design for construction purposes and a record plan, which is often used long after construction has been completed.

The basic longitudinal section plan contains a profile illustrating the relationship between the natural surface and the design bed, banks and water levels along the channel. The plan shows:

- Description of holdings supplied
- Natural surface levels
- Supply levels
- Bed and bank levels
- Design flow rate and discharge level
- Hydraulic gradeline
- Location of all structures
- Meter outlet locations
- Required land acquisition widths
- Soil types
- Bore information
- Survey bench mark locations

The longitudinal plan also refers the reader to the general locality plan, cross-sectional plans, hydraulic design details, earthwork schedules and structure plans which supplement it. Enough cross-sections should be prepared to allow accurate computation of the earthworks volumes. This depends primarily on the uniformity of the topography.

A typical design drawing for channel refurbishment showing plan, long section and typical cross-section is shown in w2774_ls_2-24-8.dwg or typicalchannel.doc.

12.24 Australian Standards

AS3798-1996	*Guidelines on earthworks for commercial and residential developments*

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13. Life Cycle Cost Analysis

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13.1 Introduction

In many irrigation schemes, networks of channels are used to convey and distribute water. The channel network represents a major cost and the best possible value for money is vital. The maximum value is achieved when overall construction, operation, maintenance and replacement costs are minimised.

Channel construction and refurbishment decisions usually involve a considerable amount of cost estimating. Final designs are adopted after weighting the advantages and disadvantages of alternatives and comparing costs. In the past some irrigation enterprises have placed an over-emphasis on the capital cost of channels, and not enough attention has been given to life cycle costs. Some channel design methodologies focus on the minimisation of a few cost items, while the rest of the items are ignored. Experience has shown that it is unwise to assume that the best value lies in the initial cost.

Decisions made on long-lived infrastructure assets are usually irreversible and have long lasting effects once they are implemented. It is therefore important that any analysis of alternatives account for all immediate and future costs correctly and be accurately calculated.

Current thinking is to make decisions based on the full costs of the assets over the whole life cycle, using a process that is generally known as life cycle cost analysis or LCC.

This section aims to provide a basic understanding of the processes of life-cycle cost analysis, and its importance in decision making for channel design, construction, maintenance, rehabilitation and replacement. The section outlines a simple life-cycle-costing model for channels.

13.2 Life Cycle Cost Concept

13.2.1 What is life cycle costing?

Life cycle cost analysis in an asset management context is a cost driven methodology used to support decision making. Life cycle costing is also known as *whole of life costing*.

In life-cycle analysis an evaluation of the cumulative stream of costs associated with alternative courses of action are undertaken over the planned service life of an asset, including the design, construction, operation, maintenance, rehabilitation, replacement and disposal costs.

In each particular case, a life cycle cost model of sufficient detail to meet the objectives of the analysis is developed. For comparison purposes, the costs are reduced to a single value with a common basis in time, and the preferred option is usually the one with the lowest practical life cycle cost.

Historically, the emphasis had been very much on the capital cost of a channel, with less concern on the total life cycle cost. This can be a shortsighted view, and longer term thinking now places the emphasis on life cycle costing for comparison of options.

Figure 13-1 illustrates this principle of cost visibility.

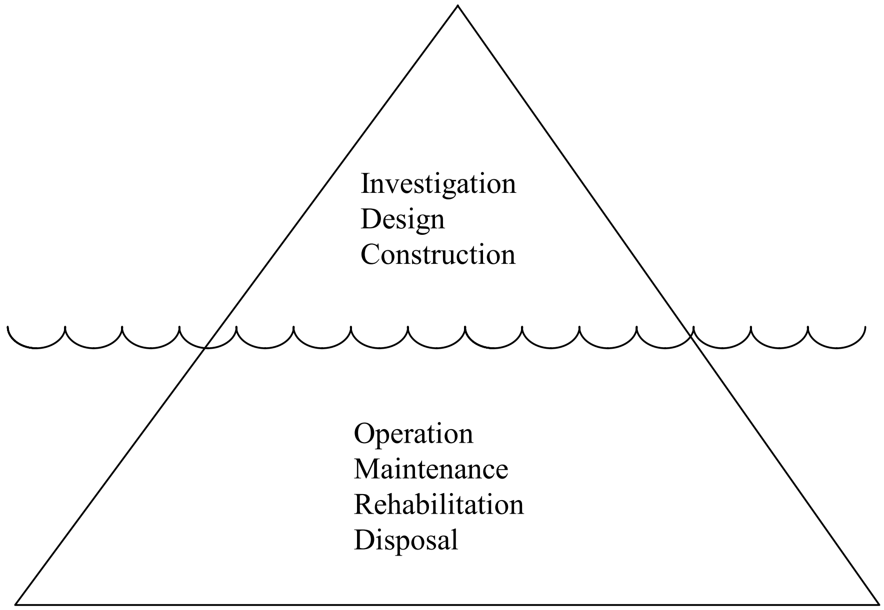

Figure 13-1 Life cycle cost visibility

13.2.2 Objective of life cycle costing

The objective of collating the total costs of an asset from its inception to the end of its life cycle, is to demonstrate which option or alternative course of action is the most cost effective. This is used as an input to design or acquisition decision making or the appraisal of maintenance, rehabilitation or replacement options during the various life-cycle phases of an asset.

Rather than following a set standard, it may be more cost effective in a particular situation, to adopt a simple low initial cost solution, with higher maintenance and reduced service life. Alternatively in another situation, a sophisticated high initial cost solution may well be justified when the longer service life, and lower maintenance and replacement costs are analysed.

The risk of over-investment if future demands or circumstances change also needs to be considered, particularly with relatively long life irrigation infrastructure.

The taxation regime applying to an enterprise can also mean that faced with the same situation, public and private enterprises may make different decisions.

13.2.3 Why is life-cycle costing important?

The total life cycle cost of an asset can exceed its initial capital cost, and a focus on initial costs alone does not guarantee value-for-money. If decisions are made without proper analysis of the life-cycle costs, the initial saving may result in increased expenditure through out the assets life or the initial cost may be higher than necessary to achieve the required performance or service life. The identification of costs enables the decision-maker to balance capital costs, operation and maintenance costs and economic lives over the total life cycle.

For example, the initial construction costs may be higher as a consequence of investment in reliability and maintainability, but the overall life-cycle cost may be lower due to extended life and reduction in operation and maintenance costs.

One of the major responsibilities of irrigation enterprises is to get the best possible value for money from its infrastructure investments, and the initial capital cost of a channel is not a reliable indicator of value. Best value means the best outcome when all relevant costs over the life of a channel are considered, and to achieve this, the total life cycle costs must be considered, not just the initial costs.

Life cycle cost analysis is therefore a valuable tool for improved asset management decision making.

13.2.4 Applications of life cycle costing

Life cycle costing can be used in a range of decision making and evaluation processes;

- comparing options with different costs and life spans
- selecting the option that can deliver the lowest practical life cycle cost
- ensuring that the best value for money is obtained
- deciding how to best allocate limited resources – time, money and labour

For example, evaluating whether to continue to maintain an existing channel for 15 years until its lowest acceptable condition is reached and the replace it, or to rehabilitate the channel in 5 years time, and then replace it after a further 20 years. The two options are illustrated in Figure 13-2 and Figure 13-3.

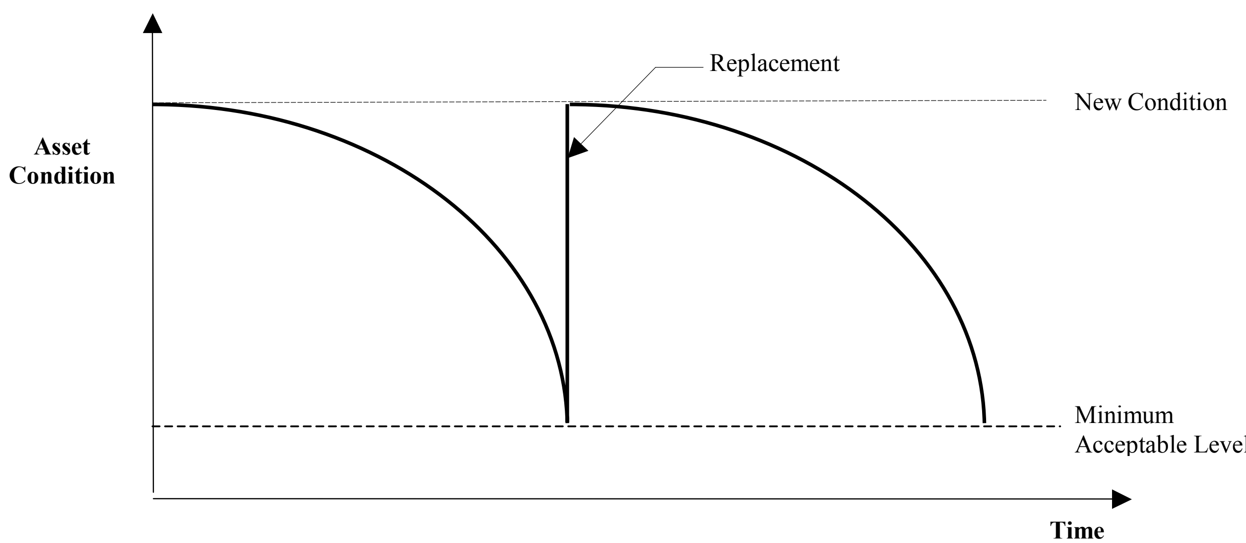

Figure 13-2 Maintain existing asset for 15 years, then replace

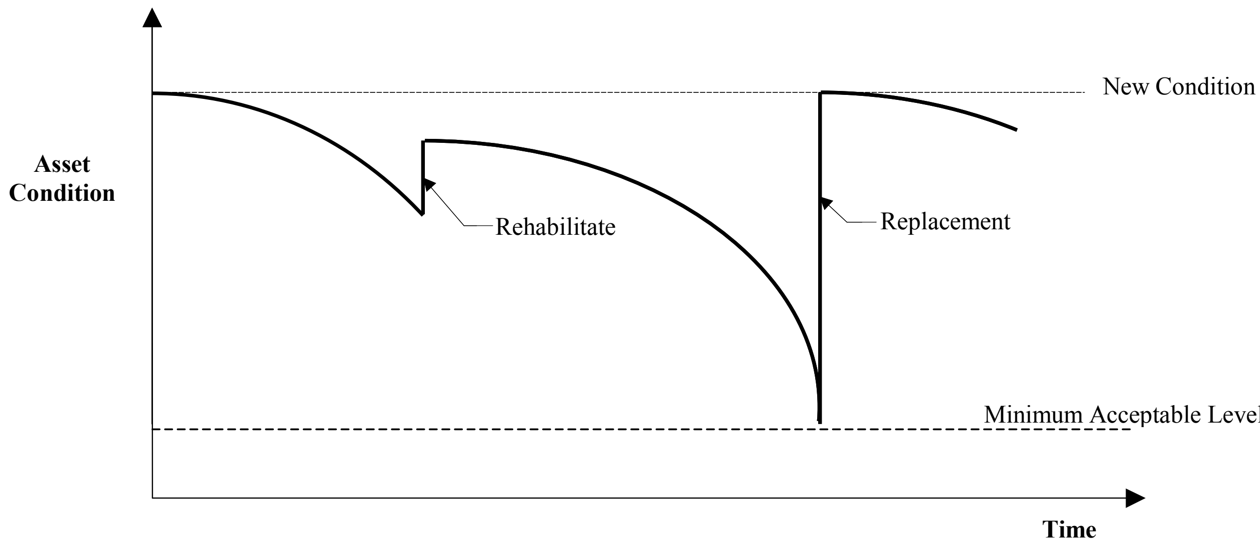

Figure 13-3 Rehabilitate channel in 5 years time, then replace after further 20 years

The applications of life-cycle costing for channels includes:

- evaluation and comparison of alternative channel design and construction approaches.
- enabling a common basis of comparison for channel options with significantly different cost profiles and life spans – pay now or pay later.
- evaluation and comparison of alternative strategies for channel operation and maintenance.
- assessing the impact of new technology.
- evaluation and comparison of different approaches to channel repair, rehabilitation, replacement or disposal.
- trade off analysis to determine the optimum performance, reliability and maintainability of a channel.
- selecting the optimum maintain/rehabilitate/replacement strategy for a channel.
- identifying the *cost drivers* that have the most significant impact on life-cycle costs of a channel so that they can be managed or designed out.
- benchmark actual life cycle cost performance of channels.

13.2.5 Benefits from applying life cycle costing

The benefits of life cycle cost analysis are seen as:

- identifying best value for money
- assessing options on an equal and consistent basis
- forcing long range considerations rather than short term thinking
- forcing total cost visibility
- reduction of long term costs and in doing so reduction of service costs

13.2.6 When to use Life Cycle Analysis

A life cycle cost analysis can be of great advantage in making high cost, long life decisions. On the other hand, there may be little value in undertaking a life cycle cost analysis of short life (less than 10 years), low cost alternatives.

A life-cycle analysis should always be considered when comparing alternatives with significantly different initial cost, life expectancy or ongoing costs. On the other hand, a life-cycle-analysis will be of little value if the life expectancy, initial cost and the ongoing costs are similar in the options being compared, or if the decision depends substantially on factors other than cost.

Major emphasis at the investigation and design phases should be placed on the minimisation of life cycle costs. A poor design may result in:

- expensive construction problems
- high ongoing operation and maintenance costs
- reduced asset life
- expensive over or under specification of reliability, performance and service life

Designers faced with the comparison of more expensive, durable materials and lower cost shorter life span alternatives should asses life cycle costs.

Care needs to be taken to avoid over analysing life-cycle-costs. The depth and accuracy of analysis should be appropriate to the value of cost involved, the strategic importance of the project and the time scales involved. There can be a danger of becoming immersed in excessive detail and a common sense approach is needed.

It is implicit in life-cycle analysis that the benefits for the different options are equal in each time interval. Where the options give rise to different potential benefits these must be considered in a broader economic evaluation process.

13.3 Life Cycle Cost Considerations

Life cycle cost analysis requires a knowledge and understanding of all the costs associated with an asset. A channel typically goes through the following phases during its life cycle, from the identification of need through to disposal:

- investigation
- design
- construction or acquisition
- operation
- maintenance
- rehabilitation
- replacement, and/or
- disposal

Figure 13-4 illustrates the typical distribution of costs over the life cycle of an infrastructure asset.

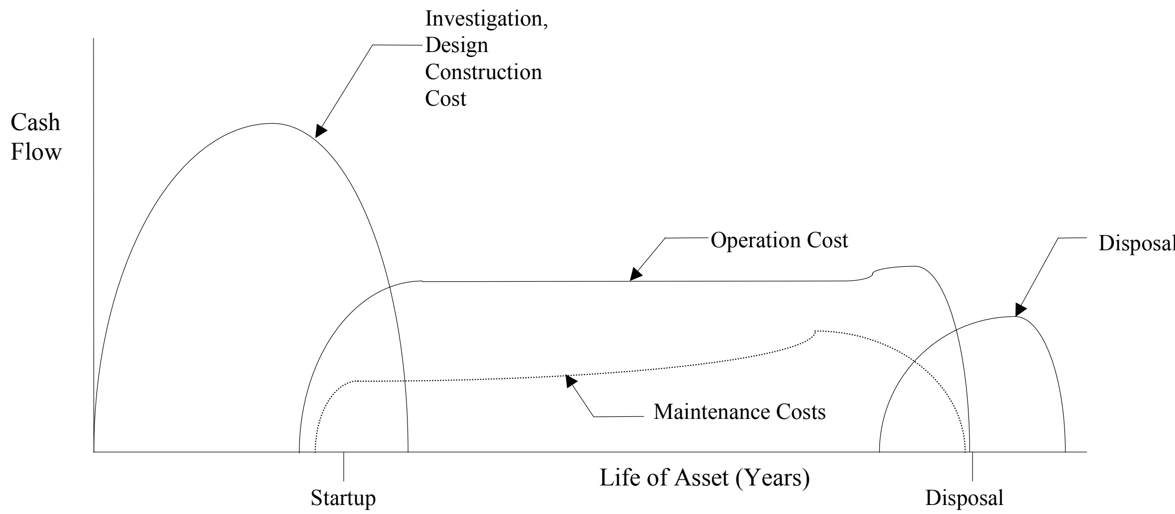

Figure 13-4 Life Cycle Cost Distribution

Decisions made early in an assets life cycle can have a much greater relative influence on subsequent construction, operation and maintenance costs than those made later in the life cycle.

Experience has shown that the opportunities for life cycle cost reduction are typically greatest in the investigation and design phases, where a major proportion of the factors affecting life-cycle costs are decided, although in general this phase represents only a small proportion of the total costs. However, a balance is required between either under-resourcing the design phase and hence non-optional solutions, or over-resourcing and incurring high design costs. This process is often called value engineering.

Diminishing opportunities exist for life cycle cost reductions during construction, and by the time the asset moves into the operation and maintenance phases almost all of the factors affecting life cycle costs have been decided. Figure 13-5 illustrates this *level-of-influence* principle.

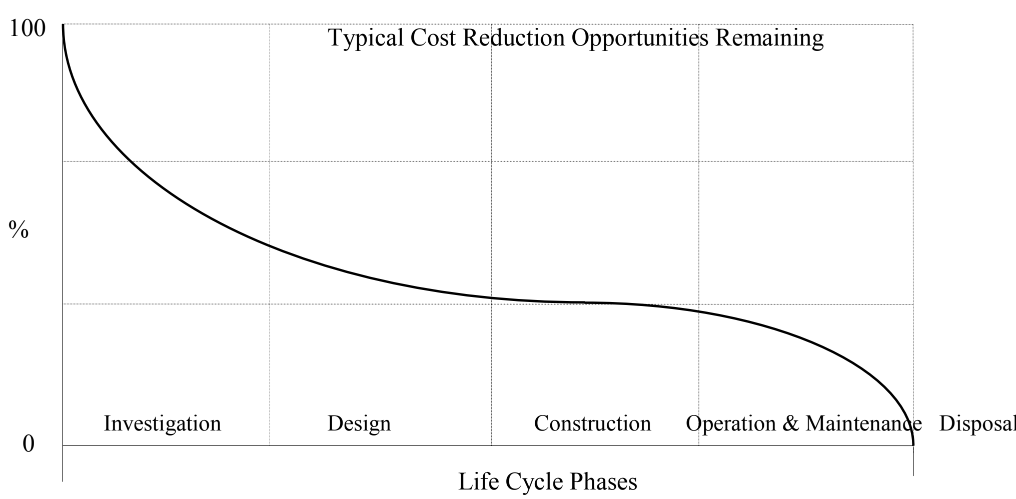

Figure 13-5 Life Cycle Cost Reduction Opportunities

The timing of the life-cycle costing analysis is crucial to optimise a channel and its associated costs. The flexibility in trade-offs and options becomes increasingly limited as the channel advances in its life cycle. This does not mean that cost reduction opportunities should not be looked for in the operation, maintenance and rehabilitation phases, but that major opportunities may have gone.

At the beginning of a new channel project, there is control over all factors determining future expenditure. A decision not to proceed, requires no future expenditure for the project. A decision to construct requires more decision-making, and once decisions are firm and commitments are made, the level of influence on future project costs decreases.

A decision made during construction, even within the remaining level of influence can still greatly impact on costs of maintaining or rehabilitating a channel. For example, lack of quality control or use of inferior materials may save construction costs, but the extra maintenance costs may consume those 'savings' several times over.

13.4 Calculating Life Cycle Costs

13.4.1 The basic steps in a life cycle cost analysis

In order to produce results that can be usefully and correctly employed, life-cycle analysis needs to be conducted in a structured and documented manner.

Australian Standard, AS/NZS 4536:1999 – *Life Cycle Costing – An Application Guide*, reflects such a systematic approach.

The method of life cycle costing used can vary depending on the type and depth of the analysis being undertaken, and some methods are more appropriate than others to particular applications.

For long life assets such as channels, the general approach to determining life-cycle costs involves the following basic steps. These are:

1. Develop analysis plan
2. Determine the evaluation period
3. Choose an analysis technique
4. Identify asset lives
5. Estimate costs
6. Adjust figures for inflation if necessary
7. Discount future monetary values
8. Generate life cycle costs
9. Determine uncertainty of figures
10. Evaluate results

Figure 13-6 describes this life cycle costing process.

Assumptions made at each step should be documented to aid interpreting the results of the analysis.

Using the steps above, life-cycle costs can be evaluated in most cases, in an objective, reliable and easily understood manner.

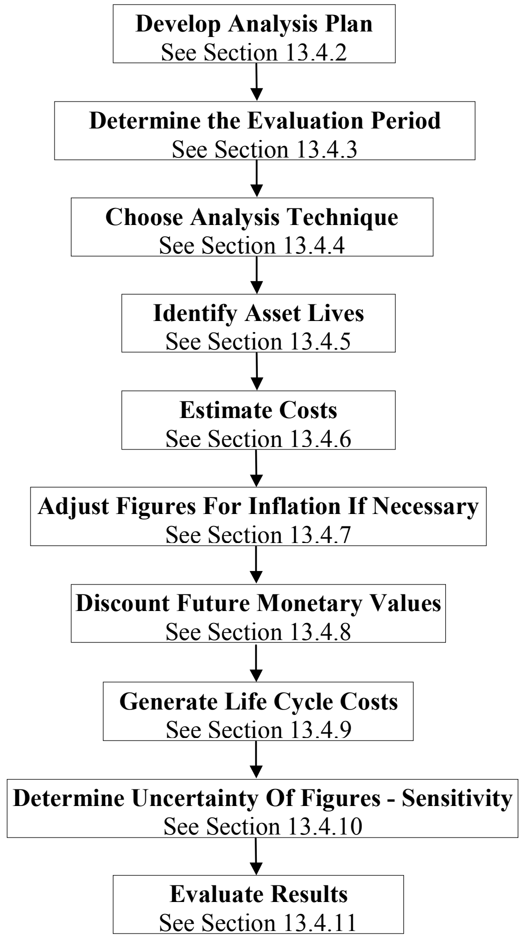

Figure 13-6 Life Cycle Costing Process

It is not possible to develop precise prescriptions that apply to all channel situations. Each case will have specific issues to be considered and the detail of the assessment needs to be tailored to the importance and value of the project.

13.4.2 Develop Analysis Plan

The range and depth of parameters to be considered in life cycle costing can vary significantly, and the analysis should begin with the development of a plan that addresses the purpose and scope of the analysis. This plan should address the following elements:

- define the objectives in terms of the output required
- delineate the scope in terms of the use environment, the operational requirements and maintenance regimes, etc.
- identify any underlying conditions, limitations and constraints which restrict the range of options
- identify the feasible alternatives or options to be evaluated
- establish the degree of accuracy required
- determine the availability, completeness and accuracy of data

- assess cost of collecting missing data, and review accuracy specified as appropriate

The accuracy required will vary in accordance with the assets significance, data availability and the cost to collect the data.

13.4.3 Determine the Evaluation Period

The evaluation or life cycle period is the length of time over which the costs are considered, and an appropriate period needs to be established for each case, depending upon the particular situation and the purpose of the analysis.

The evaluation period can be based on a number of concepts:

- planned service life
- physical life expectancy
- projected economic life

Normally, the analysis should extend over the service life of the infrastructure, and this could either be the lesser of the physical life or the economic life. In some situations, the particular period chosen will be a policy decision for the organisation concerned.

Many channel assets have a service life of 50 years, with 100 years being appropriate for major irrigation infrastructure. However, future land and water use changes, such as rural restructuring, urban development and changes in farm irrigation practices, may make the service life of some channel assets significantly less, possibly 20 or 30 years.

The following should be kept in mind when considering how far ahead the analysis should look:

- the evaluation period should be long enough to capture the full effects of the costs of the different options
- the results are likely to be more sensitive to the time horizon when the time horizon is short
- more accurate forecasts can probably be made for a shorter time horizon - uncertainty increases the further into the future they are projected
- the evaluation should be carried out with a uniform time horizon for each option under consideration. If this is not possible, the analysis should be made using Equivalent Annual Value
- the evaluation period for long lived infrastructure assets need not be more than 100 years when using the normal range of discount rates as discounted cash flows after this period become so small that it has insignificant effect on the results of the analysis
- where there is no notional end point to the service life of a channel, the evaluation period should include at least one complete life cycle of the assets involved.

Options involving assets having a salvage or residual value at the end of the evaluation period should be credited with that value at the end of the period. To avoid the need to account for the residual value of long life assets it may be simpler in some cases to compare all the options over a 100-year period, where the discounted residual value becomes almost insignificant.

The evaluation period is divided into time intervals, usually in increments of a year.

13.4.4 Choose an Analysis Technique

The analysis technique used should be a standard discounted cash flow, which takes into consideration the time value of money. Discounted cash flow analysis is a method of valuing and therefore comparing a range of different cash flows. The discounted cash flow analysis results in estimates of the present value of the sum of initial and future costs over the selected evaluation period. The analysis requires that all future costs are quantified and identified with a time period, and then adjusted to current year dollars to enable comparison.

Cash inflows and cash outflows represent benefits and costs, and the present value of all the inflows and outflows is the Net Present Value. In life-cycle analysis, the cash inflows or benefits are not included and the present value of costs represents the cash outflows only. The option with the lowest present value for an equal evaluation period is considered the most appropriate option economically.

Further details of the economic theory of present and future values should be sought from appropriate texts on the subject.

Two well known methods used in the water industry for project evaluation are Present Value (PVC), for comparing items with similar life expectancies, and Equivalent Annual Cost (EAC) for assets with dissimilar life expectancies.

Analysis by PVC - PVC is considered the most comprehensive and effective method. It converts all future cash amounts into current-year dollars using a appropriate discount rate. Once this is done a comparison of the options can be made as long as the life spans are the same.

Analysis by EAC - Items with different life spans can be compared using EAC. The EAC is the PVC averaged over the expected life of each option to give an equivalent annual value. One advantage of using annual equivalents is that costs can be discussed using much smaller and manageable numbers than would be the case if present values were used.

However, the economic validity of an option is not established by these analyses. They distinguish the least cost option. Economic validity can only be established by considering the benefits and costs of an option.

To identify and better understand the costs associated with an asset, it is a good practice to present the analysis in a spreadsheet format, identifying all the cost elements in the rows or alternatively the columns. The costs associated with the elements can be entered for each year in the relevant columns or rows.

Life cycle cost analysis can require a volume of data and degree of precision, which is difficult to manage using manual means. For large, complex projects, a manual approach to analysis is simply not practical and a software-based model is required. Spreadsheet programs such as Excel, Quattro Pro and Lotus have NPV as functions that can be used to simplify the process.

Microsoft Excel has quite a good present value function, called NPV. It also includes optimisation and what-if analysis functions called Solver and Goal Seek respectively, which can be used to find optimal solutions.

13.4.5 Identify Asset Lives

Life cycle cost analysis requires the realistic assessment of asset lives. The asset life is the period in years from the time of construction or acquisition, to the time when the asset is expected to reach a state where it cannot provide acceptable service because of physical deterioration, poor performance, functional obsolescence or unacceptably high operating and maintenance costs.

The lives of two identical assets operated under different conditions may not be the same. Similarly assets consisting of different materials may have different lives, even though they are performing the same function. Because of the many factors which determine asset lives, the appropriate lives should be assessed in each particular case.

A sound prediction of the remaining life of an existing channel is also important for life cycle costing, and this requires a careful assessment of the rate and extent of future deterioration of the channel.

An earthen irrigation channel will have a wide variation in its life and rate of deterioration because of the varying influence of:

- design
- construction methods and quality
- age of channel
- soil types
- usage history
- environment
- operating practices
- maintenance regimes – past and current
- size of bank
- velocity of flow and flow history
- depth of flow
- whether protected from animals
- whether carp are in the channels
- bank orientation to prevailing winds
- fluctuations in water levels – magnitude and rate
- extent and quality of refurbishment

The evaluation of asset lives can be quite a complex process, and at best, only an estimate of an average life can be made for most long life assets, based on the age after which the asset falls below an acceptable limit or performance or at failure. What is unacceptable performance can depend on service perceptions and expectations. Future influences can be different from those of the past.

Predictions of asset lives can be based on:

- performance modelling using condition monitoring and deterioration rates
- historical records using survivor techniques
- degradation models
- time to failure models
- accumulated experience
- accelerated testing

- engineering assessment
- professional judgement

In cases where asset life is difficult to estimate accurately, it is still useful when items are ranked in order of durability and assigned expected lives based on experience.

The economic life of an asset also needs to be recognised as distinct from its physical life. Normally, the economic life of a channel is shorter than its physical life, and failure to appreciate this fact will over-estimate benefits. The economic life of a channel is over when:

- it becomes more economic to replace the channel rather than continue to maintain it, or
- supply from the channel is no longer required, even if it still has a physical remaining life – obsolescence, or
- supply from the channel is insufficient to meet current demands and it needs to be upgraded.

13.4.6 Estimate Costs

To undertake a life cycle cost analysis it is necessary to collect or estimate costs relative to a common base date for all asset components. The total cost of a channel includes more than just the initial construction cost, and for life-cycle costing to be of value, all the relevant costs for each life cycle phase need to be identified and included in the analysis.

The choice of estimating methods used will be influenced by a number of factors, including:

- the required accuracy of the estimate
- the level of knowledge of the work
- the availability of suitable costing data
- the newness of technology
- the degree of uncertainty about future changes

Two engineering cost estimation methods frequently used by the water industry in Australia are:

Unit Rates method - Estimates are prepared using unit rates for work outputs, such as cubic metre of excavation, metres of fencing etc. The rates are based on previous experience and the actual recorded costs of similar works, using current costs or past costs updated by applicable cost indices. Each unit rate will include the cost of all labour, materials and plant appropriate to the item.

First Principle or Basic Cost method - Estimates are prepared using costs assigned to the resource inputs, such as materials, labour, plant etc, calculated to be necessary in completing each part of the work. This method is frequently used when job costing records are not available or in estimating costs for one-off work.

The costs used in these methods should be derived from the best available data, including all the direct and indirect costs (supervision, administration and overheads), from either:

- actual current costs
- actual past costs updated to present time using appropriate inflation indices
- costs determined from past or comparative experiences, test work or field trials
- direct estimates prepared from first principles experience
- budget estimates from contractors and suppliers
- unit rates from industry publications and handbooks modified to suit specific conditions and adjusted by scaling factors and escalation indices

The accuracy required will vary according to the project significance, data availability and the cost of getting data. In all cases the effort made to obtain accurate costs should be consistent with both the ability to predict the costs and the potential for the cost element to influence the decision being taken.

For comparative studies of alternative courses of action, costs that will not vary between alternatives may be eliminated, as they affect all options similarly. In these situations only the differences in costs between the alternatives need be assessed and compared. If the cost estimates are to be used as an input to NPV or BCR analysis, the true PVC of all costs will need to be calculated.

One approach, used to identify costs, involves the development of a cost breakdown structure that identifies all relevant costs of an asset over its complete life cycle. With this approach, all phases of a channel's life which attract costs are broken down into consistent cost elements over time. These cost elements are individually identified such that they can be distinctly defined and estimated.

This involves:

1. Describe the life cycle phases
2. Identify the relevant cost elements in each phase - the more detailed and accurate this list is, the more accurate will be the life-cycle-costing
3. List the cost elements in the year in which they will occur
4. Select the method for estimating costs
5. Obtain the data required to develop these estimates
6. Estimate the appropriate costs attributed to each cost element - variable, fixed, direct, indirect, recurring, non-recurring
7. Document the assumptions and level of uncertainty in the estimation of costs

This kind of approach has the advantage of being systematic and orderly thus giving a level of confidence that all relevant costs have been included. The identification of the elements and their scope should be based on the purpose and required accuracy of the life cycle cost analysis.

Checklists of typical cost elements that may occur in each phase of a channel's life are given in Figure 13-7. This list is intended as a guide only. It is not exhaustive, and not every element is relevant in all circumstances.

Timing of costs is important as early costs have greater value in today's dollars than similar costs incurred at a later time.

The most common problems that arise in life-cycle analysis are in the area of estimating costs. Estimates used in the analysis should be accurately and realistically based, reflecting the specific conditions of each case.

Life Cycle Phase	Cost Elements
Investigation	Project management Research Planning Development Feasibility study Environmental impact study Testing & evaluation Design brief
Design	Project management Site investigation Survey Conceptual design – service life & standard Preliminary design Consultation Detailed design – construction standards Cost Estimation Documentation Economic evaluation Hazard and Risk Assessment Occupational Health & Safety Planning Approvals Environmental Approvals Quality management

Construction	Project management
	Land acquisition
	Accommodation
	Security
	Signs
	Construction resources
	    labour/training
	    materials
	    equipment and facilities
	Transport costs
	Consultation
	Site access & physical site conditions
	Establishment - Move in & move out
	Road closure and road surface reinstatement
	Relocation of surrounding infrastructure - temporary & permanent
	Public protection
	Sources of danger to plant operators
	Farm works
	Survey and set out
	Compensation
	Fencing – temporary & permanent
	Site clearing
	De-watering
	Materials sources
	Haul roads
	Dust

Life Cycle Phase	**Cost Elements**

Construction (cont)	Noise
	Contractors and Suppliers
	Availability of water supply for construction purposes
	Local labour and equipment
	Earthworks
	    stripping
	    excavation (cut)
	    fill
	    compaction
	    trimming
	    haulage
	    soil export
	soil import
	Hydraulic control structures
	Lining
	Beaching
	Geofabric
	Wet weather and climatic risks
	Risks of construction delays
	Testing
	Seepage control
	Final site clean up & restoration
	Occupational Health & Safety
	Re-grassing & tree planting
	Insurance
	Supervision and inspection services
	Quality management
	Administrative overheads
	Commissioning
	Taxation

Operations	Operational resources
	    energy usage
	    labour/training
	    materials and consumables
	    equipment and facilities
	    monitoring
	Management
	Communications
	Occupational Health & Safety
	Security
	Signs
	Travel
	Administrative overheads
	Insurance
	Damage from leaks, seepage & flooding
	Water losses

Life Cycle Phase	**Cost Elements**

Maintenance	Monitoring
	Maintenance free period
	Maintenance resources
	    mobilisation
	    labour/training
	    equipment and facilities
	    materials
	Maintenance time window – continuous operation or shut down
	Maintenance cycles
	Accessibility
	Travel
	Contingent costs – interruption to supply
	Planned maintenance
	    desilting
	    fencing
	    weed control
	    access
	Corrective maintenance
	    bank topping, rebuilding and trenching
	    leak repair
	    beaching
	Technical and logistical support
	Supervision and inspection services
	Occupational Health & Safety
	Management
	Administrative overheads
	Insurance
	Communications
	Taxation

Rehabilitation	Project management
	Investigation
	Rehabilitation time window
	Design – service life & standard
	Security
	Signs
	Rehabilitation resources
	    labour/training
	    materials
	    equipment and facilities
	Contingent costs – interruption to supply
	Transport costs
	Site access and physical site conditions
	Accommodation
	Establishment - Move in & move out
	Relocation of surrounding infrastructure - temporary & permanent
	Public protection
	Sources of danger to plant operators

	Consultation Survey and set out
Life Cycle Phase	**Cost Elements**

Rehabilitation (cont)	Fencing – temporary & permanent
	De-watering
	De-silting
	Materials sources
	Haul roads
	Compensation
	Contractors and suppliers
	Local labour and equipment
	Availability of water supply for construction purposes
	Earthworks
	    stripping
	    excavation (cut)
	    fill
	    compaction
	    trimming
	    haulage
	    soil export
	    soil import
	Lining
	Beaching
	Dust
	Noise
	Geofabric
	Wet weather and climatic risks
	Risks of construction delays
	Occupational Health & Safety
	Testing
	Seepage control
	Final clean up & restoration
	Re-grassing & tree planting
	Supervision and inspection services
	Quality management
	Administrative overheads
	Insurance
	Commissioning
	Taxation

Replacement	Project management
	Investigation
	Security
	Replacement time window
	Design service life & standard Land acquisition
	Construction resources
	    labour/training
	    materials
	    equipment and facilities
	    signs
	Contingent costs – interruption to supply
	Transport costs
	Site access and physical site conditions
	Establishment - Move in & move out

Life Cycle Phase	**Cost Elements**

Replacement (cont)	Accommodation
	Road closure and road surface reinstatement
	Relocation of surrounding infrastructure - temporary & permanent
	Public protection
	Sources of danger to plant operators
	Demolition and removal
	Consultation
	Site re-establishment
	Farm works
	Survey and set out
	Fencing – temporary & permanent
	Site stripping and clearing
	De-watering
	De-silting
	Haul roads
	Compensation
	Materials sources
	Contractors and suppliers
	Availability of water supply for construction purposes
	Local labour and equipment
	Earthworks
	    stripping
	    excavation (cut)
	    fill
	    compaction
	    trimming
	    haulage
	    soil export
	    soil import
	    dust
	    noise
	Lining
	Beaching
	Geofabric
	Occupational Health & Safety

	Wet weather and climatic risks Risks of delays Testing Seepage control Final site clean up & restoration Re-grassing & tree planting Insurance Supervision and inspection services Quality management Administrative overheads Commissioning Taxation
Life Cycle Phase	**Cost Elements**
Disposal	Project management Investigation Planning Security Signs Disposal time window Statutory requirements Documentation Decommissioning De-contamination Compensation Environmental requirements OH&S factors Site access Consultation Contingent costs – interruption to supply Establishment - Move in & move out De-watering Environmental clean-up Backfilling channel Cartage of materials Noise Dust Demolition and removal of structures Reinstatement of surrounding infrastructure - road surfaces Public protection Farm works Safe disposal Supervision and inspection services Relinquishment of interest in lands Fencing – temporary & permanent Final site clean up & restoration Re-grassing & tree planting Occupational Health & Safety

	Residual value Legal fees Insurance Administrative overheads

Figure 13-7 Typical channel bank life cycle cost elements

The use of average or typical costs can result in a meaningless comparison. Costs can vary considerably from one location to another depending on site specific factors such as:

- geographical project location
- competition and availability of materials, equipment and services
- access
- site conditions
- accounting methods
- cost of labour
- level of skills
- complexity and size of the project
- industrial relations
- weather conditions
- indirect and overhead cost allocation

These need to be taken into account when analysing raw data.

For example, costs will depend extensively upon local conditions; land costs will vary greatly, the value of water will vary widely and operation and maintenance costs will differ from scheme to scheme. Costs can even change for the same locality from time to time. A cost of one time may be appreciably different a year later. Realistic life cycle costs can, therefore, only be obtained after careful estimation of costs with due regard to all relevant factors and conditions. Depending upon the scope of the analysis, it is important to obtain cost inputs from individuals who are familiar with each phase of the life cycle.

The design and construction costs are usually readily available. The future operation, maintenance and rehabilitation costs are somewhat more difficult to determine. Starting from a knowledge base of design data, historical information, industry estimates and operating conditions, reasonable estimates for these costs should be able to be developed.

Where operation, maintenance and rehabilitation costs are not well understood or predictable, reasonable allowances or contingencies should be added to these costs.

Contingencies should be allowed for as a percentage of the base cost in proportion to the amount of detail upon which the estimate is based. An allowance of 30 to 40% may be made where estimates are based on preliminary investigations, reducing to 10 to 15% when based on detailed designs. In comparing alternatives, comparable bases should be used. Contingencies are taken to include only unforeseeable eventualities, and a reasonable allowance should be included in the base cost for any predictable items such as wet weather conditions, etc.

It is known that maintenance costs of channels generally increase in time, but not enough data may always be available to make sound estimates of this relationship. In these situations, realistic assumptions will have to be made using best judgement.

If applicable, amounts for damages should be recognised in the evaluation. This would involve an assessment of the probability of a claim arising, its size, the probability of the claim succeeding and the size of the final settlement.

Water losses should be included as a cost in the evaluation where they exist and can be quantified and captured. The economic value of the water losses will depend on the particular circumstances and regulatory regime of each supply system.

Depreciation should not be included in the cash flow as it is an accounting item, not a cash item. The cost of financing should also not be included, as it is covered by using the appropriate discount rate. Sunk costs or any other costs already spent should not be included, as life cycle analysis is about future costs.

A factor that impacts directly on a life cycle cost analysis is the nature of the enterprise. Publicly owned enterprises may not receive any taxation benefits arising from deductable expenses such as maintenance, while private enterprises will have allowable expenses incurred, discounted by the prevailing company tax rate, provided that the business makes a taxable profit.

The incorporation of taxation effects into life cycle cost analysis needs to be carefully considered to ensure future cash flows are correctly projected.

It is recommended that costs allowed as deductions and costs allowed to be capitalised are separately identified in the analysis model so that the correct taxation treatment can be applied.

While interest charges and other costs of borrowings are generally allowable tax deductions, their effects are built into the selected discount rate and they are not included separately in the analysis.

13.4.6.1 Capital Costs

Unit costs will vary widely, not only with prices of labour, plant and materials at the time, but also general conditions that affect construction activities.

General conditions that affect costs include the size of project, economies of scale, availability of suitable materials, accessibility to site, weather conditions, competitive interest in work, details of design and tolerances permitted by construction specifications.

Tight specifications and construction tolerances add significantly to costs, and realistic requirements need to be established for general channel bank work.

In some past situations, quite stringent specifications have been applied that are really more appropriate to major earth works projects, rather than the construction of channel banks that are typically not much more than one metre high. Where ever possible, the liberalisation and simplification of channel bank specification should be pursued to lower construction costs.

13.4.6.2 Recurring Costs

Channel construction and refurbishment alternatives may involve different recurring costs that can have a large bearing on the overall economics and may well be the deciding factors in choosing between alternatives.

Maintenance costs that can be used confidently for estimating purposes can be difficult to obtain. Generally, maintenance and operations costs gradually increase with time. In some assets the maintenance and operations cost distribution with time may be fairly uniform. Other assets have periodically high levels of maintenance followed by long interim periods of low maintenance.

If a computerised maintenance management system is in place, past cost histories can be electronically called up as needed. With long life infrastructure assets, such as channels, some initial maintenance may be necessary to correct faults that develop soon after construction, then maintenance costs are usually much lower for some considerable period of time. Ultimately cyclic maintenance or refurbishment becomes necessary and the cost of this work may be appreciable. For this reason, cost records must cover reasonably long periods to be representative.

In comparing channel maintenance costs between schemes, contributing factors, listed below, may be so variable that suitable parallels do not exist.

- channel age and condition
- climate
- geographic location
- geological and environmental conditions
- agricultural conditions
- period of operation
- type of terrain
- water velocity
- channel capacities
- construction materials
- construction quality
- competition and availability of labour and machinery
- batter slopes
- leakage
- stock impacts
- wind
- soil stability
- burrowing animals
- weed types
- complexity and sophistication of the channel system
- levels of service provided

In view of the number and variability of the factors that have a bearing on channel maintenance costs, figures from other schemes cannot be necessarily accepted on face value but need to be critically reviewed. Direct comparison of maintenance costs between different irrigation schemes may not be meaningful, or at the very least any comparison should be done with some degree of caution and an understanding of the relative differences. Most likely, maintenance figures based on assumptions and best estimates will have to be used in the life cycle analysis.

13.4.7 Adjust Figures for Inflation if Necessary

Future costs will not necessarily change at the same rate for all items particularly when the life cycle is a long time. The impacts of technology, improvements in materials, and efficiency changes will make some costs change at a different rate than the general cost inflation. It will therefore be necessary to consider inflation, if the costs of different items in the comparison are expected to increase at different rates.

If the same rate of inflation is expected for all items, then the current values (real values) are used in the evaluation. The costs will remain constant at the base year values and exclude all inflationary changes.

If different rates of inflation are expected for different items, at more or less than the general cost inflation, then these inflated values (nominal values) are used in the evaluation, and the relative costs for the different items will escalate by the projected future changes. This process can be fairly complicated and the assumption that current price relativity will hold in future is commonly used, unless very significant differences in the relative cost movements are expected.

Nevertheless, it is a matter of choice whether inflation is included in an economic evaluation, provided the appropriate discount rates is used, depending on whether real and nominal costs are being discounted. With nominal costs, the discount rate should include an inflation component, and if real costs are used, the discount rate should not include a component for inflation.

13.4.8 Discount Future Monetary Values

The costs of different options will frequently fall at different points in time in the future and the calculation of present values makes uniform comparisons between different options possible. For example, one option may be capital intensive with low Operation and Maintenance costs, while another may have low capital cost but high Operation and Maintenance costs. The calculation of present values is called discounting and the rate used to discount cash flow is referred to as the discount rate.

The selection of an appropriate discount rate is important, as the discount rate chosen may tend to favour some options more than others, depending on the distribution of cash flow over time.

The selection of the appropriate discount rate can be an area of confusion. The discount rate is used to reduce the future monetary values to a common base of present day values. The process of discounting enables the direct comparison of amounts of money that accrue in different time periods. Discounting gives greater weight to initial costs and less weight to those in the distant future. The present value of a future sum is lower the higher the discount rate.

The discount rate is an expression of the time value of money and in simple terms is the difference between the interest rate for borrowing money and the inflation rate. There is no single rate, which can be used in all evaluations. It will vary from one type of project to another.

This effect is illustrated in Figure 13-8. It shows the present worth of $1 expended at various times in the future for three discount rates. The effect shown has greater significance to future spending at a low discount rate, and less significance at a higher discount rate.

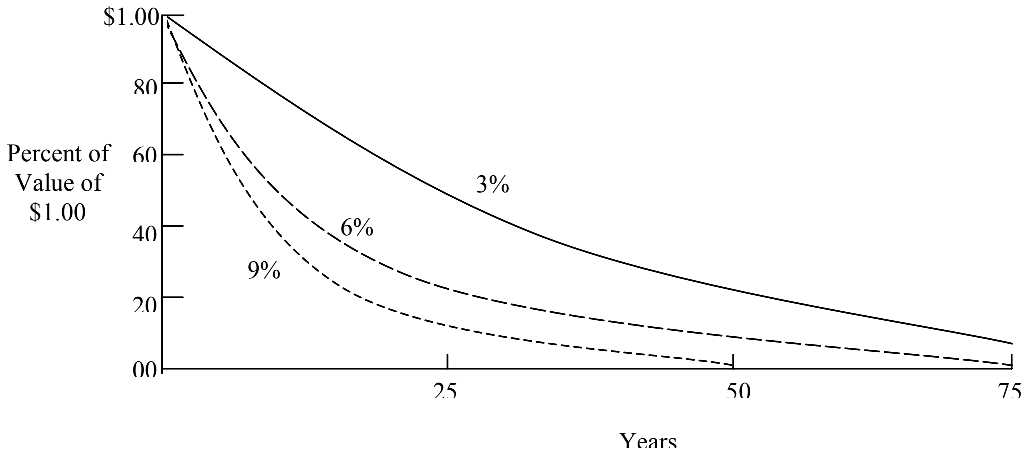

Figure 13-8 Present Value of $1 expended at various intervals and discount rates

The discount rate used for a particular case will depend on such factors as the:

- anticipated inflation rate
- cost of borrowing funds
- returns required by stakeholders
- associated level of risk and the duration of the investment.

The discount rate is not the spot rate or short term interest rate indicated in the market, which is associated with actual borrowing or investment of money.

Cash flows can be expressed in terms of nominal cash flow or real cash flow, and the discount rate must be consistent with the method used to estimate cash flows, either nominal or real. Real costs set to a current base date are the easiest concept to deal with when stating cost elements in a life-cycle analysis, because it is the cost framework most people are familiar with.

An appropriate discount rate for a long-term low risk project may be 6% to 8% real. If the project was short term or where risks and uncertainty were involved, a higher discount rate of 8% to 10% real may be advisable. Different discount rates are used by different public and private organisations. Most irrigation authorities will have policy guidelines on the selection of appropriate discount rates for use in their economic cash flow analysis. The discount rates adopted in the public sector are comparatively lower than the discount rates normally adopted by the private sector.

13.4.9 Generate Life Cycle Costs

With the model set-up, and all relevant costs and time periods defined, it is a relatively straight forward task to generate the life-cycle cost results for each alternative course of action or option defined in the Analysis Plan.

The majority of time involved in conducting a life-cycle analysis will be typically devoted to the collection and evaluation of data. The actual modelling of the data and the generation of life-cycle costs can be completed in a comparatively short period of time.

The life-cycle cost outputs should be categorised and summarised according to a logical grouping which would be relevant to decision makers.

13.4.10 Determine Uncertainty of Figures – Sensitivity

Assessing life-cycle costs can be a complex task, which requires assumptions to be made and at times subjective judgements, since most of the information is in the form of forecasts and estimates. Future developments, technology changes and use of optimistic/pessimistic cost estimates and the like, all contribute to uncertainty and risk. The further ahead the cost and life projections are, the less accurate will be the life-cycle analysis results. Uncertainty may lead to a decision which subsequently turns out to be not the best one. In these circumstances, the usefulness of the life-cycle analysis as a decision making tool is limited unless it includes a sensitivity assessment of changes in key assumptions and cost uncertainties.

Sensitivity analysis is a *what if* technique that helps to understand the level of uncertainty in the evaluation. This is done by repeat analysis with the systematic change, one at a time, of each of the variables that are subject to risk and uncertainty.

This is quite an easy process using a spread sheet program, and it will immediately show how robust the comparison is and to which input variables it is most sensitive.

The need for a sensitivity analysis should be considered after completing the initial life-cycle cost analysis. If the analysis results are not clear cut or where a particular option is heavily dependant on the assumptions made in assigning values, then it is important that sensitivity analysis be undertaken. The degree of verification of the analysis should be commensurate with the importance and value of the decision being made.

Factors found to be most influential (within plausible limits) on results should be checked for accuracy and the degree of risks associated with their estimation. If the analysis is insensitive to a particular input, an additional effort to increase the accuracy of the estimate could be a waste of time. Conversely, high sensitivity would warrant further investigation to improve the accuracy and reduce the level of uncertainty. The sensitivity analysis does not quantify the relative uncertainty in different areas. This is still left to subjective assessment.

Typical sensitivity tests that could be applied might be:

- cost estimates - plus/minus 10% to 15%
- labour costs - plus/minus 10% to 15%
- discount rates – at least two rates between 6% to 10% real
- life projections - different forecasts
- timing of costs - different years

The different results from this checking process will identify which option is the best under different situations and how sensitive the analysis is to particular estimates. This allows a decision to be made on the best option, understanding the possible effects of future changes.

13.4.11 Evaluate Results

The results of the life-cycle analysis should be documented in a report to allow decision-makers to understand the outcomes, including the limitations and uncertainties associated with the results. The report should contain the following:

- objectives and alternatives considered
- description of analysis model
- assumptions
- results - ranking of options
- sensitivity analysis
- conclusions and recommendations

All the assumptions behind the numbers need to be documented, along with supporting documentation and results from the spread sheet analysis, so that the results can be verified and replicated, if necessary.

The preferred option is usually the one with the lowest present value of discounted costs. However an element of experience or value judgement will always be required in the decision making process.

Life-cycle costs are only one decision making criteria and other real world perspectives for decision making may exist which have not been quantified in terms of costs in the analysis:

- financial
- service level
- risk
- technical
- social
- environment
- statutory
- political
- flexibility

Figure 13-9 illustrates this point.

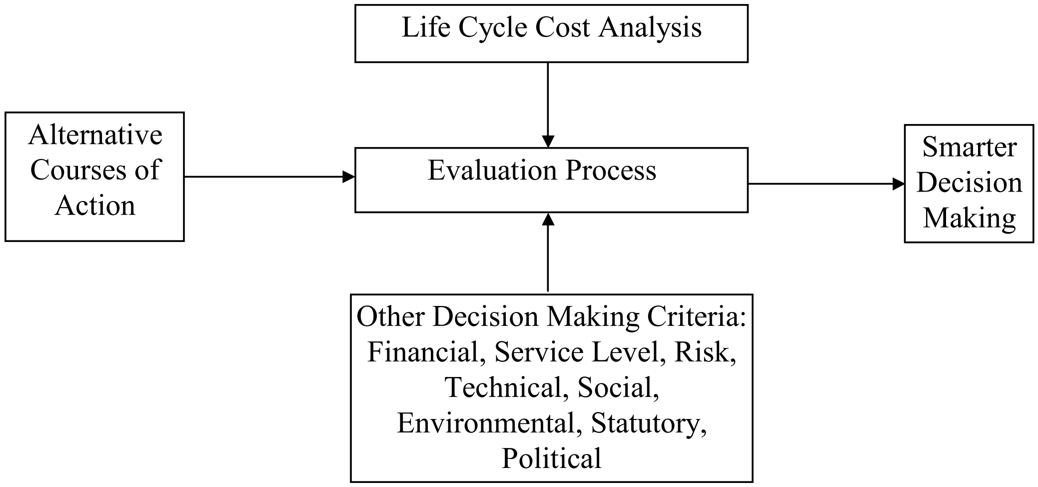

Figure 13-9 Decision Making Process

To confirm correctness and ensure objectivity, an audit of the analysis should be conducted by someone other than the original analyst.

It is important to remember that the present values calculated in a life-cycle analysis are comparative values only. They are not absolute costs and their use for other purposes would need to be considered carefully.

Life cycle cost analysis itself has no relationship to the financing of a project. Such financing and budget considerations may limit the number of feasible options or limit the amount of funds available for a particular project, but is quite separate from life-cycle analysis.

The aim is continuous improvement, with reduced risks and uncertainty in future decision making.

13.5 Conclusion

Well-informed decisions on channel design, construction, maintenance, rehabilitation or replacement requires:

- careful assessment of what is needed
- a thorough evaluation of options
- an understanding of all relevant costs on a life-cycle basis
- an assessment of any uncertainty which may impact on cost and value

Life cycle cost analysis is a valuable tool that can be used to understand the total costs of a channel over its life and make improved asset management decisions. The method is relatively simple and straightforward, and should be within the capabilities of most irrigation organisations to undertake.

It is important that an overriding focus on capital costs does not result in the development of an inappropriate asset. Failure to recognise the total costs associated with the life of the channel, ranging from the initial investigation through to eventual disposal, can leave the way open to incur significant costs in the future and to forego opportunities to add value.

Life cycle costing is very useful when applied early in channel investigation and design phases, particularly when the life cycle costs may exceed the initial capital cost. Early identification of costs enables the decision-maker to consider trade-offs and optimise the basic design approach by balancing capital costs, operation and maintenance costs and economic lives over the total life cycle.

Design is the lowest cost phase of a project, yet it is here that the greatest opportunity typically exists for minimisation of long-term costs. Life cycle costing can also be used during subsequent phases of the channel life, to optimise maintain, rehabilitate and replace decisions.

Life cycle cost analysis provides support for decision making, but does not alone represent the final decision.

13.6 Tips

- Organisations need to develop an understanding of the concepts of total life cycle cost management. To ensure success of this process, a program of education is essential. To further assist, special tools should be developed. These can be in the form of a template or a spreadsheet that can be used to standardise methods of evaluation and ensure a consistent approach is achieved. Ease of access and use of these tools will encourage individuals to embrace the concepts in practice.

- To minimise life cycle costs, operation and maintenance considerations must be taken into account in the conceptual and detailed design stages, and Operation and Maintenance staff should be consulted and their advice carefully thought about.

- Life cycle cost analysis must be objective. Influencing the results to support personal biases is self-defeating.

13.7 References

Association of Local Government Engineers New Zealand (1998), *New Zealand Infrastructure Asset Management Manual*, First Edition, Second Issue, June 1998

Australian/New Zealand Standard AS/NZS 4536:1999, *Life Cycle Costing - An Application Guide*

Goulburn-Murray Water (1995), *Investment Appraisal Manual*, Release 3

Hudson WR, Haas R & Uddin W (1997), *Infrastructure Management,* McGraw-Hill

14. Risk Analysis

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14.1 Introduction

Before commencing a channel bank project some consideration must be given to the risk of failure of the channel bank. This is known as *Risk Analysis*. During the design phase of the project each section of channel bank should be assigned a Risk Factor of Low, Medium or High.

The risk associated with a channel failing or overtopping can be defined as being the cost of the consequences multiplied by the probability of the failure occurring.

ie ***Risk = Consequences of Failure x Probability of Failure***

The design approach in the past used freeboard to address the risk of failure. As the capacity of a channel increased, so the freeboard also increased to contain supply level fluctuations and protect the channel banks and adjacent land. This approach assumed that the larger the capacity of the channel, the greater the risk of failure. This assumption has proved to be inaccurate in practice in many cases as is illustrated in the examples below:

Example 1; a small distribution channel with no outfall borders an urban housing development; there is no SCADA control, frequent fluctuations and few inspections as vehicular access is limited. Channel is in poor condition but is not programmed for refurbishment because it is thought that it will be abandoned within 20 years due to further urban development.

Example 2: a large carrier channel runs on a contour through non-irrigated grazing land with SCADA control. Operators inspect the channel weekly.

Although the consequences to the irrigation authority are high if the carrier channel fails, in loss of water, failure to supply downstream etc there are minor consequences to the adjacent landholder, whereas failure of the small channel in example 1 could cause flooding of urban housing. Despite this, traditional freeboard considerations would have given the large carrier channel possibly six times as much freeboard as the small channel. This is plainly unnecessary.

Additional freeboard should be considered for safety if valuable property would be damaged by a channel bank being breached or overtopped. This is discussed further in Section 12.13, Freeboard.

14.1.1 Consequences of Failure

The consequences of a failure may be as low or high as suggested above. To ascertain the Risk Value the Consequences of Failure are required to be assessed as High, Medium or Low based upon the following factors:

Consequences for adjacent landholders:

- Flooding of high value horticultural crops including vineyards and orchards
- Flooding of residential areas

Consequences for irrigation authority:

- Cost of repairing bank
- Loss of the water resource
- Loss of income
- Cost and to Business if bank fails – eg if channel is a major carrier a large portion of the system could be inoperable until the bank is re-constructed.
- Loss of good will from irrigators, adjacent landowners and other authorities

Consequences for other authorities:

Flooding to roads, council property, telecommunications etc

14.1.2 Probability of Failure

For long-life assets such as channel banks, the probability of failure is difficult to determine because of the variability of the environment channels will operate in, and the lack of long-term data. However to ascertain the Risk Value the Probability of Failure must also be assessed as High, Medium or Low. The main factors to be used in determining this are listed below:

- Condition of channel (new, deteriorated)
- history of failure
- Bank height (low, high)
- Fluctuations in channel (minimal, high)
- Operational control (manual, SCADA)
- Inspection of channel (frequent, rare)

If the probability of a channel failing can be reduced the overall risk associated with the channel can also be reduced. This can be achieved by monitoring the channel more frequently. For example, if a channel was inspected twice daily, the risk of the channel overtopping due to an outlet being closed early would be reduced as there would be less time for the pool to fill.

Continuous monitoring of channel levels can be carried out with a SCADA system. An alarm system to inform operators of problems will significantly reduce the probability of failure of a channel. A control system, such as automatic gates also has the ability for any extra water to allowed out of the pool if the water level rises too much. The main disadvantage with such a system is the high capital cost of installing the equipment.

14.2 Determination of the Risk Factor

The Risk Factor can be determined using the matrix in Figure 14.1.

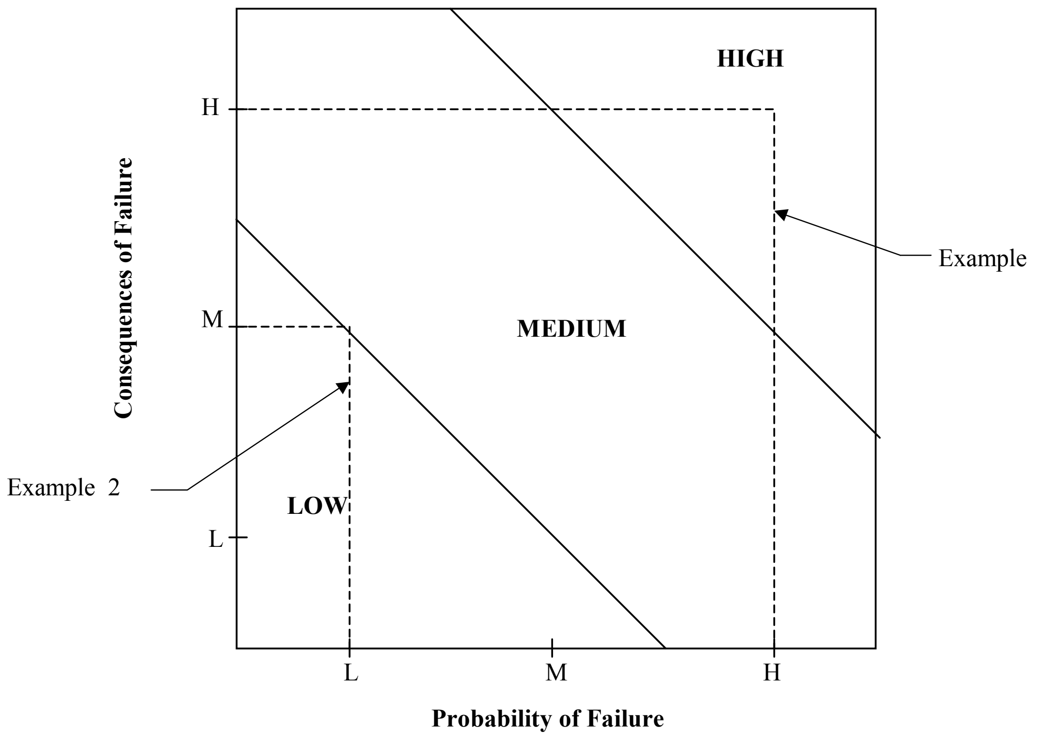

Figure 14.1 Determination of Risk Factor

From this matrix the Risk Value can be determined as Low, Medium or High.

Risk values for the examples set out above in Section 14.1above are determined as follows:

Example 1:

Consequences of failure: high
Probability of failure: high

Therefore, Risk factor: high

Example 2:

Consequences of failure: medium
Probability of failure: low

Therefore, Risk Factor: low-medium

14.3 Australian Standards

AS/NZS 4360:1999 Risk Management Standard

HB 142-1999 A Basic Introduction to Managing Risk

15. Material Selection and Testing

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15.1 Introduction

Channel banks can be constructed from a wide range of different soil types, and each general soil type has its own characteristics and problems which must be considered to ensure that the channel bank has adequate strength, durability and impermeability.

Channel banks that have a long useful life and low life-cycle cost will have been:

- designed with a good knowledge of the available bank building materials
- constructed with methods applicable to the particular soil conditions

Soils used in channel banks should be of adequate impermeability, should be free from shrinkage and swelling characteristics and should have good stability and erosion resistant properties.

A good channel bank material contains between 20 and 30% clay, with the balance made up of silt, sand and some gravel. Clay is however unstable in the presence of water. Too much clay results in the bank being prone to cracking with moisture changes. On the other hand insufficient clay causes seepage through the bank.

The two clays most susceptible to problems are dispersive clays and swelling and cracking clays. A dispersive clay is one which will erode spontaneously in the presence of water. Use of these clays can result in leakage which may lead to piping failure of the bank. Some soils contain sufficient clay, however because of the particular soil structure, the clay particles are not available for sealing and a bank constructed form this material will seep. The absence or deficiency of certain minerals in the channel water can also lead to a piping failure of channel banks constructed from certain soil types.

Because of the different physical properties of soils, a full understanding of soil selection and testing is essential so that the soils used for channel bank constructed as well as the construction techniques applied, will ensure the bank achieves its design service life at the lowest life cycle cost. Otherwise, it is likely that unsuitable material or inappropriate construction techniques will be used leading to reduced bank life, higher life cycle costs or even failure of the bank.

Soil selection and testing is not a straightforward process and consequently there does not appear to be a wide industry understanding of the subject. This section aims to provide a practical understanding of the key issues involved. It is not necessary to understand the complex soil mechanics of why soils behave differently, but rather it is sufficient to know that certain soil types do behave in particular ways, which make it more or less suitable for channel bank construction.

Earthen channel banks are generally constructed from local soils, and for economic construction the availability of suitable material is a key consideration. The important characteristics of a channel bank that are governed by the soil type are:

a) *Permeability* – how watertight the bank is.

b) *Shear Strength* – the bank's ability to carry loads under dry and saturated conditions

    a) water load on the inside of the bank
    b) traffic loads on top of the bank
    c) batter slope stability

c) *Shrinkage* – will the bank crack in dry conditions and cause leakage from the channel.

d) *Erosion Resistance* – how well the bank will withstand erosion forces due to channel water, rainfall, wind, stock and traffic.

The selection of material for channel bank construction should be made on the basis of several tests indicating the engineering properties of the soils. The most common tests carried out on soil samples for channel construction are:

- Soil Classification (indicates permeability, shear strength and erosion resistance)
- Shrinkage
- Dispersion (indicates erosion resistance to channel and rain water)

15.2 Investigation of Material

The object of the investigation is to determine:

- a suitable location to obtain material for constructing a channel bank (referred to as a Borrow Pit)
- if the material from a potential borrow pit is suitable for constructing a channel bank

Soils can exhibit variable properties depending upon such factors as location, local geology and depth of excavation. Therefore a thorough investigation must be carried out at a potential borrow site.

Soil maps can give quite accurate indications where dispersion and seepage problems are likely to occur and where suitable soils for channel bank construction are likely to be found.

Refer also to the following sections:

Section 11, Planning and Investigation
Section 12.8, Geotechnical Investigation
Section 21.3.1, Permeability

15.2.1 Borrow Pits

Where material is required for bank construction, it will have to be borrowed through the construction of pits or dams. Every attempt should be made to obtain borrow material as close to the channel site as possible. It is expensive to transport soil on a large scale from long distances, and suitable soil from the channel excavation or nearby borrow pits is essential for economy.

Potential borrow pit sites should be investigated during the design phase of the project with the haul distances and required construction techniques reflected in the cost estimation prepared for the individual project.

The most desirable borrow area contains a homogeneous distribution of material to a depth of at least several metres, with a minimum amount of stripping required and no groundwater.

Photos\borrow pits\cg1.excavatoratborrowpit.jpg

Photo 15-1 Excavator at borrow pit

The field investigation of potential borrow sites for bank material should include:

- Estimation of depth and volume of suitable soil obtainable from potential borrow pit; say 40m x 40m or equivalent. The minimum size of borrow pit for economic construction is typically 2000m^3
- Location of borrow pit in respect to roads and the distance from borrow pit to Channel Bank Construction site
- Suitability of the material.
- Moisture content
- Amount of stripping required
- Depth to watertable and its fluctuations

Potential borrow areas may be selected from local soil and/or geological maps. Most irrigation areas in Australia have had extensive soil surveys for agricultural purposes which will give some indication of suitable borrow sites.

Part of the selection of potential borrow site(s) includes negotiations with landowners who may be interested in having a water storage dam constructed on their property, or as an added incentive to landowners in close proximity to the work site the offer of financial reimbursement or payment of royalties to the landowner for material excavated from dams.

The borrow site should be pegged and mapped before samples are taken.

15.2.2 Sampling Procedure

Soil samples from a potential borrow site must be obtained to test for its relevant engineering properties. This involves putting down a series of test holes to determine the types of soils present and their thickness.

Auger boring is the most commonly used method of obtaining soil samples for channel bank construction. A 100-200mm diameter auger is generally the most readily available tool for this work. If a mechanically powered auger is used, care needs to be taken not to mix the various type of soils and confuse the actual thicknesses of the different layers.

Soil samples should be taken from a series of bore holes set out across the potential borrow site. It is recommended that boreholes be drilled on a 15 to 30 metre grid pattern, depending upon the size of the area and the uniformity of the soil, to a depth of about 3 metres across the borrow site. A 20 metre grid is most commonly used for channel bank projects. Soil samples should be taken at approximately 1.0m intervals from the surface. If there are visible changes to the soil profile in colour or structure, samples should be taken at 0.5m intervals.

With any soil profile, there may be a number of pronounced visual changes of the soil characteristics. Such changes may reflect changes in the dispersive characteristics of the soil, and it is advisable to test the soils where these changes occur. In certain soil profiles there is only a gradual change in visual characteristics of the soil over considerable depths, yet the soil becomes more dispersive with depth. For this reason, the soils of each profile should be tested where visual changes occur or at approximately 1 metre intervals.

Small auger holes do not permit the best visual inspection and selection of samples from the total profile. Care therefore needs to be exercised to ensure that representative samples are taken of the various strata. As the hole is advanced using a hand auger, each amount of soil extracted by the auger should be deposited in individual stock piles nearby to form an orderly depth sequence of removed material. Sampling from a power auger should be done by lifting the auger blade at regular intervals, taking a sample of soil from the auger blades and depositing it in an orderly depth sequence as the auger hole is advanced.

During the whole operation records must be kept. These records shall contain, a map of the borrow site including any surface features, access to the borrow site, the location of all drill holes, the amount of samples and at what depths the samples were taken. The logs of these holes can be plotted on cross-sections to show the locations of the various types of materials.

These records, used in conjunction with the results of the soil sample analysis will provide a picture of the soil conditions. Earth material from a certain zone can either be directly used or mixed with material from some other zone. A typical Goulburn-Murray Water Soil Classification Report from a borehole is shown in Figure 15.1.

Once all the information has been recorded and samples are in well-labelled sealed plastic bags then the samples can be sent to a soil mechanic's laboratory for testing, ensuring that there is a sufficient amount of the soil sample to do the testing required.

The quantity of materials needed for testing depends primarily on such factors as:

i) the number, type and purpose of tests to be performed
ii) particle size characteristics of the material and
iii) homogeneity of the natural materials

Refer Table 15-1 for the required quantities for different tests.

When the soil sampling has been completed, all test holes should be backfilled to prevent human or stock injury.

15.3 Standard of Soil Testing

Testing of bank materials is necessary to:

1. Determine its suitability for bank construction – permeability, shrinkage and dispersion
2. Provide information for design of the bank cross section.
3. Develop specifications for suitable field control and construction methods.

Each sample should undergo testing for soil classification, shrinkage and dispersion. In new borrow sites, optimum moisture content curves are required to enable moisture content to be monitored during compaction.

GOULBURN-MURRAY WATER SOILS LABORATORY

SOILS CLASSIFICATION REPORT

To:………………………………….……………… Date: 04/06/99

Project:…………………………………Channel No. 44 Bank Construction

Submitted by:…………………………..

Landowner:…………………………….

Sample No.	Location	Description	Pat Shrinkage (%)	Emerson Class No.	Moisture (%)
763	Hole 1 1.0m	Heavy Clay CH (moist)	7.8	4	29.1
764	2.0m	Heavy Clay CH (moist)	6.8	3	20.2
765	3.0m	Sandy Clay CI (moist)	4.9	2	21.7
766	Hole 2 1.0m	Heavy Clay CH (moist)	8.7	3	19.3
767	2.0m	Heavy Clay CH (moist)	7.8	5/6	18.4
768	3.0m	Medium Clay CI (moist)	5.9	5/6	21.4

Comments……………………………………………………………………………………………….

………

……………………………………………………………………………………………………

Laboratory Supervisor………………………………… Date: …../…../…..

Figure 15.1 Soil Classification Report

Soil Test	Australian Standard	Mass of Soil Required (kg)
Determination of dry density/moisture content relation of a soil using standard compactive effort (Proctor density)	AS1289.5.1.1-1993	8
Emerson (Dispersion)	AS1289.3.8.1-1997	0.1
Pat Shrinkage	Not applicable	0.5
Liquid limit	AS1289.3.1.1-1995	0.25
Plastic limit	AS1289.3.2.1-1995	0.04
Linear Shrinkage	AS1289.3.4.1-1995	0.25

Table 15-1 Soil Sample mass required for Soil Investigation Testing

Natural moisture content should also be measured. This will give an indication of how close the borrow material is to optimum moisture content and whether it requires treatment before construction. Refer Section 16.11, Moisture Content Control Tests and Procedures.

Soil Classification may be achieved by Australian Standard tests or by field identification methods.

Australian Standard tests should be used wherever possible. However, many of these testing procedures need to be conducted by experienced staff with appropriate equipment in a laboratory, and are often time-consuming and expensive. For small projects, field identification procedures may be adequate as described in section 15.10. Where staff are experienced in channel bank construction in a particular area, they can become reasonably accurate at determining soil classification and estimating shrinkage and dispersion, by field methods.

When determining the level of testing required for a particular project, consideration must be given to the risk rating of the channel bank. Refer Section 14, Risk Analysis. Where the Risk is determined to be Medium to High, more care will be required in soil testing. Consideration should be given to using Australian Standard tests for Soil Classification, Shrinkage and Dispersion. If the Risk is assessed as Low, field identification methods may be appropriate.

15.4 Soil Classification

To measure soil properties like permeability, shear strength and erosion resistance can be difficult, time consuming and expensive. It can therefore be very useful to sort soils into groups showing similar behaviour. Such sorting is *soil classification*. Soil Classification is thus the process by which a soil sample is classified into a group of soils all of which exhibit similar behaviour. The aim of a classification system is to provide a set of common definitions which will permit useful comparisons to be made between different soils. Soil behaviour and suitability for various construction purposes can then be predicted by using the classification system.

The two classification criteria relevant to channel bank construction are:

1. a broad classification into the five fundamental soil groups; gravel, sand, silt, clay and organic material, as shown in Figure 15.2.
2. the plasticity of the fine-grained fraction of the material

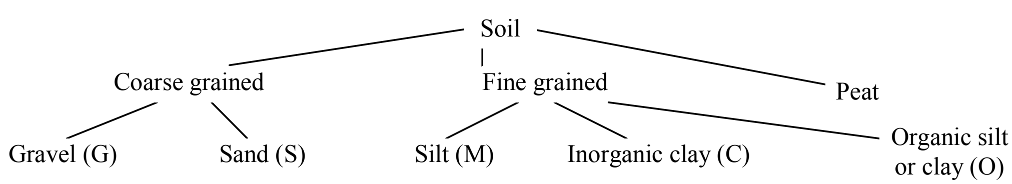

Figure 15.2 Broad Classification of Soils

Gravels and sands can be readily identified by appearance and feel, but silts and clays are indistinguishable when dry.

The Unified Soil Classification system has been widely adopted for classifying soils and will enable anyone dealing with channel banks to sensibly interpret laboratory results to a practical soil situation. Soil types are described by two letters; a prefix depending on the predominant particle size, and a suffix related to the engineering properties, for example gravels are *G*, sands *S*, silts *M*, clays *C*, organic soils *O* and Peat *Pt*. Gravels and sands are further subdivided into well-graded (*W*) and poorly graded (*P*).

Well-graded means having a favourable spread of particle size with a good representation of all particle sizes from the largest to the smallest. *Poorly-graded* means having badly balanced particle-size distribution, with an excess of same sizes and a deficiency in others, or it may mean particles of similar size, that is, a uniform grade.

A material with good grading is relatively stable, resistant to erosion or scour, can be readily compacted to a very dense condition, and can develop high shear resistance and bearing capacity.

Silts and clays are divided into those with low (L) and high (H) liquid limits. *Liquid limit* is the moisture content at which the clay or silt becomes a slurry and is measured by expressing this water content as a percentage of the dry weight of the clay or silt. If less than 50%, it is considered to have a low limit; if greater than 50%, it has a high liquid limit. A further classification often used in channel bank construction is *medium* liquid limit – this is a liquid limit between 35% and 50%.

Inorganic soils are those relatively free from the remains of living organisms; organic soils are rich in finely decomposed plant remains.

Table 15-2 shows common names of soils against the Unified Soil Classification System.

Group Symbol	Description
GW	Well graded gravels
GP	Poorly graded gravel
GM	Silty gravels
GC	Clayey gravels
SW	Well graded sands
SP	Poorly graded sands
SM	Silty sands
SC	Clayey sands
ML	Inorganic silts with low liquid limits
CL CI	Inorganic clays with low liquid limits Inorganic clays with medium liquid limits
OL	Organic silts with low liquid limits
MH	Inorganic silts with high liquid limits
CH	Inorganic clays with high liquid limits
OH	Organic clays with high liquid limits
Pt	Peat and highly organic soils

Table 15-2 The Unified Soil Classification

The study identified some confusion in the irrigation industry over the term *silt*. *Silt* is a soil classification, but it is also the term widely used to describe the layer of inorganic and organic sediment that forms on the bed of channels. To draw a distinction, these Guidelines refer to sediment deposits as *eroded channel material*.

15.4.1 Determination of Particle Size Distribution

The classification of fine-grained soils is on the basis of Particle Size Distribution, Liquid Limit and Plasticity Index. While the classification of coarse-grained soils is on the basis of Particle Size Distribution only.

A representative sample of soil (excluding particles larger than 63mm) is first classified as coarse grained or fine grained by determining whether 50% by weight of particles are less than 0.075mm in diameter. The laboratory method for grading is described in AS 1289.3.6.1 Determination of the particle size distribution of a soil - Standard method of analysis by sieving. A summary of soil classification grading is shown in Table 15-3.

Soils containing more than 50 percent of particles that are greater than 0.075mm in diameter are coarse-grained soils; soils containing more than 50% of particles less than 0.075mm in diameter are fine-grained soils.

15.4.1.1 Coarse-grained soils

If the soil is predominantly coarse grained, it is then identified as being a gravel or sand by determining whether 50% or more by weight, of the coarse grains are larger or smaller than 2.36mm.

If the soil is a gravel, it is next identified as being clean (containing little or no fines) or dirty (containing an appreciable amount of fines). For clean gravels, final classification is made by determining the gradation. The well-graded gravels belong to the GW group, and poorly graded gavels belong to the GP group. Dirty gravels are of two types: those with non-plastic (silty) fines (GM), and those with plastic (clayey) fines (GC).

If a soil is a sand, the same steps and criteria are used as for the gravels in order to determine whether the soil is a well-graded clean sand (SW), poorly graded clean sand (SP), sand with silty fines (SM), or sand with clayey fines (SC).

15.4.1.2 Fine-grained soils

Silts and clays are collectively called fines and when dry and powdered are indistinguishable by eye. If a material is predominantly (more than 50 % by weight) fine-grained, it is classified into one of six groups (ML, CL, OL, MH, CH, OH) by determining its liquid limit, plasticity index and by identifying it as being organic or inorganic. Refer Table A1 from AS1726.

Before discussing these three properties of fine material, it is necessary to comment on the change of consistency with water content for fine-grained soils, particularly clays. Fine-grained soil may be liquid, plastic or solid. These stages are related to the water content and although the transitions are gradual, test conditions have been established arbitrarily to delineate the water content as a defined point in the three stages of consistency:

Table 15-3 Important physical properties of soils and their relative suitability for channel bank construction based on the Unified Soil Classification System

Major Division of Soils			Typical Names of Soil Groups	Group Symbols	Relative Soil Properties (numbers indicate the order of increasing values for the physical property named)				Relative Suitability for Earthen Irrigation Channels (1=best 16=worst)		
					Permeability when compacted	Shearing Strength when compacted and saturated	Compacted Density	Workability as a construction material	Impermeability	Erosion Resistance	Dispersion
COARSE-GRAINED SOILS More than half of material less than 63mm is larger than 0.075mm	GRAVELS More than half of coarse fraction is larger than 2.36mm	CLEAN GRAVELS (Little or no fines)	Well-graded gravels, gravel-sand mixtures, little or no fines	GW#	14	16 (high)	15	7 (excellent)	Not suitable	2	1 (best)
			Poorly graded gravels, gravel-sand mixtures, little or no fines, uniform gravels	GP##	16 (high)	14	8	5	Not suitable	3	1 (best)
		GRAVELS WITH FINE AGGREGATES (Appreciable amount of fines)	Silty gravels, gravel-sand-silt mixtures	GM	12	10	12	5	6	5	3
			Clayey gravels, gravel-sand-clay mixtures	GC	6	8	11	5	2	4	2
			Well-graded gravel with sand-clay binder	GW-GC	8	13	16 (high)	6	1 (best)	1 (best)	2
	SANDS More than half of coarse fraction is smaller than 2.36mm	CLEAN SANDS (Little or no fines)	Well-graded sands, gravelly sands, little or no fines	SW#	13	15	13	7 (excellent)	Not suitable	8	1 (best)
			Poorly graded sands, gravelly sands, little or no fines, uniform sands	SP##	15	11	7	2	Not suitable	9 coarse	1 (best)
		SAND WITH FINES (Appreciable amount of fines)	Silty sands, sand-silt mixtures	SM	11	9	10	2	7	10 coarse Erosion Critical	3
			Clayey sands, sand-clay mixtures	SC	5	7	9	5	4	7	2
			Well-graded sand with clay binder	SW-SC	7	12	14	6	3	6	2
FINE-GRAINED SOILS More than half of material less than 63mm is smaller than 0.075mm		SILTS AND CLAYS Liquid Limit less than 50	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	ML	10	5	5	2	8	Erosion Critical	Variable. Must be tested
			Inorganic clays of low plasticity (LL≤35), gravelly clays, sandy clays, silty clays, lean clays	CL	3	6	6	4	5	11	Variable. Must be tested
			Inorganic clays of medium plasticity (35<LL≤50), gravelly clays, sandy clays, silty clays, lean clays	CI	2	5	5	3	7	12	Variable. Must be tested
			Organic silts and organic silty clays of low plasticity	OL	4	2	3	2	9	Erosion Critical	-
		SILTS AND CLAYS Liquid limit greater than 50	Inorganic silt, micaceous or diatomoceous fine sandy or silty soils, elastic silts	MH	9	3	2	1 (poor)	Not suitable	Not suitable	Variable. Must be tested
			Inorganic clays of high plasticity (LL>50), fat clays	CH	1 (low)	4	4	1 (poor)	10 (worst) Volume Change Critical	13 (worst)	Variable. Must be tested
			Organic clays of medium to high plasticity, organic silts	OH	2	1 (low)	1 (low)	1 (poor)	Not suitable	Not suitable	Not suitable
HIGHLY ORGANIC SOILS			Peat and other highly organic soils	Pt							

15.4.2 Determination of the plasticity of fine-grained soils

Clay and silt, both alone and in mixtures with coarser material, may be described according to their plasticity using their Liquid Limit. The Liquid Limit is the percentage of water mixed with a soil sample at which the sample is at the border of solid state and liquid state. The plasticity increases with the Liquid Limit, as shown in Table 15-4.

Descriptive Term	**Symbol**	**Range of Liquid Limit (%)**
Low Plasticity	L	LL < 35
Intermediate Plasticity	I	35< LL<50
High Plasticity	H	50< LL<70
Fat Clay	H	LL>70%

Table 15-4 Determination of plasticity [AS1726-1993 A2.4(b)]

Liquid limit is defined as that water content, expressed as a percentage of the dry weight of the soil, at which the soil first shows a definite shearing strength as the water content is reduced. As the water content is reduced below the liquid limit, the soil mass becomes stiffer and will no longer flow as a liquid. However, it will continue to be deformable or plastic without cracking until the moisture content is reduced to the plastic limit. Liquid limit is determined by the Australian Standard AS1289.3.1.1-1995 which describes the procedure for increasing the moisture content until the soil mass just starts to become fluid under the influence of a series of standard shocks.

