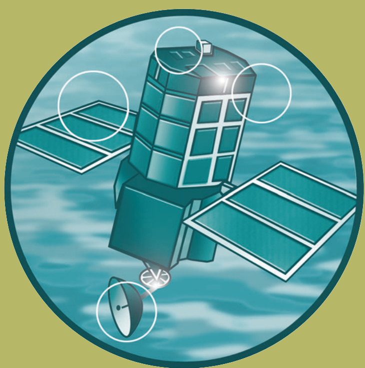
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Management of Flood Embankments

A good practice review

R&D Technical Report FD2411/TR1



Environment Agency

defra
Department for Environment Food and Rural Affairs

Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Management of flood embankments

A good practice review

R&D Technical Report FD2411/TR1

November 2007

M. Morris, M. Dyer and P. Smith

Statement of use
This document provides guidance on good practice relating to management of flood embankments. This is focussed primarily on reducing the risk of embankment failure under extreme conditions. The guide is intended for use by Defra and Environment Agency staff, as well as consultants, contractors and other Agencies and organisations involved in the day to day design, construction, management and operation of flood embankments.

The Guide is intended to act as an index for good practice, particularly to provide the non-specialist engineer or technician with an overview of practice, and to help them to understand the broad areas in which specialist advice is needed. It does not reproduce specific, detailed guidance that has been published elsewhere, and it should not be regarded as a definitive asset management manual.

Dissemination status
Internal: Released Internally
External: Released to Public Domain

Keywords
Flood embankments (or levees), asset management, flood risk management, risk assessment, embankment performance, good practice, geotechnics

Research contractor
HR Wallingford
Howbery Park, Wallingford, Oxfordshire, OX10 8BA, www.hrwallingford.co.uk
Project manager: Mark Morris
Email: m.morris@hrwallingford.co.uk

Defra project officer
Dr Mervyn Bramley, Advisor to Sustainable Asset Management Theme
Email: mervyn.bramley@blueyonder.co.uk

Publishing organisation
Department for Environment, Food and Rural Affairs
Flood Management Division,
Ergon House,
Horseferry Road
London SW1P 2AL

Tel: 020 7238 3000 Fax: 020 7238 6187 www.defra.gov.uk/environ/fcd

Published by the Department for Environment, Food and Rural Affairs (November 2007). Printed on material that contains a minimum of 100% recycled fibre for uncoated paper and 75% recycled fibre for coated paper.

PB No. 12171

Acknowledgements

The authors wish to record the contributions of the following individuals, and in particular their collective effort in drawing together the different strands of scientific knowledge, research results, good practice and site-specific experience that were found.

Core project team

Mervyn Bramley	Defra / Environment Agency (Project Manager)
Mark Dyer	Geotechnical specialist, University of Durham (now at University of Strathclyde)
John Falkingham	Independent geotechnical consultant
Mark Morris	HR Wallingford (Contractor Project Manager)
Jonathan Simm	HR Wallingford (Contractor Project Director)
Philip Smith	Geotechnical director, Haskoning UK Ltd

User representatives

James Galsworthy	Environment Agency - Wales
Jackie Banks	Technical Manager - Flood Defence Operations
Susan O'Neill	Environment Agency – North East Region
Mark Davies	Environment Agency – Wales
Michael Mawdesley	University of Nottingham, Centre for Infrastructure
Matt Crossman	Defra Flood Management
John Garrod	EA Water Management Asset Manager
Rod Bridle	Independent geotechnical consultant
Tony Butcher	Building Research Establishment, Geotechnical Group

Context of this report

Project FD2411 on “Reducing the risk of embankment failure in extreme conditions” was carried out for the purposes stated in Section 1.1. This good practice review was originally completed in 2004. This published version was edited in 2006 in line with the performance and risk based approach to Flood Risk Management (which the review espoused) that had since been implemented by the Environment Agency for Flood Risk Management.

Executive summary

Background and issues

Coastal and river flood embankments are used to protect people, property and the environment from high flood and storm water levels. They are the principal type of infrastructure (asset) used by Operating Authorities for flood management in England and Wales, and their effective performance during flood events is critical for the provision of sustainable flood risk management.

The existing asset base of flood embankments (around 7500km) has been built up over the last 500 years as flood defence infrastructure has been extended and raised to protect both urban and rural development. Flood embankments are usually built from locally available soils and gravels, and were not generally built to high standards of construction (compaction and water tightness) until the last century.

The effectiveness of a flood embankment can reduce over time for three main reasons:

- their loading either is or becomes more than they were designed for, or have historically managed, to withstand
- a higher standard of protection (e.g. frequency of overtopping) is required or some other functional requirement (e.g. crest width for access) has changed
- their materials have deteriorated over time from their intended condition

The situation under a changing climate where both deterioration and increased loading could be taking place is of particular concern.

Research programme

Against this background, Operating Authorities need a systematic process for identifying the critical issues and management actions required to ensure adequate performance of flood embankments. As little guidance existed on this, the Engineering Theme has undertaken R&D project FD2411 on *Reducing the risks of embankment failure under extreme conditions*.

The project has reviewed current knowledge and practice; identified needs and opportunities; and defined a structure (framework; processes; guidance) for future design and management of embankments, plus appropriate further research. In keeping with Government policy and the Environment Agency's *Strategy for Flood Risk Management,* the study has adopted an approach that encompasses risk, performance and whole-life costs.

The study concluded that to achieve consistent standards of management of flood embankments, and also to raise these standards to optimise their performance, require (a) better understanding and application of good practice, and (b) a range of research actions. The project has therefore reported in two principal documents:

Report 1 (this document) sets out a framework for embankment management along with a review of good practice for embankments. This has four separate (but cross-referenced) parts: A - Function and management of flood embankments; B - Performance and characterisation of flood embankments; C - Risk and risk management; and D - Good practice reference. It is written for use as guidance by flood risk management practitioners.

Report 2 identifies research actions aimed at improving the knowledge, tools and techniques available for management of flood embankments. This further programme is now underway.

Management framework

A logical asset management framework is set out for flood embankments. It takes account of their functional objectives (flood protection; Health & Safety; access etc.) and required performance, and establishes management action within an "embankment management cycle" (Figure A3.2). The starting point for effective management is a clear understanding of (a) performance requirements (or specification); and (b) the state of the flood embankment.

The steps in the management cycle are: monitoring of the state and performance of the flood embankment; condition assessment; performance assessment; identification and justification for management action; and design and implementation of works. This is consistent with the generic management cycle of "establish objectives; plan; act; check".

Performance and monitoring of flood embankments

The factors that affect the performance of flood embankments, and their potential failure under extreme events, can be complex. They may be built on low strength, permeable or compressible foundations; the strength and water tightness of material in the body of the embankment may be inherently weak or affected by animal burrows or soil deterioration.

Common hazards or causes of failure are (a) zones of weak or highly permeable material causing slippage or seepage; (b) reduction of crest level and standard of protection due to settlement or the crest being worn away in places causing overtopping; and (c) local seepage paths at junctions with other structures. Because flood embankments are rarely subject to their full loading, these "weakest links in the chain" can go undetected unless there is good monitoring and condition assessment.

The geotechnical characteristics and behaviour of the embankment and its foundations are key factors affecting performance. An improved guide to field monitoring and inspection has been produced (Table B2.1). This links geotechnical hazards with different modes of failure, and indicates potential "performance features" and further investigations in the field.

Risk-based approach

A risk and system-based approach to the management of flood embankments should be followed, particularly for prioritisation of action. This can be in line with the development of flood risk and asset systems management within the Environment Agency. It should take account of the risks attributable to the particular flood embankment within its fluvial or coastal defence system, potential failure mechanisms, and the consequences of failure. This is summarised in Part C.

Assessment, design and management action

The assessment of existing flood embankments, the design of improvements or of completely new embankments, and the specification of management action all needs to be done in a manner that takes account of good practice and utilises appropriate specialist skills. Part D provides a reference to current good practice in each main area of embankment performance.

Contents

Tables

Boxes

Figures

Plates

PART A:

FUNCTION AND MANAGEMENT OF FLOOD EMBANKMENTS

A1 INTRODUCTION

A1.1 General

There are around 7500km of coastal and river flood embankments in England and Wales. Effective performance of these embankments during extreme flood events is critical for the provision of sustainable flood risk management.

Embankments can become less effective over a period of time for a number of reasons including:

- They experience greater loading than they have been designed for or have historically managed to withstand
- The required standard of service or some other functional requirement has changed
- They have deteriorated from their intended condition - as constructed or maintained

The tendency for the performance of earth embankments to deteriorate with time is of particular concern when considering the increasing loading that will continue to be placed on defences as a result of climate change, and the increasing rate of occurrence of extreme events.

Ensuring that flood embankments are designed and maintained to achieve optimum performance requires that the design and management of these embankments is considered within an appropriate asset management framework. This report is one of two documents that provide an overview and guidance towards achieving this approach.

Report 1: Provides an overview of the proposed embankment management framework and its implementation along with a review of good practice for management of flood embankments (this document)

Report 2: Addresses needs and proposes actions for future flood risk management of flood embankments

A1.2 Aims and objectives

The need for improved guidance on the design and management of embankments across coastal and fluvial areas has been established through the Defra/Environment Agency Concerted Action on Operation and Maintenance. This need is supported through experience gained in recent UK flood events. The need to take a risk-based and whole life approach to the management of flood embankments is consistent with the Environment Agency *Strategy for Flood Risk Management (2003-2008)* and its new Incident and Flood Risk Management (IFRM) structure.

The design and management of flood embankments needs to draw on many civil engineering disciplines including hydraulics, geotechnics, survey inspection techniques, modelling and data analysis, and risk management. During the past decade there have been a range of developments, research projects and initiatives from which the operating authorities can learn and develop improved methods to enhance performance.

The aim of this guide is to present an overview of embankment performance issues and guidance on good practice for dealing with the principle aspects of embankment design, operation and management. It does not offer detailed guidance on specific methods and practice, but rather a compendium of good practice through which practitioners may identify realistically achievable improvements, and move towards ensuring that consistent standards and approach are achieved.

To achieve consistency, and also to raise standards to provide maximum performance from flood embankments will require a range of initiatives in addition to adoption of the good practice, as presented within this guide. Ongoing and future initiatives are discussed in the separate project report on Framework for Action under FD2411.

A1.3 Scope and users of the guide

This guide applies to a wide range of flood defence embankments. It covers all types of fluvial and coastal embankment, but does not include revetments or sea / river walls where the defence structure is predominantly constructed from rigid concrete, steel or masonry with a minor or residual earth core. Stone breakwaters or mounds are also not included.

The technical content of the information provided is aimed at individuals within the flood risk management industry who are responsible for managing or inspecting flood embankments. It is assumed that readers will have an awareness of basic flood management issues but not necessarily technical knowledge of design and construction processes.

Separate parts of the guide cover an overview of the Function and Management of Flood Embankments (Part A), Performance and Characterisation of Flood Embankments (Part B), Risk and Risk Management (Part C) and Good Practice Reference (Part D). The good practice reference informs the reader of the current state of knowledge and practice in a particular area and provides references to relevant sources of detailed guidance. Where guidance is limited and / or expert judgement is required to assess or manage the situation, guidance is offered on the likely severity of the issue and hence the degree of expertise required to deal with it.

This document does not attempt to reproduce detailed best practice guidance, but rather acts as a reference to it in order to highlight the elements of embankment design which are considered to be essential.

A2 FUNCTION AND FORM OF FLOOD EMBANKMENTS

A2.1 General

In order to manage flood management systems to achieve optimum performance, it is important to understand the nature and potential variability of typical flood embankments. This section introduces the generic components of a flood embankment and reviews how these may vary from site to site.

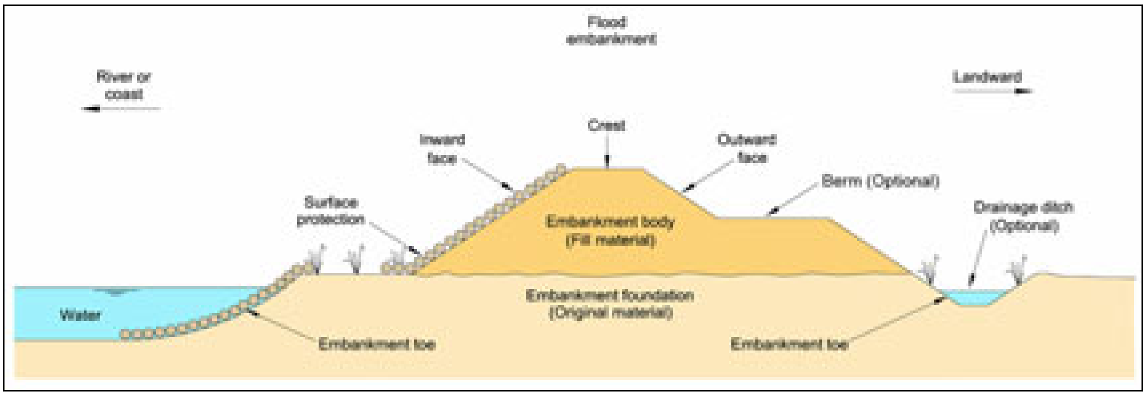


Figure A2.1 Typical features of a flood embankment

Figure A2.1 introduces some typical features of a flood embankment. These include:

<u>Embankment body</u>
The main embankment structure providing the mass obstruction against flood water.

<u>Toe of embankment</u>
The bottom of either the outward or inward embankment faces.

<u>Inward face</u>
The embankment face exposed directly to water to varying degrees.

<u>Outward face</u>
The embankment face on the landward side and hence not normally exposed directly to water, except under overtopping conditions.

<u>Embankment crest</u>
The top of the embankment. Typically flat and (ideally) several metres wide for safe access.

<u>Berm</u>
Horizontal addition to basic trapezoidal cross-section to provide additional soil mass or for access. Generally on landward side.

Surface protection
Sometimes termed ‘revetment’. A protective layer covering part or all of any embankment face. The protective layer may be natural (e.g. grass), manmade (e.g. concrete) or a combination of different materials.

Drainage ditch
Also known as ‘soke’ ditch or ‘delph’ ditch, they are typically found close to the outward toe of the embankment to drain any seepage and control water levels through the embankment. Larger ‘delph’ ditches may exist as a result of borrow areas used for embankment construction (i.e. embankment material taken directly from the ground behind the bank).

A2.2 Principal function and forms of flood embankment

There are a variety of situations in which a flood embankment may perform its principal function of Flood Defence. These are in (a) fluvial and (b) coastal Flood Defence. The role of the embankment in reservoirs for use in flood attenuation should also be recognised (see Box A2.1).

The issue of embankment size is not addressed specifically under each of the chapters. It has been assumed that for each case, the embankment size is taken as ‘fit for purpose’. This means that an embankment may range in size from perhaps 0.5m up to 5 to 10m or even higher. Whilst loading conditions on the embankment will change with size (i.e. water pressure etc.), the key embankment performance issues remain similar.

This section reviews the function, and different ways in which flood embankments are typically used for fluvial, reservoir and coastal defences.

A2.2.1 Fluvial flood defence

The purpose of flood embankments is to constrain and direct the passage of floodwater along a river valley or water course.

River channel
Where the in-bank carrying capacity of a river channel has been enhanced through the construction of flood embankments along both banks.

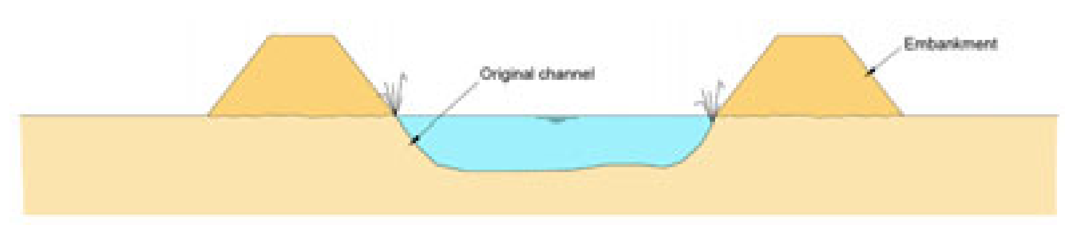


Figure A2.2 River channel embankment

Plate A2.1 River channel embankment

<u>Two-stage channel</u>

Where the flood capacity of a river channel has been enhanced through the construction of flood embankments along both banks, but at least one of the embankments has been set back from the river channel to incorporate part of the floodplain. During flood conditions water will flow along both the river channel and the contained section of floodplain. This offers the advantage of increased flood carrying capacity whilst allowing secondary use of the floodplain (e.g. farming, recreation etc) and maintaining normal flow within the defined channel.

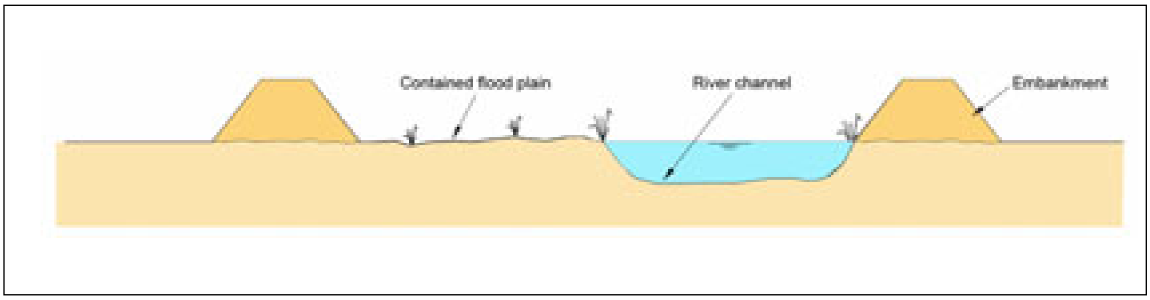


Figure A2.3 Two-stage channel

Plate A2.2 Two-stage channel

<u>Perched channel</u>

Where the flood capacity of a river channel has been enhanced through the construction of flood embankments along both banks, but the river channel and / or water level typically remains higher than local ground level. This occurs where river channels and flood embankments have been progressively raised over long periods and / or ground levels have dropped – as is typical in the Fens in East Anglia through consolidation of peat.

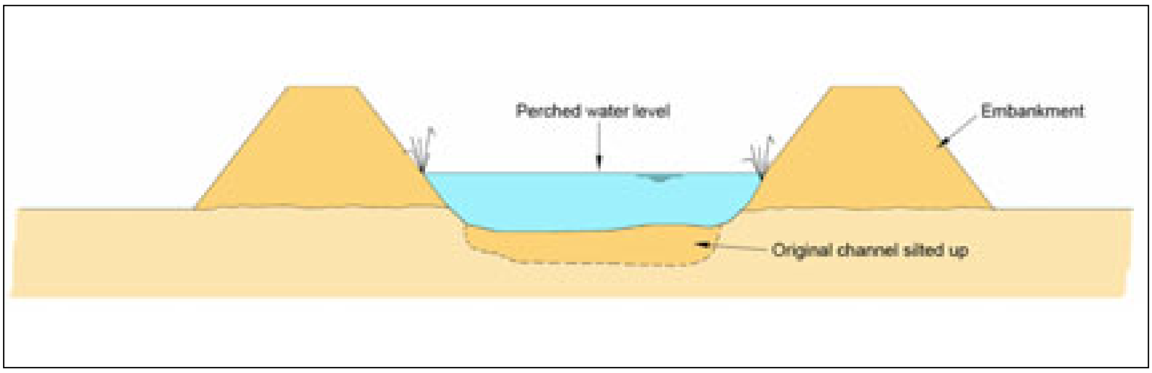


Figure A2.4 Perched channel

Setback or secondary (retired) defences

Flood embankments may be located a significant distance away from the river channel. This can occur intentionally, when the floodplain is very large and primary defences close to the channel are known to overtop, or unintentionally where the river may have meandered significantly over the years and earlier defences are left remote from the current position of the river. In addition, flood embankments may also have been constructed to control and regulate flood water on the floodplain.

Where additional embankments have been constructed, it can become difficult to determine the true flood defence line since it may not be immediately obvious which embankments are the current robust line and which are not.

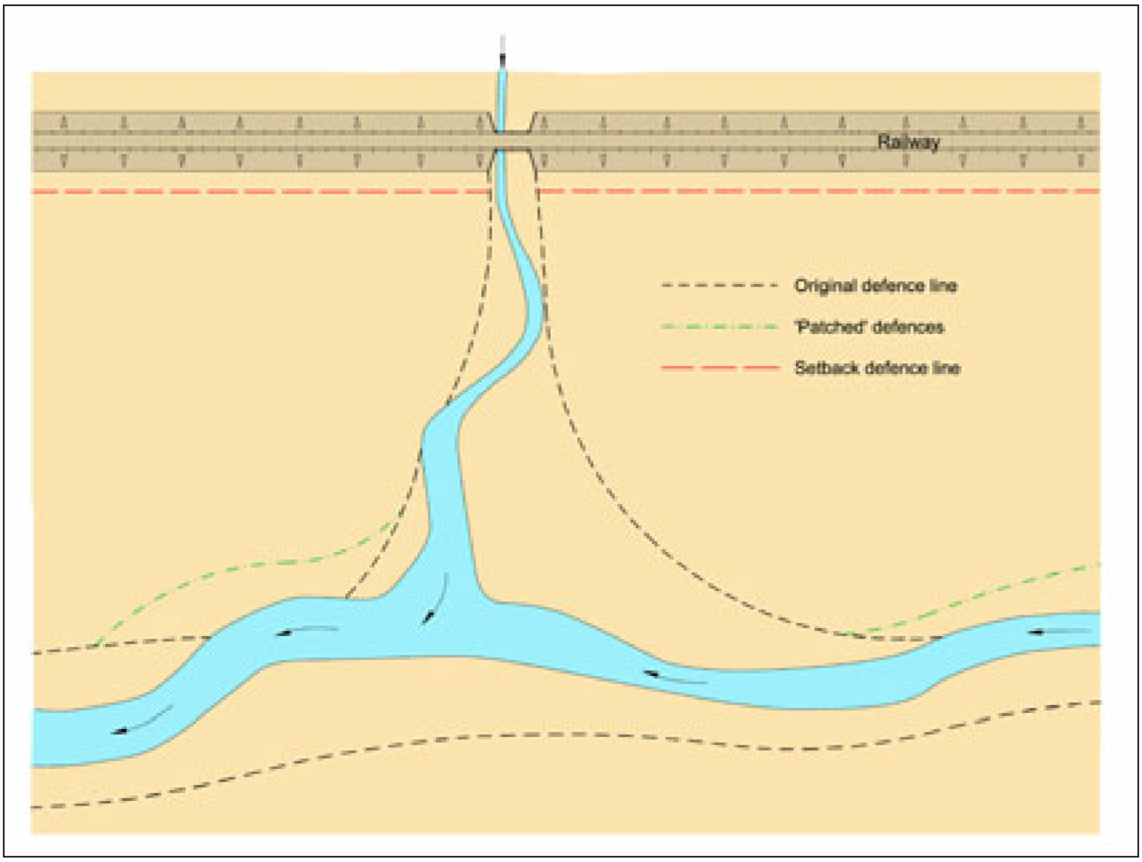


Figure A2.5 Defences set back from the main river channel

Plate A2.3 Flood embankment in front garden of house

A2.2.2 Reservoirs

Reservoirs may be constructed for a number, or combination, of reasons including flood attenuation, water supply, recreation and power generation. Reservoirs are created by retaining water behind an impermeable barrier of some type. This function is no different to that performed by a flood embankment and the transition from fluvial flood embankment to embankment dam can be gradual. Between the two extremes (i.e. 0.5m flood embankment to a 30m high embankment) are storage ponds holding water for farmland, ponds, ornamental lakes, boating lakes etc. Also, some reservoirs only operate during extreme flood conditions, since they are designed to retain floodwater during an extreme event in order to prevent worse flood conditions further downstream. During dry or normal conditions these reservoirs may store no water at all, and are often referred to as washland reservoirs.