Plastic Limit is defined as that water content, expressed as a percentage of the dry weight of the soil, at which the soil mass ceases to be plastic and becomes brittle, as determined by the Australian Standard procedure AS1289.3.2.1-1995.

Plasticity Index is the difference between the *liquid* and *plastic limits* and represents the range of moisture within which the soil is plastic. Silts have low plasticity indexes, while clays have higher indexes.

Clays are the plastic fines. They can be divided into ones of low liquid limit (L < 50) and ones of high liquid limit (H > 50).

Silts are the non-plastic fines. They are inherently unstable in the presence of water and have a tendency to become *quick* when saturated. Silt masses undergo change of volume with change of shape (the property of dilatancy), in contrast to clays which retain their volume with change of shape (the property of plasticity).

15.4.3 Boundary Classifications

Many natural soils have characteristics of two groups because they are close to the borderline between the groups either in percentages of the various sizes, or in plasticity. For this substantial number of soils, boundary classifications are used; that is, the two group symbols most nearly describing, the soil are connected by a hyphen, such as GW-GC.

Proper boundary classification of a soil near the borderline between coarse-grained and fine-grained soils is accomplished by classifying it first as a coarse-grained soil and then as a fine-grained soil. Such classifications such as SM-ML and SC-CL are common. This type of dual classification is done for all soils which are determined to have between 40% and 60% of fine (or coarse) material.

Within the fine-grained division, boundary classifications can occur between low liquid limit soils and high liquid limit soils as well as between silty and clayey materials in the same range of liquid limits. For example, one may find ML-CH and OL-OH soils; ML-OL, ML-CL and CL-OL soils and MH-CH, MH-OH and CH-OH soils.

15.5 Shrinkage

Shrinkage is a measure of how much a soil sample will contract when it is completely dried out. It is important to test for shrinkage to give an indication of how a channel bank will behave in dry conditions. A high shrinkage will indicate that bank cracking could be a serious problem if the bank is not adequately protected.

Black cracking soils have what is called a *high shrink-swell capacity*, that is, when they dry they contract appreciably opening up large cracks in the soil which go to considerable depths. When wetted up after rain, the clay expands, and the cracks close up. However, this expansion can take weeks or months.

A number of these cracking soils are erodible and water flowing through cracks in the bank can cause the bank to break down and finally fail. Channel banks constructed with these soils will generally perform satisfactorily provided they are protected from drying out and cracking.

15.5.1 Linear Shrinkage

The Australian Standard shrinkage test is *Linear Shrinkage.* Linear Shrinkage is measured by placing a sample of soil at Liquid Limit in a mould. The sample is then dried in an oven until no water remains in the sample. The distance that the sample shrinks away from the mould is then measured. This test is described in AS1289.3.4.1-1995 – Linear Shrinkage.

15.5.2 Pat Shrinkage Test

The Pat Shrinkage Test is a non-Australian Standard test which measures the shrinkage of a sample of soil from the plastic limit. Although this is not an Australian Standard test, it is simple to perform, and gives a good indication of the shrinkage and subsequent cracking behaviour of the soil. The Pat Shrinkage test is described in Figure 15.3.

The Pat Shrinkage Test is a more realistic model of what happens to an earthen channel bank in dry conditions than the Linear Shrinkage Test. Channel Banks are compacted at or near Optimum Moisture Content which is very close to the Plastic Limit. Therefore it is recommended that the Pat Shrinkage Test is used to test for shrinkage.

1. **Preparation of Pat**

   Take approximately 100 grams of soil. Dry or add water to the soil sample until it becomes plastic enough to be moulded by hand. Preparation of the moulded soil is complete when a pocket penetrometer reading of between 86 - 188 kPa is obtained. The soil is then compacted by hand into a metal ring of 51 mm diameter and 6.4 mm in height and the soil levelled using a spatula. The soil disc or pat is then carefully ejected from the ring and placed on a ventilated drying tray (old sieve).

2. **Drying of Pats**

   The pat is allowed to dry slowly overnight at room temperature to avoid cracking. The following morning the pat is placed in the oven (105 - 110 degrees Celsius) and allowed to dry out completely. When pat is dry, remove pat from oven and place it in the desiccator, where it is allowed to cool to room temperature.

3. **Shrinkage Determination**

   When cool, the pat is removed from the desiccator and diameter of pat measured. Reduction in size is recorded as a percentage of its original size.

Figure 15.3 Pat Shrinkage Test

Limit values, therefore assisting with soil classification. This correlation will only be reliable for a particular area's soils. Correlation values of Pat Test Shrinkage, Liquid Limit and Linear Shrinkage for Goulburn Valley soils in northern Victoria are in Table 15-5.

Group Symbol	Plasticity	Pat Test (% Shrinkage)	Liquid Limit	Linear Shrinkage (%)	Comment
ML CL	Low	1.4 – 3.6	10<LL<35	4 – 9	
MI CI	Medium	3.7 – 5.9	35<LL<50	9 – 14	
MH CH	High	6.0 – 8.4	50<LL<70	13 – 19	
CH	Very High	8.5 -	LL>70	20 -	Fat clay

Table 15-5 Correlation of Pat Test with Liquid Limit and Linear Shrinkage in G-MW

15.6 Dispersion

The term dispersive clay or dispersion refers to the stability of soil aggregate when exposed to water.

There is a tendency for certain clays to break down in water and form a suspension of extremely fine particles. These clays are called dispersive and can be highly erosive. The presence of dispersive clays in bank material has a severe magnifying effect on deterioration, increasing the extent and spread with which it occurs. Tunnelling (holes through the bank), seepage and slumping in channel banks are a common problem. Dispersive clays are found in many Australian areas and all irrigation channel bank material should be tested for dispersion unless extensive experience in an area has shown dispersive clays are not present..

Channel banks constructed with some dispersive clays can perform satisfactorily, but special precautions need to be taken.

Rainfall and runoff on exposed slopes of dispersive clays can cause severe erosion. The erosion often results in rilling and gullying on the slopes. Vegetation cover alone may not prevent surface erosion of channel banks constructed of dispersive clays.

Channel banks constructed of dispersive clays can suffer problems because of internal erosion through cracks or other openings. These problems usually take the form of *pipes* or *tunnels* through the bank material.

Coarse-grained soils do not disperse in water. However fine-grained soils, silts and clays, have varying dispersive characteristics. Dispersion of earthen channel banks occurs when individual colloidal clay particles pass into suspension, following an ionic reaction between clay particles, pore water and channel water constituents. Dispersive clays differ from ordinary clays because they have a higher relative content of dissolved sodium in the pore water, whereas ordinary clays have a preponderance of calcium and magnesium cations.

Normal clays have a flocculated or aggregated structure because of the electrochemical attraction of the particles to each other. Dispersive clays have an imbalance in the electro-chemical forces and this imbalance causes particles to be repulsed by one another. Because clay particles are very small and have a low mass, the particles are easily detached and transported by water. Dispersive clays are most easily eroded by water that is low in ion concentration such as rainwater.

Dispersion is a major cause of *erosion* and deterioration of channel banks, and *piping* due to dispersive soil is a common cause of channel bank failures. It is therefore critical that all potential borrow materials are tested for their dispersion characteristics. Colour is no a distinguishing feature of dispersive clays.

Typically, dispersive clays are low to medium plasticity and classified as CL in the United Soil Classification System. Other classes that may also have dispersive clays are the ML and CH.

The tendency for a soil to disperse can be measured by the Emerson Class Number (AS 1289.3.8.1). This method describes how soils are divided into seven classes on the basis of their coherence in water with one further class being distinguished by the presence of calcium-rich minerals. The Emerson Class Number is a simple test to perform, requiring minimal equipment. Therefore experienced staff in a laboratory are not necessary to obtain adequate results for this test. Other more elaborate tests, taking into account more variables and allowing better differentiation of degrees of dispersiveness are available, but are considered unnecessarily elaborate for use with channel bank materials. The characteristics of each soil for each Emerson Class No. are described in Table 15-6.

Emerson Class No.	Degree of Dispersion	Testing condition	Determination of Emerson Class No.
1	Very High	Air-dried crumb	Air-dried crumbs of soil show strong dispersing reaction, ie a colloidal cloud covers nearly the whole of the bottom of the beaker, usually in a very thin layer – the reaction is evident within 10 minutes. In extreme cases the water in the beaker becomes cloudy leaving only a coarse residue in a cloud of clay.
2	High	Air-dried crumb	Air-dried crumbs of soil show a moderate to slight reaction consisting of an easily recognisable cloud of colloids in suspension usually spreading in thin streaks on the bottom of the beaker. A slight reaction consists of the bare hint of cloud in water at the surface of the crumbs.
3	Moderate	Soil remoulded at plastic limit	Soil remoulded at the plastic limit disperses in water
4	Low	Soil remoulded at plastic limit	Remoulded soil does not disperse in water. Soil is tested to check that calcium carbonate or calcium sulphate is not present.
5	Very low	1:5 soil/ water suspension	Remoulded soil does not disperse in water and the 1:5 soil/water suspension remains dispersed after 5 minutes
6	Negligible	1:5 soil/ water suspension	Remoulded soil does not disperse in water and the 1:5 soil/water suspension begins to flocculate within 5 minutes.
7	Nil	Air-dried crumb	Air-dried crumbs of soil remain coherent in water (do not slake) and swell
8	Nil	Air-dried crumb	Air-dried crumbs of soil remain coherent in water (do not slake) and do not swell

Table 15-6 Degree of dispersiveness by Emerson Class No.

The degree of dispersion depends on the strength of the ionic forces bonding the clay particles together, as well as the salinity of the water. Most soils are more likely to be dispersive in distilled water. The Emerson test was originally created to test agricultural soil's tendency to disperse with rainfall.

For the Emerson test to be meaningful in assessing the tendency of channel bank soil to disperse, it is necessary to model:

1. Rainwater falling on the bank
2. Channel water flowing past the bank

The Australian Standard uses distilled water which models rainwater adequately. However a laboratory solution must be made up to model the channel water. This is known as *channel water equivalent* which is a representative average chemical composition of water for the irrigation area concerned. Therefore this test must be carried out using both distilled water and channel water equivalent.

Even when channel erodibility may not be a problem, rainfall can cause surface erosion of the exposed slopes.

Tests should not be conducted using a spot sample from the channel concerned because:

- water quality may vary throughout the irrigation season, eg run of river flows after rainfall or directly from a dam.
- it may have one-off impurities.
- highly turbid water can cause difficulty in distinguishing the degree of dispersion or slaking.

The solution used to model channel water from the Goulburn and Murray Rivers in northern Victoria is given in Figure 15.4. The chemical composition is similar throughout the Murray-Darling basin, although salinities vary. In other areas a *channel water equivalent* should be made up by a chemist which takes account of the local chemical composition and salinity of the respective channel water.

***Channel Water Equivalent* chemical composition for Goulburn and Murray River water at approximately 1000EC units salinity**
0.293g - Sodium Chloride (NaCl) 0.255g - Magnesium Chloride (crystals) ($MgCl_2.6H_2O$) 0.306g - Calcium Chloride($CaCl_2.6H_2O$) 1 litre Distilled Water

Figure 15.4 Channel Water Equivalent for Goulburn and Murray River water

The collection of soil samples should recognise that dispersive clays can occur as random lenses in soil profiles and dispersive properties can vary laterally and vertically. Wide variations in dispersive characteristics may occur within short horizontal and vertical distances in a an area.

One can never rely on colour or other visual features to distinguish between dispersive and non-dispersive soils. Tests must be used.

15.7 Engineering Properties of Materials

Having determined the particular group to which a soil belongs, it is necessary to recognise the factors which control the properties of soils within the group. Engineering properties of prime importance to earthen channel banks are:

- Permeability
- Workability
- Stability
- Erosion Resistance
- Shear Strength
- Compressibility
- Density

15.7.1 Coarse grained soils

In this category, the gravel and sand groups have similar properties as far as the properties in the list above are concerned. Well-graded sands and gravels are normally stable materials exhibiting high shear strength and high density. They are relatively easy to compact and their properties are not affected to any marked extent by the addition of water.

However the presence of even a small amount of fine material with the coarse grained soils can have a very important effect on the properties of the material. Thus, in the Unified Soil Classification, considering the difference between the SP group with less than 5% of fine material and the SC group with greater than 12% of fine material. The SP group would have permeability to high for bank material, whilst SC would be quite acceptable. So a small increase in the percentage of fines can make all the difference in the acceptability of a possible channel bank material.

There is a tendency to reject soils with a small percentage of fines on the grounds that the material will be too permeable. In fact, materials in the SC and GC groups (with 20 to 30% good clay portion) are the best materials with which to build earthen channel banks. These materials exhibit high densities and shear strengths, are easy to work and when well compacted, are relatively impermeable, and shrinkage and swelling characteristics are limited.

15.7.2 Fine Grained Soils

The engineering properties of the fine-grained soils vary to a much greater extent. These properties depend on whether the material is dominantly a silt or a clay, and on the degree of plasticity. In general, the properties of these materials are very dependent on the amount of moisture present, because the properties change with change of moisture content. Strict attention to moisture content control is therefore necessary during compaction.

Changes in moisture content after compaction can substantially alter the properties of the material in the embankment causing shrinkage and subsequent swelling on re-wetting. It can change the in-situ shear strength and compressibility characteristics, and any or all of these changes can cause potential problems.

Silts and clays may appear similar and may exist in the same size ranges on any grading chart, but they are most easily distinguished by their behaviour in the presence of moisture. Silts in general make up the non-plastic portion of the fines and are inherently unstable in the presence of water, even though silts with high liquid limits are relatively impermeable. Generally, silts are difficult to compact. The liquid limits may vary from 20% up to 100%, but the plasticity index, (the difference between liquid and plastic limits) is very small.

Clays, on the other hand, make up the plastic portion of the fines. Liquid limits may vary from 10% to 100% and the plasticity indexes are generally high. Clays are generally impermeable. Optimum moisture contents are high and usually the higher the clay content and the higher the liquid limit, the higher also is the optimum moisture content. (Optimum Moisture Content is the water content at which maximum compaction can be achieved for a given compactive effort). The higher the moisture content at which compaction is required, the more difficult the material is to work.

High compressibilities are also indicated by high liquid limits and high compressibilities might increase the dangers of piping failure, unless adequate construction controls are introduced. High liquid limits also serve to indicate lower saturated shear strengths and hence the necessity for flatter batters.

The relative properties of the various groups under the Unified Soil Classification system are set out in Table 15-3. This indicates the relative desirability of all classes of material from an earthen channel bank perspective:

- Impermeability
- Erosion resistance
- Dispersion

This assembles the identification and classification properties of Table A1 in AS1726-1993 *Geotechnical Site Investigations*.

15.8 Material Acceptance Criteria

Specifically for earthen channel banks, the bank material should have:

- Low permeability when compacted
- Good stability when compacted – free from excessive shrinking or swelling
- Good resistance to erosion from flowing water or wave action
- Good shear strength (slope stability characteristics) when compacted and saturated
- Ability to be easily compacted
- Low dispersion properties

Guidelines for Material Acceptance can be found in AS 3798, *Guidelines on earthworks for commercial and residential developments*. Sections 4.1, 4.2 and 4.3 of this standard may be useful in developing a specification.

The following criteria shall be used to select appropriate bank material:

15.8.1 Soil Classification

Based on the Unified Soil Classification System, Table 15-3 has been drawn up, giving general guidance on the properties and suitability of various types of soils for channel bank construction. The numbers in Table 15-3 indicate the order of increasing values for the property named. Thus the permeability of the most permeable soil, poorly graded gravel, is indicated as 16, the highest permeability number. The erosion-resistance characteristics of materials are indicated in the order of suitability, where 1 equals best.

A well-graded sand and gravel with a clay binder (GW-GC) is considered the best material. Clayey gravel soils (GC) are considered next best, sand with clay binder (SW-SC) the third best, etc. Silty gravels have been used with success. The best materials of this type have just enough silt to provide sealing qualities and have sufficient gravel for erosion resistance. Silty or sandy clay soils having a plasticity index of less than 7 are not considered suitable. Fat clays (ie inorganic clays of high plasticity) may not be suitable for channels which are subject to wetting and drying because of swelling and shrinking, unless it has an adequate protective cover.

If the soil is weak in one of its characteristics, treatment of the soil or protection of the bank may be required as described in Section 15.9.

Some borderline soils which are pervious at natural density become less pervious when compacted. It may be economical to mix two or three soils to obtain the type of material desired. Where gravelly soils are encountered in the channel excavation, silt or clay soils may be imported for mixing with the gravelly soils. From 20 to 50 percent fine material may be required, depending on the characteristics of the fine and the gravelly soils. The blending of materials often allows a considerable reduction in haul quantities and thus a saving in cost. The blending operation can be accomplished with mixing machines, by blading, or with harrows.

A degree of caution must always be exercised when using soil classifications, since the conduct of the index tests inherently involves disturbance of the soil. They may not always give a good indication of the behaviour of the insitu, undisturbed soil.

15.8.2 Shrinkage

Clay, even though relatively impermeable, may not make the best channel banks if it shrinks and swells too much.

Material of low shrinkage, Pat Shrinkage < 4%, is preferred and normal cover treatment should be adequate.

Material in the medium range 4% < Pat Shrinkage < 7% is acceptable if special care is taken in applying a protective cover as described in Section 17.

High shrinkage materials, Pat Shrinkage > 7%, are not recommended for bank construction unless the material is appropriately treated. Refer to Section 15.9.2.

Inspections should be carried out in the first year after construction of a new channel bank to identify any early signs of drying cracks.

15.8.3 Dispersion

Dispersive soils can be a problem in channel banks. In appearance, they are like normal clays that are stable and somewhat resistant to erosion, but in reality they can be highly erosive and subject to severe damage or failure. It is important to understand the nature of these materials and to be able to identify them so they can be avoided or treated.

Acceptance criteria for dispersive soils:

In *Channel Water Equivalent* Emerson Class No. ≥ 4 (AS 1289.C8.1-1980)

In *Distilled Water* Emerson Class No. > 1

For these limits no special treatment for dispersion should be necessary and the bank material can be compacted to the standard 95% of maximum dry density.

15.8.4 Summary of Material Acceptance criteria

A summary of channel bank material acceptance criteria is given in Table 15-7.

	Channel Bank Material Acceptance rating		
Acceptance Criteria	**Preferred**	**Acceptable**	**Low Quality** (may be acceptable with treatment. Refer Section 15.9.)
Soil Classification	GW-GC GC SW-SC SC	GM SM ML CL CI	GW GP SW SP MH CH
Pat Shrinkage	Pat Shrinkage<4%	4%<Pat Shrinkage<7%	Pat Shrinkage>7%
Dispersion *Channel Water Equivalent*	Emerson Class No. ≥ 4	Emerson Class No. ≥ 4	Emerson Class No. ≥ 1
Distilled Water	Emerson Class No. ≥ 4	Emerson Class No. ≥ 1	Emerson Class No. ≥ 1

Table 15-7 Summary of Material Selection Criteria

15.9 Use of Low Quality Materials

It will not always be possible to obtain bank material to the standard set out in Section 15.8. To find material which meets the standard can take considerable time and involve hauling over significant distances. Soil classification, shrinkage and dispersion tests may indicate that the material is not adequate for channel bank construction. However, with appropriate treatment, some low quality materials may become acceptable.

The erosion of channel banks is dependent on the material properties and the channels' operation. Channel banks constructed of silty and sandy materials with little course gravel are susceptible to scour. If these are to be used, the cost of reducing the velocity with a larger section, as compared with the cost of a smaller section with its higher velocity and protecting the lining with gravel cover should be evaluated.

15.9.1 Soil Classification

A summary of remedial treatments for the different groups under the Unified Soil Classification system is set out in Table 15-8.

Group Symbols	Suitability for Earthen Irrigation Channels			Remediation Techniques	Comments
	Impermeability	Erosion Resistance	Dispersion Resistance		
GW	Not suitable	2	1 (best)	Mix clay with gravel to form a GW-GC material.	
				Line the channel with a clay or geomembrane liner	
GP	Not suitable	3	1 (best)	Mix clay with gravel to form GC material	
				Line the channel with a clay or geomembrane liner	
GM	6	5	3	May require clay or geomembrane liner to improve impermeability	
GC	2	4	2	NO TREATMENT REQUIRED	
GW-GC	1 (best)	1 (best)	2	NO TREATMENT REQUIRED	
SW	Not suitable	8	1 (best)	Mix clay with sand to form a SW-SC material.	
				Line the channel with a clay or geomembrane liner	
SP	Not suitable	9 coarse	1 (best)	Mix clay with sand to form SC material.	
				Line the channel with a clay or geomembrane liner	
SM	7	10 coarse Erosion Critical	3	May require clay or geomembrane liner to improve impermeability.	
SC	4	7	2	NO TREATMENT REQUIRED	
SW-SC	3	6	2	NO TREATMENT REQUIRED	
ML	8	Erosion Critical	Variable. Must be tested	Will probably be highly dispersive. Treat as per Section 15.9.3.	
CL	5	11	Variable. Must be tested	Requires protective cover over batter and crest. Test for dispersion.	
CI	7	12	Variable. Must be tested	Requires protective cover over batter and crest to protect bank from moderate shrinkage. Test for dispersion.	
OL	9	Erosion Critical	-		Not suitable due to the decay of organic matter
MH	Not suitable	Not suitable	Variable. Must be tested	Will have a high shrinkage % and probably be highly dispersive. Treat as per Section 15.9.2and 15.9.3.	This material is not suitable without a large amount of treatment.
CH	10 (worst) Volume change critical	13 (worst)	Variable. Must be tested	Will have a high shrinkage %. Treat as per section 15.9.2. Test for dispersion.	
OH	Not suitable	Not suitable	Not suitable		Not suitable due to the decay of organic matter

Table 15-8 Remediation Techniques for Low Quality Channel Bank Materials

15.9.2 Shrinkage

Fat clays (expansive clays) are generally not suitable for channel banks which are subject to wetting and drying, because of swelling and shrinking properties that can lead to cracking. Materials of very high shrinkage (Pat Test > 7%) are unsuitable for channel bank construction unless they are carefully treated by placing a blanket of sand or gravel over the bank or the bank material is chemically treated. Three possible treatment methods are outlined below:

1. Sand or Gravel Cover

A minimum of 150mm of well-graded sand (SW) or well-graded gravel (GW) with less than 5% fines is required over the crest and outside batter to prevent drying of the compacted bank.

Where the exposed bank is higher than 1.5 metres or the bank is in a more arid environment the thickness of sand or gravel should be increased to about 300mm.

With very high shrinkage material, a cover of topsoil and vegetation will not be adequate to protect the bank from cracking.

Refer to Section 17 Protective Cover.

2. Chemical treatment

Chemical treatment of bank material with relatively small quantities of substances such as lime, gypsum or other suitable chemicals can reduce the plasticity, shrinkage and expansion properties of soils generally in proportion to the amount of chemical used. Laboratory testing and expert advice should be sought to determine the best type and quantity of chemical required for a particular bank material to raise the shrinkage limit of the soil to the point that drying cracks cannot develop. The laboratory quantities are generally increased to account for the poorer mixing and proportioning in a field situation. The cost of the chemical, its transportation and application is also likely to be significant.

A typical treatment sequence would consist of:

1. The required quantity of chemical is uniformly spread over the surface area of a 100-150mm thick layer of soil to be treated.
2. The chemical is thoroughly mixed at a specified moisture content into the layer of soil using a rotary type mixer.
3. The layer is compacted to the specified density.
4. The process is repeated for successive 100 to 150mm thick layers of the bank.

Alternatively the treatment can be applied as a 200 to 300mm *blanket* over the outer surface of the bank, thereby reducing the expense of treating the entire bank. It is best mixed in two stages – the first with soil to a depth of 100-150mm over the surface of the bank and then compacted, followed by a second mixing of soil and gypsum say in the borrow pit, which is then spread in a 100-150mm layer and compacted over the surface of the bank. This procedure is used because it is not possible to adequately compact a single 300mm layer of soil.

The uniform application and thorough mixing of the chemical can be difficult to achieve, especially on the batter slopes.

Soils treated with 2 to 3 percent of hydrated lime have a high initial pH and the initial establishment of vegetation may be difficult.

3. Inside batter Protection

Highly plastic soils are not subject to shrinkage while they are covered by water. If exposed, say during the non-operational period, they will crack as the banks dry out. Protection provided by crushed rock lining (refer Section 18.4, Rock Armour) will reduce the amount of bank cracking.

Controlled filling of the channel with water at the start of the operational period will also enable the bank to take up water at a slower rate giving the material time to swell and close up some of the cracks. Large cracks may take weeks or months to close up.

15.9.3 Dispersivity

As far as possible the use of highly dispersive clays in channel bank construction should be avoided. If a soil is found to be dispersive, then careful control of moisture content and compaction must be applied if it is to be used.

The deterioration or failure from internal erosion of channel banks constructed from dispersive soils occurs when two thing happen simultaneously:

i) Water rapidly saturates the soil, causing the clay to break down and form a suspension of extremely fine particles.

ii) The channel bank is sufficiently permeable to allow water to seep through carrying the dispersed clay. The slow seepage increases in local areas to form a *pipe*. Enlargement of the *pipe* proceeds from the inner face with the material remove passing downwards. The *pipe* eventually emerges at the outside face, at which stage it enlarges rapidly.

Knowing these causes, appropriate steps can be taken to prevent this occurrence. Three methods of treating dispersive soils follow:

15.9.3.1 Mixing of soil

Throughout Australia it is common for dispersion to increase with depth in undisturbed soil. These are called duplex soils where there is a very defined colour change between the topsoil and the subsoil. If bore logs show there is relatively low dispersion (high Emerson No.) material in the upper profile but high dispersion (low Emerson) at depth, it still may be possible to use all of the material if it is well-mixed through the profile. An average Emerson No. can then be obtained.

This can only be achieved with good excavation practice. A hydraulic excavator can extract material in the borrow pit by excavating right through the profile and mixing before placing on tip trucks. Bulldozers and loaders will generally only be able to excavate in horizontal layers.

It is generally not practical to selectively place discrete zones of dispersive and non-dispersive soils in a channel bank. This type of technique is used in larger embankments and dams.

15.9.3.2 Increase compaction

An effective control method is to reduce the permeability of the soil to a value where the voids are too small to allow rapid passage of water and dispersed clay through the bank. This can usually be achieved by compacting the channel bank to at least 98% of maximum dry density, using more compactive effort and with the soil slightly wetter than optimum, ie moisture content range from optimum to optimum+3%.

It is essential that uniform compaction is achieved. Otherwise the water will rapidly find any less compacted area and *pipe* out.

Secondly, in order to stop the water saturating the soil in the bank too quickly, a blanket of stable compacted non-dispersive soil can be placed over the inside batter slope. This slows the entry of water into the dispersive soil in the bank giving the material time to swell and block the *piping* process.

Material of Emerson Class No. 2 and 3 (in channel water equivalent) can be used if the following treatment is carried out.

1. Compaction to at least 98% of maximum dry density. The moisture content during compaction must be carefully controlled to be at or marginally above the optimum level. This is not as easy with dispersive soils, as they can be difficult to wet up. A suitable sheepsfoot roller may be required to properly compact these troublesome soils. Unless compaction tests can demonstrate otherwise, a sheepsfoot roller is recommended for the compaction of highly dispersive soils.

   Special care is required to avoid drying cracks that might occur during interruptions of bank placement in hot dry weather. Always thoroughly scarify and wet the surface of the proceeding layer before placing additional layers.

2. Inside batter protected from erosion (crushed rock, gravel or other). Refer to Section 18, Inside Batter Treatment.

3. Crest and outside batter protected in accordance with Section 17, Protective Cover.

15.9.3.3 Chemical Treatment

Several chemical additives can be introduced to dispersive soils to promote better stability of the soil when contacted by water. These include slaked lime powder (Limil), hydrated lime, fly ash, agricultural lime, magnesium chloride, powdered gypsum and finely crushed filtered alum. Typically 3 to 5% by dry weight of these chemicals well mixed into the bank material and then the treated soil, compacted, will significantly reduce dispersivity. The concept is to add calcium to the soil replacing the sodium cations and converting it to a non-dispersive material. The process is effective apparently long lasting, but is expensive. It is essential that the chemical is thoroughly mixed with the soil, and that moisture content and compaction are tightly controlled.

Depending on the particular circumstances, chemical treatment may be applied to:

- all the bank material
- the entire outer surface of the bank – *blanket* treatment
- waterface of the bank only – *plate* treatment

Expert advice should be sought to determine the best type and quantity of chemical stabilisation for a particular dispersive material. Common gypsum is relatively insoluble, and is not likely to be as effective as other sources of calcium. Fine-grained gypsum, such as phosphogypsum, is more soluble. Lime, on the other hand, has low solubility and will not be as effective. Agricultural lime by itself has not proven as effective.

The advantages of using hydrated lime to treat dispersive clays are that the method has a long history and that the plasticity of the treated clay is reduced. The disadvantages include the cost of the raw material, hydrated lime, and the processing and curing methods are costly. Curing of clays after mixing with lime is necessary to reduce the brittleness of the compacted fill. Soils are generally cured for a minimum of 48 hours before transporting and compacting into a fill. Also greater amounts of water are needed for the curing process. Another disadvantage of hydrated lime is the increase in the pH of the treated soil and the attendant difficulty in initial vegetation establishment.

Quick lime is sometimes used instead of hydrated lime and may be more readily available in some locations. Because of its caustic properties, quick lime generally is used in pelletised form or as a slurry, rather than powdered form. Pelletised quick lime is slightly more difficult to incorporate and mix intimately than hydrated lime, which is a fine powder. More water is required to complete the reaction of quick lime than hydrated lime. Greater safety precautions are necessary when handling quick lime because of the hazard created by the heat generated when the lime reacts with water. Some of these objections are handled by using a slurry prepared from quick lime.

Both granular and liquid alum have also been used to treat dispersive clays. Soils can be immediately compacted after mixing with alum, with no curing period, because alum does not strongly affect the plasticity or brittleness of the soils. This is an advantage in that the processing costs are reduced, but a disadvantage in that the tendency of the clays to crack is not reduced with the alum.

Another disadvantage to the use of alum to treat dispersive clays is that less history and documentation of field performance is available to testify to its efficacy.

Fly ash is a waste product from the burning of coal at many power plants. Tests have shown that the addition of 4 to 6 percent by dry weight of fly ash to dispersive clays generally renders the soils non-erosive. The planned source of fly ash should be tested when contemplating using fly ash because the composition of fly ash varies considerably with the type of coal burned to produce it. Fly ash does not materially affect the plasticity of the treated soil.

Tests have not shown gypsum to be very effective in treating dispersive clays.

Other additives, such as magnesium chloride, have been considered. Tests on dispersive clays treated with this chemical have shown it to be effective. The primary questions concerning this and other chemicals that have few field trials is whether they have adequate longevity and how they may affect subsequent establishment of vegetation.

Material of Emerson Class No. 1 can only be used if there is substantial *blanket* of higher quality material over both the crest and batters or it is chemically treated as described above.

In existing channels, the addition of chemical additives, well-mixed in and compacted with the upper 200 to 300mm of the outer surface layer of the bank, may be beneficial in stabilising the bank material. Refer to Section 15.9.2, Shrinkage, Chemical Treatment.

15.9.3.4 Sand Filter Zone

The internal erosion or *piping* of channel banks constructed from dispersive clays can be prevented by the placement of a vertical sand filter zone in the bank.

Fine clean sand is placed in a 0.5 to 1 metre wide vertical trench excavated in the constructed bank, extending from the bank subgrade up to the height of the maximum water level.

Eroding water flowing through the dispersive clay carries particles of the eroded soil to the sand filter interface. Plugging of the flow occurs as particles build up on the face of the filter. For it to be effective, the sand filter must not have the potential to crack itself.

Crest and batter protection from external erosion would also be required. Refer to Sections 17 and 18.

15.10 Tests for Small Projects

There is a view that the level of investigation, design, material testing and construction control used on large channel projects cannot be justified on small low cost projects. While that may be the case in some situations, it is not just the size or the cost of the channel works that should be the deciding factor in determining the amount of care that is taken in design and construction, but rather *the consequences of a channel failure*. The total potential damage and economic loss that may result from a failure of the channel bank also needs to be considered.

The scope of investigation and testing carried out is usually proportional to the size of the project. A large channel project would justify the expense of detailed investigation and laboratory testing, but on a small project laboratory testing facilities may not be available.

Where laboratory testing facilities are not available, the following simple *field identification* procedures may be useful to determine whether the material is suitable for bank construction.

However, satisfactory results from these tests require a degree of skill and experience, and testing conducted by in-experienced staff should be treated cautiously. Confidence in these testing procedures is improved where the results are periodically checked with laboratory tests, and the operator receives confirmation of their field testing.

15.11 Field identification of soils

When time and facilities do not permit laboratory testing of a soil, the use of the following field identification procedures will permit a reasonably accurate Unified Soil Classification to be made.

Field identification techniques of soils are also referred to as *Hand Classification.* Field identification appropriate to channel bank construction are as follows:

15.11.1 Particle Size Distribution

Gravels and sands can be readily identified by appearance and feel, but silts and clays are indistinguishable when dry.

A representative sample of soil (excluding particles larger than 63mm) is first classified as coarse grained or fine grained by estimating whether 50% by weight of particles can be seen individually by the naked eye (about 0.075mm). Soils containing more than 50 percent of particles that can be seen are coarse-grained soils; while soils containing more than 50% of particles smaller than the eye can see are fine-grained soils.

15.11.2 Coarse-grained soils

If the soil is predominantly coarse grained, it is then identified as being a gravel or sand by estimating whether 50% or more by weight, of the coarse grains are larger or smaller than 2.36mm.

If the soil is a gravel, it is next identified as being clean (containing little or no fines) or dirty (containing an appreciable amount of fines). For clean gravels, final classification is made by estimating the gradation. The well-graded gravels belong to the GW group, and poorly graded gravels belong to the GP group. Dirty gravels are of two types: those with non-plastic (silty) fines (GM), and those with plastic (clayey) fines (GC).

If a soil is a sand, the same steps and criteria are used as for the gravels in order to determine whether the soil is a well-graded clean sand (SW), poorly graded clean sand (SP), sand with silty fines (SM), or sand with clayey fines (SC). Sand is visible to the eye.

15.11.3 Fine-grained soils

Three simple tests which can be used to differentiate silts from clays are described below:

Hand-Rolling test

Classification of soils as clay (C) or silt (M) is carried by rolling a sample in the hand. Silts have a gritty feel while clays are greasy. Some experience and skill is required to correctly classify a soil which is borderline clay-silt.

Handling Test

Moisten the sample and feel it; clay should feel sticky. Then squeeze it between the thumb and forefinger; if it contains enough clay, it should be possible to form a flexible ribbon about 2mm thick and at least 40mm long.

Shine Test

A dry or slightly moist sample of soil is cut with a knife. A shiny cut surface indicates a highly plastic clay while a dull surface suggests silt or clay of low plasticity.

If a material is predominantly fine-grained, it is classified into one of six groups (ML, CL, OL, MH, CH, OH) by estimating its dilatancy (reaction to shaking), dry strength (crushing characteristics), and toughness (consistency near the plastic limit), and by identifying it as being organic or inorganic. Note that silt and clays are collectively called *fines* and when dry and powdered are indistinguishable; so their distinction is made not on size but on their different behaviour to simple manual tests.

Soil Classification of fine-grained soils by hand classification is summarised in Table 15-9. The procedures described are to be performed on the minus 0.2mm size particles. For field classification purposes, screening is not intended, simply remove by hand the coarse particles that interfere with the tests.

<table>
<tr><th></th><th></th><th>Dry Strength
(crushing characteristics)</th><th>Dilatancy
(Reaction to Shaking)</th><th>Toughness
(Consistency near Plastic Limit)</th><th>Group Symbol</th></tr>
<tr><td rowspan="6">Fine Grained Soils
More than half of material is smaller than 0.075mm</td><td rowspan="3">Silts and Clays
Liquid Limit less than 50</td><td>None to Slight</td><td>Quick to Slow</td><td>None</td><td>ML</td></tr>
<tr><td>Medium to High</td><td>None to very Slow</td><td>Medium</td><td>CL</td></tr>
<tr><td>Slight to Medium</td><td>Slow</td><td>Slight</td><td>OL</td></tr>
<tr><td rowspan="3">Silts and Clays
Liquid Limit greater than 50</td><td>Slight to Medium</td><td>Slow to None</td><td>Slight to Medium</td><td>MH</td></tr>
<tr><td>High to very High</td><td>None</td><td>High</td><td>CH</td></tr>
<tr><td>Medium to High</td><td>None to very Slow</td><td>Slight to Medium</td><td>OH</td></tr>
<tr><td colspan="2">Highly Organic Soils</td><td colspan="3">Readily identified by colour, odour, spongy feel and frequently by fibrous texture</td><td>Pt</td></tr>
</table>

Table 15-9 Field Identification Procedures on fraction smaller than 0.2mm

Clays are the plastic fines. They can be divided into ones of low liquid limit (L < 50) and ones of high liquid limit (H > 50). A clay of low liquid limit will have very slight to no dilatancy, medium dry strength, and medium toughness; whereas a clay of high liquid limit will have no dilatancy, high dry strength and will be very tough.

Silts are the non-plastic fines. They are inherently unstable in the presence of water and have a tendency to become quick when saturated. Silt masses undergo change of volume with change of shape (the property of dilatancy), in contrast to clays which retain their volume with change of shape (the property of plasticity). Silts with low liquid limit will have medium to quick dilatancy, almost no dry strength, and no toughness. Silts with high liquid limit will have slight to no dilatancy, slight to medium dry strength, and slight to medium toughness.

15.11.3.1 Dry Strength (crushing characteristics)

After removing particles large than 0.2mm size, mould a pat of soil with a volume of 10cm^3 (a fistful) to the consistency of putty, adding water if necessary. Allow the pat to dry completely and then test its strength by breaking and crumbling between the fingers. This strength is a measure the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.

High dry strength is characteristic for clays of the CH group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when powdering the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

15.11.3.2 Dilatancy (Reaction to shaking)

After removing particles larger than 0.2mm size, prepare a pat of moist soil with a volume of 10cm^3 (a fistful). Add enough water if necessary to make the soil soft but not sticky.

Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil.

Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, shows a moderately quick reaction.

15.11.3.3 Toughness (consistency near plastic limit)

After removing particles larger than 0.2mm size, a specimen of soil about 10cm^3 in size is moulded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. The specimen is then rolled out by hand on a smooth surface or between the palms into a thread about 3mm in diameter. The thread is then folded and re-rolled repeatedly. During this manipulation the moisture content is gradually reduced and specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together with a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicates either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays. Highly organic clays have a very weak and spongy feel at the plastic limit.

15.11.4 Boundary Classification

Proper boundary classification of a soil near the borderline between coarse-grained and fine-grained soils is accomplished by classifying it first as a coarse-grained soil and then as a fine-grained soil. This type of dual classification is done for all soils which are visually judged to have between 40% and 60% of fine (or coarse) material.

15.11.5 Plasticity

The hand classification method in the Description & Field Identification column in Table 15-10, can be used to determine whether the sample is of low, medium or high plasticity.

Descriptive Term	Symbol	Description & Field Identification
Low Plasticity	L	May appear cloddy when dry, but dry lumps can readily be broken by and powdered by pressure of the fingers and thumb. Will roll into a thick soft thread that is easily broken. When dry will brush from the hands.
Intermediate Plasticity	I	Fine textured soil smooth to the touch. May be moulded into various shapes, will roll into a thread but breaks on bending slightly.
High Plasticity	H	Very fine textured soil, smooth and very greasy. Rolls into a very fine thread without breaking. Thread will bend to about 45° without breaking.
Fat Clay	H	Threads will bend almost in two without breaking.

Table 15-10 Determination of plasticity by Field Identification

15.11.6 Rapid Dispersion Test.

Fill a clear glass jar half full (100ml) of distilled water or rainwater, gently place a pea-size crumb (5 to 10 grams) of dry soil sample into the jar and leave undisturbed for at least an hour, without shaking. At the end of the waiting period, the interface between the soil sample and the water should be carefully examined. The occurrence of a colloidal *cloud* at this interface is an identification of dispersive soil. With a highly dispersive soil it will have dispersed into a dense *cloud* in that time, whilst a less dispersive soil will have a local *cloud* encircling the original soil particle. With a non-dispersive soil, the area around the soil particle will be clear.

A variation on the above test is to use two glass jars, one containing distilled water and the other a sample of the proposed channel water. If the channel water becomes quite cloudy in the lower part of the jar, then it is probable that a bank built of the test clay will *pipe* if special precautions are not taken. If there is little sign of a dispersive cloud of clay fines in the channel water jar, but definite cloudiness in the jar of distilled water, *piping* is not likely, but scouring by rainwater is probable unless there is a protective cover.

Care should be taken to ensure that the sample is representative. It is advisable to duplicate the test for each soil. Stirring or shaking the water must be avoided.

Sometimes it will be noted that the whole soil mass breaks down rapidly when placed in water. This is not dispersion, it is *slaking*.

15.12 Australian Standards

AS1726-1993	*Geotechnical Site Investigations*
AS1289.2.1.1-1992	*Determination of the moisture content of a soil – Oven drying method (standard method)*
AS1289.3.1.1-1995	*Soil classification tests – Determination of the liquid limit of a soil – Four point Casagrande method*
AS1289.3.2.1-1995	*Soil classification tests – Determination of the plastic limit of a soil – Standard method*
AS1289.3.4.1-1995	*Determination of the linear shrinkage of a soil – Standard method*
AS1289.3.6.1-1995	*Determination of the particle size distribution of a soil – Standard method of analysis by sieving*
AS1289.3.6.3-1995	*Determination of the particle size distribution of a soil – Standard method of fine analysis using a hydrometer*
AS1289.3.8.1-1997	*Soil classification tests – Determination of the Emerson class number of a soil*
AS3798-1996	*Guidelines on earthworks for commercial and residential developments*

15.13 References

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Horton AJ & Jobling GA, *Farm Water Supplies Design Manual – Volume 1 Farm Storages* Second Edition Farm Water Supplies Section, Irrigation Branch, Queensland Water Resources Commission

Poulton D (1986), Irrigation Services Branch, Rural Water Commission, *Recommended Laboratory Procedures for the Assessment of Soil to be used on the Construction of Farm Dams*

US Department of Agriculture, United States Soil Conservation Service (1991), *Dispersive Clays*, Soil Mechanics Note No. 13, Soil Conservation Service Engineering Division, February 1991

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16. Compaction Control

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16.1 Purpose

During this research project, it was identified that university engineering courses do not generally cover earthworks compaction particularly fully, and many engineers entering the irrigation industry have a lack of understanding of the problems of earthworks under-compaction, over-compaction and poor moisture control.

This section aims to give the reader a basic understanding of the soil mechanics, compaction equipment, procedures and testing involved in achieving adequate compaction of earthen channel banks.

16.2 Scope

In Australia, the maximum height above natural surface of water in irrigation channels is typically 1 to 2 metres, and rarely is 2 to 3 metres exceeded. In these situations, the investigation, compaction control and testing facilities used on major earthworks projects are not warranted, and this section covers the compaction control measures considered appropriate for the construction of earthen banks up to 3 metres in height using cohesive soils.

16.3 Field Compaction

The field compaction process can include any or all of the following steps:

1. Select borrow soil.
2. Alter the moisture content of the borrow soil: lower it by partial drying or raise it by the addition of water.
3. Mix the borrow soil to make it uniform and break up lumps.
4. Load borrow soil, haul to the site and dump it.
5. Spread the dumped soil into layers.
6. Compact the soil either according to a specified procedure or until specified properties are obtained.

16.4 Compaction Fundamentals

Compaction is defined as the application of mechanical energy to a soil in order to remove the entrapped air and to force the particles closer together, thereby increasing the density and reducing the void ratio.

The reduced void ratio and increased soil density obtained by compaction improves the channel bank construction characteristics of soil in several respects:

- *Reduced permeability* - The minimum permeability will occur at the minimum void ratio.
- *Increased strength* - The maximum shear strength occurs approximately at the minimum void ratio.
- *Improved volume change characteristics* - If large air voids are left in the soil, they may subsequently be filled with water, which may reduce the shear strength of the soil. This increase in moisture content may also be accompanied by appreciable swelling and loss of strength in some clays.

- *Increased stability* - The maximum erosion resistance occurs at the minimum void ratio.
- *Reduced compressibility* - Large air voids may lead to subsequent consolidation under working loads causing settlement during service.

The normal means of measuring the effectiveness of compaction is to measure the dry density and moisture content of the compacted soil and relate these values to pre-determined laboratory values. For example, 95% compaction means that the soil in place in the field should have a density of 95% of the maximum obtained in the laboratory.

Three important factors effect compaction:

- the soil's characteristics
- amount and type of compaction effort applied to the soil
- moisture content of the soil

16.4.1 Soil Characteristics

The different sizes of particles within a given soil will effect compaction. A soil is described as well-graded if it contains a good, even distribution of particle sizes. If a soil is composed of predominantly one size particles, it is said to be poorly graded. Refer Figure 16.1. In terms of compaction, a well-graded soil will compact more easily than one that is poorly graded. In well-graded material the smaller particles tend to fill the empty spaces between the larger particles, leaving fewer voids after compaction.

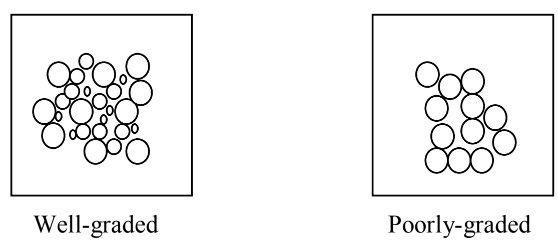

Figure 16.1 Soil grading

The highest dry densities are produced in well-graded coarse-grained soils, with smooth rounded particles, due to dense mass of interlocking particles. A summary of the compacted density of different soil types is found in Table 15-3, Section 15, Material Selection and Testing.

16.4.2 Compaction Effort

Compactive effort refers to the method employed to impart energy into the soil to achieve compaction. Compactors are designed to use one or a combination of the following types of compactive effort:

- Static weight (or pressure)
- Manipulation (or kneading)
- Impact (or sharp blow)
- Vibration (or shaking)

All compaction equipment utilises static weigh or pressure to achieve compaction. Most compactors combine static weight with one or more of the other compaction forces. Since soil tends to be displaced laterally by the force of the compaction effort, the most efficient compaction is obtained when such displacement is minimised.

Manipulation or kneading of soil while under pressure assists in achieving compaction in many soils, particularly the plastic soils. Impact and vibration are also helpful in compaction. The forces involved are similar except for their frequency. Impact involves delivering blows at a low frequency, usually below 10 cycles per second. Vibration involves higher frequencies and may extend to 80 or more cycles per second. Vibration is particularly effective in compacting cohesionless soils such as sand.

16.4.3 Moisture Content

Moisture content or the amount of water present in a soil is very important to compaction. If high densities are to be achieved, the control of the moisture content of a soil is critical. Moisture content and compaction are interdependent and experience has shown that where the moisture content of the material is too dry or too wet, the possibility of achieving the required density is very difficult, if not impossible.

Moisture content is defined as:

$$\frac{\text{weight of moisture present in the soil}}{\text{weight of the dry soil}}$$

and is usually expressed as a percentage.

The shearing resistance to relative movement of the soil particles is large at low moisture contents and dry soil resists compaction because of this friction between the particles. Water lubricates the particle surfaces, thus helping them slide into the most dense position. As the moisture content increases, the lubricating effect also increases. It becomes progressively easier to disturb the soil structure, and the dry density achieved with a given compaction effort increases, but only up to a certain point. Beyond this point, additional water contact forces the particles apart, making compaction less effective.

Soil experts have determined that in practically every soil, there is only one moisture content at which it is possible to obtain maximum density with a given type of compaction and compactive effort. This is called the *optimum moisture content*. If the dry density is plotted against the moisture content for a given compaction effort, it will be seen that the dry density reaches a peak, after which any further increase in moisture content results in a lesser dry density.

Figure 16.2 shows the relationship between dry density and moisture content. It is called a *compaction curve*, *moisture-density curve* or a *Proctor curve*.

The moisture content at which compaction is most readily achieved is called the *Optimum Moisture Content*. The corresponding density is called the *maximum dry density*.

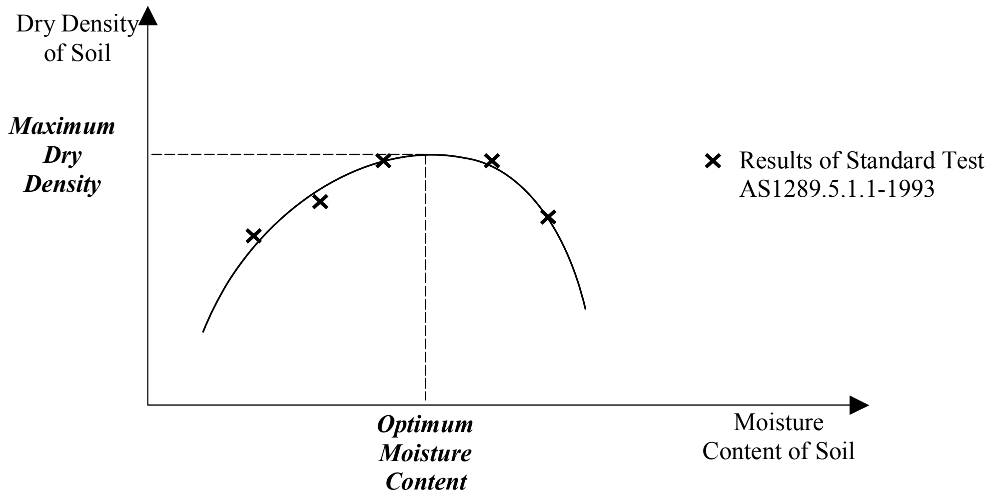

Figure 16.2 Dry Density vs Moisture Content for standard compaction effort

The important information with respect to water condition is the moisture content relative to optimum. Generally, a variation from the optimum moisture content of 2% wet to 2% dry is acceptable for channel bank construction. Refer Section 16.9.

During construction it is vitally important that each layer of material placed is compacted correctly. The two indicators of adequate compaction are moisture content and dry density. Both the maximum dry density and the optimum moisture content depend on the compaction effort used.

16.5 Results of Poor Compaction Control

Permeability, strength, stability and *settlement on saturation* increase as the moisture content and compactive effort are decreased from the optimum moisture content and from the maximum density. The permeability increases very rapidly.

When an earthen channel with banks constructed of suitable but poorly compacted material is filled for the first time, it behaves according to one of three broad patterns:

- The bank holds for a while, then a small muddy trickle appears on the outer batter. The trickle grows to a much larger flow which quickly erodes a tunnel or *pipe* through the bank.
- The bank seeps initially, but the seepage takes up in a relatively short time.
- The bank seeps steadily without any sign of the seepage taking up, but the bank remains intact and does not fail.

The chances of these problems occurring can be minimised if the correct equipment, compaction method and site control systems are used, consistent with the characteristics of the material being worked.

16.6 Compaction Control

Compaction control is the process of ensuring that the specified density is achieved in minimum time at the lowest cost. Compaction control needs to be seen as an integral part of bank construction procedures, and reporting methods that clearly show the results being achieved and trends developing should be used.

The soil density required for a channel bank project is usually specified as a percentage of the maximum density obtained for that soil in a standard laboratory test.

Compaction will fail to meet the required density where:

- moisture content is not within specified range
- the layer thickness is excessive
- insufficient passes are applied
- an unsuitable compactor is employed
- markedly different material from the tested borrow material occurs
- excessive gravel or rocks present
- roller pressure is insufficient
- the roller has clogged with soil
- frozen materials are placed

The object of compaction control measures is to ensure that the soil is placed, with reasonable certainty, within the limits imposed by the specification.

This involves making decisions on the:

i) Moisture content to be used
ii) Compaction to be achieved
iii) Type of equipment to be used

Moisture content, compactive effort and layer thickness are all interdependent. The compactive effort can be increased by increasing the dynamic force or increasing the number of passes or reducing the layer thickness.

The generally adopted approach is to fix two of these factors and then vary the third to achieve the required density. In channel bank construction, it is normal to nominate the layer thickness and the optimum moisture content and then control the compactive effort in the field so as to obtain the required density.

16.6.1 Thickness of Soil Layers

The bank material should be spread in loose layers, each layer being placed approximately horizontal and compacted to the required density at the optimum moisture content. The thickness of each layer is a major variable in compaction operations.

Selection of the correct layer thickness is critical to optimum density and production rates. Too thin a layer and over-compaction occurs. Too thick a layer and homogeneous densities are not achieved.

Optimum compaction of most channel bank material is found to occur in loose lift thicknesses of 150mm or less. The lift thickness which may be used to achieve a required density will vary with the soil and compactor characteristics, and to determine the maximum lift thickness, it is necessary to make a field test. In general, it is recommended that lifts be kept thin for best results.

As a general guide the thickness of loose lift for various types of compaction equipment are as follows:

- Bulldozer and Scrapers - 100 to 150mm
- Sheepsfoot Rollers - up to 200mm depending on the size, weight and length of the tamping foot
- Tamping Foot Vibrating Compactors - up to 225 mm

For Tamping Foot and Sheepsfoot Rollers, the compacted lift thickness should not exceed the length of the roller foot. This suggests a maximum loose lift thickness of 50mm greater than the length of the feet.

The layer thicknesses are specified in loose measurement, that is, uncompacted.

16.6.2 Number of Passes

The number of passes of compacting equipment to achieve the required soil density will depend on the soil and compaction characteristics, and the layer thicknesses.

Generally, equipment should be selected to produce the desired compaction with 4 to 8 passes.

Figure 16.3 shows the typical effect of the number of passes on soil density, with the increases in density reducing as the number of passes increases.

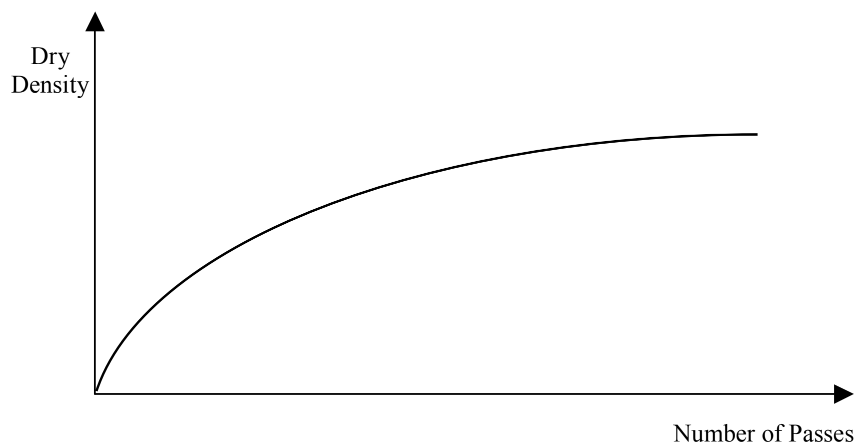

Figure 16.3 Dry Density vs Number of Passes

Extra passes of compaction equipment produce rapidly diminishing returns, and in some soils, it is necessary to double the number of passes, in order to increase the compaction from 95% to 100% of standard maximum dry density.

16.7 Methods of achieving Compaction Control

Specifications for channel bank work may be classified as:

(1) Method Specification or

(2) Acceptance Specification

In the past, a *method specification*, (also called *prescriptive specification*) was often employed to ensure adequate compaction, particularly in government projects. The minimum compactive effort to be performed was specified. For example, not less than 8 passes of a compactor across each successive 150mm layer. This method of compaction control usually requires a supervisor to be employed to ensure that the specification method is carried out correctly.

Acceptance criteria (also called *performance specification*) sets targets for the contractor to attain, eg achieve 95% maximum dry density, and does not describe the methods to be used. It is the contractor's responsibility to achieve this result.

Acceptance criteria testing is recommended for channel bank construction projects. However with small low-risk projects and repair works it may be appropriate to employ a method specification.

Care must be taken to ensure that only one of these methods is used for any one item. The contractor must not be directed in detail how to do a particular task and at the same time be held responsible for the end output.

16.7.2 Method Specification

The *method specification* has an input focus. It is useful for smaller projects where testing facilities are limited and the soil conditions are likely to be fairly uniform, and the compaction operation reasonably easy to control.

A method specification will be prescriptive and include specific procedures for moisture conditioning, minimum number of passes of a given sized and type of compactor over each layer, and maximum layer thickness, with no mention of required test results.

The type of equipment and method to be used is tightly specified; say 6 passes of a sheepsfoot roller of specific size and weight over 150mm loose layers at optimum moisture content.

These factors can be decided beforehand by field trials with the actual soil and the actual plant to be used in construction of the bank.

For small sections of low risk channel banks, it may be more economic to adopt the method specification approach and use higher compaction effort. This approach is typically conservative, and the compaction achieved can be appreciably higher than the design requirement.

Typical clauses in a Method Specification:

The minimum compactive effort to be performed is specified; ie not less than eight passes of the roller on each successive layer of the bank.

The sheepsfoot roller should exert a compactive effort of not less than 2,000 kilopascals on each foot, with all feet in effective contact with the soil.

The actual number of passes required to achieve the target compaction should be verified before hand by field trials of the compaction equipment on the soil to be used. Density tests should be taken at say 6, 8 and 10 passes to obtain optimum pass number.

If the number of compaction passes have been specified on each lift, it is important that the proper number of passes are made, as too few passes can lead to a considerable drop in the required degree of compaction.

16.7.3 Acceptance Specification

The *Acceptance Specification* has an output focus. No limitations are placed on how the required output must be achieved, allowing innovative and flexible solutions to be applied.

Where the site is more dispersed and the soil more varied, it is better to specify the results to be achieved, rather than to lay down the type of equipment and method. Generally a *no value to be less than* acceptance criteria for compaction is specified.

Acceptance testing, based on a comparison of the density achieved in the field with that of some reference density established in a laboratory (usually maximum dry density), provides an indirect measurement of the performance of the compacted bank material.

Sections 16.8 to 16.13 describe the procedures to be followed when carrying out *acceptance testing* of field compaction. In considering these sections, it will be necessary to establish the quantifiable performance requirements for the work and the relevant test procedures for verification.

16.8 Compaction Control Acceptance Criteria

The designer should be conscious of not over-specifying the level of compaction required, simply for the sake of expediency. In some soils, eg expansive clay soils, over-compaction may actually impair subsequent performance. Furthermore, increasing the required relative compaction may result in substantial cost increases and possible delays in completion.

When a compaction *failure* is identified by testing during bank construction, the placed layer will have to be either ripped and re-compacted, or removed and the placement and compaction processes repeated. Re-testing of the effected area must then be carried out.

16.8.1 Moisture Content

Laboratory testing and field experience has shown that a Moisture Variation of between 2% dry and 2% wet of Optimum Moisture Content is generally acceptable for channel bank compaction.

16.8.2 Density

In most situations, the acceptance criteria for compaction is not specified as an absolute dry density but as a minimum relative compaction; for example*, a minimum of 95% of maximum dry density*.

Control over the density of channel banks involves the control of moisture content of the material being compacted and regular testing of the compacted material to ensure that the required density is being achieved.

Low permeability and high stability and erosion resistance are important criteria for channel banks, and this leads to a reasonably high target compaction of 95% to 98% of maximum dry density being specified for channel bank projects.

This percentage should be established for each project.

A field density of 95% of maximum dry density should provide adequate stability, erosion resistance and impermeability for most channel bank projects. Some difficult soils may require a field density of 98% of maximum dry density to overcome stability problems. Refer to Section 15, Material Selection and Testing.

In most soils, a much greater degree of compactive effort is required to achieve 98% as against 95% density, and the decision to specify higher levels of compaction needs to be soundly based.

In levees used for flood control, low permeability is important, but generally not as significant as in channel banks, and target compactions in the range of 90-95% of standard maximum dry density are often specified.

Soils that have pronounced expansive qualities sometimes tend to swell or heave if they are over-compacted. Therefore for certain soils, problems can be caused by over-compaction.

16.8.3 Quality Assurance

The application of quality assurance in civil earthworks is not straightforward, and there is a need for caution when applying quality assurance principles to channel bank earthworks. A technical overview of the work is required, with responsibilities and authorities clearly defined, and compliance auditing and check testing.

There is however no substitute for the use of proper construction equipment and experienced machine operators.

16.9 Compaction Specifications

A typical specification for channel bank compaction would be:

1. Material placed within the moisture range from 2% dry to 2% wet of the optimum moisture content obtained on the same material using AS1289.5.1.1-1993.
2. Field compaction to achieve a dry density not less than 95% of the maximum dry density as obtained on the same material using AS1289.5.1.1-1993.

A weakness identified in a number of irrigation authorities was the inappropriate use of specifications developed for other projects. Specifications have at times been taken from a previous project with different soil conditions and applied where the techniques do not adequately cover the type of material being used. Specifications need to be appropriate to each job and prepared with a full understanding of the soil conditions.

Refer to Section 15, Material Selection and Testing.

Tight specifications and construction tolerances add significantly to costs, and realistic requirements need to be established for general channel bank work. In some past situations, stringent specifications have been adopted that are really more appropriate to major earthworks projects, rather than the construction of channel banks that are typically not much more than one metre high. Where ever possible, the liberalisation and simplification of channel bank specification should be pursued to lower construction costs.

16.10 Compaction Equipment

16.10.1 Types of Equipment

There are many types of compaction equipment available, ranging from hand operated equipment through to high-speed self propelled rollers. Within the range of rollers there are a number of different types:

- Tamping foot rollers
- Grid or mesh rollers
- Vibrating rollers
- Smooth drum rollers
- Impact rollers
- Rubber tyred rollers

Combinations of these types are also available such as vibrating tamping foot roller.

There is no single item of plant able to compact all material – rock, clay, sand and gravels. In achieving density with cohesive soils the vibrating rollers are the least efficient and the high-pressure rubber tyred rollers the most efficient.

For channel banks low permeability is as much of a requirement as density and smooth drum rollers and rubber tyred rollers can lead to layering of the compacted bank with planes of high permeability at the interfaces of the layers. This does not occur with a tamping foot roller because of the mixing action of the long feet.

Grid or mesh rollers, smooth drum rollers, pneumatic tyred rollers and vibrating plate compactors are generally not suitable for channel bank construction.

Some irrigation authorities prefer channel banks to be compacted with a sheepsfoot roller. While sheepsfoot rollers will potentially achieve a high level of compaction, their restricted manoeuvrability on channel banks can be a problem, and their mixing action, while being very desirable in some soils, requires a large power input from the prime mover. Because of the high equipment operating costs, modified feet have been developed. These modified feet knead the soil in a similar fashion but with a much lower power requirement than the sheepsfoot roller. These modified tamping foot rollers can also compact a wider range of soils at a wider range of moisture content than sheepsfoot rollers.

Rather than universally using sheepsfoot rollers, the need and effectiveness for such equipment should be assessed on a project by project basis, depending on such factors as the soil types, size and scope of works, required compaction, cost and availability of equipment.

16.10.1.1 Tamping Foot Roller

Tamping foot rollers use a drum about 1 metre in diameter that is equipped with a large number of protruding feet to achieve compaction. These rollers come with a variety of feet shapes and sizes and include the traditional sheepsfoot roller for clay-type soils. The tamping foot roller is designed to achieve compaction through a combination of static weight and manipulation. The amount of contact pressure varies with the contact area of the feet and the weight of the roller.

Other types of tamping foot rollers use a somewhat different foot design than do sheepsfoot rollers. Generally, a tapered shank is used with a foot designed to minimise lateral displacement of soil during entry and withdrawal.

A tamping foot roller compacts under the feet and not under the drum. As the roller moves over the ground the feet penetrate into loose soil compacting it from the bottom up, and the roller rises to the surface or *walks out* of the ground as the soil becomes compacted. In most channel bank materials this usually takes place after about 8 to 10 passes of the roller depending on its size and the soil type.

Tamping foot rollers can achieve high densities and effectively compact troublesome soils. However, tamping foot rolling will not ensure success, unless the roller is able to apply sufficiently large pressure to produce a uniform distribution of density throughout each lift.

Laboratory testing and field experience has shown that foot pressures of at least 1.8 Mpa are necessary to ensure a uniform density throughout the layers. The foot size should also be as large as possible while developing the necessary minimum contact pressure.

If the foot pressure exerted by the roller is low, the lower sections of each lift will not be properly compacted, and the roller will walk out after a few passes.

Walking out does not necessarily mean that the soil is compacted, but only that the upper section is strong enough to support the roller. The water content of the soil also has to be high enough so that the soil does not develop enough strength to support the feet before compaction is complete.

The specification for a tamping foot roller may stipulate certain diameters, foot lengths and weights. Generally these include the:

- diameter of the drum – usually not less than 1 metre
- length of the drum – about 1.2 times the diameter
- size of the tamping feet – minimum length of 150mm for a 150mm loose layer
- weight of roller when fully ballasted

If a roller fails to walk out after a reasonable number of passes, it indicates that excessive shearing of the soil is occurring because either the contact pressure is too high or the moisture content of the soil is too high.

The tamping foot should be long enough to penetrate through the layer of soil and into the top of the layer underneath. The roller should be ballasted to the correct weight and the cleaning rack well maintained to prevent clogging of the tamping feet. When a tamping roller is operating properly it should sink right through the top layer. This indicates that it is working the bottom of the layer and the top of the previous layer.

Tests indicate little change in density due to change in rolling speed as long as tearing and displacement of soil do not become excessive. High-speed tamping foot rollers minimise such displacement. Speed is usually limited by tractor power and job conditions.

16.10.1.2 Vibrating Rollers

The effectiveness of vibrating rollers depends on the frequency and amplitude of vibration as well as on their static weight. The density obtained with a vibratory compactor depends on the travel speed and the number of passes. The allowable speed is determined by the soil type and desired depth of compaction as well as vibrator characteristics. Vibratory compactors are most effective on granular, non-cohesive soils. However, at low frequency and high amplitude they are also effective in cohesive soils. Vibrating compactors tend to dry out the soil, which can be an asset when working with moist soils.

Vibrating rollers have much greater ground contact areas and hence lower pressures. With the vibrator operating at correct speed the contact pressure is increased by the dynamic load of the vibrating mechanism. This increase in pressure is greater on hard surfaces than on soft ones, and the full quoted static plus dynamic load is unlikely to be achieved on clayey channel bank materials. However, penetration to the bottom of the layer can be achieved with appropriate selection of moisture content and layer thickness. Operation is very dependent on the vibrator operating at full speed. The cost of operating the roller and the difficulty pulling it is increased by operating the vibrator, so there is an incentive for an unsupervised contactor to slow down or stop the vibrator. The result of this will be inadequate compaction at the bottom of the layer with apparent compaction at the top.

16.10.1.3 Smooth Drum Rollers

In the cohesive soils used for channel bank construction, smooth drum rollers can cause layering and planes of weakness in the compacted bank. Therefore they are not commonly used in channel bank construction. However, smooth drum rollers have been used successfully on channel banks with thorough scarifying between each lift.

Smooth drum rollers are generally used either where a crushing action is required, as when compacting crushed rock, or where a smooth surface is required, when finishing the surfaces of channel linings.

16.10.1.4 Rubber Tyred Rollers

Rubber tyred rollers consist of a large number of pneumatic-tyred wheels, and are most effective in compacting fine-grained soils, including very fine sands.

Similar to smooth drum rollers, they can cause layering and are therefore not suited to channel bank construction.

16.10.1.5 *Non-Circular Impact Rollers*

The non-circular high energy impact rollers are a relatively new type of compactor. They are capable of compacting a broad range of soils over a wider range of moisture contents. In bank construction, permeability is just as important as density, and the flat drum of the roller can lead to laminations in the compacted bank with planes of high permeability at the interfaces of the successive layers. Impact compactors have non-circular drums that are drawn along at high speed, approximately 12-16 km/hr. As the drums rotate the corners on the non-circular slope raise the drum allowing them to fall to the ground onto the flat compacting faces. Use of this type of roller on new channel bank construction should be subject to on-site testing of effectiveness.

Earlier generations of Impact Compactors had four compaction faces on a single drum. Later versions of the Impact Compactor have dual drums with 3 and 5 compaction faces. The different ways manufacturers specify the rating of their impact compactors can make performance comparisons difficult.

Photos\compaction\impact compactor.jpg

Photo 16-1 Square towed Impact Compactor

Photos\compaction\landpac2.impact compaction.jpg

Photo 16-2 Three-sided Impact Compactor

16.10.1.6 *Self-Powered Compactors*

Self-powered compactors are a satisfactory substitute for standard towed rollers.

Photos\refurbishment\wakool3 compactor.jpg

Photo 16-3 Self-powered Compactor

16.10.1.7 *Bulldozer*

If the bank material is being obtained from the excavation of the channel, a bulldozer and if necessary a roller, can be used to spread and compact the bank material. If the bank material is coming from a borrow pit, dump trucks can be used to haul in the material. In these situations maximum use should be made of the truck traffic along the bank to aid compaction.

A bank, up to 2 metres high, may be able to be compacted to the required density using bulldozers to spread and compact the material, and loaded scrapers or dump trucks travelling along the bank to aid compaction, provided the material is at optimum moisture content, the material is non or low dispersive and the bank is built up in thin layers of no more than 150mm loose. A minimum of 6 to 8 passes of the dozer is likely to be required to achieve 95% of standard compaction. Use of bulldozers for compaction should be subject to on-site testing for effectiveness.

Some difficult and dispersive soil types may require a sheepsfoot roller for adequate compaction. Refer to Section 15, Material Selection and Testing.

Photos\construction\cg9 dozer spreading & trackrolling.jpg

Photo 16-4 Bulldozer

16.10.1.8 Compaction by Construction Traffic

Adequate compaction of channel banks by the traffic of loaded scrapers or trucks can be difficult to achieve and the economics would need to be looked at carefully. Layer thickness would have to reduced and additional passes of loaded scrapers or trucks would be required to achieve sufficient passes of the tyres over each portion of each layer.

Photos\refurbishment\shep1 truck dumping borrow.jpg

Photo 16-5 Truck dumping borrow material on bank

16.10.1.9 Grid or Mesh Rollers

Grid rollers are useful in breaking down oversized particles, and are limited to shallow lifts of non-sticky material.

16.10.2 Equipment Selection

Compaction equipment should be selected to yield the required density in minimum time and at a reasonable cost. The type of soil involved, the expected operating conditions and the availability of particular compaction equipment in the project area will govern the choice of equipment.

If tight control of moisture content can be achieved, a lighter compactive effort may be able to be used. In areas of high evaporation or frequent rainfall, tight control of moisture content is not practicable, and the moisture content range must be increased. This can only be tolerated if the compactive effort is also increased.

Once the compactive effort is determined, the structure and plasticity of the material will determine the suitability of the various types of compaction equipment available. On channel bank projects, equipment access to the bank area can be limited and the restricted manoeuvrability of rollers can impact on production rates.

Experience has shown that constructing a channel bank from a typical sandy clay soil in thin layers and at optimum moisture content, the maximum densities in Table 16-1 can be achieved.

Equipment	Standard Maximum Dry Density
Sheepsfoot roller	105 - 110%
Bulldozer and Loaded Scraper	95 - 100%
Bulldozer and Blade	90 - 95%

Table 16-1 Maximum Dry Density achieved by Equipment Type

These are rough averages and variations can be expected, but they provide some guidance on suitable equipment selection.

16.10.3 Compactor Operations

After the type of compaction equipment has been selected, it is necessary to determine the operational procedures to be used for compaction.

This involves determining the:

- optimum moisture content of the soil
- action necessary to change the soil's present moisture content
- lift thickness - thickness of each layer to be compacted
- compactor speed
- contact pressure and total weight
- number of passes

For vibratory compactors, the frequency and amplitude of vibration must also be considered.

16.11 Moisture Content Control Tests and Procedures

Moisture content control is critical in achieving adequate compaction.

Moisture Content Control occurs in four steps:

1. Determine Optimum Moisture Content
2. Determine Field Moisture Content
3. Determine Moisture Variation
4. Check moisture content conforms with the specification

16.11.1 Determine Optimum Moisture Content

The moisture content of the material being compacted should be controlled at or as near as possible to the *Optimum Moisture Content* to achieve the highest density for the compaction effect. Refer Section 16.12.1.

Optimum moisture content for compaction depends not only on the type of soil, but also on the type and weight of compaction equipment used. For most channel bank projects, it is practical to assume that the standard laboratory compactive effect reasonably duplicates the field compactive effort and vice versa. Perfectly correct values of maximum density and optimum moisture content can be determined only by setting up field test sections using the chosen compaction equipment. This is sometimes done on large earthworks projects, but is rarely justified on most channel bank projects.

16.11.2 Determine field moisture content

The actual moisture content of a sample from a bank can be determined by:

1. Drying the soil

Moisture content is determined in accordance with the Determination of the moisture content of a soil - Oven-drying method (AS1289.2 1.1-1992), or any of the subsidiary methods listed below:

- Sand Bath Method (AS1289.2.1.2)
- Microwave Oven Method (AS1289.2.1.4)
- Infrared Light Method (AS1289.2.1.5)
- Hotplate Drying Method(AS1289.2.1.6)

The oven-drying method has an accuracy of 0.1%. Its main disadvantage is that is a relatively slow process. The subsidiary tests are faster but should only be used when a quick result is required or an oven as specified in (AS1289.2.1.1-1992) is not available.

2. Nuclear Surface moisture-density gauge (AS1289.5.8.1-1995)

The Nuclear Gauge (AS1289.5.8.1-1995) can be calibrated to measure moisture content as well as density.

3. Time Domain Reflectometry

Time Domain Reflectometry equipment has found some application for construction moisture content determination. Despite the expense of this equipment (similar in cost to the Neutron Probe) it is recognised to be more accurate than neutron gauges for shallow moisture content determination and can be used insitu without sampling.

16.11.3 Determine Moisture Variation

The moisture variation can be determined by normal methods or by relative tests that do not determine an actual field moisture content or optimum moisture content.

16.11.3.1 Normal Method

The Normal Method of determining Moisture Variation (AS1289.5.4.1-1993) is by comparing an actual field moisture content with the Optimum Moisture Content for that sample.

16.11.3.2 Nuclear Surface moisture-density gauge

Generally the moisture content determined by the gauge is not considered accurate enough to calculate the moisture variation of the material from optimum within the accuracy requirements of the Australian Standard. However, if calibrated carefully for a homogenous soil type it can be used successfully for moisture content control purposes in the field.

16.11.3.3 Hilf Method

The Hilf Method (AS1289.5.7.1-1993) calculates a *moisture variation* percentage from the Optimum Moisture Content. Refer Section 16.12.3.3.

16.11.4 Moisture Content Control

Before material is placed on the bank the *moisture variation* from Optimum Moisture Content should be within the specified limits. For channel bank projects this is typically ± 2% of optimum.

Unless the *moisture content* of the borrow material is fairly uniform and within the specified range, the possibility of achieving the density requirement is remote. If the moisture content in a compacted layer is outside the limits and the fill should be loosened by ripping to full depth and moistened (too dry) or aerated (too wet) as necessary.

As far as practicable, the material should be brought to a uniform optimum moisture content in the borrow pit, prior to delivery to the bank.

Bank construction is best undertaken at the time of year when the natural soil moisture of the available bank material is close as possible to the optimum. Late spring, autumn or early winter are usually the best times. Construction is often difficult in mid-winter because sites are too wet, and the soil can be too dry during mid-summer.

If the soil is *too dry*, it can be wetted and conditioned by spraying with water at the borrow pit or by supplementary wetting during placement on the bank, as appropriate. Improved mixing of water will result if applied at the borrow site a few days before the soil is to be used.

Photos\borrow pits\shep5 excavator mixing borrow wet&dry.jpg

Photo 16-6 Excavator mixing wet and dry borrow material

If the soil is *too wet*, it must be allowed to dry out. If wet conditions are experienced during construction, this may mean that works are halted for a period of time to allow the material to dry before continuing with compaction. If soil is placed in too wet condition, it will be difficult to achieve the required density and failure of the bank may result.

Any major adjustments (greater than 1%) to water content should be carried out at the borrow area, at least 24 hours and up to one week before hauling of the adjusted soil to the bank. Minor adjustments of water content can be made on the bank prior to compaction. No standing water should be permitted on the bank.

For most soils used in channel banks the chances of achieving the required density are considerably enhanced if the fill is placed on the wet side of, rather than the dry side of optimum.

Care should be taken to ensure that the material has an even moisture distribution throughout each layer. Difficulty will be experienced in achieving good compaction if the moisture content varies more than 2% within a layer.

Material having a placement moisture content of more than 2% dry of optimum condition or more than 2% wet of the optimum condition should be rejected and removed or reworked until the moisture content is within these limits.

16.11.4.1 *Increasing Water Content*

In many instances, water must be added to the soil before it is compacted. When adding water to the material it should be noted that:

1. Pressurised sprinkling systems are better for increasing water content and attaining more even distribution because they have a penetrating action.

2. Blending may be necessary, too, by harrowing or plowing to give uniform absorption of water and break the dry lumps. Where there are lumps, it may take several days of curing for the water to be absorbed properly. The breaking down of lumps in borrow pits ensures maximum water penetration.

3. In arid regions, where the natural water content of soils in borrow areas is often 10 to 15 percent below optimum, it is more effective and economical to irrigate at the borrow pit and allow a week or more for penetration and curing before hauling the material to site.

4. It is important that the water is given time to soak in and so ensure an even distribution of moisture throughout the soil. This can be done by watering well in advance of excavation. Ripping or ploughing before watering can help even distribution. The use of alternative borrow pits can also help to provide sufficient time to achieve an even water distribution.

16.11.4.2 *Decreasing Water Content*

It is usually easier to add water to a dry soil than to reduce water content in a wet soil. The amount of difficulty in lowering the water content is dependent on the fineness and plasticity (permeability) of the soil and on the severity of the rain cycle.

If the construction period is not excessively rainy, wet materials can sometimes be dried by ripping or plowing to aerate the soil and evaporate the excess water. This is relatively easy for silty and sandy soils but difficult for clays as they tend to dry in hard clods and are difficult to process. Again, it is more effective and economical to prepare the soil in the borrow pit rather than on the bank.

If material too wet for proper compaction has been placed on the bank, it should either be worked with harrows to reduce the moisture content to the amount specified, allowed to dry until such time as the material contains only the specified moisture, or the material should be removed from the bank.

Some pointers:

1. Grade and compact the surface of the borrow area to prevent rain puddling and seepage into the material.
2. Provide drainage for the material in its natural state or place the material in windrows (piles) where practical.
3. Slope the construction surface.
4. Compact in a direction to facilitate drainage of the construction surface.
5. Compact the material as soon as possible after placement to minimise exposure to rainfall.

16.12 Density Control Tests and Procedures

Construction Control of Density occurs in four steps:

1. Establish a Maximum Dry Density (also referred to as a *Reference Density*)
2. Determine Field Density
3. Determine Relative Density
4. Check relative density conforms with the specification

16.12.1 Establishment of Maximum Dry Density for calculation of relative compaction

The Maximum Dry Density is also referred to as the *Reference Density*.

To permit relative compaction to be calculated, it is necessary to establish a maximum dry density. Procedures for establishing such maximum dry densities have been developed empirically over many years and standardised with the Australian Standard test procedures of:

AS 1289.5.1.1-1993 *Determination of the dry density/moisture content relation of a soil using standard compactive effort*

AS1289.5.2.1-1993 *Determination of the dry density/moisture content relation of a soil using modified compactive effort*

AS1289.5.7.1-1993 *Compaction control test – Hilf density ratio and Hilf moisture variation (rapid method)*

AS1289.5.5.1-1998 *Soil compaction and density tests – Determination of the minimum and maximum dry density of a cohesionless material – Standard method*

In each of the above procedures, a *maximum dry* density is obtained. It must be appreciated that these do not represent the maximum achievable, but that which can be achieved using the test procedures outlined.

A sample of soil is required to determine the maximum dry density for that particular soil at Standard Compaction. This is achieved in the laboratory by determination of the Dry Density/Moisture relation of a soil (AS1289.5.1.1-1993). This is also known as a Proctor Test. This standard impact compaction test determines the moisture content at which the soil will achieve maximum dry density (reference density) with the minimum compactive effort. In this test at least five samples of a soil are mixed with a varying amount of water. Each sample is then compacted with 25 blows of a standard hammer. The density of each sample is then measured.

A graph plotting final density against moisture content is plotted and a curve applied as shown in

Figure 16.2. The top of the curve corresponds to the Maximum Dry Density and Optimum Moisture Content for that sample. The disadvantage with this procedure is that the conditioning and testing can take up to a week. This is obviously impracticable for control of construction.

There are two forms of this test: *Standard Compaction* and *Modified Compaction*. When determining Maximum Dry Density, only Standard Compaction (AS1289.5.1.1-1993) is referred to in this document. Laboratory testing and field experience has shown that the moisture-density relationships produced by the Standard Laboratory Compaction test correlates reasonably closely with most channel bank field compaction procedures using the fine grained cohesive soils typical of earthen channel banks. Therefore the *Standard Compaction* test is used for compaction testing of earthen channel banks.

Modified Compaction (AS1289.5.2.1-1993) is typically used for road pavement gravels and granular materials of low plasticity where high design loads will be encountered. The compactive effort for the modified test is more than four times as great as for the standard test and this yields a greater soil density.

16.12.2 Field Dry Density

For density control, it is necessary to determine soil density actually obtained in the field and compare this with the specified soil density.

Determination of field dry density can be carried out by direct or indirect methods.

Direct methods measure *actual* density. These methods are specified in:

AS1289.5.3.1-1993 *Determination of the field density of a soil – Sand replacement method using a sand-cone pouring apparatus*

AS1289.5.3.2-1993 *Determination of the field dry density of a soil – Sand replacement method using a sand pouring can, with or without a volume displacer*

AS1289.5.8.1-1995 *Determination of field density and field moisture content of a soil using a nuclear surface moisture-density gauge – Direct transmission mode*

AS1289.5.3.5-1997 *Determination of the field dry density of a soil – Water replacement method*

Indirect methods provide an empirical measure of achieved density by measurement of another engineering property, principally shear strength. The methods include those specified in:

AS1289.6.3.2-1997 *Soil strength and consolidation tests – Determination of the penetration resistance of a soil – 9kg dynamic cone penetrometer test*

AS1289.6.3.3-1997 *Soil strength and consolidation tests – Determination of the penetration resistance of a soil – Perth sand penetrometer test*

AS1289.6.5.1-1999 *Soil strength and consolidation tests – Determination of the static cone penetration resistance of a soil – Field test using a mechanical and electrical cone or friction-cone penetrometer*

Correlation with local materials and conditions is required. Such correlation should include the effects of depth/confining pressure, moisture content, material type and local conditions when comparisons with direct methods are proposed.