<u>Flood detention reservoirs</u>
A method for controlling (attenuating) floodwater passing along a river valley is to restrict the passage of the floodwater and store the excess water. The storage area is often created through the use of flood embankments. Such storage areas may be a metre or several metres deep, but only used during flood events.

Flood detention reservoirs are therefore normally empty for long periods. There are two normal locations for a detention reservoir to contain river flooding: (1) on the line of the river with a dam across the river, or (2) off-line with a bunded basin adjacent to the river. Some of the latter types of reservoir have the outlet controlled by manually operated penstocks to release floodwater.

Flood detention reservoirs have a low-level culvert, which is permanently open and through which low river flows discharge. In the event of a large storm the reservoir fills, as the inflow exceeds the outflow. Water eventually may discharge over a spillway near the crest of the reservoir. These structures are designed to retain water temporarily, and their failure could result in uncontrolled escapes of water. Thus they are considered to be within the ambit of the Reservoirs Act 1975.

It has been argued that, since Statutory Instrument (SI) 1985 No 177 (ICE, 2000) indicates that the reservoir capacity excludes any provision for flood storage, a flood retention reservoir should not be included in the Act. However, the SI makes the exclusion in the context of reservoir overflows, not of reservoir purpose. This argument is, therefore, considered unlikely to be sustainable if put to legal test, although there is no known case on the matter. Since flood retention reservoirs, just as any other large raised reservoirs, can prove a hazard to public safety, they should be regarded as falling within the ambit of the Act.

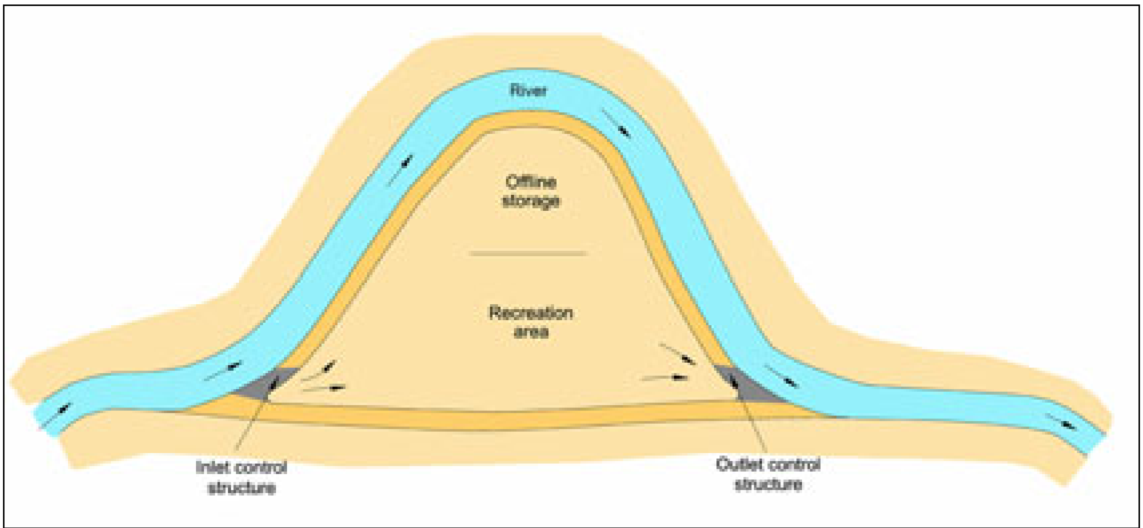


Figure A2.6 Flood retention scheme (offline)

At the extremes there are clearly differences in construction between these different types of reservoir embankment to cope with increased loads and risks, however their function remains identical – to retain a body of water behind the embankment and to pass design floods safely over the spillways. It should be noted, however, that different legislation applies to embankments that retain over 25,000m^3 of water. These fall under the ambit of the Reservoirs Act 1975 and are defined as 'large raised reservoirs'. As such, the Undertaker (Owner) has certain statutory duties placed on him, in respect of safety, with which he must comply. See Box A2.1 for more information.

Plate A2.4 Reservoir embankment

Plate A2.5 Embankment dam (bunded reservoir)

Box A2.1 Reservoir safety legislation

Any structure retaining more that 25,000m^3 of water above the local land level falls within the Reservoirs Act 1975. This requires the owner to undertake certain steps to ensure appropriate maintenance and upkeep of the reservoir, based upon the risk to life posed by possible failure of the embankment. At minimum, a qualified dam engineer (a 'Panel Engineer') must inspect the reservoir at least once every 10 years with continual monitoring carried out by an appointed Supervising Engineer. The Environment Agency is responsible for enforcement of these regulations.

ⓘGood practice

For more information on how to comply with the Reservoirs Act see:

ICE 1996. Floods and reservoir safety. 3rd Edition. Institution of Civil Engineers. ISBN: 0 7277 2503 3

ICE 2000. A guide to the reservoirs act 1975. Institution of Civil Engineers. ISBN: 0 7277 2851 2

Canals, rivers and tidal areas

The Reservoirs Act states that a canal or inland navigation is not included in the Act. It is generally accepted that structures such as weirs in rivers designed to retain water within the normal river banks are not covered by the Act. Marine Sea Defences (protecting the land from inundation by the sea) are also not covered by the Act.

River embankments that are constructed close to the river to limit flooding are not considered to be included in the Act. However, where an extensive washland area is provided with an embankment remote from the river, it is likely that this embankment will fall within the ambit of the Act.

Judgement is required by all involved in this decision as there is currently no case law established through the courts to provide definitive guidance.

Plate A2.6 Offline flood retention scheme

Plate A2.7 Control structure linking offline storage to main river

Box A2.2 Function of embankments within flood management systems

It is important to understand the full role of an embankment at all possible stages of flood management.

The principal function of the embankment will always be to protect land from inundation; however the role of the embankment within a flood management system may not be immediately obvious when on site. The embankment may defend land immediately adjacent, but may also prevent floodwater from bypassing a line of defences, and consequently protect significantly greater areas remote from the embankment itself. The risk associated with failure of the embankment may not therefore be immediately obvious and should be established when considering how the embankment and its related asset system may be designed, constructed, maintained or operated.

The focus of this guide is upon the 'immediate' performance of flood embankments. Further consideration is given to the role and assessment of flood embankments within larger asset systems in Chapter A4, and more specifically Box A4.1.

A2.2.3 Coastal flood defence

The objective of any coastal flood embankment is to moderate wave overtopping. Implicit in any practical design will be the use of a number of different (acceptable) levels of overtopping.

Along exposed coastlines, flood embankments often act as the primary defence at the top of any beach area, protecting against tidal inundation of the coastal plain. The embankment will act as part of an asset risk management system together with the beach and any beach control measures. The main causes of damage to the asset system are usually driven by wave action, although once the system is breached, flooding itself will be driven primarily by tide levels.

<u>Exposed coast</u>
Where the embankment acts as the primary defence at the top of any beach area, protecting against tidal inundation of the coastal plain.

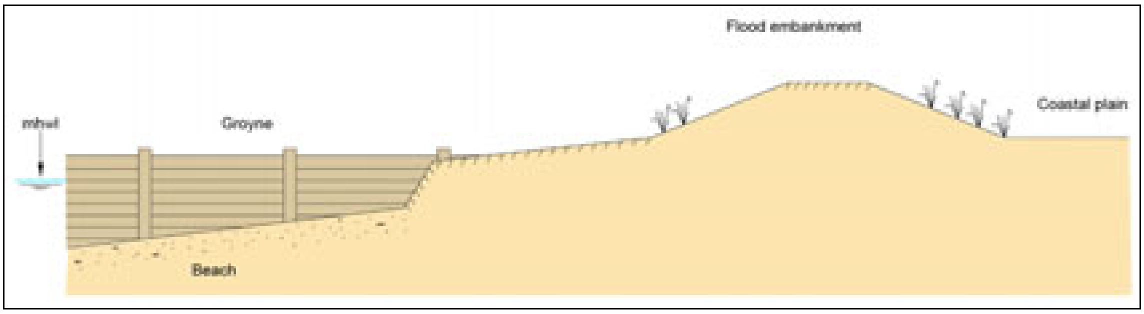


Figure A2.7 Coastal flood embankment

Plate A2.8 Coastal flood embankment (rock protection plus shingle bank on inward face)

Plate A2.9 Coastal flood embankment (with extended wall set in crest)

<u>Estuary</u>
Where the embankment protects against inundation from both a river and the sea. Flood levels may originate from either fluvial or tidal events, water quality may be fresh or saline and wave action may or may not be relevant. For such an embankment constructed close to the estuary channel, the variation in flood water level and hence height of embankment can be considerable.

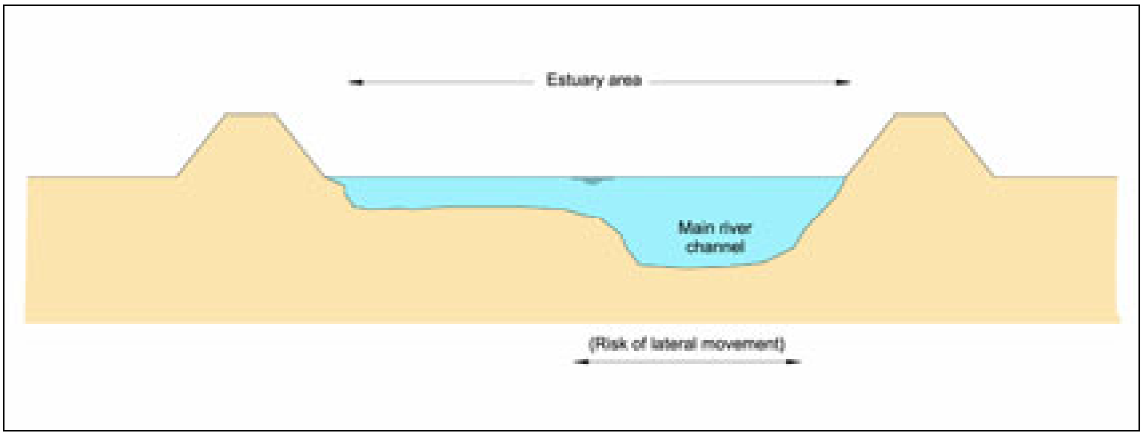


Figure A2.8 Estuary flood embankment

Plate A2.10 Estuary flood embankment (with crest eroded by pedestrian access)

Characteristics of river estuaries (and hence issues relating to embankment performance) vary depending upon the tidal range, flow conditions, ecology and type of bed materials. Some estuaries are stable, with deep water – even during low tide. Other estuaries may be morphologically active, with sediments moving down the river, dropping in the estuary and causing the mouth of the river to move. One bank will accrete whilst the other erodes. This clearly has implications for the stability of flood embankments.

Where a high tidal range creates large expanses of saltmarsh, mud or sand, the river flow typically establishes a main channel through the flats. This channel can move significantly from year to year, such as occurs in the Severn Estuary. Here lateral movement of the flow channel causes significant erosion of parts of the river bank (up to 10m per year) which in turn can quickly undermine flood embankments (Plate A2.11). In addition, a high tidal range entails daily movement of large volumes of water along both the main river channel and any side channels, streams etc. This frequent wetting and flushing of river channels can remove sediment and destabilise embankments (Plates A2.12, A2.13).

Plate A2.11 Rapid bank erosion, leading to undermining of defences

Plate A2.12 Bank instability in estuary area with high tidal range (stone placed as protection; cut off constructed to prevent progression)

Plate A2.13 Bank instability in estuary area with high tidal range

Saltmarshes are a common feature in some estuaries around the UK. Not only do these provide a valuable wildlife habitat, but they also act to minimise wave action against coastal defences constructed behind the saltmarshes. However, increasing tide levels is resulting in a loss of saltmarsh and increasing exposure of such coastal defences.

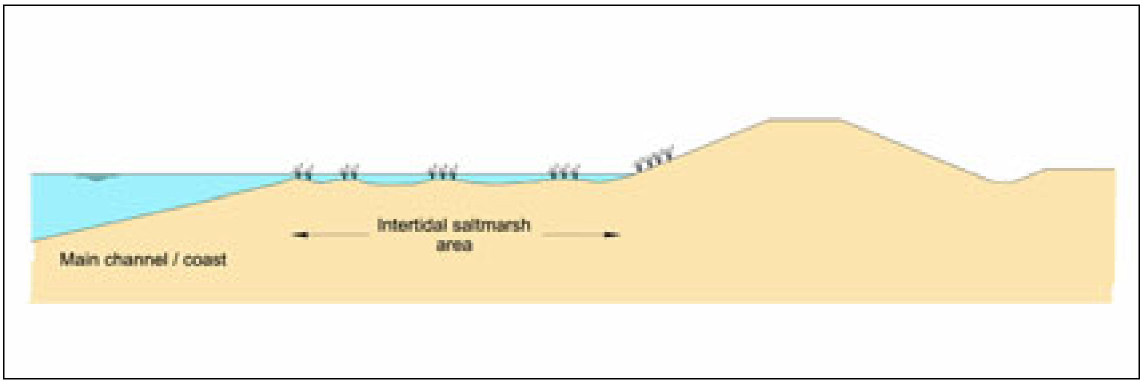


Figure A2.9 Estuary flood embankment behind saltmarsh

Plate A2.14 Estuary flood embankment behind saltmarsh

A2.3 Secondary functions of flood embankments

In addition to the principal function of flood risk management, the embankment typically also performs a number of secondary functions. These functions vary according to the site specific nature of the embankment but are important aspects of asset management that need to be considered both at the design stage as well as during operation. Integration of a number of secondary functions of a flood embankment can make the difference between the acceptance or rejection of a proposed flood risk management scheme at the planning stage.

The following sections outline a number of potential secondary functions that a flood embankment might perform.

<u>Access</u>
An embankment provides a barrier between a river or the coast and people. From an 'access' perspective, this has a number of effects, including:

- All access to the river or coast must be across the embankment
- By constructing the embankment, a linear route for access along the river or coastal frontage is provided which may be preferable to the existing routes

Consideration must, therefore, be given as to how people might legitimately access the river or coast across the embankment without an adverse affect on its performance. How this can be integrated into the design and access enhanced whilst preventing any damage to the embankment and how use can be made of accesses provided for maintenance purposes should be carefully considered.

Consideration must also be given as to how the embankment might encourage wider access and increased use of the area, whether this is advantageous or not and how this might affect the embankment integrity. For example, how will vegetation be affected by large numbers of visitors walking over the embankment?

See Section A2.5 for information relating to structures (such as access ramps, steps etc.) associated with embankments.

Plate A2.15 Ramped access to embankment

<u>Recreation</u>
Embankments provide an elevated point from which to view the river or coast and as such draw people towards them. Different aspects of recreational use of flood embankments include:

- Walking
- Cycling
- Fishing

The embankment provides an interesting, easy access and an elevated route for all of the above activities.

Features such as access routes for crest maintenance and fishing points may be created to enhance the recreational use of embankments. However, care is required to ensure that recreational use does not threaten performance standards for the primary role of flood risk management. For example, excessive use through walking or cycling, and in particular through access onto the embankment, might result in erosion that would create a preferential route for overtopping and potential breaching during an extreme flood event.

Plate A2.16 Recreational use of embankment (access to recreational area)

Plate A2.17 Recreational use of embankment (cycle route)

Plate A2.18 Recreational use of embankment (fishing – note preference for use of damaged embankment area)

Plate A2.19 Recreational use of embankment (small river based marina; access via embankment)

Farming

Use of farmland within the area of flood risk management schemes is common and practicable where land use is limited to grazing animals. The frequency of flooding is typically low (perhaps once every year or few years) and access can be planned so that animals are not trapped by rising floodwater.

Use of embankments for grazing offers both advantages and disadvantages. Managed grazing can be a very effective method for controlling vegetation growth. However, animals can pose a risk to the integrity of an embankment – primarily through surface erosion. Problems that can arise include the creation of paths along and over embankments (particularly by sheep) and the destruction of surface vegetation (erosion protection) by over-grazing or confined use during wet conditions.

Plates A2.20 and A2.21 show examples of this type of damage. Note in Plate A2.20 the collection of debris near the embankment crest within the sheep track. This indicates how the flow of floodwater has concentrated at this point during a recent event, creating a higher risk of breach formation.

Plate A2.20 Sheep tracks across embankment erode surface protection (grass) and create low spot in defence

Plate A2.21 Severe surface erosion and soil damage caused by livestock on the embankment during wet conditions

Services
The use of embankments to provide a route for laying service ducts containing telecom or electric cabling is not recommended. Whilst this is rarely done, embankments have been found with such installations. These pose potential health and safety issues as well as threatening the integrity of the flood embankment.

Environmental
Several aspects come under this general heading including:

Visual impact
An embankment may be designed, both geometrically and in terms of vegetation cover, to blend into surroundings, or to disguise or hide other features of the landscape. In such cases, where practicable, a well-designed embankment can be unobtrusive or not immediately obvious visually.

Noise (reduction) impact
The body of an embankment can absorb noise and hence provide protection against it. Strategically positioned embankments may protect residential areas from river or coastal related noise (e.g. shipping, boats, weirs, sluices etc.).

Encouragement of flora and fauna
Embankments offer the opportunity for the creation of an environmentally friendly habitat. Embankments must be maintained in good condition, hence any habitat that can co-exist with the management requirements for the embankment will be protected by default. Encouraging local flora and fauna will

also help to integrate the embankment into the local environment and hence reduce any visual impact.

Conflicts of interest may occur where embankments pass through designated areas (i.e. SPAs, SSSIs, SAC or RAMSAR sites). In these areas there may be pressure to adopt a restricted cutting regime or periods when work is not allowed at all (e.g. during the nesting season).

Care must be taken, however, to ensure that flora and fauna do not adversely affect the primary flood risk management function of the embankment. For example, burrowing animals can undermine the integrity of the embankment; excessive vegetation can affect the embankment structure by root action, and can also develop bare patches which are prone to erosion. Also, excessive vegetation can make visual inspection difficult.

Plate A2.22 Rabbit hole through outward face of embankment

Plate A2.23 Signs of extensive mole activity in crest of embankment

Plate A2.24 Uncovering a badger set burrowed into coastal embankment

Provision of 'green space' within an urban environment
When constructed through urban areas, embankments (and in particular two stage channels) offer the opportunity to create green space or recreational areas alongside the river or coast. The natural attraction of water enhances the public interest and use of such spaces.

Plate A2.25 Poor vegetation management (plus indications of bank erosion at interface with bridge abutment)

> ⓘ**Good practice**
> Guidance on issues relating to vegetation management is relatively limited. Further discussion along with selected references may be found in Chapter D3.
>
> For an environmental and sustainable approach to construction design, also see:
>
> Masters, N., 2001. Sustainable use of new and recycled material in coastal and fluvial construction – A guidance manual. Thomas Telford, London. ISBN 0727729500

A2.4 Embankments not suitable for flood management

A flood embankment has been constructed specifically to prevent the passage of floodwater. Not all embankments are constructed for this purpose. For example, road and railway embankments are not normally designed to prevent the passage of floodwater and can suffer serious damage if subjected to high flood water levels.

Railway embankments are particularly sensitive to high flood water levels. Many such embankments were constructed over 100 years ago, and were built from a wide range of relatively poor quality material. Seepage through or inundation of railway embankments can lead to erosion or collapse of the embankment and hence settlement of the track. In addition, many pipes, culverts and cattle creeps pass through railway embankments making them ineffective as a flood embankment. If emergency plans suggest the use of a road or railway embankment for flood risk management then extreme caution and careful investigation and planning is advised. Issues that may arise include:

- High seepage flow through embankment with related risk of failure
- Damage to body of embankment leading to settlement of the road or track (incurring high repair costs)
- Difficulty in locating and sealing existing pipes, culverts and openings
- Flood risk to the road or railway line may require closure and hence compensation costs (at least for the railway)

Plate A2.26 Railway embankment acting as partial barrier to flood water

A2.5 Typical structures associated with flood embankments

Structures through or over embankments are critical points to consider when reviewing the overall integrity of an embankment system. Analysis of embankment failure shows that there is a relatively high risk of problems occurring at such structures since they create a discontinuity in the embankment structure and create a focal point for flow concentration at the joint between the soil structure and a harder material. These are particularly prone to erosion during extreme events.

Typical structures associated with embankments include:

- Culverts and outfall structures
- Overflow structures
- Control structures
- Access ramps and steps
- Fencing and stiles
- Property and wall interfaces
- Bridge abutments

When considering each 'discontinuity' created by a structure placed through or over the embankment, it is important to ensure that the standard of protection and service offered by the structure is consistent with that offered by the embankment. A flood management system can be compromised by a single weak point within that system.

Plate A2.27 Failed culvert running through embankment

Culverts and outfall structures

The most common structures associated with flood embankments are drainage culverts and their inlet/outlet arrangements. Culverts can be constructed below or within the body of the embankment and, if in the form of pipes, are usually surrounded with mass concrete. Risks to the integrity of an embankment adjacent to such structures include:

- Seepage/leakage and piping along the soil/concrete structure interface which can create preferential seepage routes leading to settlement/collapse of the surrounding embankment
- Inadequate erosion protection to the base slab and wing walls from flood water or outflow discharges, leading to undercutting and settlement/collapse of the surrounding embankment
- Inlet/outlet structures provide focal points for recreational users leading to surface erosion of the embankment around the structures increasing the risk of failure of the embankment/structure interface
- Poorly designed inlet/outlet structures causing interference with flood flows leading to increased turbulence and erosive forces at the embankment /structure interface

In order to reduce the risks of failure of the embankment adjacent to culverts and outfall structures, their design should incorporate the following:

- A clay or concrete surround to pipe culverts over their entire length together with clay or concrete keys constructed within the embankment and its foundation
- Clay or concrete keys or cut-offs extended into the foundation and surrounding embankment materials to lengthen seepage paths
- Concrete keys or cut-offs provided at the outer edge of outfall base slabs

In addition to the above, extra care should be taken with the construction of the surrounding embankment material to ensure that specified fill and compaction requirements are achieved.

In addition to Plate A2.27, Plates A2.28 and A2.29 show the failure of a culvert through an embankment. Failure was as a result of excessive seepage around the culvert. This developed along the brick / soil interface and was worsened by root action from the nearby tree.

Plate A2.28 Failed culvert running through embankment

Plate A2.29 Failed culvert running through embankment

Plates A2.30 and A2.31 show an outfall structure that has been designed into the slopes of the embankment to minimise disruption to the flow. Some bed protection is provided on the upstream side and flap gates are fitted on the downstream side to avoid back flow through the structure.

Plate A2.30 Outfall structure – outward face

Plate A2.31 Outfall structure – inward face

Plate A2.32 shows an outfall constructed through a tidal embankment. This embankment is not well maintained and the irregularly placed bank protection around the outfall is failing. Note also the grille across the outfall to prevent access and vandalism.