The specification should designate which test procedure governs acceptance.

A summary of current Australian Standard methods with their main advantages and disadvantages can be found in Table 16-2.

16.12.2.1 Sand Replacement Method

The Sand Replacement method uses a very uniform sand to measure the in-place volume of a sample taken from the bank (by measuring the volume of the hole produced). The sample is measured for its wet mass and moisture content to enable insitu wet and dry density to be calculated.

Advantages:

- Well-trained operators can obtain very accurate results
- No *technology breakdown* can occur as it is a manual process

Disadvantages:

- Cannot be performed while compaction equipment is being operated that may produce sub-surface vibrations
- Takes 3-4 times as long to perform than the nuclear method
- Results take time to calculate and require access to laboratory facilities
- Conducting the test under wet conditions is difficult
- Potential for operator errors in its field application

16.12.2.2 Nuclear Surface Moisture-Density Gauge

A common method used in Australia for determining the field density of fine-grained cohesive soils is the nuclear method using a *Nuclear Surface Moisture-Density Gauge* (AS1289.5.8.1-1995). The nuclear gauge can be calibrated and used to measure field density in increments of 25 or 50mm and over depths of up to 300mm.

In simplified terms, the gauge measures the field density of the soil by counting the number of protons that pass from the nuclear source (cesium-137) to the detectors within a given time period. The gauge also measures the *thermalization* of the neutrons emitted from the source and this is calibrated to measure the apparent moisture content of the soil. Most gauges are computed to interpret the above reactions to give:

- Wet Density
- Dry Density, and
- Moisture Content

Table 16-2 Comparison of Field Density Testing methods

Testing Method	Method Type	Australian Standard	Advantages	Disadvantages	Training Requirement	Calibration Needs	Capital Costs	Operating Costs
Sand Replacement Sand Cone	direct	1289.5.3.1-1993 1289.5.3.2-1993	Relatively Accurate	• Cannot use with operating equipment • Slow • No good for wet soils	Minimal	Minimal	Field $500 Lab. $3000	Medium
Nuclear Surface Gauge	direct	1289.5.8.1-1995	Rapid results	• Cost and need for frequent calibration • Operator Safety	Advanced	Two years	$11,000	High
Hilf Rapid Method	indirect	1289.5.7.1-1993	Conventional and Fast	• Requires specialist laboratory equipment • Limited applicability of wet soil	Medium	Annual	Field $3,000 Lab $4,000	Medium
Soil strength and consolidation –9kg dynamic cone penetrometer test	density indicator test only	1289.6.3.2-1997	• Indication of density with depth • Rapid	Cannot be directly correlated with measured density	Minimal	Minimal	$400	Low

Operating Costs are defined as:

	HIGH	$750-$1000
	MEDIUM	$250-$750
	LOW	$250

The main advantages of the Nuclear Gauge for field density testing are:

- When properly calibrated and operated nuclear gauges display excellent correlation with more traditional methods. Their main advantage is that dry density can be measured in a fraction of the time required by conventional methods.
- Quick insitu readings
- Minimal operator error when used by well-trained, experienced staff
- Able to be operated while compaction equipment continues to operate nearby
- Can be operated under wet conditions

However, there are some major disadvantages which may preclude the use of this technology by small to medium irrigation authorities as follows:

- Cost of machine ($8,000 - $10,000)
- Operators require extensive training
- Requirement for frequent calibration
- Safety of operators
- Displayed readings can be misinterpreted by poorly trained operators
- Cannot operate in prescribed nuclear-free areas
- Need to have licensed operators in some states
- Limitations in confined areas such as trenches

16.12.3 Relative Density

The soil density required for a channel bank project is usually specified as a percentage of the maximum density obtained for that soil in a standard laboratory test.

The relative density can be determined by three methods:

1. Normal Method (AS1289.5.4.1-1993)
2. Nuclear Surface moisture-density gauge (AS1289.5.8.1-1995)
3. Hilf Method (AS1289.5.7.1-1993)

Refer to Table 16-2.

16.12.3.1 Normal Method

The normal method (AS1289.5.4.1-1993) compares field dry density with the laboratory compaction maximum dry density to obtain a *relative density*.

16.12.3.2 Nuclear Surface moisture-density gauge

A maximum dry density for each sample is required. If material being compacted is homogeneous (from the same borrow pit and well-mixed) the relative density can be calculated on site without requiring samples to be taken from the bank.

16.12.3.3 Hilf Method

The Hilf method (AS1289.5.7.1-1993) compares field wet density with the maximum calculated wet density achieved in the laboratory standard compaction.

The Hilf Density Ratio = Field Wet Density / Maximum Wet Density

This is a relatively rapid technique for determining moisture variation as no drying is required. A result can normally be obtained within two hours.

A typical Hilf Density Ratio Report is shown in

Figure 16.4.

The main advantage of the Hilf Test for density control is where a maximum wet density can be assigned to a relatively homogenous material, say well-mixed material from one borrow pit. Therefore a maximum dry density is not required for each field dry density sample. However a maximum dry laboratory test (maximum wet density) is required wherever homogeneity cannot be assured.

16.12.4 Density Control

The Relative Density must conform to the specification. If it does not, the compacted layer of material must be ripped up and be re-compacted.

If the Normal Method (AS1289.5.4.1-1993) of Density Control is being used, a Maximum Dry Density should be determined for each sample tested. However, if material is reasonably homogeneous and from the same borrow pit a Maximum Dry Density may be determined for a particular borrow pit. However with any visible changes to the material, Maximum Dry Density will have to be determined more frequently.

16.13 Soil Strength and Consolidation Tests (Penetration Tests)

Soil Strength and Consolidation tests are generally designed to evaluate the strength of undisturbed earth for footings and piles. However they can be used as an indirect test for density, if the moisture content and material composition is uniform.

The Dynamic Cone Penetrometer Test (AS1289.6.3.2-1997) could potentially be used for compaction control on channel banks. The instrument is manually operated and involves dropping a constant mass (9kg) on a rod of fixed length (600mm) which transmits the force to the ground via a 20mm diameter steel cone attached to the end of a 16mm diameter rod. The penetration depth is then plotted against number of drops of the weight.

The Research project for this Manual trialed a Dynamic Cone Penetrometer (DCP) for indicating the density of channel bank construction. However, it was found to be unsatisfactory because if the standard test method was followed, the 150mm compacted layer was penetrated in 2 to 3 blows. This gave insufficient information to correlate the results to actual density.

The apparatus could be modified by reducing the weight to say 4.5kg or 2.25kg. This would mean that the number of blows would be increased, therefore improving the correlation to actual density. However this would mean that the test would not conform to Australian Standards, and is therefore not recommended.

The advantages and disadvantages of the DCP for use in compaction control of earthen channel banks are shown in Table 16-3.

Hilf Density Ratio Report

Client :	EXAMPLE ONLY	Report Number:	DNR99/123 - 1
Job Number :	DNR99/123	Report Date:	16/12/1999
Project :	EXAMPLE ONLY	Order Number:	
Location :	EXAMPLE ONLY,	Test Method:	AS1289.5.7.1&5.3.1

Lab No :	AY99/164	AY99/165		
ID No :	425	425		
Lot No :	12	12		
Item No :	16	16		
Date/Time Tested :	15/12/1999	15/12/1999		
Material Source :	Insitu	Insitu		
For Use As :	Embankment	Embankment		
Sample Location :	Road: Trial Section #1 CH: 6543m OS: 1.5m L RL: FSL	Road: Trial Section #1 CH: 4865m OS: 2.5m L RL: -0.5m FSL		
Test Depth (mm) :	150	175		
Max Size (mm) :	19	19		
Oversize Wet (%) :				
Fld. Wet Density (t/m^3):	1.86	1.91		
Fld. Moisture Cont (%):	10.4	14.2		
PCWD (t/m^3) :	2.00	2.06		
Moisture Variation (%):	2.5	0.0		
Compactive Effort :	Standard	Standard		
Hilf Density Ratio (%) :	93.0	92.5		
Min Hilf Dens Ratio (%)	95	95		
Remarks:	Test locations selected by client			

Lab Number:	Soil Description
AY99/164	Sandy Clay (CI) Brown
AY99/165	Sandy Clay (CI) Brown

This Laboratory is accredited by the National Association of Testing Authorities, Australia. The test(s) reported herein have been performed in accordance with its terms of accreditation. This document shall not be reproduced except in full.	APPROVED SIGNATORY Nata Accred. No: 3201	Form Number:

Figure 16.4 Hilf Density Ratio Report

The Dynamic Cone Penetrometer is not recommended for Density Control due to the problems with correlating this test to density. Other Australian Standard penetration tests are not suitable for compaction control due to cost and/or practicality.

Advantages	Disadvantages
Cost – instrument relatively cheap to purchase. **Robustness** – The instrument is sturdy. It is suitable to be carried around in the back of a utility. **Ease of Use** – testing method is simple, requiring little training of users. **Time** consumed in testing is minimal. **Speed of Results** – very few calculations are required with this device. Once calibrated, an indication of density could be given.	Cannot be directly related to density or relative density. Using the Australian Standard method the cone penetrates a 150mm layer of material in 2 to 3 blows. This does not give enough information to correlate the results to actual density**.** **Inconsistency of results -** Readings from the test are influenced by variations in moisture content. **OH&S concerns** • With a one metre shaft, it was found that the 9kg weight would have to be lifted up to 1.6 metres above ground level, which was hard for some shorter operators. • The tester may also have difficulty carrying apparatus long distances due to the weight of the 9kg hammer as well as the shaft.

Table 16-3 Dynamic Cone Penetrometer – Advantages & Disadvantages

16.14 Testing and Reporting

To assess whether the specified requirements are being achieved, inspection and testing at regular and appropriate intervals is required having due regard to the nature of the work and the specification. Such inspections should be carried out by personnel experienced and knowledgeable in earthworks.

16.14.1 Sampling

16.14.1.1 Borrow Pit Samples

When samples are taken from potential borrow pits (refer Section 15, Material Selection and Testing) enough of each sample can also be taken to determine the field moisture content, Optimum Moisture Content and Maximum Dry Density of the material. This will give an indication before construction commences of what moisture conditioning the material may require, and give an indication of what optimum moisture content and maximum dry density will occur during compaction testing of the channel bank.

16.14.1.2 Compacted Channel Bank samples

Samples should be cut with an auger to a depth of at least 150mm (depth of layer) and sealed in a plastic bag. The bag should be marked and the sample recorded on a log sheet. Refer to

Figure 16.4. Test results can then be recorded on the same log sheet.

The location and test results for every sample should be recorded on an appropriate summary sheet to enable the construction manager to adjust the compaction procedures in light of overall trends. It is important that sampling and testing is carried out very soon after compaction so that:

- inferior work can be ripped and re-compacted with moisture adjustment if necessary, without major disruption to subsequently placed earthworks.
- sample does not lose moisture by evaporation before testing

16.14.1.3 Maximum Dry Density Samples

For routine compaction testing, the sample for determination of the maximum dry density should comprise the material recovered from the field density determination. In most instances, this mass of soil will be insufficient to allow satisfactory completion of the maximum dry density test so additional material should be recovered from immediately around the zone in which the field density determination was made.

The preparation of maximum dry density samples should be carried out in accordance with AS3798, Section 7.7. This may incur a period of conditioning.

The Hilf rapid compaction method (see AS1289.5.7.1), allows the test to be performed without conditioning provided the moisture content of the test sample is within the range of –4% to +6% of optimum moisture content (standard compactive effort). For materials with moisture contents outside these limits, conditioning for a prolonged time will generally be necessary.

16.14.2 Testing

The frequency and level of testing needs to be appropriate to each channel bank project.

The frequency of testing of density and moisture content is generally related to the rate at which material is being placed, the frequency with which changes in moisture content are required and the difference between the target and actual compaction being achieved.

For low risk works, samples should be taken at least daily to determine compaction and moisture content. Medium to high risk channel banks may require more extensive testing. This may include testing of every layer at nominated intervals along the bank.

Testing is expensive and time-consuming. Therefore, the frequency and extent of testing should be carefully chosen to assess compliance, without adding unnecessary costs or delays.

A guide to the required frequency of testing for channel bank projects adapted from AS3798 is given in Table 16-4. In variable or difficult conditions, more frequent testing may be required. These testing frequencies relate to acceptance on a *not one to fail* basis.

Type of Earthworks		Frequency of tests
Type	Description	
1	Large-scale operations	Not less than 1 test per 500m^3 of material laid, distributed reasonably evenly throughout full depth and area, or one test per day, whichever comes sooner.
2	Small scale operations	Not less than 1 test per 200m^3 of material laid, distributed reasonably evenly throughout full depth and area, or one test per day, whichever comes sooner.
3	Concentrated operations	Not less than 1 test per 100m^3 of material laid, distributed reasonably evenly throughout full depth and area, or one test per day, whichever comes sooner.
4	Confined operations (eg filling behind structures)	1 test per 2 layers per 50m^2 of material laid or one test per day, whichever comes sooner.
Note:	Tests in areas of uncertain compaction and re-tests of failed areas should be carried out. These are additional to the testing recommended in this Table.	

Table 16-4 Guide to Frequency of Field Density Tests
(Adapted from Table 8.1 of AS3798)

For channel bank projects requiring more than just a few tests to check compliance, the testing should be carried out in a number of randomly chosen locations and at the frequencies given in Table 16-4. However, for small projects, it may be appropriate to undertake testing in specific locations, based on visual appearance or past experience (eg compaction may be more difficult to achieve adjacent to existing structures).

In general, the test procedure for determination of relative compaction should not be varied for a given soil type by using more than one test procedure for either field density or maximum dry density. In particular, control of moisture content, relative to optimum moisture content determined in accordance with AS1289.5.7.1, should not be included with or compared to those determined in accordance with AS1289.5.1.1 and AS1289.5.2.1 as different results may be obtained. The use of different test procedures may be misleading for some clays of high plasticity.

16.14.2.1 Level of Maximum Dry Density Testing

AS1289.5.4.1 requires that a maximum Dry Density value be determined for each field density determination, except where the material being tested is sufficiently uniform in its particle size distribution, composition and compaction characteristics.

It is recognised that the Maximum Dry Density Testing imposes demanding requirements upon routine construction control testing resources. Where limited maximum dry density testing is permitted by the specification, it is essential that particular care be taken to compare the test results from like materials. Under no circumstances should samples of material taken from two or more field dry density test sites be combined and then used for the laboratory compaction. The result of such a laboratory test will lack relevance to the field tests from which the combined samples originated.

Refer to AS3798, Section 7 for guidelines on when considering reducing the number of Maximum Dry Density tests.

16.14.3 Reporting and Records

Test reports should include the curing procedures and sample preparation procedures adopted.

The results of the Australian Standard Tests used should be recorded on a log sheet. A typical log sheet used for the Hilf test is shown in

Figure 16.4. The Moisture Variation, Optimum Moisture Content, Field Moisture Content, Relative Density, Maximum Dry Density and Field Density should be recorded as applicable.

16.14.4 Testing Supervision

The intensity of geotechnical testing supervision may be identified at three alternative levels of responsibility, as follows from Appendix B of AS3798.

Level 1 - A geotechnical testing authority provides a full-time inspection and testing service on all earthworks (including stripping, proof rolling and associated operations) and decides the locations and timing of sampling and testing operations.

Level 2 - A geotechnical testing authority carries out sampling and testing as required or specified. The geotechnical testing authority is responsible for selecting the timing and location of sampling and testing operations within each visit made to the site. The superintendent advises when such visits are required and ensures that sufficient samples and tests are taken over the project.

Level 3 - A geotechnical testing authority carries out testing as, where and when requested by the superintendent (or possibly by the constructor), who will be responsible for the extent of testing and for recording the locations and levels from which samples and tests were requested.

16.14.5 Statistical methods of acceptance testing

Earth materials are inherently variable. Thus the density and moisture content of a channel bank will vary from any one location to other locations, even if considerable care is taken to attempt to achieve a uniform result.

The *not any to fail* specification commonly applied to channel bank projects is based on a successful history of producing suitable banks and only indirectly accounts for the inherent variability. *Statistical* methods have been applied to earthworks, in attempt to quantify the variability. In Australia, such schemes have found their main use in larger road construction projects.

In large volume earthworks, the amount of testing for field moisture content and density may be considerable. More efficient use of testing may be made by applying statistical methods to selection of test sites and to the test results.

Appendix D of AS3798 provides guidelines which may be used to develop suitable statistical specifications for channel bank earthworks.

16.15 Acceptance of Test Results

The following acceptance criteria can be used as a general guide in interpreting channel bank test results:

1. If the moisture content is within permitted range and the density requirement is equal or exceeded – Accept.

2. If the moisture content is up to 1% outside the permitted range and the density requirement is equalled or exceeded – Accept only after consideration of the material characteristics and risks involved.

3. If the moisture content is within the permitted range and the density result is up to 2% below requirements – Order additional compaction of the placed layer, and re-test before acceptance.

4. If the density is low – Reject.
   To achieve the required density, some or all of the following actions will be necessary:

   - loosen the placed layer to full depth, moisten or aerate as necessary, reduce layer thickness and undertake complete re-compaction.
   - remove the placed layer, stock pile the material, re-condition and repeat the lay down and compaction processes.

If the moisture content is drier than the lower limit by more than 1%, additional passes are unlikely to achieve required density. It will only compact the upper portion of the layer, without correcting the lower portion.

If the moisture content is wetter than the upper limit by more than 1%, additional passes may achieve the required density, provided the re-working can reduce the moisture content sufficiently to raise the density to the required level. Re-test before acceptance.

The compaction of material in too dry a condition has been found to be one of the main reasons for poor channel bank performance. This is attributed to the ease of handling materials on the dry side of optimum, and the tendency for the moisture content to drift outside the lower limit during the drier parts of the year when earth works are most frequently undertaken.

No amount of compaction will produce the required density if the material is too dry. The compacted material may be very hard, but hard fill does not necessarily mean that the required density has been achieved. A sample of clay which may have a strength approaching that of a weak concrete when it has been dried, can become mud when immersed in water.

For channel banks, where construction pore pressures are normally not a concern, the chances of achieving the required density are increased if the material is compacted on the wet side rather than on the dry side of optimum. By adopting this approach, a factor of safety is introduced against placing large quantities of dry material. Sufficient time becomes available to detect the drying out, which can be offset by pre-wetting in the borrow area, rather than attempting to make moisture adjustments on the bank.

16.16 Tests for small projects

The scope of investigation and testing carried out is usually proportional to the size of the project. The Australian Standard methods can be expensive and time consuming, requiring skilled laboratory operators with the necessary well-maintained and calibrated equipment. A large channel project would justify the expense of detailed investigation and laboratory testing, but on a small project, laboratory testing facilities may not be available.

There is a view that the level of testing used on large channel projects cannot be justified on small low cost projects. While this may be the case in some situations, it is not just the size or the cost of the channel works that should be the deciding factor, but rather *the consequences of a channel failure*. The total potential damage and economic loss that may result from a failure of the channel bank also needs to be considered.

Where laboratory testing facilities are not readily available and the risk is assessed as low, the following simple *field indicator tests* of moisture and compaction may be useful. However, satisfactory results from these tests require a degree of skill and experience, and testing conducted by inexperienced staff should be treated cautiously. Confidence in these testing procedures is improved where the results are periodically checked with laboratory tests, and the operator receives confirmation of their field testing.

16.16.1 Optimum Moisture Content

Two simple tests to approximately determine the moisture content are the *Pencil Test* and the *Squeeze Test.*

The *Pencil Test* is carried out by rolling the soil into the thickness of a pencil (5mm). The *Squeeze Test* is carried out by squeezing a handful of the soil into a ball. An indication of how the results of each test translates to compaction behaviour in given in Table 16-5.

16.16.2 Compacted Bank Density

16.16.2.1 Steel Rod Penetration Test

An approximation of the relative compacted density can be made by driving a 12mm steel rod, eg reinforcing bar, into the compacted material. The interpretation which can be obtained from this test is shown in Table 16-6.

16.16.2.2 Operator experience

Experienced bulldozer operators can sometimes know by the *feel* of the bulldozer tracks running over the bank material (ie the deformation of the bank), whether sufficient passes have occurred. Other methods of testing, such as digging heels into the top surface and bouncing golf balls are highly questionable, and should not be relied upon.

16.16.2.3 Method Specification

With small projects it may be appropriate to assign a method specification (refer Section 16.7.2), where the moisture condition of the material and the number of passes of compaction equipment of the bank is stipulated in the specification.

Pencil Test	**Squeeze Test**	**Compaction Behaviour**
Rolls to pencil (5mm dia) before crumbling. If rolled any thinner will just begin to crumble.	Stays together – no water can be squeezed out in the hand – maintains its dense structure after opening the fist.	Approximately at optimum for compaction
Rolls very fine without crumbling or smears without rolling	Sticks to the hands	Too wet for compaction (above optimum)
Crumbles and will not roll	Will not cohere	Too dry for compaction (below optimum). If heavy clay, added moisture will not distribute evenly or quickly, and care must be taken when adding water to ensure that it is mixed throughout the clay. This is often best achieved in the borrow area.

Table 16-5 Moisture Content Indicator Tests

Field Test	**Relative Density %**
Easily penetrated with 12mm steel rod pushed by hand	0-50
Easily penetrated with 12mm steel rod driven with a 2kg hammer	50-70
Penetrated 30cm with 12mm steel rod driven with 2kg hammer	70-90
Penetrated only a few centimetres with 12mm steel rod driven with a 2kg hammer	90-100

Table 16-6 Steel Rod penetration test

16.16.2.4 Drop Test

The Drop Test was designed as a quick method to test embankments in on-site mobile laboratories. It requires a large number of samples to be tested at varying moisture contents to determine a standard set of curves which are then established for a particular borrow site or regional soils.

This test was used by the State Rivers and Water Supply Commission of Victoria for much of the channel construction which occurred in the 1960's in northern Victoria. It is still being used to the present day in re-construction and new channel construction works.

The advantages of the Drop Test are:

- Quick Results
- Relatively cheap
- Can be performed with minimal training

The main disadvantages are:

- Need for accurate curves before method can be applied
- Only applicable to cohesive soils
- Determines relative moisture content, not actual.

16.17 Australian Standards

AS1289.2.1.1-1992	*Determination of the moisture content of a soil – Oven drying method (standard method)*
AS1289.2.1.2-1992	*Determination of the moisture content of a soil – Sand bath method (subsidiary method)*
AS1289.2.1.4- 1992	*Determination of the moisture content of a soil – Microwave-oven drying method (subsidiary method)*
AS1289.2.1.5-1992	*Determination of the moisture content of a soil – Infrared lights method (subsidiary method)*
AS1289.2.1.6-1993	*Determination of the moisture content of a soil – Hotplate drying method (subsidiary method)*
AS1289.5.1.1-1993	*Determination of the dry density/moisture content relation of a soil using standard compactive effort*
AS1289.5.2.1-1993	*Determination of the dry density/moisture content relation of a soil using modified compactive effort*
AS1289.5.3.1-1993	*Determination of the field density of a soil – Sand replacement method using a sand-cone pouring apparatus*
AS1289.5.3.2-1993	*Determination of the field dry density of a soil – Sand replacement method using a sand pouring can, with or without a volume displacer*
AS1289.5.3.5-1997	*Determination of the field dry density of a soil – Water replacement method*
AS1289.5.4.1-1993	*Soil compaction and density tests – Compaction control test – Dry density ratio, moisture variation and moisture ratio*
AS1289.5.4.2-1993	*Soil compaction and density tests – Compaction control test – Assignment*
AS1289.5.5.1-1998	*Soil compaction and density tests – Determination of the minimum and maximum dry density of a cohesionless material – Standard method*
AS1289.5.7.1-1993	*Compaction control test – Hilf density ratio and Hilf moisture variation (rapid method)*
AS1289.5.8.1-1995	*Determination of field density and field moisture content of a soil using a nuclear surface moisture-density gauge – Direct transmission mode*
AS1289.6.3.1-1993	*Determination of the penetration resistance of a soil – Standard penetration test (SPT)*

AS1289.6.3.2-1997	*Soil strength and consolidation tests – Determination of the penetration resistance of a soil – 9kg dynamic cone penetrometer test*
AS1289.6.3.3-1997	*Soil strength and consolidation tests – Determination of the penetration resistance of a soil – Perth sand penetrometer test*
AS1289.6.5.1-1999	*Soil strength and consolidation tests - Determination of the static cone penetration resistance of a soil - Field test using a mechanical and electrical cone or friction-cone penetrometer*
AS3798-1996	*Guidelines on earthworks for commercial and residential developments*

16.18 References

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17. Protective Cover

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17.1 Introduction

It is important that the finished surface of the compacted earthen bank be covered as soon as possible after construction is completed. This *Protective Cover* is required over the exposed crest and outside batter of the compacted bank to maintain moisture content and to minimise deterioration caused by:

- drying and surface cracking of the compacted bank
- piping or tunnelling failure of dispersive soils
- sheet erosion or rilling caused by rainfall runoff
- stock, vehicles and farm operations

Physical damage to the bank by stock and farm operations can be controlled by longitudinal fencing of banks, however this is not always practical. A protective cover over the channel bank may reduce damage that is caused by these activities.

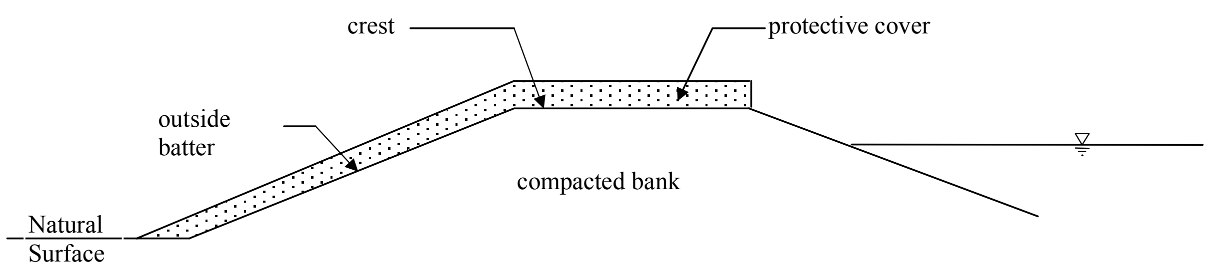

Figure 17-1 Protective Cover

This section addresses the crest and outside batters of channel banks. For Inside Batter Treatment refer to Section 18.

17.2 Cracking

During periods of dry weather it is common for some minor surface cracking to occur as channel banks dry out. This is a normal cyclic occurrence and these minor cracks should seal up during the next period of wet weather.

However, some material types are more prone to cracking than others, and where these expansive (fat) clays are used in compacted banks, deep cracking that extends below the water level can occur as the compacted bank dries out during long dry periods. Refer to Section 10.2.2, Cracking and Section 15.5 Shrinkage.

Low shrinkage material will experience less cracking problems and no special protective cover or treatment required.

Many irrigation systems report increased number of channel bank leaks and bank failures during long periods of extreme dry weather. These leaks typically occur in the top section of the bank, where cracks have opened up across the bank and extend down below the water line.

The bank dries and cracks from the top down and when the cracking zone reaches the level of water in the channel, water penetrates through the bank. Once cracking begins, it becomes a self-aggravating process. The cracks allow air to circulate deeper into the bank causing differential drying and further cracking. The problem is worsened when rainfall runs into the cracks causing accelerated erosion of the bank, particularly where the material is dispersive.

It is important to test for shrinkage to give an indication of how a channel bank will behave in dry conditions. A high shrinkage will indicate that bank cracking could be a serious problem if the bank is not adequately treated. To reduce the cracking of high shrinkage material, a protective cover is required over the outer surface of the bank.

17.3 Dispersion Failure

Deterioration of the crest and outside batter due to dispersion can be caused by rainfall runoff. Soils prone to dispersion failure are generally those with an Emerson Class Number less than 4, using distilled water. Refer Section 15.6, Dispersion.

Where possible, dispersive soils should be avoided in channel bank construction. However, in some areas the only soil material available is dispersive. If properly constructed with a protective cover, dispersive soils can provide suitable bank material. Refer to Section 15.9.3, Use of Low Quality Materials - Dispersivity.

17.4 Proven Practice Options

The three materials most often used as protective cover are:

i) Gravel
ii) Sand
iii) Topsoil with Vegetation cover

Their advantages and disadvantages are outlined in Table 17-1.

Photos\protective cover\protectivecover-scobierock2.jpg

Photo 17-1 Refurbished channel bank with rock protective cover

Protective Cover Material	Application	Advantages	Disadvantages	Notes
Gravel	Refer Specification, section 17.5.1.	1. Provides stable, long-lasting protection. 2. Useful if crest is to be used as an access track	Can be expensive if a suitable material is not available locally	In G-MW in Victoria, a crushed rock containing calcium carbonate is used which reduces cracking and dispersion in medium to heavy clays
Sand	Refer Specification, section 17.5.2.	1. May allow vegetation growth. 2. River sand is often readily available near irrigation areas.	May be washed or blown away if no vegetation is established.	
Topsoil with Vegetation Cover	Refer Specification, section 17.5.3.	Normally obtainable from new channel site or borrow pit.	1. Not suitable for crest where it is to be an access track. 2. Treatment is limited to certain periods of the year when grasses can be successfully established. 3. Mineral status of the soil may not be adequate for vigorous growth. 4. Growth can be stunted by lack of moisture. 5. Slashing or vegetation control may be required	Need a suitable climate to grow grass all year.
Chemical treatment of material available on site	The addition of lime, gypsum, and/or fertiliser to improve the soil structure and chemical composition.	Can use excess material which might otherwise have to be disposed of.	1. Cost 2. Difficult to mix well on-site.	

Table 17-1 Protective Cover Materials

17.5 Specifications

17.5.1 Gravel

Particle Size Distribution

Gravel is defined as a material where more than half of the particles are between 2.36 millimetres and 63 millimetres (AS 1726 Table A1). The grading curve of the material used should exhibit a smooth flow when plotted and tested in accordance with the Australian Standards. A typical grading specification for protective cover would be as follows, although this specification is in no way definitive:

Sieve Size	**Percent Passing**	
	Minimum	Maximum
75mm	100	
37.5mm	85	100
9.5mm	40	80
2.36mm	20	60
0.425mm	10	40
0.075mm	5	20

Application

Gravel, in a moist state, is transported to the site, spread evenly across the embankment surface area via a grader or similar machinery. The thickness of the layer shall not be less than 75 millimetre. While in its moist state the material should be compacted using conventional compaction equipment to not less than 90% of the Standard Compaction as determined by the Australian Standards Test Methods AS1289 5.3.1 and 5.1.1.

17.5.2 Sand

Particle Size Distribution

Sand is defined as material where more than half of the particles are between 0.075mm and 2.36 mm (AS1726-1993 Table A1). The grading curve of the material used should exhibit a smooth flow when plotted and tested in accordance with the Australian Standards. A typical grading specification for top cover would be as follows, although this specification is in no way definitive:

Sieve Size	**Percent Passing**	
	Minimum	Maximum
19.0mm	100	
9.5mm	80	100
2.36mm	50	90
0.425mm	15	50
0.075mm	2	15

Coarse grained sand is recommended as finer sands may be washed away by rainfall. Sand should be of a homogeneous composition. Sands with no fines (material less than 75um) should also be avoided as the particles lack the cohesion to adequately bond to the embankment and each other.

Application

Sand, in a moist state, is transported to the site, spread evenly across the embankment surface area via a grader or similar machinery. The thickness of the layer shall not be less than 75 millimetre. While in its moist state the material can be lightly compacted using a flat drum roller.

17.5.3 Topsoil

Characteristically, clay channel bank materials lack fertility. Their capacity for holding moisture is very low, and the available minerals are usually inadequate for the healthy growth of most vegetation. In order to create favourable conditions for establishment and subsequent growth, the faces of the channel bank need to be covered with topsoil.

Material requirement

- contains enough organic content to support vegetation establishment
- pH between 6 and 8
- erosion resistant material
- free from sticks, excessive amount of stones and other deleterious material
- must not be susceptible to excessive shrinkage when drying, otherwise the resulting cracks will extend through the topsoil cover into the compacted bank.
- Liquid limit < 35 (AS1289.3.1.1). Refer to Section 15.4.2, Determination of the plasticity of fine-grained soils.

Application

- A minimum 150mm thickness of topsoil is required to establish a grass root mass.
- Topsoil shall be evenly spread, in a moist state, over the finished crest at minimum 150mm thickness by conventional construction equipment, and lightly compacted to hold the material in place.

17.5.3.1 Chemical Treatment of Material available on Site

Where topsoil as described in Section 17.5.3 is not available, the addition of lime, gypsum, and/or fertiliser may be applied to improve the soil structure and chemical/mineralogical composition of the available material. The application of one or more of these additives should improve the insitu soil's ability to grow a suitable protective cover.

Application

The application rates for each of these additives vary greatly depending on the mineralogical and chemical make-up of the insitu soil. An assessment of the soil's requirements should be made by suitably qualified personnel and consideration of the additives manufacturer's instructions.

17.6 Establish Vegetation Cover

Topsoil should be planted with a grass suitable for the area and fertilised. Experience across Australia has shown that a dense grass surface will maintain channel banks in good condition much longer than bare earthen banks with little or no protective cover.

The benefits and disadvantages of vegetation cover on channel banks are described as follows:

17.6.1 Benefits of Vegetation Cover on Channel Banks

The benefits of vegetation cover on channel banks are:

- modifies the ground micro-climate, reducing variations in soil temperature and soil moisture. This in turn subdues the mechanical weathering processes that lower the cohesiveness of the soil by aggregate breakdown and loosening of the structure.
- shades the bank, and so assists in preventing differential drying leading to bank cracking
- binds the topsoil, and so provides mechanical protection from wind and rainfall erosion and stock damage
- a dense matt of grass cover will restrict the growth of undesirable vegetation, such as noxious weeds and vegetation that presents a fire risk. This is particularly relevant where the channel has been fenced in and the irrigation authority is responsible for the management of the enclosed area.

17.6.2 Disadvantages of Vegetation Growth on Channel Banks

The main disadvantages of vegetation growth on channel banks are associated with high growing species:

- taller species often do not provide the benefit of binding the topsoil because they do not spread by runners
- can become a fire hazard
- provide habitat for vermin such as snakes and rats
- provide habitat for noxious weeds which can spread into neighbouring farm land
- prevent access along bank
- these disadvantages can be reduced if growth can be cut back by controlled grazing, slashing or herbicide treatment. It is important to avoid over-grazing of banks.
- establishment of grass can be difficult in dry areas

17.6.3 Vegetation to be encouraged on Channel Banks

Different species of grass are appropriate to different areas, climates and soil types. Species selection is vital.

Vegetation to be encouraged on channel banks should have the following attributes:

- binds the topsoil and withstands erosion throughout the year
- prostrate or low growing species with widespread root system
- preferably sterile, so that seed is not passed onto neighbouring land
- spreads by rhizomes and/or stolons
- covers the bank so that noxious weeds and other unwanted growth is reduced to a minimum
- not invasive species which will be detrimental to the waterway
- will regenerate naturally and provide a long-term, self-sustaining cover
- must be easily controlled.
- drought and disease resistant
- requires little maintenance after establishment
- able to establish quickly and give a good ground cover

No single grass will have all the desirable qualities and it may be necessary to use a mixture of various grasses to provide continuous cover.

If the area can be grazed, then a selection of locally used pasture species would be appropriate. However, stock access is not recommended practice. A non-seeding vegetation cover that spreads by runners, such as Kikuyu, has the potential to compete with other plant species and reduce the noxious weed and fire hazard problems on the channel reserve. Species which bind the soil with stolons or rhizomes (runners) are generally preferred to protect the bank from erosion.

Vegetation species to be encouraged vary regionally. Table 17-2 lists *holding* grass species suitable for use in northern Victoria and southern New South Wales.

Creeping salt bush (*Atriplex semibaccata*) has been used successfully to control erosion on the faces of cuttings and embankments in arid zones, because of its prostrate habit, rapid growth rate and ability to thrive on soils with low fertility and moisture levels.

African Star Grass (non-seeding variety) has been planted on the inside batters of irrigation dams in northern New South Wales. It provides some protection from wave erosion and can extend over the crest if conditions allow.

In Queensland there has been little specific study into suitable vegetation for any one irrigation area. The current procedure employed by QDNR Engineering is that when a project is proposed a detailed assessment of the site conditions is carried out and forwarded to the Department of Primary Industries for a recommendation.

Some of the issues to be considered when selecting vegetation for protective cover are as described in section 17.6.4.

Species	Growing Conditions	Establishment	Advantages	Disadvantages	Notes
Kikuyu (*Pennisetum clandestinum*)	1. Prefers light sandy soils. 2. Grows best in humid conditions but will thrive in the humid micro-climate adjacent to water's edge.	Planting by runners is preferred.	Will compete with other species	1. Seeding varieties may migrate by water or into adjacent land 2. Growth can be prolific during wet and warm conditions. Therefore slashing, grazing or chemical spraying will be necessary to keep under control.	
Common Couch (*Cynodon dactylon*)		Vegetative propagation from local plants is often more successful than sowing seed.	Tolerates dry conditions, low fertility and high salinity levels better than most other species.	Can migrate into waterway.	Moderately resistant to glyphosate and atrazine. Low rates of these herbicides could encourage the spread of Couch as other more sensitive vegetation is retarded or eliminated by herbicide.
English Couch or Twitch (*Agropyron repens*)	Vigorous lawn species in areas with Winter rainfall	Seed or vegetative propagation		Can become a problem weed in natural wetland areas or pasture	
Lippia (*Phyla nodiflora*)	A prostrate perennial herb	Vegetatively propagated	1. Requires minimal mowing 2. Requires minimal water.	1. can escape and naturalise in favourable situations, particularly clayey floodplain soils, where it can quickly cover large areas. 2. Not grazed by stock and in some localities is regarded as a weed.	1. Used on channel banks in the Kerang & Cohuna (nth Vic) 2. Used on nature strips in northern Victoria 3. Free flowering and usually well worked by bees.
Kidney Weed (*Dichondra repens*)	A prostrate perennial herb similar to Lippia	Vegetatively propagated	1. Requires minimal mowing and water 2. Hardier than Lippia	Same as for Lippia.	

Table 17-2 Grasses which can be planted on channel banks in northern Victoria and southern New South Wales

17.6.4 Issues to consider before vegetating a channel bank

- The erosion potential of the embankment
- The time of year for successful establishment
- Proposed application method
- Climate
- Topsoil thickness and suitability
- What vegetation will grow in the given soil type?
- Risks and likelihood of successful establishment
- What conditions does the vegetation require?
- Is the vegetation labour-intensive in the application and continual maintenance?
- Will the proposed vegetation compliment the adjacent cropping requirements?
- Need for fertiliser
- Ensure that the vegetation selected is not noxious to the area
- costs

In dry climates, it should be determined if vegetation can be maintained or if an alternative sand or gravel cover will be necessary.

17.7 Methods of Establishing Vegetation Cover

The timing of vegetation establishment is crucial to achieving high germination rates and sustained growth. Grasses can be successfully established only in certain limited periods of the year.

In southern Australia vegetation establishment should be carried out from late autumn through to late winter, so that the grass can establish and grow during the winter-spring period. Checks should be made to ensure a complete grass cover and further work done on any bare areas.

Under dry conditions, watering may be necessary to aid establishment, and in poor soils the use of fertiliser may be required to encourage vigorous growth.

Fertiliser applied at the time of seeding can provide significant benefit in establishing vegetation cover before the onset of hot weather. Small weak seedlings are unlikely to survive the summer.

There are several methods to achieve vegetation growth on channel banks as follows:

17.7.1 Propagation From Seed And Vegetative Matter Contained In Topsoil

Topsoils can be an important source of residual seed which provides significant vegetation cover. The seeds of many desirable vegetation species may be lying dormant in topsoil collected from channel borrow sites. The types of indigenous vegetation that grow from topsoil will vary regionally. Some will give good cover while others may produce vegetation with the disadvantages listed in section 17.6.2. To encourage the growth of more desirable species a controlled management technique may be carried out such as the Rope Wick Application.

Photos\protective cover\CG1-3grassedupbank.jpg

Photo 17-2 Grass grown from seed contained in imported topsoil. Channel bank refurbished 6 months previously.

17.7.2 Rope Wick Application

Much of the topsoil used in Northern Victoria and southern New South Wales for covering channel banks contains some Couch and other creeping plant species. However these are often overtaken by Phlaris and other high-growing vegetation which are not as desirable as the prostrate species. To encourage growth of the prostrate species a *rope wick applicator* can be utilised. This consists of a rope wick attached to a boom filled with herbicide in front of a tractor. The boom can be hydraulically lifted to suit the application. The boom can be set at a level to wipe the high growth with glyphosate while missing the low-growing species.

The Rope Wick Application is a relatively cheap method of establishing vegetation growth although its limitations are that it requires specialist equipment and is only suitable to promote vegetation growth if the desirable species are already contained in the topsoil.

17.7.3 Vegetative Propagation

Vegetative propagation is the harvesting and re-planting of vegetative material to establish vegetation growth on an earthen channel bank.

This procedure has been used by Murray Irrigation in establishing *Common Kikuyu* along their earthen channel banks.

Kikuyu runners were harvested by hand from where it was established on other channel banks. These pieces of material were then planted at 1 metre intervals along the crest of newly constructed banks. With sufficient rainfall many of these banks had a complete coverage of kikuyu across the crest within two years.

Photos\protective cover\grassychannel.jpg

Photo 17-3 Kikuyu on channel banks constructed 4 years previously.

Establishing vegetation on channel banks from runners or cuttings is the preferred method to avoid seed being blown into neighbouring pasture and crops. However it has the disadvantages of being labour-intensive and therefore costly.

17.7.4 Sowing Seed

Seeding with a broadcast mixture of hardy grasses, adapted to the soils and climate of the area, is reasonably effective if done early in the growing season. The seed is applied in the specified quantities and distributed uniformly over the area. Topsoil is important in providing a suitable seed bed and encouraging even germination. Germination and establishment are also significantly improved by using fertiliser. The flatter and rougher the batter slope, the better the retention and germination rate.

Seed can be sown by hand, normal agricultural equipment in drills or by hydromulching. The advantages and disadvantages of these two methods are listed in Table 17-3.

Process	Application	Advantages	Disadvantages	Limitations	Notes
Sowing seed by hand	In southern Australia - late Autumn to late Winter allows establishment during the winter-spring period and achieve a good protective cover by Summer.	Requires no equipment	• Seed may be easily lost due to rainfall and wind • Does not provide uniform or stable distribution of seed • Application difficult in windy conditions. • Labour intensive	May require watering until vegetation is established.	An application of fertiliser may be required
Sowing seed in drills with traditional agricultural equipment	As above.	Can be achieved with readily available equipment.	Seed and young plants on batters may be lost due to rainfall and wind.	As above	As above
Hydromulching – seed, fertiliser, organic mulch and glue are mixed with water and sprayed over the exposed soil with specialised equipment. Granular fertiliser may or may not be included in the mixture.	As above.	• Achieves a uniform and stable distribution of seed • Mixture adheres to the bank so that it is not easily washed away by rainfall. • Mulch retains moisture and provides short-term protection against rainfall and wind • Higher germination rate	Relatively expensive.	Specialist equipment used by a specialist contractor.	Hydromulching has been used on clay drain batters with no topsoil in northern Victoria with a reasonable success rate.

Table 17-3 Seed sowing methods

There are a number of fibre mats or blankets commercially available to stabilise new earthworks and encourage faster growth of vegetation by retaining moisture and assisting seed germination. The bio-degradable matting which is unrolled over the required area, pegged and anchored in place, helps to protect the seeds against temperature extremes, wind, rain and birds. The use of such matting on channel banks would generally only be warranted when adverse conditions make vegetation establishment difficult, such as banks completed in the dry seasons or just prior to the stormy season in areas subject to torrential rain, and alternative sand or gravel cover material is not available.

17.8 Decision Process

A decision process diagram is shown in

Figure 17-2.

17.9 Maintenance

The behaviour of some problematic soils can be difficult to predict and there can be problems in establishing a protective vegetation cover.

It is therefore recommended that in the first year after construction of a new channel bank, close inspections be carried out to identify any signs of bank cracking or erosion.

The detection of minor problems at an early stage when repair is simple can avoid major and costly problems at a later date.

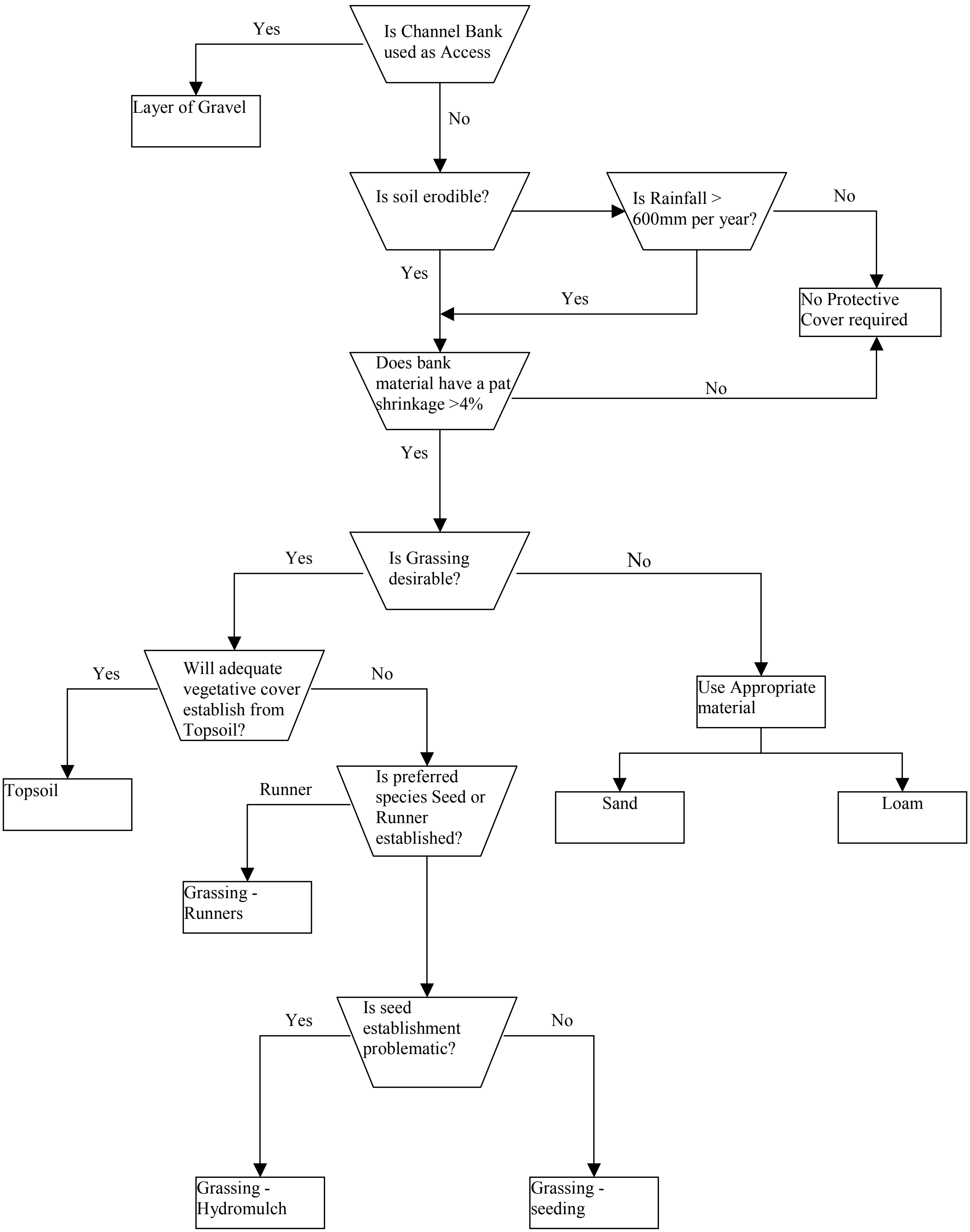

Figure 17-2 Decision support for Protective Cover

17.10 Australian Standards

AS1289.3.1.1-1995 *Soil classification tests –Determination of the liquid limit of a soil – Four point Casagrande method*

17.11 References

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18. Inside Batter Treatment

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Subject **Page No.**

18.1 Introduction

For many earthen channel banks, initial bank deterioration commences on the inside batter at the waterline region, where material is removed by continual erosion from:

- Fretting by relatively small wind generated waves
- Direct attrition from the flowing water
- Sloughing induced by water level fluctuations
- Fish and animal activity.

The erosive forces are not high and the effects may not be apparent for some period of time, but they are continuously present, and the rate of this deterioration is significantly increased if the bank is constructed from very friable, fast slaking or dispersive soils.

18.2 Scope

This section provides general guidance on treatments that can be used to prevent or reduce batter erosion, so that the life of the channel bank can be increased.

The batter treatment techniques include:

- Batter Stabilisation
  - Re-shaping

- Batter Protection
  - Rock Armour
  - Vegetation

Batter stabilisation aims to increase the stability of the batter, and batter protection aims to physically protect the batter material from erosive forces.

It is recommended that an evaluation of alternative batter treatments be undertaken on a site by site basis before selecting one for use.

The following details should be used as a guide only, and adjustments should be made to meet the local conditions.

18.3 Batter Stabilisation

Most channel banks do not decay uniformly, they typically deteriorate at different rates during their life cycle. Following construction, it takes a period of time for the design batter to deteriorate to a vertical unstable face, after which the deterioration rate accelerates, as the bank is undermined and pieces slump or collapse into the channel.

Inside batters will deteriorate over time if not maintained. They are eroded by waves, stock, slumping, aquatic animals, water erosion etc. Channels typically erode to the semi-circular profile shown in Figure 18.1.

Once a channel reaches this profile, the steep batters will continue to be undermined with a continuous bank-slumping – undermining – bank-slumping cycle. At this stage continued undermining by aquatic animals and water velocity with slumping caused by stock and the wetting/drying cycle will eroded the bank at a rapid rate. Refer Figure 18.2.

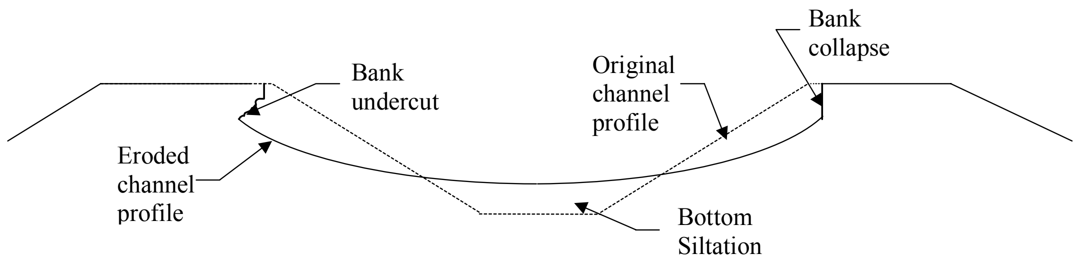

Figure 18.1 Typical eroded channel profile

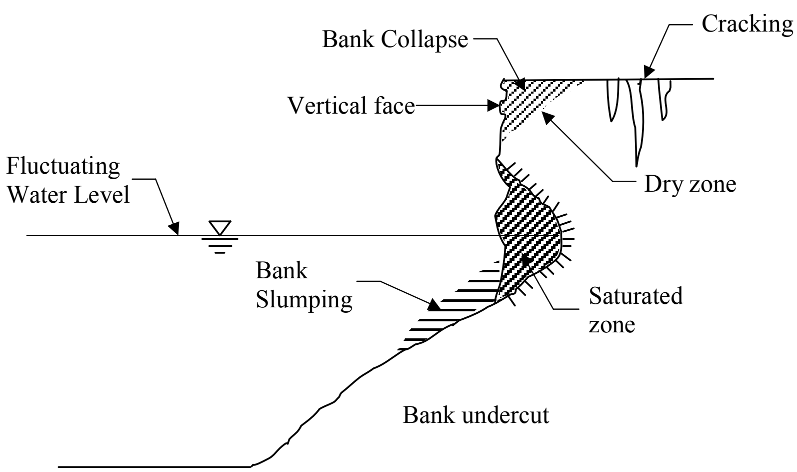

Figure 18.2 Eroded Profile Detail

Where inside batters are eroded, it is necessary to return when the channel is empty and reinstate the inside batters to a stable slope. If this does not occur, erosion of the unstable inside batter will continue with the undercutting and slumping cycle and the new bank will deteriorate at an increased rate.

18.3.1 Inside Batter Re-shaping

A simple low-cost procedure to slow the rate of bank deterioration and extend the life of the bank, is to re-shape the batters to provide increased slope stability.

Batter re-shaping or *sloper grading* is a maintenance activity undertaken in many Australian irrigation schemes. Depending on local conditions and factors, the re-shaping cycle may vary from annually to 20 years, and the effectiveness in extending the life of the bank will similarly vary widely.

Photos\inside batter\wimmera-mallee ditching.jpg

Photo 18-1 Ditcher re-grading bed and inside batters – Wimmera-Mallee Water

Section 12.17.4 discusses batter slope design issues and Table 12-11 gives a guide to maximum batter slopes.

When re-shaping the batters of existing channels, consideration should be given to flattening the recommended design slope in Table 12-11 by 0.5, or alternatively adopting the parabolic cross-section described in Section 12.17.4.2.

A slope of 1:3 (V:H) is recommended when re-established batters by pulling up eroded bank material from the bed of the channel. Before undertaking this technique, the channel should be drained and the bed material allowed to dry out as much as possible.

The decreased steepness of the batter face will slow the rate of bank deterioration, however, without additional protection, erosion of the batter will resume after treatment, and for maximum life extension re-shaping the batters is required on a cyclic basis.

The period of time between cyclic batter re-shaping will depend on the bank material, the location conditions and the actual rate of deterioration. Goulburn-Murray Water in northern Victoria has estimated that the typical re-shaping cycle of channel batters in high deterioration areas would be between 10 to 15 years, and in the moderate deterioration areas, 15 to 20 years.

Before considering batter protection techniques such as rock armouring, the effectiveness of adopting a flatter batter slope without protection should be assessed.

On the batters, the forces of gravity tend to pull soil particles down the slope, reducing the magnitude of water forces needed to cause erosion. By adopting a flatter batter slope, the resistance to erosion is increased, and slopes of 1:2.5 or 1:3 (V:H) may be enough to halt or slow batter erosion

The design standard for inside batter grades are from 1 (vertical) : 2 to 3 (horizontal), depending upon the soil type. Refer Section 12.17.4, Batter Slopes.

At regular periods the inside batters should be re-established to their design grade. This can be achieved by:

1. Cutting off the lip of the channel. This has the disadvantage that bank width is lost and the channel waterway is widened. Refer Figure 18.3.

2. Reinstate the inside bank to its original profile Refer Figure 18.4.

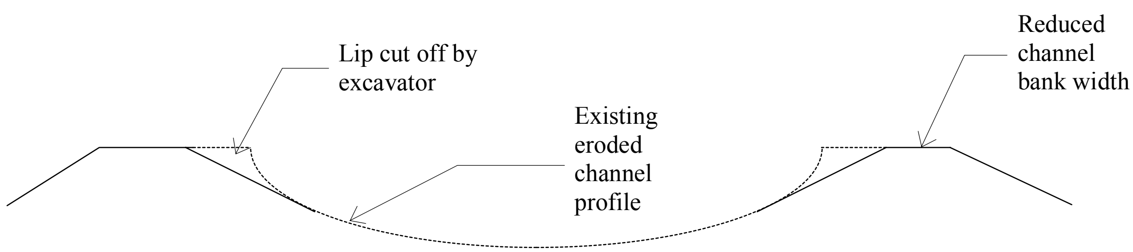

Figure 18.3 Reinstatement of 1:2 batter

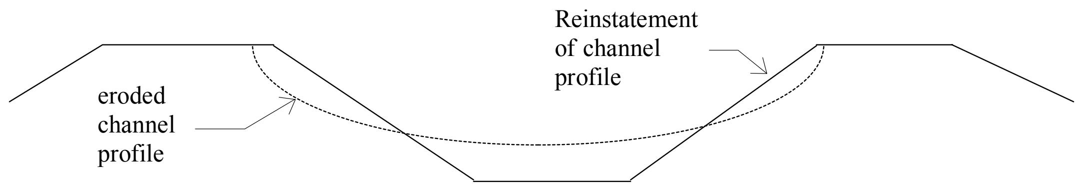

Figure 18.4 Reinstatement of channel profile

In the northern New South Wales cotton growing areas, many channels are re-graded every one or two years. Vegetation growth is removed from the banks of the channels to reduce weed infestation in the crop. Many of the channels are used to harvest rainwater runoff and pumped river diversions. Therefore the batters of these channels can rapidly deteriorate.

In irrigation areas where vegetation is allowed to establish on batters, re-grading of channel batters is effective - perhaps on a 10 to 20 year cycle.

Grading can be achieved by Excavator or sloper grading (Photo 18-2). Sloper grading uses a road grader fitted with a special side blade which can be lowered to the toe of the inside batter. The blade re-shapes the bank by pushing material in front of and up the batter. This does require the bank crest width to be wide enough for equipment to travel along the bank.

Photos\maintenance\trangie3.sloper blade action.jpg

Photo 18-2 Sloper Grading

Photos\inside batter\narrabricottonfarmchannel.jpg

Photo 18-3 Recently graded inside batters

Advantages

Prevents further deterioration due to:

- fretting
- undercutting of banks
- reduces habitat for yabbies, carp etc

Disadvantages

- channel waterway area is increased.
- This may put pressure on the system to pass more water than design capacity allows. Therefore structures may need to be increased for extra capacity.
- Bank width is reduced - this may impede access requirements
- Eventually bank will have to rebuilt. If built outside original bank cross-section, extra land will have to be acquired.
- Removes vegetation which may be stabilising the bank

Life

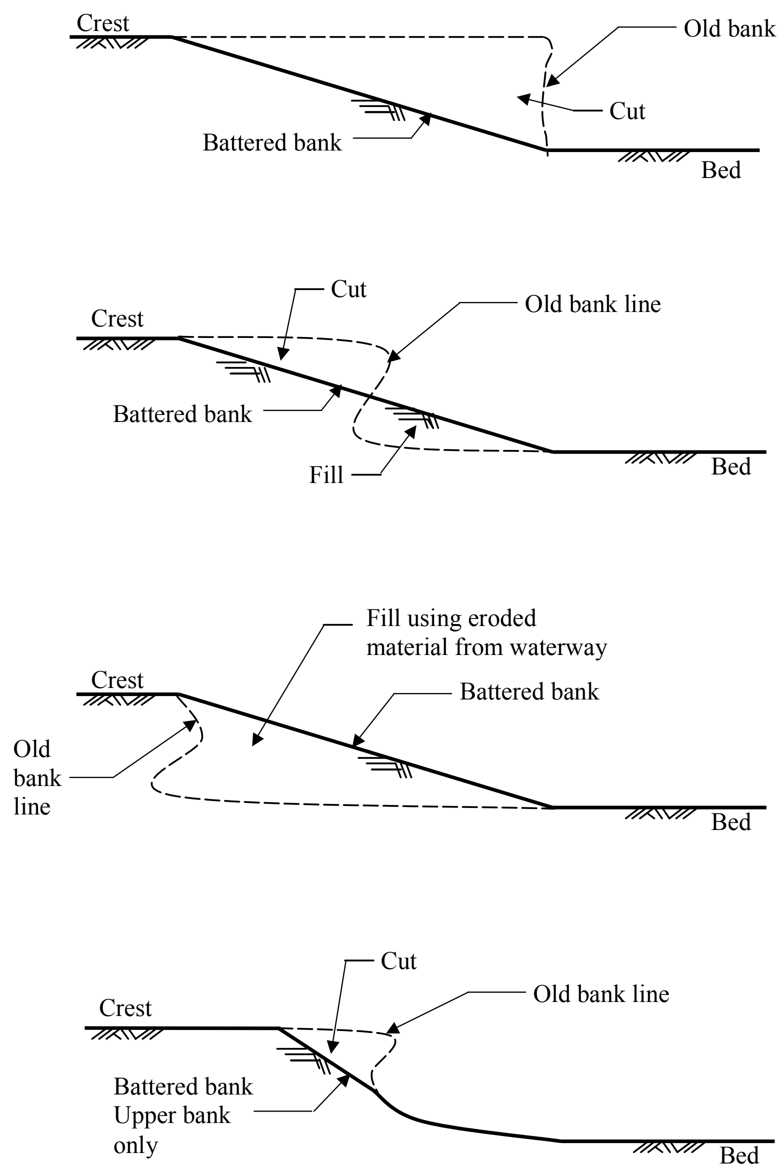

Figure 18.5 Re-shaping eroded inside batter

Limitations

Good access required for excavator or grader.

18.3.2 Natural Armouring

Armouring is a well-known natural phenomenon that is sometimes referred to as *hydraulic sorting*.

In some situations, coarse grained soils with sufficient gravel and sand-clay-silt binders can be used to provide natural armouring of channel batters.

Depending on the material suitability, it can be used as:

- bank material
- compacted lining, or
- loosely placed blanket

When the batter material is initially exposed to the erosive channel forces, it may erode at a relatively high rate, but the rate of erosion will slow over time, as the finer material is washed away and the non-moving coarser particles are exposed and accumulate on the batter.

As movement continues and scouring progresses, an increasing number of coarser non-moving particles build up on the face of the batter. Eventually enough coarse particles accumulate to shield or *armour* the batter surface, and the rate of erosion will be halted or considerably slowed.

Erosion of the bank must occur before an armoured surface can exist and the resulting eroded material will contribute downstream sediment loads to the channel system.

The effectiveness of this method is dependent on the characteristics of the material, the size of the gravel particles and the magnitude of the erosive forces acting on the bank.

Armouring is a special case of sediment transport and various relatively complex mathematical models of tractive forces provide the basis for armouring design. There are a number of technical publications on this subject that can be referred to for further details.

18.3.3 Stabilisation of Batters using Eroded Channel Bank Material

The basic principal behind batter stabilisation is to extend the useful life of a channel asset by removing eroded bank material (EBM) from the bed of a channel and placing it on the inside batter of the bank. This then acts as a sacrificial layer, protecting what is left of the clay core of the bank. This method is described in Section 20.5, Re-forming Channel Banks with Waterway Material.

18.4 Rock Armour

Beaching or rip-rap is a traditional engineering solution to erosion problems, where rock is laid as a protective surface covering. This study found that the terms *beaching* and *rip rap* were being used interchangeably by the irrigation industry, and no distinction is drawn in these Guidelines between the two terms.

While rock beaching is a very effective solution, it is also expensive and provides protection well in excess of that normally required for channel batters. Apart from localised high scouring forces encountered below structures, at drops or on bends, the erosive forces normally acting along the batters of earthen irrigation channels are relatively low, and traditional heavy rock beaching is an over-protection.

Rock armour consisting of a relatively thin layer of lighter crushed rock, rock rubble or coarse gravels placed on the surface of the channel batter has been found to prevent or reduce bank deterioration by physically protecting the batter material from the erosive forces.

Photos\inside batter\CG7channel2armour.jpg

Photo 18-4 20mm diameter rock armour placed in 1992

Photos\inside batter\CG7channel3armour.jpg

Photo 18-5 75mm diameter rock armour placed in 1992

Whether, batter erosion is identified as a potential problem at the design stage of a new channel or develops into a problem on an existing channel, a layer of rock armour can be used to protect the batters.

Gravity alone holds the rock in place, the protective layer is flexible, local damage or loss can be easily repaired by the addition of rock and wave run-up is reduced.

The technique has been used in Canada and Queensland, and trialed in Victoria to provide protection and stability to eroding batters. It works effectively and is relatively low cost, provided suitable rock material is available locally.

18.4.1 General Design Considerations

18.4.1.1 Extension of Bank Life

Rock armour slope protection can be relatively expensive, but on a life cycle cost basis, it is likely to be economically attractive if suitable rock material is available locally. Rock armour can stop or reduce the erosive impacts of dispersive soil, bank slumping, wind and wave action and yabbies and carp.

In Alberta Canada, which has an extensive network of earthen irrigation channels, most rehabilitated channels have rock armour protection. The irrigation authorities have been using rock armour slope protection for over 30 years and they believe that rock armour at least doubles the life expectancy of a channel bank.

18.4.1.2 Batter Slope

The rock must be on a stable batter slope so that no sliding down the face will occur.

Where the friction between the rock and the face of the batter is less than the internal friction of the rock mixture, partial or complete failure of the rock armour can occur where the rock slides down the batter slope.

Overseas studies have been carried out to determine what batter slopes should be used for rock armour, and it has been found that 1:2.5 (V:H) is the optimum slope.

A batter slope of 1:3 (V:H) was found to be better, but only marginally and at a higher cost. A slope of 1:2 (V:H) may work satisfactorily on smaller channels, but on larger channels the potential for failure at 1:2 (V:H) was found to be unacceptably high.

Smooth or grounded gravel will have a higher tendency to slide, while an angular crushed rock will be more stable.

Refer to Section 12.17.4 on Channel Batter Slopes and Section 22.8.9.4 on Lining Batter Slopes.

18.4.1.3 Nominal Thickness of Rock Armour

For economy, the rock should be available near by and placed as thin as possible for adequate protection.

A rock armour thickness of 0.1 - 0.15 metre should be adequate for most conditions. Where there are high velocities and the erosion conditions are more severe, the size and thickness of rock may need to be increased.

The armour thickness should be a minimum of 1.5 times the largest rock diameter to ensure bank material is not washed out through voids in the armour.

Depending on the placement method, a minimum uniform thickness of 0.1 metre may be difficult to achieve on batters, and quality control measures will be needed to monitor thickness variations.

18.4.1.4 Limitations

The limitations of rock armouring include:

- Availability of suitable rock
- Access to channel bank for transport and placing rock
- Can be a high cost solution depending on rock availability

In some Australian irrigation areas, suitable rock material is scarce and has to be transported in over long distances. In these situations, batter protection using rock armour is unlikely to be economical.

18.4.1.5 Construction Considerations

Placing the rock material can be done as follows:

1. If the inside batter of the bank is badly eroded, with undercutting and near vertical face, it is desirable to reinstate the batter slope before the rock armour is placed. This will be less expensive than using rock to re-establishing the batter slope as major savings in rock volumes can be achieved.

   Refer to Section 18.3.1, Inside Batter Re-shaping.

2. Rock material is placed on the crest of the bank using trip trucks at a rate based on the size of the channel.

   For example, material placed at a rate of one cubic metre per eight linear metres, will give a cover of approximately 0.1 metre thick on an eroded channel of about 500 ML/D capacity.

3. The rock material is worked into a windrow using a grader and placed on the water edge of the bank crest. Refer Figure 18.6.

4. To help place the rock material in the eroded area on the batter, the water level in the channel should be at full supply in order to slow the material and stopping it from falling to the bed of the channel. Without water, most of the rock settles in the bed of the channel rather than on the batters.

5. Using a grader, the windrow of material is swept over the edge of the bank and down the inside batter to establish a *beach belt* of rock armour between the maximum and minimum channel operating levels. Refer Figure 18.6. Experience will help determine the correct speed that the grader should be operated at.

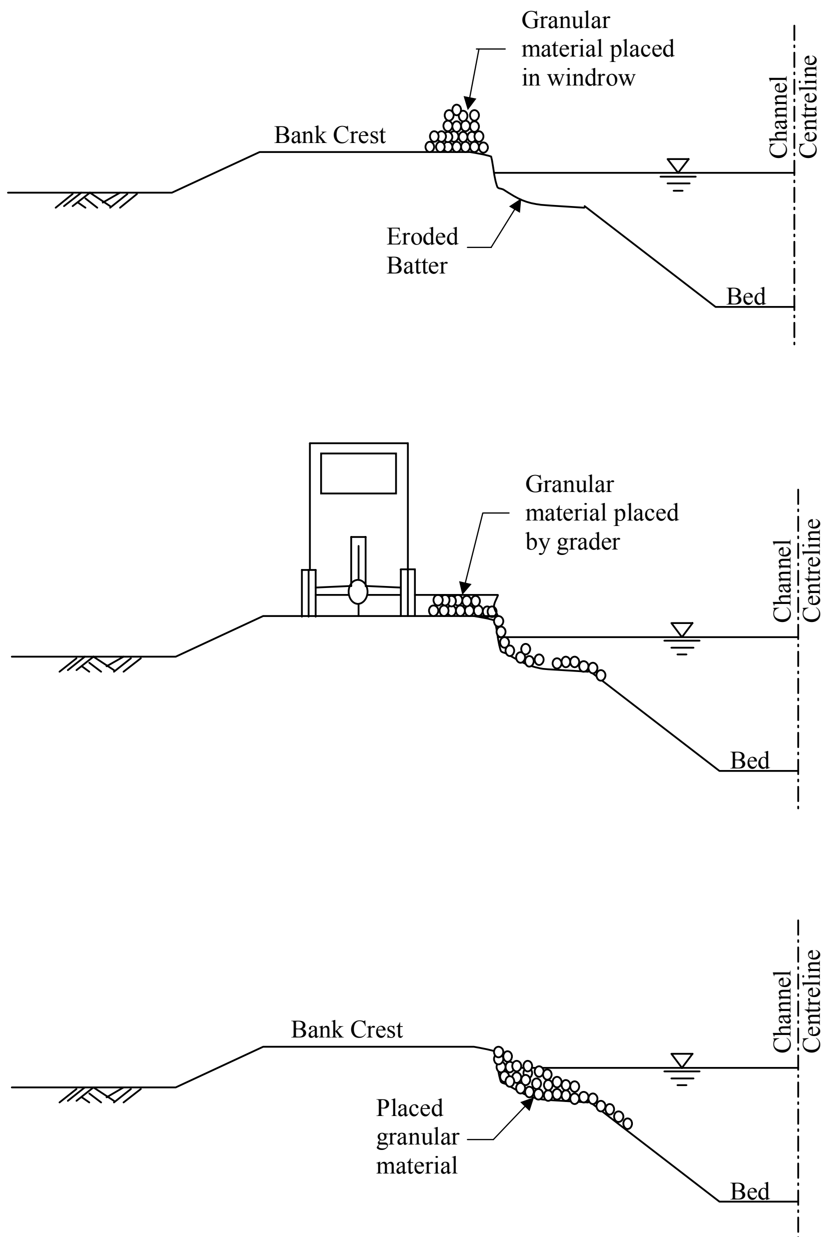

Figure 18.6 **Repair of slumping batters with granular material**

18.4.1.6 *Use of Geotextile*

A geotextile filter fabric between the bank and the rock layer should not normally be necessary, as the erosive forces are unlikely to be high enough to wash to any gross amount the underlying cohesive material used in channel bank construction through the reasonably well-graded layer of protective rock.

18.4.1.7 *Coefficient of Roughness*

Refer to Section 12.11.1.

18.4.1.8 *Extent of Protection*

Rock armour can be applied to the:

- Waterline
- Batters
- Bed and batters

For most channels and particularly those constructed with dispersive clay, bank protection is required primarily at the critical waterline zone between the minimum and maximum channel operating levels where the most erosive forces of rilling, waves, slumping, wetting and drying are acting on the bank.

While protection at the water level is considered the most important, the extent of protection appropriate will depend on the particular channel. This will be influenced by such factors as cost of protection, the degree of risk, rate of erosion, the mechanisms causing erosion and whether bed erosion is a problem.

Section 15, Material Selection and Testing, and Table 15-3 will assist in comparing the relative erosion resistance of materials.

For newly constructed channels with a clean trapezoidal shape, the rock can be placed from the crest of the bank down the batter to the toe. Refer to Figure 18.7.

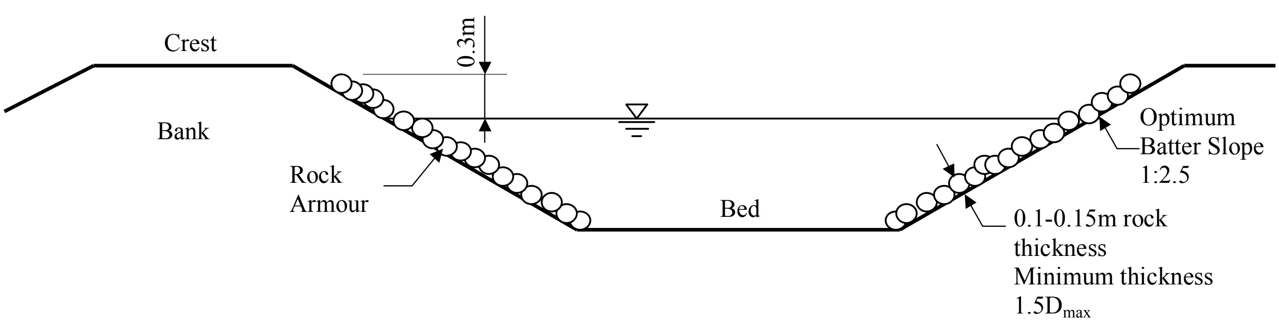

Figure 18.7 Typical Rock Armour Application

On large deep channels, placing rock armour over all of the batter face may be a high cost that cannot be economically justified. To reduce the amount of rock required in these situations, it may be an option to form a bench or false toe to hold the rock armour in place on the batter at least 0.3 metre above and below the maximum and minimum channel operating levels. Refer to Figure 18.8.

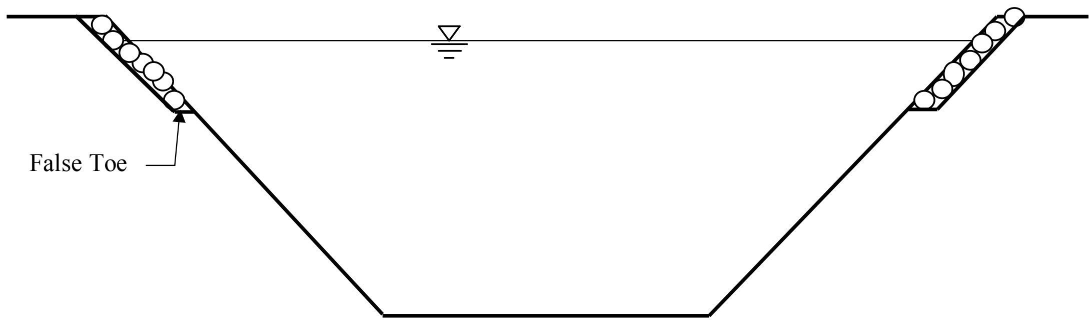

Figure 18.8 Protective layer of rock material – upper batter (suited to large deep channels)

Channels that have been in operation for a period of time, and have banks constructed from materials susceptible to scour and erosion, tend to develop an unstable vertical face at the waterline zone and a bench below the waterline formed from the eroded bank material. Where this natural bench has formed, it is possible to use it to hold the rock in place at the right location on the batter, reducing the amount of rock that would otherwise be require to cover the surface from the crest down to the toe. Refer to Figure 18.9.

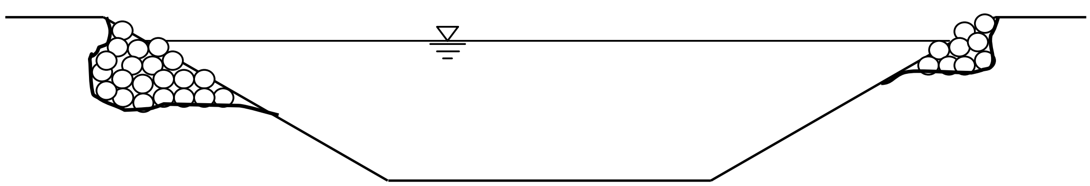

Figure 18.9 Beach belt of rock material to protect the bank

Sections of channel in fill are more important to protect than cut sections, as the erosion can cut into the access track, reduce the width of the bank, cause leaks and possibly a breach of the bank.

18.4.1.9 Type and Grade of Rock Armour

The rock armour should be hard, dense, durable, reasonably well-graded and resistant to water and weathering action. Suitable rock types are sandstone, granite, limestone and basalt, and can take the form of:

- coarse gravel
- crushed rock
- rock rubble

The rock armour should not be single sized, but composed of a reasonable well-graded mixture, of sufficient size to not be dislodged by the velocity of the water and the forces of the waves.

A well-graded mixture minimises the presence of voids within the protective layer through which the underlying material can be washed out, creates an interlocking layer of rock and minimises the area of individual rocks exposed to drag forces from the flow.

With the velocities encountered in channels, there is a relatively wide grading envelope that will work well as rock armour. The important requirement is the most economical material that is readily available and requires minimum screening or working of the raw product.

Goulburn-Murray Water in Victoria has trialed a number of different material sizes and types, and a size 75 mm minus has been found the most suitable for placement and the protection it offers.

The rock armour has been used in Queensland where material of 25mm to 50mm nominal diameter has been found to be the most suitable size.

It has been found that material with too many fines does not work as well, and clay mixed with the granular material is an advantage, as it holds the material together on the batters and helps to stop it rilling. In Victoria, Goulburn-Murray Water has found that crushed rock containing calcium carbonate has the additional benefit of helping to reduce cracking and dispersion in medium to heavy clays.

For economic reasons best use needs to be made of locally available materials. The suitability of rock within reasonable distances should be carefully examined, and the adoption of tight material size and grading specifications should be considered in light of the costs and benefits.

If it is the only material available, a gravelly clay could be loosely spread on the batters to provide protection. As the finer particles in the material are washed away over a period of time, the heavier non-moving particles will build up on the surface of the bank, until sufficient protection is provided and further erosion is stopped or considerably slowed by this *armouring* effect.

Refer to Section 18.3.2, Natural Armouring.

Where there is high water turbulence or the velocity exceed 1.5 metres per second the rock size and thickness should be increased accordingly, and this type of protection is more correctly referred to as *beaching* or *rip-rap*, than the rock armour discussed in this section.

The most commonly used design techniques for rip-rap are based on tractive forces and the condition of incipient motion of a rock in flowing water, and such analysis techniques are outside the scope of this manual.

18.4.1.10 Cellular Confinement System

A cellular confinement system is used overseas for channel erosion control, and while it is available in Australia, the study did not identify any sites where it had been use on Australian irrigation channels. A series of three-dimensional polyethylene cells, when expanded, simulate a honeycomb structure that holds the infill material in place and limits the forces at work on it.

The polyethylene honeycomb panels, which are supplied in collapsed form, are expanded over the erosion prone surface to form a set of regular hexagonal cells, all linked together. Once expanded, the cells are filled with gravel or other rock materials.

The confinement system would be advantageous in areas of Australia where suitable rock armour material is scarce, as it allows the use of smaller sized rock in significantly lower quantities, including materials that would otherwise not be suitable to use.

18.4.1.11 Design Issues

To halt the erosion of the inside batters, consideration should be given to incorporating rock armour, either:

i) the time of initial construction, or
ii) after the channel has been in operation for some time

The potential for batters to erode and the degree of protection thus required, can be assessed at the design stage by considering the erosive forces and the soil classification and dispersivity. Where the batters are going to suffer significant erosion, consideration should be given to providing rock armour at the time of initial construction.

However, as the rock armour protection can be applied after a channel has been in operation, an alternative and more cost-effective approach may be to *wait and see*, possibly 10 years after initial construction, until there is definite evidence of its need. Periodic inspections of the channel will identify emerging problems, and the rates of deterioration evident can be used in an economic evaluation of batter protection options.

Placing the rock material can be done as follows:

1. The batters are over-excavated by the thickness of the proposed rock armour and trimmed to line.

2. Rock won from a quarry or a similar source is transported to site and dumped.

3. The rock material is placed on the batter and loosely spread or racked over the face of the batters to a uniform thickness. The rock should be handled and placed to avoid excessive segregation. Rock can be carefully pushed over the bank, or placed by the bucket with an evacuator or front-end loader starting at the toe and working up the slope.

4. Variations in rock size and thickness should be monitored and compensated for. A geo-fabric filter under the rock layer should not be necessary.

5. The finished surface should conform to the design profile of the channel and present a uniform matt appearance.

18.4.1.12 Maintenance

Rock armour is relatively easy to maintain. It is flexible and will tolerate movement and settlement of the channel bank and adjoining structures. Periodic inspections should be carried out to identify any localised dislodgment or loss of rock, slumping or excessive settling. Additional rock should be placed where necessary if the integrity of the rock layer is threatened. Care needs to be taken when desilting channels to ensure that rock is not lost, and stock that can dislodge the rock need to be excluded from the channel.

18.5 Vegetation

Vegetation of the right character, height, density, width and elevation can be used to protect the inside batters of channel banks from moderate erosive forces. There is wide evidence that grasses can be used to bind channel batter material above the water line and dissipate the energy of waves striking a channel bank. In coastal areas, kikuyu and para grass are good, or in the drier areas African Star grass, Rhodes grass or para grass are suitable species.

Vegetative protection will not be effective where there are large and prolonged channel water level fluctuations. Grass will die back where it is immersed for greater than 2 to 3 days, and it can not be effectively established and maintained at the critical erosion zone on channel batters where there is changing water levels. Water level fluctuations must be of short duration and within tolerable limits to sustain the selected vegetation.

Key issues are:

- Vegetation must be given positive protection by the total exclusion of livestock
- Vegetation protection will be less effective where the underlying soil is either dispersive, fine-grained or of low cohesion.
- Suitable soil depth, texture and fertility are required for vegetation establishment and sustained growth.
- The batter to be planted should be covered with a layer of topsoil to a minimum depth of 150mm. Refer to Section 17.5.3 Topsoil.
- The most critical period for success or failure is during the establishment year.
- A range of technical skills are required to properly evaluate each particular site, assess the soil suitability, determine any necessary soil treatments, select the plants and establish them to achieve the desired level of bank protection.

18.5.1 Aquatic Plants

The stability of channel batters can be improved by encouraging water tolerant and aquatic plants to grow along the waterline.