Plate A2.32 Outfall structure – tidal embankment

Plate A2.33 Typical small culvert structure passing through embankment

Plate A2.33 shows a typical small culvert structure passing through an embankment. On long-established embankments, culvert outlets can be obscured by heavy vegetation. If original records have been lost, their inspection may be overlooked.

Plate A2.34 Outfall structure undercut by bank erosion

Plate A2.34 shows the remains of a small outfall structure that has been undermined through bank erosion and slumping.

ⓘPoints to note

Culverts and outfall structures built through and into embankments can create weak points vulnerable to failure.

Key performance issues to note include:

- Has the culvert been provided with a concrete surround and adequate cut-off keys?
- Has the inlet/outlet structure been built with its wall tops protruding into potential flood flows creating the risk of local scour?
- Has the inlet/outlet structure been angled correctly or does it create a disturbance to the flow of water or trap debris?
- Has adequate protection been provided below the structure's base slab or can discharges from the structure, or flood flows, erode material and undercut the structure?

ⓘGood practice

For guidance on the design of culverts and outfall structures, the following documents are recommended:

CIRIA, 1996. Small embankment reservoirs. CIRIA Report 161, ISBN 0860174611
CIRIA, 1997. Culvert design guide. CIRIA Report 168. ISBN 0860174670.

Overflow structures

In some situations, flood embankments are expected to overtop periodically. For example, the standard of defence may be set to a probability of overtopping of 2-4% rather than 1% (i.e. to between a 25 and 50 year return period event, rather than a 100 year event). In these circumstances, undesirable overtopping and risk of damage to specific lengths of embankment may be reduced by controlling and defining the location where overtopping might occur. This is typically done through construction of a length of embankment with a lower crest, and also by providing protection against erosion along this length. Plates A2.35 to A2.38 show an example of such an arrangement where the crest was formed from grass/concrete precast units and the damage that occurred when overtopping took place before protective vegetation could be established on the inward face. Plate A2.35 shows the final structure – note the debris caught on the crest indicating successful recent operation.

Plate A2.35 Embankment overflow structure

Plate A2.36 Overflow during construction

Plate A2.37 Partially completed works after overtopping incident

Plate A2.38 Damage to outward slope of embankment

ⓘPoints to note

By their very nature, overflow structures are designed to pass flow under flood conditions. This means that floodwater may be turbulent and debris laden. Key points to note include:

- Ensure that adequate protection against flow has been designed into the overflow structure. The design should prevent undercutting of the structure at any point, and protection may need to extend some distance beyond the structure
- Ensure that flow downstream of the structure will not erode material creating a headcut process leading back to the structure
- Ensure that appropriate vegetation management is implemented to avoid both damage to the overflow structure and a reduction in spillway capacity

ⓘGood practice

For guidance on the design of overflow structures, the following documents are recommended:

CIRIA, 1987. Design of reinforced grass waterways. CIRIA Report 116
CIRIA, 1996. Small embankment reservoirs. CIRIA Report 161

For guidance on calculating flow over side weir structures:

May R, Bromwich BC, Gasowski Y, Rickard C (2003). Hydraulic design of side weirs. Thomas Telford, London. ISBN 072773167X

Control structures

Control structures are typically constructed across a flow channel and hence may be integrated into flood embankments that run parallel to the channel. Structures may be constructed within the channel, and hence be designed to overtop or drown out at high flows. Whether constructed to control flow up to the same level as flood embankments or not, it is important that adequate consideration has been given to the interface between structure and embankment in order to minimise disturbance to flow and hazard of erosion around the interface.

An adequate cut-off carried down to less impermeable material should be provided below the structure, and also the abutments at each end of the structure should normally be carried past the centre of the flood embankments. Where structures are designed to overtop, protection of the downstream surfaces should be provided to prevent erosion (stone pitching, rock rip-rap, concrete slabs etc).

Plate A2.39 Control structure across entire channel

Plate A2.40 Control structure within flood channel

Access ramps and steps

Where pedestrian or traffic access is required over an embankment, then either ramps or steps may be constructed. Care should be taken to ensure that any such structures do not pose an obstruction to or a concentration of flood flows, which might in turn lead to local erosion of the embankment / structure interface. This is particularly important on the inward face of wave-overtopping embankments where the overtopping flows may concentrate along the face of any obstruction formed.

Figure A2.10 and Plate A2.41 shows ramped access directly over an embankment. These are typically larger constructions, designed for allowing cars and boats to access the river or coast. Consideration should be given as to how the ramp extends into the flood risk area and how this intrusion might focus flood flows, resulting in scour of the ramp and embankment.

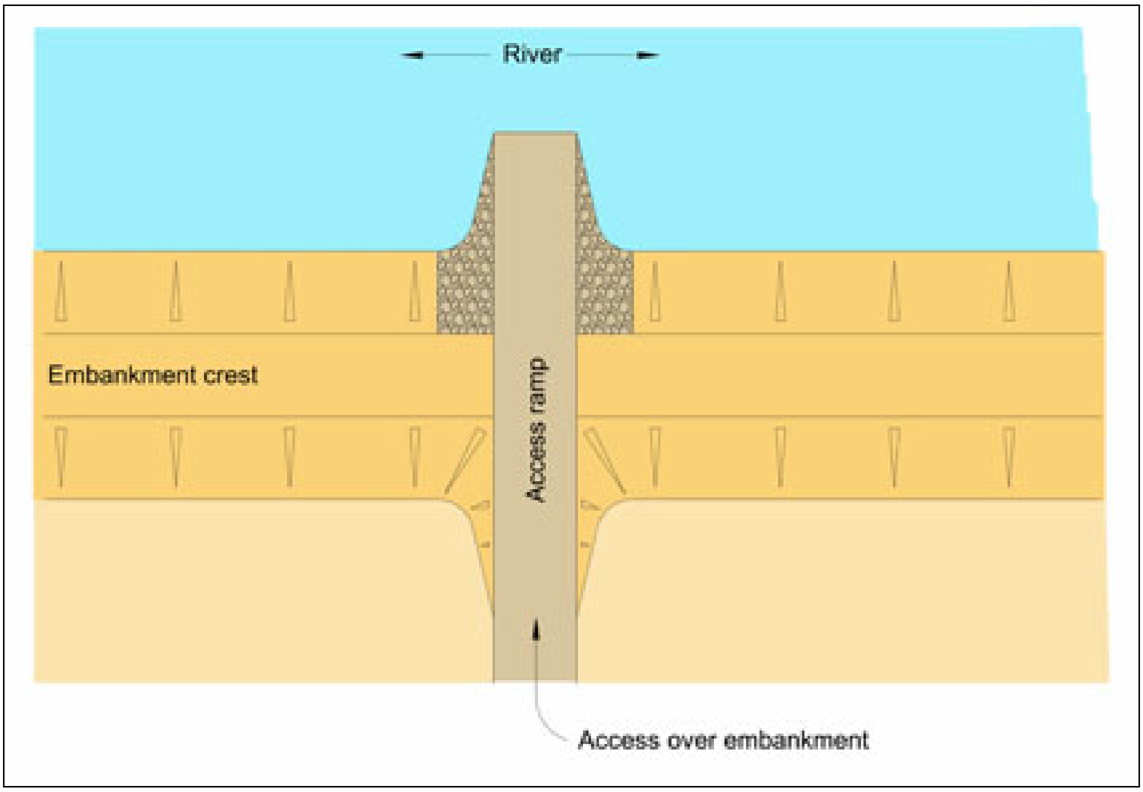


Figure A2.10 Ramped access over embankment

Plate A2.41 Ramped access over embankment

Figure A2.11 and Plate A2.42 show a parallel access ramp onto a flood embankment. These may provide car and boat access where space is limited for construction, but are more often designed for maintenance access. Consideration should be given to the type of vehicle and access that such a ramp permits onto the embankment. Unauthorised vehicle access along earth embankments can cause serious damage to the crest. Access ramps and adjacent crests can be provided with surface protection to prevent vehicle damage.

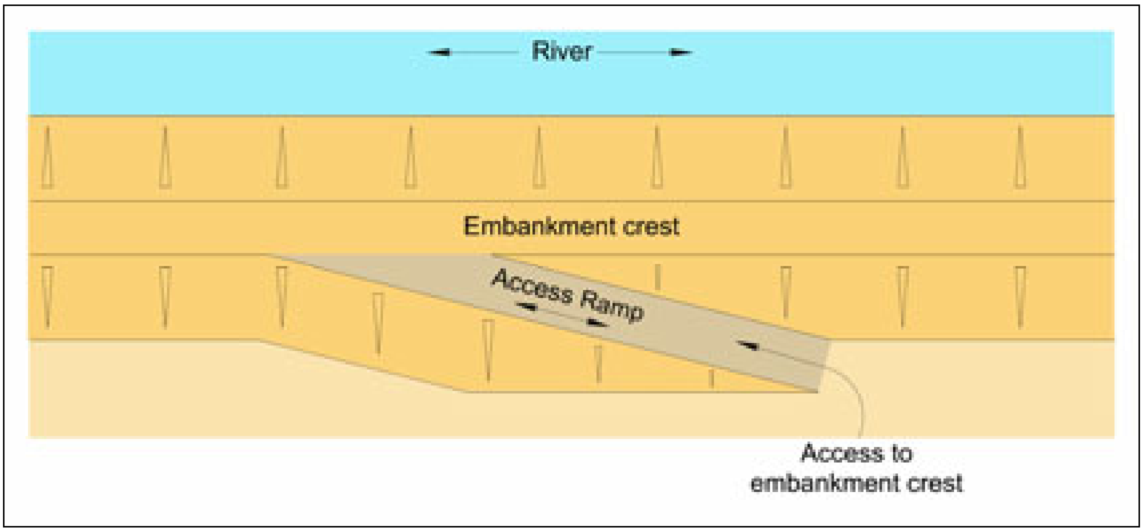


Figure A2.11 Parallel ramp access onto embankment crest

Plate A2.42 Parallel ramp access onto embankment crest

Plate A2.43 Ramped access onto an embankment

Figure A2.12 and Plates A2.44 to A2.48 show stepped access onto flood embankments.

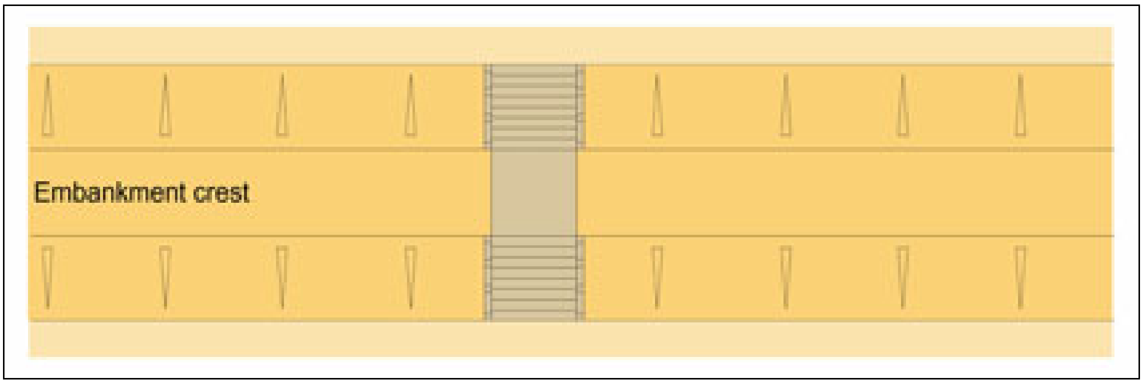


Figure A2.12 Stepped access onto an embankment

Plate A2.44 shows stepped access onto a coastal flood embankment. Note erosion of the crest in all three directions from the top of the steps. Plates A2.46 and A2.47 show stepped access across the inward face of the embankment. On the adjacent far side of the steps in Plate A2.47, cyclists have eroded the bank to form a gully 200-300mm deep. These steps appear to be used as a main route for accessing and leaving the embankment – note the erosion of the crest stops at the top of the steps.

Plate A2.44 Stepped access onto embankment

Plate A2.45 Stepped access on inward face of embankment

Plate A2.46 Stepped access on outward face of embankment

Plate A2.47 Stepped access on outward face of embankment (note erosion of bank adjacent to steps)

Plate A2.48 Stabilising erosion on inward face of embankment (installation of 5 small steps)

Plate A2.48 shows how simple steps have been created to prevent further erosion of the embankment face, caused by walkers climbing the inward face of the embankment.

<u>Fencing and stiles</u>

In many situations, fencing is required to extend across or along embankments. In some situations, these may also include stiles for pedestrian access. Care should be taken to ensure that the design of fencing does not trap debris and pose an obstruction to flood flows, which in turn might lead to local erosion of the embankment. The fence shown at Plate A2.50 is not well designed and has caused large amounts of debris to be trapped thus causing an obstruction to flows. The fence shown in Plate A2.51 will catch debris during higher water level conditions.

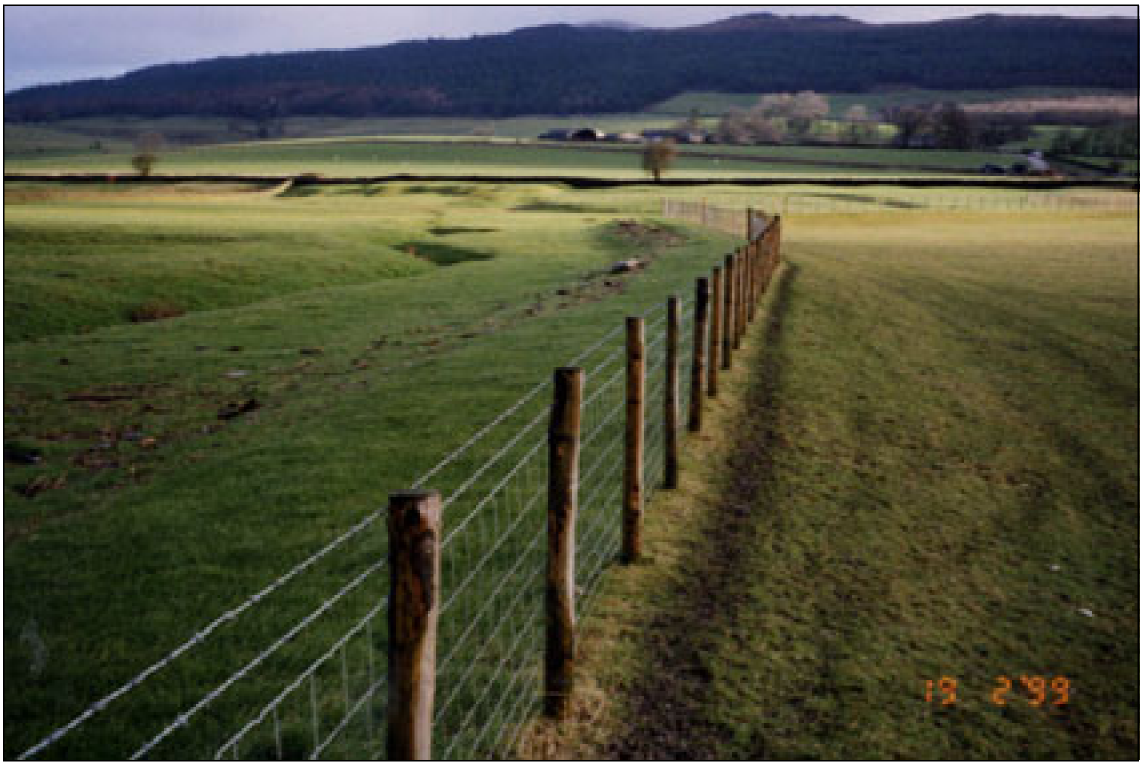


Plate A2.49 Fencing constructed along embankment

Plate A2.50 Fencing constructed across washland spillway

Plate A2.51 Fencing on inward face of embankment

Property and wall interfaces

Where various structures are constructed within embankments, the interfaces provide preferential seepage routes making the risk of piping beneath the structure more likely. It is therefore important to ensure that design details and the provision of cut-offs and keys are carefully considered. Plate A2.52 shows a smooth transition between three defence types:

- Low embankment with blockwork protection and flood defence level raised by addition of a low wall on top of embankment (foreground)
- Larger embankment with blockwork protection
- Embankment with natural vegetation (background)

Plate A2.52 Interface between embankment and solid defences/structures

Where buildings have been constructed close to an embankment, or the embankment is adjacent to or within private property, there is an additional risk that works will be undertaken that may affect the performance of the embankment. The person undertaking this may be unaware of the effect of such actions. Plates A2.53 to A2.56 show examples of such situations.

Plate A2.53 Housing constructed in / on embankment

Plate A2.54 Housing constructed immediately behind embankment; garden extended across the embankment

Plate A2.55 Different standards of vegetation management

Plate A2.56 Embankment constructed within front garden of residential property

Bridge abutments

In some special cases of flood embankments (e.g. high-level carrier drains), it is not unusual for access footbridges to span across the watercourse. The abutments of the bridge will normally be founded on the upper levels of the embankment. The abutments should be designed to cause minimum interference with flood flows and local surface protection of the adjoining embankment areas should be provided. Drainage of the rear faces of the abutments may also be incorporated to prevent high hydrostatic pressure developing.

Plates A2.57 and A2.58 show differing levels of bridge deck in relation to embankment crest. Plate A2.59 shows erosion problems at the transition between an embankment and brickwork leading to a concrete bridge abutment (left of picture). Efforts have been made to prevent further erosion by placing bagging. However erosion has continued to cut behind this protection and poses a threat to embankment integrity. Plate A2.60 illustrates the complex geometry and features that might be found at abutments.

Plate A2.57 Interface between embankment and bridge abutment

Plate A2.58 Interface between embankment and bridge abutment (low soffit railway bridge)

Plate A2.59 Interface between embankment and bridge abutment (note embankment erosion)

Plate A2.60 Typical 'mixed' construction at transition between embankment and bridge abutment

A2.6 Effects of legislation, ownership and third party action on flood embankments

Earlier sections of this chapter describe how the function and form of flood embankments depend upon a number of factors. Whilst the primary function is flood risk management, the form and use of an embankment may be influenced by other physical factors such as vegetation, location, associated structures etc. However, legislation, ownership and direct or indirect action by 'third parties' can also affect the way in which an embankment is constructed, maintained or used and hence its performance.

A2.6.1 Ownership and third party actions

Plates A2.53 to A2.56 show a range of different situations where embankments either fall within, bound or are immediately adjacent to private property. In such situations, there is a tendency for the vegetation to be managed differently. This may be beneficial or detrimental, depending upon the particular approach.

Where the embankment is wholly within a private property, issues of access and right to undertake works may arise. These rights need to be established clearly with the property owner to avoid any misunderstanding.

Third party action may threaten the integrity of an embankment or the ability to access and maintain or repair an embankment. For example, construction of garden features or building works that cut into the main embankment body immediately affect the structure. This may also limit or prevent access along the embankment. Such actions may be undertaken by a third party in full knowledge or complete ignorance of the problems that may be generated. Ensuring that the third party is aware of the function of the embankment and any requirements for access and maintenance is the first step to avoiding such problems.

A2.6.2 Legislation

Legislation can affect the way in which an embankment may be constructed or maintained. Whether the legislation is local or national, regulations may restrict the nature, timing and / or extent of construction or maintenance works. This in turn may affect the way in which desired embankment performance is achieved. For example, regulations protecting flora and fauna may prevent maintenance activities during certain times of the year and limit the extent of any construction work. Tree preservation orders may affect the removal of trees growing in or adjacent to embankments.

A2.7 Summary of key issues under Chapter A2

Summary of key issues under Chapter A2:

- The principal features of a flood embankment have been defined
- The principal function of a flood embankment is to prevent or restrict inundation of land behind the structure from water in front of it
- Flood embankments have secondary functions that include provision of access, recreation and environmental habitats
- Embankments are used for flood management in a wide range of locations and designs. Height may vary from less than a metre up to ten or more metres. Loading may vary from occasional to permanent
- Embankments that create reservoirs storing volumes greater than 25,000m^3 of water are subject to Reservoir Safety legislation. This requires a specific programme of inspections to be undertaken under special supervision
- Embankments typically form part of a larger flood management system. Performance of the embankment should be considered within the asset system management framework
- Structures built through or over embankments can provide a weak point both in terms of a physical interface and in the standard of service and protection that they offer within the overall defence system
- Maintenance, integrity and performance of an embankment may also be affected by both third party action and local or national legislation. Third party actions may be planned, unplanned or through ignorance. Land ownership and proximity of the embankment to private property can help to confuse perceived rights and function

Summary of key questions when considering the performance of an existing embankment:

- Is the embankment crest sufficiently high?
- Is the embankment or its foundations sufficiently impermeable?

- Is the embankment sufficiently resistant to erosion from wave attack, overtopping and overflowing?
- Is the embankment adequate for a navigable waterway (if appropriate)?
- Are structures built through the embankment properly designed to prevent seepage and piping from occurring?
- Does the embankment have secondary functions?

A3 MANAGEMENT FRAMEWORK

A3.1 General

A framework for the management of flood embankments has been developed. This is consistent with the generic Environment Agency asset management framework and the Agency Management System (Figure A3.1).

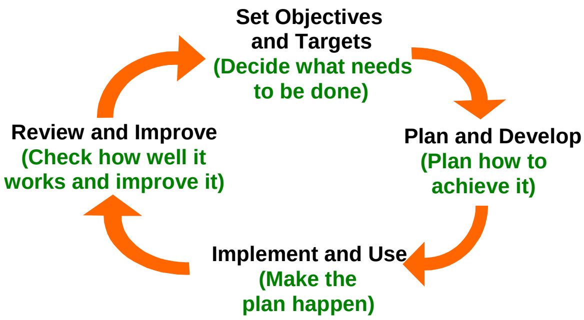


Figure A3.1 Environment Agency 4-stage management process framework

The framework for the management of flood embankments is presented in Figure A3.2. Links to relevant chapters of this report have been shown with each stage of the management framework. The reader may therefore use this diagram to access quickly information relating to a specific stage in the management framework.

Considering each stage of the framework in turn:

A3.2 Objectives

Functional objectives:

Before progressing to stages within the embankment management cycle, it is important to identify first the functional role and objectives of the flood embankment. This is covered in Chapter A2. The primary function of a flood embankment is to prevent or limit the degree or extent of inundation of land behind the defences. An embankment may however have a number of secondary functions that need to be considered including, for example, environmental, recreational, visual impact etc.

Performance objectives and indicators:

In order to define and assess embankment performance, it is first necessary to understand the nature and state of an embankment, and subsequently how this may respond under various load conditions. Features of typical embankments are considered in Chapter B1.

Having reviewed the nature and potential state of the embankment, its potential performance may be considered. This is detailed in Chapter B3. Performance under different scenarios is considered through the Source-Pathway-Receptor

(S-P-R) concept for flooding, and in more detail through Cause-Consequence (C-C) diagrams. Establishing an understanding of potential behaviour then permits identification of any specific inspection requirements, including performance indicators for the embankment and how these indicators relate to information collected during visual and more detailed inspections.

A3.3 Embankment management cycle

Condition assessment
A first stage in the management cycle is to determine the condition of the embankment. Chapter B3 details current and best practice for condition assessment, including tiered assessment techniques, visual, non-intrusive and intrusive techniques.