Photos\inside batter\CG4channel1armour.jpg

Photo 18-6 Weed growth at waterline reduces fretting

The water tolerant and aquatic plants encouraged or planted on inside batters should have the following characteristics:

- Able to form dense stand along the water's edge without intruding into the waterway or over the bank
- Prefers water's edge
- Ability to survive drought stress of short duration
- Capable of enduring short duration inundation without serious damage
- High survival rate
- No further maintenance required after establishment
- Non-invasive species to local agriculture
- Ability to self-regenerate insitu

- Able to survive during non-operational or winter period
- An availability of seed or rhizome supply

The best plant for a given site should be selected based on a consideration of the degree to which it meets the required characteristics, its adoptability, rapidity of establishment and its reasonable availability.

Advantages

- Roots bind the soil and the plants act as a buffer against wave turbulence.
- Reduces erosion of batter from fretting, waves, rainfall and stock damage
- Biological systems can potentially be considerably cheaper than engineering solutions

Disadvantages

Unsuitable species could:

- grow into and reduce waterway area
- may spread as a weed into irrigated pasture and crops
- can provide food source and habitat for unwanted aquatic animals such as carp
- can be difficult to transplant and establish on a mass scale
- uncertainty of successful establishment

18.5.1.1 Aquatic Plants suitable for Northern Victoria and the Riverina

River Club Rush (*Schoenoplectus Validus*) - Grows up to 3m tall. Spreads through rhizomatous root growth. Likes permanently wet conditions

Spike Rush (*Eleocharis Acuta*) - Grows to less than 1m tall. Spreads through rhizomatous root growth. Likes wet/dry cycle.

Sedge (*Carex Appressa*) - Grows to about 1.2 to 1.5m. Grows in clumps. Likes wet/dry cycle.

Common Rush (*Juncus Usitatus*) - Grows to about 1.2m to 1.5m. Grows in clumps. Likes wet/dry cycle.

Some introduced plants which may establish themselves:

Water couch (*paspalum distitchum*) can be a weed in small, slow-flowing channels. However in large channels this plant can provide some protection to the banks.

Umbrella sedge (*cyperus eragrostis*) or *cyperus australicus* can also provide some protection.

Plants to be discouraged

Cumbungi (*typha* species) - high growing species which will migrate into and reduce waterway capacity, particularly small shallow channels – too rampant – likely to spread throughout the channel.

18.5.2 Decision Making Criteria

The method of inside batter treatment will vary according to the local conditions. Factors to be considered are:

- Required life of channel bank
- Is wind/wave action likely to cause rapid erosion
- Quality of compacted bank material – does it require protection from environment.
- Ability of the soils to support vigorous vegetation.
- Is vegetation a problem to local agriculture
- Cost and availability of local crushed rock or gravel material
- Time of year

18.6 References

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19. Channel Bank Construction

Table of Contents

Subject **Page No.**

19.1 Introduction

This section sets out the basic principles of sound channel bank construction.

The economics of earthworks will depend on equipment selection and construction approach.

Good quality construction is necessary if a channel bank to have a long life with a low life-cycle cost.

Photos\construction\cg4 new channel construction.jpg

Photo 19-1 New Channel Construction

A typical cross-section of a new channel is shown in Figure 19.1.

Readers should refer to the following sections for related information:

Planning and Investigation	Section 11
Earthen Channel Design	Section 12
Material Selection and Testing	Section 15
Compaction Control	Section 16

19.2 Setting out Works

Setting out is the transfer of the information contained on the design plan to the site. This is done by survey. Care needs to be taken during setting out of works as even small errors can have an adverse effect on the overall cost of the project.

When constructing a new channel it is generally desirable to balance as much as possible the cut and fill of earthworks. At the design stage, a mass diagram, which shows the accumulation of cut and fill with distance, can be used to optimise this balance.

Accurate survey set out is therefore required to ensure the design dimensions, levels and earthwork quantities are achieved in the field. In some irrigation schemes, it was observed that the actual constructed dimensions of channel banks were greater than the design dimensions, and while this may have been dictated by construction equipment, survey control is necessary to ensure that the earthworks costs do not significantly over-run the design estimates. Obviously, channel banks must be constructed to the minimum design levels, batter slopes and dimensions.

The location of the channel should be marked in the field with centreline, boundary and slope stakes, as shown in

Figure 19.2.

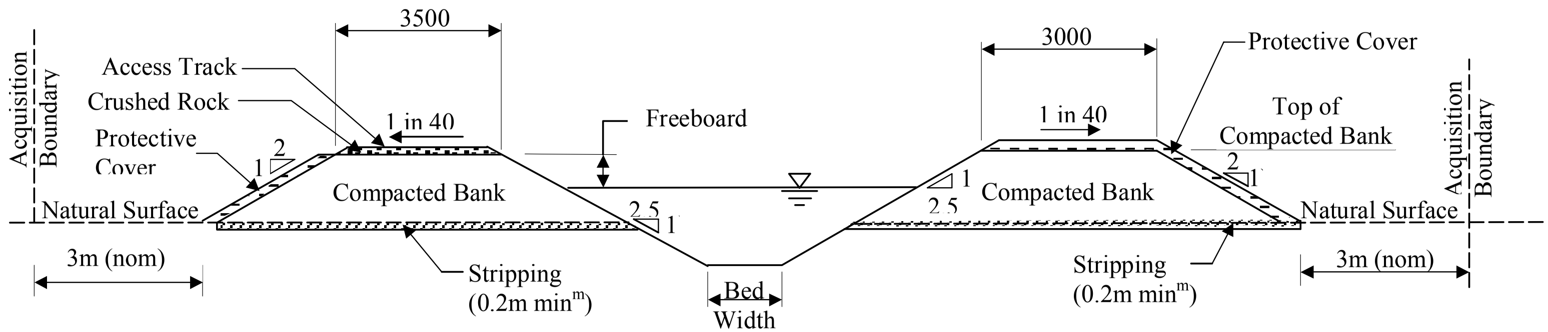

Figure 19.1 Typical New Channel Cross-Section

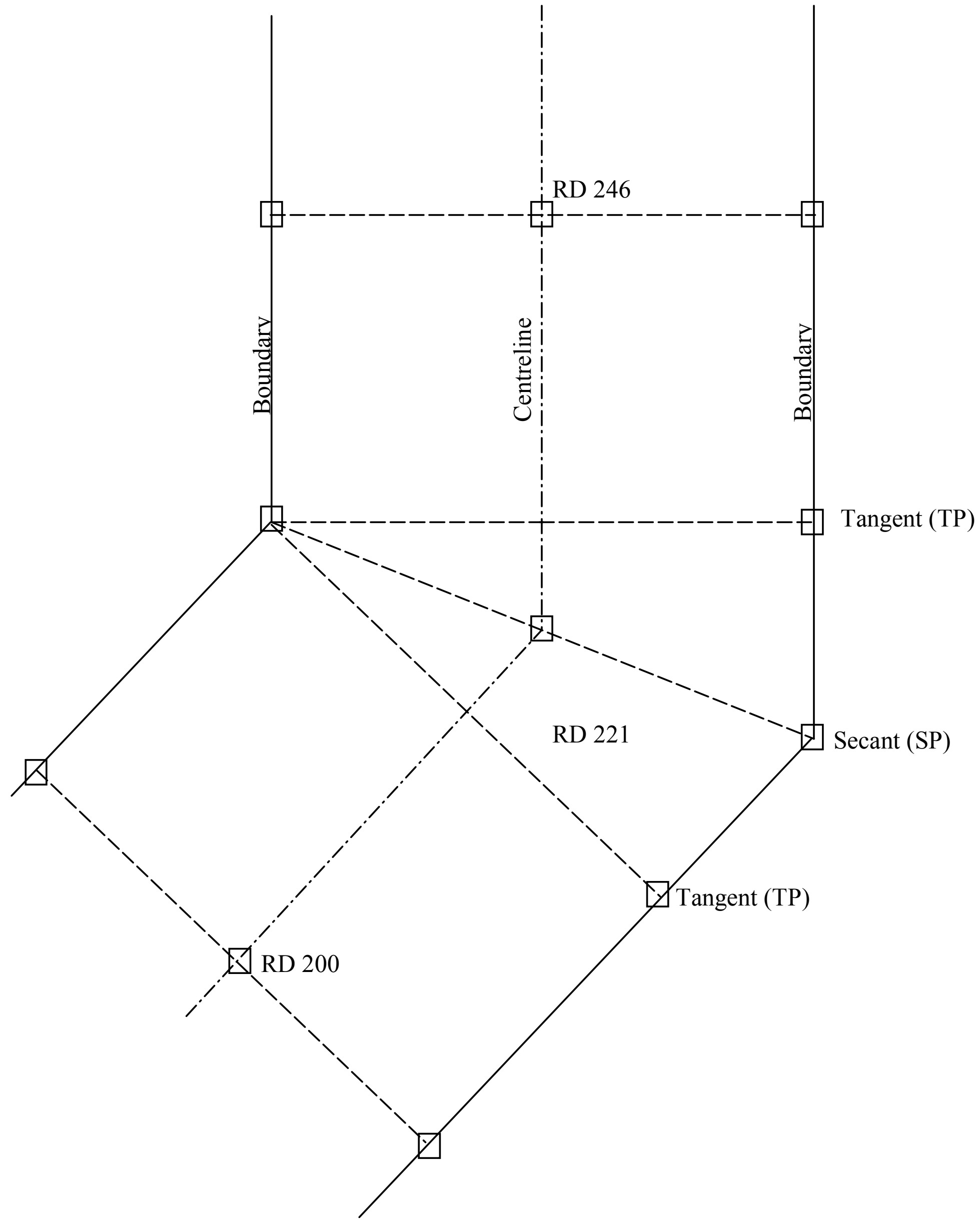

Figure 19.2 Survey Set out for New Channel Construction

A typical survey set out for new channel construction would be as follows:

1. *Centreline of channel*

   Engineering pegs are placed along the centreline at every angle and at 100 metre intervals. The required depth of cut can be indicated on marker stakes alongside the pegs.

2. *Channel Reserve Boundary*

   Title pegs are placed at:

   - 100 metre intervals between angles
   - three title pegs at every angle; two tangent point and one secant point (Refer

- Figure 19.2)

3. *Temporary Bench Marks (TBMs)*

   Temporary Bench Marks are generally required at:

   - Structures; regulators, culverts, meter outlets, etc
   - Angles
   - every 200 metres between the above

   TBMs can be placed on existing stable structures or can be constructed from a stake driven into the ground. Normally they are positioned on the boundary of the channel tenure where they cannot be destroyed or buried by construction equipment. A stake with flagging tape should be placed beside the TBM for visibility.

4. *Earthworks Stakes*

   A wooden earthworks stake is to be placed at

   - the intersection of natural surface with cut & fill, and
   - the outside toe of the bank

   Earthworks Stakes are to be placed at 25 metre intervals along the alignment. Four earthworks stakes are required at each cross-section. (Refer Figure 19.3.)

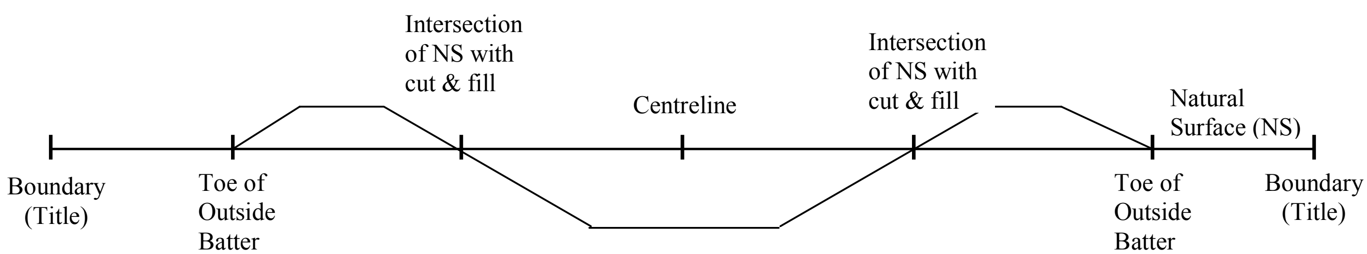

Figure 19.3 Survey set out cross-section

5. *Structures*

   Structures are set out independently of the channel survey set out. However peg(s) indicating the location of the structure and a TBM should be installed prior to channel construction, so that any changes in bed and/or bank levels can be accommodated.

19.2.1 Pegs and Stakes

Survey Pegs used for channel set out include Title pegs at the boundary and Engineering pegs to be used along the centreline and as TBMs.

Indicator stakes are normally placed next to pegs with flagging tape for visibility.

A colour system with stakes and pegs is useful to avoid confusion on site. The colour system normally used is:

White – all title pegs and indicator stakes on boundary of channel land acquisition or other points of title importance

Red – all reference pegs and stakes; centreline and TBMs – to be retained if possible.

Yellow – earthworks stakes of a temporary nature – eg the intersection of natural surface level and cut & fill, outside toe of bank, etc.

When the setting out is complete, all unnecessary pegs or stakes should be removed, particularly those left by any previous survey work. Unless this is done, construction personnel may be misled, which could lead to expensive errors.

19.3 Equipment Selection

Overseas, automated mobile machines have been designed for constructing large earthen channels, and laying membrane liners and placing rock armour. While these machines are generally considered effective, they are large, inflexible and limited in application.

During the research project, no specialised or customised channel bank construction equipment was identified in Australia. Instead, a variety of different types of conventional earth moving and compaction equipment were being employed on channel bank construction.

It was apparent that the availability and cost of the different types of equipment is a major determining factor in selection, and to minimise costs, it is extremely important that the design and construction allow for the most efficient use of readily available equipment.

The only real criteria for the selection of construction equipment should be the overall unit cost of production, and for each item of available equipment the productivity and cost should be estimated and compared.

For the most economic construction, the plant limitations, production rates of compaction plant, haul units and loaders need to be matched to the conditions of each particular job. The actual production achieved being limited to the lower value of the compaction plant capacity, the hauling fleet capacity and the loading units capacity.

The planning and management of earthmoving operations is not covered in detail in this manual and readers will need to consult other technical references on the subject.

Performance data for numerous types of construction plant operating under a variety of conditions are provided in technical publications and by manufacturers. The best approach is to begin with the ideal performance and then discount this to an anticipated practical output using efficiency factors that reflect the actual conditions expected on the site.

As a rule of thumb actual practical production on most channel bank projects is seldom higher than 50% of ideal theoretical production. The following factors all play a part in evaluation of actual production:

- Operator capability
- Weather conditions
- Time effectiveness
- Plant availability
- Management
- Material factors
- Grade
- Distance
- Haul road condition
- Waiting and standby time

The capabilities and limitations of available construction equipment need to be considered at the channel design phase.

Selection of the compaction equipment requires careful consideration of the job specification requirements.

Photos\construction\cg3.new bank batter.jpg

Photo 19-2 Excavator shaping inside batter

Various types of equipment for construction of channels are available including scrapers, bulldozers, hydraulic excavators, draglines, end dump trucks, front-end loaders, backhoes, graders, compactors and water-carts. Table 19-1 shows their functions, advantages and disadvantages for use in channel construction.

The type and combination of construction equipment used should be based on an assessment of:

- size, height and length of the channel works
- site and access conditions
- location of borrow pits, if required
- volume of soil to be moved
- length and condition of haul roads
- type of soil, soil stability, soil wetness
- degree of bank compaction required
- load supporting ability of the ground
- locality of water for construction purposes
- availability and cost of different types of equipment
- volume of soil to be moved per unit of time
- possible sources of danger to plant operators, for example power lines.
- degree of accuracy required
- time allowed to complete the project
- construction economy

Equipment	Clearing	Stripping	Excavation of borrow pit	Excavation of channel waterway	Loading of borrow material	Haulage	Spreading	Moisture Control	Compaction	Trimming	Protective Covering	Advantages	Limitations
Scraper		✔	✔	✔	✔	✔	✔		✔		✔	• Suitable for relatively short haul distances (1km) • Efficient on large channels for moving waterway and borrow material to banks • Will aid compaction	• Cannot mix different layers of borrow pit material • Fully loaded scrapers are generally prohibited from public roads because of heavy wheel loads and interference with road traffic • Need manoeuvring or working space difficult to operate on restricted site • Costs increase as the haul distances increase • Limited by terrain, length of haul and supported ability or ground
Bulldozer	✔	✔	✔	✔			✔		✔	✔	✔	• Versatile • Can be used to excavate borrow pit, although this is more efficiently carried out by an excavator • Useful to excavate waterway and spread on smaller channels • Can use cross-dozing technique to shift material from waterway up batters onto bank	• Tracks alone may not be sufficient to achieve required compaction. • Limited by length of push or haul
Hydraulic Excavator			✔	✔	✔					✔		• Can dig from the face, mix material in borrow pit, and load into hauling units • Versatile	
Dragline			✔	✔									• Hydraulic excavators are more efficient and versatile.
Dump Trucks						✔			✔		✔	• Truck traffic along the bank will aid compaction • Rear-dump trucks are suited to tipping into restricted sites where maximum manoeuvrability is required. • Large capacity trucks can be used over relatively long haul distances	
Front-end loader					✔						✔	• Required to load material from borrow pit on to dump trucks if using a bulldozer to excavate.	• Limited by the digging ease of the material • May be necessary for a bulldozer to work material to be loaded
Backhoe				✔							✔	• For small channels may be used for excavating channel waterway	
Grader	✔	✔					✔			✔	✔	• Useful for spreading access track gravel or topsoil • Can be used for stripping. Material can be loaded from a windrow by a front-end loader	• Graders are limited to use where stripping can be windrowed.
Roller									✔			• A range of towed and self-propelled rollers to suit material and site conditions. • Refer to Section 16, Compaction Control.	
Water Cart								✔			✔	• Wetting material at borrow pit or on bank	• Wetting of material should only be carried out by an approved water cart.

Table 19-1 Construction Equipment

19.3.1 Construction Equipment

The basic equipment operations, which are needed in channel bank construction are:

- Clearing
- Stripping
- Excavation of borrow pit
- Excavation of channel waterway
- Loading of borrow material
- Haulage
- Spreading
- Moisture control
- Compaction trimming
- Protective covering

Typical construction equipment may consist of:

Borrow Pit	Hydraulic Excavator Scraper Bulldozer Loader
Carting	Dump trucks Scraper
Bank	Bulldozer Tamping foot roller

19.3.2 Compactors

Refer to Section 15, Compaction Control.

A diagram showing suitability of Compaction Equipment for various types of channel bank materials is provided in Appendix E of AS3798.

19.4 Typical Construction sequence

Typical construction sequence for a new channel may consist of:

1. Site Preparation – clearing, stripping and foundation treatment.
2. Construction of compacted bank from channel excavation, lead along the channel or borrow.
3. Complete channel waterway excavation and place any surplus material in spoil bank.
4. Batter and trim earthworks.
5. Place protective cover over outer batter and crest (if no access).
6. Access Track.
7. Longitudinal fencing if protection required.

Photos\construction\cg7 tipping imported clay.jpg

Photo 19-3 Tipping imported clay onto bank

19.5 Site Preparation

19.5.1 Clearing

The entire area to be covered by the channel should be cleared of all scrub, trees, and stumps. The roots of all trees should be removed. Resulting excavations under the channel banks should be backfilled and compacted to the same standard as that required for the subsequent channel bank construction.

19.5.2 Stripping

The area on which the channel banks are to be constructed and area from which the cut is to be removed should be stripped of all vegetation topsoil and material that is unsuitable as a foundation or incorporation into the compacted bank.

This would typically involve removing the topsoil to a depth of about 0.2m. If suitable, the topsoil should be deposited in temporary stockpiles for later placement as protective cover over the completed bank. The temporary stockpiles should be located on each side of the work, where it cannot be unintentionally contaminated by clay material excavated from the channel or imported from borrow. Care should be taken to ensure that the topsoil meets the requirements set out in Section 17.5.3, Topsoil Specification and Section 15.8.2, Shrinkage.

The purpose of the stripping is to restrict seepage passing under the bank, by ensuring that the bank is keyed into a solid and relatively low permeability seat. If this is not done the bank is very likely to leak or ultimately fail completely.

Inadequate stripping of bank seats in the past was identified during the course of this research project to be a frequent course of channel bank leakage and seepage in Australia.

Stripping effectively increases height of the bank and reduces the depth of excavation. Stripping is mostly carried out by bulldozers.

The underlying material that is unsuitable for topsoil or bank construction should be stripped and hauled to waste.

An assessment of the actual site conditions should be carried out to determine if a greater depth of stripping is required to cut through upper layers of pervious or unstable material and extend into a solid base. If the subgrade consists of deep layers of unsuitable material, it may not be possible or economic to strip down to a stable low permeability base, and an alternative channel design using an internal lining may have to be considered. Refer to Section 22, Channel Lining.

19.5.3 Foundation treatment

The surface of the stripped area under each bank should be levelled and scarified to a depth of 0.2 metres, moistened and compacted, preferably with equipment to be used in subsequent bank construction. The depth to which scarifying is carried out should not exceed that which can be compacted. The degree of compaction achieved should be consistent with that specified for subsequent channel bank construction. The aim of scarifying and compaction is to ensure a good bond between the subgrade and the first layer of the bank.

If the compacted surface of the subgrade is too dry or too smooth to bond properly with the first layer of the bank, it should be scarified to a shallow depth to ensure proper bonding. When a sheepsfoot roller is being used and the subgrade layer can be penetrated by the roller's feet, no scarification is usually necessary.

In the case of a channel that runs on a contour around a steeply sloping hill, special precautions need to be taken to adequately bench out the area under the banks to form a sound key into the subgrade.

19.6 Bank Construction

19.6.1 Planning

Planning for bank construction should include, but not be limited to:

a) The quantity and quality of the channel bank material
b) The expected rate of output of the earthmoving, delivery and spreading equipment;
c) The compaction specification to be met; and
d) The availability and effectiveness of particular items or types of compaction equipment

Construction is best undertaken at the time of year when the natural soil moisture of the available bank material is close as possible to the optimum. Late spring, autumn or early winter are usually the best times. Construction is often difficult in mid-winter because sites are too wet, and the soil can be too dry during mid-summer.

The availability and cost of different types of construction equipment will be a determining factor in the construction approach.

The basic operations, which are needed in channel bank construction, are:

- Excavation of channel waterway
- Borrowing material for bank, if required
- hauling
- spreading
- compaction

19.6.2 Excavation of Channel Waterway

Depending on the size of the channel, the magnitude of the project and the site conditions, a hydraulic excavator or scraper can be used to make the cut.

Photos\canada\girl.jpg

Photo 19-4 Scraper

A hydraulic excavator working along the centreline of the channel can create the initial pilot cut to the design bed level, followed by excavators working from the sides pulling back the batters to the design slope.

Photos\construction\cg2.pilot trench.jpg

Photo 19-5 Pilot trench for new channel

The material excavated to form the channel waterway, if suitable, can be used on the banks. Unsuitable material or surplus material is formed into spoil banks or hauled to waste.

Excavated material in excess of bank requirements at any cross-section can be used to make up deficiencies at other cross-sections.

19.6.3 Borrow Pits

Material for bank construction is obtained either from the channel excavation, if it is suitable, or from borrow. The borrow material is taken from pits constructed well clear of the channel line. For economy, borrow pits should be located as close as possible to the site of the channel works. However in some situations, it may be necessary to travel a considerable distance from the channel to obtain suitable material.

In some of the larger irrigation schemes in Australia, haul distances of 5 km are common and can be up to 10 km, adding significantly to earthwork costs.

Photos\borrow pits\shep7 excavator loading tipper with borrow.jpg

Photo 19-6 Excavator loading Dump Truck at Borrow Pit

In selecting borrow sites consideration should be given to:

- Suitability of the type of material available
- Volume of channel bank material required
- Volume and depth of soil obtainable from potential borrow pit(s)
- Bulking factor of borrow material (refer section 19.6.4)
- Distance from borrow pit to Channel Bank Construction site
- Location of the borrow pit in respect to roads
- Moisture content
- Amount of stripping required
- Depth of watertable

Refer to Section 15, Material Selection and Testing.

Where a haul road can be built, scrapers can be used. If the borrow material has to be moved several kilometres over public roads, the choice would be a front-end loader, or excavator that would load dump trucks.

Whether or not a front-end loader or an excavator would be used depends on whether the bottom of the borrow pit can support a front-end loader and haul units. If the bottom is too soft, an excavator that can sit outside the borrow pit and load a hauling unit at the same level would be required. Borrow pits are usually most efficiently worked with a Hydraulic Excavator. The advantages of an excavator are the mixing of borrow material through the profile and occupational health & safety, as the machine and operator remain on the surface.

The quality of bank material and the control tests to be used as the acceptance criteria should be specified in the construction specification. The suitability of material should be determined by tests described in Section 15, Material Selection and Testing.

The borrow pit should be stripped of topsoil before excavation. Topsoil should be stockpiled if necessary for use as protective cover on top of banks.

The soil should be well broken up in the borrow pit before it is hauled to the channel bank.

A bulldozer and front-end loader may be used although the bulldozer will need to work at the floor of the borrow pit.

The soil should be well broken up in the borrow pit by ripping before it is hauled to the channel bank. Soil should be mixed through the vertical profile with an excavator to give a better consistency of soil in the bank. This is achieved by the excavator scraping soil into the base of the borrow pit, mixing before loading onto a Dump truck for carting to the construction site.

Photos\borrow pits\shep6 excavator mixing.jpg

Photo 19-7 Excavator mixing material through the layers of borrow pit

If the soil is too wet, then the borrow pit can be ploughed to evaporate excess water, the soil can be spread out to dry or the works delayed. If the borrow material is drier than optimum, water can be sprayed onto and mixed with material before hauling to the construction site.

The material is transported and placed by scrapers or transported to the site by end or bottom dump trucks and placed.

19.6.4 Volume of Earth Materials

In a typical earthmoving cycle, the respective densities of material are, *natural, loose* and *compacted*. This is illustrated in Table 19-2.

It is important in earthmoving calculations to convert all volumes to a common unit of measure. The natural (solid) cubic metre is commonly used for this purpose.

When a cubic metre of material is compacted its volume will be reduced. This is expressed with respect to natural cubic metres and not loose cubic metres.

Earth Material Condition	**Natural** (material in its natural state)	**Loose** (material after excavation or loading -30% swell)	**Compacted** (material after compaction - 25% shrinkage)
Volume of Earth Material	1 m^3	1.3 m^3	0.75 m^3
Mass of Earth Material	1800 kg	1800 kg	1800 kg

Table 19-2 Earthmoving Material Cycle

19.6.5 Hauling

If more material is required than can be acquired form the waterway cut, haulage will be required from a borrow pit. This may be achieved with a scraper if borrow pits are relatively close to the works (up to 1 kilometre), or by dump trucks for longer distances.

Haul roads between the borrow pit and the channel site should be direct as possible and maintained in good condition.

19.6.6 Spreading

Proper placement and compaction of the bank material is important and needs to be tightly controlled.

After the material is hauled to the site it can be spread by bulldozers or road graders.

Photos\construction\cg5 new bank construction.jpg

Photo 19-8 Bulldozer spreading borrow material on new bank

The method of excavation, transport and placement should ensure that the bank material is placed in a mixture as uniform as practicable. Such uniformity will assist in providing consistent relative compaction from the chosen plant and work practices.

Bank material should be spread loosely in near-horizontal layers of uniform thickness, deposited systematically across the bank area. Material in the layers should be substantially homogenous and free from lenses, pockets or lumps of soil greater than two-thirds of the layer thickness. Lumps include *curls*, which can be formed by the blade of the bulldozer or scraper.

The thickness of each layer will vary according the material being placed and the equipment being used. If compacted with:

- bulldozer or scraper — no more than 150 mm loose thickness
- sheepsfoot roller — no more than 200 mm loose thickness

Each bank layer thickness should be such that the bottom of each layer is compacted to the specified relative compaction and can be tested by the specified test methods. While compaction may be achieved in deeper layers by using heavier equipment or increasing the number of passes, the relative economy of various options may need to be examined.

A layer that is spread too thick will not give the desired density for given compaction effort.

The maximum particle size of any rocks or other lumps within the layer, after compaction, should not exceed two-thirds of the compacted layer thickness.

If the compacted surface on any layer is too dry or smooth to bond properly with the next layer, it should be moistened and scarified before the next layer is placed.

Photos\construction\cg6 ripping btw layers.jpg

Photo 19-9 Bulldozer scarifying bank layer before placing next layer.

If the surface of any compacted layer is too wet for proper compaction of the next layer, it should either be removed, allowed to dry or harrowed to reduce the moisture content to the required amount, and then re-compacted before the next layer is placed.

19.6.7 Compaction

The compacted bank should be placed in layers of 0.15 metres or less.

During bank construction, there needs to be careful control over compaction control.

The material can be compacted using dozers, scrapers, trucks, rollers or other heavy machinery, to a density of at least 95% of the laboratory maximum dry density, in successive layers of not more than 150mm loose.

Each layer of bank material should be compacted as a systematic construction operation, using plant that is specifically assigned to the compaction task and which tracks progressively across the surface of the channel bank. Construction and earthmoving plant may be routed to assist in this regard.

To ensure that the moisture content and density requirements of the compacted bank are being met, field and laboratory tests need to be made at regular intervals. Refer to Section 16, Compaction Control. Materials not meeting the specified moisture content and density requirements, as determined by testing, should be reworked until the specified results are obtained. Re-working may include removal, reconditioning, re-rolling or a combination of these.

If there is a delay in the placement of subsequent bank layers, moisture content of the previous layer must be checked before further bank material is placed. If this layer has wetted up or dried out, this may inhibit compaction or cause heaving of subsequent layers.

If the compacted surface on any layer is too dry or smooth to bond properly with the next layer, it should be scarified to a shallow depth and moistened before the next layer is placed to ensure proper bonding with the overlaid material. Where a sheepsfoot roller is being used and the layer can be penetrated by the roller's feet, no scarification is usually necessary.

When compacting by track rolling it is important that the surfaces of successive layers are lightly scarified to minimise laminations in the bank.

The surfaces of all bank layers should be shaped to provide drainage and to prevent ponding which will cause deterioration of previously compacted bank layers.

19.6.7.1 Moisture Control

An adequate water supply needs to be available for construction purposes.

During bank construction, control of moisture in the bank material is imperative. Moisture should be kept within the specified limits, generally between 2% wet or dry of *Optimum Moisture Content*. Refer Section 16, Compaction Control.

Material having a placement moisture content of more than 2% dry of the optimum condition or more than 2% wet of the optimum condition should be rejected and should be removed or reworked until the moisture content is within these limits.

As far as practicable, the material should be brought to the optimum moisture content in the borrow pit, prior to delivery to the bank. If the moisture content of the borrow material is non-uniform, the material should be mixed to provide a consistent moisture distribution. Care is required to ensure that mixing or blending does not produce segregation of the borrow material. Supplementary water if required, can be added to the material by sprinkling on the bank.

Control of moisture content should be applied not only to the upper layer of uncompacted material, but also to the material of the previously compacted layer. This surface material should be brought to within the specified moisture range before it is covered by a new layer.

If the moisture content of the borrow material falls below the specified minimum, water should be added either on the bank layer or at the cut/borrow area before it is transported to the bank area. Water applied on the borrow material should be finely sprayed and uniformly blended throughout the full depth of the material. It is important that the water is given time to soak in and so ensure an even distribution of moisture throughout the soil. This can be done by watering well in advance of excavation. Ripping or ploughing before watering can help even distribution. The use of alternative borrow pits can also help to provide sufficient time to achieve an even water distribution.

Photos\borrow pits\shep4 wetting borrow.jpg

Photo 19-10 Wetting borrow material

The surface of each compacted layer must be kept moist. Any water lost through drying must be replaced by spraying from a water cart, being careful not to puddle or over-water. No standing water on the bank should be permitted. If this cannot be done, then the zone should be removed before placing the next layer.

Refer to Section 16.8.1, Moisture Content.

If the borrow material is too wet for proper compaction, the material should either be worked with harrows to reduce the moisture content to the amount specified, allowed to dry until such time as the material contains only the specified moisture content or the material should be removed from the bank. Drying of the material may be accelerated by aeration or by blending with drier materials.

Surface heaving may occur as a result of compacting material approaching saturation. The development of surface heaving on channel banks may be avoided by the following:

a) Ensuring that the moisture content of materials during placement avoids near saturation at the specified density.
b) Providing drainage on the surface of channel banks and preventing the ponding of water on channel bank layers.
c) Selecting appropriate earthmoving and compaction equipment.

If rain is threatening or the site is to be left unattended, the upper surfaces of bank layers should be crowned and if possible, sealed with rubber-tyred or smooth-wheeled plant and graded to prevent ponding.

Compaction operations should cease during very wet or freezing weather conditions as they will hamper compaction.

19.6.7.2 Density Control

A specified density of 95 to 98% of the Maximum Dry Density will normally provide adequate stability and impermeability (refer Section 16.8.2).

Where density testing shows the relative compaction of the bank material to be below the specified level, all material represented by the test, or tests, should be rejected.

The rejected material should be re-worked or further compacted until it exceeds the minimum compaction requirements, as confirmed by further testing. Additional moisture blending or drying out may be required to facilitate re-compaction. Re-working may include removal, re-conditioning, re-rolling or combinations of these.

19.6.8 Batter slopes

The correct slopes on the inside and outside batters should be maintained during construction of the bank.

19.6.9 Trim

The standard of surface trim of the completed earthworks should be specified in the documentation.

Upon completion of the compacted bank, all slopes should be trimmed to remove loose material, which may cause small slides or erosion. The final trim of batters is usually done by hydraulic excavator.

The trimmed and compacted outside batter face should have a roughened surface to reduce run-off velocities and aid re-vegetation.

The surface of the finished waterway section should be trimmed to provide an even surface in contact with the water.

19.7 Construction Tolerances

Bank construction levels should be regularly checked to ensure that the compacted bank is within the tolerances. If the bank is constructed too high, unnecessary costs are incurred, and if the bank is constructed too low the channel freeboard is reduced and the safety of the channel can be compromised.

Typical construction tolerances for earthen channel banks are as follows:

Bank height -0m to +0.1m	(Refer to Section 12.18)
Crest width -0.2m to +0.2m	(Refer to Section 12.18)
Moisture Content -2% to +2% of *optimum moisture content*	(Refer to Section 16.8.1)
Bank Density -0% to +5% of *maximum dry density*	(Refer to Section 16.8.2)

Rigid adherence to these tolerances may at times prove impractical and it is recommended that reasonable judgement be exercised in controlling tolerances. Tight specifications and construction tolerances add significantly to costs and realistic requirements need to be established for channel bank work. Where ever possible, the liberalisation and simplification of channel bank specifications should be pursued to lower construction costs.

19.8 Construction Records

Adequate records need to be kept during construction, including conditions encountered, works as executed, testing and any alterations to the specification and drawings. As a minimum, these records should show the following:

a) Location of any trees or large shrubs that may have been removed.

b) Levels after stripping.

c) Materials exposed after stripping and the criteria upon which the decision to cease stripping was made.

d) The areas in which bank material is placed.

e) Types of bank material in various zones, if applicable.

f) Levels after completion of the channel bank.

g) Location and level of each compliance test, together with test results. Where a test is a re-test of an area which was previously rejected, this should be stated.

h) Action taken where testing indicated that the specified criteria had not been met.

Any areas in which the channel bank material or compaction is to be of a lesser or greater standard than elsewhere on the site should be clearly identified.

19.8.1 Daily Site Records

For larger projects, daily diaries and detailed drawings of works, as executed, should be maintained by site staff. For smaller projects, simpler records may suffice in summarising the works as executed.

Site records must be kept in order to track progress and costs of each earthworks project. Types of information would include:

- No. of personnel on site
- Plant on site
- Volume of earth placed
- No. of compaction tests
- Work hours
- Breakdown and standby times
- Instructions issued
- Conversations between parties
- Visitors to site
- Weather info: rainfall, temperature range, visibility

19.8.2 Geotechnical reports

In addition to the daily site record, a daily geotechnical report may be appropriate.

i) A daily geotechnical report, generally appropriate for larger projects. An example *Daily Geotechnical Report* is given in Figure C1 of AS3798.

ii) A geotechnical site visit record; and

iii) An earthworks summary report, generally appropriate for small projects.

19.9 Final check survey

When construction of the bank is complete, a check should be made on all levels and dimensions to ensure conformity with design. The final check survey may consist of the following measurements:

a) Levels on each bank crest, and channel bed, at 25 metre intervals

b) Widths of bed and bank crests at the same points as levels are taken.

Ensure the batter slopes are neatly finished and the site has been satisfactory cleaned up.

19.10 Access Tracks

Tracks are formed on bank crests simply by finishing the bank with an outward cross fall of 1 in 40 and sheeting with a 100mm layer of gravel, if all weather access is required.

19.11 Sediment Control during Construction

Channel construction projects can lead to environmental damage when soil, exposed by earthworks, is eroded and transported as sediments by stormwater runoff.

The minimisation of erosion and the prevention of sediment movement should be considered as an essential component of any project.

An erosion and sediment control plan appropriate to the individual site should be prepared, for all projects that could contribute to sediment contaminated runoff. The plan may include the following actions:

- minimise the extent and duration or earthworks disturbances
- install filter/sediment fences on low sides of sites
- re-vegetate and stabilise all bare areas as soon as possible.
- construct temporary catch drains
- divert clear runoff water around site
- install silt traps
- limit and control site access
- locate stockpiles away from drainage lines and divert runoff around them.

Typical control devices that are available include grass filter strips, sediment filters such as straw bales and silt fences.

The Plans should comply with the relevant State guidelines or Codes of Practice.

In Victoria they are:

- Environmental Guidelines for Major Construction Sites (EPA 1996)
- Construction Techniques for Sediment Pollution Control (EPA 1991)

19.12 Protective Cover on Crest and Outside Batters

As soon as the bank has been constructed to its design height, a protective cover should be placed over the crest and batters, to prevent the drying out and cracking of the compacted bank. Refer Section 17.

19.13 Control of Inside Batter Erosion

Where soil types, wind and wave action are likely to cause accelerated deterioration of the inside batters, some form of protection should be considered. These methods are described in Section 18.

19.14 Protective Fencing

Longitudinal fencing can protect channel banks from stock, adjacent farm practice etc. Fencing should be erected as soon as practicable after the completion of the earthworks. Refer Section 12.22.

19.15 Inspection

When construction of the channel is complete, a check should be made on all levels and dimensions to ensure conformity with design. All batters should be neatly finished and the site clean up, access track, protective cover, inside batter protection and fencing should all be in accordance with design.

19.16 Documentation

Documentation throughout a channel construction project is important:

- to ensure that the channel is constructed in accordance with the design drawings and specifications.
- to take into account any adjustments to the design which may been made during construction.
- for ongoing asset management of the channel by the channel operator.

Essentially the documentation process consists of

1. *Design Phase*: Design Plans and Specifications
2. *Construction Phase*: Collect *as constructed* data and create *as constructed* drawings.
3. *Commission the asset*
4. *Operation and Maintenance Phase*: Implement maintenance programs and condition monitoring

19.17 First Filling of Channel

The first filling of a new channel that has never had water in it should be done gradually, sometimes over a period of several days and preferably not faster than 0.3m in water height per day to allow the banks to consolidate.

19.18 Site Restoration

Restoration of areas affected by construction activities such as borrow pits, stockpiles, excavated or fill batters, spoil disposal areas, haul routes, stormwater control, worksites, should be included in the drawings and specifications so that materials such as topsoil, mulched native vegetation (which can contain useful seedstock and nutrients) and bulk fill materials used for restoration are identified and preserved for re-use. Restoration works should be completed before the constructor vacates the site.

19.19 Guidelines on Field Quality Control for Small Projects

19.19.1 Material Selection

Refer Section 15.10, Tests for Small Projects.

19.19.2 Compaction

Refer Section 15.10, Tests for Small Projects.

19.19.3 Physical Dimensions

At all times the dimensions should be within the tolerances in the specification Refer Section 19.7.

19.20 Example Specifications

1. Stripping should remove all topsoil. Trees and root systems within the existing channel banks are to be completely removed.

2. Stripped foundation for compacted banks to be ripped to minimum 0.2m deep and then compacted as specified in Note 3 before any new material is placed.

3. Compacted banks are to be constructed from selected material that is not dispersive in channel water, placed in layers not exceeding 150 millimetre in depth and compacted to a minimum of 95% of the maximum dry density determined in accordance with Standard Compaction Test as specified in AS1289.5.1.1. Where laboratory determined compaction curves are not available, the allowable variation from optimum moisture is –2% to +2%.

4. The constructed bank tolerances are –0m to 0.1m in height and –0m to 0.2m in width.

5. Protective cover is to placed over crest and outside batter as soon as possible after completion of compacted bank. Protective cover is to comprise of topsoil or equivalent material from stripping to minimise shrinkage and dispersion of compacted bank and encourage grass cover.

19.21 Australian Standards

AS 1726-1993	Geotechnical site investigations
AS 1289.3.8.1-1997	Soil classification tests - Dispersion - Determination of Emerson class number of a soil
AS 1289.5.3.1-1993	Determination of the field density of a soil - Sand replacement method using a sand-cone pouring apparatus
AS 1289.5.3.2-1993	Determination of the field dry density of a soil - Sand replacement method using a sand pouring can, with or without a volume displacer
AS3798-1996	Guidelines on earthworks for commercial and residential developments

19.22 References

Environment Protection Association of Victoria (1991), *Construction Techniques for Sediment Pollution Control*

Environment Protection Association of Victoria (1996), *Environmental Guidelines for Major Construction Sites*

Mason RG (1967), *Survey Division Handbook*, State Rivers and Water Supply Commission of Victoria, June 1967

Nelson KD (1985), *Design and Construction of Small Earth Dams*, Inkata Press, Melbourne

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20. Channel Bank Refurbishment

Table of Contents

Subject **Page No.**

20.1 Scope

Australia's earthen irrigation channels are ageing and considerable lengths of channel bank will require refurbishment in the next 20 years. There comes a time when refurbishment of a channel is necessary because of:

- physical condition
- changing water and land use
- inadequate initial design
- operational efficiency
- economic position
- environmental constraints

Like other infrastructure problems, available funds will be limited and irrigation managers will need to seek the most cost-effective solutions.

In the southern States, large-scale irrigation development has substantially finished. Fewer new channels are now being constructed and the emphasis is turning more to the maintenance and refurbishment of existing channels.

Refurbishment works on existing irrigation channels generally have constraints due to operational requirements, climate conditions, drainage of channels and the short periods available for work. Thus channel bank refurbishment presents special challenges.

While there are some texts on how to design and construct new irrigation channels, virtually no texts or manuals could be identified during the course of this research project on the special problems of refurbishing old irrigation channels.

This section provides information on earthen channel bank refurbishment techniques that have generally proved to be practical and cost-effective under Australian conditions.

Reference should also be made to Section 19 on Channel Bank Construction, for details that apply equally to new channel construction and channel bank refurbishment.

20.2 Introduction

Earthen channel banks deteriorate with the passage of time. Bank material pushed into the waterway by stock, combined with erosion of the batters and sediment deposition, reduces waterway areas and creates conditions that encourage the growth of aquatic weeds. Capacities are therefore reduced and they are re-gained by raising operating water levels and steeper water surface grades. The consequent reduction in freeboard combined with increased rates of bank erosion, results in the need for earthworks to be refurbished.

As channels reach the end of their life deficiencies in the channel's performance may occur as follows.

1. Poor level of customer service
   - inadequate capacity
   - inadequate supply level – command

2. Cost to Authority
   - high operational costs – need for close supervision by operational staff
   - high maintenance costs
   - reduced metering accuracy of Dethridge outlets
   - reduced operational inefficiency
   - increased water losses

3. Safety
   - reduced freeboard and increased overtopping of channel
   - increased risk of failure due to deteriorated banks.

4. Damages to adjacent property and environment
   - increased rates of seepage, leakage and overtopping – damage to property, agriculture and roads
   - increased water logging, ground water accessions and loss of production

The decision to refurbish a channel bank is usually based on one or more of the following factors:

- poor levels of service to customers
- inadequate capacity
- low operational efficiency
- low structural integrity – the channel is in danger of failing physically
- exceedance of economic life – high operation and maintenance costs

Channel bank refurbishment will give extra life to an existing channel and can be applied at several stages of a channel's life cycle as shown in Figure 20.1.

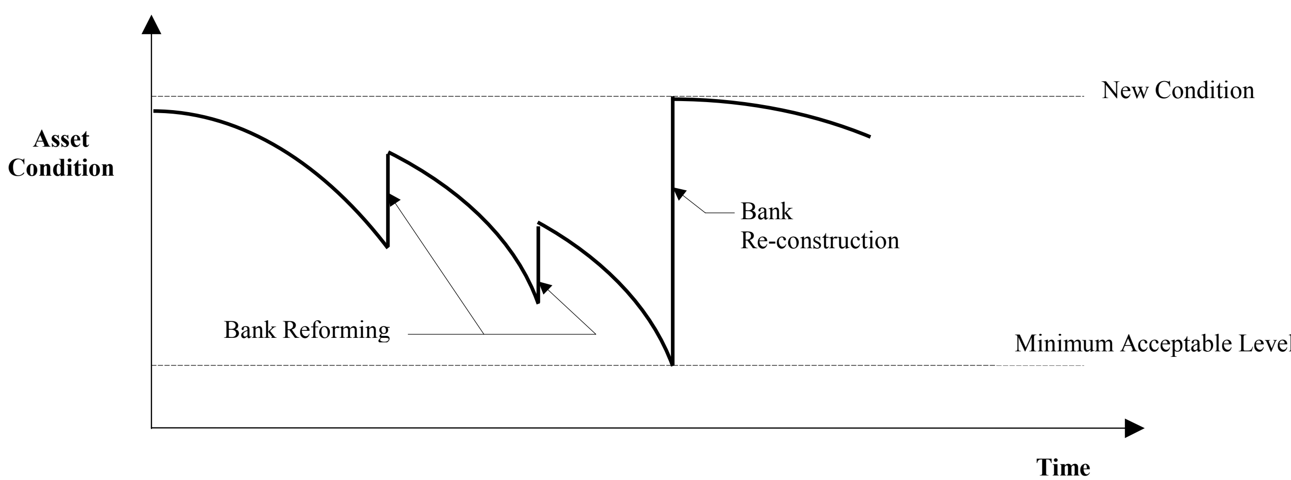


Figure 20.1 Earthen channel life-cycle

Refurbishment includes bank *re-forming* and bank *re-construction.* Re-forming can extend the life of a channel while bank re-construction gives an *as new* status to the bank. Channel bank re-construction is often referred to as *Channel Remodelling*, particularly in Victoria.

Bank re-construction normally requires material to be imported to the site, while bank reforming may use eroded bank material (EBM) and old bank material as the re-construction material.

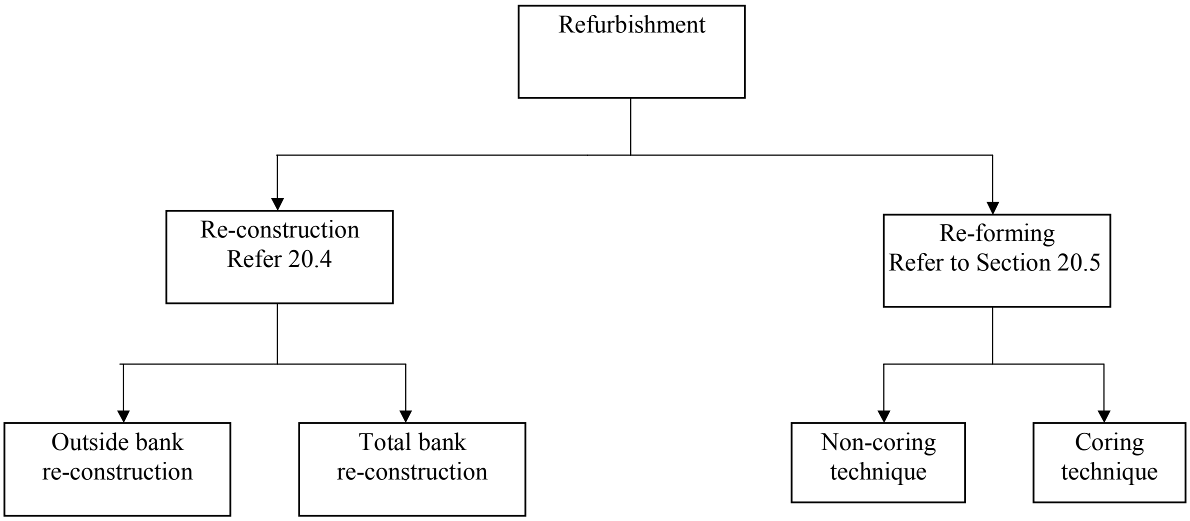


Figure 20.2 Refurbishment options

20.3 Design Procedure

Refurbishment investigation will depend on the size and scope of the project. Although design for refurbishment is based on the same engineering principles as are used in the design of new earthen channels, it requires a rather different form of preparatory investigation. Refurbishment usually deals with channels that have been supplying water to farms for a very long time, but have become inadequate. These channels need to be investigated thoroughly to find out precisely why they are inadequate before refurbishment measures can be proposed. Since refurbishment may change the way in which water is supplied to irrigators, may require more land to accommodate the channels, and may temporarily disrupt farming activities, the re-design must have regard to the rights and needs of irrigators in developing refurbishment proposals.

The investigation and design procedure for channel refurbishment typically covers the following steps:

1. Assessment of the current and future physical conditions and constraints:

   - operational risks and security of supply
   - change in circumstances since construction
   - review previous investigations
   - frequency of complaints from customers
   - consultation with channel managers and operators
   - assessment of channel performance
   - levels of service
   - operational efficiency
   - channel flows
   - deliveries

- outfalls
- proximity to urban development
- land use capability
- water quality
- soil types
- water trading history
- farming trends
- water logging groundwater problems loss of production
- location of any features which could effect design or construction
- seepage
- leakage
- assessment of original design plans and records
- inspection of works
- asset condition and remaining life
- access
- freeboard
- flow measurement and control
- level fluctuations
- existing channel and structure capacity
- command problems
- safety
- maintenance costs
- metering accuracy
- engineering survey
- geotechnical investigation
- environmental issues
- heritage issues

2. Determine physical requirements for the channel:

- design supply levels
- required service life
- regulator/check-type locations and water surface profile
- determine capacity requirements
- location, type and size of channel structures
- operational mode; automatic control, upstream level control, downstream level control
- determine required water levels
- channel waterway
- bank topping and widening
- channel de-silting
- storm influence water
- freeboard
- flow measurement and control
- outfall facilities
- channel shutdown
- SCADA

- meter outlet locations and type
- earthworks cross section
- need for seepage control
- cross drainage (subways/siphons)
- access for operation and maintenance
- land acquisition type and extent
- fencing
- availability of borrow material suitable for bank construction
- public utility services requirements – works of other authorities
- environmental effects
- farm works reinstatement

3. Identification of Options including non-asset solutions

   - Refurbish channel
   - Rationalise channel
   - Replace with pipeline
   - Cease supply

4. Preliminary estimates of cost and economic evaluation of feasible options

5. Detail design of most cost-effective option:

   - identify farm works (landowner consultation)
   - determine structure widths (bridges/culverts)
   - identify public utility/services requirements
   - prepare earthwork schedule
   - prepare structure detail designs
   - prepare farm work designs if required

6. Preparation of design drawings

   - locality plan
   - longitudinal sections
   - schedule of works
   - structure details
   - land acquisition details
   - farm works

7. Prepare estimate of cost

20.3.1.1 Site Inspection

The first action in an investigation is an inspection of the channel. The designer needs to have an overall visual impression of the size and condition of the channel, with attention to the general standard of earthworks and structures, the type of country and farming through which it passes, and any other associated facilities or services.

20.3.1.2 Surveys

Survey is required to locate the existing channel in relation to title boundaries, define exactly the dimensions and levels of the earthworks and all structures, and locate and describe all features within the proximity of the channel.

The intervals at which cross-sections of the earthworks should be surveyed depend on the uniformity of the channel waterway and banks. Where the width and depth of the waterway and the height and width of the banks appear to be fairly constant over a length of channel, intervals of 150-200 metres may be suitable. Where these vary considerably, for example, where a channel crosses a depression, closer intervals may be specified. Inspection of the channel will indicate the intervals that should be specified to obtain a complete representation of the channel.

Survey Specification, section 20.10.

20.3.1.3 Consultation

Essential information can be obtained by discussing aspects of the existing channel and proposals for refurbishment with operations staff and landholders.

The designer needs to carefully weigh information offered in discussion and recognise and discard that which is erroneous or misleading and accept useful factual information as an essential part of the analysis.

It is important that the landholders be consulted. Landholders to be affected by proposed works should be interviewed and they should have the opportunity of putting their views and these views should be considered in the design.

Certain design proposals may raise strong objections from landholders, and in some cases, lengthy negotiations and examination of alternatives will be necessary before a contentious matter is resolved.

All landholder negotiations should be fully documented to form a record of dealings.

20.3.2 Identification and Solution of Problems

The following operational requirements must be satisfied:

1. Channel capacity must be adequate to provide a satisfactory service
2. The safety of the channel must be assured
3. Supply levels must be adequate for adjacent land to be irrigated
4. Channel must be capable of efficient operation
5. Channel must be able to be satisfactorily maintained

20.3.2.1 Seepage

The loss of water by seepage through the bed and batters of earthen channels can have undesirable consequences. This is discussed in full in Section 21.

In the case of channel bank refurbishment, the question of seepage needs to be considered from two points of view, that is, the existing rate of seepage from the channel if no waterway excavation is proposed, and the potential rate of seepage after refurbishment whose waterway excavation is proposed.

Where there is any reason to expect seepage problems, investigation is required.

20.4 Re-Construction Techniques

Re-construction is different from new construction in that the works are related to an existing operating channel, as opposed to first-time construction on a green field site.

It is often necessary to arrange for works to be carried out in both the irrigation and non-irrigation seasons to achieve a balanced use of construction resources and to avoid adverse weather conditions.

The channel section may be refurbished completely by re-construction of the banks and excavation of the waterway or the banks can be re-constructed alone.

The typical sequence in a complete re-construction is as follows:

1. Stripping
2. Construction of the compacted bank
3. Shaping the batters
4. Excavation of the waterway, if required
5. Bed of channel graded out to allow for drainage
6. Application of Protective Cover over Crest and Outside Batters
7. Application of Inside Batter Protection, if required
8. Fencing, if required
9. Construction of Access Tracks, if required.

Two general approaches to bank re-construction are used in Australia:

- Outside Bank Re-Construction
- Total Bank Re-Construction:

20.4.1 Outside Bank Re-Construction

Outside Bank Re-Construction retains a small width of bank so that the new bank can be constructed while the channel is operational. The total bank is not replaced. The outside of the existing bank is removed leaving approximately 0.5 metre minimum bank width at the water level to contain water during construction, and imported material is then used to reinstate the bank.

Photos\refurbishment\CG5-19-6channelremodelling.jpg

Photo 20-1 Outside Bank Remodelling – one third of original bank remains adjacent to waterway

In this method, the new banks are not constructed on the location of the old banks, but at the back of the old banks. This allows year-round construction while channels are operating and so avoids works being restricted to the short non-operational periods where there is often poor site conditions due to wet weather.

With outside bank re-construction, the established silt seal is not disturbed. Whereas with total bank reconstruction, the silt seal is removed and this may increase seepage for a period of time in lighter soils.

There are disadvantages to this method as against total re-construction of channel banks:

- The technique further widens the waterway width than its original design; therefore velocities are slow, and increased siltation and weed growth may occur.
- Increased evaporation and seepage as there is a greater water surface and wetted perimeter
- Increased volume of water required to fill channels
- Land acquisition may be required to accommodate a wider channel profile

• Material Selection	Refer Section 15
• Compaction	Refer Section 16
• Construction	Refer Section 19
• Waterway excavation, if required	Refer Section 20.4.1.5
• Re-batter inside batters	Refer Section 20.4.1.5

A typical re-construction approach would consist of:

1. Dozer strips the outside portion of bank down to solid base, a minimum of 200mm below natural surface level, leaving approximately a 0.5 metre minimum bank width at the water level to contain water during construction. The water face of the bank is left untouched at this stage.

2. Dozer scarifies the surface of the bench.

3. Trucks deliver material onto the bench from the borrow pit.

4. Dozer spreads and compacts material on the bench in layers to required compaction density.

5. When the compacted bank design height has been reached, protective cover is placed over the crest (if no access) and outside batters.

6. The waterway is enlarged, if required.

7. The inside batters are re-shaped to establish a stable profile.

8. If required a layer of protective granular material is placed on the water face of the bank.

9. Access track is constructed.

10. Longitudinal fencing if protection is required.

Refer to Section 19 on Channel Bank Construction.

20.4.1.1 *Stripping*

With outside bank re-construction, stripping actually takes the form of benching to prepare a suitable shape for the placement of new bank material. Depth of stripping to a reasonably solid impermeable base will depend on site conditions. The width of the bench will depend on the bank cross-section, the width of construction equipment or the access required for trucks. The stripped material is stockpiled clear of the finished bank toe or run into the old borrow pits (if existent). Sufficient bank width is left to hold water in the channel while reconstruction is completed. Short sections only should be opened up at a time to minimise the risk of banks failing in the process.

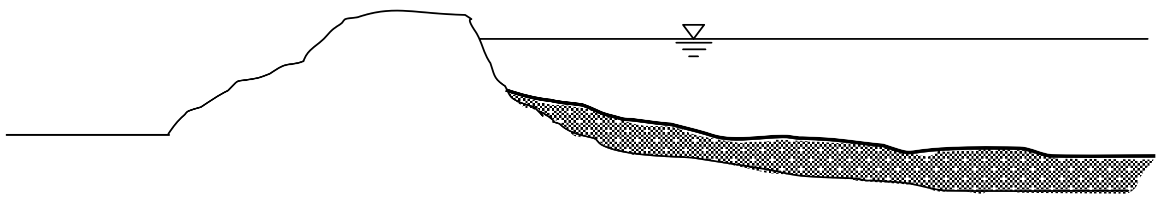


Figure 20.3 Existing deteriorated bank

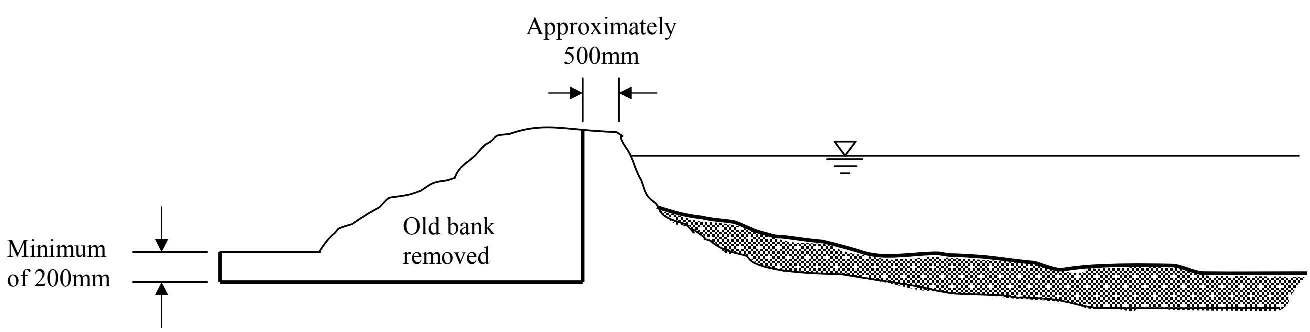


Figure 20.4 Outside Bank Remodelling – removal of old bank and stripping

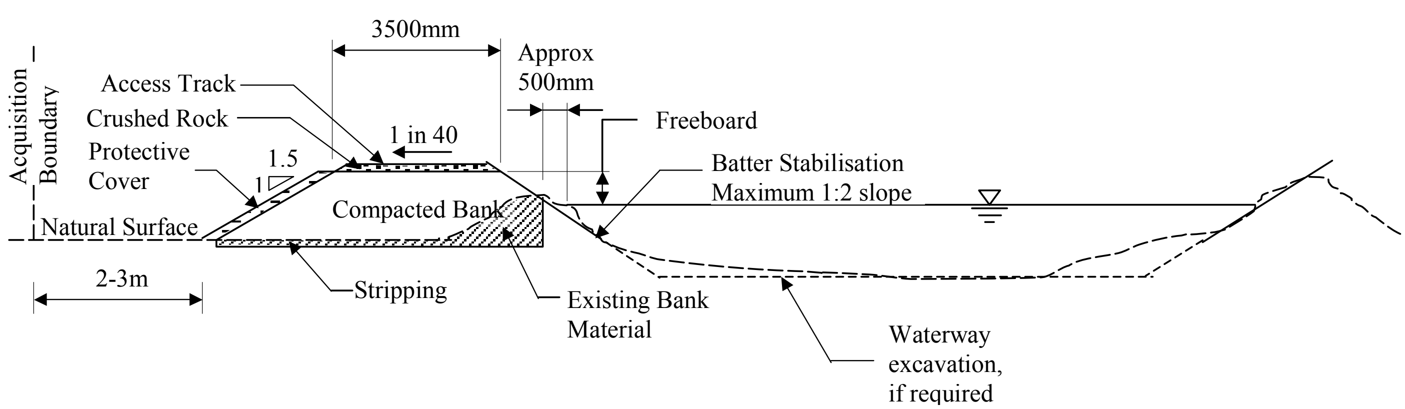


Figure 20.5 Re-constructed bank & re-establishment of inside batter

20.4.1.2 *Excavation*

Excavation may comprise full or partial waterway enlargement, or may be confined to re-shaping of the batters.

20.4.1.3 *Compacted Bank*

Material that is suitable for construction of bank is obtained from borrow sites. Sites are selected after testing of soil samples and agreement with landholders on suitable locations for borrow sites.

Excavation can be carried out with either bulldozer and loader or hydraulic excavators. Material is transported to the channel bank by tip-trucks and placed on the prepared bank seat in layers. Each layer is spread and trimmed by the bulldozer and watered if necessary to ensure correct moisture content. Compaction can be achieved through loaded trucks and bulldozers passing over the layers, or by compaction equipment such as sheepsfoot rollers. Material is placed, compacted and trimmed in successive layers until the re-design height and width of the compacted bank are achieved. The diagram in Figure 20.6 illustrates the construction cycle for a typical compacted bank.

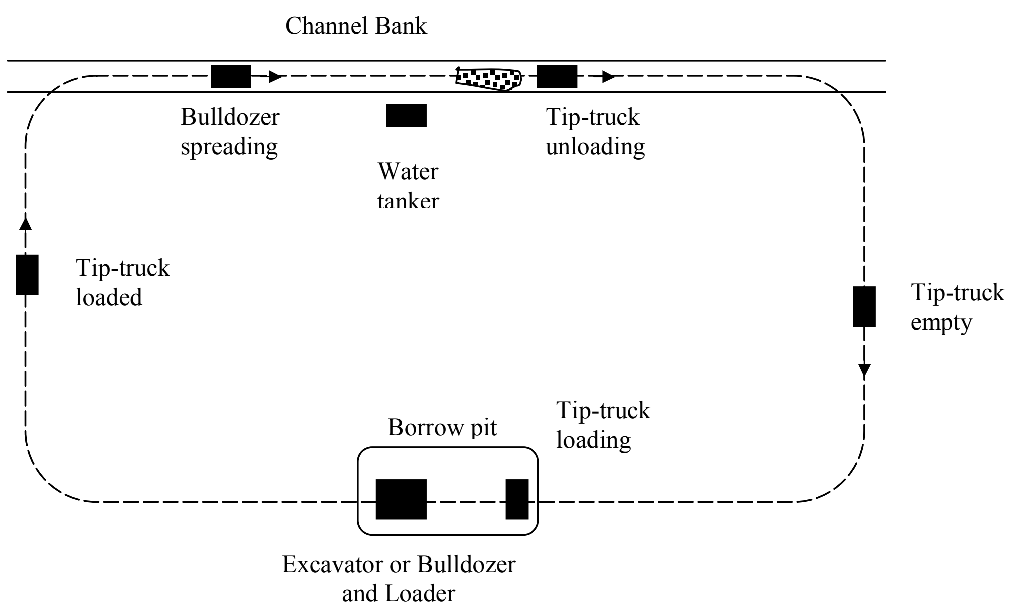


Figure 20.6 Typical compacted bank re-construction cycle

20.4.1.4 *Haul Roads*

Heavy Truck traffic between the borrow pit and the work site can cause accelerated deterioration of public roads and the trucks must be kept within the limits of their gross vehicle weight.

Prior to commencement of haulage on public roads, the Road Authority should be advised.

All public roads to be used by trucks should be inspected before and after the works to assess if any damage has occurred, and whether compensation to the Road Authority may be payable.

20.4.1.5 *Waterway excavation and re-battering of inside batters*

Is carried out by hydraulic excavator working from the newly constructed bank along either or both sides of the channel. The material is placed on the outer batters of the compacted banks.

20.4.1.6 *Protective Cover over Crest and Outside Batters*

Appropriate material, refer Section 17, is placed over the compacted bank.

20.4.1.7 *Batter Re-establishment*

Where inside batters are eroded, it is necessary to return when the channel is empty and reinstate the inside batters to a stable slope. Refer to Section 12.17.4 Batter Slopes and Table 12-11 for a guide to the maximum batter slopes recommended for saturated bank materials. Slopes of 1:2 are the steepest that should be considered unless granular material is provided for bank protection. Refer Section 18, Inside Batter Treatment. If this does not occur, erosion of the unstable inside batter will continue with the undercutting and slumping cycle and the new bank will deteriorate at an increased rate.

20.4.1.8 *Fencing*

Refer Section 12.22.

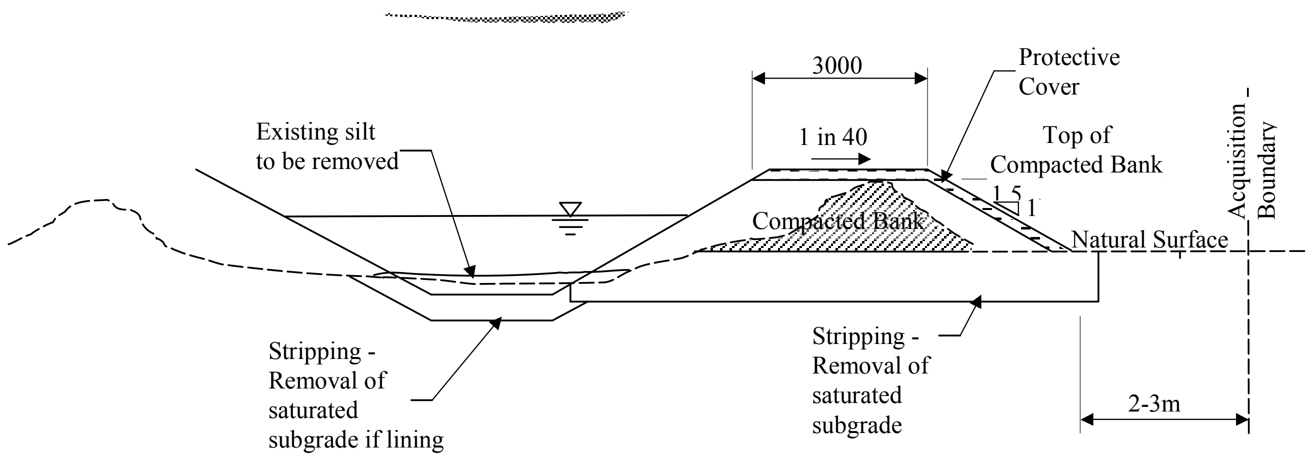
20.4.1.9 *Access Tracks*

Refer Section 12.17.10.

20.4.2 Total Bank Re-Construction

This technique is also referred to as Inside Bank Re-construction.

A diagram showing total bank re-construction is shown in and Figure 20.8. Outside bank re-construction is not always an appropriate technique and total bank re-construction may be required.



F tal Bank Re-Construction

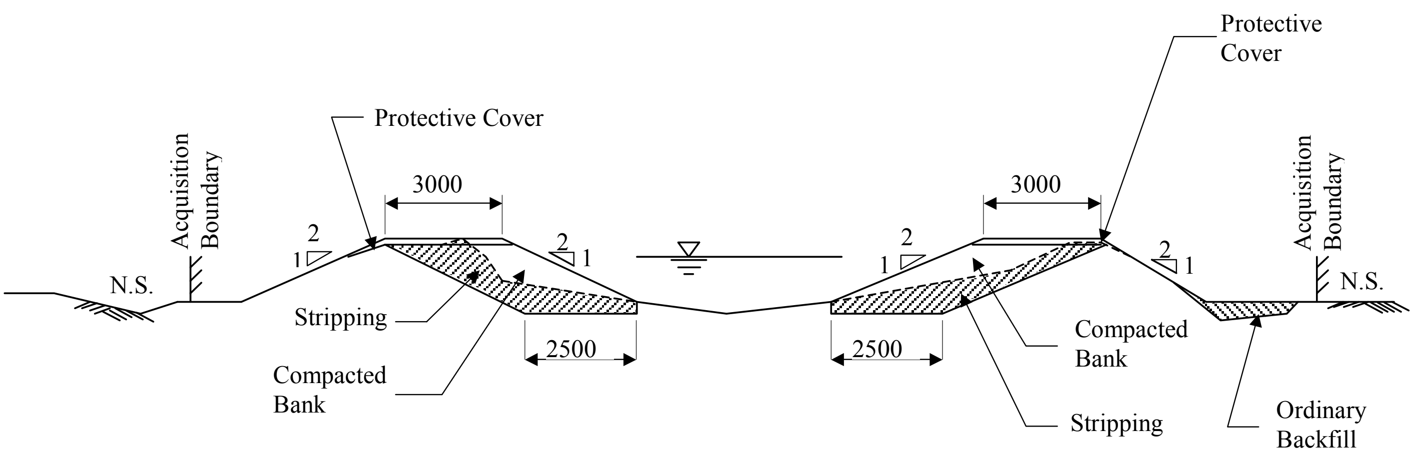


Figure 20.8 Alternate Inside Bank Re-construction Technique

The advantages are:

- can be used where there is limited space available to build onto the outside of the bank
- avoids the need to relocate adjacent on-farm works
- waterway width and channel filling volume is not increased
- seepage and evaporation losses are not increased

As the entire bank must be removed, this technique can only be carried out during the non-operational period.

Stripping is required to remove all the deteriorated sections of the existing bank and EBM from the bed of the channel. Then re-construction can proceed as for a new channel.

Refer to Section 19 on Channel Bank Construction.

A typical re-construction approach would consist of:

1. The channel is de-silted using a hydraulic excavator
2. Dozer completely removes the old banks down to natural surface level
3. The area under the banks is stripped down to a solid base
4. Dozer scarifies the surface under the banks

5. Material is delivered by trucks from borrow pit
6. Dozer spreads and compacts material in layers to required compaction density
7. Compacted bank is constructed to design shape and height
8. Protective cover is placed over the crest (if no access) and outside batters of the compacted bank.
9. Inside batter is trimmed to line and if required a layer of protective granular material placed on the water face. Refer to Section 18, Inside Batter Treatment.
10. Access Track is constructed.
11. Longitudinal fencing is installed if protection is required.

Photos\refurbishment\shep3 tipping&spreading.jpg

Photo 20-2 Dump truck tipping borrow material to be spread by bulldozer

Photos\refurbishment\shep2 track rolling.jpg

Photo 20-3 Bulldozer track rolling

Because the work is being carried out within an existing channel, the subgrade could well be saturated and it may be necessary to over-excavate and backfill with imported material, to overcome the wet ground conditions and support the trucks. Consequently, more imported material will be required compared with new channel construction.

If the de-silted channel bed is assessed as having an unacceptably high seepage rate, it will need to be lined. Refer to Section 22, Channel Lining.

The cost of total bank re-construction is usually higher than outside bank rebuilding because the:

- sub-grade can be saturated and it is necessary to over-excavate and backfill with imported material
- wet weather conditions encountered during the non-operational period are not favourable for earthworks
- seepage rate from the channel bed after desilting can be unacceptably high and it is necessary to line the bed

20.4.3 Deficiency in quantity of soil for bank re-construction

When a channel bank is in need of re-construction it has generally lost most of the earth it was originally constructed with, by erosion. Therefore material must be found to re-construct the bank. With new channels the earthworks can be usually balanced between cut and fill to reduce the amount of imported material. However, with channel re-construction a greater quantity of imported earth is required.

Refer to Section 15.2 Investigation of Material.

For economic construction, borrow material should be sought as close to the channel site as possible. Material for bank re-construction is normally obtained by opening up borrow pits on properties in the immediate vicinity of the works.

The borrow pits are generally used by landowners as farm re-cycling dams, and all landowners within economic distance of the work site should be approached either personally, by letter or through advertisement in a local paper to determine if they are interested in the construction of a farm dam. This could include an offer to pay royalties for material excavated from dams, as an added incentive to landowners in close proximity to the work site. For economical construction, the minimum size of a dam is typically 40m x 40m.

A typical earthworks equipment cycle for re-construction works is shown in Figure 20.6.

In some situations, it may be acceptable to over-excavate the channel waterway and use this material to re-construct the outside of the channel banks or top the crest of the bank to increase freeboard.

20.4.4 Fill against structures

Fill, adjacent to structures, such as pipes, culverts, abutments, retaining walls or other structural components, may need to take into account the following:

a) The strength or age of cast in-situ concrete before filling can commence.

b) The filter zone to be provided adjacent to weep holes or other subsoil drainage systems

c) The quality of fill. Sand, natural gravel or quarry products may be specified to facilitate compaction in confined areas, to minimise differential settlement which might otherwise overload the structure or to divert seepage to subsoil or other foundation drainage systems.

d) The type and method of compaction compared with normal fill construction. Fill should be brought up equally on each side of pipes and culverts, to avoid unbalanced loading. The first layers of fill over the top of structures will require careful placement. The design should specify the depth of fill to be placed over pipes or culverts, or special conditions which might apply to other structures. In some cases, internal propping may be required if normal compaction is to be used immediately above or adjacent to structures.

20.5 Re-forming Channel Banks with Waterway Material

The material that erodes from the inside batter of a channel bank and deposits at the toe of the bank and on the bed of the channel is often referred to as *silt*. *Silt* is a scientific term used to describe a soil particle size and type, (refer Section 15.4). In this manual this waterway material is referred to as *eroded bank material (EBM)*. This is a more appropriate term to use, as this material often contains clay from the original bank. It may also contain materials which have been carried by the channel water. Refer Figure 20.9.

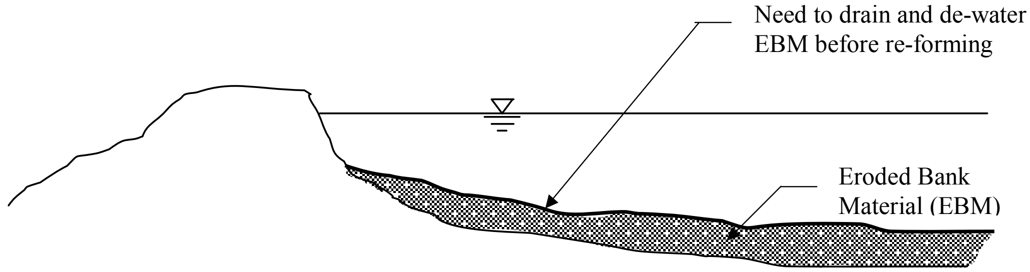


Figure 20.9 Existing Channel Profile

The degree of effectiveness of some measures reviewed is in some part based on judgement. For some there is limited data available to make a technical determination of their long-term effectiveness.

In the past EBM has often been placed over the crest and outside banks during cyclic de-silting operations.

Trials have been undertaken by Goulburn-Murray Water to use this material for re-forming of banks and stabilisation of inside batters.

The advantages of using EBM to stabilise channels banks are:

- the availability of material
- Re-constructs the channel inwards rather than outwards thus decreasing eliminating the need for land acquisition.
- EBM removal can reduce weed growth in the channel waterway and increase capacity

The limitations of using EBM are:

- The available EBM needs to be of reasonable quality. If it is of high shrinkage, cracking of the crest will occur. Highly dispersive material is also undesirable. Testing of the EBM is required at the investigation stage of the works to see if this treatment is feasible.
- material may slip down the face of the bank back into the bed of the channel.
- If the material is placed in a near saturated condition, material will not be well-compacted leading to shrinkage and cracking which reduces the effective life of the treatment. It is preferable that the EBM is dry as possible and the channel should be drained out and left to dry before the works begin.
- there maybe increased weed growth from disturbed EBM
- Removal of EBM from bed of channel may lead to increased seepage.
- There is often very little available EBM near structures due to greater turbulence. This can be overcome by importing clay to re-build banks around structures and rock-lining – this is a structural issue rather than an earthworks issue and can extend the life of the structure.

20.5.1 Bank re-forming – non-coring technique

The purpose of bank re-forming is to extend the useful life of a channel bank by taking EBM from the bed of a channel and placing it against the inside batter of the bank and the crest. The EBM then acts to stabilise the inside batter face and increase freeboard, if required.

Non-coring methods of repair increase the bank width by re-forming the bank with EBM while leaving the bank's core intact.

This method is illustrated in Figure 20.10.

Bank re-forming with EBM is typically carried out as follows:

1. channels are selected for bank re-forming according to the suitability and availability of EBM.
2. the channel is drained and the EBM is de-watered as much as possible.
3. topsoil is stripped from crest and stockpiled
4. any hollows encountered in the inside batter are filled with good clay fill, if available
5. EBM is excavated from the bottom of the channel and placed onto the inside batter and crest of bank, then shaped so that the inside batter is at a maximum slope of 1:3 and the crest is restored to a trafficable width.

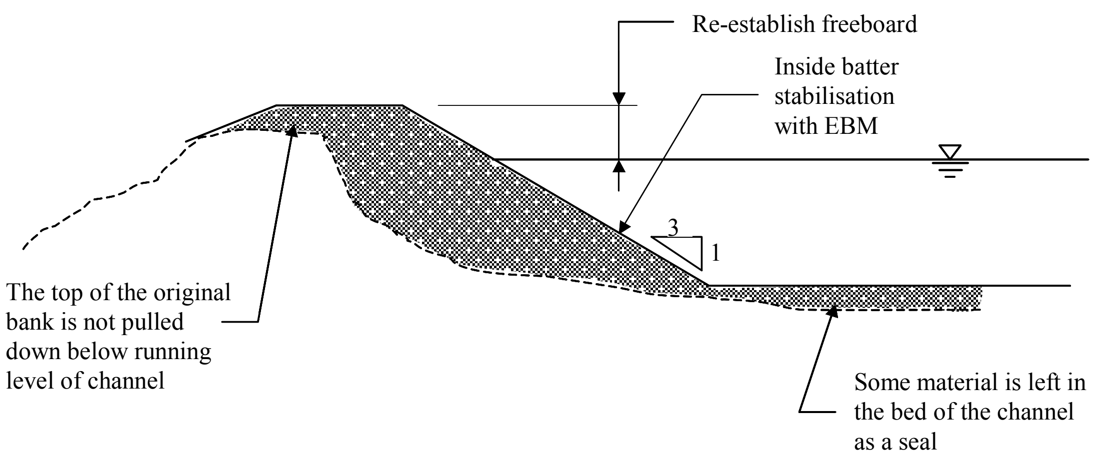


Figure 20.10 Profile after EBM Stabilisation

6. Material is left to dry
7. Crest of bank is rotary-hoed
8. The crest is shaped and trimmed with a bulldozer or grader.
9. Protective cover (refer Section 17) replaced on crest (if no access) and outside batter.
10. A layer of protective granular material is placed on the waterface if required.
11. Access track is constructed.
12. Longitudinal fencing is installed if protection is required.

Limitations of method

- Need to use with a degree of caution. G-MW has found, depending on suitability of EBM, and the deterioration conditions acting on the bank, that the life of the bank may be extended by 10-15 years. However the life extensions have varied significantly and a more conservative life extension of 5-10 years may be more appropriate to use in economic evaluations.

- Need to be cautious with this technique when increasing the original design water level by more than 150mm.

Photos\refurbishment\Cohuna channelsEBM3.jpg

Photo 20-4 Deteriorated Channel

Photos\refurbishment\Cohuna channelsEBM4.jpg

Photo 20-5 EBM pulled back into channel bank

Photos\refurbishment\Cohuna channelsEBM1.jpg

Photo 20-6 channel bank reshaped with EBM

Photos\refurbishment\Cohuna channelsEBM2.jpg

Photo 20-7 Re-formed channel

Further treatment

To allow the batter stabilisation to last for a longer period of time, the following techniques could be considered as part of the works:

1. Inside Batter Protection - beaching/gravel/granular armouring placed on the inside batter over the top of the EBM.

   Limitations of treatment:

   - Possible slip failure of EBM caused by the granular lining
   - Granular material slipping down batter as water washes underlying EBM away

2. Use of lime or cement to stabilise the EBM before it is placed on the inside batter

   Limitations of this treatment:

   - Mixing of lime or cement into the EBM to achieve the required stability
   - Leaching of the lime from the material over a period of years

20.5.2 Bank Re-forming – Coring Technique

As well as stabilising channel banks, EBM may be used to re-form banks using a coring technique. This method is used to prevent leaks from deteriorated channel banks. The typical process of bank re-forming using EBM in conjunction with coring is described below and illustrated in Figure 20.11.

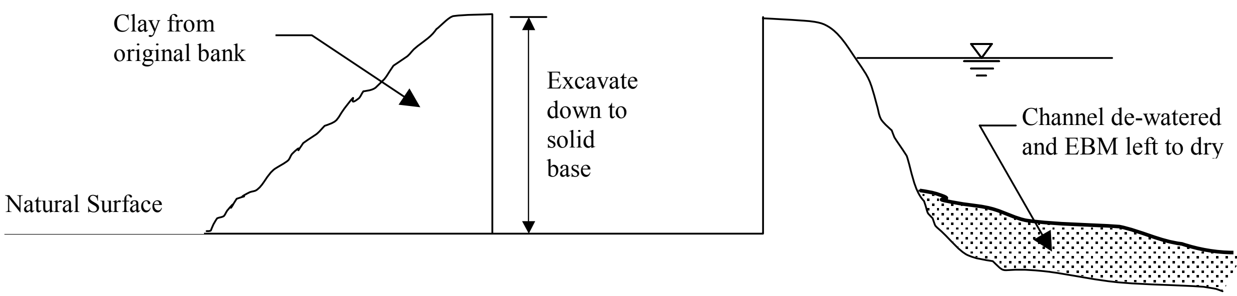


Figure 20.11 Core Excavation

1. The EBM in the channel is assessed to determine its suitability and quantity.
2. The channel is drained and the EBM is de-watered as much as possible.
3. The bank crest and batters are stripped of topsoil and vegetation.
4. A core is excavated in the centre of the bank down to a reasonably solid low permeable base using an hydraulic excavator. Refer Figure 20.11.
5. Excavated clay from the core is spread and compacted with excavator bucket against the outside batter
6. Excavated core is filled with EBM from the channel.
7. EBM is spread over the inside batter and crest and shaped.
8. After the EBM material has dried, rotary hoeing or scarifying of the bank crest is carried out.
9. Protective cover is placed over the crest (if no access) and outside batters.
10. Inside batter is trimmed to line and a layer of protective granular material is placed on the waterface if required.
11. Access track is constructed.
12. Longitudinal fencing is installed if protection is required.

EBM which is dispersive can be used. Dispersion will not affect the core until the inside batter has eroded to the core.

With the moisture within the bank, the bottom to the core remains relatively moist, reducing the chance of the whole core shrinking and pulling away from the rest of the bank, particularly if protective cover is placed over the re-formed bank. This method does however, take good clay from the core of the bank, while the EBM is placed back into the bank, thus the integrity of the compacted bank is compromised.

At some sites the rate of deterioration of the inside batters has been observed to increase significantly when the core of bank made up of the EBM is exposed to the water in the channel.

Some irrigation managers have found core trenching to be a satisfactory refurbishment option, with channels in good condition 15 years after trenching.

Nevertheless the majority experience has been less satisfactory and the consensus view seems to be that core trenching with EBM has an effective life extension of about 5 years. Core trenching should therefore be used with a degree of caution.

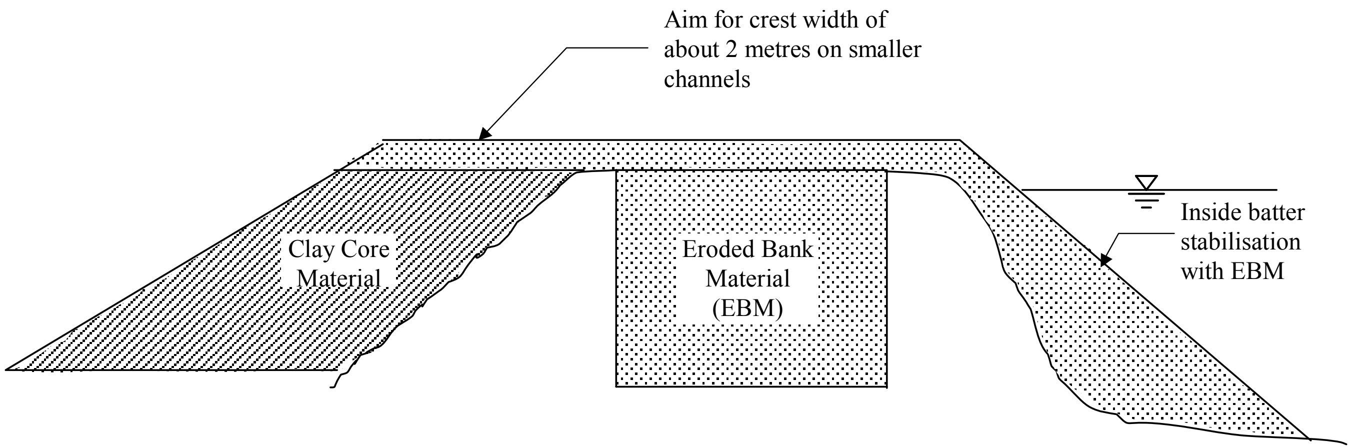


Figure 20.12 Core filled with EBM

The success of core trenching is heavily dependent on the technique and the material used. Use of saturated EBM from the waterway should be avoided. Refer Photo 20-8. The EBM should be let dry as much as possible. Also all vegetation and organic material should be removed from the EBM before placing in core.

Photos\refurbishment\Cohuna channelsEBM7.jpg

Photo 20-8 Saturated material used to fill core. On drying core cracks and becomes crumbly

Photos\refurbishment\Cohuna channelsEBM6.jpg

Photo 20-9 Cut through channel bank showing original compacted bank with layer of silt placed over the top

20.5.3 Case Study

The Torrumbarry 3/1 and 16/1 channels were rehabilitated during 1997 in the following manner:

- channels were selected according to the availability of EBM
- already had enough freeboard so that any works would not bring this below normal operating ranges.
- Channel was drained. When water level had dropped, the topsoil was stripped and stockpiled.
- Any hollows encountered in the batter were filled with good clay fill
- Eroded channel material was pulled up from the bottom of the channel onto the inside batter and crest of the channel bank. The material placed on the crest was surplus.
- In some locations the crest of the banks was later rotary-hoed as cracks up to 40cm in depth formed in the EBM material as soon as it dried out.

Photos

Pyramid Hill Channel 16/1 before batter stabilisation

Pyramid Hill Channel 16/1 after batter stabilisation

Rotary hoe after batter stabilisation

Pyramid Hill Channel 3/1 leakage after stabilisation

Rotary hoe working after cracking on Pyramid 3/1 Channel

20.6 Construction Equipment

Refer to Section 19.4 on equipment selection for new channel bank construction.

Typical bank re-construction equipment may include:

Borrow Pit	Bulldozer and Loader or Hydraulic Excavator
Carting	Dump trucks
Bank	Bulldozer Tamping Foot Roller

Scrapers are used less on channel bank re-construction projects because of the general need to import borrow material from some distance over public roads.

Some types of compaction equipment are also not well suited to channel bank re-construction because of their limited manoeuvrability and the restricted site access in the more intensively developed irrigation schemes.

20.7 Backfilling of Original Borrow Pits

The early methods of constructing channels involved scooping up earth from the waterway and adjacent to the channel in a *cross-dozing* type of operation. This formed borrow pits that run more or less continuously along both sides of many old channels. These fill up with water and cause weed growth, yabby activity, access restriction, leakage, seepage, waterlogging and groundwater accessions.

Consideration should be given to backfilling these old borrow pits. Any type of material can generally be used to fill the borrow pits:

- Surplus stripping
- EBM (eroded bank material from the waterway)
- Non-selected material borrowed for the purpose

20.8 Inside Batter Re-establishment

Trimming of inside batter slope – to re-establish a stable face

It is apparent that bank deterioration is accelerated by the formation of a vertical or undercut inner face. It is recommended that inner batter slopes be restored where sufficient bank width otherwise exists, in an effort to extend bank life.

Refer to Section 18, Inside Batter Treatment.

20.9 Channel Bed

Bed of channel should be graded out to remove humps and allow for drainage of the channel at the end of the operational period.

20.10 Specifications

Sample Survey Specification

1. Traverse line to be pegged at 200 metre intervals along the crest of one bank and at all angles.
2. Traverse to be connected to nearest crown allotment corners at all road crossings.
3. Bench marks to be provided at road crossings and at intervals of one kilometre maximum.
4. Cross sections to be levelled at intervals … metres and to extend … metres outside bank toes. EBM and solid bed levels to be recorded.
5. Features within … metres of the channel, which could affect re-design or re-construction, to be located and described, for example farm channels, dams, and laneways, telephone and electricity lines, buildings and other structures, and significant trees.
6. All channel structures to be located and described.

NOTE: Individual specifications may be modified or extended as required.

20.11 Australian Standards

AS3798-1996	Guidelines on earthworks for commercial and residential developments

20.12 References

Dunstone G (1998), *Inspection of Silt Stabilised Channels in the Pyramid Hill and Torrumbarry areas*, internal G-MW report, March 1998

Rural Water Commission of Victoria (1988), *Irrigation and Drainage Practice* 1988

21. Channel Seepage

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21.1 Introduction

Because earthen irrigation channels are rarely constructed through perfectly watertight ground, there will always be some seepage.

The estimation of seepage losses is important for both existing channels and for those planned for the future.

The primary function of most channel lining is to control seepage. Although erosion resistance, reduced channel dimensions, increased structural stability or reduced maintenance may be of greater importance in special cases, extensive channel lining is usually not justified if the seepage losses are low.

Estimates of seepage losses are needed for computing water budgets, for analysing system efficiencies, for sizing of planned channels and for input to hydrologic models.

It is therefore important to be able to realistically measured or predicted seepage losses from an existing channel and the location of probable seepage areas in a proposed channel.

Refer to Section 22.2, for typical seepage rates from earthen channels.

However, it has been observed in Australian and overseas studies that losses in earthen channels are typically highly variable and are often very unpredictable.

Channel seepage rates are not constant and significant variations over periods of 24 hours have been recorded. In many cases, the sensitivity and accuracy of the measurement method is insufficient to adequately evaluate the magnitude of the seepage losses.

As well, channel seepage is difficult to accurately measure, expensive and potentially subject to significant measurement error if not undertaken correctly. Because of the uncertainties, reliable prediction of channel seepage losses, is difficult to do with a high level of confidence.

No entirely satisfactory methods for measuring seepage have been developed. Estimating channel seepage is both difficult and inexact. Generally, measurements indicate the magnitude of seepage rather than providing precise quantitative values.

21.2 Seepage from Channels

This study identified some confusion across the irrigation industry between seepage and leaks, with the terms being used interchangeably at times.

Channel Seepage is defined as the diffuse movement of water through the bed and banks of irrigation channels into sub-surface layers.

Channel Leakage, is defined as the loss of water through a bank as a result of a specific point source of damage such as cracking of bank, holes through bank, cut through a bank, voids around a structure, cracks or deteriorated joints in a lined channel, burrowing activity by aquatic animals and tree roots. Leakage water is generally found on the surface, though some of it may percolate into the ground.

Seepage is a complex hydrologic phenomenon. Because of the many variables involved, no single method for computing the rate of seepage has been developed. When water is flowing in a channel it immediately starts to move into the air spaces between the particles making up the wetted perimeter of the channel. This movement is a combination of capillary flow and percolation. The capillary flow is caused by the capillary attraction of the fine passages between the particles of the bed material, whereas percolation is caused by the action of gravity enforcing the water through the pores of the bed material. The action of gravity is always downward, but capillary attraction operates in all directions and may cause the water to rise above the level of the water in the channel. Capillary movement is extremely slow and is normally small in comparison with percolation.

Refer to Section 22.4.1, Waterlosses and Section 22.5.10 Acceptable Seepage Rate.

21.3 Factors Affecting Seepage

Seepage processes can be quite complex and the interpretation of seepage test results from a channel require a knowledge of the factors affecting it.

The rate of seepage and the slope of the seepage gradient leading from earthen channels are related to:

- Characteristics of the material at the soil-water interface and below the channel bed
  - permeability of the bed and banks of the channel
  - permeability of the underlying soil layers
  - percentage of entrapped air in the soil
  - action of capillarity and gravity
  - chemistry of the soil
  - soil temperature
- Channel geometry
  - depth of water in channel
  - channel shape and wetted perimeter of the bed and banks
- Characteristics of channel water
  - chemistry of water
  - salinity of water
  - amount of sediment carried and deposition of silt
  - length of time that water has been in the channel
  - water temperature
- Flow characteristics
  - velocity of flow
  - total time of channel operation
- Position of the watertable and hydraulic gradient
  - location of watertable relative to the channel
  - irrigation of adjacent land
  - evaporation from watertable via capillary rise
  - groundwater pumping in vicinity of channel
  - surface and sub-surface drainage in vicinity of channel
- Ground slope at right angles to direction of channel flow
- Microbiological activity
- Barometric pressure and weather conditions
- Surrounding vegetation of the channel

Since many of these factors are closely related, act simultaneously and some of them tend to counteract each other, so it is difficult or practically impossible to determine the relative contributions of each to seepage. Therefore, the factors thought to be least important to seepage losses, such as soil temperature, velocity of flow and ground slope at right angles to the flow, generally are not taken into account.

The main factors known to have a definite effect on seepage rate can be grouped as follows:

1. Characteristics of the channel surface and subsoil.
2. Depth of water in the channel, wetter perimeter of the channel and the depth to groundwater.
3. Amount of sediments in the water, velocity in the channel and length of time the channel has been in operation.

Group 1

Permeability is the soil property that indicates the relative ease with which water will flow through the soil. Permeability is the ability of a soil to conduct or discharge water under a hydraulic gradient. This property is mainly dependent on the porosity of the soil, shape and arrangement of the soil particles, soil density and degree of saturation.

Coarse-grained soils are highly pervious and have high permeability co-efficients; fine-grained soils are much less pervious and have low co-efficients.

The co-efficient of permeability K, cm per sec, is defined by Darcy's law:

$$Q = KiA$$

Where; Q = rate of flow of water through soil mass, cm^3 per sec
i = hydraulic gradient or total head lost per unit of flow distance, cm per cm
A = total cross-sectional area of soil through which flow takes place, cm^2

A survey of the soil profile along a proposed channel alignment is the most important single step in a pre-construction seepage investigation. This survey should determine the location, extent and physical characteristics of the various underlying soil layers. The sequence of permeable and impermeable strata and the capability of these strata to transmit water will largely determine the amount of water lost by seepage.

Group 2

The following relationships have been found to exist between seepage and water depth in the channel, depth to groundwater and wetter perimeter of channel:

1. Seepage losses generally increase with increase of water depth in the channel, although the two factors are not directly proportional. Depth of water has been found to have more influence on seepage rate when the rate is high than when the rate is low.

2. Seepage losses increase as the difference between water level in the channel and watertable system below the channel increases; when the difference is five times or more the surface width of the channel, seepage losses reach the upper limit or the infinity condition. As the net head available to drive the seepage water through the soil is reduced, the rate of seepage reduces. Where channel levels do not fluctuate significantly, variations in watertable levels determine seepage losses. If the water table level is above the water surface in the channel, water will seep into the channel from the surrounding area.
3. The distribution of seepage losses across the channel bed and sides depends upon the position of the watertable or impermeable layer. When the watertable is shallow, the seepage from the sides is greater than that from the bed, and the reverse is true with a deep watertable. In all cases the maximum seepage losses occur at the toe of the slope – that is, at the junction of the bed and sides of the channel.
4. The significant depth within which the nature of the soil effects seepage losses has been found to be five times the bed width of the channel. Laterally, at a distance ten times the bed width of the channel the effect of seepage losses on the original watertable is insignificant.
5. The larger the wetted perimeter, the greater the seepage. The potential for seepage increases with a larger surface area in contact with water.

In accordance with item 3, it is advisable to construct wide, shallow channels in areas with a high groundwater table and narrow, deep channels in areas with a low watertable.

Group 3

Material suspended in channel water is carried by seepage water into the pores in the soil in which the channel is constructed. If the water contains considerable amounts of suspended material, the seepage rate may be reduced in a relatively short time. Even small amounts of sediment will have sealing effects over a period of time. If the velocity is reduced the sediment-carrying capacity of the water decreases, resulting in settlement of part of the suspended material. This forms a thin, low permeable layer along the wetted perimeter of the channel which decreases the seepage.

Refer to Section 22.7.6.1, Sediment Sealing.

The more often the channel is used, the less is the rate of seepage, for the soil pores tend to become saturated and with time partially seal. On the other hand, in a channel which is used only for short durations or intermittently with long intervals between use, the dry surface has to undergo the cycle of saturation over again, affecting seepage and there is reduced opportunity for a sediment layer to form.

The permeability of the soil of the bed and batters of the channel are the main factors in the potential for getting high seepage losses. Factors which will limit the maximum seepage rates are the occurrence of a less permeable layer at some depth below the surface, the occurrence of a shallow watertable and the presence of a silt layer. From widespread seepage measurements there is evidence that higher seepage losses occur through the upper batters of channels. This may be caused by:

- the presence of insufficiently consolidated material in the upper bank
- the absence or thinness of a sediment layer
- the presence of more permeable material in the upper batter because of biotic activity

21.3.1 Permeability

A high permeability generally leads to increased seepage.

Permeability is a porous medium's capacity for transmitting water.

Permeability is generally the most important factor in determining the rate of seepage. Permeability is influenced by both the size of the pores and the percentage of pore space or porosity of the material.

The rate at which water can flow through the pore spaces in the soil is influenced by the absolute size of the pores, flow occurring quite freely in the case of sands and gravels but slower in the case of clay soils.

For a given size of pores, the permeability increases with the porosity, but materials such as clay which have high porosity have relatively low permeability. The passage of water through a soil depends on the size, shape and continuity of voids. This is because permeability also varies roughly as the square of the diameter of the pore spaces, and since in clay the pore spaces are very small, the permeability is also small in spite of the high porosity. The presence of gravel in a clay-silt decreases the permeability because it reduces the porosity. Gravel alone, if made up of particles of uniform size, has a high permeability because the interstices between the particles are not filled with finer material and consequently the pore spaces are relatively large. Soils made up of gravel in a matrix of clay have a relatively low permeability to water and are quite stable. Such a material is excellent for channel construction as described in Section 15, Material Selection and Testing.

In most channels the dominant factor in determining the rate of seepage is the permeability of the lining of the channels. In unlined earthen channels this is the material that the banks and bed are constructed from. Where velocities in channels are relatively slow (less than 0.45 m/s) the bed will be partially sealed by silt and clay carried in the water.

The permeability of channel banks and bed will depend upon:

- Type of material used
- Compaction of that material
- Whether banks are wetted up. If channels are drained during the non-operational period cracks may open up. However once the banks are wetted they tend to seal up themselves. However, this may take several weeks or more, depending on the bank material and the size of the cracks.
- Age of the channel system. Permeability of channel bed, in particular, reduces with time, due to clogging of pores by organic debris.

The distribution of seepage losses across the wetted perimeter, ie bed and sides of channel, depends upon the position of the underlying watertable or impermeable layer. When the water-table is at a shallow depth, the contribution by the sides is greater compared to the bed and the reverse is true for the case of a deep watertable.

Refer also to the following sections:

Section 11, Planning and Investigation
Section 12.8, Geotechnical Investigation
Section 15.2, Investigation of Material

21.3.1.1 Hydraulic Conductivity (K)

The hydraulic conductivity is defined as *the flux of water per unit gradient of hydraulic potential* – a measure of the ability of soil to conduct water.

The hydraulic conductivity of the channel bed normally has a major impact on seepage while the hydraulic conductivity of the material underlying a channel is likely to vary both along the channel length, and at depth.

21.3.2 Effect of Channel Geometry on Seepage

An increased wetted perimeter generally leads to increased seepage.

An important factor with respect to seepage is the width of the water surface W and the water depth, d in the centre of the channel. Refer Figure 21-1. For given values of W and d, seepage increases from a triangular cross-section to trapezoidal and rectangular cross-sections. The magnitude of the increase depends on the soil and watertable conditions.

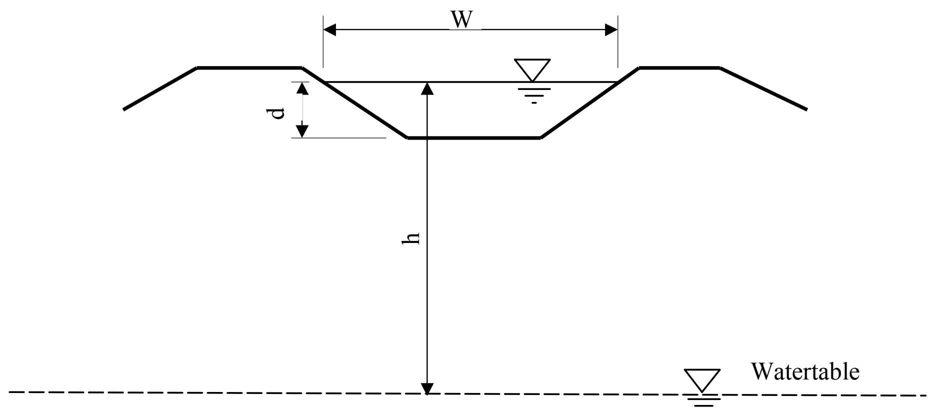


Figure 21-1 Seepage factors

However with greater depth a greater discharge along the channel is achieved. Discharge will increase more with greater depth than seepage. Therefore increasing the depth of the channel will increase the efficiency.

21.3.3 Hydraulic Gradient

The lower the watertable, the higher the seepage. Refer Figure 21-1.

The hydraulic gradient is essentially determined by the head difference between the watertable and channel water level, *h*. The watertable can vary with farm irrigation practice, evaporation and rainfall. Therefore seepage may vary with these factors, particularly where watertables are relatively high.

In the case where the groundwater is high, it may even cause a gain to the channel.

21.3.4 Water salinity

The higher the salinity, the higher the seepage.

The presence of electrolytes (ie salt) can arrest the tendency of clay particles to disperse and promote aggregation of soil particles which in turn increases the porosity of the soil medium and hydraulic conductivity. This is reaction is dependent on the soil type.

When the electrolyte concentration and composition of channel water exceeds 500-800 EC, flocculation of clay particles will occur, leading to increased hydraulic conductivity of clay material lining the channel.

Saline water is not generally used in irrigation channels but drainage or groundwater may be discharged into irrigation channels. It is important that such water is diluted with fresh water to minimise increased seepage.

21.3.5 Variation over Year

Seepage rates from earthen channels at a single point can vary over a year and it is unusual to measure a consistent seepage value for a given reach of channel.

In seasonally used channels, the seepage rate will be higher at the beginning of the season when water is first turned into a dry channel, and will decrease as the banks and subgrade approach saturation. Cracks in the surface of the channel swell and seal and more steady state conditions are established.

This behaviour is illustrated in Goulburn-Murray Water tests on aged silt-sealed channels through fine sandy loam where the initial seepage rates were 0.005 to 0.02 m^3/m^2/day for the first 5 to 10 days after filling, and then an average seepage rate of 0.002 m^3/m^2/day for the balance of the season.

Seepage losses during a year can also be influenced by variations in turbidity, water temperature, weed growth, microbiological activity, hydraulic head and evaporation. As evaporation increases during the summer, watertables can be lowered and the increased hydraulic head leads to higher rates of seepage.

Investigations in northern Victoria found that the seasonal variation in channel seepage was mainly due to fluctuations in the shallow ground water levels underlying the channel, changing the available head driving seepage.

In a channel on a fine sandy loam soil, measured seepage rates varied between 0.014 m^3/m^2/day and 0.034 m^3/m^2/day over a three year period. At another site on loam soil, the measured seepage losses varied from 0.005 m^3/m^2/day to 0.009 m^3/m^2/day.

Measurement of seepage provides only a *snapshot* at a given point in time for a given section of channel, and the extrapolation of measurements over an entire channel system should be treated with caution.

21.4 Channel Seepage Consequences

Seepage from irrigation channels can have adverse economic and environmental consequences. These consequences include:

- Loss of a valuable natural resource
- Cost to irrigation authority
- Cost to adjacent landowners
- Regional consequences

21.4.1 Loss of the Water Resource

Seepage from earthen channels can lead to loss of water and reduced efficiency of water distribution. Inefficiencies can have major implications for the adequate supply of water, if seepage is not considered in the design process.

In most irrigated areas of Australia the available water resource is fully allocated. It is estimated that average seepage loss in irrigation channels in Australia is 4% (*ANCID pamphlet, 2000)* of the water delivered. However specific locations along a channel system can have much higher seepage rates than the average. The one method to make more water available is to increase the efficiency of the distribution system. Therefore if channel seepage can be reduced, more water can be made available to the environment and for consumptive use; industry, agriculture and urban use.

21.4.2 Cost to Irrigation Authority

The cost to the Irrigation Authority from channel seepage can include:

- loss of water
- loss of income from water lost from channel system
- higher operating costs of channel system
- physical damage to channel
- reduced efficiency of the supply system
- costs of litigation and compensation for damages
- accessions to rising watertables
- soil salinity
- surface waterlogging
- loss of reputation as an irrigation manager

21.4.3 Cost to Adjacent landowners

The local effects of excessive seepage can be waterlogging of areas adjacent to channels which in turn causes:

- loss of productive land
- reduced production
- land value degradation
- increases in farm operating costs
- local salinisation problems
- localised (perched) groundwater systems

Where a channel has relatively high seepage, the development of a groundwater mound beneath the channel is likely. When this mound approaches the land surface, a discharge area adjacent to the channel may develop. Refer Figure 21-2. Groundwater discharge restricts the growth of non-salt tolerant species which leads to productivity losses. Continual discharge eventually inhibits the growth of salt tolerant plants as well, exposing the soil to erosion.

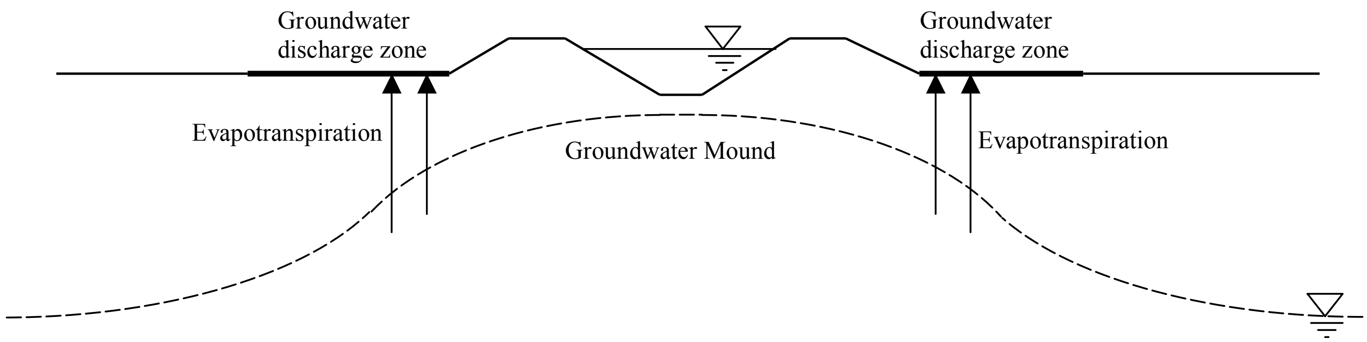


Figure 21-2 Local effects of Channel Seepage

Accessions from on-farm structures, such as channels and storages, and agricultural activities also contribute significantly to local groundwater levels.

21.4.4 Regional Consequences

Channel seepage can contribute to the general problems of rising groundwater levels and the formation of perched watertables with consequent loss of productivity of lower lands, as follows:

- loss of productive land
- land value degradation
- increases in watertable levels
- increases in salinisation of soil and water
- loss of vegetation
- loss of bio-diversity
- increased farm operating costs
- increases in infrastructure maintenance and replacement costs

Seepage losses from irrigation channels can add pressure to regional aquifers potentially raising groundwater levels across a broad area. Rising groundwater levels result in waterlogging and likely salinisation of surface soils. Rising groundwater tables and subsequent land salinisation has been observed in many irrigation areas in Australia. Crop yield is significantly influenced by shallow, saline groundwater table lying within a critical depth (less than 2m) below the land surface.

Channel seepage is one of the several sources of accession to the watertable that contributes to the rise in the watertable and it can be difficult and costly to separate the effects of other regional and farm management influences on groundwater levels. The relative importance of channel seepage depends on an evaluation of all factors in a groundwater balance. With the treatment of seeping sections of channel, a slower rise in the regional watertable can be anticipated, but the long-term impacts can be very difficult to assess and may make little or no difference.

Channel seepage can be expected to have a more immediate and detrimental effect on soil salinisation when the channels are located in an area where high watertable levels are already experienced, and lower where the watertable is substantially lower.

Generally, additional roadway deterioration is noticeable in areas where watertables are shallower than 2 metres.

In areas with high regional watertables, channel seepage may not be the only cause of the problem of salinity and waterlogging. In such circumstances, it may be difficult to separate the influence of channel seepage from regional factors. Therefore the relative contribution of channel seepage to total accessions is difficulty to identify. However, where channel seepage is a significant point source of groundwater recharge, any reduction is likely slow the rate of rise of the regional groundwater table.

Regional groundwater pumping may be a better net solution to achieve the same outcome.

Where regional groundwater levels are low relative to the surface, channel seepage may not be an environmental issue. For example; seepage from a channel system may be a valuable source of recharge to groundwater resources. Seepage reduction in that case, may prove to be a greater environmental risk by reducing regional groundwater reserves.

21.5 Channel Seepage Measurement

21.5.1 Seepage measurement units

Considerable data from overseas and Australian literature is available on seepage losses from irrigation channels and several different units are used in literature to define the amount of seepage losses from a channel. The most frequently used units include:

i) a percentage (%) of the total water volume released in the channel at its head

ii) a rate of loss of water depth per 24 hours (mm/day)

iii) a rate of volume loss per unit area of wetted perimeter per 24 hours (m^3/m^2/day).

In Australia the first two seepage measurement units are commonly used. The first unit is often used to account for system losses. It is also used when quoting the results of the inflow-outflow method of seepage measurement.

The second measurement unit is commonly quoted in Australia when using direct measurement techniques of ponding or seepage meters. However this unit has some ambiguity, and may be confused with several different seepage measurements as follows:

- hydraulic conductivity co-efficient *K* of the channel wetted perimeter in mm/day.
- direct rate of loss of water depth per 24 hours (mm/day) from pondage and seepage meter measurements. This does not take into account the wetted perimeter of the channel.
- rate of volume per unit area of wetted perimeter, simplified from m^3/m^2/day to mm/day by multiplying by 1000.

The third seepage measurement unit (m^3/m^2/day) is not commonly used in Australia, although it is the standard unit used by the US Bureau of Reclamation and ICID. It describes definitively the actual channel seepage process, taking into account the geometry of the channel. It is considered to be the most meaningful, and the recommended seepage measurement unit is therefore $m^3/m^2/day$. It is the unit adopted in these Guidelines.

Comparison of seepage rates is difficult when confronted with imperial measurements or different metric units. Conversions for several commonly used seepage units are given in Table 21-1.

1 ft^3/ft^2/day	=	0.3048 m^3/m^2/day
1 mm/day	=	0.001 m^3/m^2/day
1 m^3/m^2/day	=	1000 mm/day
1 ft/day	=	304.8 mm/day

Table 21-1 Equivalent Units

21.6 Estimation of Seepage from Proposed Channels

There can be a significant economic advantage if the decision to line a channel is made at the design stage rather than at a later date when the need becomes apparent during operation. An evaluation of likely seepage losses is therefore an important element of the design phase.

During the design of a channel, the importance of good soil surveys and groundwater studies is often under-estimated by engineers. A little more invested in studies and analyses before construction, can save money later.

Refer to discussion in Section 22.4, Need for Lining.

In some situations, the decision to line or not line a proposed channel can be reached from soil surveys, geomorphological information and visual observations of the channel material, provided the material is of a type that is obviously very pervious or impervious. New channels have been lined during construction if high permeability soils, such as prior streams or sand drifts were encountered. However, when the permeability of the channel material is in doubt, the decision may be reached either by applying comparative seepage data or by estimating potential seepage using the hydraulic conductivity determined from permeability tests.

Seepage is proportional to soil permeability and one method of predicting seepage losses consists of estimating or measuring the hydraulic conductivity (permeability) K of the soil through which the channel is to be constructed.

These tests and calculations are elaborate, time consuming and expensive if accurate results are to be obtained. Values of soil hydraulic conductivity K obtained from simple field permeability tests are at best only relative indicators and it is difficult to compare absolute seepage rates. Unless a precise prediction of seepage is of particular importance, and unless the investigations and calculations are conducted by specialists, the results obtained may not warrant the time and cost.

The simplest method estimating the magnitude of seepage losses would be to adopt known seepage losses from existing channels of similar size and shape constructed in soils of similar permeability with a similar watertable.

A quantitative prediction of seepage losses can be obtained by calculation. A variety of empirical formulae and analytical methods have been developed for the calculation of seepage from irrigation channels. The use of empirical formulae can only produce rough estimates, whereas analytical methods can give more accurate results when applied to conditions for which they have been developed. However, analytical methods are generally quite complex. Because these methods are based on theoretical analysis and various assumptions have to be made that may not be justified by conditions in nature, seepage estimates cannot be expected to agree closely with actual rates.

There are a number of technical publications on these methods that can be referred to for further details. Refer Section 21.11, References.

Seepage rates usually decrease noticeably with age, particularly if the water carries sediments. Because these sedimentation and aging processes are not taken into account in the pre-construction permeability tests, the seepage rates determined are likely to be higher than will actually occur.

21.6.1 Measurement of Soil Hydraulic Conductivity (*K*)

Of particular importance in the empirical and analytical methods of predicting seepage rates is the proper determination of the hydraulic conductivity (*K*) of the soils.

The range of permeability is extremely large. For example, a clean gravel carries water at a rate of about one thousand million times that of a clay. Typical values for natural soils are shown in Table 21-2.

Soil Type	m/s
gravel	$K > 10^{-2}$
clean sand	$10^{-2} > K > 10^{-5}$
silt	$10^{-5} > K > 10^{-8}$
fissured clay	$10^{-4} > K > 10^{-8}$
intact clay	$K < 10^{-8}$

Table 21-2 Typical Values of Permeability of Natural Soils

The hydraulic conductivity of the material underlying a channel is likely to vary both along the channel length and at depth.

Soil permeability can be measured in either the laboratory or the field and the accepted methods for determining soil hydraulic conductivity are well documented in the technical references, therefore the methods for *K* measurement are only briefly described here to provide an appreciation of the practical issues involved.

The hydraulic conductivity of the subsoil below the channel is required:

- to estimate the seepage rate of a channel by Darcy's Law if a direct method of seepage measurement is not carried out.
- as a parameter in seepage and groundwater movement models

The hydraulic conductivity of a soil can be measured in the field with the auger hole permeameter test. There are various types of permeameters which have been developed for measuring the permeability of soils in the laboratory but they are not suitable for testing channel permeability due to the large number of variables that determine permeability of a channel.

The in-situ field techniques for measurement of K can be divided into those that measure K of the soil above the watertable or in the absence of a watertable, and those that measure K of the soil below the watertable.

The water used in these tests must be a *channel water equivalent* because of the effect of the chemical constituents in the water on *K*.

The absolute accuracy of permeability measurement by auger hole is not good as the test is sensitive to various hard to gauge factors, such as anisotropy, smearing and swelling. Factors such as compaction of the sides of the hole by the auger and washing out of clay fines during fill leads to a result which may be ten times too great or ten times too little. This is a wide range and test is best as an indication of relative seepage. The point measurements are often highly variable and can produce inaccuracies when extrapolated to the channel as a whole. It is however, a relatively quick and easy test.

There are numerous hydraulic conductivity formulae in the literature which are based on analytical or numerical solutions that use various approximations, and care is needed in selecting the most appropriate formulae to use.

21.6.1.1 Measuring hydraulic conductivity above the watertable

Most irrigation channels are constructed in areas with a relatively low watertable. Therefore, those methods developed for measuring *K* in soils above the watertable are the most important for seepage investigations.

The general principle of these methods is to wet a portion of the soil, preferably to positive soil-water pressures, and create in this wetted zone a flow system of known behaviour for the evaluation of *K*. Devices have been developed either for simple one-dimensional (ie vertical) flow or for axisymmetric flow. Vertical flow measurements refer to seepage from channels to deep groundwater tables, whereas axisymmetric flow measurements relate to seepage from channels to shallow groundwater tables.

Methods based on vertical flow measurements are:

- infiltrometer techniques
- air-entry permeameter

Methods based on axisymmetric flow systems are:

- well permeameter
- variable head permeameter
- double-tube permeameter

Wherever possible, the test should be conducted at representative sites along the channel centreline and at the bed level of the channel.

21.6.1.2 Measuring hydraulic conductivity below the watertable

The average hydraulic conductivity over a relatively large soil region can be obtained with pumping test techniques established for groundwater investigations.

Faster and simpler ways of obtaining K are the:

- auger hole method
- piezometer method
- tube method
- multiple well technique

The K values thus obtained are, however, confined closely to the quite shallow and small diameter holes employed in these methods.

The general principle of the auger-hole permeameter method, and with slight modification also of the piezometer and tube techniques, is simple:

a) A hole is bored into the soil to a certain depth below the watertable;

b) A quantity of water is removed from the hole after equilibrium conditions have been reached;

c) As the surrounding groundwater seeps into the hole again, the rate at which the water level rises in the hole is measured and then converted by a suitable formula to the hydraulic conductivity of the soil.

Auger holes are rarely bored deeper than 1 metre below the watertable. Diameters range from 4 to 8 cm.

Measurement of Hydraulic Conductivity (K) below the Watertable:

- *Local* values of K can be estimated by installing a vertical tube in the soil to below the watertable, allowing the water level in the tube to become in equilibrium with the watertable, removing a volume of water from the tube, and measuring the subsequent rate of rise of the water level in the tube for calculation of K.
- *Regional* values of K can be obtained with pumping test techniques of wells for evaluating aquifer transmissibility

21.6.1.3 *Laboratory methods of measuring permeability*

Laboratory tests of soil permeability along the line of a proposed channel may be made on samples of either disturbed or undisturbed material.

The material is placed in a cylinder and water is allowed to flow through the sample under a defined head in either a constant-head permeameter or a falling head permeameter, depending on the relative permeability of the soil. The recorded rate of flow through the soil is used to determine the average co-efficient of permeability *K*.

Seepage rates based on permeabilities of undisturbed samples should be reasonably accurate if a large number of samples are tested, careful technique has been followed, and a satisfactory formula for converting permeability into seepage is used. However the method is time consuming and expensive.

Seepage rates based on permeabilities of disturbed samples are not considered to be accurate as the stratification and particle arrangements of the sample that has been re-compacted to the insitu density and placed in the permeameter may differ widely from those of the soil in its natural state.

Experience has shown that the laboratory methods for permeability determinations are not as reliable as field methods; however, laboratory tests may be helpful for locating areas of relatively higher seepage – qualitatively, not quantitatively.

21.6.2 Channel Seepage Modelling

Groundwater movement can be a very complex process. It is dependent on many factors which can change over time. Groundwater modelling is carried out to include all of the significant factors which incorporate the groundwater flow system. These concern the hydro-dynamics of seepage flow systems and the measurement of hydraulic properties of soil. Seepage from channels is just one part of this equation.

A detailed treatment of seepage modelling is beyond the scope of this manual. The reader interested in such information should refer to other technical references listed in Section 21.11.

Groundwater models are used to:

- show the impact of accessions to the groundwater on local areas
- waterlogging/salinity impacts to local areas/regions over time

A simplified groundwater flow system is presented in Figure 21-3, which shows all the major components of recharge and discharge crossing the control volume. These components are also known as stresses of the system. Recharge can originate from lateral inflow, exchange with the lower aquifer, rainfall, irrigation and channel seepage.

Discharge can be from groundwater pumping, evapotranspiration, lateral outflow and exchange with the lower aquifer. The position of the water table at any time depends on the hydraulic properties of the soil and the stresses applied on it at that particular time.

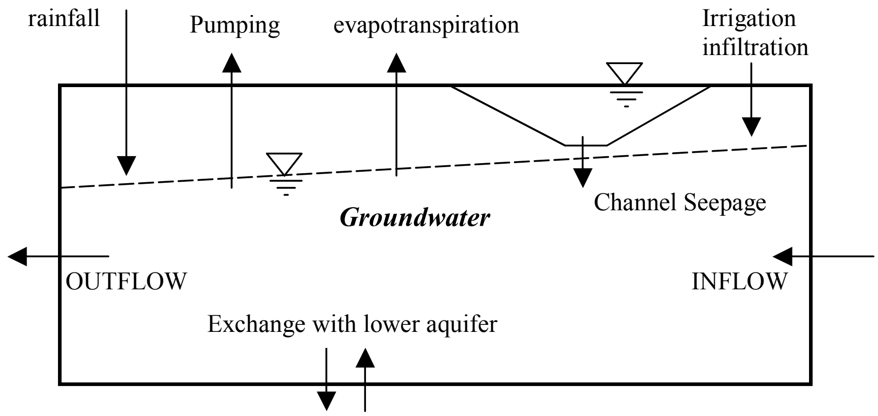


Figure 21-3 Flows through a control volume

Groundwater flow model uses include:

- estimate what seepage will occur from a proposed channel
- estimate what seepage will occur after rehabilitating an existing channel, or
- assess a range of seepage remediation techniques for an existing channel.
- evaluate the effect of different geological layers under and adjacent to the channel
- evaluate the effect of channel shape; ie width, depth, slopes of batters
- evaluate the effect of vegetation adjacent to the channel
- evaluate the possible benefits of remedial measures, eg lining
- evaluate field measurements of seepage relative to soil permeability and groundwater levels
- evaluate what proportion of accessions to the groundwater are from channels as against other sources
- evaluate the effect of channel seepage on regional or sub-regional groundwater systems
- estimate channel seepage volumes without direct measurement.

In Australia the modelling of channel seepage is not practiced routinely. This may indicate a lack of faith that modelling will be useful, or a belief that the costs are too high relative to the gains in knowledge.

Modelling of channel seepage flow is complicated due to the factors below:

- channels of irregular cross-section
- natural processes in the channel of erosion, sedimentation, biological action etc.
- non-uniformity of sub-soil in horizontal as well as vertical extent
- variation in evaporation rates and capillary rise throughout the year
- changing elevations of the water surface in the channel
- changing elevation of the watertable
- the effect of the chemistry of the channel water on the hydraulic properties of the soil. This causes hydraulic conductivity to change in time as well as in space. the hydraulic conductivity is also affected by the air content of the soil.

- the degree of saturation of the sub-soil. Complete saturation, even below the watertable, is the exception rather than the rule. The volume of entrapped air below the watertable can vary with time, depending on the air content and the temperature of the channel water, the temperature of the soil, and barometric pressure. Unsaturated conditions also occur where the soil-water pressures are less than atmospheric.
- salt transferral up through the soil layers

Various modelling techniques can be used to simulate groundwater movement, ranging from simple analytical models to complex process models. The complicated dynamics of the seepage process are very difficult to represent with a mathematical equation. To accommodate all of these variations a fairly complex non-steady state model is needed. However where the flow systems and the evaporation process may be simplified, an analytical model may provide solutions of sufficient accuracy.

21.6.2.1 Analytical Models

Darcy's Law

Darcy's Law is a simple equation which can be used to estimate seepage. According to Darcy's Law the velocity of flow through water-bearing sand is directly proportional to the head consumed. This law is generally assumed to apply to all saturated water-bearing materials in which the pores are of capillary size and the flow is laminar.

$$Q = K \times A \times \Delta h / \Delta l$$

Where,

Q = quantity of water in unit time (m^3/day)

K = hydraulic conductivity of the soil (m/day)

A = wetted area of the channel bed and banks (m^2)

$\Delta h / \Delta l$ = the average hydraulic gradient in the *close vicinity of the channel*. (m/m)

Δh = change in potential energy (head) of water between two locations (m)

Δl = distance in seepage water has travelled between two locations (m)

Advantages:

Simple and quick

Limitations of Darcy's Law:

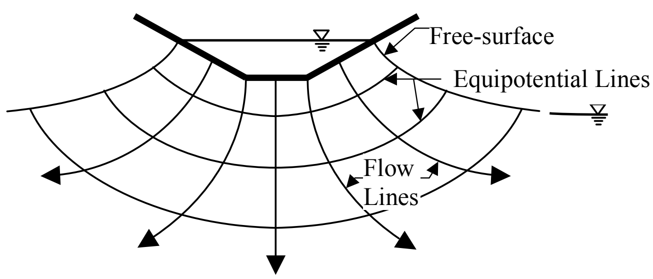
- Difficulties in measuring average saturated hydraulic conductivity between the channel wetted perimeter and the groundwater
- Lack of spatial information on the variation in hydraulic gradient between the channel and groundwater.

Flow Nets

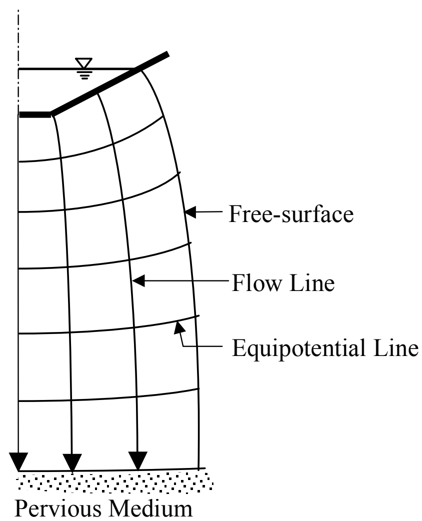
A flow net is a system of squares or rectangles formed by flow lines and equipotential lines. Flow nets are a useful way to model seepage for known boundary conditions and to visualise how seepage water travels from the channel to the watertable.

The flow net is drawn according to where the boundaries are known or estimated, being the position of the watertable and the position of any impermeable layer. The position of the free-surface (or watertable) can be determined by placing piezometers across the cross-section of the channel at 5 to 10 metre intervals. The layers of sub-soil can be determined by bore logs.

Flow-nets for two typical cases, a shallow and deep watertable shown in Figure 21-4.



Watertable at shallow depth



Watertable at a large depth

Figure 21-4 Flow-net for estimation of seepage loss from unlined channel

A flow net can be used to determine three useful items of information; rate of flow, head and gradient.

21.6.2.2 Process Models

Process based models simulate channel seepage and dissipation by evaporation and deep leakage over time.

A reliable groundwater process model reflects all important natural processes and should provide the facility to impose relevant human interventions on the system. Important features which are common for irrigation areas include:

- natural and constructed drainage lines
- supply channels with particular emphasis on representation of sites where significant seepage losses may occur
- infiltration of irrigation water and evapotranspiration of the agricultural crops on specific soils
- capillary rise from shallow watertable areas
- groundwater pumping schemes and pumping of saline groundwater to evaporation basins.

Two dimensional *Numerical Groundwater Models* simulate the aquifer groundwater flow in the horizontal plane based on time steps. These are divided into a grid using finite differences or elements. The transmissivity, storativity and groundwater height of each cell determine groundwater flow. Recharge and discharge factors including deep leakage to other aquifers are superimposed, adding or removing a volume of water each time step, therefore are additional factors affecting groundwater height with time.

In three dimensional models the linkages between aquifers are dealt with in a more integrated way, or unsaturated flow processes may be included. The main issue is how the channel seepage process is included in these models and how accurately the distribution of the accessions to sinks is represented.

It is found that channel seepage is usually represented as a simple Darcy type groundwater flow equation, describing flow from the channel bed to the groundwater system, assuming that this flow is vertical:

Numerical flow models can be applied to a channel cross-section, with all layers represented by finite element or finite differences cells. This technique has been successfully applied by Wachyan and Rushton (1987) for steady state flow conditions. An important issue is the treatment of the boundary condition of the watertable, which slopes away from the channel and varies both spatially and in time.

Numerical groundwater models tend to involve large efforts in time and resources. They usually describe the groundwater flow process very well, however calibration procedures are complicated. Numerical groundwater models are not usually specifically designed to simulate channel seepage or are not calibrated against channel seepage data. Therefore they tend to be less useful as evaluation or prediction tools.

21.6.2.3 Calibration of Models

The most difficult aspect of seepage prediction for a given channel lies in the evaluation of the boundary conditions and of the hydraulic properties of the soil.

A first step would be to interpret the permeability of various layers from bore logs and generic values for hydraulic conductivity. These may be sufficient to get estimates based on an analytical approach.

Data from indirect measurement procedures such as EM surveys or tracers can be used to calibrate models.

The data requirements for calibrating models of channel seepage, both spatially and in time include hydraulic conductivity of various layers, transmissivity and watertable conditions over time, as well as meteorological data. Intense investigations of this nature may only be justifiable for large projects.

21.6.2.4 Accuracy of Models

Theoretical treatment of the seepage flow system begins with the simplification of the soil and boundary conditions, particularly for mathematical treatment. The accuracy of the seepage predicted for a given channel depends largely on how well the pertinent soil, watertable and boundary conditions are characterised. Although such models may yield relatively accurate results, the model for which the solution is obtained is always a simplified version of the field situation. Therefore the solution is an estimate at best.

In Victoria, it has been found that the results of these models often bear little resemblance to measured field losses, probably because of the complex and variable soil and silt conditions in the wetted perimeter of channels.

Modelling may be seen not so much as a means of determining seepage, as providing an understanding of the *sensitivity* of seepage to changes in some of the parameters modelled.

21.7 Measurement of Seepage from Existing Channels

The objectives of post-construction seepage measurements may be:

- to determine overall seepage losses from an existing channel system, in order to evaluate regional impacts or develop efficiency improvement strategies.
- to locate reaches of channel that have high seepage rates, for consideration of lining or other forms of remediation.
- to evaluate the effectiveness and useful life of channel linings, by measuring losses initially and after some years of service.
- to check the predicted seepage losses in completed reaches of a channel system under construction, so that the design of the incomplete parts of the system can be modified if necessary.
- to measure the seepage rates of lined and unlined channels as comparative data for the planning and design of other irrigation projects.

21.7.1 Seepage Studies

To establish the most economical remedial measures to reduce seepage from a channel it is necessary to estimate the origin, magnitude and direction of seepage.

Suspected areas of high permeability can sometimes be identified from a knowledge of the soil and geological conditions along the channel alignment. Higher rates of seepage should be suspected with channels located on lighter soils. The need for seepage control works on existing channels may be identified when it is clear that adjacent properties are being affected.

In high watertable areas even a small quantity of seepage may be detected by visual observations. On the other hand, in deep watertable areas it is possible that no surface effects are evident on land adjacent to channels having high seepage losses.

There will be many locations where the origin and magnitude of seepage losses are not obvious and a seepage study will be required to detect and measure the losses.

Seepage losses can vary widely along different sections of channel depending on soil and geological conditions. In some irrigation schemes a high proportion of total seepage can be caused by relatively short sections of high seepage rate channels. If the sections of channel where the seepage is the greatest can be located and treated, this can present the most cost-effective means of reducing overall seepage losses.

However it should be noted that inaccuracies in channel flow measurement can at times create the perception of severe seepage losses, and some channels suspected of having high seepage losses may have no such problem. The suspected *seepage* losses may simply be due to inaccurate flow measurement.

Generally more than one method of detecting and measuring seepage is used in a channel seepage study:

- Visual observations for signs of seepage
- Pondage tests
- Inflow-outflow studies
- Seepage meter
- Aerial photography
- Piezometer survey
- Mapping of salinised areas along the channel
- Soil maps and surveys
- Water balance estimates
- Water chemistry analysis
- ElectroMagnetic (EM) survey
- Permeameter

Any assessment of methods needs to consider the differences between seepage quantification and seepage identification, the time available, the likely magnitude of seepage losses, the availability of equipment and skilled technical personnel, and the trade offs between cost and accuracy.

A staged investigation of seepage sites may involve:

(i) *Initial Identification*

Identification of suspected high seepage sites by visual inspection of localised problems, landholder reports and knowledge of soil and geological conditions.

Visual indicators of seepage are weed growth or bare ground beside a channel, the presence of *spongy* ground underfoot, unhealthy crops or pasture near a channel and the presence of water on the ground surface next to a channel.

However seepage may occur through the bed of a channel and so directly into an underlying aquifer, thus the evidence of the seepage may not be apparent on the ground surface. In these situations, slow filling and fast emptying channels may be tell-tale signs of high seepage losses.

(ii) *EM Survey*

Electro-magnetic (EM) survey to prioritise sites for installation of piezometers

(iii) *Piezometers*

Piezometers to identify if there is a direct hydraulic connection between the watertable and the channel water.

(iv) *Pondage Test*

Pondage test to measure actual seepage from a channel

(v) *Idaho Seepage meter*

Seepage meter to make point measurements of infiltration rates along the channel and on the bed and banks of the channel.

A number of channel seepage studies in Australia have estimated overall seepage losses by relating a constant seepage rate to each soil type underlying the channels. This may be an appropriate methodology in some situations, but research has shown that seepage varies according to a range of factors and is not constant during the irrigation season. As the assigned seepage rates do not consider factors other than soil permeability influence seepage, results of this type of methodology, while still useful, need to be applied with some degree of caution.

Channel seepage measurements on the same soil type, can show a range of results, and using upper and lower seepage rates for each soil type rather than a single figure, may be a more realistic approach, which reflects the level of confidence in the results.

Taking into consideration other factors which influence seepage, such as depth to the watertable and channel size would further increase confidence in the results.

It is important that when methodologies for channel seepage estimation are used:

- they are applied correctly having in mind the assumptions associated with the method
- two or more methods are used to obtain reasonable confirmation
- adequate description and reporting is included
- upper and lower bounds or confidence limits based upon realistic estimates of the errors are provided.

21.7.2 Measurement techniques

Seepage losses cannot be predicted accurately without extensive on-site investigations. Seepage rates from existing channels can be determined by *direct* measurement or estimated by *indirec*t measurement.

It is difficult to make any general assumptions regarding seepage from unlined or lined channels or from channels constructed in various types of soil. The most unambiguous way of determining seepage from a channel is to make direct seepage measurements.

Indirect measurements is based on a knowledge of the relevant hydraulic properties of the soil and the boundary conditions, such as depth to groundwater, channel cross-section and depth of water. These methods are often useful in determining the source and flow paths of seepage. However to the estimate rate of seepage, some form of direct measurement should be used.

There are a number of methods available for the direct and indirect measurement of seepage as follows:

Direct measurement:

- Pondage Test
- Inflow-Outflow Test
- Seepage Meter

Indirect:

- Piezometric Survey
- Geophysical Technique
- Hydrochemical Tracers
- Remote Sensing

Precise determination of seepage losses are difficult to make and each method has its own advantages and limitations. No single method is adoptable to all conditions encountered.

The ponding and inflow-outflow methods yield average seepage for a section of channel, while seepage meters give the seepage rate for a small unit of area. Each of the methods can give widely varying seepage rates for the same channel.

The pondage test generally gives more certain results while seepage meters give useful comparative results.

Regardless of which method is used, it is important to understand that variations in seepage measurement at a single point occur over time and that it is therefore unusual to measure a consistent seepage value for a given reach of channel.

Seepage has been described by Bouwer (1965) as being a transient process due to changing conditions in the channel and groundwater system. Therefore, measurement of seepage provides only a *snapshot* at a given point in time for a given section of channel. It may therefore not be valid to extrapolate measurements over an entire channel system. The results of a single test must also be treated with caution, as measurements from various techniques can have large variations.

21.7.3 Direct Measurement

21.7.3.1 Pondage Method (static seepage test)

The pondage test is a common method of seepage measurement in Australia and is considered to be the most accurate and dependable method of determining seepage.

The procedure involves estimating the rate of seepage from the loss of water in a ponded section of channel over a fixed time, after allowing for evaporation and rainfall.

The volume of waterloss from the drop in water level and the physical dimensions of the ponded cross-section provide the data necessary to compute the seepage rate in m^3/m^2 of wetted area/24 hours.

$$\text{Seepage} = \frac{\text{Water at start} + \text{Rainfall} - \text{Water remaining} - \text{Evaporation}}{\text{Wetted Area}}$$

This method requires a representative channel reach to be ponded. The reach is filled to Full Supply Level, and as far as possible all inflow and outflow points are sealed. All inflow and outflow is then carefully monitored (including rainfall and evaporation), together with any changes in storage volume. Channel water height is measured at both ends of the channel reach being tested and averaged. The channel wetted area is measured to calculate seepage loss per unit area of the channel in contact with water. The channel water surface area is measured to calculate the area of water subject to losses through evaporation and addition from rainfall. Any loss from the reach, in addition to the observed losses, (leakage and evaporation) is then attributed to seepage.

The ponded section of channel should be long enough that the artificial end areas are not very large compared to the total wetted area of the pond. Three percent is considered a maximum desirable ratio of the end area to the totalled wetted area, and smaller values are more desirable.

In northern Victoria a conversion factor of 0.7 is generally applied to evaporimeter readings to represent more closely the actual evaporation loss from open channels. (A pan evaporation is mm x 0.7 = Evaporation from channel in mm.)

Since observations can be made reasonably accurately, the result should be a good indication of the average seepage loss from the reach of channel. The results from this method are generally used as the standard of comparison for other methods of seepage measurement. However the costs of conducting the tests can be relatively high, and the pondage method is generally not used unless the importance of the tests warrants the expenditure. The costs associated with conducting a pondage test on a channel will vary according to such things as the test location, access, channel dimensions, reach length, number of sections and the duration of the test.

The duration of a test is normally three to five days. Prior to commencement of readings, a period of several days may be required to wet up the soil profile and establish reasonably steady state seepage conditions. The overall expected accuracy would be within ±5% of the quoted seepage rate. Pondage tests are normally suspended during periods of high rainfall or wind.

Advantages:

- Provides reasonably accurate figures for the average seepage loss from the pool, especially when the seepage losses are small.
- Can be used to test short reaches of channel as well as hard-surface lined channels
- It is a straightforward manual method, thereby eliminating problems associated with electronic and mechanical measuring devices, estimation or approximation.

- Changing inflows and outflows, pooling effects and other problems associated with the dynamic test method are negated.

Limitations:

- Requires channel to be taken out of service during the test making it extremely difficult to perform during the irrigation season. This method is therefore best suited where irrigation is seasonal, and ponding can be carried out during the non-operational period. However groundwater conditions before or after the season are likely to be unsteady and unrepresentative. Tests should be avoided at extremely low temperatures or under conditions which differ appreciably from the operational period.
- If the reach of channel to be tested is not located between existing weirs or regulating structures, temporary watertight dams or bulkheads are required to isolate and impound water in the channel reach. The need to construct impermeable barriers across the channel to form the pool can be relatively costly. In large channels it may be difficult to adequately seal all inflow and outflow structures and the cost of conducting the tests can be relatively high.
- The difficulty in obtaining an accurate measurement of the volume of water evaporated during the test which may be of the same order of magnitude as the loss of water through channel seepage
- Does not simulate actual running conditions as the water level drops during the test without being refilled. Flowing water (ie velocity head) may have some effect on seepage rates. However, the difference is probably inconsequential in view of the measurement errors.
- The method is difficult to apply in channels with steep gradients because the length of pond which can be obtained under such conditions is small and the end area becomes significant compared to the total wetted area.
- The still water in the pool may seep out at a different rate than the flowing water in the channel. This may be caused by the sealing effect of suspended material settling in the still water, by the growth of algae on the wetted perimeter, especially on lined channels, and by a change in the groundwater table when the channel upstream and downstream from the ponded reach are at lower levels.
- The test should be conducted with water at the normal supply level in the channel. The provision of water in the non-operational period can be difficult to organise and quite large amounts of water can be required to fill the pool, particularly where the pool must be topped up several times before the banks and bed become saturated and a reasonably constant seepage rate is established.
- The average seepage rate is measured, and does not show the variation in seepage rates or localised high losses from different parts of the channel reach.

Further details of this test can be found in the ANCID Workshop 1998 paper *Measurement – Pondage Test* by Leon Tepper of Thiess Environmental Services.

A variation to the ponding method consists of adding water to the channel reach to maintain a constant water surface elevation. The accurately measured volume of water added is considered to be equal to the seepage loss, and the elapsed time establishes the rate of loss.

21.7.3.2 *Inflow-Outflow Method (Dynamic Seepage Test)*

This method of determining seepage essentially involves a water or mass balance within the section of channel being studied.

The channel is set up to run in a stable and steady state condition at close as possible to full supply level during the test period. Channel level, gate openings, flow meters, leaks etc, are monitored throughout the test. All inflows to and outflow from the section are carefully measured together with the evaporation and rainfall applicable to the reach. The difference is attributed to seepage.

In larger channels inflow and outflow monitoring can be either by current meter gauging throughout the test, or by carrying out a sufficient number of area/velocity discharge measurements, to establish accurate rating factors to be applied to any flow recording devices within the system being tested. In smaller channels, weirs, flumes and orifices can be used to measure the flow.

It may take several days to obtain steady state conditions in the section of channel under test and once established, flow measurements are usually carried out over several hours.

The expected accuracy is within ± 5% of the total flow. The inflow-outflow method utilises measurements at the upstream and downstream ends of the reach being studied and can be no more accurate than these measurements. In some situations the errors can be greater than the seepage losses.

Advantages:

- Reflects actual operating (dynamic) conditions and requires very few theoretical assumptions.
- Is more convenient than a Pondage Test as it is carried out while the channel is in operation. The channel's operation is only interfered with to the extent that flows need to remain steady.
- Can be made fairly easily on long channel reaches where an indication of the general order of magnitude of seepage is required.
- The method is sufficiently accurate in channels with large seepage losses, however great care is required where the seepage losses are only a small proportion of the total flows. Seepage losses of 3-4% would be outside the normal accuracy of flow measurement.
- Is an important diagnostic tool in the first stage of loss assessment.
- Applicable to both unlined and lined channels

Limitations:

- Flow measurements by inflow-outflow method are not sufficiently accurate for the close determination of seepage losses in short reaches of channel or where there are low seepage rates. The inflow-outflow method requires a reach long enough to obtain measurable losses.
- There are difficulties associated with accuracy given that seepage is normally a small proportion of the total channel flow. A small error in one of the flow measurements will produce a relatively large error in the computed seepage.
- Temporary measuring weirs can introduce considerable headloss, which may make their use impracticable.

- Skilled hydrographers are required to make accurate current meter measurements.
- Unless seepage losses are large, the errors manifest in measuring flows, are often similar in magnitude to the seepage losses within the section under test. Area/velocity measurements made under good channel flow conditions would generally be within an accuracy of 5% although errors could easily be greater. Low velocities and changing flow conditions are the major cause of errors of a greater magnitude.
- It is very important to have steady unchanging inflow to, and outflow from, the section of channel otherwise large errors can be introduced. However, in practice it is extremely difficult to maintain steady conditions when a channel system is operational.
- To obtain satisfactory results, the reach must be selected so as to avoid inflow and outflow which cannot be accurately measured.

21.7.3.3 Seepage Meter Method

Seepage Meters can be used to determine the seepage rate at a particular point in a channel. A seepage meter is basically a modified version of the permeameter developed for use under water.

There are several types of seepage meter. The meter essentially consists of a covered watertight cylindrical infiltrometer (bell). The 30-60cm diameter bell is connected by a tube to a Marriott reservoir which allows the rate of loss of water from the bell to be measured as it seeps through the channel subgrade area isolated by the bell. The seepage rate is computed from the volume of water lost in a known period of time and the area under the bell. The most commonly used type in Australia is the *Idaho Seepage Meter*.

Spot measurements are made along banks and beds of operating channels typically at 50 to 200 metre intervals depending on the variability of seepage rates. The meter isolates a small area of channel at a time and measures the seepage under the normal operating conditions in the channel.

To assess the cross-sectional seepage behaviour, a number of measurements can be taken across the channel section at each interval to identify the *batter* and *bed* seepage rates.

Measurement of seepage using seepage meters is cheap and relatively quick, taking 15-30 minutes to complete each measurement. However due to the variability of results from point to point, a large number of measurements are required in order to obtain a median estimate with some statistical confidence.

Work in Australia comparing ponding results with seepage meter results suggest that the Idaho meter will underestimate the real seepage rates. Therefore seepage meters are useful for comparison of seepage between sites, but are generally less reliable for estimating actual seepage rates.

Seepage meter should be installed with the least possible disturbance of the channel material. Disturbance of the soil during insertion of the meter can cause indicated seepage rates to be higher than actual. To ensure accurate measurement the seepage bell must be sealed watertight into the bed of the channel.

Imperfect seal will cause the meter result to be less than the actual rate of seepage.

Advantages:

- Suitable for measuring local seepage rates in channels, particularly useful for rapidly locating zones or short sections of a channel where seepage is relatively high and where lining should be considered.
- Ease of operation – rapid, direct and relatively low cost seepage measurement.
- The seepage meter is not considered an accurate means of measuring total seepage losses. Its main value lies in determining approximate locations of relatively high seepage losses. If tests are made at close intervals through a reach, a better indication of the average loss rate can be determined.
- Tests using the seepage meter can be conducted in channels without interfering with their normal operation.
- Seepage meter can be used during the irrigation season which means that watertable and channel water surface conditions should be relatively steady and representative of those encountered during typical operations.
- Seepage meter can be used on the sides of the channel as well as the bed.
- Provides a good indication of the order of magnitude of seepage rates.

Limitations:

- The seepage meter provides only a short-term spot measurement of seepage loss rate, and a number of measurements on both the channel sides and bed must be made to provide a reasonable estimate of losses.
- Seepage meters cannot be used in hard or very gravelly material because of the difficulty of forcing the bell into the channel to achieve a seal.
- Steep eroded batters cannot be measured for seepage because of the instability of the meter.
- Difficult to obtain accurate results when seepage losses are low – under 0.003 m^3/m^2/day the seepage meter has been found to give unreliable results.
- Aquatic weeds can prevent the insertion of the bell in the channel. The weeds cannot be removed without affecting the seepage rate.
- High water velocities where the flow of water is greater than 0.6m/s result in a pressure difference between the water inside the bell and in the channel, and thus producing unreliable results.
- Seepage meters cannot be used on channels deeper than 1.2 metres because of the physical limitations of the equipment.
- Seepage meters can be used during normal channel operation; but their use is restricted to unlined or earthen lined channels, whereas pondage and inflow-outflow methods can be used on either lined or unlined channels.
- Operator error using the meter can result in erroneous measurement and operator experience plays a significant role in obtaining reliable results. The seepage meter has a reputation of being highly subject to operator error, which suggests that the data should be treated with some caution.

- Wave action and channel level changes during the test can produce unreliable results. Tests should be undertaken in relatively calm conditions.
- Rotting organic matter in the silt on the channel bed can release methane gas when the bell is inserted and the resulting pressure difference can affect the accuracy of results.

21.7.4 Indirect Measurement

These methods, which are use to trace and detect seepage, are essentially limited to the qualitative indication of the distribution of seepage along a channel. The aim is to locate sections with excess seepage. These methods are described below:

21.7.4.1 Piezometric Surveys

Where high seepage rates are suspected, and locally high watertables are evident, installation of piezometers adjacent to the channel can be undertaken to evaluate watertable trends.

A piezometer is a borehole sunk to below the groundwater level. Piezometers are normally constructed with a PVC pipe of 50-100mm diameter sunk into the ground.

A typical piezometer installation involves drilling a 150mm diameter hole, into which a 50mm diameter PVC pipe is inserted. The lower one metre of the pipe is slotted to allow groundwater entry and the space between the inserted pipe and the excavated hole is backfilled with a fine gravel to within one metre of the natural surface. The top 1 metre is then backfilled with a clay plug to prevent surface water entry, and a PVC cap is fitted. Refer to Figure 21-5.

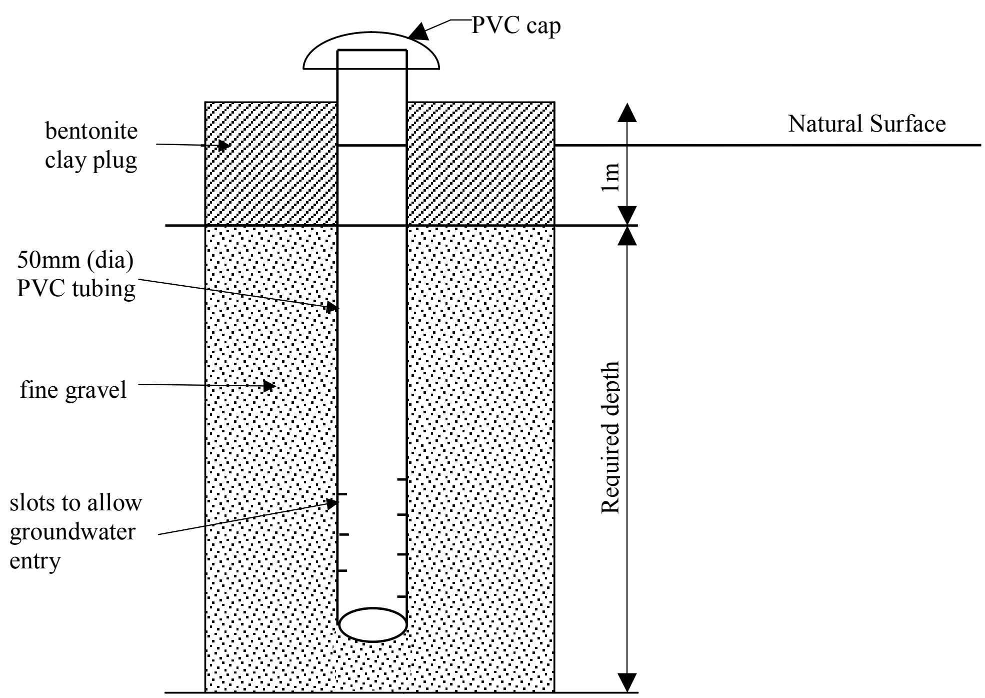


Figure 21-5 Typical piezometer construction and installation

The groundwater level can then be determined with a measuring tape or electric probe. This provides a simple method of monitoring groundwater levels over time.

Where channel seepage is suspected, a series of piezometers can be installed at a right angle to the centreline of the channel, at regular intervals (say 10 metres) from the toe of bank. If there are high groundwater levels tapering away from the toe of bank this indicates a level of seepage.

Piezometers can be used to identify high seepage zones along the channel and to indicate the effectiveness of any remedial works.

Generally piezometer readings are taken for a full year to compare the change in watertable level at the site between the irrigation season, when the channel is full, and when the channel is drained.

Groundwater observations do not yield specific qualitative results, but show in general the groundwater table fluctuations when the channel is filled or emptied. This indicates whether or not the channel is the source of seepage.

21.7.4.2 Geophysical Techniques

Electro-magnetic (EM) units can be used to measure the electro-magnetic properties of soil over a shallow depth from the surface. These properties reflect the combined result of interactions of soil texture, soluble salt content, water content and lithology. If three of these factors are reasonably constant over a study area then the EM reading reflect changes in the other variable.

Fixed frequency electro-magnetic units, EM38, EM31, EM34 etc, have been used to map seepage along channels in Australia, the numbers referring to the frequency used. The EM method can quickly provide high density information which cannot be obtained by other means.

The methodology involves conducting EM traverses parallel to a channel and recording resistivity values at regular intervals. The optimum EM equipment and coil separation for investigating the process of channel seepage is dependent on site conditions.

An EM unit measures the electro-magnetic properties of the soil. Electro-magnetic methods use a transmitter coil energised with alternating current to induce very small electric currents in the shallow earth. These induced currents generate a secondary magnetic field which is sensed by a receiver coil located a short distance from the transmitter coil. The depth of penetration depends on the distance between transmitter and receiver coils and whether the coils are vertical or horizontal.

The response at the receiver coil gives an averaged electrical conductivity over the depth of penetration. The electrical conductivity is primarily a function of the salinity of any contained water and the soil lithology. When both lithology and salinity are varying, the interpretation of EM traces can be difficult. However, in the case of channel seepage, higher permeability soils and low salinity water in areas of high channel seepage will enhance each other to produce a low conductivity and high resistivity response. Therefore, the EM unit can potentially be used to map areas with high permeability soils and low salinity water emanating from the channel.

Once the relationship between channel seepage and EM response is established for one site, channel seepage over a wider area along the channel may be estimated from EM results. However the relationship between channel seepage and EM response is site specific and depends on the particular soil and groundwater conditions at the site.

Qualitatively, the results of the EM survey can be used to highlight lengths of channel which are likely to have higher seepage. EM surveys can be used as a predictive tool for estimating relative channel seepage and where other backup information is provided can be used to estimate absolute seepage.

21.7.4.3 Hydrochemical Tracers

Hydrochemical tracers can be used to detect and track the movement of water from a channel to boreholes located adjacent to, or at some distance from the channel.

Hydrochemical Tracers include:

- stable isotopes, eg Oxygen 18, Deuterium, ^{2}H
- EC
- CFCs

Use of Natural Tracers

- Tracer input needs to be quantifiable
- The signature of the irrigation water needs to be differentiable from that in the tracer matrix
- Need to know when the tracer was applied or the concentration of the tracer needs to be time dependent.
- To estimate the seepage rate using tracers, need information on the mechanism of seepage.

Advantages:

- Useful for measuring low to intermediate rates of seepage (0.01-0.03 $m^3/m^2/day$)
- The use of tracers adds confidence to seepage estimates using water balance alone
- Useful for calibrating groundwater models by tracking the path of seepage from the channel to a borehole.

Limitations:

- Cannot distinguish channel accessions from farm irrigation accessions
- Without knowledge of the seepage process, a tracer will only indicate how far the seepage travels but not the seepage rate.
- Best used in conjunction with other seepage measurement techniques so that seepage rate can be estimated. Refer to Section 21.7.1, Seepage Studies.

Stable Isotopes

The basis of testing the isotopes is that the channel water has a distinct isotope composition compared to the regional groundwater and so both sources of water have a unique isotope signature. The isotope signature will be a combination of the two sources based on the relative contribution channel water and regional groundwater at each test site. Consequently the isotope compositions for bores near the channel closely match the channel water while those distant from the channel match the regional groundwater.

Isotopic tracers can indicate where the leakage is going and how long it has taken to get there.

Electrical Conductivity (EC)

Using a similar concept of water signature, the measurement of the EC from bore samples can be used to indicate the relative contribution of channel water and regional groundwater at the bore site.

Chloro-Fluoro Carbons (CFCs)

- Useful to distinguish older groundwater from accessions to the groundwater from irrigation channels and farming practice.
- Useful to define water < 50 years old

21.7.4.4 Remote Sensing Techniques

Remote Sensing Techniques are useful to determine where seepage may occur in an irrigation region. Some of these techniques are:

Soil Classification – using existing soil maps to track where high permeability soils intersect with channels – prior streams, lunettes, sandy soils

Aerial photography [visible, infra-red (IR)]
Salinity discharge in an area can be mapped using aerial photography with ground truthing. The results from this task can be used to assist in the delineation between the effects of channel seepage and that caused by regional groundwater processes.

21.8 Seepage Remediation Techniques

Channel seepage remediation techniques can be broadly classified into two groups as shown in Table 21-3.

Reduction of Permeability	**Interception of Seepage Water**
Bank Refurbishment/Reconstruction	Core trenching, vertical cut-off walls
Re-compaction	Seepage interception drains
Channel Lining	Tree Planting
Sedimentation and Biological Sealing	Groundwater pumping
Pipelining	
Re-alignment of channel	

Table 21-3 Channel Seepage Remediation Techniques

Each of these methods has its inherent advantages and disadvantages and the selection as to which is most appropriate for a specific installation depends on the environmental, geological and hydro-geological conditions.

The different methods used to reduce seepage or the effects of seepage are shown in Figure 21-6.

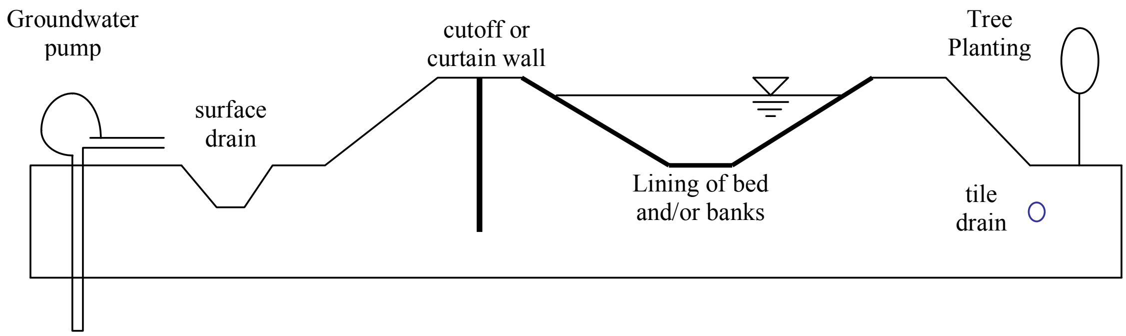


Figure 21-6 Seepage remediation methods

Measures which result in a lowering of the watertable beneath a channel can increase the rate of seepage from the channel by increasing the head difference between the water level in the channel and the groundwater level.

21.8.1 Bank Refurbishment / Re-construction

If channel banks are seeping bank re-construction may be a cost-effective option to reducing seepage. Refer to Section 20.4, Re-construction Techniques. This treatment is only useful if seepage is through the banks of the channel.

21.8.2 Core Trenching

Where seepage from a channel has been identified as unacceptably high, core trenching of the banks may be an effective remediation method. The core trench acts as a vertical sub-surface barrier that limits or contains the lateral seepage from the channel.

Core trenches are also known in Australia as cut-off walls or key trenches.

A vertical trench is excavated down to a low permeability layer adjacent to the channel waterway, typically through one or both of the channel banks depending on conditions, and re-filled with a low-permeability substance. Various materials can be used in the trench, such as:

- clay
- concrete
- flexible membrane
- chemical
- slurry wall
- bentonite
- sheet pile

The cost is highly dependent on the depth and type of core material.

To be most successful, there needs to be a low permeability layer, usually clay to *key* the base of the core trench into.

This method is typically used to treat seepage through the porous banks of channels and can also be used as a cut-off wall below the level of the bed to reduce lateral bed seepage affecting adjacent land. Its effectiveness is dependent upon whether the cut-off can be adequately embedded into a low permeability foundation layer.

A typical core-trenching approach using clay fill would consist of:

1. Excavate a trench in the centre of the channel bank 1-2 metres wide using an excavator or backhoe to a depth below the seepage path.
2. Import clay material and backfill trench by placing clay in layers and compacting using a sheepsfoot roller attached to the boom of an hydraulic excavator or a small self-propelled vibrating trench roller.

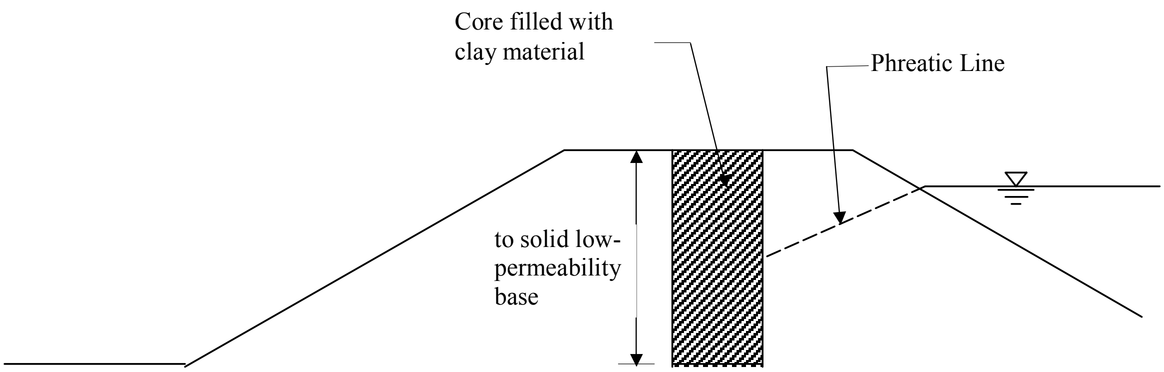


Figure 21-7 Core-Trench

The success of core trenching is highly dependent on site conditions, with the required vertical depth of the core trench based on piezometric surveys or seepage modelling.

Experience at some sites suggests that there is an initial reduction in seepage losses, however seepage then increases as new seepage paths develop under or around the core trench. Some researchers have assessed core trenching to be less than 50% effective in reducing seepage losses.

The life expectancy of core trenching varies considerably (2-25 years) depending on the type of core material used and the site conditions.

21.8.3 Re-compaction

The construction methods used in the past have meant that some existing channel banks have not been adequately compacted ant the rate of seepage through the more permeable banks can be relatively high.

Insitu compaction of the banks to increase the impermeability of the soil is a possible remedial technique to reduce seepage, however the effectiveness of conventional compaction equipment is limited to the upper layers of the bank.

High energy impact rollers are able to increase the density of bank material to effective depths of up to 2.5 metres. This method relies on the significant depth of influence of the high energy compression and shear waves generated by the impact roller to overcome the inter-particle friction and tighten up originally poorly compacted zones with the banks. The increased bank density, required number of passes and depth of influence will depend on the characteristics of the roller, the bank material and the moisture content within the bank.

The compaction process would generally proceed as follows:

- The top of the bank is graded off to remove the topsoil and provide a reasonably level surface for compaction. Turning bays are constructed at appropriate intervals. The existing bank has to be wide enough to provide sufficient clear distance (some 1-2 metres) between the roller and the edge of the bank.
- The crest of the bank is compacted with a 3-sided impact roller. The higher energy levels of the 3-sided roller are considered to be the most suitable for bank compaction.
- Compaction is conducted on a daily basis for 10 to 15 days with a few hours of compaction each day. This is to allow the dissipation of the high pore pressures that will build up in the bank.
- A total of 60 to 100 passes may be necessary to achieve the required density at depth.
- Depending on the initial bank density, large settlements may occur in the first few days, with the rate of settlement reducing as the compaction proceeds. The resulting settlement of the bank will reduce the freeboard and reinstatement of the bank height may be necessary.

The effectiveness of compaction diminishes as the number of passes increases and field trials may be necessary to optimise density and compactive effort. Impact compaction can also be used on the channel bed to increase impermeability and reduce seepage.

Non-circular high energy impact rollers have been used in Australia to reduce seepage through the dynamic compaction of existing channel banks. However, limited information is available on the effectiveness of this type of treatment. An impact roller was used by Murray Irrigation on a section of the Mulwala Canal near Finley, NSW to increase bank density by up to 18% after some 70 to 100 passes. Settlement of the compacted bank was up to 400mm.

Photos\compaction\landpac1.impact compaction.jpg

Photo 21-1 Impact Compactor

Refer to: Section 16.10.1.5, Non-Circular Impact Rollers

21.8.4 Channel Lining

Refer Section 22, Channel Lining.

21.8.5 Sediment Sealing

Refer Section 22.7.6.1, Sediment Sealing (silting).

21.8.6 Surface interception drainage

21.8.6.1 Surface drains at toe of bank

Open surface drains along a channel will not generally intercept seepage as they will be too high above the free surface. To make open drains deep enough to be effective, the high construction cost, extensive land requirements and high maintenance costs make them impractical. (Refer Figure 21-6). However they can be useful to intercept leakage from deteriorated channels banks.

Drains require effective disposal which may be achieved by pumping back into the channel.

21.8.6.2 Regional Drainage Systems

Most irrigation areas in Victoria and New South Wales are in very flat areas. For instance the natural grade of land in Central Goulburn area of Goulburn-Murray Water is 1 in 10,000. The natural drainage lines tend to be depressions that fill in wet years rather than perennial streams. Construction of regional drains along these depressions has intercepted seepage due to the high watertables (2 metres or less from the surface) experienced over much of the irrigation areas.

21.8.7 Interception Drainage

This seepage control method can be more accurately described as a countermeasure against seepage water reaching the watertable. Essentially, the concept aims to retrieve the water that has already leaked out of the channel and to return it to the channel.

The concept consists of a horizontal perforated pipe set at 2 to 3 metre depth running along each side of the channel and between 5 to 10 metres away from the channel, with collection sumps and pumps, to pump the water back into the channel.