Performance assessment
Having identified performance objectives and indicators and undertaken a condition assessment, evaluation of embankment performance is simply a comparison of observed against required performance. This is also reviewed under Chapter B3.

The need for management action / identifying preferred option
Having identified the performance of the embankment, and any shortcomings against requirements, the next steps are logically to assess the need for action and subsequently to identify and implement the preferred option. Taking these steps requires an understanding of the shortcomings in performance and the techniques available for rectifying these. Chapter B2 presents a review of the S-P-R and C-C diagrams, and subsequently relates the various issues to the review of current good practice presented under Part D of this document. This chapter provides a quick means of reference for best practice relating to specific aspects of embankment performance.

Design and implementation
Design and implementation of works requires an understanding of both the hydraulic and geotechnical issues affecting performance of the embankment. The design and commissioning process is reviewed in Chapter B4.

Monitoring
Monitoring embankment state and performance completes the management loop. Results from updated monitoring, permits a review of condition, and so the cycle continues. Chapter B3 provides an overview of embankment monitoring with reference to good practice.

A3.4 Future development of the management framework

Improving the performance of flood embankments may be sought through a number of routes. This report presents a management framework and best practice review to promote consistent standards and approaches through the use of existing tools and knowledge. However, the Environment Agency supports the development of improved tools and techniques to enhance the performance of flood risk management assets, as a continuing process. Report

2 introduces the initiatives currently underway and indicates how these are contributing to a common approach to performance-based asset management as well as building upon existing knowledge, practice and data collected in the field.

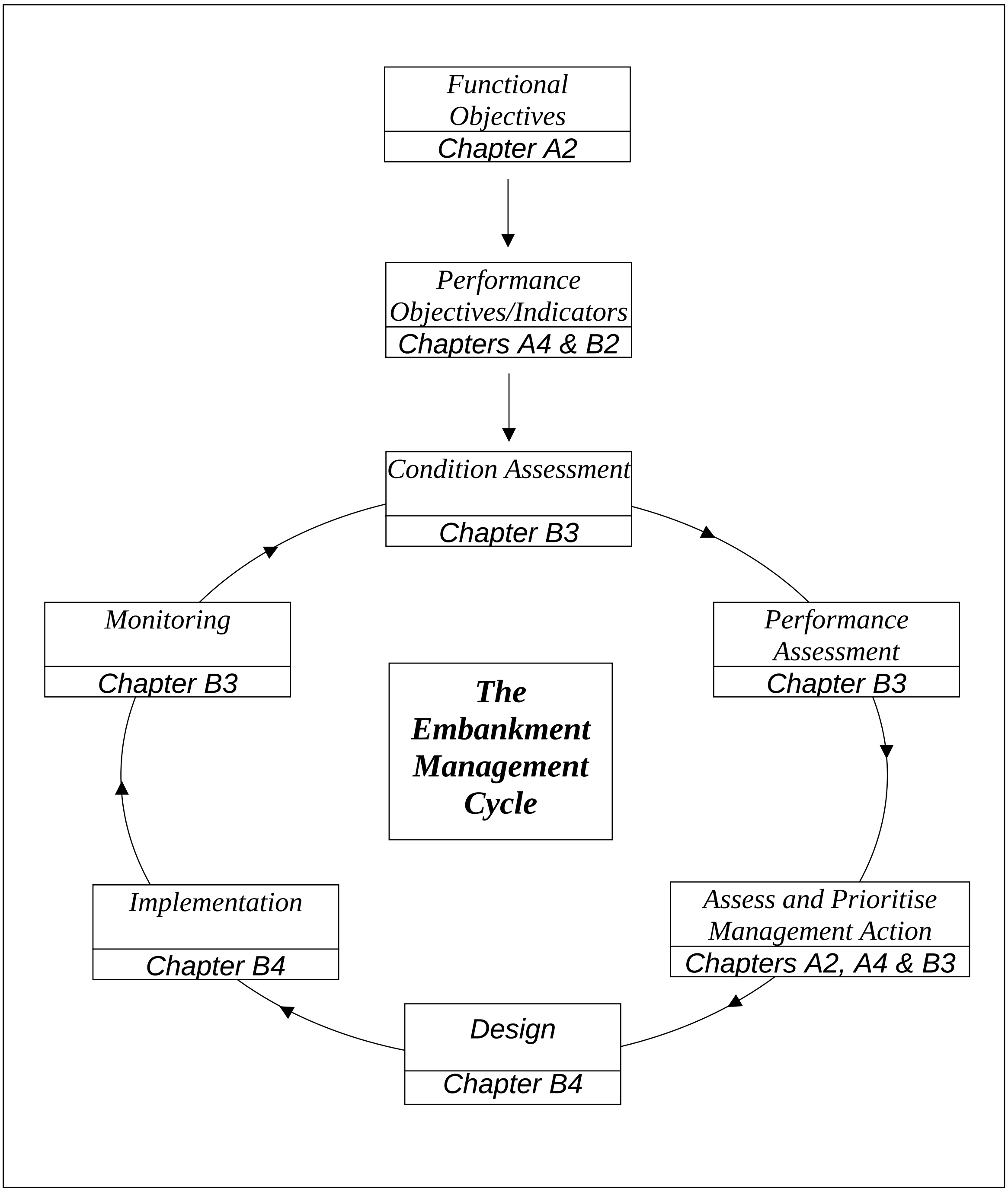


Figure A3.2 Framework for management of flood embankments

A4 RISK, AND PERFORMANCE RELATED TO FLOOD EMBANKMENTS

A4.1 General

Part C of this review summarises the key concepts of risk, performance and whole-life costing that Defra and the Environment Agency have established in order to develop a risk and performance based approach to the management of flood defence assets (e.g. flood embankments) and the systems that they comprise.

This chapter considers how concepts of risk and performance may be applied to flood embankments and the role that they play in the overall performance of flood management systems (typically covering a sub-catchment or coastal unit). Embankment performance is then analysed through the use of Cause-Consequence (see Section B3) and Source-Pathway-Receptor diagrams (see Section C1) to explain the range of ways in which an embankment may respond under varying load conditions.

A4.2 Applying risk concepts to embankments within a flood management system

The concepts of flood risk management and system performance outlined in Part C of this document apply across the board to fluvial and coastal flood management systems. These concepts need to be applied to the management of flood embankments if improved embankment performance and flood risk management approaches are to be achieved. This will be done through the management process shown in Figure A3.2.

The focus of this report is based on adopting a risk based approach to the design and management of flood embankments, with the embankment considered as part of a flood management system. The integrity of the flood embankment and the potential flood risk should be considered for a range of design conditions (i.e. what will happen if the embankment is overtopped in extreme flood events) as distinct from a single deterministic design standard of protection (SOP).

It is not possible to remove flood risk associated with embankments entirely, or indeed any flood management asset. The remaining risk (residual risk) will always need to be considered and where appropriate mitigated through other measures. For example, it may only be practicable to maintain the level of flood embankments to protect against a 1% annual probability event. If the flood risk posed by events greater than this is considered unacceptable, measures such as adaptation of the embankment to accommodate overtopping, use of temporary defences, emergency evacuation plans etc. may necessarily be used in order to reduce the residual risk to an acceptable level. The optimum solution may only emerge by adopting a strategic approach (based on the sub-catchment / coastal unit) as distinct from a localised (e,g, reach-based) approach.

Taking a systems and risk based approach to design and management, all flood management assets must be constructed, operated and maintained to standards that recognises the role of that asset as part of the overall flood management system. This can involve consideration of various overtopping or failure scenarios as illustrated in Box A4.1.

Box A4.1 Example of different design conditions for flood embankments

It is important to consider the overall function of an embankment in all potential circumstances. The function of the embankment within a flood management system, in comparison to its apparent 'local' function, may significantly affect the loading on the embankment and consequently the way in which the embankment should be designed, constructed and maintained.

For example, Figure A4.1 shows a schematic plan of a conurbation constructed across a river meander. Upstream of this, a smaller river joins the main river through the left bank. Both rivers have flood embankments constructed along either side of the channel. Through the conurbation, these embankments are well protected and integrated into the urban development (e.g. the river face is protected by stone and the crest and landward face are concreted to provide a walkway through the urban centre). The tributary upstream is equally protected by flood embankments, but these are earth embankments with grass growing across all faces.

Taking a reach-based approach, you might consider this arrangement to be acceptable. The immediate threat of embankment failure to the urban development (location A) is mitigated through the construction of significant embankment protection measures (stone, concrete etc.). Away from the conurbation, where the risk from flooding is less (location B), the embankments are protected only by grass.

However, considering the overall flood management system, if the embankment at location B were to breach, then floodwater from the main river channel could pass up the tributary channel and through the breach. This could then flood across the floodplain and inundate the conurbation downstream. The integrity of overall flood management system at B then becomes just as important as those at A.

Understanding the role and importance of different parts of a flood management system will be developed through a combination of (a) local knowledge and experience, including asset performance during flood events, and (b) planning and design studies (including catchment or shoreline management planning).

To assist in the adoption of a consistent and rigorous approach to flood risk management, common terminology and approaches are being adopted. A useful concept that underpins all current initiatives is consideration of flood risk in terms of the flood source, pathway and receptor. Figure A4.2 shows how this concept may be applied to a flood embankment. Applying this concept rigorously helps to 'order' the large number of factors that may influence the overall task of flood risk management.

Flood risk management planners and managers will need to consider all the above issues to varying degrees in prioritising limited resources for the construction, maintenance and upgrading of flood management assets (including flood embankments). To support this management process, a number of decision support tools and techniques are being developed which will enhance the way in which embankment performance may be determined and assessed. An introduction to some of these initiatives is given in the following sections.

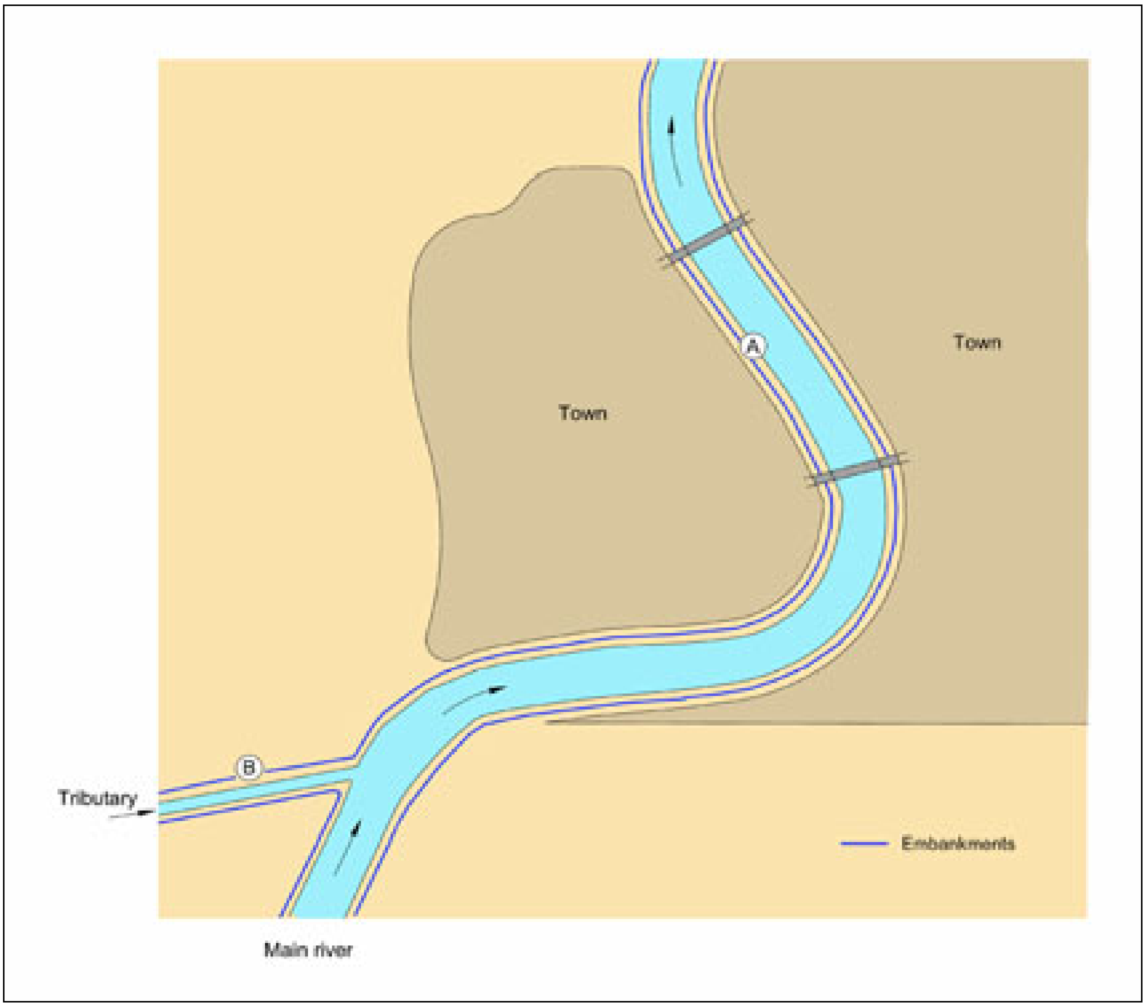


Figure A4.1 Example of flood embankments around town

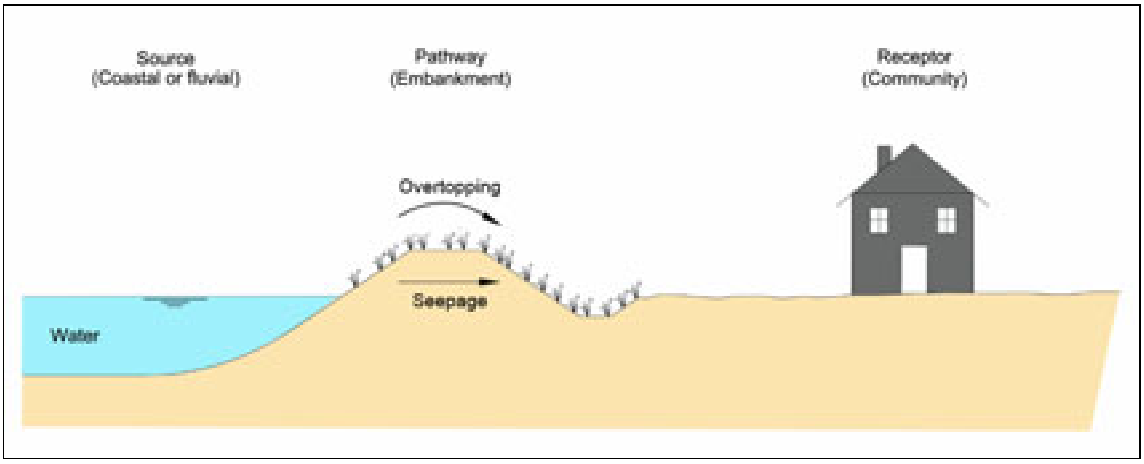


Figure A4.2 Source-Pathway-Receptor representation of flood defence embankment

Plate A4.1 Flood water spreading across floodplain areas via multiple routes

A4.3 Linking risk and performance

As explained in Part C, issues of performance and risk are closely linked. Performance can generally be considered to be the achieving of a desired outcome, and risk to be some measure of the probability and consequence of failing to do so.

Performance can be defined as 'the degree to which a process succeeds when evaluated against some stated aim or objective'.

The concept of performance is applied at the national policy level (e.g. High Level Targets), the strategic planning level (e.g. reduction in properties at risk via Catchment Flood Management Plan), as well as the flood management assets systems level with its individual assets and components such as flood embankments. With future decision support tools in flood risk management, performance objectives are being developed and applied in a tiered way so that policy and strategic planning informs the asset management process, and conversely plans are informed by the condition of assets and other functional requirements within the asset system.

This is outlined in Figure A4.3 below where different types of decision support tools inform different risk-related outputs or decisions at three distinct levels or "tiers". The performance of flood embankments is represented in a simplistic way in model tools at the national level, and in a generalised way (e.g. using a standard fragility curve) at the catchment / shoreline level. Performance will be represented in a more comprehensive manner, with the embankment condition represented in the fragility curve, at the scheme or asset level. Thus for embankment management at this level, the manager requires tools that enable the effect of management interventions (e.g. grass management; crest raising) on performance in terms of embankment resilience under extreme flood conditions and consequent reduction in average annual damage. (See Chapter C and Figure C.1.3 for further background).

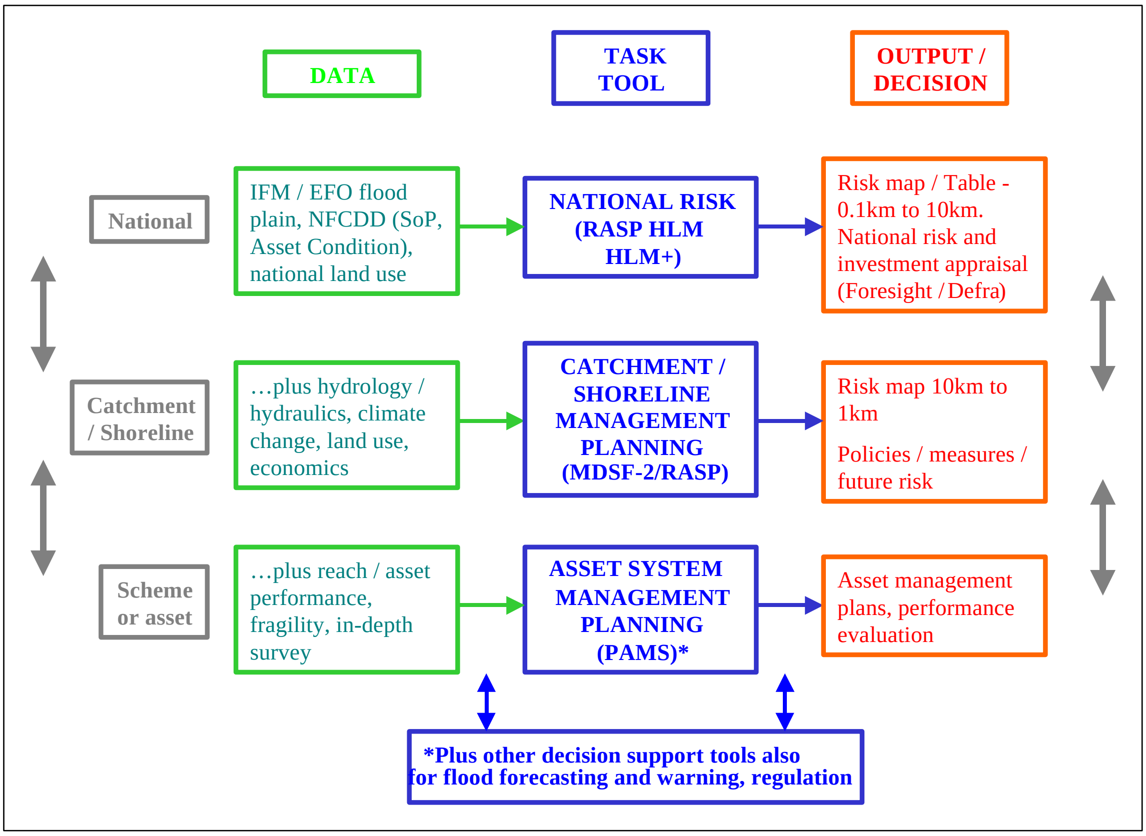


Figure A4.3 Tiered planning tools for flood risk management

A4.4 Development of risk management tools

The use of decision support tools for flood risk management involving embankment performance has been described above and illustrated in Figure A4.3. These require a clear framework for data collection, management and analysis within which the flood manager can operate in the management (planning, maintaining, operating and improving) of flood defences. This framework must cover:

- Procedures for identification and collation of data
- Tools for storage of and access to relevant data, at the asset, catchment / shoreline and national levels
- Tools for assessing flood loading in the flood management system
- Tools for analysing asset performance and supporting performance based asset management
- Tools for inundation modelling, for analysing flood damage, and for prioritising risk reduction measures

This level of data management and analysis is only possible with the development of modern computational systems. Some of the above tools already exist. The development of others is currently underway - a number under the joint Defra / Agency research programme. These initiatives should all be completed to a working level during the next 5 years and will establish a more informed approach to flood risk management in the UK for many years beyond. Some tools are being implemented earlier than this in logical 'measured steps forward'. A summary of key initiatives is presented below. Details of relevant web links are also provided where available. Further information can be obtained from the relevant Defra and Agency development managers.

A4.4.1 National Flood and Coastal Defence Database (NFCDD)

The NFCDD is being progressively developed to provide a single, easily accessible, and definitive store for data on fluvial and coastal assets, supported by and available to all flood defence and coastal protection operating authorities. As regards flood embankments, NFCDD will provide information on:

- Location, composition, and conditions
- Inspection histories

As the rational survey and condition assessment of flood embankments develops, so the NFCDD will become a repository of related data. The exact level of data to be stored on the NFCDD will need to be confirmed as the related decision support tools (and particularly PAMS) are developed. NFCDD is managed by the Environment Agency; for more information see www.environment-agency.gov.uk and search under NFCDD.

A4.4.2 Risk Assessment for Strategic Planning (RASP)

The RASP project is developing methods for assessing risk to floodplain areas associated with *systems* of defences (principally flood embankments) as opposed to the simpler assumption of a single defence protecting a flood plain area. This methodology therefore underpins the decision support tools (such as the MDSF) in the three tiers indicated in Figure A4.2. At these three different tiers, RASP will deliver high, intermediate, and detailed level methodologies providing:

- The basis for national assessments of risk, including baseline assessments and regular updates
- Methods for assessing risk for catchment and shoreline planning
- Methods for more detailed, site specific risk assessments and risk attribution required for maintenance activities, improvement schemes, comparing different flood risk management options, and prioritising management interventions.

RASP has made important steps in utilising standard Geographical Information Systems to support simple user visualisation of flood risk (as average annual damage over grid squares). Development to date has focused principally on the High (1 – National) level in which the embankment function is represented as a simple switching device that fails at the designated standard of protection (SOP). Development at levels 2 and 3 will be done in conjunction with the MDSF and PAMS. The RASP programme is being carried out under the Defra / Environment Agency R&D Programme by HR Wallingford. For further information see www.rasp-project.net.

A4.4.3 Modelling and Decision Support Framework (MDSF)

The MDSF provides a data processing and modelling system, supported on a customised Geographic Information System, to carry out hydrology, hydraulics, flood extent, economic and social impacts assessment and calculations required for Shoreline and Catchment Flood Management Plans (SMPs and CFMPs). This enables the SMP and CFMP programmes to be carried out in a consistent way, by using common data structures and scenario models, and avoiding duplication of effort. The MDSF thus addresses the shoreline / catchment tier indicated in Figure A4.2. The embankment and its overtopping / failure is currently represented by a simple switching device as in the High level of RASP. However, the next development of MDSF will represent the embankment via a form of fragility curve.

The ongoing development of the Modelling and Decision Support Framework (MDSF) is being carried out by HR Wallingford, Halcrow, CEH Wallingford and Middlesex University (FHRC) under the Defra / Environment Agency R&D Programme. For further information see www.mdsf.co.uk

A4.4.4 Establishing a Performance Based Asset Management System (PAMS)

The PAMS project was established in parallel with this project on embankments under the Defra / Agency R&D programme through the same O&M Concerted Action. It aims to take measured steps forward in developing a performance-based approach for identifying and prioritising works needed to manage flood defence assets, adopting the systems-based and risk reduction approaches discussed in Section A.4.2 and Part C. This is the detailed “scheme or asset” tier of risk management planning tools shown in Figure A4.3 and supported by the RASP methodology. The performance and management of the flood embankment within the flood management system is a key element of PAMS, which will provide a means of identifying the optimum management intervention to achieve a particular outcome in terms of improved performance.

The project is organised in three phases. Phase 1 is a scoping study to define the project fully. Phase 2 will (a) draw together the results of other R&D projects (including the results and recommendations of this project), (b) develop the required methodologies, (c) pilot these at river, estuary and coastal demonstration sites, and (d) produce the initial ‘measured steps forward’. The final phase will produce supporting manuals and software. For the Environment Agency, this will take a further step forward from the Flood Defence Management Manual (FDMM) and Management System (FDMS) to provide performance-based tools. A key element of the PAMS project is that it provides a co-ordinated means of drawing together and delivering a number of R&D and other development initiatives to the Environment Agency and other operating authorities.

PAMS will build on the “Source / Pathways / Receptor / Consequence” approach to risk management (see Figure A4.2; Figure C1.3), as well as R&D from the NFCDD, RASP and MDSF projects described above. Of particular relevance to flood embankment management, PAMS will also draw on current development work on performance and reliability (representation of fragility curves and deterioration); asset inspection and condition indexing; and resource prioritisation. For more information, see www.pams-project.net.

A4.5 Construction risk

The focus of discussion on risk and embankments within this document relates to flood risk arising from the failure of the embankment to act as a barrier to the passage of floodwater for whatever reason. Risks associated with the design and construction process are not detailed here, although it is worth noting that the risk of geotechnical problems or failure of an embankment is greatest during initial construction or during embankment modification works. Typical problems include slips triggered by heavy plant manoeuvring on the embankment and / or excavation and emptying of soke ditches (Plate A4.2).

Plate A4.2 Embankment slip failure following drainage of soke ditch

Guidance on construction risk may be found in the following references:

Construction Risk
Construction risk in coastal engineering
Simm J, Cruickshank I, 1998. Thomas Telford. ISBN 0727726862.

Construction risk in river and estuary engineering
Morris M, Simm J, 2000. Thomas Telford. ISBN 0727728628.

A4.6 Summary of key issues under Chapters A3 and A4

Summary of key issues under Chapters A3 and A4:

- A framework for the management of flood embankments has been presented (Figure A3.2). This follows the Agency's management process and established the cyclic nature of the embankment management
- In establishing management objectives, it is important to establish the functional and performance objectives of each embankment. Performance objectives will depend mainly upon its role in reducing flood risk, but may also be related to safety, environmental habitats etc
- Flood embankments typically form part of a system for flood management. The performance objectives of an embankment in reducing flood risk should be established by considering the system as a whole under a range of conditions
- Improved performance of flood embankments can be achieved through the use of consistent standards and by adopting current best practice. Developments are underway to establish the link between management intervention and improved performance, particularly in reducing flood risk
- The flood risk associated with any embankment, and the reduction in risk (i.e. benefits) from any management intervention to improve or adapt the embankment, will be progressively addressed through the development of the PAMS decision support tools. The early developments of the tools ('measured steps forward') will provide some improved understanding

PART B:

PERFORMANCE AND CHARACTERISATION OF FLOOD EMBANKMENTS

B1 FORM AND CONSTRUCTION OF FLOOD EMBANKMENTS

B1.1 General

Flood embankments essentially act as low-level dams for short retention periods. For the majority of the time, most embankments are exposed to no, or to low, hydraulic head and remain largely unsaturated. However, during flood events, an embankment may need to withstand a rapid rise in water level on the outward face, along with the corresponding changes to internal water pressure (and perhaps seepage) driven by the higher hydraulic gradients across the embankment. The increase in head on the embankment may be further exaggerated by the use of demountable flood defences on the crest of the embankment.

Accurately predicting the performance of flood embankments and understanding potential breach initiation or other failure mechanisms under these extremes in loading is difficult. This is further compounded by the long lengths of flood embankment that exist to protect rivers, estuaries and coastlines which make a comprehensive condition assessment of all embankments logistically difficult to implement. Nevertheless knowledge about the type of fill material used to construct embankments and the method of the construction does allow the performance of the embankment to be considered in a rational manner and, if appropriate, analysed using principles of soil mechanics.

This chapter provides a review of embankment construction along with information about typical foundation performance with reference to historic breaches and general experience of embankment performance.

B1.2 Traditional methods of construction

Many flood embankments are relatively old structures that have evolved over decades or even centuries from original constructions. In contrast with the modern construction of embankments for highway and dam projects using heavy earth compaction equipment, many flood embankments have been built using low cost traditional techniques. These traditional methods have often evolved to suit local sources of fill material, which have been excavated from surface deposits or retrieved from river sediments. As a result, the construction of flood embankments can be highly variable across the country, and this can affect the performance and potential failure mechanism for embankments. Of these traditional construction methods, three common techniques are used as illustrated in Figure B1.1

B 1.2.1 Excavation from adjacent ground/Delph ditches

The most common method for construction of flood embankments has been to excavate soil from the adjacent ground, particularly a neighbouring ditch, called a Delph ditch, which runs along the landward side of the embankment as illustrated in Figure B1.1a. The excavated soil would typically be a fluvial deposit from an historic flood plain that was composed of fine silt and clay sized particles, rich in organic material. For shallow embankments, the excavated soil would typically be placed in layers using light compaction equipment without necessarily complying with an engineering specification to achieve a target density or permeability.

B1.2.2 Use of warping silt traps

In some regions, fill material from adjacent ground and Delph ditches has been supplemented by trapping sediment from the river flow, which is often heavily loaded with sediment during flood events. This is the case in the Midland Region where warps or silt traps have been constructed along the riverside of an embankment. The silt traps are typically constructed from mounds of cobbles and boulders with stakes along the toe of existing flood defence embankments. As a result a berm is formed at the front toe of the embankment, which provides greater resistance against toe erosion, as shown in Figure B1.1b, as well as improved global stability.

B1.2.3 River dredgings

In the past, in the Anglian Region, sediment has been dredged directly from the riverbed to raise existing embankments. The method involves constructing bunds along the crest of the embankment by partly excavating a trench into the crest, which is subsequently filled with river dredgings as illustrated in Figure B1.1c. The river dredgings are predominantly silts, which allow water to freely drain away. The technique is analogous to the method of constructing a tailings dam, where consolidated tailings are used to construct the embankment shoulder. However, when adopting this approach consideration must also be given to the risk of excavating contaminated material. Such material requires disposal through licensed areas and is not appropriate for use in embankments.

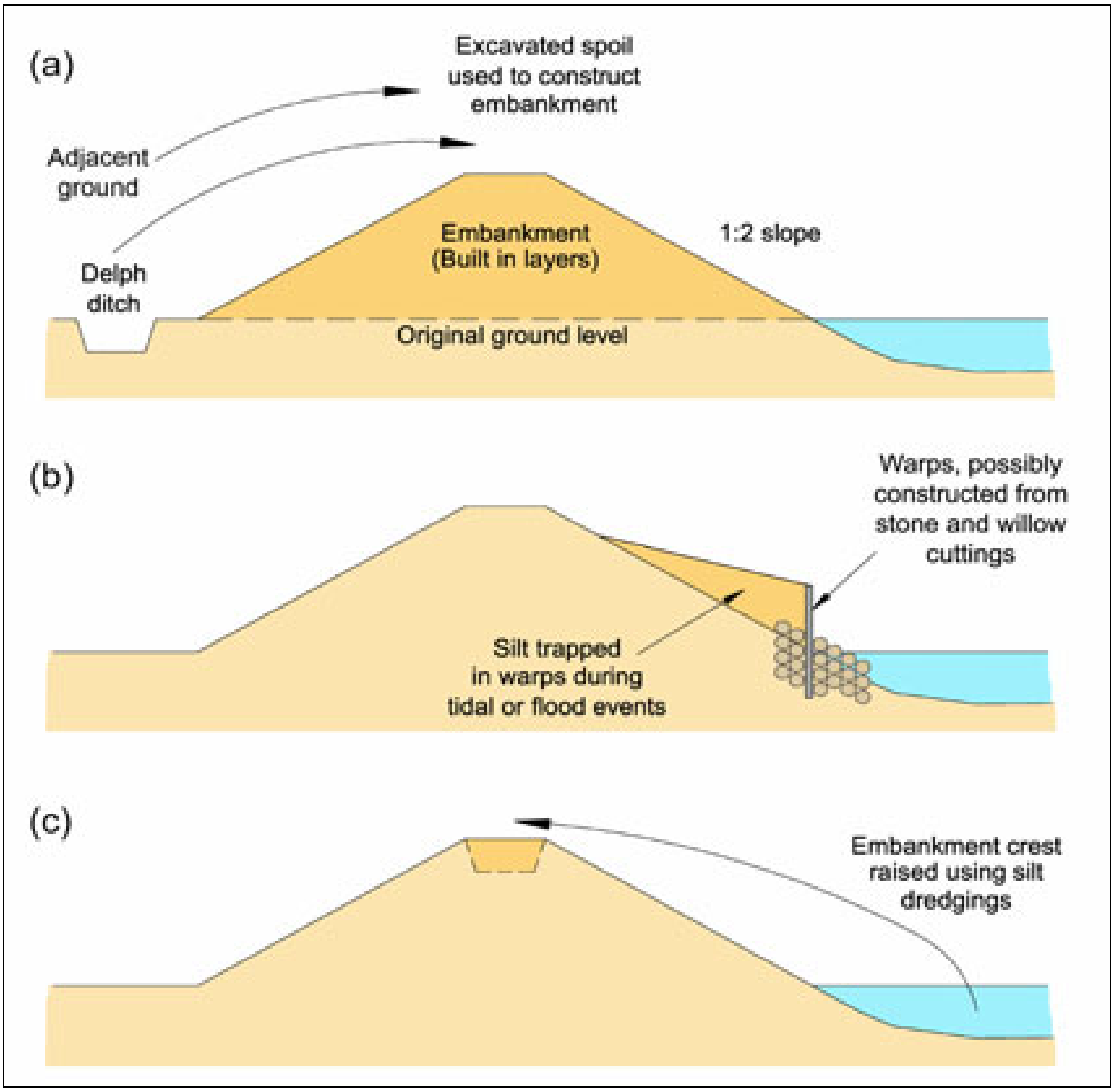


Figure B1.1 Traditional methods of construction

ⓘ **Points to note:**

- Embankment geometry varies according to type of material used and construction history. Ideally, an embankment should have a crest width of greater than 2.5m to allow access along the crest for operations and maintenance vehicles
- Whilst the slope of inward and outward embankment faces might sometimes exceed 1 in 2 (according to construction material), stability problems will be encountered as the face is steepened. Poorly controlled maintenance activities can result in bank steepening through excessive removal of soil when cutting vegetation
- Changing the slope of an embankment affects the way in which waves run up the face and potentially overtop the embankment. There is also anecdotal evidence that the grazing habits of sheep are affected by the gradient of embankments

See **Section D3** for more information on managing embankment vegetation.
See **Section D9** for information on wave overtopping.

B1.3 Recent methods of construction

Recent embankments are typically constructed in layers using standard compaction specification akin to highway construction as shown in Figure B1.2.

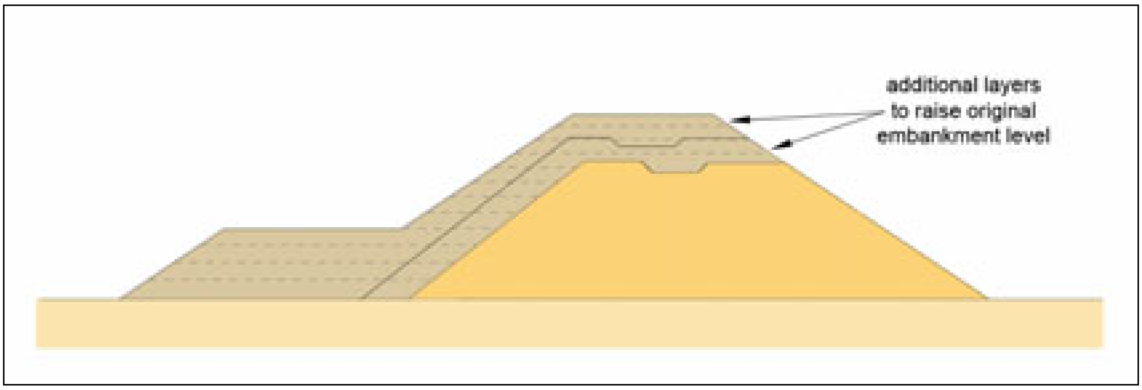


Figure B1.2 Embankment with layers

In cases where the fill material is considered to be too permeable, a less permeable core could be incorporated into the construction, as shown in Figure B1.3. In practice, an impermeable core is not often used, even where highly permeable fill materials such as quarry waste or silty sand is used (such as in North Wales). Nevertheless it would be feasible to design the core or cut off to control unacceptable internal seepage and inundation of water behind an embankment that could otherwise pose a threat to the long-term stability. For example, the core may be built from a more impervious local material, probably with higher clay content, or could be formed by steel sheet piling or construction of a concrete, asphaltic concrete or cement bentonite cut-off wall.

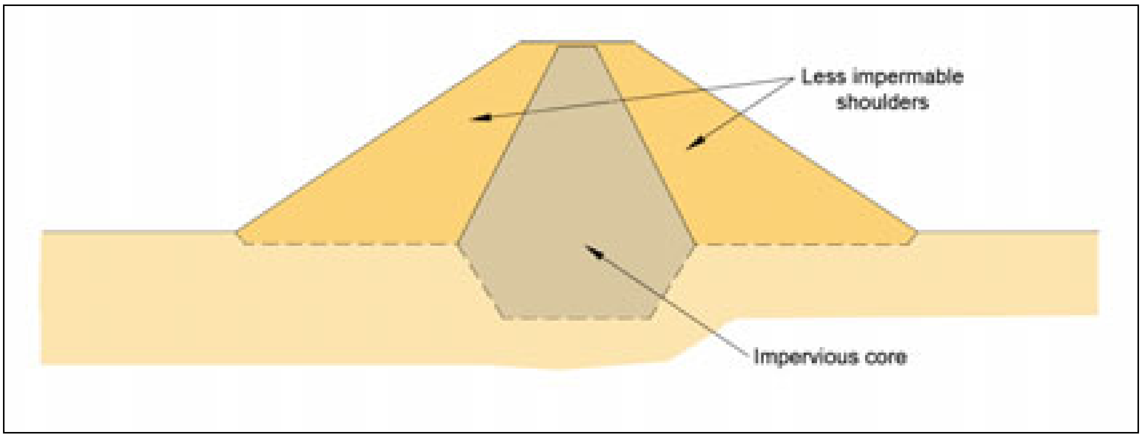


Figure B1.3 Embankment with an impervious core

In some situations (typically in the Netherlands, Germany and Denmark), sand embankments are protected by a layer of clay beneath the inward-facing revetment surface layer. In effect, the embankment has a porous but stable core into which seepage is prevented by an impermeable barrier of clay which itself is protected by some form of surface layer such as vegetation.

Stability of the embankment may be enhanced through the use of geotextiles to provide longer-term surface protection, increased face stability or to provide temporary reinforcement or protection whilst vegetation is established. Where embankments are placed on soft ground or where the width of the base of the embankment is restricted by lack of space, alternative materials can be considered which may be either of lower density and / or of increased shear strength. This may simply be a question of providing reinforcement with geotextiles or geogrids to an embankment of otherwise traditional construction. However, lightweight materials such as polystyrene blocks or tyre bales can also be used with appropriate precautions (such as wrapping the new materials with heavy-duty impermeable membranes and / or careful consideration of internal drainage).

ⓘ **Points to note:**

- Where embankments have been raised a number of times over the years, (i.e. decades, or longer) the fill materials used may be different. In the event of extreme loading or failure, the various layers may respond differently (i.e. rate of seepage or erosion)
- When an embankment relies upon an impervious core or layer, the body of the embankment typically supports and protects the core. Both shoulders and core are required to provide a stable structure
- Where a river channel is maintained near an embankment, it is possible to consider using the dredged material in parts of the embankment. Fine or silty material may be unsuitable, but coarser sands and gravels or well-graded material could be used to form parts of the embankment where permeability was not an issue. Use of dredged material in this way will avoid the increasing costs of disposal (including landfill tax)

See **Section D2** for guidance on embankment condition assessment.

B1.4 Underlying geology and earthwork materials

A review of traditional earthfill materials used to construct flood embankments (Environment Agency, 1996) found a wide range of soils and rocks used as fill material depending on the local geology and particularly the superficial deposits. A list of the fill materials used to construct flood embankments along several major rivers and estuaries is given in Table B1.1. It is not an exhaustive list of the fill materials used for embankment construction but it does illustrate the broad range of material used. As might be expected for embankments constructed along major rivers and estuaries in the southern and eastern parts of the country, alluvial clays and silts are a common source of fill material. In comparison, the absence or shortage of alluvial soils in North Wales has led to the use of aeolian sand, shingle or even slate waste as fill material. The use of such a wide range of materials has implications for the performance of embankments and in particular the susceptibility to different failure mechanisms. For example the use of slate waste in the Mawddach Estuary has resulted in high seepage rates through flood embankments with the risk of piping failure. Likewise the use of sand and shingle for the construction of flood embankments at several other estuaries along the west coast of Wales has resulted in high seepage rates that cause flooding of adjacent roads. In contrast the use of highly plastic clays in the Anglian Region has lead to fine fissuring, which has increased internal seepage and reduced resistance to erosion from overtopping. Apart from local geology, other waste materials used as sources of fill material include colliery spoil, demolition material and blast furnace slag.

Table B1.1 Typical fill materials used for flood embankment construction in England and Wales

Region	Typical earthwork materials
Anglian	
Ouse Washes; Forty Foot Drain	Kimmeridge Clay and fluvial sediments (silts)
Thameside Marshes	London Clay / Thanet Sand / alluvium (clays)/ Hoggin (clayey sand)
Southern	
River Ouse	Chalk and alluvium (silty clay)
River Rosher	Wealden clay and alluvium (silty clay)
Midland	
River Severn (Argae)	Alluvium (silty clay)
North West	
River Wyre (Preesall)	Morainic drift
River Duddon (Haverigg)	Estuarine alluvium (sand)
River Gowy	Alluvium (silt)
North East	
River Aire (Upper and Lower)	Alluvium
River Calder,	Alluvium
River Don / Dearne / Rother	Colliery spoil and alluvium (silts, clays)
Wales	
Borth Estuary	Peat
Mawddach Estuary	Slate waste and quarry
Porthmadog	sand and quarry overburden
Dyssyni Estuary,	Sand and shingle
Wentlooge Levels	Alluvium (silty clay)

In addition to providing a source of fill material, superficial deposits generally form the founding strata (i.e. foundations) for flood embankments and can strongly influence settlement and stability as well as sub-surface seepage. Soft organic clays and peat along the Ouse Washes and Forty Foot Drain have led to considerable settlement and cracking of flood embankments such as the Middle Level Barrier Bank. In comparison, continuous and especially isolated buried channels of coarse-grained deposits can cause excessive sub-surface seepage. This can lead to piping and embankment collapse, as has been reported for embankments along the River Blackwater in Essex.

An initial analysis of historic breach location suggests that location also appears to correlate with the location of solid and drift deposits. An example of this is the correlation of breach location with river terrace deposits or glacial sand and gravels along the Rivers Roach, Crouch, and Blackwater in Essex (as shown by the BGS 1:50,000 and 1:63,360 geological maps).

B1.5 Embankment protection and strengthening measures

B1.5.1 General

There are a wide variety of ways in which flood embankments may be protected to help ensure that consistent and acceptable standards of flood defence are maintained. Selecting the most appropriate measure(s) will require careful consideration of the embankment location, function(s) and loading. Protection measures are typically required to perform satisfactorily under a range of conditions. For example, whilst the embankment may remain unsaturated and retaining a relatively low water level for the majority of time, it may be required to withstand a rapid rise and fall in flood water level, in conjunction with heavy rainfall. The transition from low to extreme load conditions may take only a few hours, yet the embankment must be able to withstand these rapid changes and extreme loading.

Protection measures typically have multiple functions. For example, sheet piling along the toe of an embankment may protect against erosion of the bank, but it will also increase stability of the outward face and reduce seepage through the embankment. Similarly stone protection may protect against wave or flow erosion, but it may also increase stability of the embankment.

When considering the design of protection measures it is important to consider:

- The dependency of bank integrity and stability upon the measure
- How maximum value may be gained from different potential solutions

When inspecting embankments, failure of a specific protection measure may have greater implications for embankment integrity than is immediately obvious. Many bank slip failures are directly as a result of failure of erosion protection measures.

The following sections provide an overview of embankment protection measures. Additional information on external erosion and protection may be found in Section D10.

B1.5.2 Toe protection

Vulnerable areas of an embankment include the toe area of both inward and outward faces. If the toe of either slope is eroded or undermined, then it reduces the stability of the embankment face above and can lead to slipping of the embankment face, which can eventually threaten the embankment crest level and standard of protection. Protection of embankment toes, particularly on the outward face, is therefore a common feature of many embankments and can be achieved in a number of ways, depending upon the threat posed. Figures B1.4 and B1.5 show two examples of toe protection to the outward face.

Failure of sheet piling through erosion around the toe, or failure of tie rods or anchors, is a common occurrence that can lead to the subsequent failure of an embankment. Where an embankment is designed or known to overtop, or could be exposed to wave action from floodwater on the inward side, protection of the inward toe, typically using stone, may also be undertaken.