This concept is only effective where the watertable is already shallow. Where watertables are deeper than the intercepting pipeline, seepage water tends to migrate vertically downwards from the channel and will not be picked up by the pipe. Refer to Figure 21-4. Also the soil in the vicinity needs to be sufficiently permeable to enable seepage water to be efficiently drawn to the pipeline.

There are on-going costs associated with the pumping and pipeline maintenance (root clearing) and the recurrent costs can be relatively high.

21.8.8 Groundwater interception

An alternative to preventing channel seepage is the construction of groundwater interception schemes involving groundwater pumping for shallow bores or tile drainage located adjacent to the channel. Groundwater pumping may be the most suitable option where a pumpable aquifer is present. Where hydraulic conductivities are lower, tile drainage may be a more practical and cost-effective option.

Groundwater interception is effective irrespective of the water source, and may be more cost-effective than other remediation techniques where the channel seepage is providing unwanted groundwater accessions and localised salinity problems.

When the intercepted groundwater is of a reasonable quality, it may be reinjected into the supply system and re-used. However re-injection of groundwater into the channel system will impact on channel water quality which may induce increased seepage. Where groundwater is of a relative poor quality, alternative disposal options must be available.

There is an on-going operation and maintenance cost associated with groundwater pumping. In addition, pumping can induce greater seepage due to an increase in the net available head. Control of seepage through groundwater pumping therefore requires careful planning.

Design of seepage interception scheme involving conjunctive use (ie use of groundwater) needs to include:

- a target operating depth for pumping
- rotational operation of the channel and groundwater pumps to ensure that waterlogging/salinity control is achieved without significantly increased seepage.

21.8.9 Tree Planting for Seepage Interception

Under the right site conditions water tolerant trees and grasses planted along channels can be used to lower the local watertable levels associated with seepage. The transpiration of water by the trees and grasses can reduce, if not prevent, the processes of waterlogging and salinisation.

Several studies have been carried out which indicate that planting trees adjacent to channels can potentially reduce the watertable level around the area of influence of the plantation.

Tree plantations do not prevent seepage, they intercept the groundwater seepage flow.

Trees can generally be used effectively along channels with low seepage rates of up to about 0.01 m^3/m^2/day. Other methods are generally more effective to combat seepage where rates are higher than 0.01 m^3/m^2/day.

A study investigated the impact of planting trees and salt tolerant grasses, on groundwater pressures adjacent to channels in the Mallee area of Victoria. Monitoring indicated that there was groundwater drawdown below the tree belts after three years. This is illustrated by Figure 21-8 which show the groundwater profiles at right angles to channel for a treebelt interception planting.

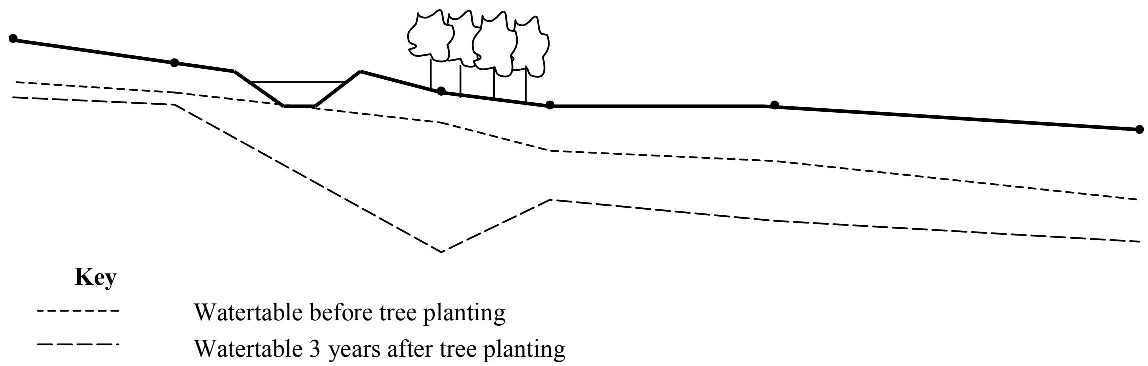


Figure 21-8 Watertable profiles at a channel site where a tree belt was planted

While tree planting adjacent to channels can be effective in intercepting seepage, increased seepage losses can occur, particularly on lighter soil types, due to the lower groundwater levels and the increase head difference, inducing higher seepage rates. No water savings are achieved by tree planting as trees only intercept seepage, not prevent it.

At some sites, however, tree plantations may not be appropriate for seepage interception. Tree plantations planted on heavy soil types in shallow watertable areas are more likely to utilise groundwater from the regional watertable as well as seepage and are therefore more susceptible to salt accumulation. The result can be the development of a discharge zone within the plantation leading to concentration of salt in the rootzone, which restricts the water use and growth of the tree plantation.

Photos\seepage\BoortNo2channel4trees.jpg

Photo 21-2 Trees planted outside boundary fenceline

21.8.10 Re-alignment

In some situations re-alignment of a channel may be an option to eliminate a high seepage section of channel.

This would involve constructing a new channel in a different location to avoid high permeability soils, such as prior streams or sand drifts, or large head differences between channel water level and the groundwater table.

21.9 Decision Making Criteria

This project has not addressed this as this will be addressed in the ANCID Seepage Project. Refer Section 21.10.3, Stage 3 – Decision Support System.

21.10 Further Research

In October 1998, the Australian National Committee on Irrigation and Drainage (ANCID) conducted a two-day industry workshop on the issue of channel seepage. The aim of the workshop was to draw together current knowledge on channel seepage, with the focus on channel seepage assessment and remediation. Several recommendations were ensuing from this workshop, which were accepted by ANCID in March 1999.

Workshop recommendations seen as necessary to support the rural water industry were to:

- Establish an industry Task Force to co-ordinate channel seepage investigation and remedial action;
- Develop standard terms and methodologies related to channel seepage
- Refine the science of channel seepage assessment and reduction
- Develop standard guidelines to assist with channel seepage measurement, impact assessment and remedial works;
- Develop a decision support system; and
- Develop a rapid method of assessing zones of high seepage in various geological profiles

These recommended actions resulted in the adoption of a three stage project designed to provide best practice information on channel seepage measurement and remediation and to develop a suitable decision support system.

The ANCID project has been successful in receiving significant funding commitment from several agencies who are participating in a collaborative arrangement aimed at addressing the recommended actions. The project will span four years and will involve an estimated total expenditure of close to $2.5 million. Task Force and Project Steering Committees have been established with representation from the water industry and the funding partners. Three specific project *Stages* have been formulated to investigate and address unanswered questions on channel seepage measurement and control.

In addition to the Task Force and Committee arrangements, there is also a wider communication program in place designed to keep interested groups informed of the project work.

21.10.1 Stage 1 – Channel Seepage Measurement and Monitoring

The key planned activities, some of which are already underway, include:

- A literature search and report on what is currently known about the measurement and monitoring of channel seepage.
- Consultation with the Australian rural water industry regarding current procedures used to understand and deal with channel seepage.
- The update of the ANCID *Rural Water Industry Terminology and Units* booklet, designed to provide an easy look-up reference for terms commonly used in the industry.
- Field trials demonstrating a range of different methods to quantify channel seepage.
- Conducting an industry workshop to discuss the project results and conclusions.

- The preparation of a best practice guidelines manual for the quantification and measurement of channel seepage.

Stage 1 has progressed to the point where reports are now available on current knowledge and procedures used in the rural water industry, a report on a literature review of seepage measurement techniques and a draft version of the updated ANCID *Rural Water Industry Terminology and Units* booklet. These products will be available on ANCID's website (*www.ancid.org.au)* from November, 2000. Copies are now available in CD format from the Stage 1 contact. Refer Section 21.10.4.

21.10.2 Stage 2 – Channel Seepage Remedial Works

The Stage 2 project is designed to target remedial actions appropriate to repair channels to reduce seepage losses. This project is therefore focussing on best practice standards in construction techniques. The key activities are expected to be:

- Review the current national and international work practices.
- Examine different remedial techniques using field trials.
- Prepare a best practice manual giving guidelines and techniques for remedial construction measures.
- Release for review the project outputs at a future ANCID Workshop, co-ordinated with the third stage of the project.

21.10.3 Stage 3 – Decision Support System

One concern raised by the water industry has been the difficulty in deciding whether it is justified to expend considerable funds on repairing channels suffering from seepage. The known issues relate to not only the construction costs but also measures necessary to quantify the value of water savings. Social issues as well as benefits to the local environment including changes to the local groundwater regimes, associated surface soil health and bio-diversity are all to be considered.

The third stage of the project is targeted at providing the tools to undertake the detailed justification analysis. This project is expected to involve the following:

- Development and documentation of a suitable integrated and interactive tool that can be used as a practical guide to investing in channel seepage control investigations and remedial works programs.
- Linking the tool to the *World Wide Web* to obtain up to date information and is to be supported with audio and visual aids for training users
- Demonstrate the tool at one of the above-mentioned workshops for review before consolidating and releasing it to industry.

21.10.4 Further Information

Further information can be obtained from the ANCID website (*www.ancid.org.au*) or from the following:

Stage 1 Project: Mr Peter W Jackson
Wimmera Mallee Water
PO Box 19
HORSHAM VIC 3402
Email: peterjac@wmwater.org.au

Stage 2 Project: Mr Evangel Aseervatham
Murray Irrigation
443 Charlotte Street
DENILIQUIN NSW 2710
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Stage 3 Project: Mr Kevin Devlin
DNR State Water Projects
PMB 5013
AYR Qld 4807
Email: Kev.Devlin@dnr.qld.gov.au

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22. Channel Lining

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22.1 Introduction

The conservation of valuable water resources for agricultural and environmental purposes is becoming increasingly important. Water that seeps from earthen channels can also contribute to groundwater accessions and increasing land salinity. One way of reducing the amount of water lost from earthen channels through seepage is the installation of relatively impervious linings.

This section provides information on the principle types of earthen channel linings, the relative merits of lining channels, the selection of lining type, their design, and methods of construction, effectiveness and durability.

The section deals specifically with irrigation channels where the applied lining needs to have sufficient strength against the scouring effect of flowing water. The information is therefore not necessarily applicable to the lining of water storages, although similar techniques are used for both.

22.2 Background

The efficiency of the channel distribution system – that is, the transport of water at minimum cost and with minimum water loss – affects the total economy of an irrigation project.

Two general categories of channels are used in irrigation schemes, unlined and lined. Only comparatively small proportions of the total length of channels in Australia are lined. This contrasts with overseas where a much larger proportion of irrigation channels are lined. The reason for this difference is that most channel linings are installed to reduce seepage due to high soil permeability, and the seepage rates from irrigation channels in Australia are relatively low compared with the seepage rates in other countries.

Some existing channels in Australia are located in permeable soils, and it is questionable whether open earth channels would now be chosen as the means of distributing water in some of these locations. However, when first constructed many years ago, moderate seepage rates were considered acceptable in terms of the much deeper watertable levels of the time and a lack of appreciation of the long-term effects of constant groundwater accessions.

Measurement of seepage losses from irrigation channels in northern Victoria taken between the 1960's and 1980's by Idaho meter and pondage tests, typically range form 0.0024 to 0.1160 m^3/m^2/day. Variations in measurement are high, but the median value is 0.0092 m^3/m^2/day. Because seepage measurements are more likely to be taken on channels suspected to have high seepage rates, the results are considered to be an over-statement of the general seepage losses. A more representative range for unlined earthen channels in northern Victoria and southern NSW is therefore considered to be 0.005 to 0.009 m^3/m^2/day depending on the proportion of permeable soils in the region.

United States references give a wide range of seepage rates for unlined channels, but common values vary from 0.02 to 0.3 m^3/m^2/day. Seepage rates from United States channels before they were lined have been as high as 0.4 to 0.9 m^3/m^2/day. The US Bureau of Reclamation refers to channel seepage losses of 0.06 m^3/m^2/day as being relatively low. By comparison, some Irrigation Authorities in Australia consider channel seepage rates of over 0.03 m^3/m^2/day to be high. Figures for unlined irrigation channels in India show seepage rates generally vary from 0.025 to 0.60 m^3/m^2/day.

22.3 Types of Linings

To be successful, a channel lining must reduce seepage to an acceptable level at reasonable cost and maintain effectiveness for the length of time required. An ideal channel lining material should satisfy the following requirements:

- cost-effective
- low permeability
- reasonably long service life
- capable of selective application
- resistance to mechanical damage, weathering and biological deterioration
- flexibility over a range of temperatures
- low roughness co-efficient
- reasonably low capital and maintenance costs
- easy to repair

A wide range of channel linings have been tried in Australia and overseas with varying degrees of success, at widely varying costs, and each has its own specific features and promoters. There is however, relatively little information available on the long-term costs and effectiveness of many of the channel linings under Australian conditions. While many lining treatments perform well under laboratory conditions, climatic and operational conditions can effect their performance in the field.

The different types of linings are commonly classified into three groups according to the materials and methods used in their construction. These are:

1. Earth Linings
    - Compacted earth lining
    - Compaction of insitu channel material
    - Bentonite type lining
    - Compacted soil-cement lining
    - Modified soil lining
    - Soil sealants

2. Flexible Membrane Linings
    - Exposed Lining
    - Covered Lining

3. Hard-Surface Linings
    - Concrete lining
    - Asphalt Lining
    - Brick Lining
    - Stone Lining

The different types of channel linings are discussed in Section 22.7 to Section 22.9.

22.4 Need for Lining

In the past, the approach to lining of irrigation channels in Australia, has generally been re-active:

– *Are the seepage losses from an unlined channel too high?*
– *Will lining be required?*

To conserve valuable water resources and secure other benefits, a shift in thinking is required, where lining of all earthen channels should be considered at the design stage and justification put forward for the use of unlined channels.

Since the extent of channel seepage and its related impacts are highly variable between sites, the decision to use an unlined channel should be based on the physical and economic considerations of each individual case. If lining is to be feasible, the benefits clearly need to outweigh the costs of lining.

Linings are principally installed in irrigation channels to:

- reduce water losses, thus freeing up saved water for consumptive and environmental use.
- decrease channel seepage, thus reducing soil waterlogging and salinisation damage, and lowering drainage requirements.
- reduce channel dimensions and land acquisition costs.
- permit higher velocities in channels through deep or difficult excavation, thereby reducing cross sectional areas, volumes of excavation and costs of construction.
- increase the structural stability and safety of the channel.
- permit larger flows through channels located on flat grades by decreasing the roughness factors, thereby reducing cross sectional areas, volumes of excavation and costs of construction.
- reduce the annual costs of operation and maintenance.
- increase the capacity of existing channels by decreasing the roughness factors and reducing seepage losses.

In Australia, the reduction of water losses through seepage is normally the governing factor in channel lining decisions. However, channel linings are expensive, and a lined channel may cost up to twice as much as an equivalent unlined earth channel. In order to avoid unjustified expenditure on lining where channel seepage is within acceptable limits, water losses along channels need to be realistically measured or predicted with and without lining. Refer to Section 21.5, Channel Seepage Measurement.

In considering the need for lining, it should be noted that the natural process of sediment deposition will take place to some extent in all earth channels at low velocities of flow. Experience indicates that significant initial siltation can take place directly after new earthworks construction, followed by slow increases in silt thickness thereafter. In deciding whether lining is needed, a judgement should be made regarding the possible adequacy of siltation as a natural form of seepage control.

In view of the high cost, decisions on whether or not to line channels should be based on an analysis of the benefits and costs. In certain situations, this can be a relatively straightforward process, however because of the large number of factors to be considered and the value of some benefits, such as environmental and social, it can be difficult to quantify in dollar terms, and the justification process can sometimes be far from straightforward.

No irrigation authority in Australia was identified that had objective criteria, that included local and regional scale impacts, to determine when channel lining was justified.

A consistent process by which sites are identified and prioritised is required. Some of the key issues that need to be considered in an analysis are listed in Table 22-1. Usually more than one benefit accrues and this list is intended as a guide only. It is not exhaustive, and not every issue is relevant in all circumstances.

Unlined Earthen Channel	**Lined Channel**
Water losses - seepage - leakage Environmental Impacts - rising water tables - seepage damage - salinisation and waterlogging - degraded land - leakage and flooding damage - road damages Maintenance costs - bank repair and beaching costs - scour and erosion - weed control - leak repairs - removal of silt deposits Economic life of channel bank Legal and business risks	Reduced water losses - reduced seepage losses - value of water savings - reduced accessions to ground water - reduced loads on drainage system - environmental effects - recovery of degraded land - reduced road damages - reduced pumping costs Reduced operation and maintenance costs - reduced weed growth - less damage from animals - protection against scour and erosion - reduced silt removal Savings in channel construction costs - reduced flow resistance - higher velocities - reduced cross sections - reduced areas of excavation - reduced cost of channel structures - increased flexibility in channel location - reduced land acquisition width - reduced need for drop structures Increased channel capacities - reduced flow resistance - higher velocities - reduced headloss - reduced seepage losses Increased structural safety Additional cost of lining - capital cost of lining - seepage monitoring costs - service life of lining - channel cleaning - maintenance of lining

Table 22-1 Unlined Earthen Channels vs Lined Channels

In assessing the benefits, the distinction needs to be drawn between lining at the time of new channel construction and lining of existing channels. The full benefits of lining are only obtained when the lining is included in the initial design stage. At this time, lining may reduce the storage and diversion requirements, allow smaller channel sections, smaller and fewer structures, reduced pumping costs where pumping is necessary and reduction in land acquisition requirements. The type of lining will also determine some of the benefits that can be considered in an economic analysis.

Details on some of the key decision making issues are set out below.

22.4.1 Water Losses

The primary benefit of reducing channel seepage is the value of the water saved and to be recognised as a benefit, water savings must have an economic value, and be able to be quantified and captured. The quantitative determination of seepage with and without lining in existing channels and the prediction of seepage from proposed channels, is therefore of major importance in identifying the sections of channel in which the greatest losses occur, the rates of loss and the amount of lining required.

The problem is that accurate measurement of channel seepage losses is difficult and costly.

In a number of Australian irrigation schemes, it has been found that a high proportion of the total seepage volume is caused by relatively short sections of high seepage rate channels. These sections are characterised by intersections with prior streams, sand drifts or deficient channel construction practices. The identification and lining of these sections can therefore have a significant impact on the overall seepage losses, and present the best opportunities for seepage control.

This is illustrated by investigations which attributed 37% of channel seepage losses in the Coleambally Irrigation Scheme to 6% of the channel length, and 93% of the channel seepage losses in the Berriquin Irrigation Scheme to 3% of the channel length.

In some situations it may not be necessary to line the entire channel cross-section to provide the required seepage reduction. If the majority of seepage is occurring from either the bed of the channel or the sides then minimising the seepage through these sections of the channel only may be the most cost-effective approach.

Locating the higher permeable reaches of a channel can be a difficult problem, and more economic and accurate methods of locating and measuring seepage are required so that lining requirements can be better defined. The identification and qualification of channel seepage losses is discussed in Section 21.7, Measurement of Seepage from Existing Channels.

The conveyance of water through open channels or even pipelines involves the loss of some amount of water. The water losses in unlined earthen channels are highly variable depending on local conditions. Information from a number of overseas technical references indicate that recorded water losses in unlined irrigation channels around the world are typically 20 to 40% of the total water diverted depending on soil types and other local conditions.

In the recent Benchmarking Report for Australian Irrigation Water Providers for the 1998/99 season prepared by the Australian National Committee on Irrigation and Drainage, average distribution efficiencies for mainly open unlined channel systems was 77%. From the Benchmarking study, reported efficiencies for open channel systems are Ord River 75%, Burdekin River 87.4%, Coleambally Irrigation 81.2%, Goulburn-Murray Water 74.6%, Murrumbidgee Irrigation 79.7% and Murray Irrigation 79.5%.

Figures for existing earthen channels in northern Victoria located on average clay loam soils are typically leakage 3-4%, seepage 2-3% and evaporation 2-3% of average diversions at the channel offtake.

Water loss figures in some literature need to be treated cautiously as some figures are for seepage only, while others are in fact total conveyance or transmission losses. Conveyance losses through an earthen channel system depend on a number of physical, operational and climatic factors, and can include:

- operational outfalls and spills
- seepage
- leakage through banks and at structures
- evaporation
- over-delivery to irrigators
- transpiration from channel weeds
- channel filling
- theft, as well as
- *perceived losses* due to measurement errors.

Average 10 year water balance figures for Goulburn-Murray Water's open channel irrigation areas are given in Table 22-2.

Outflow	**Percentage of Total Inflow**
Total Deliveries	74%
Outfalls	8%
Leakage	2%
Seepage	2%
Evaporation	2%
System Filling	2%
Domestic & Stock supplies	1%
Meter Error	3%
Unaccounted balance	6%
Total	100%

Table 22-2 Average water balance figures for Goulburn-Murray Water

The figures represent averages and they vary between Areas as well as between seasons due to deliver volumes, climatic conditions and other factors. The unaccounted for balance is mainly attributed to inflow-outflow measurement errors.

Lining of channels will not eliminate all conveyance losses, and it is necessary to carefully distinguished the losses that can be realistically saved by lining. Even, lining of a channel will not reduce the seepage loss to zero, because the lining material used will not be completely impervious.

Due to the lack of supervision at the time of construction, the use of poor quality material and many other reasons, imperfections can easily occur in linings. If the lining is not installed correctly or not properly maintained, the benefits of lining will not be realised.

Seepage losses from properly constructed concrete lined channels should normally be relatively small. However, subsequent cracking due to expansion or settlement or poor construction or maintenance can result in large losses. Other types of lining are also susceptible to varying amounts of seepage losses, depending on type, quality of construction and local conditions. The possibility of appreciable losses from lined channels, particularly after a period of years, should be kept in mind when preparing water saving estimates.

There will be situations where channel lining is not necessary or cannot be economically justified. In the foreseeable future, it will not be cost effective to line all channels and economics dictate that lining efforts need to be concentrated on those sections of channels that have the highest seepage rates and hence would benefit the most from lining.

Care also needs to be taken when talking about water savings. It is commonly inferred that channel seepage is lost water. In some situations this is valid, but in others it may not be, for example where the seepage water recharges an aquifer.

If the aquifer is fully committed to productive use and seepage losses were reduced, then recharge would decrease and depletion of the aquifer would occur. It therefore may not be possible in all cases to consider the water savings from channel lining in isolation, but rather a broader river basin perspective may be required to identify if the reduction in seepage represents a *real* water saving.

Taking refurbishment, or periodic restoration, as an essential part of the long-term maintenance of earth channels, there will be periods in the life of a particular channel when the water losses are high (before refurbishment) or low (after refurbishment) and its efficiency is respectively below or above average.

An earth channel system will inevitably contain channels which are about to be refurbished, channels just refurbished, and those in between. The overall system efficiency is thus the resultant of cyclically varying individual channel efficiencies. The average efficiencies of individual channels, and probably their refurbishment cycles, will also vary in relation to soil types. Thus, at any point in time, channels that are then in good condition *subsidise* those then in poor condition and so the system efficiency is maintained.

The question of lost water becoming available for delivery can only arise when the overall system efficiency is increased on a permanent basis. This could follow from improved operational techniques or conversion from earth channel to pipeline. The refurbishment of a particular channel does not, however, have this result and therefore does not, in fact, make recovered losses available.

22.4.2 Soil Waterlogging and Salinisation

Another significant benefit of reducing channel seepage is the reduction in accessions to groundwater, which contribute to local and regional land salinisation and waterlogging, and results in loss of productivity and bio-diversity.

The extent of the influence of channel seepage on soil waterlogging and salinisation problems can be difficult to determine, and in most cases requires careful analysis.

Channel seepage can be expected to have a more immediate and detrimental effect on soil salinisation when the channel is located in an area where high water table levels are already experienced, and lower where the watertable is substantially lower.

The effects of seepage are not always readily evident, particularly the long term effects of constant ground water accessions. The area of influence of a seeping channel depends on a range of factors including differential head, topography and soil types. It can have localised, as well as regional impacts. Seepage can effect areas immediately adjacent to the channel or it can be transmitted via a pervious underground stratum to lower areas some distance from the channel. Evaporation from seepage effected areas close to channels can account for part of the water loss from the channel and reduce seepage contributions to regional groundwater.

In the Tatura area of northern Victoria, modelling indicates that some two thirds of channel seepage eventually recharges the regional aquifer. The remaining third is lost to evaporation from the watertable or goes into storage in the surface aquifer.

Where watertables are less than two metres below the surface, this can have a detrimental effect on sealed and unsealed roadways, leading to increased deterioration and higher maintenance costs.

Channel seepage can be one of several sources of accessions to the watertable. In areas subject to high water tables it can be difficult to isolate causes, and lining of channels may not eliminate the waterlogging. An option to channel lining may be a surface or sub-surface drainage system to intercept and remove the seepage water. Watertable levels themselves have a significant influence the rates of channel seepage. Where watertables rise close to the surface, the seepage rate tends to decrease due to the reduction in the hydraulic gradient.

It is worth noting that the rate of seepage loss is not always a reliable indicator of potential damage. The formation of perched watertables and water logged areas adjacent to channels have been observed where the seepage rates are relatively low.

22.4.3 Reduced Channel Dimensions

If linings are constructed at the same time as the channel construction, the loss of water will be reduced and the sizes of channels can also be reduced to deliver the same amounts of water.

To supply a given discharge, the cross sectional area of a hard-surface lined channel can be reduced as the friction loss is less and the permissible velocity is greater. Table 12-3 gives a range of Coefficients of Roughness *n* according to Manning's formula for unlined earthen channels with various characteristics. Earthen channels range from 0.017 to 0.030. Coefficients of Roughness *n* compiled from a number of technical references for different types of lined channels are given in Table 22-3. It should be noted; the flow resistance in hard surfaced lined channels can vary seasonally because of aquatic growths on the lining surface.

Surface Condition	**Value of *n***
Concrete - well finished	0.014
Concrete - average finish	0.015
Concrete - poor finish	0.017
Soil cement - well finished	0.015
Soil cement - rough finish	0.016
Shotcrete – normal	0.017-0.018
Shotcrete – maximum	0.019-0.023
Precast concrete flume	0.012-0.016
Brickwork	0.013-0.018
Stonework	0.018-0.0225

Table 22-3 Values of Manning's *n* for Lined Channels

In channels lined with exposed hard-surface materials such as concrete, higher velocities are permissible than are normally possible in earthen channels. The maximum non-erosive velocities in earthen channels through different soils are shown in Table 12-5, and they range roughly from 0.45 to 1.5 m/s. A properly designed and constructed reinforced concrete lining will withstand velocities of any magnitude considered feasible for channels, provided the water depth is sufficient to reduce the flow rate below the critical point and control pulsing. Velocities from 1.5 to 2.5 m/s are permissible with unreinforced concrete. Velocities less than 2.5 m/s are used to avoid the possibility of converting velocity head through a crack to pressure head under the lining and lifting the lining.

Where hard-surface linings such as concrete are used, the gradient of the bed can be increased and the batter slope made steeper. The narrower width reduces the land area required for the channel, and reduced the land acquisition costs. Where the acquisition involves high value agricultural land, the reduced requirement for a lined channel can be an important factor.

Hard-surface lining also provides flexibility in channel location. Channels can follow abrupt contours since the erosion hazard associated with increased water velocities is controlled. Hard-surface lined channels can be used on steeper gradients where advantageous, which may eliminate drop structures necessary for erosion control in earthen channels on the same slope.

If the lining of an existing channel changes the hydraulic conditions, it may be necessary to modify regulator and offtake structures. Similarly, if the lining used on an existing channel requires flatter batter slopes, additional land acquisition may be required.

Earthen linings and buried geomembrane linings do not permit velocities higher than in unlined channels and the dimensions can not be reduced. Their economic justification depends on the value of the water saved by reducing seepage and on benefits from preventing waterlogging and salinisation.

22.4.4 Reduced Operation and Maintenance Costs

Where channels are supplied by pumping plants and seepage loses can be reduced by lining, savings in pump size and operating costs can be achieved.

The type of channel lining being considered will influence the savings in maintenance costs. For hard surface linings such as concrete, the benefits can include reduced weed problems, less damage from animals, reduced silt removal and protection from scour and erosion.

A large item of recurring maintenance on many channel systems is weed control, and hard surface linings such as concrete, which are relatively impenetrable by weeds, can greatly reduce the cost of weed control in the channel waterway. Seepage from unlined channels can also stimulate the growth of land-type weeds outside the channel banks, and lining can deter this.

The greater velocities permissible in channels with hard surface linings can also reduce maintenance costs when silting and erosion are significant problems. Hard surface linings are resistant to erosion, and if the slope of the channel is sufficient to use high velocities, the need for routine silt removal can be reduced. The silt, by remaining in suspension at the higher velocities, does not settle as much in the channel, but rather more of the silt is deposited on the land being irrigated.

In areas where burrowing animals and yabbies are prevalent, channel leaks occur as a result of holes burrowed through the banks. The cost of repairing the banks, the loss of water and the property damage caused by the escaping water can be considerable, and hard surface linings being practically impenetrable to burrowing animals will largely deter such actions.

These benefits would generally not be applicable to channels with earthen or buried membrane linings. Buried membrane linings or compacted earth linings do not prevent weed growth in the channel. Maintenance costs related to aquatic and bank weed control, therefore, are not reduced by these types of lining. However, if the buried membrane linings or compacted earthen linings had a substantial crushed rock or gravel cover this would substantially reduce erosion, discourage burrowing animals and provide less favourable conditions for weed growth compared to an unlined channel.

An adequate maintenance regime for concrete lined channels can be relatively costly, if the integrity of the lining is to be preserved, especially towards the end of its life. Cracking must be identified and repaired promptly, and weeds controlled on the crest of the channel bank, where they encroach in the waterway, and roots widen and conceal cracks. Water leaking from cracks for an extended period can erode the subgrade and cause the failure of an entire section of lined channel.

Refer to Section 13, Life Cycle Cost Analysis.

22.4.5 Structural Safety

The stability of the banks and bed of unlined channels can be a problem when the channel is located on high fill, on steep side slopes, in areas of sandy and silty soils, or the channel section is a combination of earth and rock. Lining may be justified to reduce the danger under these circumstances of channel failure caused by slippage, erosion or burrowing animals.

Options to channel lining would include construction of wider banks and providing toe drains. As assessment of the need and value of increased safety would consider the probability and consequences of injury or loss of life, property damage, loss of farm production due to delay in water delivery and repair of the channel breach.

22.4.6 Increased Capacity

If increased capacity is required in an existing unlined channel to meet greater demand and the required increase in capacity is relatively small, the installation of a hard-surface lining may be an economic solution. The reduction in seepage losses and the improved hydraulic properties of a hard-surface channel may provide the increased capacity at a lesser cost than enlarging the channel section. This could be a particular advantage where additional land acquisition for a larger channel section is not available or available only at a high cost. If the required additional capacity is relatively large, enlargement of the channel section will generally be required.

22.5 Selection of Lining Type

Generally speaking no one particular type of lining can be considered the best or most economical for use in all locations. Each type of lining has its own specific technical and economic merits and limitations depending on such factors as specific site and soil conditions, location, experience of installation crews and weather conditions during installation. A particular type of lining may be advantageous for one locality, but may be unsuitable for use at another location.

The same material need not be used for the whole cross-section of a channel, as the material for lining the bed can be different from that used on the batters. There are also situations where any channel lining will not be necessary or justified.

Selection of the best type of lining needs to be based on a careful analysis of the local factors and conditions for each channel. The objective is an efficient and durable channel lining at the most economic cost.

The range of factors that influence the selection of the most appropriate type of lining for a particular channel include:

- Principle purpose of lining
- Soil characteristics
- Topography
- Groundwater levels
- Climatic conditions
- Land use
- New or existing channel
- Operation and maintenance

- Channel size and importance
- Acceptable seepage rate
- Service Life
- Availability of construction materials
- Availability of labour and equipment
- Benefit cost analysis
- Financial aspects

The sequence in which the above factors are listed does not necessarily reflect their order of importance, as this will depend on the local conditions.

22.5.1 Soil Characteristics

An examination of the soils along or near the line of a proposed or existing channel will provide guidance on the best type of lining. Permeable soils, soils which may expand or settle upon becoming wet or those soils through which piping may occur need to be identified.

Failures have occurred where rigid-type linings such as concrete have been constructed on swelling and expansive clays, collapsible soils or piping action has lead to the loss of support for the lining. Where channels have to be excavated in such soils, a more flexible-type of lining, such as a compacted earth or a buried geomembrane lining, may be better suited.

If sufficient amounts of sand and gravel are found, this may favour the choice of a concrete or compacted soil-cement lining. If the soils have the required properties, a compacted earth lining should be considered. If the soil is not suitable for a compacted lining, it may still be useful as cover material for a geomembrane lining.

Using compacted earth or covered geomembrane lining, the decision to line permeable strata or areas in a new channel can be deferred until the excavation is in progress, and the need for and extent of lining can be definitely established.

22.5.2 Topography

Earth linings and buried membranes are normally best suited to slightly sloping or flat land, because of the lower permissible flow velocities, which can be one sixth of those in unreinforced concrete lined channels. Concrete is more resistant to erosion than most other lining materials, and therefore is preferable with high water velocities. Furthermore, hard-surface lined channels can better follow contour lines because the radius of curves can be much smaller than in earth lined channels.

22.5.3 Groundwater Levels

The location of the channel bed with respect to the groundwater table is particularly important. If the groundwater level is above the bed level of a channel, surface water drawdown or emptying the channel can cause external hydrostatic pressure on the liner. Unless under-drainage is provided, this pressure has to be met by the dead weight or elasticity of the lining. Failures have occurred where linings were too light or too rigid to resist the pressure. Compacted earth linings have performed satisfactorily under these conditions and seldom suffer serious damage from high groundwater. Concrete linings are susceptible to rupture by outside hydrostatic and soil pressures and under-drainage is the only means of correcting the problem. However, under-drainage can be costly and complicated.

Because of its weight and plastic characteristics, compacted earth lining can withstand considerable hydrostatic pressure without loss of effectiveness and it can be used in many instances without under-drains under the lining where the channel intersects the groundwater table. In colder climates concrete lining is not recommended in areas of high groundwater levels, as frost expansion can crack the lining when the channel is empty. In the Australian climate, frost heave is generally not encountered.

22.5.4 Climatic Conditions

If large areas of lining work on existing channels has to be done quickly in the period between irrigation seasons, often when the weather is cold or wet; low temperatures, wet sub-grades and difficult plant operating conditions may prohibit installation of some types of linings. A geomembrane lining may be the better choice under these circumstances. The geomembrane materials can be manufactured in long and wide sheets, making it possible to line long lengths of channel in relatively short periods of time.

Concrete linings are susceptible to damage from alkali water and from alternate freezing and thawing action. Another disadvantage of concrete lining under more severe exposure conditions, is its lack of extensibility, which results in cracks as contraction takes place from drying, shrinkage and temperature changes.

Concrete linings are particularly vulnerable in cold climates. Frost may cause heaving of slabs where subgrades contain too much moisture. Disintegration along water lines may be caused by freezing and thawing where channels contain water during winter months. In cold climates, compacted earth linings may be damaged by the frost action of freezing and thawing.

22.5.5 Principle Purpose of Lining

The principle reason for installing a channel lining will influence the selection of lining type. There can be a range of reasons for using a hard-surface linings and these include reduced seepage, reduced dimensions and excavation costs for new channels, increased capacity of existing channels, and reduced operation and maintenance costs. On the other hand, the primary reason for installing earth and buried geomembrane linings is to reduce seepage.

22.5.6 New or Existing Channel

Whether the channel is already constructed or is planned for construction will be an influencing factor. The full benefits of lining are only obtainable when the lining is included in the design stage of a new channel system. With an existing channel, some of the potential benefits of lining will not be available, and this may mean that the cost of certain lining types can not be justified against the obtainable benefits. The time period available for lining, weather and site conditions will also influence the lining type for existing channels.

In many Australian irrigation schemes the annual window of opportunity for lining existing channels is at most 3 months and there is a limit to the amount of on-site work that can be achieved in a year.

If long lengths of existing channel have to be lined in relatively short periods of time and the weather conditions are cold and wet; the low temperatures, wet subgrade and difficult plant operating conditions do not favour hard-surface linings or earth-type linings. Where as, a covered geomembrane lining may be a better choice under these circumstances.

22.5.7 Land Use

In areas of high land value and intensive cultivation, the fullest productive use of land is made, and land acquisition costs are high. Such situations favour the installation of pipelines or hard-surfaced lined channels with steep batter slopes. It would be expensive in such cases, to use a buried membrane lining which normally requires a 1 (vertical) : 3 (horizontal) batter slope.

22.5.8 Operation and Maintenance

If the operation of a channel system requires frequent filling and emptying or causes frequent water level changes, a hard-surface lining will normally perform best. With earth linings and earth-covered membrane linings, these conditions would speed up the deterioration process considerably and would require increased maintenance.

Most earth type linings do not prevent weed growth and do not withstand velocities higher than unlined channels. As well, de-silting operations must be carefully conducted to avoid damaging the lining.

The maintenance of earth linings and earth-covered membranes, such as weed control and silt removal, will therefore be very similar to unlined channels, and these higher maintenance costs should be assessed in a life-cycle cost analysis in comparison with the higher installation cost of hard-surface linings.

The adoption of exposed membrane linings or soil sealants may be limited by the hazard of livestock, de-silting operations or vandalism.

When existing channels are lined, the time available to carry out the work may influence the choice of lining. If the off-season shutdown is too short for the channel to dry out sufficiently for installation of a hard-surface lining, over-excavation and installation of a compacted earth lining or a covered membrane may be the better solution.

22.5.9 Channel Size and Importance

In smaller channels the economy of compacted earth lining becomes less attractive. Generally, the larger the channel, the lower the unit cost because heavy earth moving equipment can be used effectively, while the size and manoeuvrability of equipment suitable for working in smaller channels is much more restricted. Another reason is the unfavourable ratio of over-excavation to total excavation in smaller cross sections. Covered geomembrane linings are more suited to smaller channels.

Concrete linings are suitable for both large and small channels, for both high and low velocities.

Compacted earth and covered geomembrane linings can be used on comparatively small lengths of channel, say 300 metres, without any elaborate arrangements or extra costs.

22.5.10 Acceptable Seepage Rate

The objective of channel lining is rarely to completely stop all seepage, but to reduce the seepage to an acceptably low rate. Some irrigation authorities are using a target seepage rate of 0.002 to 0.003 m^3/m^2/day for channel lining projects. However the basis of this target was not always apparent and its adoption may have been somewhat arbitrary.

Seepage from channels can be reduced to acceptable limits by lining, however the cost of lining all channels in an irrigation scheme may be prohibitive. Seepage can vary widely among different reaches of a channel, and overall seepage losses can be reduced to acceptable limits at reasonable cost by lining reaches of channel where seepage is greatest, if these reaches can be definitely located. The challenge is to identify these sites when there is no easy method of monitoring seepage losses on an extensive and continuous basis.

Acceptable seepage rates will depend on the individual circumstances of each project and will influence the choice of lining. No channel lining is completely impervious. The overall permeability of a lining depends partly on the intrinsic properties of the material, and partly on the existence of flaws. Probably the most impermeable and long-lasting is a concrete lining placed over the top of a geomembrane, while the least durable are some of soil sealant treatments. Indicative permeabilities for different channel lining materials are given in Table 22-4.

Type of Lining	Expected Seepage Rate Reduction	Indicative Permeability m^3/m^2/day
Compacted earth	70-90%	0.0005 – 0.002 but varies widely
Bentonite lining	60-70%	0.0005 – 0.001
Chemically stabilised soil	60-90%	0.0005 – 0.001 but varies widely with material used
Concrete	70-95%	Below 0.0005 if well constructed & maintained
Geomembrane	85-95%	0 - 0.0005 but varies
Unlined – ordinary clay loam		0.005 – 0.025

Table 22-4 Indicative Channel Lining Permeability's

Reported seepage rates in Australia and overseas for the same type of channel lining can vary significantly depending on such factors as depth of water, level of watertable, lining thickness, local conditions and construction standards. Direct comparisons can therefore not always be made.

If the value of water lost through seepage is high or the secondary effects are particularly adverse, the aim should be to adopt a relatively watertight lining.

However, the cost of more impervious linings needs to be justified. A lower cost lining may be able to reduce high seepage losses to within more acceptable limits, while higher cost and more impermeable linings would be difficult to economically justify.

The thickness and material composition of linings are frequently designed so that the seepage loss through the lining is not more than 0.002-0.003 m^3/m^2/day. However, losses of say 0.006 m^3/m^2/day may be acceptable, when subgrade soils are very pervious and better lining materials are not economically viable, the cost of better lining material being too high for the value of the water saved.

Using compacted earth lining, partial sections and partial reaches of channels can be lined as required to limit seepage losses through particular strata or reaches. Covered membrane liners are normally installed only to reduce water loss from seepage.

In deciding whether seepage control measures are needed, a judgement should be made regarding the possible adequacy of siltation as a natural form of control. If the water in a new channel will contain considerable amounts of fine silt particles, the natural self-sealing effects should be taken into account and may make lining of the channel unnecessary. Refer to Section 22.7.6.1, Sediment Sealing (Silting).

When comparing figures on seepage losses in lined and unlined channels, it should be noted that for an equal unit loss, the total volume lost per unit length of channel is greater for an unlined than for a hard surface lined channel. For example, the wetted perimeter of a concrete lined channel is about 30% less than that of an equivalent capacity unlined channel.

22.5.11 Service Life

The service life of a liner is the period from construction to the time when the liner can no longer perform its design function. If the liner has been installed for seepage control, then its service life has effectively ended when the liner has deteriorated to a point where the seepage rate has increased to unacceptable levels.

The service life of liners can be highly variable and depends on the type of lining, quality of the lining material, the quality and accuracy of installation, climatic conditions, and channel operation and maintenance procedures. A lack of past performance data for the different types of linings under Australian conditions is a problem, and at best only estimates can be made for some lining types.

The effective life of concrete lining is largely determined by the rising cost of maintenance as the channel lining ages and is deemed to end when maintenance becomes so costly that it is more cost-effective to replace. Properly designed, constructed and maintained, a reinforced concrete lining should normally have a service life of 50 to 60 years. Under similar conditions, an unreinforced concrete lining placed on suitable foundations may have a life of 40 to 50 years before significant maintenance and rehabilitation expenditure is required. The life expectancy of soil sealants or thin exposed membranes may be two years, but could still be economically feasible as temporary linings under certain conditions.

Refer to Section 13, Life Cycle Cost Analysis.

22.5.12 Availability of Construction Materials

Generally, the most economic lining is that which makes the best use of locally available materials. For economic reasons all the heavy materials used to construct the lining should be available at the site or within reasonable distances. The suitability of natural soils for lining should therefore be carefully examined, and the extent of use of off-site materials needs to be considered in light of transport facilities. The light weight per unit area of geomembrane liners, allows shipment of the lining material long distances without excessive transportation charges.

The cost of compacted earth linings are most attractive where the excavated materials are suitable or where suitable materials are available close by the channels.

22.5.13 Availability of Labour and Equipment

The choice of lining can be governed by the relative supply of labour and equipment. If the workforce or contractors in a project area are familiar with a certain method of channel lining or particular construction equipment is available at reasonable costs, this should be taken into consideration in the decision making process.

For compacted earth lining, the availability of earth moving and compaction equipment is a major consideration, while concrete lining requires suitable placement machinery and skilled labour.

22.5.14 Benefit Cost Analysis

The costs of a given lining need to be weighted against the obtainable benefits. An evaluation of the geological and hydro-geological conditions of an area should produce a limited number of technically feasible lining options, and the final selection can then be based on a site specific benefit-cost ratio of the competing liners. The benefit-cost ratio must be greater than one if lining is to be feasible at all. Costs and benefits should be assessed as present values over the life cycle of the individual channel, in order to properly reflect the different service lives, capital and maintenance costs, water savings, benefits and eventual replacement costs of the liners, and the other specific factors inherent in a given project.

The capital costs of installing different types of channel linings are highly dependent on site specific factors. Costs can vary widely, not only with prices of labour and materials at the time of installation but also general conditions that affect construction activities. General conditions that affect costs include size of project, availability of suitable materials, accessibility to the site and competitive interest in the work. Costs of particular types of linings are also affected by lining thicknesses, other details of design and tolerances permitted by construction specifications.

Unfortunately one of the difficulties will be, that while the initial costs of most lining types can be estimated with a reasonable degree accuracy, there is a general lack of reliable information on the long term costs of maintaining different types of linings and the realistic lengths of time that they can be maintained satisfactorily without replacement (service life).

Careful consideration of the future economic value of water is required. The capital cost of the lining and the amount of water saved will usually be the determining factor in the benefit-cost assessment, and the water losses should not be arbitrary predictions. A realistic estimate will consider that losses in a lined channel generally increase with years of service and that losses in a unlined channel may decrease because of the natural sealing effect. The total volume of seepage water lost per annum will be a function of the seepage rate and the duration that the channel is in operation each year.

22.5.15 Financial Aspects

Theoretically the most economical solution should be adopted regardless of cost; however, in practice financial constraints can determine whether lining, and which type, can be afforded. When the costs of the most economic but expensive solution exceed available funds, a choice must be made between:

- adopting a less expensive lining, which allows for the initial lining of the channel system within the given financial limit; or
- construction of the more expensive lining at the initial stage of channel construction as far as funds permit, leaving the rest unlined until further funds allow completion.

As lining needs to coincide with the initial channel construction to gain its full advantages, it is generally more economical to adopt the less expensive lining, rather than to line only a portion with a costlier type.

22.6 Monitoring of Effectiveness

Seepage testing of channels that have been lined should be undertaken:

i) in the year following the works to check the effectiveness and identify any deficiencies in construction techniques or materials. It needs to be recognised that it may take up to six months to reach new steady state conditions.

ii) at periodic intervals to obtain an indication of the effectiveness over time and the expected remaining life of the lining. Channel linings do not have infinite lives and all linings will deteriorate to a point where the seepage rate will increase to an unacceptable level and remediation works are again necessary.

Many irrigation authorities in Australia have carried out seepage controls works on channels, but only in a very few cases has there been any rigorous post-implementation testing of their effectiveness and impacts over an extended period of time. This is considered a deficiency in current management practices.

22.7 Earth Linings

22.7.1 Compacted Earth Lining

22.7.1.1 Description

At times, the soils present along a proposed channel alignment may not be suitable for unlined channel construction, because of high permeability, or low resistance to erosion. To improve these properties, a compacted earth lining with better characteristics can be used on an over-excavated channel section.

With advancements in soil engineering and earth moving equipment, compacted earth linings are one of the most common types of irrigation channel lining used in Australia and overseas.

A lining of compacted earth can be a relatively low cost means of controlling seepage. It can also withstand considerable external hydrostatic uplift pressure and it can be used over expansive clays. Where suitable earth material is available with a minimum of haul and the job is large enough to fully utilise heavy earth moving plant, this has proved to be one of the most durable low cost linings.

The whole of the lining can be made from:

- imported earth compacted into place if suitable clay is available near the site of construction, or
- the properties of the in-situ soil can be improved by mixing it with imported material and then compacted into place to give an impermeable soil structure.

Photos\Lining\clay lining.jpg

Photo 22-1 500mm thickness claylining – Coleambally Irrigation

If the channel section cuts a pervious as well as impervious soil stratum, lining of the impervious part is not necessary, and the lining can be:

- Bed and Batters
- Bed only
- Batters only,

depending on the location of pervious zone in the channel cross section. Refer to Figure 22.1, Figure 22.2 and Figure 22.3.

Loosely placed earth blankets have been tried overseas and appear in some technical literature on channel linings. This type of lining consists essentially of a loose uncompacted earth blanket of selected clay soil dumped and spread to about 0.3 metre in thickness on the channel bed and batters. Its effectiveness in reducing seepage is limited and is dependant on the earth being impervious in a loose state. The service life will also be relatively short, possibly only a few years, if the material is not adequately stable to resist erosion and scouring. Although loose-earth linings can reduce seepage losses under certain conditions, they are not as effective or as durable as compacted-earth linings. Their use is therefore not recommended other than to correct temporary or emergency seepage conditions.

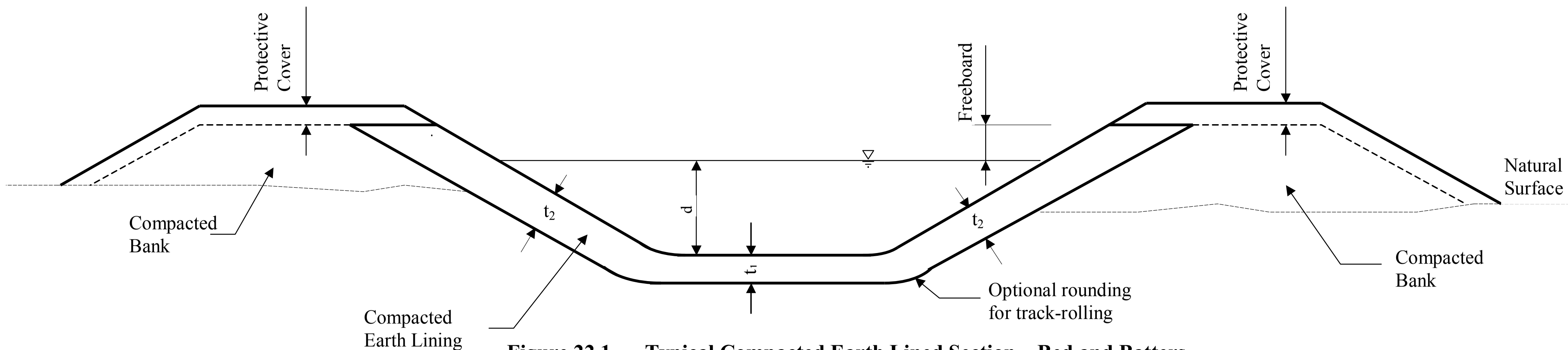

Figure 22.1 Typical Compacted Earth Lined Section – Bed and Batters

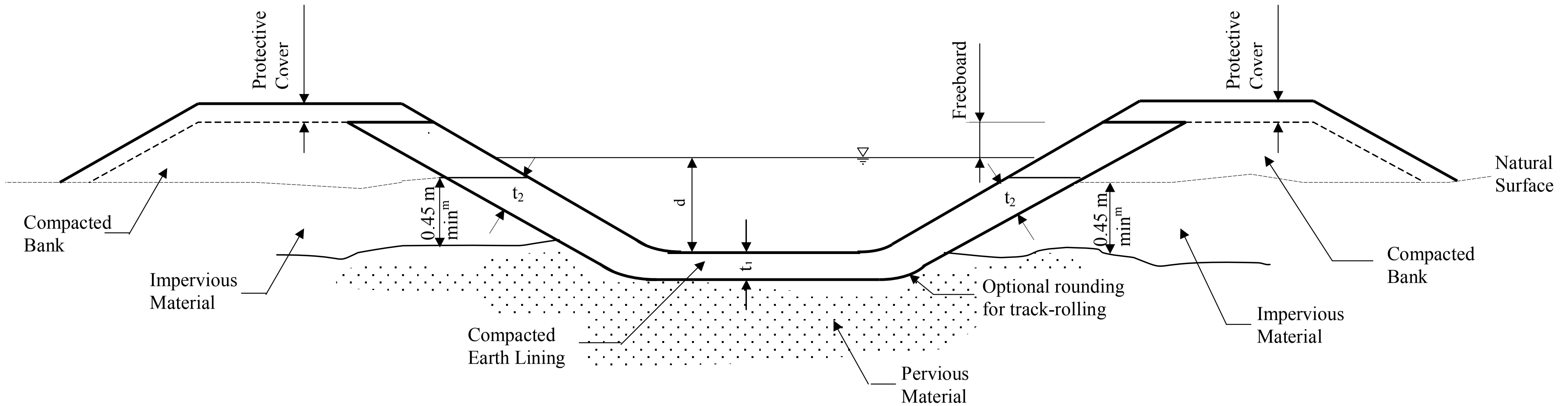

Figure 22.2 Typical Compacted Earth Lined Section – Bed only

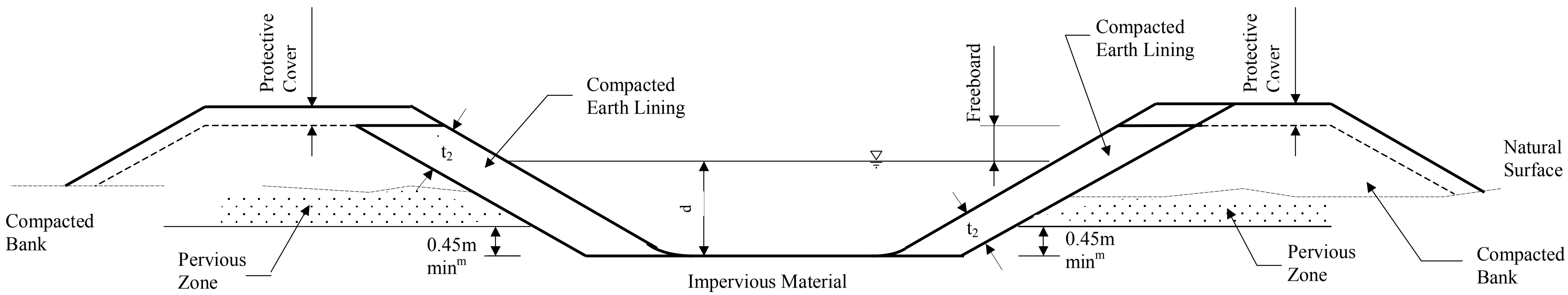

Figure 22.3 Typical Compacted Earth Lined Section – Batters only

22.7.1.2 *General Design Considerations*

For design purposes, an earth lined channel can be considered in much the same as an unlined channel, and the design issues are addressed in the following sections of the Manual:

Cross section Section 12.17

The batter slopes must be designed for stability of the combination of the earth lining and the in-situ soil underlying the imported earth lining.

If it is proposed that compaction plant will operate across the channel section, the profile should be designed with an adequate radius between the batters and the channel bed, and the maximum batter slope should be limited to 1:2.5 (V:H) or flatter.

Coefficient of Roughness Section 12.11.1

Permissible velocities Section 12.11.2

Freeboard Section 12.14

Service Life

Compacted earth linings have been widely used for a long time and have more of a proven performance history. The effective service life of a compacted earth lining will depend primarily on local conditions and the stability of the lining material used.

There is a belief held by some irrigation authorities that a compacted earth lining is permanent and there is no requirement for future replacement. In practice, this is not the case; long-term physical changes occur and the lining will eventually deteriorate to a point where the seepage rate increases to an unacceptable level.

A life of 30 to 40 years could be expected, if the lining has been properly constructed and maintained, and the batters are adequately protected. Less stable lining material, under more severe conditions may have a life of 20 to 30 years.

Physical weathering, erosion, wetting and drying, frost, disturbance from channel maintenance, animals, vegetation and fish will all impact on the life of the lining, reducing the soil density of the compacted layer and thus lessen the effectiveness of the lining over time. Operating channels at heads and velocities greater than those for which the channel has been designed for will reduce the life of the lining, and sloughing of the bank batters will dislodge the lining material from the top of the batters. Where the groundwater table is higher than the channel bed, seepage pressures into a de-watered channel can cause the deteriorated lining to slough.

22.7.1.3 *Lining Materials*

It is expensive to transport soil on a large scale from long distances, and suitable soil from the channel excavation or nearby borrow pits is essential for economy.

The suitability of materials for earth lining is the same as for unlined earthen channels, with specific emphasis on the permeability and erosion resistance characteristics. Available lining material should be tested to determine its maximum density, optimum moisture and permeability.

Section 15, Material Selection and Testing for earthen channels will assist in selecting materials for compacted- earth linings. In general, soils best suited for use in compacted earth lining are well-graded gravels or sands with enough clay binder or lean clay to fill voids and provide a material with a low permeability. The presence of gravel and sand particles increases the resistance to surface erosion from water. Silts can be used, but if the silt is cohesionless, erosion protection may be required.

Other types of soils, such as heavy clays subject to volume change, and silty sands and gravels, should be used with caution.

Irrigation channels in Australia are generally not subject to severe frost actions and soil susceptibility to freezing should not need to be a consideration in material selection.

In some situations, it may be economic to mix coarse soils with fine silt or clay soils to make an impervious stable blended lining. Thorough mixing is critical. The two materials can be blended in layers and compacted as the lining is placed. Soils that are borderline from a permeability standpoint can often be satisfactory if compacted to higher densities.

The use of gravel or crushed rock protection over the top of less a stable material to prevent the erosion of the lining should be considered as an economic option. Linings constructed of silty and sandy materials are susceptible to scour. If these materials are readily available nearby, the cost of reducing the velocity by use of a larger section should be compared with the cost of either hauling in more erosion resistant material, or maintaining a smaller section with its higher velocity and protecting the lining with a gravel or crushed rock cover.

Photos\Lining\cg11 rock lining.jpg

Photo 22-2 Earth lined channel with rock armour

If highly plastic soils are to be used for lining, the batter slopes should be made flatter, because of the loss of stability when these types of soils become saturated. Also, the surface of plastic soils, if of the expansive type, can be easily eroded and the lining lost unless protected by crushed rock or by maintaining a low water velocity.

A minimum plasticity index of 10 is recommended for compacted linings to ensure the soil has sufficient cohesion to resist erosion from flowing water and wave action.

A maximum liquid limit of 45 is recommended for linings to ensure that the soil is not difficult to process and remains stable upon saturation.

22.7.1.4 *Lining Thickness*

The thickness of lining used will be dependent on a number of factors, including:

- nature of the sub-grade material
- groundwater levels
- the strength and permeability of the lining material
- method of construction and type of plant employed
- the frequency of wetting and drying of the lining
- allowance for erosion and scour
- allowance for unintentional removal of part of the lining during desilting
- allowance for penetration by fish and animals – carp/yabbies

Deep and dense cracks can develop on the surface of compacted earth liners under alternate wetting and drying conditions due to the high shrinkage properties of clay materials. Alternate wet and dry cycles, freezing thawing, piping, animals, vegetation, shrinkage and cracking are serious hazards to all types of compacted earth linings. They reduce the soil density of the compacted layers and thus lessen the effectiveness of the lining as a water barrier, and this need to be taken into consideration when establishing a lining thickness.

The minimum required thickness should first be determined by laboratory testing of the soil proposed for the lining. Based on soil permeability, seepage through a lining of given dimensions can be calculated and the thickness designed to control seepage to the desired rate. Final thickness of lining is then fixed considering local conditions, the equipment to be used and the construction method to be adopted. Where there is high quality lining material with sufficient clay content, the thickness can theoretically be relatively small. However, the practical considerations above will frequently dictate a greater thickness of lining.

Smaller thicknesses are possible on the bed, compared to the batter, where compaction of the material is more difficult to achieve, and loss of the lining is more likely from erosion, wave action, wetting and drying, and animal and fish damage.

Lining thickness requirements will vary and general guidance on selection of lining thickness is shown in Table 22-5.

Depth **d**	**Bed Thickness** t_1	**Batter Thickness** t_2 (measured at right angles to the face)
0.5	0.30	0.45
>0.5 to 1.25	0.45	0.60
>1.25 to 2.0	0.60	0.75
Over 2.0	0.60	0.90

Table 22-5 – Approximate Compacted Earth Lining Thicknesses (m)

These thicknesses point to one of the main disadvantages of earth lining – the considerable amount of over-excavation required.

If the material to be used in the earth lining does not have the desired sealing quality at the above thicknesses, it will be necessary to increase the lining thickness. If crushed rock or gravel is available near the site, placing a protective cover over the earth lining can reduce the required lining thickness.

A thinner type of compacted earth lining, usually 0.15 to 0.3 metre of compacted cohesive soil, has been used overseas, but its use is not recommended because of durability concerns and the high risk of damage to the thin lining from erosion or maintenance operations.

22.7.1.5 Subgrade Preparation

The preparation of the subgrade is an important consideration.

The subgrade treatment for earth linings will typically involve over-excavation of the channel section by the thickness of the lining. In existing channels it will be first necessary to completely remove all silt deposits and vegetation from the channel waterway. The section is then roughly re-shaped and trimmed prior to placing the compacted lining.

It may be found in lining existing channels that a saturated sub-grade will require deeper excavation or special construction methods such as a geofabric membrane between the subgrade and the liner to combat the soft wet conditions.

Silty subgrade soils that are dry and of low density are subject to subsidence and special construction methods may have to be employed to ensure a stable bank.

If a highly pervious zone containing mostly coarse material is encountered in the channel cross section, a geotextile filter fabric may be required between the native material and the lining to provide stability and prevent loss of lining material into the subgrade.

If the subgrade is fine-grained, ripping and re-compaction should be considered.

The combination of high groundwater levels and low water levels in a channel can result in unbalanced hydrostatic bank pressures on a lining. However the weight and plastic characteristics of compacted earth linings mean that damage by flotation is rarely regarded as an issue and under-drains should not be necessary.

Because of the many different subgrade conditions that may be encountered, the costs can vary considerably between sites.

22.7.1.6 Construction Considerations

To minimise the costs of earth linings, it is extremely important that the lining design and construction scheme allow the most efficient use of available earth moving and compaction equipment. In larger channels this usually poses no particular problems, but in smaller channels the size and manoeuvrability of equipment is a critical consideration.

A typical construction sequence would involve:

a) Channel Shaping
- Desilting (existing channel)
- Excavation
- Removal
- Trim

b) Lining
- Borrow material
- Haulage
- Place material
- Compact material
- Trim and batter

The channel waterway is first over excavated by the thickness of the proposed lining, and the lining material is obtained from borrow sites after its suitability has been established from testing samples.

In most cases, the earth lining is placed directly onto the formation that has been excavated in the natural material or onto the natural material that has been formed into a compacted bank. There may be occasions where a geotextile filter fabric is required to prevent the migration of the lining material into the natural material. This may happen for example when the natural material is a coarse gravel.

A variety of different construction plant can be employed in placing earth linings to achieve proper thickness, compaction and trimming. Transportation and placing of material may be done with scrapers or the material may be transported to the site by end or bottom dump trucks and placed and levelled by dozers or road graders.

The normal types of compaction plant, such as dozers and sheepfoot rollers, can be used for compacting the lining material. The method of operating the plant would depend on the size of the channel and the thickness of lining to be placed. All material should be compacted in successive layers not exceeding 0.15 metre thick.

Tight control of the density and moisture content is critical in placing earth linings. If the soil is too dry, water must be added to obtain fairly uniform moisture distribution for compaction. This is usually done by wetting and conditioning in the borrow pits and supplementary wetting during placement. If too wet, the soils must be spread to dry or the work delayed.

Compaction operations along channel beds generally involve no difficulties. Compaction operations along the batters are more difficult because the material must be compacted along sloping planes.

Refer to Section 16, Compaction Control.

For larger channels, the bed can be compacted by the longitudinal movement of the plant along the channel. The batter slopes can be similarly compacted, but the finished thickness of the lining will depend upon the size of the plant used. For smaller channels the batter slopes can be compacted by operating the plant up and down the batters. To permit the smooth cross-dozing operation of the tracked plant, the angle at the bottom of the batter can be rounded by providing a circular transition at a 5-metre radius from the batters to the channel bed.

Alternatively, the batters may be compacted using a sheepsfoot roller attachment on the boom of a hydraulic excavator working from the top of the bank.

The surface of the finished lining should be trimmed to provide an even surface in contact with the water.

If the specified lining thickness on the batter slopes is too thin for efficient use of larger equipment:

- the batter lining can be over-constructed to accommodate the larger equipment and then trimmed back to the required lines or alternatively,
- the operating width for the batter slopes can be increased sufficiently for larger equipment by sloping the layers towards the bed of the channel. Thus, instead of placing and compacting the material in horizontal layers, layers on a slope up to 1 (vertical) : 4 (horizontal) are used. Refer to Figure 22.4.

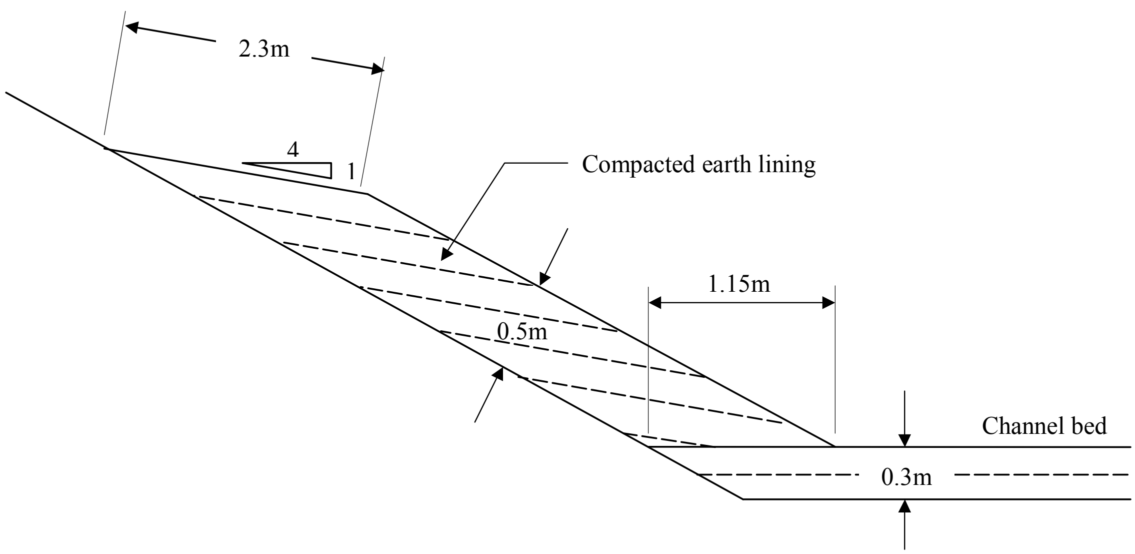

Figure 22.4 Compaction of Batter Lining on a 1:4 Side Slope

For small channels there is a problem of placing and compacting the relatively thin earth linings with large and efficient equipment. This has been solved in some situations by completely filling and compacting the over-excavated channel waterway as one solid section, and then cutting the final channel waterway out of the compacted material using an excavator with a V shaped bucket.

Where the earth lining finishes above the water line of the channel, the exposed ends of the lining need to be treated as compacted bank and provided with a protective cover. Refer to Section 17.

The sealing around control structures in the channel system is a potential weak point that requires specific attention, as scouring and shrinkage of the lining can result in seepage losses from around these structures.

The rate of filling the channel for the first time should be carefully controlled so that the force of water inflow does not scour the lining, and initial rapid fluctuations in water level should be avoided while the lining material consolidates and stabilises.

22.7.1.7 Degree of Compaction

Tight control of the density and optimum moisture is essential in placing compacted earth linings. A density from 95 to 98% of the maximum dry density will normally provide adequate stability, erosion resistance and impermeability. Insitu density tests should be regularly taken during construction to check that the compaction procedures are producing the desired results. If the specific density is not attained, the material must be further compacted.

Refer to Section 16, Compaction Control.

As the primary function of a compacted earth lining is to reduce seepage, the impermeability of the soil in a compacted state is prime importance. The water losses of a proposed lining can be estimated from the results of laboratory permeability tests on compacted soil specimens, the thickness of the proposed lining and the water depth.

22.7.1.8 Moisture Control

Refer to Section 16.11, Moisture Content Control Tests and Procedures.

22.7.1.9 Additional Protection against Erosion

Refer to Section 12.11.4.

22.7.1.10 Minimum Radius of Bends

Refer to Section 12.16.2.

22.7.1.11 Fencing

Where earth-lined channels are exposed to animals they need to be longitudinally fenced to protect the lining from damage and premature failure caused by live stock. Refer Section 12.22.

22.7.1.12 Maintenance

If properly designed and constructed a compacted earth lining requires no special maintenance. Normal earthen channel maintenance should ensure a long service life. However, particular care needs to be exercised during mechanical weed control and desilting operations to avoid damaging or removing the lining, as it can be difficult to distinguish between the bottom of the sediment and the top of the lining.

This requires knowledge of the channel cross-sectional dimensions, thickness of the lining and skilled machine operators who respect that knowledge.

Compacted earth-lined channels should be periodically re-surveyed to check bed and bank erosion, and to provide an indication of the expected remaining life of the lining.

With time, the lining on the bed and batters of the channel will become more permeable and there is little that maintenance programs can do to halt this deterioration process. Sloughing of the bank batters will dislodge the lining material from the top of the side slopes and regular attention to batter stabilisation may be required to arrest this. Sealing of the lining around the base of channel structures may require attention as scouring, shrinkage and animal/fish activity can lead to loss of integrity and increased seepage losses.

22.7.2 Compaction of Insitu Channel Material

This procedure consists of scarifying, adding moisture and compacting using appropriate equipment the insitu material in the channel bed and batters to a higher density.

If the in-situ soil is suitable, this can be one of the simplest and least expensive methods of reducing permeability. To be effective the soil must have sufficient clay content and be well graded; suitable soil types include fine soils and well-graded coarse soils with fines. The method has been used in Australia, but very little information is available on its effectiveness. However, overseas literature indicates that significant reductions in seepage rates can be achieved with this method. Seepage rate reductions of 12 to 33% have been reported in the United States. With a ten-percent reduction of pore spaces, permeability can be reduced by 5 to 7 times in clay, and the permeability of sandy soils can be reduced 3 to 4 times by the same degree of compaction.

In order to achieve the most effective compaction and to destroy any cavities produced by animals and plant roots, the soil should be first loosed by scarifying to a depth of about 0.2 to 0.3 metre and then wetted, before compacting the soil using machines with impact, vibration or vibro-impact action. The moisture and density requirements are established by laboratory tests.

22.7.3 Bentonite Type Lining

Bentonite is a natural clay-like substance formed from the deposition of volcanic ash in seawater. Its chief constituent is the clay mineral montmorillonite. Bentonite is distinguished from other clays by its extreme fineness, highly absorbent nature and its property of swelling in water.

Bentonites can be divided into two general classes – high swelling and low swelling – depending upon their reaction in water. The high swelling type, sodium bentonite, absorbs nearly five times its weight of water and at full saturation occupies a volume 10 to 15 times its dry bulk in the form of a gel. This swelling capability gives bentonite its water sealing power, and in theory makes it a useful material for seepage control where the channel material contains insufficient clay, such as sandy or gravelly soils with less than 10% clay contact. Provided the bentonite can be kept continuously wet and be obtained at a reasonable cost.

Bentonite deposits vary greatly in montmorillonite type clay content, and therefore differ considerably in expansion characteristics. Consequently, care needs to be taken in evaluating bentonite clays and relating the required lining thickness to their properties. Selection of a good quality bentonite and careful control during placement is required.

Bentonite can be used for:

- sediment sealing
- pure buried membrane liner
- mixed bentonite-soil blanket

Sediment Sealing With the channel full of water, dry high swell bentonite in granular form is sprayed over the water surface with a shotcrete-compressed air system. The granular form is used to speed up sinking, and the theory is that the small bentonite particles will be sucked into the channel's wet perimeter, swell and plug the soil voids. However, instead of penetrating the soil, the dispersed bentonite largely forms a thin surface coating on the soil which shrinks upon drying, and does not reform to produce a seal after having dried. The thin surface coating is also highly vulnerable in channel situations to damage by scour, erosion from intermittent flows, desilting operations, vegetation, fish and animals. The results from bentonite sediment sealing can vary widely. It has been found to be effective in channels for no more than a year, and sometimes only for a few months.

Generally Bentonite sediment sealing of channels has very short lived effects and experience has shown that it cannot be used with any long-term confidence to reduce seepage rates.

Pure Buried Membrane Liner Straight bentonite in powdered form is typically spread 20 to 50 mm thick, depending on quality, over a smooth, firm and dry channel subgrade using a mechanical spreader. The bentonite layer is then covered by at least 0.3 metres of stable earth and compacted using a smooth drum roller. A uniform thickness of bentonite over the perimeter of the channel is important and this can be difficult to achieve, especially on the batter slopes. Care also needs to be exercised to ensure that the bentonite layer is not disturbed by the placement of the cover material. As well, caution needs to be exercised to insure that the gel-like membrane formed in the presence of water does not pipe through a course subgrade.

Mixed Bentonite-soil blanket Bentonite in powdered form is uniformly spread over the surface area of a dry channel at the determined rate of application and thoroughly mixed into the top layer of the soil using a rotary type mixer. The material is then compacted using a smooth drum roller to form a 100 mm thick blanket over the channel section. When the bentonite is hydrated with water, it fills the voids within the compacted layer, provided the two materials have been adequately mixed together. The amount of bentonite typically required can range from 5 to 25% by weight depending on the soil type, and should be pre-determined by laboratory tests. The bentonite blanket is very vulnerable to damage in a channel situation and a cover of stable earth or crushed rock at least 0.3 metres thick is usually spread over the thin lining for protection. A lower compaction standard than for earth lining is acceptable as the layer is for protection and stabilisation only. Spreading a uniform thickness of bentonite can be difficult, adequate mixing and compacting the material on the batter slopes can also be hard to achieve and for moist fine-grained soils, the thorough mixing of the bentonite can be virtually impractical because of the sticky conditions. Under these difficult mixing conditions a pure buried liner of bentonite may be a more suitable method of treatment.

Bentonite channel linings in Australia and overseas have been found to frequently loose their effectiveness after only a few years of service, due to the decomposing effect of wetting and drying, hard water and other contaminant and weathering factors. As well, bentonite may not be effective where the porosity of the subgrade material is high, such as in the case of a prior stream location.

Given their relatively high installation cost compared with other seepage control methods, the use of bentonite type linings should be looked at with some degree of caution.

22.7.4 Compacted Soil Cement Lining

Soil mixed with an optimum percentage of cement and water can be compacted into a hard and stable concrete-like material. Stabilisation of soil with cement to improve its engineering and stability properties has been used for many years. Overseas it has been used in the lining of channels and water reservoirs, however no sites were identified in Australia where compacted soil-cement had been used for irrigation channel linings. No information was therefore available on the effectiveness, cost and service live of this type of lining.

A compacted soil-cement lining is commonly 100mm to 150mm thick and a typical installation sequence would consist of:

1. Portland cement is uniformly spread over the area to be treated.
2. The cement is mixed into the soil using a rotary tiller, while water is added simultaneously to the mixture.
3. When the cement and soil are thoroughly mixed and the moisture content is at optimum, the mixture is compacted by flat drum or rubber-tyred compactors.
4. After the mixture has been compacted to the specified density, the lining is cured for 7 days, using the same methods employed for thin concrete sections.

Laboratory tests are required for each different soil type to determine:

- how much Portland cement is needed to adequately harden the soil?
- how much water should be added to achieve optimum moisture content?
- to what density should the soil-cement mixture be compacted?

The amount of cement, which is related to the particular soil type, is likely to be in the range from 5% to 15% by weight, high enough to produce a durable watertight lining, but not too high to cause serious cracking. In general, a well graded gravel or sand requires about 5% cement by weight, while a plastic clay soil may require about 13% or more.

A range of soils can be used, however for ease of mixing and placement and a low cement content, the soil should be a well-graded sandy gravel material. Soils with more than 35% of silt and clay particles are generally not suitable. The chemical content of the soil, particularly the amount of sulphate and the degree of salinity, is also a limiting factor, and soil-cement stabilisation will not be suitable for all soil types. The suitability of available soils and the proper proportions of cement should be determined by laboratory tests.

The durability and water tightness of the compacted soil cement lining is essentially dependent upon the soil used. The service life is largely dependent upon the cement content, and while reports in overseas literature are variable, lives of 10 to 20 years have been achieved where the conditions of exposure are not severe. Insufficient mixing is frequently responsible for early erosion or pockets and lenses of soil without cement. Although compacted soil-cement is less durable than concrete lining, the lower initial cost may make it economic where suitable sandy soils are available from the channel excavation or nearby.

The use of compacted soil-cement requires the employment of machinery for insitu mixing and compaction, which because of the equipment's restricted manoeuvrability, can limit its use to relatively large channels. Due to the steepness, it is also difficult to mix the material in-place on the batters of most channels, and the soil-cement needs to be mixed elsewhere and transferred to the channel batters for placement and compaction.

22.7.5 Modified Soil Lining

If the available soils are below the requirements for slope stability, erosion resistance and permeability, their natural deficiencies may be able to be overcome by treatment with relatively small quantities of substances, such as lime, cement, gypsum and certain chemicals such as polyacrylamides.

Cement and lime are standard stabilisation admixtures used in road construction. Cement, when mixed in small quantities with soil is called *cement stabilisation* in contrast with *soil-cement,* which contains cement in larger quantities. The addition of portland cement or hydrated lime reduces the plasticity, shrinkage and expansion properties of soils and increases soil stability, generally in proportion to the amount of admixture used. Laboratory tests are required for each different soil type.

With a plastic fine-grained soil that already has low permeability, 2 to 6% by weight of cement or lime will significantly improve the stability characteristics of the soil. Adequate mixing and good compaction are essential for effective performance.

A modified soil lining is commonly 450 to 600mm thick and a typical installation sequence would consist of:

1. The required quantities are spread on the top of each loose soil layer.
2. The material is mixed at a specified moisture content with the loose soil by a rotary type mixer. It may be necessary to add the water in a number of stages with the soil being re-mixed between each stage.

3. When the required final water content has been reached the layer is compacted by sheepsfoot rollers in the normal manner as for earth lining.

Photos\Lining\BerriganMainChannel1LimeStabilisation.jpg

Photo 22-3 Berrigan Main Channel Lime Stabilisation

Photos\Lining\BerriganMainChannel2LimeSpreading.jpg

Photo 22-4 Lime spreading

Photos\Lining\BerriganMainChannel4WaterCart.jpg

Photo 22-5 Water cart applying water to activate lime

Photos\Lining\BerriganMainChannel5ActivatedLime.jpg

Photo 22-6 Activated Lime

Photos\Lining\BerriganMainChannel3RotaryHoe.jpg

Photo 22-7 Rotary hoe working activated lime into bed of channel

Photos\Lining\BerriganMainChannel6bankcompaction.jpg

Photo 22-8 Excavated working activated lime into inside batter

Photos\Lining\BerriganMainChannel7bankcompaction.jpg

Photo 22-9 Compaction attachment

Installation on the channel batters can be difficult and this method lends itself more to situations where treatment of the channel bed only is required.

Where the soil is coming from a borrow pit and not from the natural subgrade, mixing may be carried out in a central stationary mixer. This method allows closer control of the proportioning and mixing of the materials.

While this may be feasible under certain conditions, the increased cost of the material, its transportation and thorough mixing are likely to be significant. Little information is available in Australia on the effectiveness, cost and service lives of these types of treatments when used for channel linings, and there is virtually no information on their performance after some years of service. Subsequent cracking of the lining may be an issue.

22.7.6 Soil Sealants

Soil sealants are natural or artificially processed materials that can be either injected into water, mixed into the soil, sprayed onto the soil or injected into the subsoil to reduce channel seepage losses and increased soil stability. The materials used include natural silts and clays, bentonite, resinous polymers, petroleum-based emulsions, sodium chloride, sodium carbonate, sodium silicate, calcium chloride, sodium tripolyphosphate and other chemicals. The amounts and methods of application vary widely. Some of the materials are expensive or toxic, and some are suitable for sealing only certain soil types.

The addition of sodium salts to a soil can be used to reduce permeability. The sodium ions, upon saturation cause the clay particles to disperse, clogging the pores and reducing permeability. However treatment with sodium salts can increase erodibility as the dispersed soil particles are unstable in flowing water. Seepage may also start to increase after several years as the sodium applied in the treatment is leaked out.

Sodium Tripolyphosphate (STPP) is a chemical that has the opposite effect to gypsum. It has been widely used in Australia to reduce the seepage from farm dams, but no irrigation channels could be identified where STPP has been used. STPP aims to disperse clay particles that are naturally highly stable. It is used in red and brown soils that are very stable, and have high porosity. Laboratory tests are needed to determine the suitability of STPP for individual soil types and the required rated. Not all soils react favourably to STPP. Treatment is done in a similar manner to that of the mixed bentonite-soil blanket. STPP is ineffective in sandy soils or soils with a high calcium carbonate content.

The lining resulting from treatment with chemical soil sealants is usually a relatively thin layer, which is susceptible to damage by shrink and swell cracking, erosion, scour in flowing water, puncture, wetting-drying, freezing and thawing, soil micro-organisms, weathering and destruction by de-silting operations, plants or animals. Expert advice should be sought before using soil sealants, as wrong treatment is not only expensive but can aggravate seepage or erosion problems.

The soil sealant must not be toxic or subject to degradation which could contaminate the channel water or adjacent groundwater.

No sites were identified in Australia where soil sealants had been used for irrigation channel lining, other than limited experimental sites. Consequently little information is available on their effectiveness, cost and life under Australian conditions. However, overseas experience with soil sealants shows that they can provide a good sealing action during the first few years of service but then rapidly deteriorate, with continuing effectiveness dependant upon the treatment being repeated periodically.

Soil sealants require more experimentation and evaluation before they can be recommended for general use in channel seepage control. Problems exist in regard to their effectiveness over time and the unit costs of treatment. It is possible that more water may be saved more cost-effectively by using conventional lining methods than by soil sealants. The use of soil sealants should therefore be looked at with some degree of caution. As the cost of some soil sealing treatments is relatively low compared with other lining methods, repeated applications of sealants may be a viable alternative or the use of soil sealants may be an economic means of temporarily saving water during periods of water shortage.

22.7.6.1 Sediment Sealing (Silting)

A natural process of deposition will take place to some extent in earthen channels at low velocities of flow and a layer of sediment is virtually universally present in all Australian irrigation channels. Experience indicates that significant initial siltation can take place directly after new channel construction, followed by slow increases in thickness thereafter. The sediment layer is typically thickest in the centre of the channel and tapers to a thin layer on the upper batters.

The prolonged waterborne deposition of material over the wetted area of an unlined channel can under certain conditions reduce seepage losses. The sediments may be accumulated naturally or added artificially. A natural sealing of channels occurs if the water in the channel carries considerable sediments and the earthen channel formation remains undisturbed. The sediments may be carried into the channel system from outside sources or from erosion of the unlined channels.

If the channel ageing is allowed to proceed uninterrupted the fine inorganic and organic sediments penetrating the voids in the underlying channel material, coupled with bacterial activity, will gradually clog the soil voids, thus reducing permeability. Reduction in seepage losses of 20% or more have been reported in overseas literature. This is usually a gradual process which may take several years, depending on the sediment content of the water. Natural sediments are fairly effective as long as the sediment is continuously supplied.

Once an effective sediment seal has developed, controlled sediment removal operations from channels have been found to generally not significantly increase seepage rates, either because the thin surface layer is re-established in a relatively short period from the disturbed material within the channel, or the sealing layer is in the sub-surface of the channel bed and is not affected by the sediment removal.