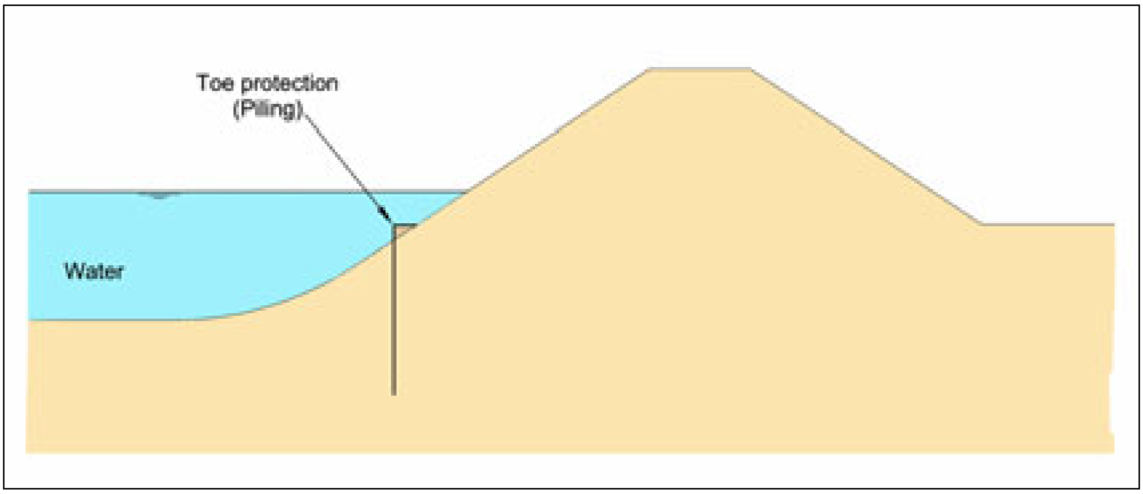


Figure B1.4 Toe protection using sheet piling

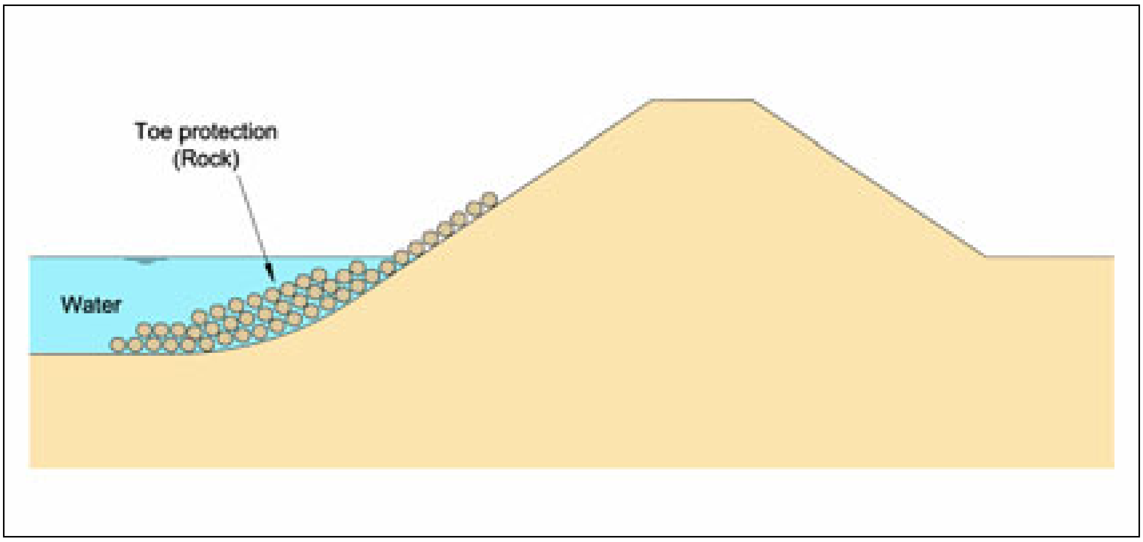


Figure B1.5 Toe and inward face protection using rock (rip rap)

Plate B1.1 Rock protection with sheet piling to stabilise bank

Plate B1.2 Failure of anchor in sheet piling protection

ⓘPoints to note

- Any toe protection design should take into consideration channel morphology as well as likely flow velocities and wave action. Positioning a new embankment relative to a morphologically active river channel is a careful balance between risk of scour and cost of land take

See **Section D10** for more information on methods for protecting embankments.

B1.5.3 Use of revetments for surface protection

Where there is a known threat to the surface / face of an embankment, various protection measures may be employed. Since an embankment may have a range of secondary functions as well as its primary flood defence role, protection measures may be required for a range of threats, and may also be constrained in their nature.

Threats to embankments include:

- Erosion of inward face through water current, undercutting or wave action
- Erosion of crest and inward face through wave action and overtopping/overflowing
- Damage to embankment body through burrowing animals and vegetation growth
- Erosion of crest through third party use, including recreational, animal etc. (see Table B2.1 for a more extensive summary)

There is a range of methods for protecting embankments. These can include the use of:

- Stone (Figure B1.6 & Plate B1.3)
- Concrete (cast in situ or precast units) (Figure B1.7; Plates B1.4, B1.5, B1.6 and B1.7)
- Bitumen (ashphalt) matting, open stone ashphalt
- Grass / concrete precast units
- Geotextiles (Figure B1.8; Plate B1.8a and B1.8b)
- Sheet piling (steel, recycled plastic etc) (Figure B1.9 and Plate B1.9)
- Selected vegetation
- Restricted use / access

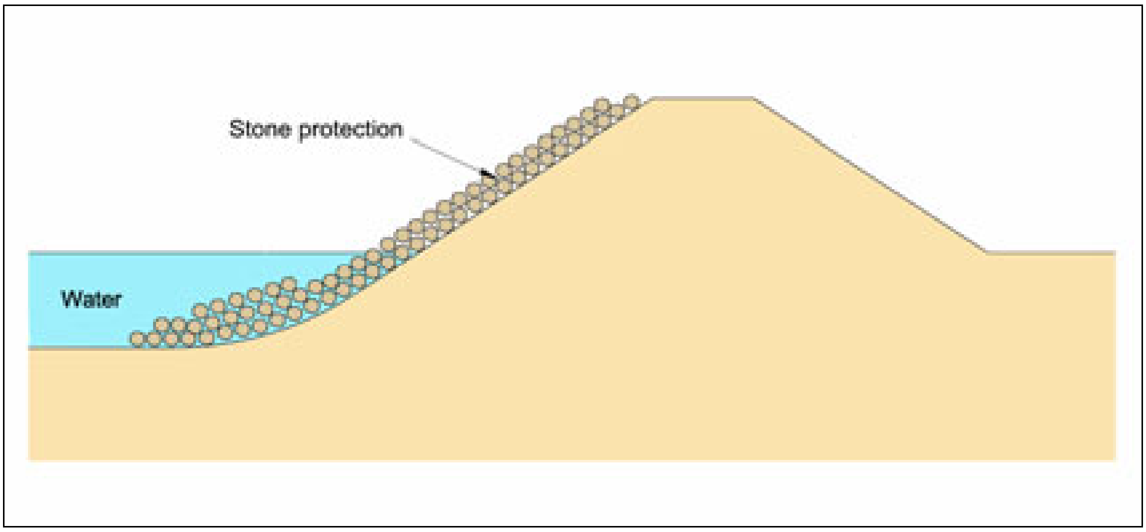


Figure B1.6 Toe and inward face protection using stone / rock rip rap

Plate B1.3 Toe and inward face protection using stone / rock rip rap

Plate B1.4 Bank instability

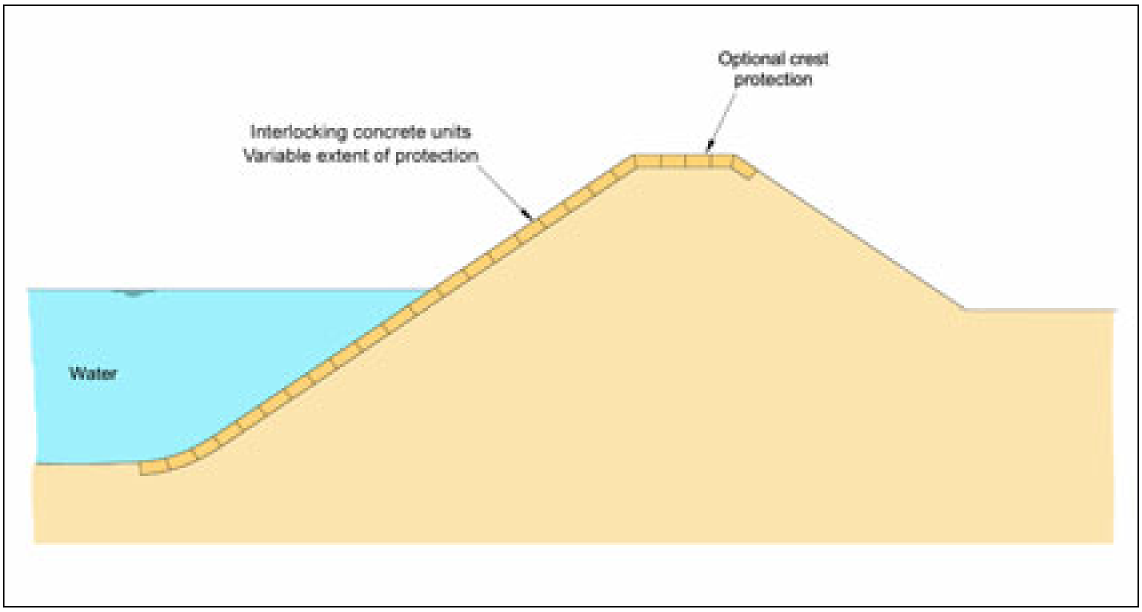


Figure B1.7 Toe and inward face protection using concrete blocks

Plate B1.5 Toe and face protection using concrete blocks (stable in distance failing in foreground)

Plate B1.6 Concrete slab protection

Plate B1.7 Poor detailing at end of slab protection (allowing embankment erosion behind protection)

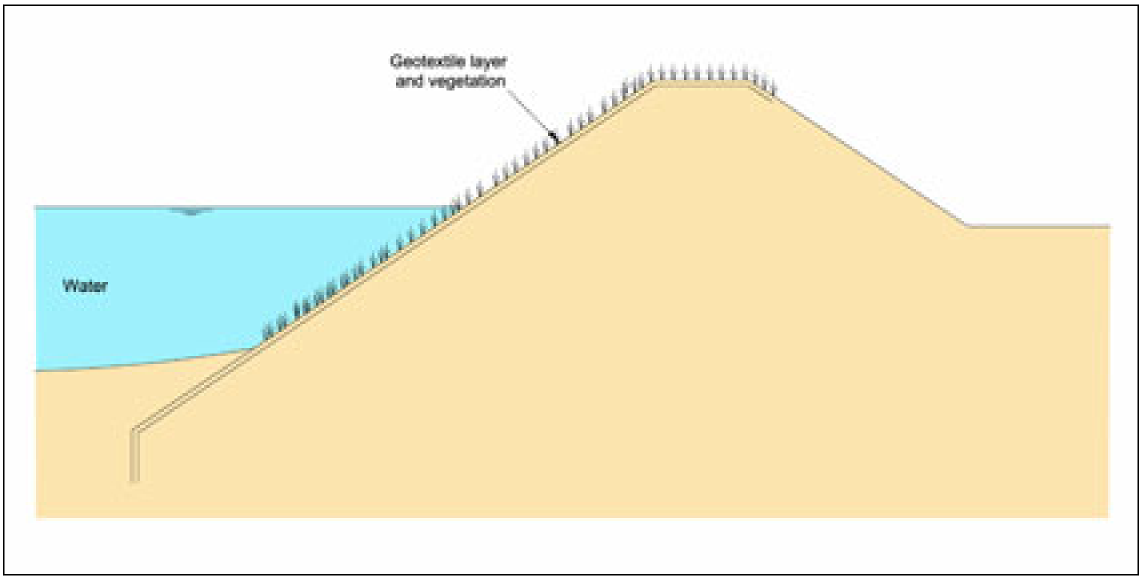


Figure B1.8 Toe and inward face protection using geotextile and vegetation

Plate B1.8a Toe and inward face protection using geotextile and vegetation (under construction)

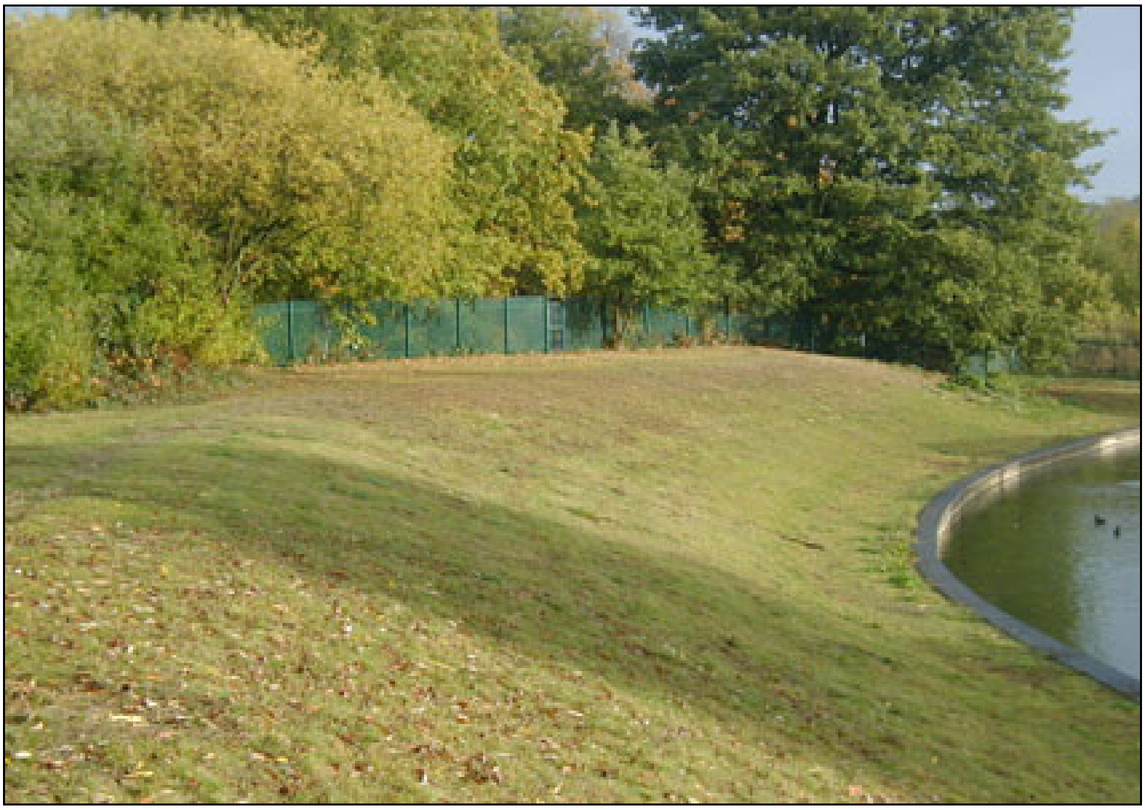


Plate B1.8b Toe and inward face protection using geotextile and vegetation (after vegetation is established)

B1.5.4 Seepage control

As discussed in Section B1.5.1, measures taken to protect an embankment can perform multiple functions in strengthening or protecting the embankment. A good example of this is the use of sheet piling – either along the inward face or through the body of the embankment. In addition to providing protection against surface erosion and stability to the inward face or shoulder, the sheet piling will also form a barrier against seepage through the embankment.

In situations where burrowing animals pose a threat, or where bushes are proposed on the embankment for landscaping purposes, sheet piling may also be used to provide a solid barrier against burrowing or root action, whilst also limiting seepage flow.

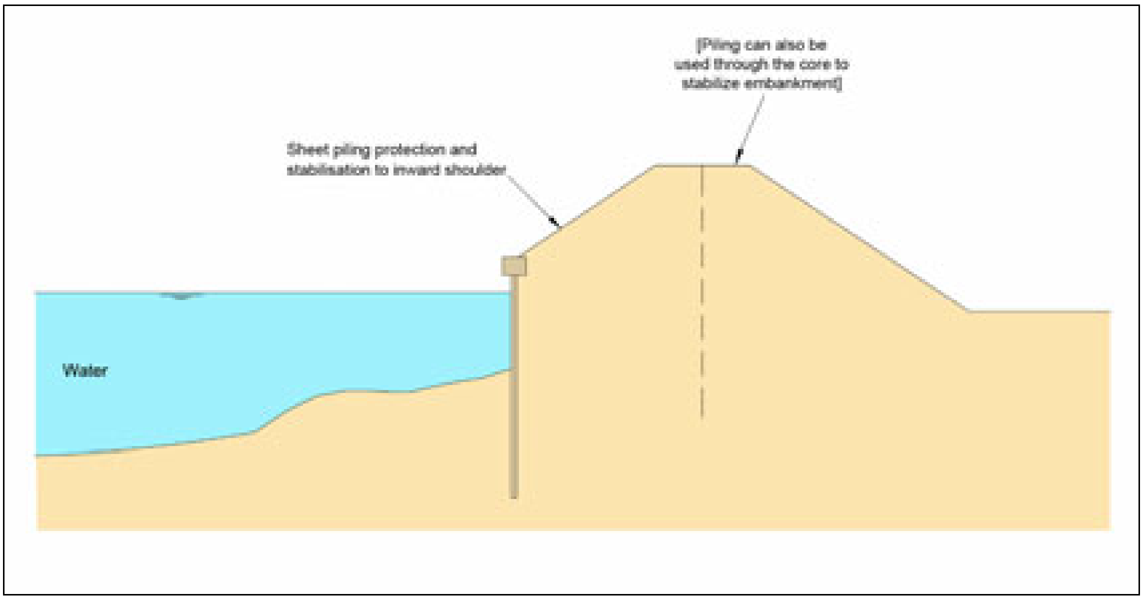


Figure B1.9 Toe and inward face protection using sheet piling

Plate B1.9 Toe and inward face protection using sheet piling (timber clad)

B2 FACTORS AFFECTING THE PERFORMANCE OF FLOOD EMBANKMENTS

B2.1 General

Although there are several geotechnical factors that can affect the performance of a flood embankment, the individual factors can be divided into two main groups depending on whether the hazard develops in the foundations or the embankment itself. A simple guide to the range of hazards and risks that can occur is shown in Table B2.1. The table is based on a general understanding of geotechnical processes involved with embankment performance supported by case histories about embankment failures during the last 50 years, including the 1953 North Sea floods. This assessment of the geotechnical factors affecting the performance of embankments show that hazards stemming from the founding strata could potentially result in excessive settlement, deep seated slope instability, large scale lateral movement, excessive under seepage or hydraulic uplift pressures. In comparison, the hazards emanating from the embankment itself are identified as surface or toe erosion (outward and inward faces), excessive internal seepage and shallow slope instability. Some of these hazards are short term such as global instability due to construction on soft clays whilst others would be long term caused, for example, by fine fissuring resulting in excessive internal seepage, which would lead to potential internal erosion or instability of the outward face.

By identifying the geotechnical and hydraulic processes that can affect the performance of flood embankments in this way, it is possible to develop a more rigorous framework to improve practice for the construction, inspection and maintenance. This is illustrated by the last column in Table B2.1 that sets out the ground conditions to be considered by a site investigation either for new build or maintenance of existing embankments. There is however a danger that too much detail at one location could obscure the broader picture for a particular length of flood defence embankment that stretches over several kilometres. The challenge posed by these differences in scale needs to be addressed by combining specialist engineering skills and advances in data collection systems, such as GIS and remote sensing, within the overall risk framework for performance-based asset management discussed in Section A4.4.4.

Table B2.1 Geotechnical factors affecting the performance of flood embankments

Element	Hazard	Field observations	Risk	Geotechnical process	Ground conditions to consider / investigate
Founding strata	Settlement	Low crest levels	Low crest levels leading to overtopping	Consolidation of underlying strata (including dissipation of excess pore pressures) or embankment fill material	Consolidation and compression characteristics of underlying soils. Secondary consolidation and creep of soils and fill. Differences in horizontal and vertical permeability of foundation material
	Deep rotational failure	Tension cracks on embankment crest. Settlement of part of crest. Lateral displacement of embankment toe. Heave of ground in front of toe	Catastrophic failure of embankment	Shear failure during construction or embankment raising	Shear strength of fill and foundation soils, in particular undrained shear strength of clays. Possible longer term gain in strength due to consolidation
	Translational sliding	Distortion of embankment crest leading to bulging along outward face	Catastrophic failure of embankment	Lateral hydraulic force exceeds shear resistance of founding strata along base of embankment or desiccation of organic fill leading to a reduction in dead weight	Shear strength of soft clays and organic soils directly beneath the embankment. Desiccation of peat and organic fills leading to a reduction in dead-weight
	Seepage and piping	Seepage or ponding of water in front of embankment	Seepage causing internal erosion and piping	Under-flow of flood water leading to erosion and slope instability	Presence of highly permeable strata beneath embankment either leading to excessive seepage
	Uplift pressures	Heave of embankment toe	High pore pressures causing instability	Build up of uplift pressures in confined permeable strata due to hydraulic continuity with flood or high water load on inward face	Presence of highly permeable strata beneath embankment leading to build up of pore pressures due to confinement
Embankment structure	Shallow slope instability	Shallow translational slumping or slippage of embankment side slopes. Possible tension cracks on embankment crest, settlement of crest, lateral displacement of embankment toe or heave of ground in front of toe	Damage to outward and inward faces of embankment leading to a loss of integrity or a reduced resistance to seepage or overtopping	Instability during rapid drawdown after flood or high water load on inward face. Longer term slippage of slopes due to pore pressure equalisation, reduction in soil suction or progressive failure. Erosion of toe along outward face due to river migration	Compaction of fill material in relation to moisture content. Build up of pore pressures after lengthy period of high water load resulting in saturation of fill material or leading to uplift. Swelling of over-consolidated clay fill leading to shallow slips. Repeated shrinkage and swelling of clay fills leading to progressive failure. Reduction in soil suction pressures in partially saturated soils following infiltration of rain and/or high water load
	Internal seepage and erosion	Cracking within embankment body. Visible seepage on outward face of embankment, particularly during "bank full" conditions. Sediment in water. Animal burrows. Local variations in growth of vegetation	Washout of embankment fill material leading to local settlement, preferential seepage paths, piping and eventually breach	Excessive seepage caused by desiccation and fine fissuring. Excessive seepage due to highly permeable fill material. Loss of embankment material through burrowing or washout of fines	Shrinkage of medium and highly plastic clay leading to fine fissuring. Excessive seepage through coarse-grained fill leading to piping at critical hydraulic gradients
	Erosion of inward face and toe	Bare soil, loss of material visible Undercutting at base of slope	Increased risk of seepage or instability	Erosion of inward face and toe due to river / coastal migration or wave erosion	Shear strength and grading of embankment material. Geomorphological assessment of long term river or coastal migration
	Erosion of outward face	Bare soil, loss of vegetation	Reduced resistance to overtopping	Erosion of outward face due to over flow	Selection of suitable topography, topsoil and vegetation. Possible use of geotextiles

B2.2 Typical failure mechanisms

B2.2.1 General

As discussed earlier, common failure mechanisms that may manifest themselves over an embankment's lifetime could include the following (as illustrated in Figure B2.1 below):

- Settlement
- Global instability (rotational and translational failures)
- Seepage and piping
- Shallow slope instability (and softening)
- Erosion

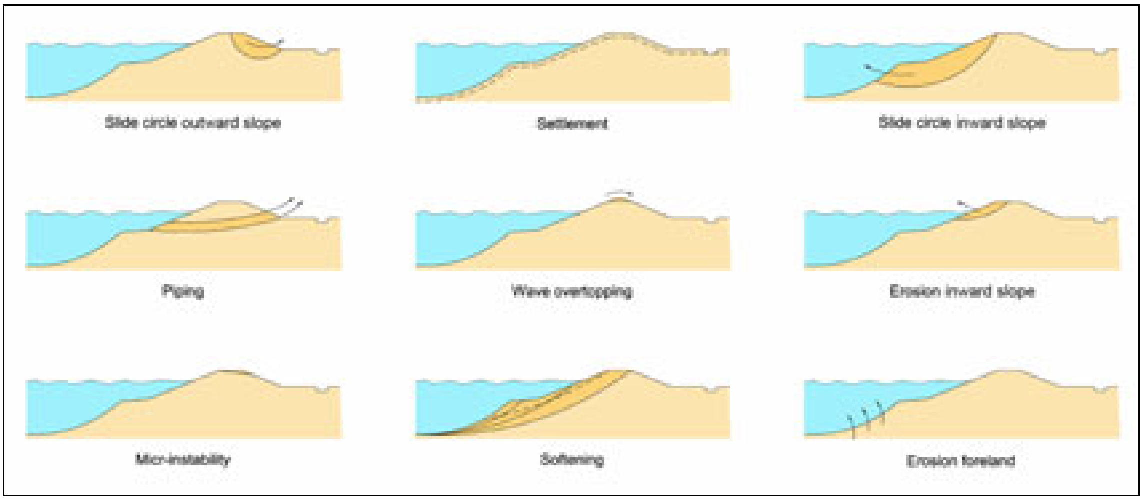


Figure B2.1 A selection of typical failure mechanisms (TAW 1999)

Whilst failure is typically associated with high hydraulic loads (i.e. flood levels), rapidly varying hydraulic conditions – such as rapid falls in water levels following prolonged periods of high water level – can also lead to instability.

B2.2.2 Settlement

Almost by definition, most flood embankments have been constructed on flood plains. Many will, therefore, have been built on foundations which contain layers of soft clay or peat. It is a characteristic of these materials that they undergo relatively large time-dependent settlements as they consolidate under an imposed load. This is particularly the case for larger embankments of over two metres high. For historical floodbanks which can be many centuries old, much of this settlement will already have occurred and possibly been obscured by subsequent filling. In contrast, newer embankments constructed to full height in one lift may be prone to large ongoing settlements of perhaps hundreds of millimetres. In addition, the process of embankment raising will often trigger further settlement, especially where fill material is placed over the side slopes and toe of an embankment.

The obvious problem caused by settlement is that the embankment may not achieve its primary purpose of providing an impermeable barrier to a required level, causing a reduction in the standard of protection. One issue of particular concern is the time dependency of the consolidation process; an embankment that meets its height requirements one year will not necessarily meet those objectives in subsequent years. Another problem caused by settlement is distortion induced cracking of the potentially brittle fill material. This will make the embankment more permeable as well as being more prone to damage and possibly breach as a result of overtopping (which will be more likely as a result of the settlement).

B2.2.3 Deep rotational failure

Deep rotational failures will tend to be initiated by changes to an existing situation. Examples of causes include a new embankment being built or an existing embankment being raised, a high load being applied to the crest, an unusually high retained water level or the excavation of a ditch at the toe of the embankment. Changing the size and condition (i.e. water level) of a soak or drainage ditch is a common cause of problems, particularly with soft clays and silts. One particular form of deep rotational failure, often referred to as a 'blow-out' failure, can be triggered by high groundwater pressures acting in a permeable layer beneath the embankment.

Deep rotational failure will usually manifest itself as cracking and downward displacement of part of the crest, bulging of the embankment slope, particularly the base, and heave of the ground in front of the toe. It results in a softening of the embankment fill and a weakening of the foundation soils. If it does not trigger a breach in itself, this may quickly follow unless immediate repairs are carried out.

B2.2.4 Seepage and piping

In theory, seepage through or under an embankment constitutes a failure of a flood embankment to perform its main function of water retention. However, especially in its early stages, the volume of water lost is often relatively small and this seepage is acceptable. If left untreated, finer particles of soil will probably be washed out of the embankment or its foundation by the flow. Thus, the problem is one of progressive deterioration; as the soil becomes more permeable, the flow rates increase and as a result, more particles of soil are eroded. Seepage will also increase the likelihood of slip failure as a result of changes to the soilwater regime within the embankment, causing a weakening of the fill materials or increasing the uplift pressures beneath an embankment toe.

Seepage through an embankment is generally caused by the presence of permeable layers or lenses within the fill or by the existence of cracks or fine fissures as described above (see Figure B2.2). Seepage beneath an embankment is most likely to be caused by a permeable layer (sand, gravel or possibly peat) within the foundation soils. The occurrence of seepage will usually be indicated by areas of standing or flowing water, by damp patches on the ground in front of the embankment or on the side of the embankment or by changes in the type or condition of vegetation. Seepage may not always be apparent; in some cases it will only be noticeable during conditions of high water level or flood.

Fine fissures form as a result of weathering of clay fill (in particular, the annual process of drying in the summer and wetting in the winter). They have the effect of increasing the permeability and decreasing the strength of the clay fill within the embankment. Fine fissures predominate near the surface of embankments in the zones which are not frequently wetted. Embankments with fine fissures will therefore be more at risk during flood events when water levels approach the crest in extreme flood events. Many of the embankment failures recorded during the 1953 floods were attributed to loss of soil and subsequent breaches induced by fine fissuring.

Fine fissuring will only be visible to the naked eye on careful inspection, particularly if the surface vegetation cover is good. Even if cracking near the surface is observed, it will not be possible to determine the depth to which the cracking penetrates without careful excavation and inspection. Such an approach is not usually advocated because the damage caused by the inspection may be worse than that caused by the cracking itself. However, the tendency for a clay to crack seems to be related to its plasticity and hence basic classification tests can give a good indication of an embankment’s propensity to form fine fissures. Fine fissuring and its management is the subject of ongoing research.

B2.2.5 Shallow slope instability

Many fluvial flood embankments in the UK have been constructed over a period of many years with locally won clayey soils. There has not always been a high level of design or construction control and many embankments have been constructed on the basis of local experience with locally won materials and with construction techniques of varying quality.

When a clayey material is compacted to form a flood embankment, its initial shear strength will depend on the characteristics of the material’s constituent soil particles, the soil’s moisture content and the degree of compaction. Over a period of time, however, the soil will weather and potentially soften from the surface down. This effect will be aggravated by seasonal variations; the embankment will dry and possibly crack over the summer months and these cracks will then form a pathway for water in the autumn or winter (by infiltration of rain or seepage of flood-water). For steep sided embankments, this softening process will reduce the factor of safety against shallow slip failure, potentially to a point where surface slumping occurs. This process will be inhibited to a certain extent by the tendency for vegetation to desiccate and reinforce the soil near the embankment surface. The tendency for slumping is highly dependent on the side slopes of the embankments. Many river embankments are over-steep as they were initially constructed with as little fill as was needed for the embankment to stand up in the short term.

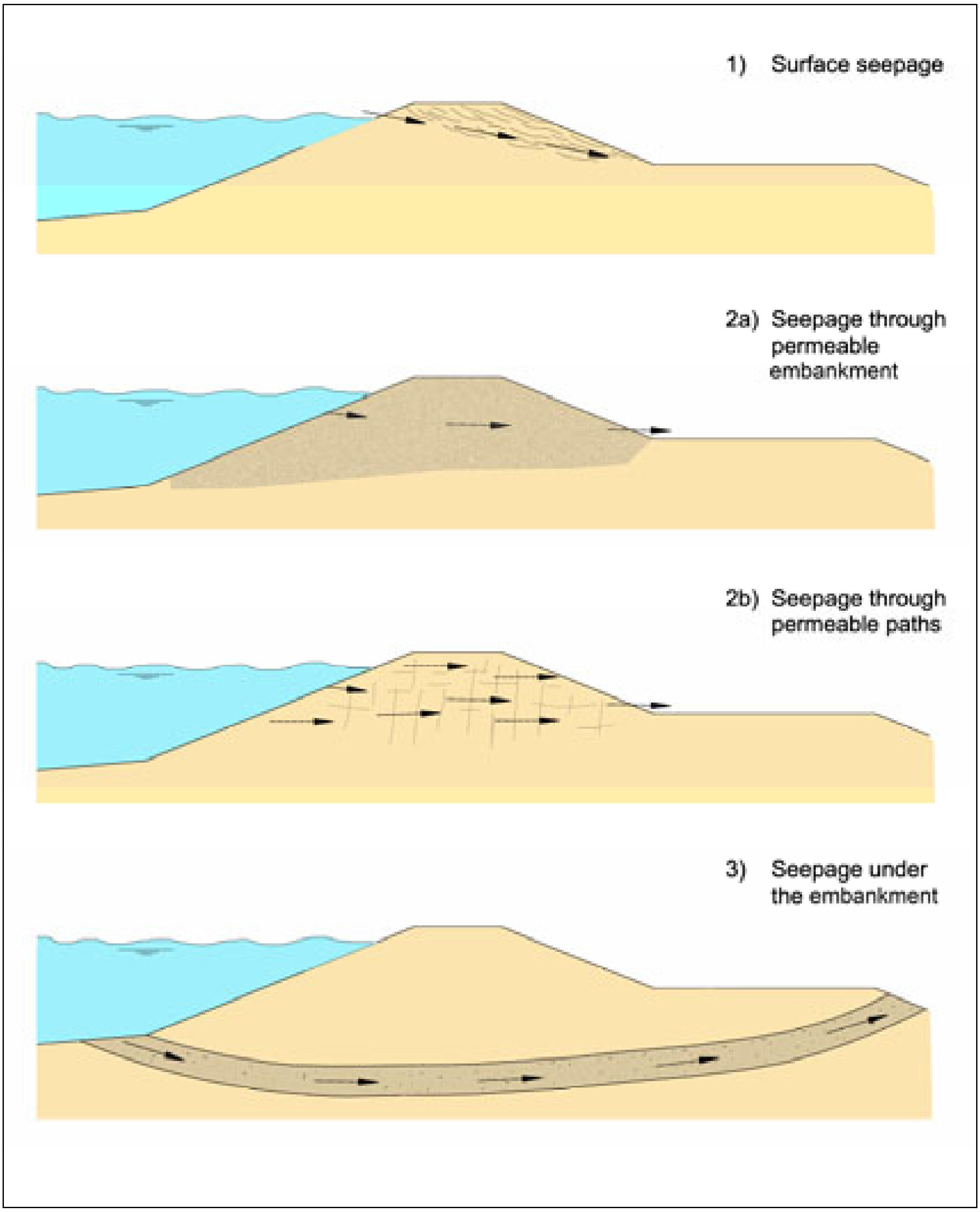


Figure B2.2 Potential seepage paths (Coltrup, 1984)

Shallow slip failures will usually manifest themselves as a furrowing or ridging of the surface of the side slopes. Where vegetation is effective at strengthening the topsoil near the surface, there will be a tendency for failure surfaces to be pushed deeper into the embankment. However, the failure surface itself will generally not be more than one metre deep. The tendency for shallow slips to form can be exacerbated on the river face by high river levels over a period of time being followed by a rapid draw-down of flood water level. Shallow failure surfaces will not generally threaten embankment integrity in the short term. However, if they are not dealt with, then the softening front may progress deeper into the embankment. In addition, in a cracked, distorted and furrowed state, the side slopes of the embankment will be more vulnerable to erosion, particularly from wave action and overtopping.

B2.2.6 Erosion

The problem of erosion can be split into two parts: external erosion and internal erosion. External erosion of a riverbank is mainly caused by the action of waves, currents or turbulence within the channel. For example, wave action, propeller wash from vessels using the river or high velocity flow on the outside of a meander. External erosion can cause fill material to be washed from the face of the riverbank leading to loss of section and undermining. This will eventually lead to slippage, slumping and softening of the embankment slope.

External erosion can also occur due to lateral movement (meandering) of the entire river channel, or a deeper flow channel within the main river channel. This process can undermine the flood embankment leading to deep or shallow slope instability as well as direct erosion. (See Section A2.2 for more information).

Internal erosion is the process of washing out of soil particles by seepage flows through an embankment. If this internal erosion is not controlled at an early stage, it may lead to voiding and hence settlement of the crest or the onset of piping as the flows increase with time. The phenomenon of internal erosion is considered to be an inevitable consequence of seepage and as such, has already been addressed above.

B2.3 External factors affecting embankment performance

Section B2.1 introduced geotechnical factors and mechanisms affecting embankment performance. This section considers external factors that can affect performance. These cover a wide range including:

- Vegetation
- Animal activity
- River or coastal morphology
- Third party action
- Legislation
- Climate change

B2.3.1 Vegetation

Appropriate and well-maintained vegetation can provide a valuable surface protection layer, which can reduce or prevent slope erosion and prolong the life of an embankment, even during extreme overtopping or overflowing events. It is generally considered good practice to maintain the embankment clear of trees and bushes, with a dense sward of grass or short vegetation. Trees and bushes can lead to destruction of the embankment body through root growth / action and may provide a focal point for local scour during extreme flood conditions. Likewise, once the surface vegetation has been damaged at one location, the integrity of the whole area and hence the embankment can be compromised leading to possible surface erosion.

Plates B2.1 to B2.8 show a range of conditions and issues associated with vegetation type and condition. More detailed information on how vegetation may affect performance can be found under Chapter D3 of this report.

Plate B2.1 Root action contributing towards failure of a culvert through embankment

B2.3.2 Animal infestation

Burrowing by small animals (e.g. rabbits and badgers) have been linked to several embankment breaches (see Tables B2.2 and B2.3). The burrowing activities can damage the integrity of embankments in two ways. Firstly, burrowing can remove or destroy surface vegetation which can lead to surface erosion particularly on the outward face. In addition, deep burrowing can create internal channels that can cause piping and excessive internal seepage.

Plate B2.2 Root action contributing towards failure of culvert through embankment

Plate B2.3 Excessive vegetation along embankment

Plate B2.4   Tree growing through embankment

Plate B2.5   Poor vegetation quality on rear face of embankment

Plate B2.6 Weed cuttings dumped on inward face of embankment

Plate B2.7 Different vegetation management on each riverbank (note fence protruding into channel)

Plate B2.8 Higher vegetation growth within flow channel

B2.3.3 River or coastal morphology

Changes in local morphology can lead to undermining of flood management structures and subsequent failure. Whether the cause is longshore or offshore sediment movement, resulting in lowered beach levels and greater exposure to wave action or lateral movement of a river or flow channel, the end effect is the same. Ground levels adjacent to the embankment are lowered leaving the embankment less stable or exposed to more rapid erosion, or a combination of the two.

Where morphological effects are causing damage, the source of the problem may not always be immediately obvious. For example, works on a river to stop meandering or protect bed levels at one location, may have an adverse affect tens or hundreds of metres away. Coastal works at one location may result in changes to longshore sediment movements that have an impact many kilometres along the coast.

Plates A2.11 and A2.34 both show damage caused through changes in river morphology.

B2.3.4 Third party action

Actions by third parties can result in damage to or failure of an embankment. Often actions taken are by people unaware of the function or performance of a flood embankment. The situation typically arises where embankment is adjacent to or within areas of private property.

Common problems include:

- Excavation into embankments for property or garden features
- Construction on or in an embankment (property, garden features, fences etc)
- Inconsistent maintenance of vegetation
- Blocked access for maintenance
- Inappropriate and unauthorised bank and embankment protection measures

Plates A2.53 to A2.56 show a range of these problems.

B2.3.5 Legislation

Legislation can affect the way in which an embankment can be maintained or modified. If the embankment falls within a designated area (SSSI etc.) then depending upon the purpose of the legislation, maintenance or works of any type might be affected. Under these conditions a balance and agreement must be made with the enforcement agency in respect of works on the embankment.

Plate B2.4 shows a tree growing through an embankment. This tree is protected and hence cannot be removed. A balance between embankment condition and maintenance of the tree has been made.

B2.3.6 Climate change

Climate change may affect flood embankments in a number of ways. For example, factors may include:

- Increased peak flood conditions
- Variation in duration of storm / wet periods
- Increased intensity and duration of dry summers

Variation in the duration of particularly dry or wet periods will begin to affect the condition of embankment body material. For example, longer drier periods may lead to the desiccation of clay fills and peats. Plate B3.18 shows an example of lateral sliding of an embankment which has occurred due to drying of the peaty fill material.

At present the extent of these impacts of climate change is still uncertain.

B2.4 Case histories of instability and breaching in England and Wales

Although research has been carried out into breach formation and the overall stability of flood embankments and there is general understanding of good practice, there is a shortage of well-documented case histories about embankment failures. This is partly due to the unpredictable and violent nature of an embankment breach. Often the researcher is left with scant evidence of the failure event such as occurred in the 1953 North Sea floods. Instead it has often been more fruitful to examine partial failures where the evidence of instability is still intact. Nevertheless interviews of principal flood engineers in the Environment Agency followed by a review of several case histories about partial failures or extensive repairs to flood embankments in the UK (Environment Agency, 1996) allowed a series of case histories to be collated as listed in Tables B2.2 and B2.3. In most cases the embankments were up to 4m in height apart from the larger embankments for the Forty Foot Drain and Ouse Wash in the Anglian Region.

Although not exhaustive, the field records identify the main modes of failure of flood embankments across different regions in England and Wales as follows:

- Erosion of the inward face and crest due to wave action
- Erosion of the outward face and crest due to overtopping
- Shallow slippage of inward face due to erosion of toe
- Shallow slippage or erosion of outward face linked to piping through animal burrows or excessive seepage through fissured clay fill leading to breach formation
- Shallow slippage of the inward face after rapid lowering of flood levels due to poorly constructed revetment
- Deep seated slippage of outward face due to excessive hydraulic uplift pressures in the underlying strata
- Large scale translational movement due to low strength organic soils acting as founding strata
- Deep seated slope instability caused by embankment construction on soft clays

(Note that various embankment failure modes are illustrated with sketches and photographs in Section B3.3).

In North Wales, for example, the use of slate waste and sand/shingle as fill material has resulted in high seepage rates through some embankments. Although the embankments have remained stable, adjacent roads have become flooded and impassable. The use of peaty fill material in North Wales has also led to embankment breaches caused by block failure. In contrast on the eastern side of the country the soft alluvial clays have caused two different problems. Firstly, soft organic clays in the vicinity of the Ouse Washes and Forty Foot Drain have led to excessive settlements and cracking along the crest of major flood embankments. Secondly, the uses of medium to highly plastic clays as fill material along estuaries in Essex and Kent have resulted in finely fissured embankments. Shrinkage of clay fill has also been compounded by the low rainfall on the eastern coast of the country. The fine fissures have been linked to slope instability either by contributing to slope failure after drawdown of floodwaters or increased seepage through the landward slope, similar to reports for the 1953 North Sea floods.

Table B2.2 Recorded breaches or partial failures of flood embankments in Southern and Eastern England post North Sea floods 1953

Region	Mode of instability	Underlying drift geology
ANGLIAN REGION		
River Blyth (nr. Blythburgh)	Slippage of inward face following rapid drawdown linked to tension cracks in clay fill (PI = 20 to 50)	Alluvium Glacial sands and gravels Boulder clay
River Alde (nr. Ham Sluice)	Slippage of outward face linked to fine and major fissures present in clay fill. Seepage reported through and under embankments linked to historic Dutch mattresses of vegetation	Alluvium Glacial sands and gravels Boulder clay
Breydon Water (Great Yarmouth)	Seepage reported through and under embankments	Complex geology of Breydon Formation containing buried sand channels and layers of peat
Forty Foot Drain	Bank slippage linked to erosion from wave action	Alluvium Peat (Silt dredgings used for fill)
Ouse Washes	Major longitudinal and lateral cracking of new embankment	Alluvium Peat
THAMES REGION		
Crayford Marshes	Excessive hydraulic uplift pressures beneath stratum of peaty clay alluvium leading to slope instability of the outward face	Peaty clay overlying stratum of sand and gravel in hydraulic continuity with R Thames
SOUTHERN REGION		
River Ouse (Southease, Lewes)	Catastrophic breach linked to historic slip over old river course and revetment constructed using very poor quality chalk	Alluvium
River Ouse (upstream of Lewes)	Historic problems with seepage from groundwater springs	Alluvium River terrace deposits
River Rother (Monk Bretton Bridge, Rye)	Significant seepage of high tide linked to known badger set in the embankment. Potential breach avoided by rapid backfilling with Wealden Clay	Alluvium
River Arun (Downstream of Ford bridge)	Problems with seepage through outward face and erosion of inward face by wave action	Alluvium

Table B2.3 Recorded breaches or partial failures of flood embankments in Central and North West England and Wales post North Sea floods 1953

MIDLAND REGION	Mode of instability	Geology
River Severn (Vyrnwy Confluence)	Recurring slippage linked to rapid drawdown following prolonged period of high river flow compounded by toe erosion at bends in the river	Alluvium River terrace deposits
River Severn Argae	Slippages caused by erosion from meandering river	Alluvium River terrace deposits
River Trent (Susworth, Derrythorpe Butterwick, Bosley Dyke)	Seepage through discrete zones within embankment linked to design life (30 years)	Alluvium River terrace deposits
Lower Trent and Lower Severn	Shallow slips on over-steep slopes (typically 1 in 1)	Alluvium River terrace deposits
NORTH WEST REGION		
River Mersey	Build up on lower berm causing instability and possible breach of upper berm	Alluvium River terrace
River Gowy	Blow out of Armorbloc revetment linked to excessive pore pressure following rapid drawdown	Alluvium (silt) Glacial sands and gravels
River Wyre	Extensive rabbit infestation of embankment	Alluvium Blown sand Peat
River Duddon	Complex glacial ground conditions leading to construction difficulties and increased costs	Morainic drift
Fleetwood Estuary (Piling)	Failure of stone mattress and 1 in 3 slope linked to internal erosion of fine sand fill behind mattress. Reinstated at 1 in 6 slope with reinforced turf revetment. Material was locally obtained from borrow pits in salt marsh	Alluvium Blown sand
WALES		
Borth Estuary	Breaches have occurred in embankments constructed from peat resulting in large translational block movement	Peat Blown sand Alluvium
River Dovey	Breached during 1965 Flood	-
Mawddach Estuary	Embankment constructed from slate waste. Piping through embankment reported but nevertheless stable at high seepage rates	Alluvium
Mawddach Estuary	Breaches caused by large translational movement for embankments built from peat.	Alluvium Peat
Dyssini Estuary	High seepage rates through sand embankment and beneath neighbouring road	Blown sand Alluvium
River Conway	Breached during 1965 Floods	Morainic drift Alluvium River terrace deposits
Malltraeth District	Rabbit infestation of embankments linked to breaches	Blown sand Alluvium

B2.5 Case histories and research worldwide

Many of the types of embankment failure or problem in the UK have been reported in other countries where similar ground conditions and geology exists. Some examples of embankment failures in The Netherlands and USA are given in Table B2.4. Not surprisingly the similarity of soil conditions in The Netherlands and Anglian Region have resulted in similar problems with excessive settlement of embankments built on soft organic clays. In the USA, reported breaches of embankments for the 1991 floods in the Lower Mississippi River Basin have been attributed to piping failure due to animal infestation or sub-surface seepage through buried channels of coarse-grained soil or else overtopping of the embankment that led to slope erosion.

Table B2.4 Some breaches and embankment failures in USA and Europe

Country	Mode of Instability	Geology
Lower Mississippi Flood Basin, 1991 Floods	i) Boiling or piping of sand behind flood embankments ii) Breaches linked to animal infestation iii) Breaches linked to overtopping	Marshes Alluvium (sand)
Bergambacht, Holland	Excessive lateral movement of embankment inland attributed to uplift pressures	Alluvium (clay and sand) Peat
Markiezaatsdam, Holland	Excessive lateral deformation causing major longitudinal cracking, linked to the development of plastic zones in the clay founding strata	Alluvium (clay) Peat
Streefkerk, Holland	Excessive lateral movement with longitudinal cracking as above	Peat Alluvium (clay and sand)

Research into geotechnical performance of flood embankments has tended (naturally) to concentrate on materials relevant to the local geology. For example in The Netherlands, extensive laboratory and field studies have been undertaken into breach formation and propagation due to overtopping of sand embankments or clay covered, sand core embankments.