This behaviour is shown in United States tests where the seepage rate from a channel before the removal of sediments was 0.19 m^3/m^2/day, after removal the rate was 0.58 m^3/m^2/day and after 1 year of natural silting the rate was 0.23 m^3/m^2/day.

Provided the channel is not over-excavated, it appears from available information that controlled channel desilting, has little effect on seepage, although there could be a partial, temporary increase.

Where the water is relatively clear and sediments are added artificially for a short period of time (puddling), the degree of sealing obtained is short-lived and regular re-treatment is required to provide a continuous seal. Experimental sealing of small dams by artificial clay puddling and algal inoculation have reduced seepage rates by 20-30%. However the sealing was only effective for a relatively short period after treatment and was not subject to the scouring effects of flowing water.

22.7.7 Cost of Earth Linings

The capital costs of earth linings vary considerably according to the prevailing conditions on a project. Lining costs are typically expressed in terms of $/m^2 of channel area, and the most important factors influencing the unit cost of earth linings are:

Size of the Project (length) A project involving the placement of significant quantities of lining material, allows the effective use of large earth moving equipment, thus reducing the cost per square metre considerably through economies of scale. Higher unit rates would be expected for shorter project lengths due to the lower economies of scale and the fixed cost components of a project.

Size of Channel (capacity) Usually, the larger the channel, the lower the unit cost because larger and more efficient earth moving equipment can be used. Smaller channels can restrict equipment manoeuvrability and reduce efficiencies.

Weather Conditions In addition to equipment operating problems, weather conditions influence the costs of placing lining materials within the specified moisture content. This factor is obviously quite variable.

Quality of Material The local material is not suitable and must be improved, the cost will increase significantly, with the need for mixing, increased lining thickness or provision of a protective cover.

Source of Material The lowest cost linings are those where the material is available close to the site of the works or can be obtained from the channel excavation. The cost of importing soil and the economics of increasing haulage distances will vary according to each separate set of lining conditions.

Other factors affecting the cost of earth linings are site establishment, desilting requirements on existing channels, ease of access, channel bed foundation conditions, mixing requirements, optimum moisture content for compaction, subgrade preparation and cover materials.

22.8 Flexible Membrane Linings

22.8.1 Description

A geomembrane (flexible synthetic liner) is a thin flexible low permeability liner, which combined with the strength of the base soil, can be used to reduce seepage. Geomembranes have been developed in recent years to such a point that they can be considered as a viable option in any channel-lining situation. The geomembrane is laid over the entire wetted surface of the channel and usually covered by a protective layer of earth. Figure 22.5 shows a typical section of a geomembrane lined channel.

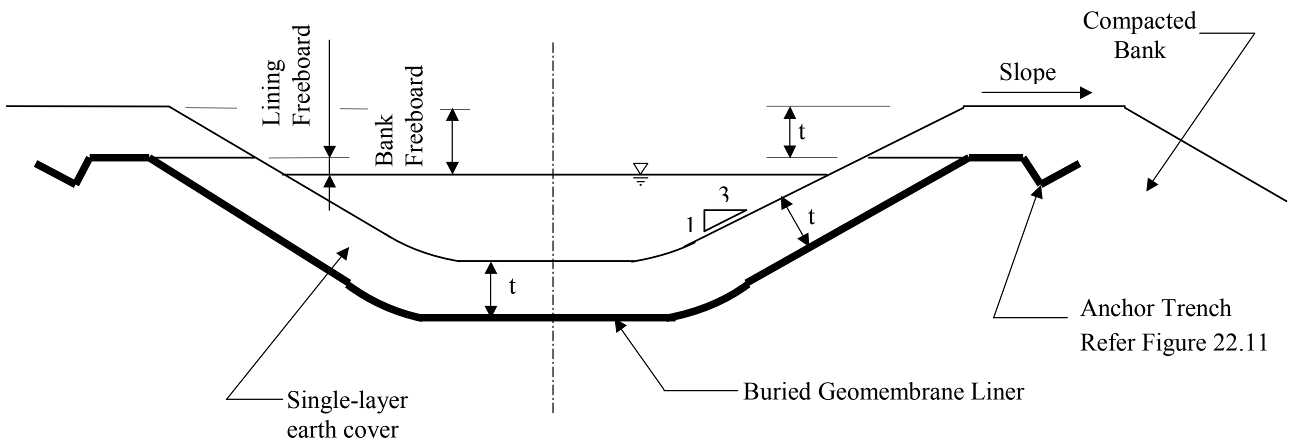

Figure 22.5 Typical section of buried geomembrane-lining installation

Geomembrane liner systems are commonly used for containment of solid and liquid hazardous materials, for waste water and process liquid containment as well as for water supply storage. There is also a growing use of floating membrane cover systems for water supply protection as well as for odour control and gas harvesting from waste water systems. This section covers the special needs of geomembrane liners used as liners in earthen channels.

Geomembrane materials are merely thin barriers of very low permeability material, generally ranging in thickness from 0.5 to 2mm, and they offer very little structural capacity. They can only transmit hydrostatic head to a properly compacted stable subgrade. Thus they require appropriate structural support and careful treatment to give results that live up to expectations.

Geomembrane materials are usually part of a system designed to contain liquids. The liner system may be as simple as a prepared base and liner or it may be as complex as systems comprising primary, secondary and even tertiary liners complete with drainage systems above and below, and leak detection and collection systems between the liners.

Although they can assist with shear forces on slopes the geomembrane materials are not competent structural members and require a suitable supporting material to be effective. There are materials that can sustain higher shear forces and others that can accommodate movement with less likelihood of rupture. Some of the geomembrane materials require a very smooth surface to support them whilst others are able to accommodate rougher surfaces without loss of effectiveness.

Membrane liners can overcome the problems with compacted earth linings of sourcing low permeability clays in sufficient quantities and reliance upon correct compaction control.

One of the most important questions a potential geomembrane user must ask relates to the degree of effectiveness that is required. To achieve an geomembrane which absolutely does not leak is difficult, if not impossible, and a realistic understanding of the consequences of minor leakage can be a key factor in achieving the desired outcome.

Geomembrane channel linings can be divided into two categories according to whether or not the liner is exposed or covered. The same geomembrane materials can be used in either the exposed or covered applications.

22.8.1.1 Exposed Lining

This type of lining is placed on the subgrade of the channel and is directly exposed to deteriorating factors. If the geomembrane liner is to be exposed, it should offer appropriate weathering performance, and it should maintain its physical properties for the life of the application under the expected environmental exposure.

Installations in various parts of Australia and overseas has shown that geomembrane materials exposed to UV radiation, high temperature variations, weather, abrasion, wave vibration, wind forces and erosion can deteriorate rapidly. Some relatively thin exposed channel liners installed in Australia have failed on the batters within 5 to 10 years of installation. Exposed membranes also have little resistance to field hazards, such as plant puncture, fire, weed burning, floating debris, groundwater uplift pressures, livestock traffic, vehicle traffic, maintenance equipment, animals and vandalism.

Because of its relatively short service life of 10 to 20 years under the more severe Australian exposure conditions, the economic use of exposed geomembrane linings may be limited to special cases, such as the temporary emergency linings of short sections of channel, where there is little hazard of damage or prices are competitive. With the latest materials and increased thicknesses, lives of 20 to 40 years are claimed, but until proven these need to be looked at with some degree of caution.

A life cycle cost analysis should be undertaken to determine the best option.

A Manning's coefficient of roughness n of 0.012 may be applied for hydraulic calculations of channels lined with exposed geomembranes. The channel bank batter slope should not be steeper than the natural sub-grade soil will permit.

Potential fire damage is another issue that needs careful consideration. Membrane liners are also very slippery and may be a safety hazard. If a person or animal falls into a lined channel, it could be very difficult to climb out.

The potential advantages of using exposed membrane linings in comparison to covered linings include:

- channel batter slopes can be increased with subsequent cost savings in reduced excavation and land acquisition
- elimination of the need for protective earth cover
- undetected damage to a lining is minimised
- replacement of lining, if required, is easier
- decreases the roughness factor and permits higher velocities in channel, thereby reducing cross-sectional areas and costs of construction

The materials used in exposed liners are usually thicker and heavier which can make the installation process slower with the potential for more joins.

22.8.1.2 Covered Lining

Experience has shown that geomembranes can effectively control seepage over a considerable period of time when covered with a non-erosive material that protects them from exposure to the elements and from physical damage by turbulent water, animals, livestock, fire, plant growth, vandalism and maintenance equipment.

If covered, the choice of lining material also expands greatly as problems associated with UV exposure, temperature variations, environmental stress cracking, high watertable pressures, wind and wave forces, fire and physical damage are significantly reduced.

Earth and crushed rock or gravel are generally used as the covering material. Services lives of 20 to 50 years could reasonably be expected as long as the protective cover remains intact, but will depend on the erosion resistance of the cover material, maintenance, plant hazard, animal damage and channel drawdown.

To provide a covering material will be considerably more expensive than an exposed liner, however a significantly longer life can be expected. While geomembrane liners are relatively easy to transport and place, the economics will be largely dependent on the suitability of soil from the channel excavation or nearby as cover material. The channel section also has to be over-excavated to the extent of the soil cover, which increases the earthworks costs of the channel.

The disadvantages of providing a liner covering include, the additional cost of excavation and placement of cover material, limitations on the batter slope due to the stability of the cover material and the liner cannot be easily inspected or repaired.

22.8.2 Membrane Liner Types

Geomembranes liners are manufactured from a variety of materials in a variety of ways and this results in a wide range of properties which can be varied to suit the needs of a particular application. An ideal geomembrane liner would have the ultra-violet and chemical exposure resistance characteristics of High Density Polyethylene (HDPE), and the flexibility and mechanical properties of polyvinyl chloride (PVC), in a thermally welded package. Unfortunately this ideal geomembrane is not yet available and it is necessary to work between a number of areas of compromise.

In discussing the different types of geomembrane materials that are available the terms and descriptions that are in common use will sometimes be recognised by polymer chemists and others as being less than strictly correct. These common terms are used below since the aim here is to convey meaning and understanding to engineers using the materials who are perhaps more familiar with construction using soils or concrete.

The range of geomembranes available is extremely wide with new products appearing regularly on the market from a range of manufacturers.

The following are the more common types of geomembrane and a descriptive tabulation of properties is given in Table 22-6.

22.8.2.1 Polyethylene

The most common form of polyethylene used for liners is known as high-density polyethylene (HDPE) and is very similar to the material used in black polyethylene pipes. Strictly speaking it is based on a medium density resin but the addition of carbon black tends to increase the density.

HDPE is generally cost-effective over large areas but requires well prepared surfaces.

It has a very strongly crystallised structure, which contributes to its broad chemical resistance, and excellent UV resistance for which it is well known. However it is less well known for its lack of flexibility, its high coefficient of thermal expansion and its brittle behaviour particularly in developing brittle stress cracking at low stresses.

The base polymers have been developed to improve the Environmental Stress Crack performance considerably in recent years but this is still an area worthy of great care in design and seaming especially in the areas around extrusion fillet welds.

HDPE seaming has embraced the hot wedge automatic welder which produces dual fusion track seams with great reliability and efficiency that can be readily tested by the air pressure test.

These seams still require significant attention to seaming hygiene but are less operator dependent and create a less influential heat affected zone. The older extrusion fillet welding method which creates a large heat affected zone is still used mainly for details such as connections, T-junctions and patching. It requires skilled operators for effective repair work in service.

Table 22-6 Flexible Membrane Liner Comparison

Attribute	HDPE (smooth and textured)	LLDPE (smooth and textured)	PVC (smooth and embossed)	EIA	CSPE –R (scrim-reinforced)	FPP	Sprayed Bitumen	GCL
Thickness Range for general Channel Lining use	0.75 – 1.5 mm	1.0 - 1.5 mm	0.5 - 1.0 mm	1.14 mm	0.8 – 1.5 mm	1.0 mm (unreinforced) 1.14 mm (reinforced)	1.5 – 2.0 L/m^2	Variable
Expected life in years (exposed)	20+	not recommended	10 - 20 (depends upon formulation)	20	not known	20	2-5	NA
Expected life in years (covered)	50+	not known	20 - 30	50+	not known	50+	10	20+ (longer if constantly hydrated)
General Chemical Exposure	Excellent	Good	Fair	Excellent	Excellent (when cured)	Excellent	Fair	Fair
Hydrocarbon Exposure	Good	Good	Fair	Excellent	Good (when cured)	Good	Poor	Poor
Weathering (UV Exposure)	Excellent	Fair	Poor	Excellent	Excellent (when cured)	Excellent	Fair	Poor
Thermal Stability	Poor	Poor	Good	Good	Excellent (when reinforced)	Good - excellent when reinforced	Poor	Good
Tensile Performance	Good	Good	Good	Excellent	Excellent	Good - excellent when reinforced	Poor	Good
Uni-Axial Elongation Performance	Excellent	Excellent	Good	Fair	Good	Excellent	Poor	Fair
Multi-Axial Elongation Performance	Poor	Excellent	Excellent	Fair	Good	Excellent	Fair	Fair
Puncture Performance	Fair	Excellent	Excellent	Excellent	Good	Good	Fair	Good
Installation Damage / Abrasion Resistance	Fair	Fair	Excellent	Good	Good	Excellent	Fair	Good
Seaming Methods	Thermal/ Excellent	Thermal/ Excellent	Thermal or solvent bonding/ Good	Thermal/ Excellent	Thermal or solvent bonding/ Good	Thermal/ Excellent	Sprayed laps	Laps only
Repair in Service	Good	Good	Good	Good	Poor – requires Adhesives	Excellent	Good	NA
Stress Cracking	Fair	Good	Does not occur	Does not occur	Does not occur	Does not occur	N.A.	Does not occur
Flexibility in Detailing	Fair	Excellent	Good	Good	Good	Excellent	Good	NA
Roll Cost	Low	Low/medium	Medium	High	High	Medium	Low	Medium

Polyethylene has also appeared in more flexible forms based on very low density (VLDPE) and linear low density materials (LLDPE) and whilst these have had some advantages in mechanical behaviour there have been some disadvantages with the compromised durability and chemical resistance from the less crystalline structure. These forms of polyethylene have some potential interest under soil cover where their UV performance is not an issue and their excellent survivability is an advantage.

Polyethylene liners will have an effective specific gravity in the order of 0.94 which means that they will tend to float if water gets underneath them due to leakage or due to ground water levels.

HDPE in the thicknesses generally used for channel lining is not very flexible and can be hard to handle and fit to the channel section. HDPE cannot be readily pre-fabricated into large panels and is generally installed from rolls.

Specialist equipment is required to efficiently handle and lay the material across the channel profile. Polyethylene is delivered to site in large rolls, usually up to 6 metres wide, and all the seaming is done on-site. Polyethylene can be successfully installed in cold and damp conditions, although it is difficult to weld in wet conditions. The material is also difficult to handle in windy conditions and installation times will increase substantially.

LLDPE and VLDPE have difficulty in achieving adequate durability and UV performance in exposed lining situations.

22.8.2.2 *Polyvinyl Chloride (PVC)*

The basic structure of polyvinyl chloride is quite brittle and the material used as a geomembrane achieves its soft flexible structure by the extensive use of additives known as plasticisers. It is the presence and potential mobility of the plasticisers that make PVC susceptible to contact with various chemicals and to exposure to UV radiation. All of these influences can lead to loss of plasticiser and a reversion to the brittle behaviour. If these influences can be avoided or controlled, then PVC remains the most flexible and workable membrane of all.

For all installations, except short term, it will be necessary to cover PVC with soil, or other cover material to provide protection from UV radiation, and if this cover is also needed for mechanical protection, PVC may well be a good choice. PVC behaves very well in multiaxial tension, has excellent puncture resistance and is unaffected by stress cracking. The specific gravity of PVC is generally around 1.20, which means that it will not float without assistance.

PVC geomembrane seaming was formerly carried out by chemical bonding using solvent based systems but recent years have seen PVC applicators embracing thermal fusion welding using both hot air and hot wedge methods. Thermal seaming of PVC is still not yet universal in the way it is with HDPE and reasonable seams can be obtained with hand held equipment. Solvent bonding is effective but a perception of quality control difficulties is leading to heat and high frequency welding being favoured for lining work.

PVC is very flexible, easy to handle, readily conforms to the channel shape, surface preparation can be less than ideal and can be pre-fabricated into large panels. However PVC does not have good UV performance and overseas durability experience in exposed situations may not translate to Australian conditions where the UV exposure is more severe.

PVC is susceptible to damage from burrowing aquatic animals, will stiffen with age and becomes brittle at 0°C making it difficult to handle in cold climates.

22.8.2.3 Chlorosulphonated Polyethylene (Hypalon or CSPE)

CSPE is based on the use of chlorine and sulphur to modify and soften the polyethylene structure in order to make the material more workable and facilitate seaming. CSPE geomembranes are always scrim reinforced for dimensional stability.

CSPE materials are capable of factory fabrication using semi-automatic welding practices but field installation requires the use of solvent seaming. The construction methods used with CSPE do not allow effective non-destructive testing of the welds. A CSPE quality control program depends on the diligence and competence of the factory and field fabrication techniques.

When fresh it is amenable to seaming by both solvent bonding and thermal methods but it crosslinks or cures with exposure such that normal welding becomes more difficult and in fact impossible after one year. Once cured, modifications or repairs must be carried out using two part solvent-based adhesives with extensive abrasion and solvent scrubbing of the seam area. The solvent bonded field seams also tend to suffer a decline in strength after a number of years primarily due to polymer softening and scrim pullout.

CSPE provides very good chemical resistance, excellent UV exposure performance and are not subject to cracking and embrittlement with long term exposure. Recently it has been suffering from cost pressures due to environmental aspects of its manufacture.

The specific gravity of Hypalon is generally around 1.45 which means that it will not float without assistance.

22.8.2.4 Flexible Polypropylene (FPP)

Flexible Polypropylene has developed as a result of recent polymer catylisation developments that have enabled flexible FPP sheets to be produced by extrusion or calendering. They are provided in both unreinforced and reinforced form and provide a choice in terms of tensile behaviour.

The unreinforced polypropylene membrane materials are typically very flexible with excellent elongation capability. The reinforced materials have low elongation but also have very low coefficients of thermal expansion.

Seaming of FPP is very easy using thermal methods on both old and new sheet. The welding methods allow a full destructive and non-destructive QC/QA regime.

FPP resistance to common chemical exposures is quite good, it has excellent mechanical properties, as is the UV performance for properly stabilised polymer packages. There is no concern over ESC cracking in polypropylene. They can be expected to maintain superior physical properties including extensive multi-axial flexibility, which makes it especially suited to situations where soil movement is expected.

The specific gravity of Polypropylene will normally be around 0.95 which means that it will float unaided but it can readily be produced with specific gravity around 1.05 by use of additives if flotation is not desired.

22.8.2.5 *Ethylene Interpolymer Alloy (XR-5 or EIA)*

EIA geomembranes are an alloy of PVC resin with a special ethylene interpolymer (EI) which results in a flexible plasticiser free material. EIA geomembranes maintain the advantages of PVC but have a high degree of durability and chemical resistance especially in relation to hydrocarbons and extreme temperatures. They are typically fabricated with a high strength reinforcing scrim but it is difficult to generate the full strength of this scrim through the welded seams.

As a thermoplastic material EIA can be thermally bonded using the conventional thermal welding techniques. EIA has some excellent applications experience in high UV exposed solar ponds as well as hydrocarbon containment and in biogas collection covers.

The specific gravity of EIA liners is generally around 1.30 which means that it will not float without assistance.

22.8.2.6 *Geosynthetic Clay Liners (GCL)*

Geosynthetic Clay Liners are a factory produced product which make use of bentonite clay as the sealing layer usually encapsulated by two geotextile layers for containment during handling and installation. Their effectiveness is dependent on the thin uniform layer of sodium bentonite clay swelling when hydrated by relatively clean water and forming a continuous low permeability barrier. For it to be successful, at least a 300mm thick cover of fine-grained soil is required over its entire surface to provide an effective confinement load preventing loss of the bentonite gel and uncontrolled swelling vertically rather than laterally.

When confined, a 6mm thick GCL typically expands to form a flexible low permeability layer some 25mm thick.

The question of slope and sliding stability on channel batters needs to be considered carefully as the hydrated bentonite can provide a very low friction interface if it is able to come to the surface of the GCL. The low shear strength can be improved by stitch bonding or needle punching the geotextile layers together so that the shear forces are borne by the yarn or fibre reinforcement.

GCL's have the advantage of relatively simple transportation and installation. The carpet-like product in a roll/sheet form requires little specialised installation equipment or labour. Installation of GCL's does not require any specific seaming as overlaps (usually with extra bentonite added) is all that is required. GCL's have potential use as temporary repairs of other membranes and joining around structures provided that adequate soil cover is available.

GCL's can be relatively expensive and because of their weight and stiffness, can be difficult to use in some channel lining situations. GCL's can be too stiff to follow the section of smaller channels and their weight can make manual installation slow and difficult in channels.

GCL's can be used to fully line channels or can be installed at specific high seepage areas on channels. GCLs have the ability to self seal and self heal if damaged.

GCL's are a relatively recent development and they have been used widely in landfills for groundwater protection. However, little information is available in Australia on their effectiveness and service lives when used for channel linings, and there is virtually no information on their channel performance after some years of service. Contact with high salinity water can have a long term impact on effectiveness. Refer to Section 22.7.3 on Bentonite Type Linings.

22.8.2.7 Spray Applied Membranes

Spray applied membranes based on polyurethane and polyurea are often used for concrete tanks and similar structures where installation conditions are difficult for a polymer sheet liner. They are normally too expensive for earthen channel use but may merit consideration for complex structures.

Spray applied bitumen membranes have the advantage of simple and mobile equipment that is readily available in most areas. A non-woven geotextile of about 150-200 g/m^2 is generally used as a substrate or carrier since this reduces the likelihood of local thinning under pressure.

Bitumen membranes need to be covered or require regular maintenance if left exposed. They are generally not suitable for use with potable water.

The normal installation method is based on the following steps:

a) Excavation of the channel cross-section
b) Subgrade is shaped to achieve a relatively smooth firm surface
c) Spray a base coat of 1.0 L/m^2 of class 170 bitumen on to the soil base
d) Place the geotextile and roll it into the bitumen surface
e) Spray a seal coat of 0.5-1.0 L/m^2 onto the geotextile
f) Allow it to cool before placing a cover of earth or gravel or both

Bitumen membranes can be sprayed directly onto soil, but for improved effectiveness and durability, a geotextile underlay is recommended. The geotextile is laid over the channel section on a prepared channel bed and batters, and anchored to the top of the channel banks.

The base coat and seal coat rates may be varied in order to achieve adhesion to the surface and impregnation of the geotextile. The key factor is that the geotextile will absorb about 1.0 L/m2. This is essentially an adaptation of a technique being used to control reflective cracking and extend the life of road seals.

There is discussion about the suitability of geotextile materials based on either polyester or polypropylene fibres. Polyester has a high melting point and is unaffected by hot bitumen whereas polypropylene begins to melt at 140^{o}C and bitumen from a tank at 150^{o}C can effect the geotextile. There is a converse argument that the polypropylene achieves a better bond because of the temperature relationship although it would obviously be prudent to avoid bitumen spray temperatures that cause distortion or shrinkage.

Failure of bitumen membranes is typically caused by too thin a membrane coating, penetration by weeds or rupture due to movement of the cover material. In hot climates, uncovered bitumen membranes absorb heat and soften, encouraging weed growth that can penetrate through the lining. Winter conditions can also present difficulties and this technique may not be well suited to winter applications where cold, moist and wet conditions prevail.

Australian and overseas experience with spray applied membranes has generally not been good, with problems of poor quality control in the field. Use of sprayed applied membranes should therefore be looked at with some degree of caution.

22.8.3 Performance Requirements

The most important performance parameters of geomembrane liners are Permeability, Durability and Mechanical Performance. These are outlined below.

22.8.3.1 Permeability

Common to all channel liner applications is the requirement to provide a relatively impermeable barrier and to maintain this over a reasonably long service life appropriate to the individual application. Whilst polymer based geomembrane materials themselves can be some 10,000 times less permeable than a compacted-earth liner, the vagaries of their installation and field seaming means that some leakage will occur.

Critical to the success is not only the material selection, but the accompanying preparation, installation and quality control program. The geomembrane construction methods and seaming practices should follow a QC/QA program that allows meaningful inspection and testing both in the field and from the laboratory.

22.8.3.2 Durability

The durability of a geomembrane to survive as long as required by the life of the project, in the environment in which it is used, is of paramount importance. An important consideration is also the survivability of the geomembrane during placement so that the lining is not damaged by construction procedures. The geomembranes are often exposed to the direct sunlight both permanently or during construction and initial use, and resistance to damage by UV light can be an important consideration.

In other instances the liner will be covered by soil and this will provide protection from UV radiation and animals, but will also impose a requirement for survival during the soil placement.

There are also issues related to HDPE which is subject to brittle cracking due to thermal effects or Environmental Stress Cracking and the combination of these effects with thermal expansion and contraction.

Workability in the field is also an important consideration and the geomembrane should be capable of reliable fabrication which produce seams that match the basic tensile properties of the material for its expected service life.

22.8.3.3 Mechanical Performance

Mechanical performance will normally mean tensile performance but simple tensile tests can be misleading and for many applications consideration must be given to other factors such as modulus and elongation capacity in both simple tensile mode and in multiaxial mode. Very often the forces on a geomembrane may be such that resistance is futile and survival as an effective barrier is achieved by the capacity to give and accept deformation without rupture or excessive thinning. In the case of existing channels in clay soils the introduction of a liner can dramatically change the moisture content of the surrounding soil giving rise to significant soil and structural movement.

There is also the question of low stress brittle cracking which may be enhanced by chemical contact in some highly crystalline membrane types such as HDPE. Other membranes have very low modulus and low tensile capacity in isolation and these are often provided in a multilayer-reinforced form with a high tensile polyester scrim when better tensile performance is required.

Another issue to channels is protection from animal and human entry and the potential for physical damage by puncturing by animal hoofs or even vandalism.

22.8.4 Important Properties

22.8.4.1 Tensile Properties

High tensile strength at low elongation are very useful properties for geomembranes but for most geomembranes used in environmental and hydrotechnical applications the capacity of a membrane to resist the forces of larger scale soil movements has little chance of being adequate. With such movement the membrane will survive and retain its integrity if it is able to elongate with minimal thinning and thereby maintain an effective barrier.

Some membranes such as HDPE can also be subject to brittle Environmental Stress Crack failure at low stresses especially with chemical exposure.

This means that every effort must be made to minimise the load and stresses applied to a membrane. This will generally require a firm well prepared substrate to support the membrane and may also require a protective geotextile cushion.

A common and misleading argument is based on the use of tensile test results to show that a particular membrane has a high elongation factor and therefore a high survival capacity. Several materials which behave very well in simple tensile tests actually behave quite poorly in multiaxial or large scale burst type tests which do more to simulate real out of plane loading circumstances such as may occur with subgrade subsidence or point loading.

When designing critical liner systems it is common to pursue a factor of safety of around 4 against ultimate elongation. This means that for a material such as HDPE the available elongation for local surface effects, thermal effects and local deformation is around 5% in a multiaxial mode whereas for a material such as PVC or FPP the available elongation is in excess of 20%.

If the potential mode of failure places the liner materials into a purely uniaxial mode then the elongation capacity of a HDPE liner material would be increase greatly.

Figure 22.6 illustrates strip tensile and multiaxial strain characteristics for typical polymeric geomembranes and Figure 22.7 shows some multiaxial burst (500 mm dia) response curves.

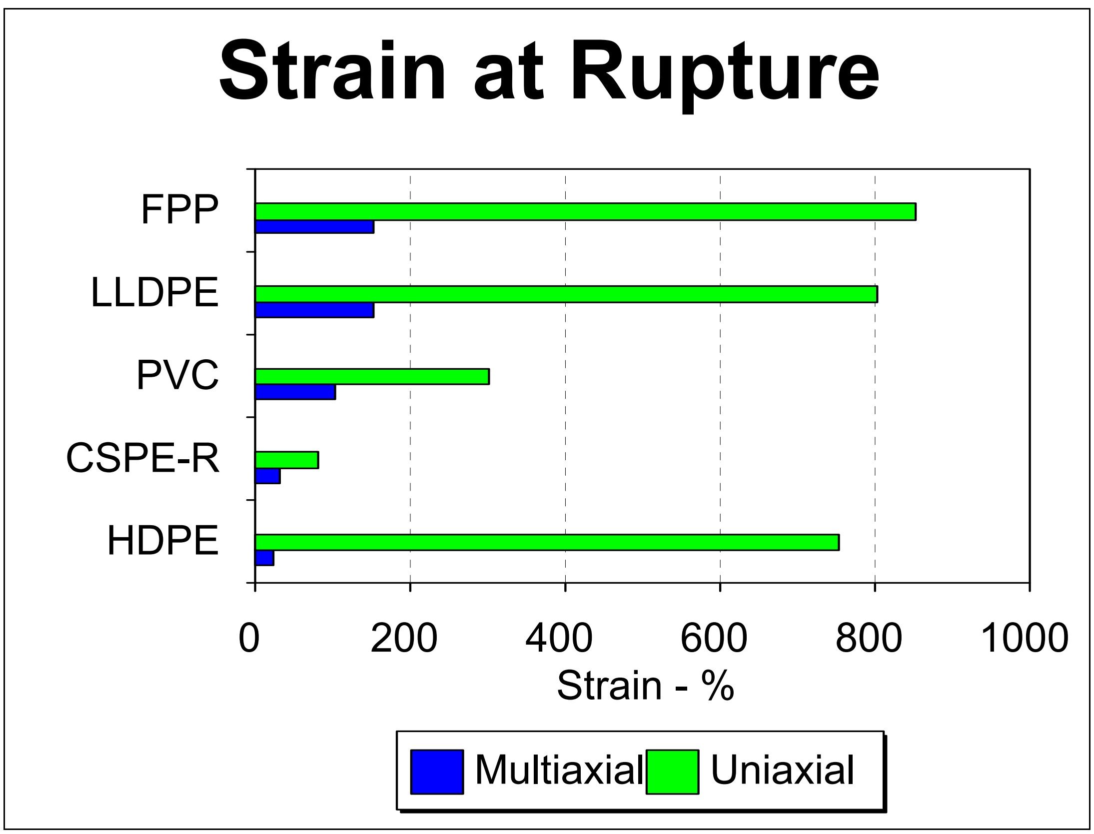

Figure 22.6 Strain at Rupture

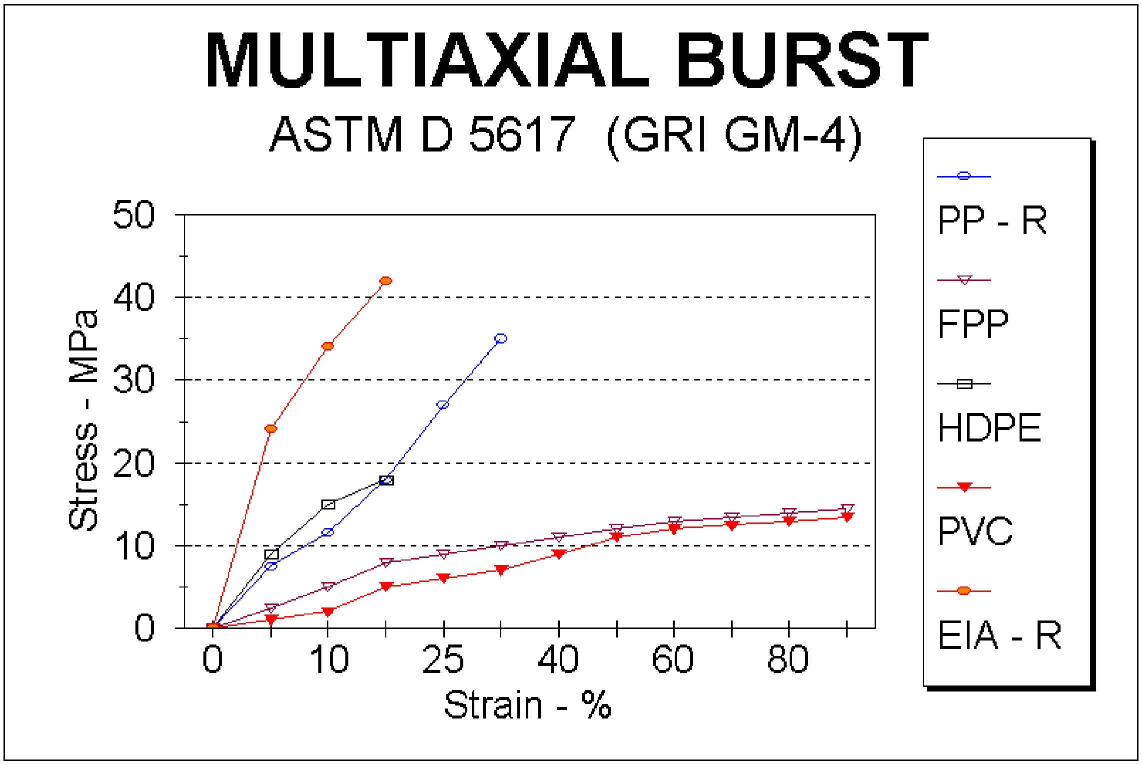

Figure 22.7 Multiaxial Burst

22.8.4.2 Thermal Effects

A geomembrane on a channel face may be exposed to significant levels of UV radiation generating quite high temperatures sometimes in excess of 60°C. These higher temperatures are normally seen in membranes with black surfaces. When the channel is running full of water the membrane is protected but not when the channel is empty. The variation in temperature during the daily cycle can also be quite high with a range of 40°C quite common.

Table 22-7 sets out the coefficients of thermal expansion for several typical membrane types as well as a typical expectation for thermal expansion in a channel situation.

Material	Thermal Co-efficient of expansion	Increase in length over 10 metres for a 40°C temperature rise
HDPE	2×10^{-4} cm/cm/°C	80 mm
FPP Unreinforced (PVC is similar)	12×10^{-5} cm/cm/°C	48 mm
FPP Reinforced	2×10^{-6} cm/cm/°C	0.8 mm

Table 22-7 Co-efficients of thermal expansion

These thermal expansion and contraction effects can be significant in long term exposed applications where a monolithic membrane can expand down slopes and not return fully on cooling due to surface friction and associated effects. These conditions will give rise to thermal creep with a gradual build up of stress at the crest of the slope which will release by creep and possible necking or, in the case of HDPE, is likely to give rise to brittle stress cracking.

For these reasons it is recommended that geomembrane liners are always covered. Refer Section 22.8.1.2.

22.8.4.3 Puncture Resistance

In channels there are two potential modes of puncturing the membrane. One is by hydraulic pressure or soil pressure on the membrane over a rock or other sharp object and the other is by an object such as an animal hoof as it tries to get out from the channel.

Set out in Figure 22.8 is a comparison of puncture strengths for geomembranes. These results are based on a cone penetration test which determines the cone height at which the membrane can survive at a standard pressure. Unfortunately this data relates to perpendicular puncture pressure rather than local point puncture or tearing from a hoof or similar.

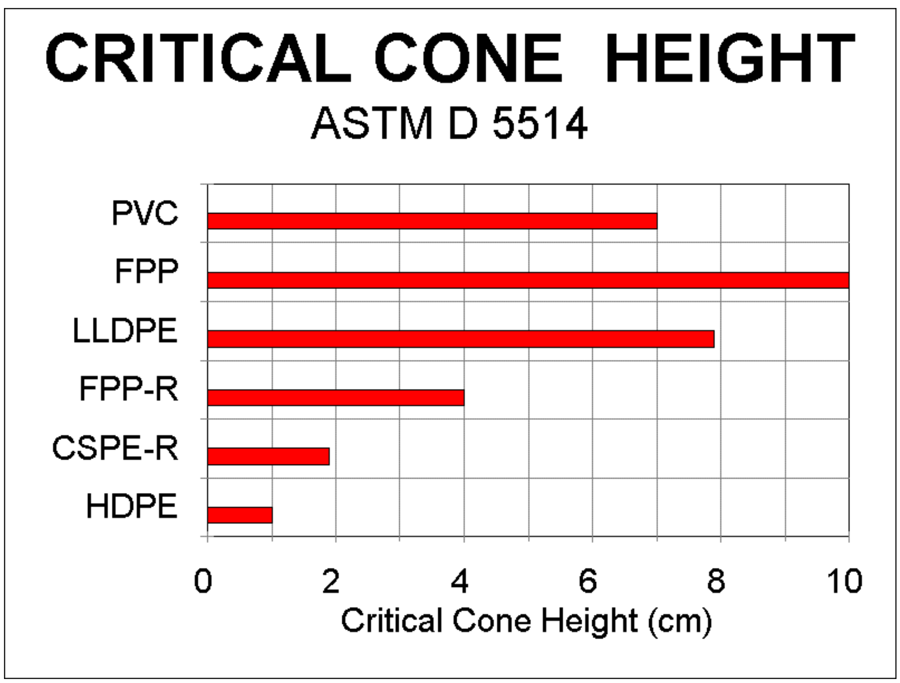

Figure 22.8 Critical Cone Height

It is recommended that geomembrane liners are always covered.

22.8.5 Installation, Seaming and Quality Management

Installation of the liner may involve deployment from a Loader or from an Excavator with a suitable spreader bar arrangement. It is normally preferable to deploy along the length of the channel rather than transverse as this will result in less seams and longer seam runs suitable for automatic welders.

Joints are the weakest points and are therefore critical. Thermal seaming of these liners requires dry conditions and installation with water in the channel is generally not practical.

It is possible to reduce the out of service time by preparing the liner in advance along the side of the channel and pulling it into place once the channel is dry. Another technique is to float half the liner from each side so that when the channel is emptied a single seam has to be made along the centre of the channel.

Geomembranes are lightweight and are manufactured in a large variety of roll and panel sizes which makes them easy to deploy over large areas. The effectiveness of geomembranes has been greatly enhanced by the advent of better and more positive seaming methods which are often based on the application of controlled heat by a hot wedge or by hot air. It is possible now to produce seams which can reflect the underlying strength of the geomembrane material and which can be readily verified by inspection and testing. Methods such as the dual fusion track seam with an air gap have enhanced the capacity to check the quality of the seaming work quickly and effectively on a broad scale.

A cross-section of a double seam which shows the hot wedge twin track jointing system is shown in Figure 22.9. The welding machine is self-propelled and produces twin parallel seams. To test the joint, air pressure is used in the tunnel between the welds to ensure an adequate seal has been achieved.

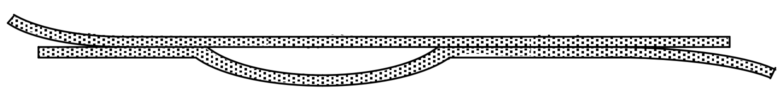

Figure 22.9 Typical Overlay Weld

It is still a necessity for proper quality control sampling and testing of the weld process to be implemented along with constant inspection to ensure cleanliness and proper control of the seaming process. There is also the question of seaming methods for detail areas and methods for sealing the membrane to concrete structures or at other termination points that may require edge sealing. Welding required to fit the lining around structures can be done using extrusion welding techniques, however the use of extrusion welding should be limited where possible as the heat generated in the welding process can contribute to brittle crack problems in the future. Welds that are subject to constant stress are prime candidates for environmental Stress Crack problems regardless of the welding technique used.

The welding and seaming methods should be equally applicable to new geomembrane materials and to the repair or modification of the materials after many years of service. The welding methods should not alter the material properties in the weld zone with undesirable effects such as environmental stress cracking (ESC) and modification to the crystalline structure of the material.

Another factor is the ability to have local people carry out satisfactory repairs to the geomembrane in service. For some membranes this can be a simple process with hand held equipment whilst for others it may be more complex.

The use of double-sided bonding tapes to joint and repair geomembrane liners has not proven successful. Simple overlaps of geomembrane sheets has also not proven to be satisfactory, and increases the required material significantly.

In addition, the natural flotation of a geomembrane may impact on its function in service and may also impact on the available installation methods if the facility is full of water for example. One may wish to float the material into position and in other cases one may prefer that it sinks readily without covering.

Another type of liner is the in-situ spray or trowel type of materials such as bitumen or polyurethane that can be used in conjunction with a geotextile carrier over earthen surfaces. These have the advantage of not requiring specific edge sealing but they are generally not as secure as a sheet membrane and will normally requiring covering to give adequate durability.

Yet another type of liner is the Geosynthetic Clay Liner (GCL) which is a geotextile sandwich based on bentonite clay. These require soil cover for confinement pressure but are otherwise easy to use and repair. A GCL must be kept quite dry until it has soil cover in place since the uncontrolled swelling of the bentonite can literally tear the product apart.

A sound QC/QA program is essential to the success of any geomembrane lining project. The program should cover the design and procurement phases as well as the manufacture, fabrication and field installation phases of the work. A typical geomembrane liner QC/QA program would cover the following areas of activity:

a) Design and review to ensure compatibility of the liner system with exposure conditions, functional requirements and site preparation.
b) Review of manufacturing process from raw materials procurement through batching, processing, packaging, identification, storage and shipping.
c) Review of site preparation and installation arrangements to ensure suitability, and adequacy of storage and handling arrangements.
d) Review of factory and field seaming procedures including physical inspection, preparation, welding equipment and the taking of destructive and non-destructive test samples.
e) Review of soil cover procedures including material selection, plant and placement techniques.

The adoption of the ISO9000 series of standards should be encouraged although certified compliance is difficult to achieve because of the variety of locations and individual site variations.

22.8.6 Anchoring

The anchoring requirements may be a major influence in selection especially if the available time for installation is limited.

Edge fixing and adequate freeboard provision is necessary to prevent water overflowing the top edge and seeping down behind lining, where it can push the lining out or cause slippage failure of the batter slope.

The polymeric membranes (HDPE, PVC, PP etc) all require edge fixing which will usually be achieved by an anchor trench on top of both banks along the entire length of the channel. The trench needs to be set back at least 0.5 m and preferably 1.0 m from the crest and can be rectangular or a triangular cut with a grader blade. It is backfilled over the liner with the spoil material with nominal compaction. Refer

Figure 22.10 and Figure 22.11.

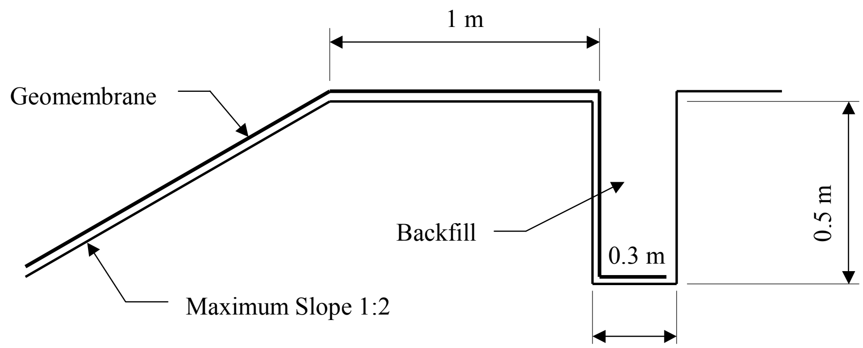

Figure 22.10 Typical Anchor trench – rectangular trench

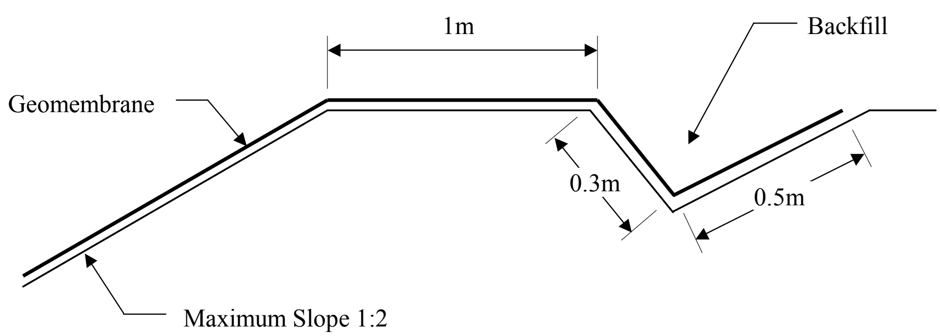

Figure 22.11 Typical Anchor trench – V notch

22.8.7 Attaching to Structures

The liner can be terminated at the ends into an anchor trench or with a mechanical batten fixing to a concrete structure. Refer

Figure 22.12. If the concrete forms part of the new work there are elements which can be cast into the concrete surface for subsequent welding of the membrane.

At structures the geomembrane can be bonded to cut-offs. It may not be necessary to directly connect the geomembrane to structures where a satisfactory seal can be achieved using an anchor trench. The geo membrane can be laid against the structure and backfilled with impervious clay material to seal the liner-structure interface.

Some lining methods expand and contract significantly and it is important that final fixing is undertaken while the liner is in its coolest state. If the liner is smoothed out and fixed during the heat of the day, it may contract overnight and tear away from its fixings.

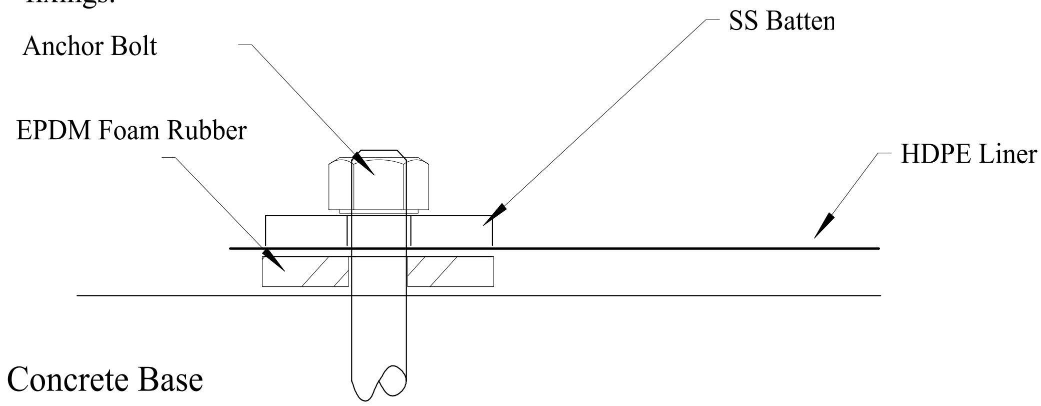

Figure 22.12 Typical Edge Termination

22.8.8 Factors in Geomembrane Selection

22.8.8.1 Economic Considerations

For all except simple exposed liners, the actual geomembrane material contributes a relatively small component of the overall cost of the lining. Other contributing factors include surface preparation, installation and protective cover. Attempts to reduce project costs by simple reduction in geomembrane cost may be ineffective and result in poor performance.

In order to achieve economic and satisfactory lining systems it will be preferable to look closely at geomembrane performance against cost and to compare the total life-cycle costs of systems, which include factors for:

- surface preparation
- liner availability and delivery cost to site
- liner supply and installation, including QA/QC
- size of sections of liner and ease of joining
- protective cover
- expected service life

In some situations a better performing yet more expensive geomembrane can justify its selection because it can perform with less rigorous surface preparation and lesser degrees of protection. Cost figures for lining should not be borrowed from other projects or from literature, but should be calculated for the specific project conditions. Since material characteristics are changing rapidly owing to improved manufacturing methods, choice should be based on the latest information available.

Refer to Section 13, Life Cycle Cost Analysis.

There is also the question of suitable thickness in the different types of membrane. The suppliers of FPP and PVC membranes have argued that their product can be used successfully in much thinner gauges than is required for HDPE and have pointed to the puncture test and elongation results as evidence of this. This argument has merit in terms of puncture over rocks or substrate movement and a practice has developed of using a thickness ratio of 0.5 to 0.67 for FPP or PVC against HDPE.

In this respect a paper from the 1998 International Conference on Geosynthetics by Peggs and Thiel proposed a useful method of comparing geomembrane liner types based on a numerical comparison of required performance parameters and the performance capabilities of candidate liner types. This involves establishing a factoring matrix with the relevant parameters and performance scored numerically and multiplied out for each candidate system. This tends to exaggerate differences so the numerical scoring needs to be carefully considered.

Material costs of geomembranes vary widely with thickness, width and type. The light weight per unit area permits transport of geomembranes over long distances at relatively low costs.

A broad evaluation of geomembrane material costs for rolls of similar thickness is given in the table in Table 22-6.

22.8.8.2 Other Considerations

A geomembrane is by definition a flexible impervious barrier and the majority of geomembrane materials are less dense than water and therefore float unaided. Whilst this can be an advantage for some applications it can give problems if water is able to get under the geomembrane from groundwater or other sources.

If there is a possibility of water accumulating under the membrane then there are a number of issues to be considered:

- Will the water affect the surrounding soil structure and therefore the stability of the channel itself?
- Is there a need for some kind of underliner drainage or pressure relief system?
- Is there a need for cover over the liner?

Consideration of all of these issues becomes a complex exercise and simple geomembrane comparisons are unlikely to be conclusive.

It is very possible that a liner type that appears to offer an initial economic advantage may not be advantageous at all when all of the associated factors are taken into account. This is particularly true of earthen channels where the use of soil cover may be a convenient approach and a lesser degree of liner system security may be acceptable in some cases.

If the channel is used to supply domestic water, the geomembrane should meet the requirements of recognised controlling bodies. The liners should not provide a source of any hazards substance either from the base material or from secondary materials such as bonding agents, adhesives or cleaners.

22.8.9 General Design Considerations

22.8.9.1 *Geomembrane Thickness*

The type of geomembrane material and its thickness will influence the seepage rate. Table 22-6 sets out recommended geomembrane thicknesses for general channel lining use.

Membranes less than these thicknesses, particularly in the 0.2mm to 0.375mm range, have generally not proven satisfactory as they are easily punctured or damaged during handling, installation and placement of the cover material.

Buried geomembranes as thin as 0.15 to 0.2mm thickness have been used in the past but their effectiveness in reducing seepage losses has been highly dependent on the amount of physical damage to the lining. Evidence indicates that there has been extensive damage to these linings, resulting from mechanical equipment during installation, subsequent maintenance operations, loss of cover due to erosion or livestock or from external hydrostatic pressures.

With regard to thickness, it needs to be recognised that by adopting a thicker material, the overall strength and durability characteristics of the geomembrane are significantly increased, while the overall cost of installing the complete covered geomembrane lining is only increased by a marginal amount, when the purchasing and installation of the geomembrane and the placement of the cover materials are included.

Literature from North America can use the unit *mil* for geomembrane thicknesses. This is an imperial unit and should not be confused with the metric *mm*. The conversion for typical geomembrane thicknesses are:

8 mil = 0.2 mm
10 mil = 0.25mm
20 mil = 0.5 mm

22.8.9.2 *Service Life*

Refer to Table 22-6 for guidance on the expected service lives of the different geomembrane materials.

Geomembranes are subject to varying degrees of deterioration when exposed to heat, ozone and ultra-violet radiation. The effects of aging and exposure include loss of strength, loss of flexibility and elasticity, and shrinkage. Some geomembranes are liable to attack by animals and insects, particularly rodents and termites.

22.8.9.3 *Subgrade Preparation*

To avoid damaging or puncturing the geomembrane liner, proper preparation of the subgrade is important. The channel cross section must be over excavated to provide for the required waterway area, plus the cover material before placing the membrane.

In existing channels it will be first necessary to completely remove all silt and vegetation deposits from the waterway. It may be found in existing channels that a saturated sub-grade will require deeper excavation or special construction methods to combat the soft and wet conditions.

Generally the native soil subgrade should be disturbed as little as possible in the excavation or reshaping operation. The subgrade, on both the batters and bed, should be firm, reasonably dry and relatively smooth, with all sharp objects removed that might puncture the geomembrane liner. Dragging the subgrade with a heavy chain or tractor track can be a rapid and effective method of smoothing the channel subgrade. Rolling the subgrade with a compactor to obtain a smooth surface should not be required. Rolling was a conservative practice specified in the past, that is no longer considered necessary with the modern generation of geomembranes.

The degree of compaction of the bank supporting the membrane is not as critical as it is for rigid linings, but a compaction of 85 to 90% of maximum dry density is recommended to minimise the risk of tearing due to differential settlement or heaving.

HDPE is not a very forgiving material and requires a high standard of subgrade preparation. Some other liner materials are more forgiving of less than perfect conditions and they are well worth considering if local conditions make surface preparation difficult or expensive. The key to this survival capacity can be found in comparing multi-axial elongation performance, but it must be remembered that the alternative materials may have less desirable durability or other properties.

The use of a parabolic section for membrane lined channels instead of a trapezoidal section can improve the efficiency of desilting operations and significantly reduce the associated damage to the cover material.

If the site has rock faces or other features that require some treatment a surface application of shotcrete with a geotextile covering is a common preparation for a liner which can be fixed at intervals by mechanical fasteners.

Special precautions may have to be used in areas with high water tables to prevent back hydrostatic pressure.

The treatment of the subgrade with a soil sterilant to control weed growth has been a practice specified in the past. This is no longer a recommended practice because of the potential adverse environmental effects of soil sterilant use.

22.8.9.4 Batter Slope

Whether or not the geomembrane is to be exposed or covered is the first decision criteria for batter slopes. For exposed geomembranes, the batter slopes can be constructed steeper than covered geomembranes. In exposed situations, the batter slopes can generally be as steep as the batter material allows. Depending on the subgrade material stability this may be 1:1.5, but the recommended maximum slope for exposed liners is 1:2. Refer Section 12.17.4, Batter Slopes.

The steepness of the channel batters is primarily dependent upon the cover material used. It is normally much flatter than the angle of repose of the subgrade material, otherwise the cover material may slip down the liner. Recommended maximum batter slopes for the subgrade and the cover material are set out in Table 22-8.

Cover type	Thickness of Earth fill (m)	Thickness of Crushed Rock (m)	Maximum slope of membrane liner (V:H)	Maximum slope of Cover (V:H)
Earth	0.3 – 0.6	N/A	1:2	1:3
Earth and Crushed Rock	0.2 - 0.3	0.1 – 0.15	1:2	1:2.5

Table 22-8 Cover Thickness and Inside Batter slopes for Geomembrane Lining

Typical cross-sections for lined channels are shown in Figure 22.13 and Figure 22.14.

Longer radius curves are recommended at the intersection of the batter slopes and the bed to improve stability and to more closely approximate the final shape of the channel section after it has been in operation.

Photos\canada\small channel.jpg

Photo 22-10 Typical channel Alberta, Canada – membrane lined channel with rock ballast

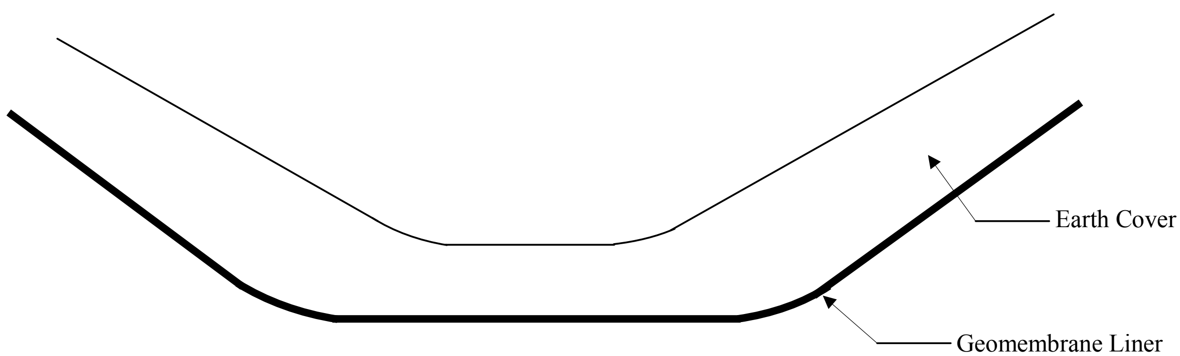

Figure 22.13 Geomembrane liner with Earth Cover

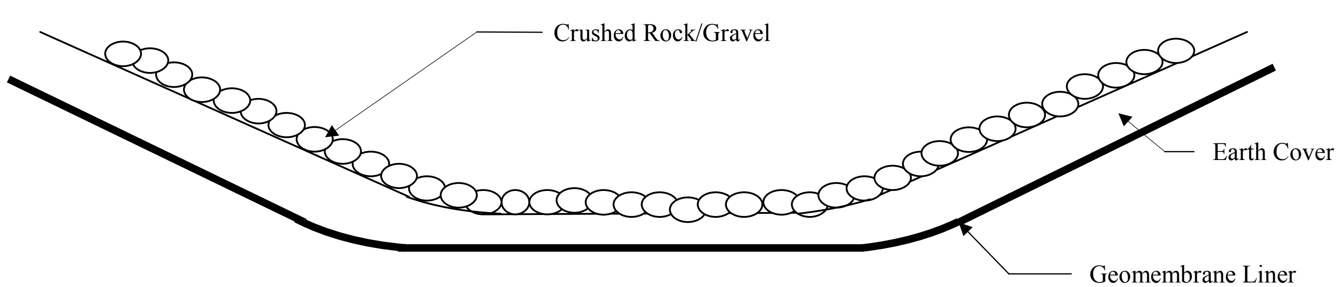

Figure 22.14 Geomembrane liner with Earth and Crushed Rock Cover

The use of a parabolic section for membrane lined channels instead of a trapezoidal section can improve the efficiency of desilting operations and significantly reduce the associated damage to the cover material.

To effectively protect the membrane, the channel section must be completely stable so that little or no erosion or sliding will occur. To achieve this the batters must be made statically stable, even though the cover is composed of unconsolidated earth which is saturated, rests on a membrane that introduces a weak shear plane and is supported by a subgrade that may be dry, wet or saturated. HDPE liner faces are very low friction surfaces, and a textured sheet rather than smooth can be used for added slope stability.

The recommended batter slope for earth covered geomembranes is 1 (vertical) : 3 (horizontal). A batter slope of 1 (vertical) : 2 (horizontal) is the steepest that should be considered. However, if, the cover is composed of relatively unstable material, such as rounded uniformly graded sands, fine gravels or silty sands, a flatter slope must be used. Laboratory tests of available cover material are desirable to determine the appropriate batter slopes.

The reasons for the recommended 1 (vertical) : 3 (horizontal) batter slope for covered geomembrane liners are as follows:

- It is considered to be the steepest slope on which the earth cover material will remain stable during drawdown.
- Minimises the amount of downslope tension that can develop within the geomembrane owing to the weight of the overlying earth cover material.
- Minimises the possibility of the geomembrane becoming torn due to the long-term creep effects of the cover material slowly migrating down the channel batter slopes.

The stability of the cover material can sometimes be improved by compaction. If good material for cover is not readily available, selection of less desirable soils and improving their stability by rolling may be an option. Compaction equipment should be used with care and only after sufficient cover has been placed to protect the membrane.

Slippage of the cover material down the geomembrane slope has can be problem, particularly during rapid draw down, and even more so, when two layers (crushed rock over earth) of cover are used. The stability of the cover material can be improved by:

- adopting a flatter batter slope
- compaction of cover material by rolling
- selection of cover material that is reasonably free draining without loss of fines
- using a longer-radius curve between the batter slopes and the bed
- using a single blended layer of earth and granular material by mixing the gravel into the earth
- avoiding rapid fluctuations in water level

Smooth or rounded gravel will have a higher tendency to slide, while angular crushed rock will be more stable.

22.8.9.5 Cover Material

Geomembranes have little resistance to the various field hazards and need a cover for protection from damage. This is usually achieved by using a cover of:

- Earth, or
- Earth with Crushed Rock/Gravel upper layer

The second option has benefits of reducing maintenance costs by deterring aquatic animals and weeds, and reducing erosion of the cover material. However, it adds a significant cost.

Figure 22.15 shows a typical profile of a Geomembrane-lined channel.

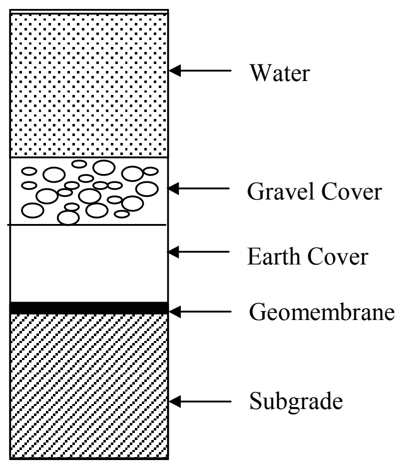

Figure 22.15 Typical Covered Geomembrane profile

The selection of the type and thickness of the cover material is a key consideration in reducing the life-cycle costs of membrane liners. The excavation for, supply and placement of the cover material is a significant cost component, and the cover material has a major influence on the life of the lining. For economy, the material should be locally available and placed as thin as possible for adequate protection of the membrane.

The cover material must remain stable on side slopes of the channel, resisting sloughing, erosion and wave action.

The cover material needs to have the following physical properties:

- It must be reasonably free draining so that it will remain stable during drawdown.
- It must be coarse enough to resist erosion due to flow and wave action.
- It must not be too coarse otherwise the geomembrane can be damaged during cover placement. A well-rounded gravel placed close to the liner can be acceptable.

The thickness of the earth cover for geomembranes depends primarily on the erosion resistance of the material and the local conditions, such as scour and wave action, the potential for removal of cover during desilting and exposure to mechanical damage. The minimum depth of earth cover recommended in literature is 0.15 metre, however a cover depth of 0.25 to 0.4 metre provides substantial additional protection. For a clayey gravel or an equally erosion resistant material a minimum thickness of 0.3 metre is recommended where threats to the cover integrity exist. If the cover material is fine grained and non-cohesive, a greater thickness will be required or crushed rock protection. An analysis of the relative economy of using a crushed rock cover with a smaller section, as compared to a larger section and thicker cover of less stable material, should be made.

The cover thickness should also be increased downstream of structures to provide additional protection against localised scouring. Refer to Table 22-8 for guidance on cover thicknesses.

For best results, the available earth and crushed rock cover material should be laboratory tested to determine if they meet the desirable requirements for grading, slope stability and thickness. Section 14, Material Selection and Testing, will assist in comparing soils for relative erosion resistance and stability.

Improper choice and placement of protective cover can easily damage geomembranes. To minimise damage to the geomembrane, the cover material must be carefully placed by a means that does not result in direct loading on the liner by construction equipment or puncturing of the lining by the free fall of material from overhead equipment.

22.8.9.6 Coefficient of Roughness

The *n* value for a uniform channel section covered with gravel and sand can be determined from the *Strickler Equation*:

$$n = 0.028 d_{50}^{0.1667}$$

where d_{50} is the size in metres for which 50 percent of the bed material by weight is finer.

Refer to Section 12.11.1.

22.8.9.7 Permissible Velocities

In additional to being statically stable, the cover material must be able to resist the scouring effects of the flowing water, and the maximum permissible velocity in covered membrane lined channels is limited by the erosion resistance of the cover material.

The maximum permissible water velocity in a covered membrane lined channel will be less than that in an unlined channel constructed from soil having the same characteristics as the cover material of the membrane lined channel. The reason for this are that earth covers are generally placed without a high level of consolidation and in this state the material is more susceptible to scour.

As well, velocities which are permissible in unlined earthen channels, where some erosion can be tolerated, may be too high for covered geomembrane lining where shallow scour could remove or significantly reduce the thicknesses of the protective cover material.

The maximum non-erosive velocities for different soil types are discussed in Section 12.11.3 and are set out in Table 12-5.

From overseas literature, it appears that the recommended maximum velocity for covered geomembrane lined channels is about two-thirds of that permissible for unlined earthen channels in similar materials.

22.8.9.8 Freeboard

Adequate freeboard provision is necessary to prevent water overflowing the top edge and seeping down behind lining, where it can push the lining out and cause slippage failure of the batter slope.

Refer Section 12.14.

22.8.9.9 Minimum Radius of Bends

Refer Section 12.16.2.

22.8.9.10 Additional Protection against Erosion

Additional protection against localised erosion of the cover may be required at bends and structures.

Refer Section 12.11.4.

22.8.10 Construction Considerations

The important considerations when using geomembranes as a channel liner are:

- Batter slope — Section 22.8.9.4
- Subgrade — Section 22.8.9.3
- Anchoring — Section 22.8.6
- Installation, sealing and quality management — Section 22.8.5
- Cover — Section 22.8.9.5

A typical construction sequence would consist of:

1. Excavation of the channel section
2. Preparation of subgrade
3. Installation of the liner
4. Placing cover material or ballasting of the invert

Some lining materials expand and contract significantly, and it is important to carry out the installation in the contracted relaxed state with slack in each direction so that thermal contraction or the weight of the cover material will not induce stresses. If the weather conditions are very hot then it is advisable to install the liner during the coolest time of day. Installation should also be avoided in strong winds where wind uplift can cause damage to the liner. To avoid damage, the exposed liner can be held in place by sandbags, car tyres or small piles of earth until the cover material is placed.

If a tear occurs in the liner during installation, it should be prepared by placing a sufficiently large piece of liner material over the damaged surface and sealing the two sheets together.

It is important to ensure that exposed geomembranes are adequately anchored to resist wind and water uplift. This will involve anchoring in trenches and possibly some form of ballast on the bed and batters to prevent uplift of the lining material.

To prevent early deterioration by wind and mechanical damage, the placement of the cover should begin as soon as the geomembrane lining is judged to be properly installed. The proper placement of the cover material is important to avoid possible puncturing, tearing or stressing of the membrane. The top edges of the lining should be anchored in trenches along the side slopes of the channel, prior to placement of the protective cover. Excavators, backhoes, conveyors or trucks can place the material with care, covering the bed of the channel first and then starting at the toe and working up the batter slopes. Additional cover of crushed rock or gravel can then be applied. It is not necessary to compact the cover material by rolling, but rather spreading and dragging to attain the required finished shape and uniform thickness will be generally sufficient.

There is a danger that the cover material may slough down the bank during placing, and this can carry the membrane down the slope with it, causing the membrane to rupture. Careful placement of the cover material and placing the material on the channel bed and lower portions of the batter slopes first, should reduce the risks of this type of construction failure.

The rate of filling the channel for the first time should be carefully controlled so that the force of water inflow does not scour the cover material, and initial rapid fluctuations in water level should be avoided while the cover material consolidates.

Geomembrane panel layout, panel assembly and field installation are all described in the attached specifications:

- *Specification for Supply and Field Installation of HDPE Geomembrane Liners*
- *Specification for Supply, Panel Fabrication and Field Installation of Flexible Geomembrane Liners based on Unreinforced Polypropylene, PVC and non-crystalline materials*
- *Specification for Supply, Panel Fabrication and Field Installation of Flexible Geomembrane Liners based on reinforced Polypropylene, Ethylene Interpolymer Ally and similar materials*

Guidelines for Geosynthetic Clay Liners can be found in the attached *Geosynthetic Clay Liners Specification Guidelines*.

22.8.11 Fencing

When livestock, particularly cattle, have access to the channel waterway, the channel needs to be longitudinally fenced to protect the liner and its cover from damage. Refer Section 12.22.

22.8.12 Maintenance

Frequent inspections of exposed linings are required to ensure that if any damage occurs to the lining, it is repaired and integrity of the liner is maintained.

A properly selected, designed, manufactured and installed geomembrane liner covered with earth or earth and crushed rock should not require any special maintenance, other than ensuring that the protective cover remains intact. This will principally involve regular inspection and repair of the cover material, the control of weed and tree growth in the cover material, and the careful execution of mechanical desilting operations to ensure that it remains intact to protect the geomembrane beneath.

Periodic visual inspection and monitoring of the condition of the liner and anchor system (trenches and metal strips) should be carried out. Regular inspection of the protective cover has been found to be cost-effective as repair of a damage geomembrane can be difficult and costly.

It is important that the specified thickness of cover is maintained. During the first operating season, the loosely placed cover undergoes some consolidation upon saturation. Minor repairs of the cover material may be required and additional cover material should be placed in any areas where sloughing down the batters has occurred.

Possible maintenance needs for covered geomembrane linings are set out in Table 22-9.

Maintenance	Response
Puncture or rupture of the membrane	Fence channel to stop animal access if cause Patch damaged membrane Increase protective cover
Slumping of the subgrade or cover material down the batters	Refer to Section 22.8.9.5 on Cover Material
Plant growth in the cover material	Remove plant growth
Desilting of the channel	Use more care in desilting operations Use laser level control on excavators
Localised scour or erosion of the cover material	Provide or add to the gravel protective blanket
High channel running level damaging the membrane anchor	Operate channel to avoid water overtopping the lining
Uncontrolled surface water runoff entering the channel and damaging the cover on the batter slopes	Provide surface water inlets
Washing out of anchor trenches	Repair and re-direct rain run-off away from trenches

Table 22-9 Maintenance Needs for Covered Geomembrane Linings

Whether or not a covered geomembrane has been punctured or ruptured can be difficult to determine. Locating the rupture can be equally difficult and repairing it costly, requiring the section of the liner to be uncovered, dried, cleaned and patched.

The use of a parabolic section for membrane lined channels instead of a trapezoidal section can improve the efficiency of desilting operations and significantly reduce the associated damage to the cover material.

It is useful to provide markers to indicate the location of the lining to individuals involved in channel maintenance activities.

Potential fire damage is an issue that needs consideration. Most lining material will melt if exposed to fire and it is important that the edges of exposed linings are kept clean and clear of dead grass where fires are likely.

Weeds can establish themselves on earth liner covers and maintenance costs related to aquatic weed control can be the same as unlined earthen channels.

22.8.13 Summary

Successful implementation of a liner requires careful choice of design and materials as well as a comprehensive QC/QA program.

The perfect geomembrane for all applications does not exist. The performance of different types of geomembrane can vary widely and a material that is well suited to one application may not be well suited to another. Care should be taken in selecting a material to look at the real performance requirements of the specific application and to review all of the associated aspects involved with the use of a particular material including those related to maintenance and channel operations.

These specifications and other documents are standard documents intended for guidance for standard projects. Review of the intended membrane choice and construction details and documentation by an experienced geosynthetic engineer is always prudent.

22.9 Hard Surface Linings

These linings are the type placed directly on the subgrade of the channel and are exposed to the wear, erosion and deterioration of the flowing water. This category includes all linings constructed of concrete, asphalt, brick and stone. Concrete which includes in-situ, precast, grouted fabric mats, shotcrete, reinforced and unreinforced linings, is the most common hard surface linings used in Australia.

Hard-surface linings are outside the scope of these Guidelines and readers should refer to Section 22.10 for detailed references on this type of lining.

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23. Measures to Reduce the Rate of Deterioration

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Deterioration of channels can be arrested at several phases of a channel's lifecycle as illustrated in Figure 13-5, Life Cycle Cost Reduction Opportunities. These phases are Design, Construction, Operation and Maintenance. The deterioration factors from Section 10 are listed in Table 23-1 with the phases and specific action that can be taken to reduce the rate of deterioration.

		Phases at which deterioration can be arrested			
Deterioration Factor		**Investigation & Design**	**Construction**	**Operation**	**Maintenance**
Channel Design	Design Life	✔			
	Shape of channel cross-section	✔			
	Depth, width and capacity of channel waterway	✔		Ensure channel is run at or below design capacity	
	Bank height above natural surface	✔	✔ High banks may require more care in Compaction Control, Outside batter, crest and inside batter erosion control		✔ Outside Batter, Crest and inside batter erosion control
	Bends Channel reach length Orientation of channel in relation to prevailing winds	✔	✔ Inside batter erosion control		✔ Inside batter erosion control
	Meander formation				✔ May require remedial action such as inside batter protection.
Bank Material	Soil Type	✔ Material Selection and Testing	✔ Material Selection and Testing		✔ Control of Inside batter Erosion Control of Erosion of Crest and Outside batter
	Bank heaving and slumping	✔ Material Selection and Testing	✔ Material Selection and Testing	✔ Filling and Draining of Channels	✔ Control of Inside batter Erosion Control of Erosion of Crest and Outside batter

Deterioration Factor		Investigation & Design	Construction	Operation	Maintenance
Construction	Construction Technique		✔ New Channel Construction		
	Construction quality control		✔ Compaction control		
	Old Borrow pits adjacent to channel	✔	✔		
Operation	Degree of operational supervision	✔ Adequate access Provision of SCADA		✔	
	Water level fluctuations	Provision of SCADA control		✔	✔ Control of Inside Batter Erosion
	Channels running above operating level	✔ Provision of SCADA control		✔	
	Overtopping of banks	✔ Provision of SCADA control		✔	
	High flow velocity	✔		✔	
	Turbulence at structures	✔		✔	
	Channel filling and drawdown			✔	
Maintenance	Maintenance techniques				✔
	Vegetation and weed growth				✔
	Vegetation and weed control techniques				✔
	Adjacent trees	✔			✔

Deterioration Factor		Investigation & Design	Construction	Operation	Maintenance
Stock and Vermin	Stock	✔ Fencing Protective Cover	✔		✔
	Aquatic animals, ie Carp, Yabbies	✔	✔ Control of Inside Batter Erosion		✔ Control of Inside Batter Erosion
	Vermin, ie rabbits, foxes	✔	✔ Control of Erosion on Crest and Outside Batter		✔ Control of Erosion on Crest and Outside Batter
Adjacent landholders	Adjacent farming practice	✔ Land Acquisition	✔ Fencing		✔
	Farm vehicle traffic on bank	✔ Land Acquisition	✔ Fencing		✔
Environment	Wind/wave action	✔	✔ Control of Inside Batter Erosion		✔ Control of Inside Batter Erosion
	Rainfall	✔	✔ Control of Erosion on Crest and Outside Batter		✔ Control of Erosion on Crest and Outside Batter
	Channel water quality	✔	✔ Control of Inside Batter Erosion		✔ Control of Inside Batter Erosion

Table 23-1 Activities to reduce the rate of deterioration by phase

23.1 Reduction of Deterioration – Investigation and Design Phase

The action to be taken to reduce deterioration at the Investigation and Design phase of a project can be found in Section 11, Planning and Investigation and Section 12, Earthen Channel Design, particularly:

Section 12.14, Freeboard

Section 12.17, Channel Cross-Section

Section 12.20, Rights over Land

Section 12.22, Protective Fencing

23.2 Reduction of Deterioration – Construction Phase

Actions to be taken to reduce deterioration at the Construction phase of a project can be found in Section 19, Channel Bank Construction. Also

Section 15, Material Selection and Testing

Section 16, Compaction Control

Section 17, Protective Cover

Section 18, Inside Batter Treatment

23.3 Reduction of Deterioration – Operation Phase

23.3.1 Rate of Channel Filling and Draining

23.3.1.1 Priming

A great deal of care is needed when running water for the first time in new earthen channels, as the banks and backfill around structures may not be sufficiently compacted and settled. Priming, the progressive filling of a new channel over several weeks, will enable the banks to absorb moisture and settle; thereby avoiding many problems and any weaknesses that do develop can be detected and repaired before breaks occur. If conditions permit, priming of new channels should be started 2 to 3 weeks before water is needed. This allows time in case the need to repair the channel develops during the priming.

23.3.1.2 Filling

The filling of earthen channels at the start of operational periods should not be done rapidly. In old channels, water should be turned in from 1 to 2 weeks before delivery will be required at full-flow depth. In more dispersive soils, rapid filling of the channel can lead to the fast saturation of the bank material, causing the clay particles to disperse which speeds up the bank deterioration processes and can lead to piping failure and leakage.

23.3.1.3 Draining

Draining water out of a channel too quickly may be more harmful than filling too quickly. The rapid draining of channels can lead to the slumping of the saturated bank material into the channel and the speeding up of bank deterioration processes considerably, with the steeper the batter slope, the greater the impact.

The acceptable draining rates will depend on the individual bank material, batter slopes and bank height. A maximum rate of change in water level should be established for each channel system in order to minimise damage from rapid water level fluctuations. As a rule of thumb, experience has shown that the rate should be limited to about 150 mm in 24 hours for a typical trapezoidal channel section in average clay loam soils.

23.3.2 Operating at Design Level

To ensure that a channel bank has a long service life with minimum losses from seepage and leakage, it is important that the channel is not operated well above its design discharge level for extended periods of time.

Channel design capacities are broadly based on the watering requirements of the short periods of peak demand. Channel flow rates are normally held reasonably steady at about the design figure during these peak periods, but at other times flow rates are considerably less than design and subject to change as the demand changes. Careful operation is required to minimise water level fluctuations at these times.

However, open channel systems are inherently complex to operate and they afford little tolerance for error. Their non-linear flow behaviour and the long times needed for flow changes to travel the length of a channel make them difficult to regulate. Consequently there are considerable fluctuations in a channel system above and below the design levels.

Alternate wetting and drying, shrinkage and cracking, vegetation and animals acting on the top of a channel bank, reduces the compacted density and thus lessens the water-tightness, slope stability and erosion resistance of the top section of bank.

Where channels are operated well above their design level, with very little freeboard, this places increased pressure on any weaknesses in the channel bank and increases rates of leakage, seepage and bank deterioration.

The consequences of this are operational difficulties, reduced freeboard and reduced channel safety, accelerated wear, increased scour and erosion, deterioration of channel capacity due to siltation from scour and erosion, increased leaks, seepage and overtopping. The increased seepage, leaks and overtopping reduces operational efficiency, increases water losses, and can contribute to groundwater problems and water logging.

Limited encroachment on channel freeboard should only be planned during major channel system regulations or during short periods of maximum irrigation demand. Full freeboard should be maintained at all other times in order to ensure that the safety of the channel is protected.

While some degree of extra flow may be tolerated in most earthen channels, experience has shown that when channels are operating close to the top of the compacted bank, the rates of erosion, slumping and leakage increases significantly. Reducing the channel running level reduces stresses on the top section of bank, reducing maintenance problems and the rate of deterioration, and extending the life of the bank. Running channel 100 to 150mm lower has shown significant benefits in life extension and reduced maintenance.

The water level that channels are operated at can affect the rate of seepage. Raising the channel water above the designed level will increase the head of water on the bank and bed and this will increase the rate of seepage through the bank and bed. This leads to increased losses of water from the channel system and increased accessions to the water table.

23.3.3 Channel Level Fluctuations

Unless the inside batters are protected by a cover of crushed rock or gravel material, rapid fluctuations of the water levels in earthen channels should be minimised to avoid the slumping of the bank material.

Under the less stable saturated soil conditions, the high pore water pressure in the bank can induce slumping of the batters into the channel. Drawdowns in excess of 150 mm in 24 hours should be minimised, and severe drawdowns of more than 300 mm in 24 hours should be avoided wherever possible.

Experience has shown that rapid fluctuations in water level speed up the bank deterioration processes considerably, with the steeper the batter slope, the greater the impact. Where large water level fluctuations are eliminated, it has been observed that the rates of bank deterioration can be slowed significantly.

Close control of water levels is particularly important to protect newly constructed earthen banks while they are undergoing the initial aging and stabilising process.

23.3.4 Discharging Drainage Water into Channels

The practice of discharging drainage water into earthen channels to relieve flooding of adjoining properties after rainfall can speed up the bank deterioration processes.

It is recommended that this practice not be allowed, other than in special circumstances and only then after due consideration of the risks and long term implications.

In accepting the drainage water, conveying it through the channel system and outfalling it, the following adverse impacts can occur:

- scour of the channel banks and bed at the discharge point
- slumping of the channel banks due to the rapid rise and fall in water levels
- erosion of the channel section from higher water velocities
- overtopping of the downstream sections as the channel capacity reduces
- deterioration in water quality
- chemical contamination of water
- spread of diseases

23.3.5 Draining Channels during Non-Operational Period

Irrigation channels are filled and drained many times over in their life. For many irrigation schemes that do not supply water to irrigators for the whole year, draining the channels during the non-operational period is standard practice. However, some irrigation schemes prefer to not drain their channel systems. The advantages and disadvantages of draining channels are outlined below:

Advantages of Draining	Disadvantages of Draining
• Allows for inspection, maintenance and renewal of assets • Reduced rate of aquatic weed growth in spring • Reduced stock damage to banks • Reduced destructive activity of carp and yabbies • More efficient channel desilting operations • Reduced seepage to the watertable • Improved water quality on refilling	• Loss of valuable water resource • May lead to bank drying, cracking and leakage • Increased potential for rain erosion on inside batters • No stock and domestic water available • Rapid draining can cause slumping of banks • Loss of stock control where channel acts as a fence • May cause initial leakage from drop-bar structures on refilling

Retaining water in channels during the non-operational period and thus eliminating the need to refill channels at the start of the next irrigation season, may be a means of temporarily saving water during periods of water shortage.

To reduce the negative impacts, it may be possible to hold water in one third of the channel system and drain the remaining two thirds on a rotational basis.

However, water held in the channel system by Goulburn-Murray Water over two winters during a period of water shortage in 1999 and 2000, resulted in prolific aquatic weed growth. The quantity of water saved was reduced by leakage through structures and outfalls and the quality of stored water deteriorated due to groundwater and drainage discharges.

This degraded the quality of water retained in the channels to such an extent that it was necessary to not only drain the system before refilling for the next season, but also flush the channels with fresh water. The net result was a greater loss than if the channels had been drained at the end of the season.

Unless exceptional circumstances exist, the advantages of draining channels during the non-operational winter period are considered by Goulburn-Murray Water to outweigh the disadvantages.

Each irrigation authority needs to weigh up the advantages and disadvantages of draining and make its own informed decision.

23.4 Reduction of Deterioration – Maintenance Phase

The history of irrigation is replete with examples of the folly of neglecting maintenance. The best-constructed systems will eventually fail if maintenance is neglected. Maintenance activities should begin the day a new channel is placed into operation and continue throughout its life. Typical irrigation channel maintenance issues are shown in Figure 23-1.

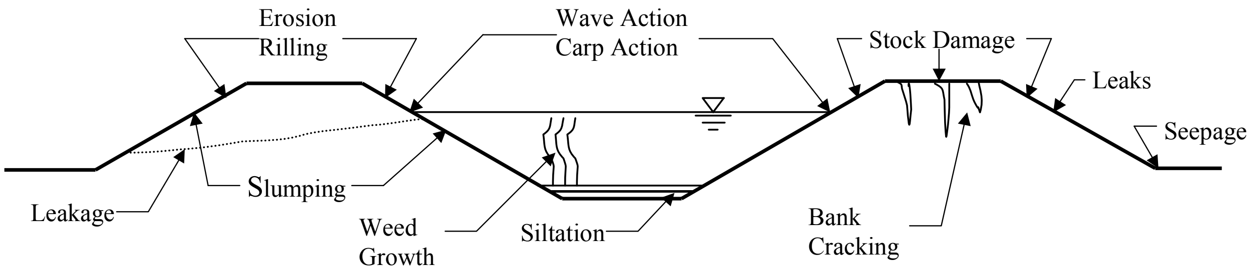

Figure 23-1 Maintenance Issues

The objectives of channel maintenance include:

- provide the required level of customer service
- obtain the longest bank life
- achieve the lowest life cycle cost
- avoid interruptions in service delivery
- achieve the highest delivery efficiency

Each irrigation authority needs to establish an appropriate level of maintenance expenditure for its channel system depending on such variable factors as:

- design and construction standards
- channel size and characteristics
- channel age and condition
- adjacent farming impacts
- trees and vegetation growth
- complexity of the system
- water velocity
- bank materials
- environmental conditions
- levels of service provided
- fluctuations in water level
- topography
- geographic location
- climate
- agricultural conditions
- period of operation
- stock and animal impacts
- weed types
- usage history
- operating practices

A well-managed preventative and corrective maintenance program is required to optimise the life of a channel. Preventative maintenance is scheduled maintenance, performed to minimise deterioration, extend the useful life of a channel and minimise corrective maintenance. Corrective maintenance refers to unscheduled maintenance caused by failure, damage, defects or any other unsatisfactory situations and usually requires swift action.

Channel bank maintenance activities can include:

- regular inspections
- weed control
- silt removal
- removal of debris
- scour and erosion repair
- repair of stock damage
- repair of protective fencing
- re-levelling of uneven access road surfaces
- repair of bank and batter protective covers
- leak repair
- inside batter re-establishment
- repair of bank cracking
- vegetation and tree removal
- repair of beaching
- topping of bank to restore freeboard

To efficiently maintain a channel, it is necessary for those responsible for maintenance to be familiar with the design of each section of channel; the capacity, slope, cross section, and the design drawings should be available for reference.

The types of channel maintenance are very diverse and the means for accomplishing the work are constantly being improved. New equipment and techniques developed for other purposes have been successfully adapted for the maintenance of irrigation channels, and irrigation system managers and maintenance personnel should always be alert to the development of new equipment, techniques and materials, and their possible adoption to channel maintenance activities.

23.4.1 Inspection

The detection of minor faults at an early stage when repair is simple and economical is crucial in minimising maintenance costs. Timeliness of maintenance is very important and the key to good maintenance is frequent inspections. Although this applies to many situations, it is especially important in the care and maintenance of earthen channels.

Regular inspections of the channel should be made to identify needed bank maintenance, such as:

- aquatic weeds in the waterway
- leaks through bank
- water erosion of inside batter
- rain and wind erosion of bank
- burrowing animals in the bank
- tyre ruts in access tracks
- stock management
- seepage from channel
- disturbance of protective cover
- silt accumulation in the bed
- debris in the waterway
- terrestrial weeds on the bank
- tree growth on the bank
- access road condition
- debris in cross drainage structures
- stock damage
- cracking of the bank material
- slumping of batter slopes
- scour at structures
- integrity of protective fencing
- piping through banks
- rilling of the batters
- sink holes in the crest

All channels are subject to deterioration in varying degrees. While the timing of some recurring channel maintenance can usually be predicted with reasonable accuracy, because channel banks deteriorate with time at a rate that is difficult to accurately predict, other maintenance needs can be determined only by a careful on-site observation. A critical maintenance task is therefore regular inspections by experienced personnel to identify maintenance requirements as deterioration develops.

The reasons for undertaking a regular inspection program include:

- identifying bank maintenance needs
- identifying unsatisfactory or unsafe conditions as they develop
- identifying damage or interference to the banks
- reviewing effectiveness of maintenance program

In as much as uncorrected minor maintenance needs can grow rapidly into major and costly maintenance problems, regular inspections should be made, beginning immediately after the channel is constructed. When construction is essentially completed a formal inspection of all work should be made and any uncompleted work and deficiencies listed. This defines work remaining and transfers responsibilities for the channel from the constructor to operator. The inspection should be made by a team representing the design, construction and operating staff.

The frequency of inspections is dependent upon such factors as:

- size and importance of channel
- age and condition of the bank
- trends in deterioration
- consequences of bank failure
- particular circumstances

Depending on these factors, the inspection frequency may vary from monthly to yearly, but should be made at least:

- immediately after the first filling of the channel
- annually
- after an unusual event such as heavy runoff or flooding.

23.4.2 Weed Control

Weed control practices are considered to have a major influence on channel bank maintenance costs and lives.

Excessive weed growth in channels means that the water level in the channel must be higher to pass the required flow. Channels running too high increase the head on the bank and lead to increased seepage, leakage, overtopping and bank erosion.

The loss of capacity in irrigation channels through the growth of aquatic weeds is a widespread problem in Australia. A range of submerged, floating and emergent weeds can severely reduce channel capacities.

Research into aquatic weeds in irrigation channels has shown growth patterns to be changeable and influenced by many factors making the problem difficult to deal with. Each irrigation system needs to develop its own weed control programs that are environmentally acceptable and keep weed growths down to tolerable levels.

23.4.3 Desilting

The deposition of sediment in channels may be objectionable or desirable, depending on the extent to which it occurs.

In systems diverting from rivers carrying an excess amount of sediment, deposits may be so extensive as to seriously affect channel capacity. Siltation of channels reduces the waterway and increases the likelihood of dense aquatic weed growth that will cause channels to run above design levels. Periodic removal of silt is necessary to restore original design capacity and control weed growth.

Compared with other countries where more use is made of river run with high silt loads, the majority of river systems used in Australia for irrigation do not carry sufficient sediment to cause rapid and excessive siltation problems. In most situations, the rate of deposit is relatively low and where there is some margin of capacity available in the channel, the sediment is usually allowed to collect over many years until the amount is sufficient to make its removal by hydraulic excavators economical.

A deposit of sediment over the channel bed and batters can under certain circumstances be a benefit in reducing seepage losses. This is usually a gradual process that may take several years. However, once an effective sediment seal has developed, it appears from available information that carefully controlled channel desilting operations do not significantly increase seepage rates, provided particular care is exercised during desilting to avoid over-excavation. Refer to Section 22.7.6.1 - Sediment Sealing

The design cross section of a channel can be severely damaged by excavators mechanically removing silt and weeds in an uncontrolled manner. The batter slopes can be increased to an unstable angle, increasing the rate of bank deterioration and siltation of the channel. The bed can be over-excavated so that the channel no longer drains out, accentuating weed problems if water lies in the bottom of the channel during the non-operational period. A channel lining can also be removed.

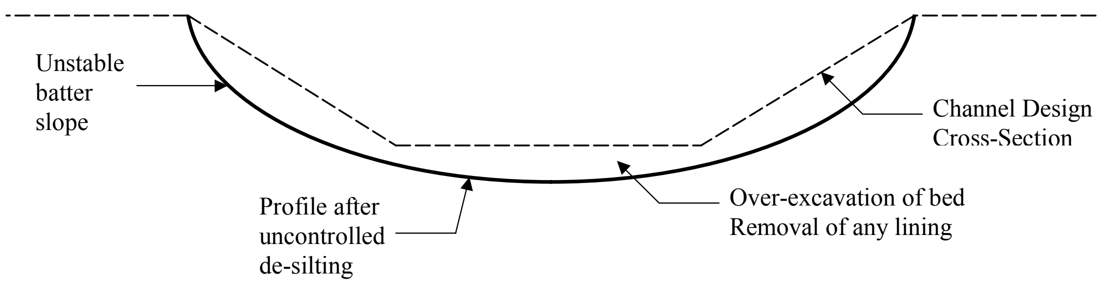

Figure 23-2 De-silting Operations

Good visibility and level control is required to avoid these problems. Experience has shown that using excavators when the channel is empty, rather than full of water, increases work productivity and controls the over-removal of material from the channel cross-section. Where ever possible, chemical weed control should be used to minimise the amount of mechanical weed removal necessary.

Silt removed from the waterway should be deposited far enough away to prevent subsequent slumping into the channel. Placement next to fences should be avoided, as the height of the fence can be reduced and rusting of the bottom wires can occur. Without special treatment, the silt should not be placed on top of the bank, as this will kill the protective cover of vegetation and can leave the bank exposed to erosion and cracking.

23.4.4 Inside Batter Re-Shaping

Bank deterioration is accelerated by the formation of a near vertical or undercut inner batter. The unstable face increases the bank undercutting and slumping cycle.

Where sufficient bank width exists, the inner batter slopes should be re-shaped on a cyclic basis to improve batter stability and extend bank life. This technique is also referred to in Australia as *batter trimming* and *slope blade grading*.

Refer to Section 18.3.1 on Inside Batter Re-Shaping, Section 12.16.4 on Batter Slopes and Table 12-11 for a guide to the maximum batter slopes recommended for saturated bank materials.

23.4.5 Stock Damage

Stock can cause extensive damage to earthen channel banks and significantly shorten their lives. It is particularly important to keep stock off channel banks constructed from dispersive clay. Stock tramp and graze the banks bare of grass cover, exposing the bank material to rain and wind erosion, drying and cracking. Damage to banks by cattle can be very severe, particularly where cattle use the channel bank as a track in wet weather or cross through the channel. Cattle eat the grass cover on the banks and at the water's edge, trample down the batters, push material into the waterway and adversely impact the water quality.

To prevent damage, siltation and pollution, it is important that channel banks are not used for stock access, stock watering or grazing. Where channel banks are exposed to stock it is important that longitudinal fencing be constructed as soon as possible after the channel bank is completed. Fencing also reduces the possibility of human and animal drowning. A protective cover over the channel bank may also reduce the damage that can be caused by stock.

Light stocking rates may be acceptable. This has the advantage of reducing vegetation growth which may become a fire hazard or a habitat for noxious weeds and vermin. Ideally, stock should be watered by piped supply to troughs.

Some irrigation authorities have by-laws where damages costs can be recovered from landowners that allow their stock uncontrolled access to channel banks.

23.4.6 Bank Cracking

During extended dry periods, there will be some minor cracking as channel bank material dries out. However, some soils types are more prone to cracking than others and cracking can be a serious problem. There are three main types of cracks due to the compacted bank drying out; transverse, longitudinal and shrinkage.

Repair methods for cracks include:

- ripping the bank, re-working and compacting the bank
- digging out the cracked zone and re-compacting with imported borrow material

To prevent the bank drying out, a protective cover should be placed over the outer surfaces of the bank. Refer to Section 17 – Protective Cover.

Transverse cracks are those that run straight through the bank, and can allow water to start leaking. This type of crack can be formed when a bank has dried out, and on filling, becomes saturated below the seepage line, and slumps. The bank material above the seepage line stays dry and firm, forming a bridge over the saturated material, and a horizontal crack develops along the seepage line. Such cracks are difficult to treat and usually the affected section of bank will have to be re-constructed.

Longitudinal cracks develop parallel to the bank crest. Large cracks of this type should be filled with the same material used in the bank to prevent rain from collecting in them and further damaging the bank. Filling the cracking can be difficult in practice, and it may be necessary to trench out the crack before filling, so that the material can be compacted.

Shrinkage cracks develop in a random pattern of both transverse and longitudinal. In heavy clay soils they have been known to reach depths of 1 to 2 metres.

23.4.7 Leaks

Leakage through earthen channel banks is a common problem. Wetness, unusually lush growth on the outer batter or surface water lying outside the channel, can indicate varying degrees of leakage.

Leaks can be caused by:

- piping through the bank
- cracks forming in the bank due to drying of high shrinkage clays
- leakage paths created by burrowing animals
- cavities caused by the rotting of old root systems through the bank.

A careful inspection of banks is required to identify leaks. Inspections should be carried out after channels are filled at the beginning of each irrigation season and at periods of peak channel flow, since bank leakage is likely to be the most pronounced at these times.

The rate of flow from leaks might be small or large, steady or increasing, clear or muddy. If the flow rate is muddy and increasing, this would indicate the need for greater urgency of repair work.

23.4.8 Vegetation

Trees and shrubs, from either intentional planting or natural seeding, should not be allowed to grow on or immediately adjacent to channel banks.

Trees send out their roots over long distances to seek food and water. When a tree dies the roots will rot and form tunnels which allow water to leak through the bank. The tunnels thus formed can lead to failure through piping erosion, and are exacerbated by the presence of dispersive clays. It is not only dying trees that cause problems. Trees that are alive and apparently vigorous can have dying roots with similar consequences. Shrubs can provide a habitat for burrowing animals and these can do serious damage to a channel bank.

Channel operation and maintenance activities can also be hampered by stands of trees and undergrowth on or immediately alongside channel banks:

- trees can fall over or drop limbs, damaging the bank, fences and structures or impeding the flow in the channel
- the root systems of some species (eg. Willows) can severely restrict the channel waterway
- access for operation and maintenance can be impeded
- the margin of land for disposal of silt can be reduced
- controlled grazing for weed control may not be possible in the years it takes the trees to be come established

Trees should be located at least 3 metres and preferably 5 metres from the toe of the bank. Certain species should be avoided altogether eg. willows and other shallow rooted trees, particularly water seeking varieties.

Naturally seeded shrubs and trees should be eradicated when they are still young, otherwise later cutting or chemical treatment can create leakage paths along rotted root systems through the bank.

Requests can be received from landholders and Landcare Groups wishing to plant tree and shrub plantations adjacent to channels, and each irrigation authority should develop appropriate guidelines on tree planting for its particular geographical location to ensure future problems do not arise.

23.4.9 Erosion

There are a number of forms and causes of erosion. Many are preventable, or easily remedied in their early stages. In all cases, the presence of dispersive clays in a bank has a severe magnifying effect and increases the speed with which it occurs.

Examples include:

- Batter Erosion; where channels have been built out of dispersive soils, the batters at water level are inclined to erode. When this develops into a problem, the batters can be protected by placing rock armour. Refer to Section 18 on Inside Batter Treatment.
- Stock damage; stock should be excluded from channel banks.
- Rilling; the formation of multiple small erosion gutters down either side of the bank due to rainfall runoff. This usually happens when there is no protective cover on the bank. To rectify refer to Section 17 on Protective Cover and Section 18 on Inside Batter Treatment.
- Tunnelling; tunnelling failure can begin with the formation of a pothole or wheel rutting on top of the bank which holds water from rainfall which eventually forms a larger hole. A sinkhole is formed as rainwater in the pothole creates a tunnel downwards through dispersive soil. Dry weather access tracks constructed on channel banks should not be used during wet weather, because the wheel rutting can lead to significant bank damage in dispersive soils.

23.5 Reduction of Deterioration due to Carp

Carp

Figure 23-3 Carp (*Cyprinus carpio*)

23.5.1 Background

Carp (*Cyprinus carpio*) originated in China and spread throughout Asia and Europe as an ornamental and aquaculture species. Carp were released into the wild in Australia on a number of occasions in the 1800s and 1900s but did not become widespread until a release of *Boolara* strain carp from a fish farm into the Murray River in 1964. The spread of carp throughout the Murray-Darling Basin coincided with widespread flooding in the mid 1970s (see Figure 23-4), but carp were also introduced to new localities, possibly through their use as bait. Carp are now the most abundant large freshwater fish in the Murray-Darling Basin and are the dominant species in many fish communities in south-eastern Australia. A recent NSW Rivers Survey found that carp represent more than 90% of fish biomass in some rivers and have reached densities of up to one fish per square metre of water surface. The growth rates and population densities of carp have been found to vary enormously between habitats due to water conditions, spawning success and the availability of food.

map

Figure 23-4 Distribution of Carp in 1970, 1977 and 1998

Carp up to 10 kilograms in body weight are relatively common in south-eastern Australia although than can grow as large as 1.2 metres and 60 kilograms. Carp can tolerate water temperatures as low as 4°C and as high as 35°C, salinity levels of 14 % (seawater is 35%), relatively extreme pH levels (from 5.0 to 10.5), and polluted and poorly oxygenated water. Female carp can produce up to 1.5 million eggs per year.

Australian waterways and irrigation channels provide the optimum conditions for carp to thrive with warm, shallow water, nutrient enriched silt, a lack of predators and a lack of competitors. In these conditions carp have a fast maturity (one year as compared with up to two years for other fish species).

Little research had been conducted on wild carp until recently. While research has been gathering pace in recent years, our knowledge of carp is still rudimentary, particularly as it relates to Australian conditions.

23.5.2 Impact of Carp on Natural Waterways

There is clear evidence that carp can increase water turbidity and damage aquatic plants. There is also some evidence that carp increase water nutrient levels. It is less clear what the impacts of carp are on native fish populations - many of which were in decline before carp became widespread. Carp may make aquatic habitat less suitable for native fish breeding and survival, but there is little evidence of carp feeding directly on native fish whereas small carp provide a food source for a number of native fish and bird species.

There is no clear research evidence that carp cause bank erosion as it is difficult to isolate the effects of carp from other influences such as high flows, excessive water extraction, lack of riparian vegetation and livestock access.

The development and exploitation of water resources has affected native fish by altering the frequency, duration, timing and size of low and high flow events. The increase of still-water habitats behind weirs also provides greater spawning habitat for introduced fish, including carp. Habitat disturbance has therefore favoured invasion by carp and made many habitats less suitable for native species.

Therefore environmental rehabilitation is seen as a way of changing the environmental variables to favour native fish. Potentially by increasing native fish numbers, particularly larger predators, predation pressure on carp will be increased. Provision of more natural water flows will also improve the environment for native fish, as well as making conditions less favourable for carp and thereby reducing their impact. Therefore carp management should not just focus on physical removal of carp.

Refer to Section 23.5.12 for more information on research on carp control methods in natural waterways.

23.5.3 Impact of Carp on Earthen Irrigation Channel Banks

Carp cause deterioration of earthen channel banks in their feeding habits.

Carp feed on bacteria, micro-organisms (such as micro-invertebrates and other animals) and epiphytic algae (algae that grows on plants but is not parasitic). *Epiphytes* can be seen as a type of slime on aquatic plants, such as ribbon weed (*Vallisneria spp.*) and floating-pondweed (*potamogeton sp.*). These food sources are also present within the soil.

The areas in which carp feed are often similar to that of yabbies where high levels of organisms are abundant. In Goulburn-Murray Water the vegetation in areas where carp feed has been observed and found to be notably distinct. Water Couch (*Paspalum* spp.), Sedges (*Cyperus* spp.), Rushes (*Juncus* spp.) and common grasses are frequently present where carp feed. Also the vegetation present are often narrow-leaved plants (*monocotyledons*). Plants contribute to the survival of carp by providing a substrate for the epiphytes to grow on, releasing nutrients to feed the organisms and providing shelter for the organisms which carp then feed on.

Carp contain large sucking mouths which extend and contract when foraging in aquatic plants and soils. They can vigorously attack the batters and bottom silts of earthen channels, sucking up mud and then dispelling it back into the water as they select organisms for their food. This action can seriously erode channel banks and increase the turbidity of the surrounding water. *Mumbling* of channel beds and batters is evidence of the presence of carp.

Photos\mumbled.jpg

Photo 23-1 Channel bed showing *mumbling* (indentations) caused by Carp foraging

Carp frequently feed from yabbie burrows which are located at the rootzone of plants on the channel bank. Carp vigorously attack these areas removing the soil in their search for food. The soil in this area can be removed from the root zone of the plants to such an extent that sections of the banks are undermined with edges collapsing into the waterway.

Carp are well adapted to feeding from the bottom, taking mouthfuls of sediment into their mouth and expelling inedible particles. This mode of feeding requires fine sediments and is not possible where the bottom consists of large gravel or cobbles. (*Koehn 2000*).

The power generated as carp dispel mud when feeding in channels causes two main visible effects:

- erosive feeding behaviour causing undermining and slumping of channel banks
- re-suspension of sediment that increases turbidity and exacerbates physical wear of pumping machinery

Although carp have been blamed for undermining and slumping of channel banks, there is much evidence that other factors such as uncontrolled stock access, wind/wave action and rilling caused by rainfall may have a more significant impact on erosion of channel banks than carp.

Roberts and McCorkelle (1995) investigated the role of carp in channel bank erosion by excluding carp from sections of bank over the nine month irrigation season. Undercutting and bank slumping was observed to occur in all sections studied, including where carp were excluded, and so these effects could not be solely attributed to carp. This highlights the problem of isolating the effect of carp from other effects such as high flows, lack of vegetation on the crest and inside batter and livestock access.

There are two main approaches to control the damage caused by carp to channel banks:

1. Removal of Carp
2. Habitat Manipulation

23.5.4 Removal of Carp

The obvious method to reduce deterioration caused by carp is to remove them from channels. However complete removal of carp is difficult and generally only a reduction in the carp population can be achieved. Therefore removal will have to take place on a regular basis to ensure numbers do not increase to high levels which cause major damage. However, if the number of carp removed is trivial compared to increases in carp populations through recruitment and immigration then a great deal of effort can be expended for little or no reduction in impacts.

Female carp mature at 2-4 years and may produce more than one million eggs per year. However density-dependent factors may strongly influence juvenile carp survival, so that higher fish population densities do not necessarily produce more young carp, and as the carp population increases, the number of young carp surviving may actually decline. The implication of this for reducing carp populations is that the size of the reproducing population will need to be substantially reduced to have any marked effect on the carp population.

There are several methods of removal as follows:

- Physical control
- Chemical control
- Biological control

23.5.5 Physical Control

Physical controls which have been investigated in Australia include removal of carp from waterway by draining or fishing.

23.5.5.1 Draining of Channel System

Most irrigation systems can be drained relatively easily. In southern Australia many channels are drained through the winter non-operational period which can result in fish kills.

The advantages of draining waterways are:

- an immediate response
- relative ease
- low cost
- low man-hours

A study of the Campaspe Irrigation System during the winter of 1999 of two channels; one which was drained and one which was left filled (Brown 2000), supports the theory that when channels are not drained between each irrigation season there is a tendency for the carp population to build up or at least remain relatively stable. Whereas when channels are drained between irrigation seasons the carp population may be *re-set* to a significantly lower level.

However when channels are drained, some water remains in them. Dead-end spur channels, shallow pools and many structures such as culverts are lower than the bed of channels and these can retain enough water for carp to survive during the cooler months of the year until the channel is refilled. On refilling, the surviving carp can be supplemented by carp entering the system from rivers or headworks storages and no real reduction in carp numbers may be achieved. Also, altering the water level without drying out the waterway, appears to stimulate the carp, rather than deter them. Increases in the water level, generally increases the flow which simulates a flood. To the carp, a flood represents an increase in optimal environmental conditions (particularly, food sources). This results in increased activity of the carp both in feeding and breeding.

Thus, control of carp by draining channels without complete emptying, is unlikely to be effective on its own.

23.5.5.2 *Fishing*

Fishing competitions for carp have become popular in recent years but have a negligible impact on carp populations. However commercial fishing and targeted electro-fishing can reduce the carp population in a particular area if carried out in a strategic manner.

Commercial Fishing

While commercial harvesting is not feasible on a widespread basis, it may be used as a form of carp management to reduce damage caused by carp in some restricted areas. At low densities, commercial carp harvesting is not profitable and so will often fail to reduce carp densities enough to meet damage control goals.

The largest carp harvester/processor in Australia (Gippsland Lakes, Victoria) processed 900 tonnes of carp in 1999 for domestic and export markets, with a target of 1000 tonnes for the export market alone in 2000. Retail prices for whole carp are up to $7 per kilogram in some Sydney shops. There is some potential to increase the value of carp with further processing (smoked and canned fish etc). However, currently much of the commercial catch is used for low-value products such as fertiliser (15 cents per kilogram) and crayfish bait (50 cents per kilogram).

There is a widespread belief that commercial use of carp can solve the carp *problem*. The reality is that carp are currently a low-value product, which limits commercial offtake to areas that have high carp densities and good access to waterways and markets. Nevertheless, there is some potential to increase the recreational and commercial removal of carp by promoting carp as a target fish and increasing the value of carp products.

Several commercial ventures have been attempted to process carp into fertiliser, pet food etc. However commercial fishing of carp across the Murray-Darling Basin is not expected to have any significant effect on carp numbers as currently less than five percent of their waterways are commercially fished. This could be increased if there was a market developed for carp. However, if a commercial venture proves successful, there would be pressure to maintain a threshold level of carp rather than eradicate them.

Electro-Fishing

This process involves an electro-fishing unit mounted in a boat. An electric current is discharged into the water through electrodes suspended on a boom from the boat. Fish are temporarily stunned (approx 30 seconds), float to the surface and are then picked up using a hand net. Any native fish can then be returned to the waterway while the carp are destroyed.

electro-fishing

Photo 23-2 Electro-fishing unit mounted in boat

Electro-fishing is generally not considered suitable for carp removal in irrigation channels because of:

- difficulty in getting a boat of this size and weight in and out of channels with steep batters.
- restricted movement along channel waterways because of numerous bridges, checks, syphons, fences etc. necessitates multiple boat launches.
- limited distance of the stunning effect on the fish allows many to escape the treatment. Electro-fishing is not 100% effective, varying with turbidity, conductivity as well as channel depth and width.
- time-consuming and expensive

Electro-Seining

Electro-Seining is a modification of electro-fishing using an energised seine net to herd fish, and eventually stun and capture them. A boat mounted unit consists of two booms on the boat which herd the fish together. A greater quantity of fish can then be netted.

23.5.6 Chemical Control (Poisoning)

Poisoning may be used to eradicate carp from small isolated areas (e.g. farm dams).

Chemical products which are known to kill carp include Rotenone, Endosulfan, antimycin, acrolein and copper sulphate. These chemicals were developed for purposes other than poisoning fish and are not approved for use as fish poisons in Australia, although fish kills resulting from their use have been reported.

Acrolein, a herbicide used to control submerged weeds, is known to kill fish and significantly reduce carp numbers during treatments. Although this is not the intention, acrolein will kill fish at relatively low doses by disrupting their oxygen uptake. Acrolein, like all chemical control options, are non-selective, ie chemical control will kill all fish in the irrigation system.

The widespread use of poisons is not possible in aquatic habitats, because species-specific poison for carp are not yet available and the risk to non-target native fish species is unacceptable in most cases. The negative impacts of fish kills to the eco-system and the community is indeterminate, and so chemical control should be carefully considered before implementation. The use of chemicals, in or near waterways, is controlled by environmental regulations.

23.5.7 Biological Control

Biological control is the introduction of a natural predator to a pest.

Advantages of a biological control program can include:

- minimal effect on non-target species
- inexpensive (cost per hectare)
- the biological control can remain in the environment and have a continuing effect

The disadvantages of a biological control program can be:

- extremely expensive to set-up (sometimes $millions)
- lengthy to set-up (often over ten years)
- potential risk of the disruption of the native environment
- strict guidelines to be met

Pelicans and cormorants can be significant predators of carp, however, only smaller (more manageable) sizes of carp are preyed upon. It is possible that foxes may prey on the larger sizes of carp. However, it is unknown how effectively natural predators control carp.

The use of viral agents for biological control, such as the Spring Viraemia Carp Virus (SVCV) is considered to be unreliable for technical, commercial, conservation and logistic reasons and some sectors of the public have expressed concerns about the use of viral control agents.

Potential molecular approaches include immuno-contraception to reduce carp fertility and the introduction of a fatality gene into the carp population which can then be triggered chemically or by some other means. However, there are currently no biological or contraceptive control agents suitable for use against carp, and gene technology is not yet at a stage where it can be used for carp control. Therefore carp management in the immediate future will rely on environmental rehabilitation, physical removal, poisoning where appropriate, and most importantly, reducing their spread.

23.5.8 Prevention of re-infestation of irrigation system

Most irrigation systems control inflow and outflow of water through structures. Therefore the potential exists to modify these structures to restrict the movement of carp. Currently there is a lack of information about carp movement patterns that would enable the viability of modifications to inflow/outflow structures for carp management to be determined.

Fish barriers have potential as cost-effective, environmentally friendly methods of carp management.

23.5.8.1 Mesh Barriers

Wire Mesh barriers have been successfully used to prevent carp from migrating into irrigation systems from lakes and rivers.

The disadvantages of this method are:

- Debris will be trapped at the mesh barriers which would then require cleaning and monitoring.
- Fish eggs can travel through wire mesh screens. Larger fish can be eliminated only until eggs hatch and develop into mature fish.
- Flood flows can overtop structures re-introducing new populations of carp.

Further options to improve screen design could be investigated.

23.5.8.2 *Electrical Barriers*

Electrical and other forms of barriers such as bubble curtains and sonic barriers have been used in other countries to exclude fish from structures such as industrial cooling water intakes, but their effectiveness against carp is unknown. However they may be ineffective in controlling carp for the following reasons:

- Carp have very short memory spans (seconds) and so, unlike cattle stock, the zap of electricity to the carp will not deter them from attempting to go through the barrier again. If the electrical barrier is disrupted, the carp will migrate through the barrier within minutes.
- In irrigation systems with many carp entry points the cost of devising, maintaining and running of electrical barriers will be expensive. However in small schemes an electrical barrier may only be required at one or two locations making them viable.
- The effectiveness of acoustic and electric barriers in excluding carp has not been tested.

23.5.9 Habitat Manipulation

Carp are an extremely successful species as they can tolerate a wide range of environmental conditions. Can survive temperatures as low as 4°C and as high as 35°C.

Unlike most other fish, carp can tolerate extremely low dissolved oxygen concentrations for several days without ill effects. High concentrations of silt do not affect them, and they often burrow into the mud to avoid temperature extremes. Salinities as high as one third seawater can be withstood for long periods.

The control of carp by habitat manipulation deters the carp from feeding and breeding in that particular area.

It is expected that as the environment improves in natural waterways for native species that they shall increase in number and so displace the carp. There is some evidence from Europe that improving the environment has driven carp away.

As irrigation channels are artificial waterways they cannot be *rehabilitated* to natural stream conditions. However some steps can be taken to modify the environment of the channels to deter carp.

To deter carp from earthen channels the vegetation which provides a habitat for organisms which the carp feed on should be removed, particularly exotic species which may provide a more favourable habitat for carp than native fish. However complete removal of vegetation will also leave the channel exposed to erosion.

23.5.9.1 *Rock Lining*

Carp damage of channel banks can be prevented by *rock-lining* the earthen channel banks. Rock-lining is an unattractive environment for carp as they are unable to feed by foraging in the sediments.

Carp have been blamed for erosion of channel banks in areas where factors such as stock access, wind/wave erosion and scouring by high channel discharge may also have contributed to the erosion. Rock lining of channel banks to prevention deterioration caused by carp will also reduce the damage by other causes.

Small sizes of rock (say less than 50mm diameter) appear to have a short-term impact on deterring the carp to feed (about five years). After this time, silt begins to accumulate on the surface of the rocks, attracting vegetation, epiphytes and micro-organisms which in turn attract carp.

Photos\inside batter\CG7channel2armour.jpg

Photo 23-3 Rock armour on left bank gives protection from Carp erosion

Beaching (stone pitching) of 150 mm diameter is often placed below regulators. This appears to have a permanent impact as a deterrent to carp.

Rock-lining of channels is expensive. For cost-effective control of carp by rock-lining, key carp feeding areas in the channel system would need to be identified.

Rock lining can be used as a rehabilitation technique where bank erosion has already occurred or constructed with a new channel.

Details of this technique are given in Section 18.4, Rock Armour.

23.5.9.2 Geomembrane Lining

A *geomembrane liner* with earth cover, (Figure 22.13) may be constructed to prevent seepage through a channel. This may provide some protection from carp for some years until the sediments again accumulate and provide suitable feed for carp. A geomembrane liner with earth and crushed rock cover (Figure 22.14) will provide a greater degree of protection against carp and other environmental factors.

23.5.10 Decision Criteria

Before undertaking a method of carp control the following steps should be carried out:

- identify which parts of the channel system are most effected
- identify the extent of erosion to channel banks caused by carp and cost to the irrigation system
- urgency to which control of carp must occur

A Decision Support Flowchart of Carp Control Options follows in

Figure 23-5.

23.5.11 Strategy to prevent damage from Carp

Carp can be seen as a problem to not only irrigation systems but as a part of the entire catchment of which they are a component. The *National Management Strategy for Carp Control 2000-2005* has been prepared with the goal of control of carp and where possible, eradication. The strategy takes a holistic approach to carp control incorporating entire catchments.

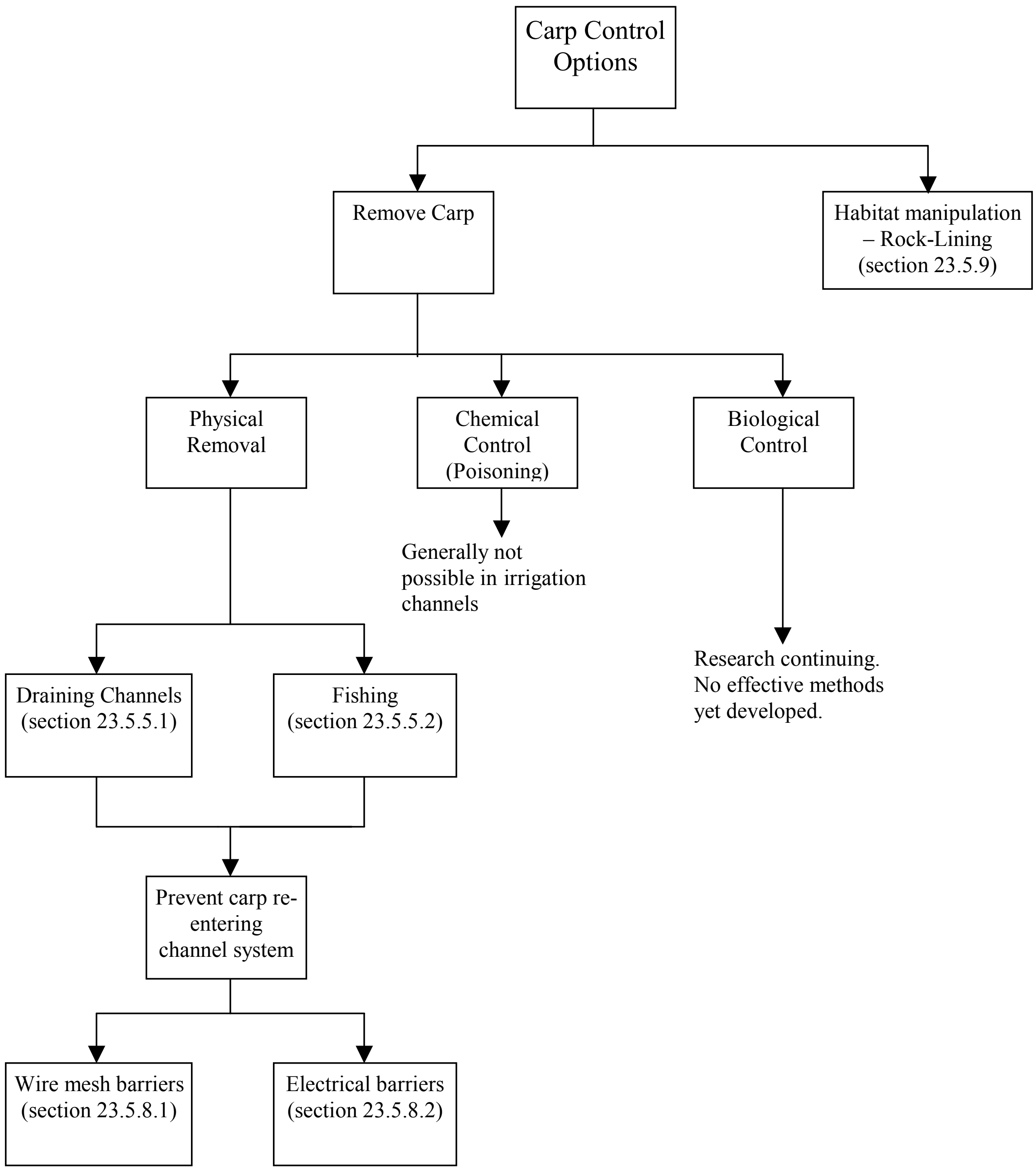

Figure 23-5 Decision Support Flowchart for Carp Control

As carp move into nearly all waterways of a catchment, a decision process must be carried out to determine in what order of priority different parts of the catchment must be treated. The booklet *Ranking Areas for Action – A Guide for Carp*

Management Groups gives guidelines on how to prioritise areas for action. A case study in this booklet addresses an irrigation area within a wider catchment with a large population of carp. The natural waterways such as rivers and billabongs are prioritised high above irrigation systems because of their high conservation values. Also it can be seen that if carp numbers are controlled in the natural systems there will be a subsequent reduction in carp numbers in irrigation systems.

If carp are identified as a major cause of deterioration to channel banks a strategy to prevent further damage may be required. This strategy would encompass several of the methods outlined in Sections 23.5.5 to 23.5.9, including draining of channels, screening and rock lining for new or reconstructed channels as well as refurbishment for badly affected channels.

More information on developing a strategy for Carp Control can be found in the *National Management Strategy for Carp Control 2000-2005.*

23.5.12 Further Research into Carp Control

Most research on carp to date has been carried out in natural waterways as they have a high conservation value and rehabilitation of natural waterways to improve water quality and bio-diversity is an increasing concern. However as more knowledge of carp and control methods becomes available, irrigation channel managers will also be able apply some of this knowledge. Also as carp numbers in natural waterways are controlled, fewer carp will reach irrigation systems. The irrigation system should be seen as a component of the larger catchment, and become part of any carp control programs implemented for the entire catchment.

Carp control is a complex issue and it is therefore important that irrigation channel managers maintain affiliations with their state Fisheries Division, Catchment Management Authorities and other relevant authorities so that a joint effort can be made to reduce the impact of carp on channel banks.

Examples of current carp research being carried out in Australia are listed in Table 23-2. Other organisations involved in providing current information about carp are listed in Table 23-3.

23.5.13 Research into Carp Activity in irrigation channels

A study was carried out during 1999 into the *Abundance and Distribution of Carp in the Campaspe Irrigation System.* This study involved sampling at several sites along a channel by electro-fishing to estimate the carp population and their movement through the irrigation system. Although much useful raw data was obtained, this study did not provide a conclusive description of where carp enter the channel system, where they feed and where they exit the channel system, if at all.

To gain a better understanding of how carp use irrigation channel habitats there is a need to study the movement patterns of fish within, as well as into and out-of, the channel system. A telemetric tagging study has been proposed by Goulburn-Murray Water (G-MW) to be carried out jointly by G-MW and the Marine and Freshwater Resource Institute (MAFRI), DNRE (Vic). This kind of study could provide information on how and when carp enter and exit the channels. Knowledge of immigration behaviour would be especially useful in developing suitable devices and operating procedures designed to control carp populations in irrigation channels.

Category	Research Area	Organisation
Monitoring	Surveys of carp populations, changes in carp densities, and recruitment patterns	NSW Fisheries, CRC for Freshwater Ecology, Queensland Department of Natural Resources, Griffith University, Tasmanian Inland Fisheries Commission
	Trends in commercial carp fishery	NSW Fisheries, CRC for Freshwater Ecology
Impact (assessment)	Effects of carp on plants and sediments	CRC for Freshwater Ecology
Control methods	Effects of river management options, such as temperature regimes and environmental flows, in controlling carp and rehabilitating native fish populations	NSW Fisheries, CRC for Freshwater Ecology
	Methods for reducing carp abundance and measuring environmental benefits	NSW Fisheries, CRC for Freshwater Ecology
	Carp control strategies	Tasmanian Inland Fisheries Commission
	Hydrologic manipulation as a carp control strategy	CRC for Freshwater Ecology, Tasmanian Inland Fisheries Commission
Ecological processes	Age and growth of carp	CRC for Freshwater Ecology, University of Adelaide
	Physiological tolerances of fish in billabongs	CRC for Freshwater Ecology, La Trobe University
	Downstream transport of larval and juvenile fish	NSW Fisheries, CRC for Freshwater Ecology,
	Effects of drying on lake ecology	CRC for Freshwater Ecology,
	Diets and competitive interactions between carp and other species	CRC for Freshwater Ecology, University of Western Sydney
	Growth, reproduction, mortality and population structures of Carp	Victorian Department of Natural Resources and Environment
	Carp recruitment sources and movements	Victorian Department of Natural Resources and Environment
	Early life history and environmental tolerances of carp	CRC for Freshwater Ecology, University of Adelaide

Table 23-2 Examples of current Carp Research in Australia (taken from Table 6 *Managing the Impacts of Carp)*

Organisation	Contact Details	Aims/Activities
National Carp Task Force	The Convenor Box 89 Rundle Mall PO ADELAIDE SA 5000 Ph (08) 8226 5994 Fax (08) 8226 5998 Editor of Cyprinus PO Box 359 ALBURY NSW 2640 Ph (02) 6021 3655 Fax (02) 6021 2025	Aim: to eradicate carp from all Australian inland waters through a co-ordinated action plan that promotes co-ordinated research, provides good information, explores commercial opportunities and seeks complementary legislation. They distribute a regular newsletter, *Cyprinus*, which gives general information about Carp Research in Australia.
Carp Control Co-ordination Group (CCCG)	Jim Barrett Executive Officer Ph (02) 6279 0139 Email: jim.barrett@mdbc.gov.au	Charter: to develop and co-ordinate a national strategy for the effective control of carp. Prepared and published several booklets listed in references.

Table 23-3 Contact Details for current Carp information

23.6 Reduction of Deterioration due to Yabbies

The burrowing activities of yabbies can cause significant damage to earthen channel banks.

Yabbies

Figure 23-6 Yabby (*Cherax destructor*)

Yabbies (*Cherax destructor*) are a native freshwater crustacean. They are distributed throughout Victoria, New South Wales, much of Queensland and South Australia. They can survive in water temperatures between 1-35°C. It is most content in water temperatures between 20-25°C. When water temperatures fall below 16°C, the yabby becomes comatose, metabolism and feeding virtually ceasing.

They generally live in burrows connected by access shafts to the water, and move freely from the burrows to open water when feeding. In the event of water drying up, they are capable of surviving over summer in the burrows. They are also capable of travelling overland to colonise new waters.

Yabbies are omnivorous but primarily vegetarian, favouring rotting leaves and plant detritus. The areas where yabbies feed are similar to carp. High levels of nutrients and organisms are abundant in these areas.

Yabbie populations are often noticed under the root zone of the plants and are evident, when water levels are reduced, by the numerous burrows in the batters of channels.

In adequately compacted banks, yabbies leave small indentations in the channel banks. In older banks that are not well compacted yabbie burrows can extend far into the *compacted* bank.

Photos\yabby burrows.jpg

Photo 23-4 Yabby burrows in bank

Where adjacent borrow pits or roadside drains are close to the channel, yabbies tend to migrate through the bank as water levels fluctuate. This is more common in older deteriorated channels. These yabbie tunnels can form leakage paths and contribute to the deterioration of a channel bank.

Yabbie damage can be controlled by:

1. Removal of Yabbies
2. Habitat Manipulation

23.6.1 Removal of Yabbies

In practice this is very difficult to achieve in channels.

23.6.1.1 Draining of Channels

Draining of channels will not eradicate yabbies. Yabbies will survive in their burrows adjacent to farm dams, even if the dam is left dry for 2 or 3 years. So long as yabbies have moist burrow available they will virtually hibernate until conditions are satisfactory for them to return.

23.6.1.2 Control with Fish

Redfin, brown trout and rainbow trout will all eat yabbies, but the conditions in channels are generally not suited to trout, which require clean cool water to survive. Redfin, a member of the perch family, accept a less critical range of conditions than trout, and yabbies are the preferred diet for full-grown redfin. However, the food supply in the channel must be adequate for the fish to grow to yabby eating size, and the treatment of weeds in the channel using chemical herbicides can be fatal to fish. Emptying channels during the non-operational period will also adversely impact on numbers and survival rate of fish.

23.6.1.3 Chemical Control

Chemical treatment is often recommended to reduce numbers of yabbies in farm dams. However chemical treatment cannot be used in irrigation channels because of the effect on other aquatic life and the downstream users of the water.

If direct access to the yabby burrows is possible, the chemical *maldison (malathion)* can be poured into the burrow. However, treating each individual yabby burrow on a channel in this way is not considered to be really practical. Maldison is also toxic to humans and animals.

Copper sulphate (blue stone) is a chemical that has been used to control yabbies, by either mixing it directly into bank material or dissolving it in the channel water. However, long term use can build up residual levels of copper in the environment, and this method of control is not recommended because of human and animal health concerns.

23.6.2 Habitat Manipulation

Habitat manipulation deters the yabbies from burrowing in channel banks. Minimisation of yabby damage by this means is considered to be more a practical approach than control. These methods include removal of drains and borrow pits, rock-lining, geomembrane lining and core trenching as described below:

23.6.2.1 Removal of borrow-pits

Borrow pits full of water, dams, farm channels and drains located next to the toe of a channel bank can provide another water source for yabbies to burrow into the bank from the outside edge. Where ever possible, borrow pits should be filled in, and farm dams and channel relocated at least 2 to 3 metres away from the toe of the channel bank.

23.6.2.2 Rock-Lining

A protective cover of crushed rock, gravel or sand either as a complete lining of the channel section or on the channel batters has proven to be an effective long term method of minimising or stopping the burrowing of yabbies through banks.

Rock Lining to deter carp described in section 23.5.9.1 can deter yabbies, however if large rock sizes are used (say 150mm+) yabbies shall be able to get between the gaps in the rock to the earthen channel bank.

23.6.2.3 Geomembrane Lining

Geomembrane lining of farm dams has been used successfully to deter yabbies. Refer section 23.5.9.2.

23.6.2.4 Core trenching

Core trenching channel banks and filling with sand, stone dust etc has been found to deter yabbies. When tunnelling, if they hit sand their tunnels collapse, so they will try another location. This procedure can be found in Section 21.8.2, Core Trenching. Core trenching however, has the following disadvantages:

- Sand/stonedust can weaken the integrity of the bank and so may contribute to long-term deterioration

- Good access to bank required
- satisfactory width of bank to exist if this procedure is to be successful
- costly
- may move the problem elsewhere in the channel system.

23.6.3 Decision Making Criteria

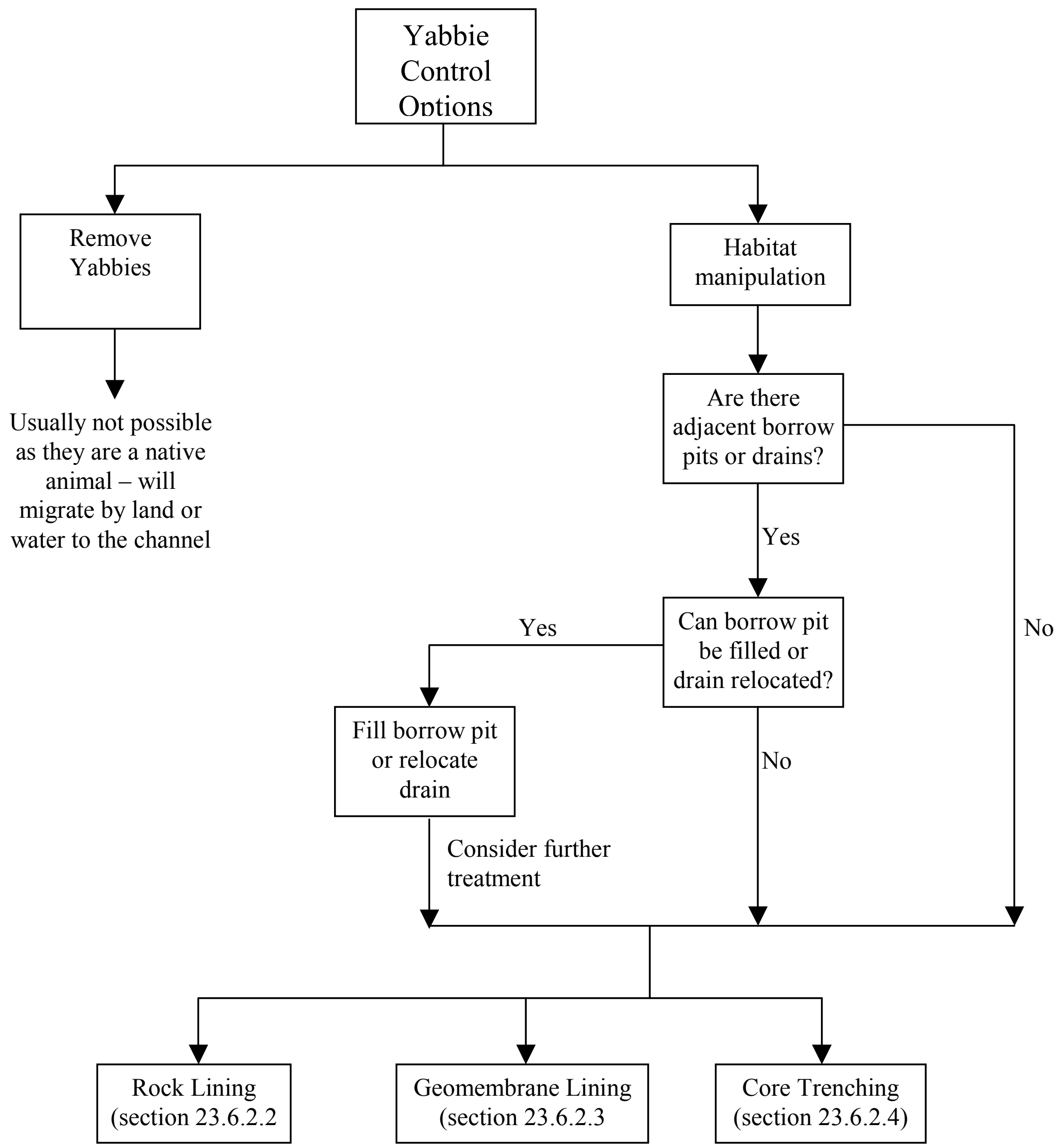

Figure 23-7 Decision Support Flowchart for Control of Yabbies

23.7 Reduction of Deterioration due to Trees

Trees planted alongside channels can have a large role to play in salinity mitigation and environmental rehabilitation. However, bank deterioration and future channel operations and maintenance requirements should also be considered.

The main disadvantages of trees planted alongside channels occur if trees are planted too close to the channel. These are:

- the obstruction of access for operations and maintenance including weed spraying, de-silting and leak repairs.
- the margin for the disposal of soil from de-silting is reduced
- may send roots through the bank, causing leakage pathways, particularly after roots die
- tree species which sucker or self-seed will re-generate and cause problems for access in the future
- trees can fall over or drop limbs, damaging the bank, fences, structures or obstructing flow in the channel
- if trees are inside a fenced channel grazing of the area for weed control is not possible in the years it takes for the trees to become established
- can impact on future works, such as capacity enlargements, access tracks and bank re-construction
- can attract unwanted public recreational use of channel, eg swimming

Trees alongside channels are generally desirable but should be planted in accordance with the guidelines to avoid the disadvantages of planting trees listed above.

23.7.1 Tree Location

- Tree location should have due regard to operation and maintenance requirements such as sufficient area for a truck or excavator to operate beside the bank.
- Access should be available to boundary fence at regular intervals, eg every 100 metres
- Clear access of at least 10 metres width, should be provided on each side of structures
- Tree planting should be offset to minimise wind damage
- Trees should be a minimum of one metre from channel acquisition boundary (fenced or unfenced), a minimum of 3 metres and preferably 5m from outside toe of banks. If the bank is in an advance state of deterioration, then trees should be a minimum 3 metres from the outside toe of a future remodelled bank.

Photos\seepage\BoortNo2channel5trees.jpg

Photo 23-5 Trees planted outside of boundary fenceline

23.7.2 Tree Species

The tree species selected should preferably have the following characteristics:

- native to the area where possible
- appropriate for the soil type and environmental conditions. Advice should be sought from the relevant local authority in this regard. (In Victoria, the Department of Natural Resources and Environment can provide this advice.)
- does not retain bushy lower limbs which may obstruct passage of vehicles or equipment along the channel
- should be of a reasonable height (10-20 metres), relatively straight and with a high compact crown
- not subject to significant branch breakage
- have root systems which will not interfere with the channel waterway
- wind-firm
- not an active coloniser through re-generation by suckering or self-seeding

In some instances pruning may be required to meet these guidelines.

23.7.3 Suitable species for Northern Victoria and the New South Wales Riverina

In general species which may be suitable for planting adjacent to earthen channels in northern Victoria and southern New South Wales are given below:

1. Tall trees (>10 m mature height)

Yellow Box	-	*Eucalyptus melliodora*
Lightwood	-	*Acacia implexa*
Blackbox	-	*Eucalyptus largiflorens*
River Cooba	-	*Acacia stenophylla*
Grey Box	-	*Eucalyptus microcarpa*
Kurrajong	-	*Brachychiton populneus*
Spotted Gum	-	*Corymbia maculata*
Sydney Blue Gum	-	*Eucalyptus saligna*
Rose Gum	-	*Eucalyptus grandis*

2. Medium trees / shrubs (3 - 10 m mature height)

Sweet Bursaria	-	*Bursaria spinosa*
Silver Wattle	-	*Acacia dealbata*
Willow Wattle	-	*Acacia salicina*
Weeping Pittosporum	-	*Pittosporum phyllyreoides*
Hop Bush	-	*Dodonea viscosa*
Hedge Wattle	-	*Acacia paradoxa*

3. Low shrubs

Gold Dust Wattle	-	*Acacia acinocea*
River Teatree	-	*Lepbospermum obovatum*
River Bottlebrush	-	*Callistemon sieberi*
Common Eutaxia	-	*Eutaxia microphylla*

Grey Parrot Pea	-	*Dillaynia cinerescens*
Lignum	-	*Muehlenbeckia floralente*

All varieties of Willow, Poplar and Swamp She-oak are not suitable and should not be planted within 50 metres of a channel.

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24. Glossary

absorption sorption *into* the *pores* of the solid phase

adsorption the process by which atoms, molecules, or ions are taken up and retained on the surfaces of solids by chemical or physical binding, eg. the adsorption of cations by negatively charged minerals

adsorption sorption *on to* the surface of the solid phase

aggregate a unit of soil structure, usually formed by natural processes in contrast with artificial processes, and generally < 10mm in diameter. Inert mineral materials, such as sand, stone dust, gravel, shells, slag, broken stone, or combinations thereof, with which cement, lime or bituminous material is mixed to bind into a mortar or concrete.

alignment the course in plan along which the centreline of a channel is located

algae single-celled, colonial or filamentous aquatic plants, distinct from vascular plants

anion negatively charge ion, eg. chloride (Cl^-)

asphalt a mix of bitumen and mineral aggregate.

barbels fleshy, sensory protrusions around the mouth of carp and some other fish. Commonly referred to incorrectly as "whiskers".

bentonite layer silicates, largely composed of smectite minerals, produced by the alteration of volcanic ash in sites

berm horizontal strip of shelf built into a channel bank or cut to break the continuity of an otherwise long slope, usually for the purpose of reducing erosion.

biological control the use of living organisms to control pests or diseases. This may involve the release of a natural or genetically modified organism.

bloom rapid, temporary increase in the population of aquatic photosynthetic micro-organisms (for example, phytoplankton or cyanobacteria) to the extent that the water becomes discoloured and, if the micro-organisms are toxin producers, unfit for drinking.

bridging or 'trampolining' the term which describes a tendency for a liner to stretch tight over a low point or change in profile rather than lie supported on the surface. It usually occurs because of the thermal expansion and contraction of HDPE and, if significant, can lead to long term stress in the geomembrane which can lead to environmental stress cracking or brittle cracking.

borrow pit a source from which material is borrowed to construct a channel bank.

bulk density the mass of dry soil per unit bulk volume. The bulk volume is determined before drying to constant weight at 105°c. The value is expressed in grams per cubic centimetre.

calcium (Ca) chemical element, Ca^{2+} - calcium cation

calendering a plastics technology term which describes the use of matched hot rollers to create a film of desired thickness or achieve a bond between layers. Calendering may be a primary process (for unreinforced film) or a secondary process.

canal see *channel*

cation positively charged ion, eg monovalent sodium (Na^+)

cation exchange capacity (CEC) a measure of the capacity to exchange cations and is equal to the sum of all exchangeable cations

channel the open irrigation device which is used to convey irrigation water. Other terms used include canals, ditches flumes and laterals. In this manual, open irrigation systems of all sizes are referred to collectively as channels.

channel lining low permeability membrane of concrete, compacted clay, bituminous or plastic material, placed on the inner face of earthen channel, or within the bank, to prevent water loss by seepage. Linings may be protected by earth cover.

channel regulator a permanent structure constructed across a channel and fitted with means of adjusting the waterway area so as to control the rate of water flow along the channel and the upstream water level. Most regulators are one of two general types which utilise different hydraulic characteristics for specific applications, ie

- overfall weir where water flows over a weir crest which can be varied in level for changing flow rates
- undershot gate having an adjustable sliding gate allowing flows to pass beneath the gate, the rate of flow being controlled by the size of the opening.

channel tenure land which the irrigation authority has rights to; whether by freehold, easement, lease or agreement

circlip remover a hand tool rather like a rowel (a tool with a shaft about 2-4 mm dia which is ground or tapered to a point) with a 90 bend near the end.

clay primary soil particles with a diameter less than 0.002mm or 2µm. Also, a texture given to soil in which the clay content is greater than about 40% by weight. Also used in an adjectival sense to describe soils which have a moderate clay content, eg. clay loam or sandy clay loam.

coagulation the aggregation of the particles of a clay sol as a result of the addition of an indifferent electrolyte

cobble substrate particles with a diameter of 64mm to 256mm.

colloid particles less than 1 µm in diameter which form a stable sol when dispersed in a continuous phase

compaction increasing the soil bulk density and decreasing the soil porosity, by the application of mechanical forces to the soil.

compaction curve the curve which illustrates the relationship between the moisture content and the dry density of a soil. Refer optimum moisture content.

critical flow occurs at the unique depth where the specific energy of a given discharge is a minimum. For any other flow, two velocities are possible. Due to this unique velocity, depth, and slope which can occur for a given discharge and channel shape, critical flow is important in the design of hydraulic structures

curls lumps of compacted soil material formed from the blade of a bulldozer of scraper

design bank level the finished bank level which consists of the maximum water level or design discharge level plus freeboard.

design discharge level (DDL) the level at which a channel will flow at its maximum designed flow rate. For most open channels, the level is parallel to the bed of the channel. It is sometimes found after construction that the channel is smoother than was assumed in design and so, at the design flow rate, the water level is below the designed discharge level. On the other hand, siltation can reduce the waterway area and weed growth can increase the roughness factor. In each case, this will reduce the capacity of the channel and cause it to run at a higher discharge level.

detheridge meter outlet positive displacement flow measurement device used to determine water volumes supplied from authority supply channel to an individual farm. The meter consists of metal wheel fitted with 8 vanes around the circumference and mounted on a horizontal axis in a concrete flume emplacement. Water flowing along the flume causes the wheel to rotate and a counting device records the number of revolutions which provides a direct measure of the volume of water supplied over a given time.

discharge flow of a channel, usually measured in megalitres per day

dispersion the process whereby a soil will spontaneously deflocculate when exposed to water having little or no hydraulic velocity. Dispersion is caused by electrostatic repulsion between clay or clay-sized soil particles, resulting in the formation of a stable colloidal soil suspension.

dispersion of earthen channel banks involves the action of clay particles passing into suspension, following an ionic reaction between clay particles, pore water and channel water constituents.

distichous in two obvious rows or ranks or alternating on opposite sides of a shoot or stem

ditch see *channel*

drawdown the vertical distance a free water surface is lowered. In a reservoir, drawdown is usually measured from the designed normal water elevation.

duplex soil a soil with a two distinct types in the upper layer. Generally at the border of these layers the dispersive characteristics of the soil increase, and further increase with depth

EC (electro-conductivity) the electrolytic conductivity of a substance, normally expressed in units of siemens per meter at 25°C.

Emerson Class No a number from 1 (extremely dispersive) to 8 (non-dispersive), which classifies the tendency of a soil to disperse in still water. Determination of the Emerson Class No. is in accordance with AS1289.3.8.1-1997.

EPDM (ethylene propylene diene monomer) a form of synthetic rubber. It is one of several synthetic rubbers (another is butyl rubber) used in a closed cell foam form to provide a compressible rubber sealing strip.

epiphytes food sources which grow on plants but are not parasitic

erodibility the capacity of soil to be eroded

erosion the process whereby soil is detached, transported and deposited by the agents of erosion - water, wind and ice

gully erosion erosion by water which forms channels or gullies

rill erosion an erosion process in which numerous small channels of only several centimetres in depth are formed; occurs mainly on recently cultivated soils.

tunnel erosion accelerated erosion by water which causes subterranean tunnels to form. Surface covering tunnel may eventually collapse, forming a gully.

erosivity the capacity of rainfall and other agents of erosion to cause soil erosion

exchangeable ions anions and cations associated with charged soil colloids which can participate freely in ion exchange

exchangeable sodium percentage (ESP) proportion of the cation exchange capacity of a soil which is satisfied by Na^+.

fetch the distance over which the wind can act over a body of water.

fishmouth is a term used to describe an open wrinkle at a seam which will nor lie flat for welding. It is often an indication of thermal movement in HDPE with one side of the sheet restrained by a seam. Each one must be cut and patched.

flume see *channel*

flocculation aggregation of the particles of a clay sol by polymeric compounds which form links between the particles

freeboard vertical distance between the designed discharge water level profile of a supply channel and the top of the channel banks.

friable a term pertaining to the ease of crumbling of soils

friction slope the available head divided by the channel length

geonet a HDPE material with an appearance similar to an expanded metal grid with openings of about 10 mm. The geonets are about 6 mm thick with hydraulic capacity similar to 300mm of open gravel.

geomembrane an essentially impermeable geosynthetic composed of one or more geosynthetic sheets

geosynthetic clay liner (GCL) a manufactured hydraulic barrier consisting of clay bonded to a layer or layers of geosynthetics. The GCL may be reinforced or unreinforced as required by site conditions. Slopes steeper than 1V:10H typically require reinforced GCLs.

geotextile any permeable textile used with foundation, soil, rock, earth, or any other geotechnical engineering related material as an integral part of a human-made project, structure or system

gilgai the micro-relief of soils produced by expansion and contraction with changes in water content. Found in soils that contain large amounts of clay, which swells and shrinks considerably with wetting and drying. Usually a succession of micro-basins and micro-knolls in nearly level areas or of micro-valleys and micro-ridges parallel to the direction of the slope.

gravel soil particles > 2mm diameter

gravimetric water content the mass of water lost in an oven at 105°c expressed as a fraction or percentage of the oven-dry mass

groundwater that portion of water below the surface of the ground at a pressure equal to or greater than atmospheric. See also *watertable.*

gypsum Mineral with the formula $CaSo_4.2H_2O$

head

available head the net head that can be utilised in overcoming friction and bend losses, after deductions are made for velocity head and entrance losses

high water level (HWL) the highest level channel water has risen to in a channel under normal operating conditions.

hydrostatic pressure the pressure in a liquid under static conditions. It is the product of the liquid's specific weight and the vertical distance between a given point and the free water surface

hydraulic conductivity the flux of water per unit gradient of hydraulic potential - a measure of the ability of soil to conduct water (seepage). In other words, is the effective flow velocity at unit hydraulic gradient and has the dimensions of velocity. It is a measure of *permeability* of a soil.

hydraulic radius the transverse flow area divided by the length of the wetted perimeter

lateral see *channel*

lime chemically, it is the material left when limestone is heated in a kiln - CaO, but often used to mean crushed limestone or soft calcareous material in soil profiles

liquid limit (LL) the boundary of the liquid state and the plastic state: determination of LL is in accordance with AS1289.3.1.2-1995

magnesium (Mg) chemical element, Mg^{2+}- magnesium cation

maintenance the operations performed in preserving irrigation channels in good condition without increasing capital costs. Repairs are part of maintenance.

Maximum Water Level (MWL) described in Section 12.12.1.2

mole mass of chemical substance or element equal to the relative molecular or atomic mass in grams

mumbling see *pock mark*

multiaxial burst a large diameter bursting test (say 300 mm dia or more) used on geomembranes and other materials to look at their behaviour when stressed in several directions in the one plane. For many materials such as HDPE the multiaxial elongation capacity is a very small fraction of their uniaxial capacity as indicated by a tensile strip test.

neutron moisture meter an instrument used to measure water content of soils. It relies upon the capacity of hydrogen in water to slow down fast neutrons emitted by a source in a probe and upon the detection of the resultant slow neutrons

optimum moisture content the water content (expressed as percentage of dry soil weight) at which a soil can be compacted to a maximum dry unit weight by a given compaction effort. This is determined in accordance with AS1289.5.2.1-1993.

oven-dry soil by definition, soil without free (not bound) water; state reached by drying soil in an oven at 105°C until there is no further mass loss

oxygen (O) chemical element, O_2 - molecular oxygen

particle size distribution the fractions of the various soil separates (clay, silt, sand) in a soil sample, often expressed as mass percentages

penetrometer an instrument to measure the resistance of soil to deformation - soil strength

permeability see hydraulic conductivity

permissible velocity the highest velocity at which water may be carried safely in a channel or other conduit. The highest velocity throughout a substantial length of a channel that will not scour.

pH a measurement to indicate the level of acidity or alkalinity of a solution where pH 1 is highly acidic, pH 7 is neutral and pH 14 is highly alkaline

phreatic line the hydraulic grade line of the seepage path from a channel waterway through the bank

piping the movement of soil particles by seeping water. Piping through a channel bank generally results in sloughing where seepage exits from the outside of the channel bank, then failure of the bank.

plant term used for *construction equipment*

plasticity index (PI) the difference between the water content at the liquid limit (LL) and the plastic limit (PL). Highly plastic soils have high PI values. Determination of PI in accordance with as 1289.3.3.1-1995.

plastic limit the gravimetric water content at below which the soil no longer is plastic and tends to crumble instead. Determination of plastic limit is in accordance with as 1289.3.2.1-1995.

plastic soil a soil capable of being moulded or deformed continuously and permanently, by relatively moderate pressure

pock mark small depression in bottom sediments caused by carp feeding activity

proctor density the relationship between the dry unit weight and the water content of a soil for a given compaction method. The *compaction curve* which illustrates this relationship indicates the maximum density that can be produced for a given soil at the optimum moisture content. This is determined in accordance with as1289.5.2.1-1993.

profile a vertical section of a soil extending from the surface through all of its horizons to the parent material

recharge the replacement of groundwater (for example, the recharging of aquifers) by rain or irrigation, or seepage from irrigation channels.

remodelling re-construction of existing earthen channel banks

rhizome stem growth which creeps beneath the soil surface, rooting at nodes to form new individuals; found in many grasses and herbs

rill erosion *see* erosion

rilling an erosion process in which numerous small channels of only centimetres in depth are formed; occurs mainly on unprotected banks

saline soil salt affected soils where the salt content (NaCl) is
>0.1% sandy soils, loams
>0.2% clay loams, clay
>0.3% if it is a subsoil

sand primary particles of soil with diameters between 2 and 0.02 mm in diameter: *coarse sand* from 0.2 to 2.00 mm and *fine sand* from 0.02 to 0.2 mm

scarify moderate tining of a channel bank layer in order that the next layer bonds with it. If scarifying is not carried out a *lamination* between the bank layers may occur, which could form a leakage path.

scrim a textile industry term used to describe various forms of base carrier on which other material is laid. In this case we are talking about an open weave polyester fabric which acts as a carrier for the polypropylene. The bonding between the two outer layers of polypropylene is mainly achieved through the gaps in the woven scrim.

setup the heaping up of water at the downwind end of an enclosed waterway caused by the frictional force from a strong wind.

silt primary particles with a diameter from 0.02 to 0.002 mm

slaking the breaking up of aggregates into smaller aggregates when air-dry aggregates are suddenly wet by water; their disruption is associated with the escape of air bubbles and the swelling of clay

slaking of earthen irrigation banks results from the reaction between the pore fluids (ie air and water) in fine grained soils, once wetted from a dry initial state. It is attributed to:

- repeated wetting and drying of channel lining from fluctuating flow level
- periodic wetting up of initially dry soil from rainfall runoff down the channel lining.

Slope The Australian Standard is to present the slope as a ratio of vertical to horizontal, and this standard has been adopted in these Guidelines.

It is worth noting that this differs from the USA standard where slope is reported as a ratio of horizontal to vertical

sloughing the softening of a soil upon saturation, resulting in insufficient strength to resist slope failure. Sloughing may be caused by shearing action or by ion selectivity.

smectite a group of 2:1 layer structured silicates with a high cation exchange capacity and variable interlayer spacing

sodic soil a non-saline soil containing sufficient exchangeable sodium to adversely affect soil structure under most conditions.

sodium (Na) chemical element; Na^+ - sodium cation, NaCl - sodium chloride (common salt)

sodium adsorption ratio (SAR) a relation between soluble sodium and soluble divalent cations which can be used to predict the exchangeable sodium percentage of soil equilibrated with a given solution. The calculation is based on the concentrations (in mmoles) of calcium, magnesium and sodium in the soil solution or irrigation water. It is approximately equal to the exchangeable sodium percentage (ESP) and is a useful indication of the sodium hazard or irrigation waters.

$SAR = [Na^+]/([Ca^{2+}] + [Mg^{2+}])^{½}$

soil piping or tunnelling…see *erosion*

soil salinity the amount of soluble salts in a soil. The conventional measure of soil salinity is the electrical conductivity of a saturation extract.

soil sample a representative sample taken from an area (potential borrow site), from which the physical and chemical properties be can determined

soil structure the arrangement of soil particles and the pore space between them

soil test a chemical or physical procedure which estimates a property of the soil pertinent to the suitability of the soil to its intended purpose

sol a homogeneous dispersion of colloidal particles (<1 µm) in a continuous phase, eg a stable suspension of clay in water is a clay sol

sorption the removal of species in the fluid phase (gas or liquid) by their association with the solid phase

spoil bank rock wastes, banks and dump depositions resulting from the excavation of ditches

steady flow a constant flow; that is the same volume in equal units of time. Also steady-state flow, permanent flow.

still water level the running surface level of the channel with no wind blowing. This will be either the supply level or the design discharge level, depending on operating method.

stolon stem growth which creeps over the ground surface, rooting at nodes to form new individuals; found in many grasses and herbs

strain elongation expressed as extension/original length %

strength of soil a measure of the capacity of soil to resist deformation

stress force applied in MPa

supply level the supply level is a design level at which adjacent commanded land can be watered. Supply level is the pool level, or minimum water level in a channel that will provide the full design flow to any irrigation outlet or offtake to a spur channel. The supply level matches the designed discharge level at the controlling check, and at very low flows it approximates the design discharge level along the reach between checks.

surface sealing the orientation and packing of dispersed soil particles in the immediate surface layer of the soil, thus greatly reducing its permeability

thermalization the thermal decay of neutrons between the nuclear source and the detectors. The rate of decay or thermalization is used to measure the apparent moisture content of the soils

tining deep ripping of the natural surface with the tines of a bulldozer or excavator in order to remove tree roots, rocks etc before forming the foundation of a channel bank or breaking up clods in a borrow pit.

topsoil a superficial soil containing some organic matter, usually darker than the underlying soils

tunnelling occurs on certain soil types when water penetrates to the subsoil by a place where the infiltration rate is higher than that of the surrounding area. The subsoil, which is of poorer structure that the topsoil and erodes more quickly, is gradually washed further downslope until it finds its way to the surface, and the clay subsoil is gradually washed out and a tunnel develops. The alternate washing out and drying out continue until only the surface soil bridges the tunnel. This usually collapses and forms a gully.

turbidity a measure of the amount of suspended solids (usually fine clay or silt particles) in water and thus of the degree of scattering or absorption of light in the water; level of cloudiness in the water.

unsteady flow flow in which features such as velocity, cross-sectional area and hydraulic slope vary in the course of time.

velocity

mean velocity defined as the rate of flow divided by the transverse area

volumetric water content the volume of water lost in an oven at 105°C expressed as a fraction or percentage of the total volume of soil

waterlogging state of land in which the subsoil water table is located at or near the surface with the result that the yield of crops commonly grown on it is reduced well below the normal for the land

water table the upper surface of groundwater or that level in the ground where the water is at atmospheric pressure. See also *groundwater*.

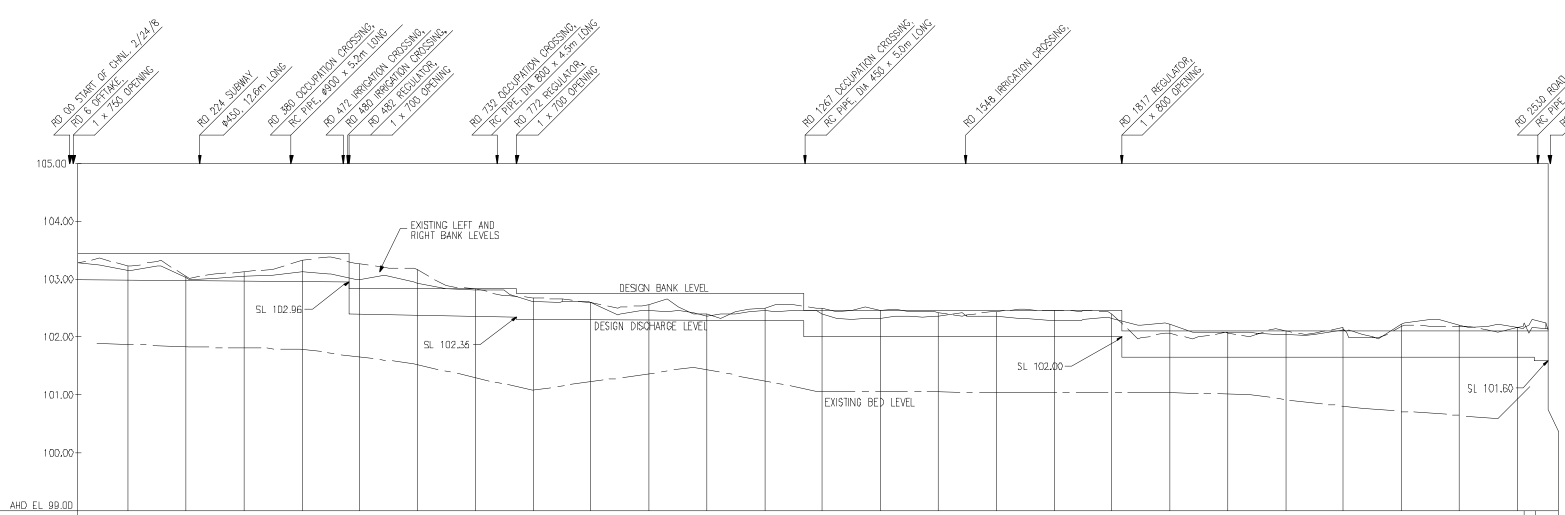
wave runup the vertical distance a wave can run up a slope, mainly dependant on the size of the wave and the batter material

yabbies (*cherax destructor*) a native freshwater crustacean

METER OUTLETS

LOCATION											
RUNNING DISTANCE(m)	472	478	480	482	755	772	1279	1548	1808	1817	2557
LEFT BANK	L13152		L13152A					L13155			
RIGHT BANK		L13151			L13153		L13154		L13156		L13157

DESIGN FLOOR LEVEL	LMO 102.58 SMO 102.66	LMO 101.97 SMO 102.05	LMO 101.62 SMO 101.70	LMO 101.22 SMO 101.30
DESIGN HIGH GROUND	102.23	102.13	101.66	101.22



LOCATION	ALLOTMENT	RESERVE	ROAD RESERVE — RESERVE
	PARISH, SECTION	TARIPTA, B	TARIPTA, NO SECTION
LAND ACQUISITION	TYPE	RESERVE	RESERVE
	WIDTH	24.90m	21.93m

DESIGN DISCHARGE ML/d	30	24	12
MANNINGS "n"	0.0275		
HYDRAULIC GRADE	0.000063 / 0.000138	0.000287	0.000078
ACCESS TRACK LOCATION	NO ACCESS		
BED WIDTH (m)	EXISTING		
BANK CREST WIDTH — LEFT	3m		
BANK CREST WIDTH — RIGHT	3m		

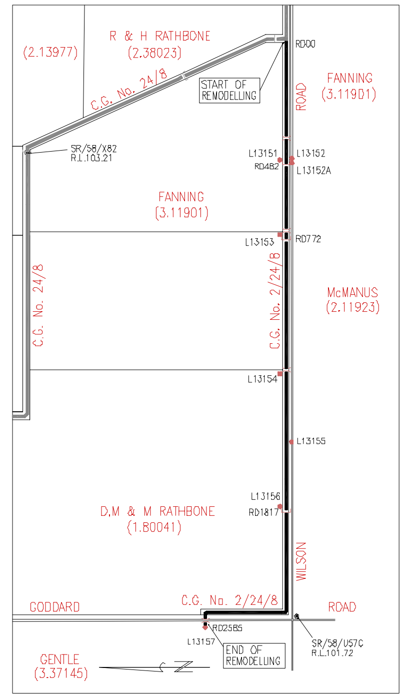
DESIGN DISCHARGE LEVEL (DDL): 103.15, 102.99, 102.99, 102.99, 102.99, 102.96, 102.96, 102.39, 102.39, 102.39, 102.35, 102.30, 102.30, 102.29, 102.29, 102.29, 102.29, 102.01, 102.01, 102.00, 102.00, 102.00, 102.00, 102.00, 101.66, 101.66, 101.66, 101.66, 101.66, 101.66, 101.65, 101.65, 101.65, 101.60, 101.60

DESIGN BANK LEVEL: 103.64, 103.44, 103.44, 103.44, 103.44, 103.44, 103.44, 102.84, 102.84, 102.84, 102.84, 102.75, 102.75, 102.74, 102.74, 102.74, 102.74, 102.46, 102.46, 102.46, 102.46, 102.46, 102.46, 102.46, 102.11, 102.11, 102.11, 102.11, 102.11, 102.11, 102.11, 102.11, 102.11, 102.11, 102.11

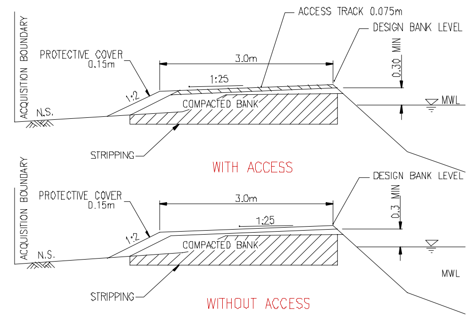
RUNNING DISTANCE (m)	EXISTING BED LEVEL	EXISTING RIGHT BANK	EXISTING LEFT BANK	NATURAL SURFACE
14	101.93	103.28	103.28	102.71
100	101.87	103.15	103.23	102.50
200	101.83	103.02	103.05	102.30
300	101.81	103.06	103.14	102.30
400	101.78	103.14	103.33	102.30
500	101.66	103.00	103.27	102.24
600	101.52	102.94	103.16	102.18
700	101.30	102.82	102.83	102.11
800	101.08	102.62	102.68	102.05
900	101.22	102.60	102.60	101.90
1000	101.37	102.47	102.57	101.75
1100	101.43	102.36	102.40	101.67
1200	101.24	102.46	102.50	101.59
1300	101.06	102.41	102.50	101.51
1400	101.06	102.32	102.47	101.48
1500	101.05	102.37	102.42	101.44
1600	101.04	102.36	102.45	101.41
1700	101.04	102.29	102.46	101.33
1800	101.04	102.33	102.40	101.24
1900	101.04	102.23	102.06	101.16
2000	101.01	102.08	102.08	101.20
2100	100.92	102.05	102.11	101.30
2200	100.80	102.13	102.15	101.40
2300	100.71	102.22	102.18	101.36
2400	100.64	102.21	102.18	101.31
2500	100.92	102.17	102.17	101.26
2557	101.14	102.13	102.14	101.16

BENCH MARKS: SR/60/U57C EL.101.72

LONGITUDINAL SECTION
RD 00-2557



LOCALITY PLAN



TYPICAL BANK SECTIONS
NOT TO SCALE

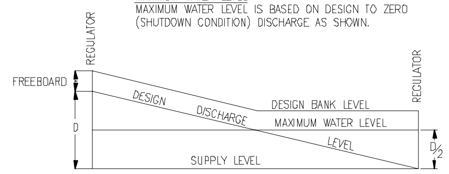
BASIS OF DESIGN

SUPPLY LEVEL
EXISTING SUPPLY LEVELS ADOPTED PROVIDING THE STANDARD ALLOWANCE OF 0.15m OVER LAND CLASSIFIED AS COMMANDED.

DESIGN BANK LEVEL
DESIGN BANK ELEVATION IS BASED ON MAXIMUM WATER LEVEL WITH 0.45m FREEBOARD.

DESIGN DISCHARGE LEVEL
DESIGN DISCHARGE LEVEL BASED ON SURVEYED CROSS-SECTIONS (SILTED) AND MANNINGS "n" 0.0275.

MAXIMUM WATER LEVEL
MAXIMUM WATER LEVEL IS BASED ON DESIGN TO ZERO (SHUTDOWN CONDITION) DISCHARGE AS SHOWN.



REV	DATE	TITLE	CHKD	CAT	M/F	TITLE	PLAN NO.
A	26/02/02	ORIGINAL CREATED				SCHEDULE OF WORKS	466719
01	29/06/00	DRAFT FOR CLIENT REVIEW				LOCALITY PLAN	466717
		REVISIONS				REFERENCES	

ELEVATIONS – TO AUSTRALIAN HEIGHT DATUM
DATE OF SURVEY – MAY 1998

SCALES
HORIZONTAL: 25 0 50 100 150 200 250 300 350
VERTICAL: 0.25 0 1 2 3 3.5

DRAWING STATUS: CONSTRUCTION

SMEC — GOULBURN MURRAY WATER

DESIGNED	M. LETIZIA	26/02/02
CHECKED	S. ROACH	26/02/02
PROJECT DIRECTOR	G. McALIECE	26/02/02
DRAWN	G. NEWTON	26/02/02
CHECKED	M. BILNEY	26/02/02
ASSETS ENGINEER (TATURA)	R. PLUNKETT	

CENTRAL GOULBURN IRRIGATION AREA

C.G. No. 2/24/8 CHANNEL REMODELLING RD 00 – RD 2557

LONGITUDINAL SECTION RD 00 – RD 2557

GMW CORR. NO.	GOULBURN MURRAY RURAL WATER AUTHORITY	SMEC PROJECT / DRAWING No.	SHEET NUMBER	GMW DRAWING No.	REVISION
1999/3481/1	40 CASEY STREET (PO BOX 165), TATURA VIC. 3616 Telephone (03) 5833 5500 Fax (03) 5833 5501	44021 / 00687	8 of 10	466718	A

PLANRIGHT CAD NAME: W2774_LS_2-24-8