In the past, research has tended to be uncoordinated, with data collected from various laboratory tests, and occasional field or prototype tests, being used to calibrate empirical models for the prediction of breach formation rate. The scarcity of reliable field data and the difficulty of scaling the interaction and behaviour of soils and water means that the reliability of existing models is limited. Recent research in this field has been undertaken through the EC IMPACT project (see www.impact-project.net from which work undertaken by various researchers may be accessed). This work collected quality data sets from field and laboratory tests to support the assessment and compare the performance of different breach models world-wide. Summary tables comparing model performance are provided. In addition, research into the uncertainty associated with breach models and the parameters used was undertaken.

Common to most existing research is a focus upon the prediction of breach formation rather than breach initiation. Future research and improved practice will need to focus on the strengthening of embankments to prevent initiation of failure as well as breach formation. Information on both the probability of failure and the extent of breach will be needed for improving the RASP and PAMS analysis (see Section A4.4). Some key aspects of these are being addressed under the FLOODsite project (www.floodsite.net).

The more recent embankment failures at New Orleans (2005) have focussed attention upon factors affecting embankment breach formation and in particular breach initiation processes. This catastrophic event has initiated a number of research and information sharing initiatives (e.g. collaboration between the US Army Corps of Engineers and the UK flood risk management community) that should help to advance understanding of these processes.

B3 MONITORING AND PERFORMANCE ASSESSMENT

B3.1 General

The framework for the management of flood embankments (Figure A3.2) introduces the process of embankment monitoring together with condition and performance assessment followed by the optional 'management action' depending upon the findings of the assessment. The efficiency and effectiveness of this process can be improved by introducing prioritised and risk based approaches into the selection of monitoring, inspection and management actions.

This Chapter first looks at the current practice for monitoring and performance assessment. Various Cause-Consequence scenarios are then considered, providing guidance on likely failure processes and performance indicators to aid inspection. This is followed by guidance on how monitoring and performance assessment tools may be improved in the future.

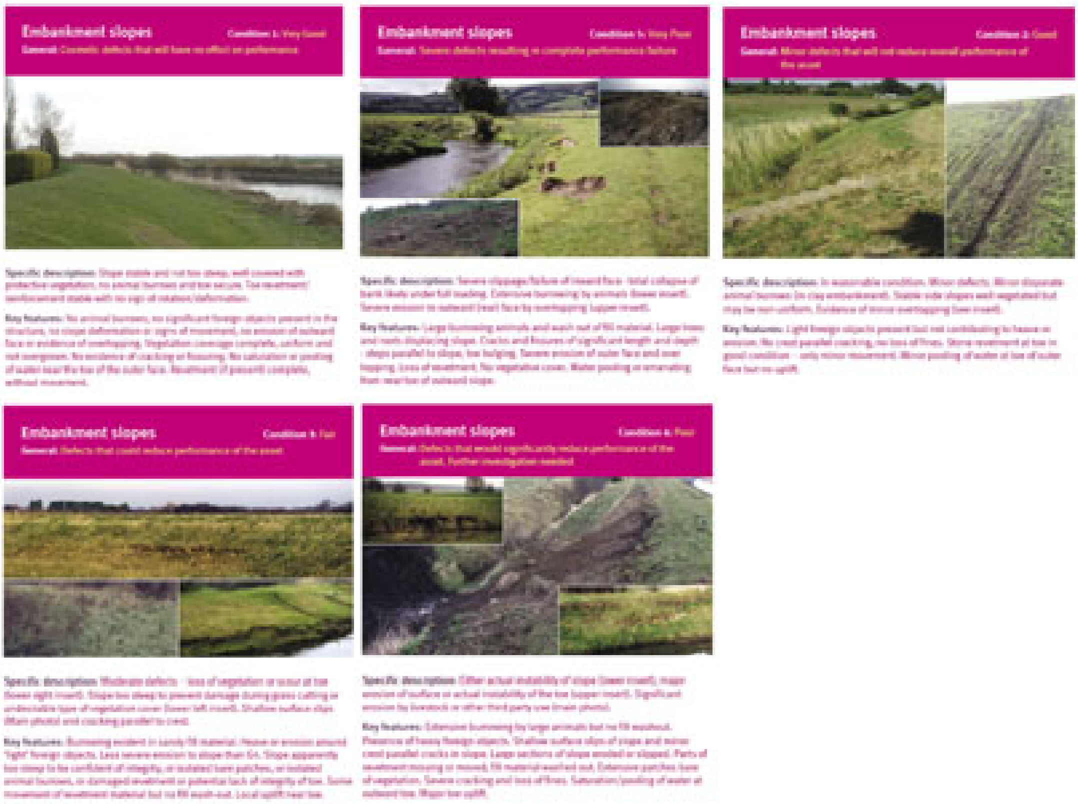
B3.2 Current approach to monitoring and performance assessment

The current approach is based around a periodic assessment and review of embankments. Allocation and application of resources varies between locations depending upon perceived priorities and site specific needs.

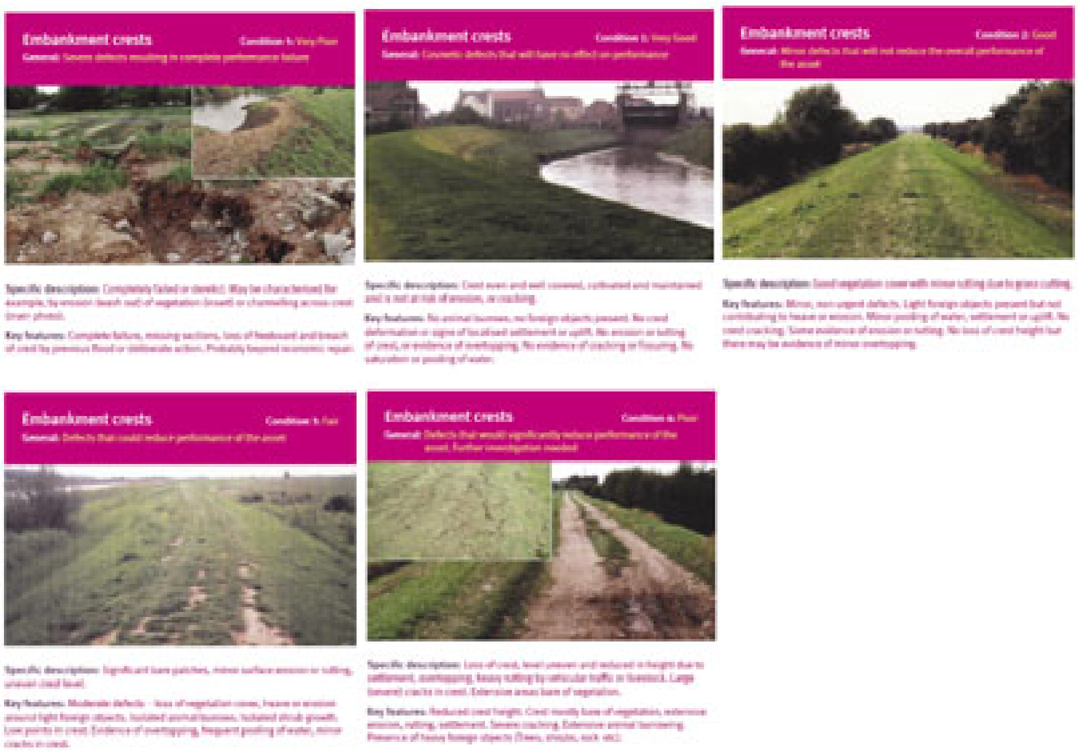
Data on embankment type and condition is typically collected through visual inspection. Where problems are noted and more detailed information is required, then further investigations or monitoring by experienced practitioners will normally be implemented on an ad hoc basis.

Guidance on what data to collect and the grades attributed to different conditions are given in the Environment Agency – Condition Assessment Manual.

> ⓘ **Good practice**
> Condition Assessment Manual:
> The Environment Agency Condition Assessment Manual (updated 2006) provides guidance on how to determine the condition of a defence when undertaking a visual inspection. This condition grade then feeds into the asset management process (see Figure B3.1). For each structure, five condition grades are given. Photos are provided as examples of the different grades. For embankments, individual assessments are made of each face and the crest. Note that this approach now incorporates some performance measures and will be further improved to provide comprehensive coverage of potential failure modes under the PAMS project (see Section A4.4.4).



Grading and guidance provided for assessing embankment slopes



Grading and guidance provided for assessing embankment crests

Figure B3.1 Condition assessment guidance for inspecting embankments

The current approach to assessment provides a framework for data collection, guidance for visual inspection and steps towards attributing risks related to the asset under inspection to receptors that would be impacted by its failure. However, the approach to asset management does not fully:

- Focus data collected on embankment failure mechanisms
- Provide a means for prioritising inspection and data collection to high risk areas
- Relate receptors at risk to specific lengths of defence, so permitting prioritised inspection, maintenance and works

Practice has varied from region to region, and the implementation of naturally consistent asset management methods is not yet complete. Typically, local knowledge of the asset system, past behaviour of the embankments and a broad awareness of implications of failure have been used to steer the frequency and location of inspections and maintenance work. Steps are being taken to incorporate this into a more formalised process for such procedures. This will help to reduce subjectivity and encourage national consistency in asset condition.

Data management is fundamental to an effective asset inspection and management system. The basic data is held in the comprehensive national database system – the National Flood and Coastal Defence Database (NFCDD). The NFCDD acts as a central store for all data relating to flood and coastal management assets, and as such will provide a common basis for data underpinning a range of flood management tools (See Section A4.4).

For more information on Condition Assessment see Chapter D2.

Box B3.1 Monitoring of reservoirs under the Reservoirs Act 1975

On-line or off-line river flood retention reservoirs, where the volume of water stored above the lowest natural ground level exceeds 25,000 cu m, fall within the ambit of the Reservoirs Act 1975. These reservoirs are defined as 'large raised reservoirs' and as such the reservoir Undertaker (Owner) is required to:

- have the reservoir inspected from time to time by an independent qualified civil engineer (the Inspecting Engineer) and obtain from him a report of the result of his inspection
- appoint a qualified civil engineer (the Supervising Engineer) to supervise the reservoir and keep the Undertaker advised of its behaviour in any respect that might affect safety

For i) above, the Inspecting Engineer's inspections/reports are usually carried out at ten-yearly intervals, provided that the reservoir has no serious problems in the interests of safety or that an inspection has not been requested by the Supervising Engineer.

For ii) above, the Supervising Engineer is required to provide the Undertaker with an annual statement, showing the actions he has to take to comply with any matters directed by the Inspecting Engineer, and ensuring that the Undertaker is complying with his statutory duties. This normally involves the Supervising Engineer with one annual visit to inspect the reservoir.

Future inspections by appointed Supervising Engineers may include preparation, by the Supervising Engineer, of relevant information sheets that would be submitted with his Annual Statement. Data from these inspections can be entered into the NFCDD for EA flood storage reservoirs.

B3.3 Cause-Consequence scenarios as aid to inspections

B3.3.1 General

Linked to the various failure mechanisms shown in Figure B3.2, Sections B3.3.2 to B3.3.7 provide information on various failure mechanisms as an aid for inspections. For each failure mechanism, the following information is provided:

- Description of failure mechanism
- List of likely performance or problem indicators
- Sketch showing failure mechanism
- Photo(s) showing examples of the asset performance or problem

The intention is that the information provides quick and relatively simple reference material to aid the inspection process.

Figure B3.2 provides a Cause-Consequence diagram presenting factors affecting the performance of flood embankments. To aid presentation, this diagram has been split into four parts covering factors associated with (a) underlying ground conditions, (b) embankment earthworks, (c) secondary structures, and (d) surface and toe protection measures. All of the factors and links presented in this diagram are consistent with the information presented in Table B2.1.

Following the Cause-Consequence diagram (Figure B3.2), information on each failure mechanism is presented. For reference:

Section 3.3.2	Settlement	Also see Chapter D4
Section 3.3.3	Deep rotational failure	Also see Chapter D5
Section 3.3.4	Seepage and piping	Also see Chapter D8
Section 3.3.5	Shallow slope instability (and softening)	Also see Chapter D6
Section 3.3.6	Erosion	Also see Chapter D10
Section 3.3.7	Translational sliding	Also see Chapter D5

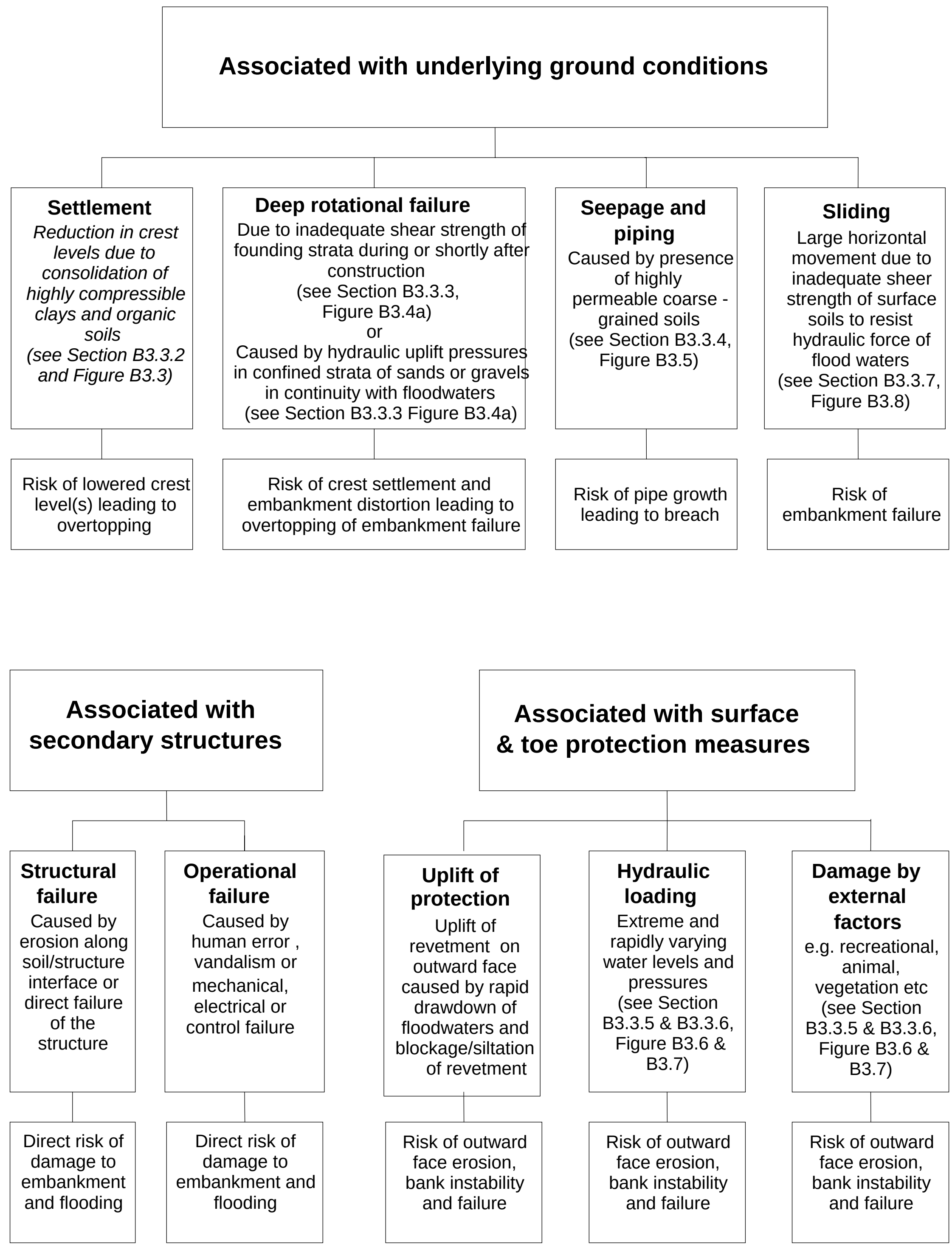


Figure B3.2 Cause-Consequence diagram for behaviour of flood embankments

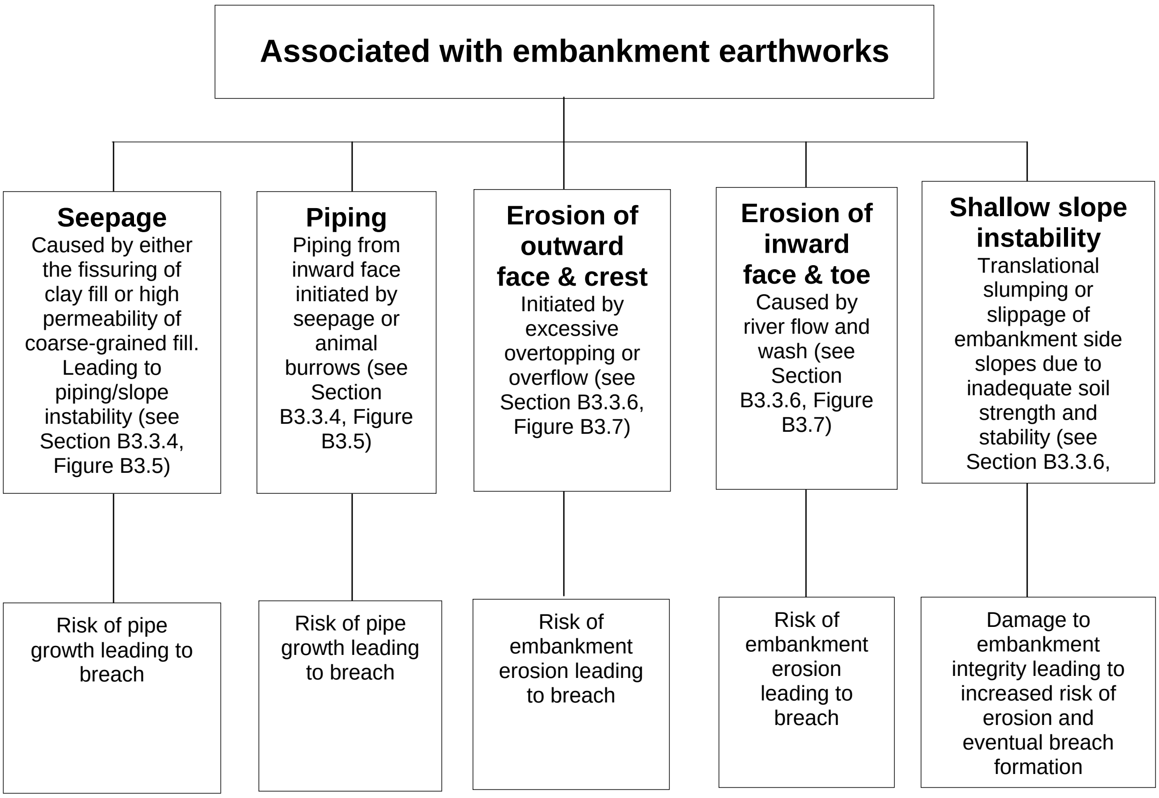


Figure B3.2 Cause-Consequence diagram for behaviour of flood embankments (continued)

B3.3.2 Settlement

<u>Overview</u>
Most fluvial and estuarine embankments have been built on flood plains that may contain layers of soft clay or peat. The underlying soils can undergo relatively large time-dependent settlements due to consolidation under an imposed load. This is particularly the case for larger embankments of over 2.5 metres height. For historical flood embankments which can be many centuries old, much of this settlement will already have occurred and possibly been obscured by subsequent filling. In contrast, newer embankments particularly when constructed to full height in one continuous operation may be prone to large ongoing settlements of perhaps hundreds of millimetres.

<u>Problem indicators</u>
Indicative signs of settlement include

- Reduction in crest level
- Possibly localised dipping of crest (irregular profile when viewed from a distance), fenceline or kerbing.
- Cracking, bulging, slumping of surface protection (e.g. concrete slabs)

See Chapter D4 for more information on Settlement.

Failure mechanisms

Figures B3.3a and B3.3b show how settlement can occur through general consolidation of material and through local settlement. Plates B3.1 and B3.2 show examples of these processes.

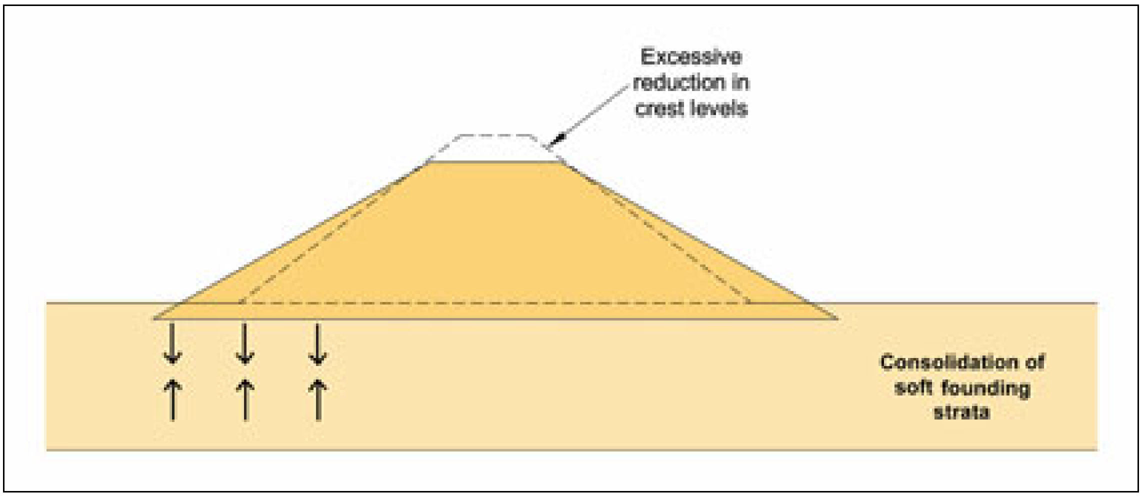


Figure B3.3a Settlement: Process and indicators

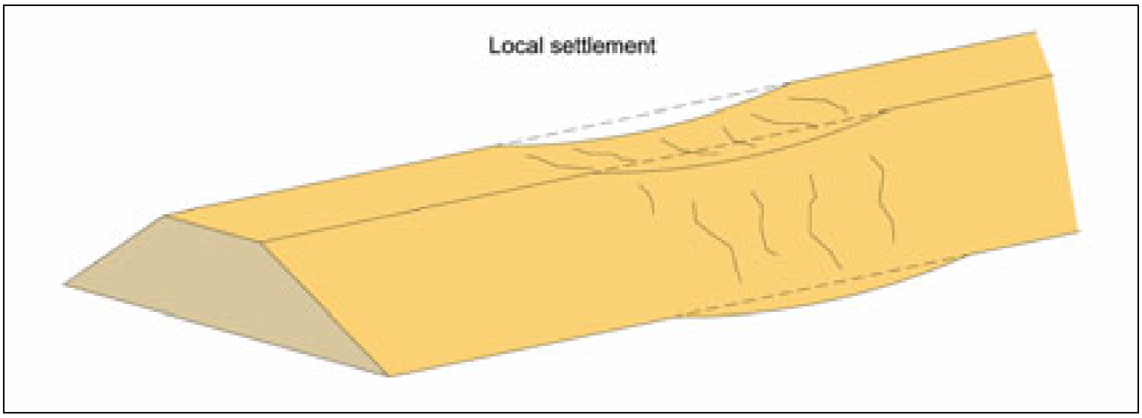


Figure B3.3b Settlement leading to a localised dip in embankment crest level

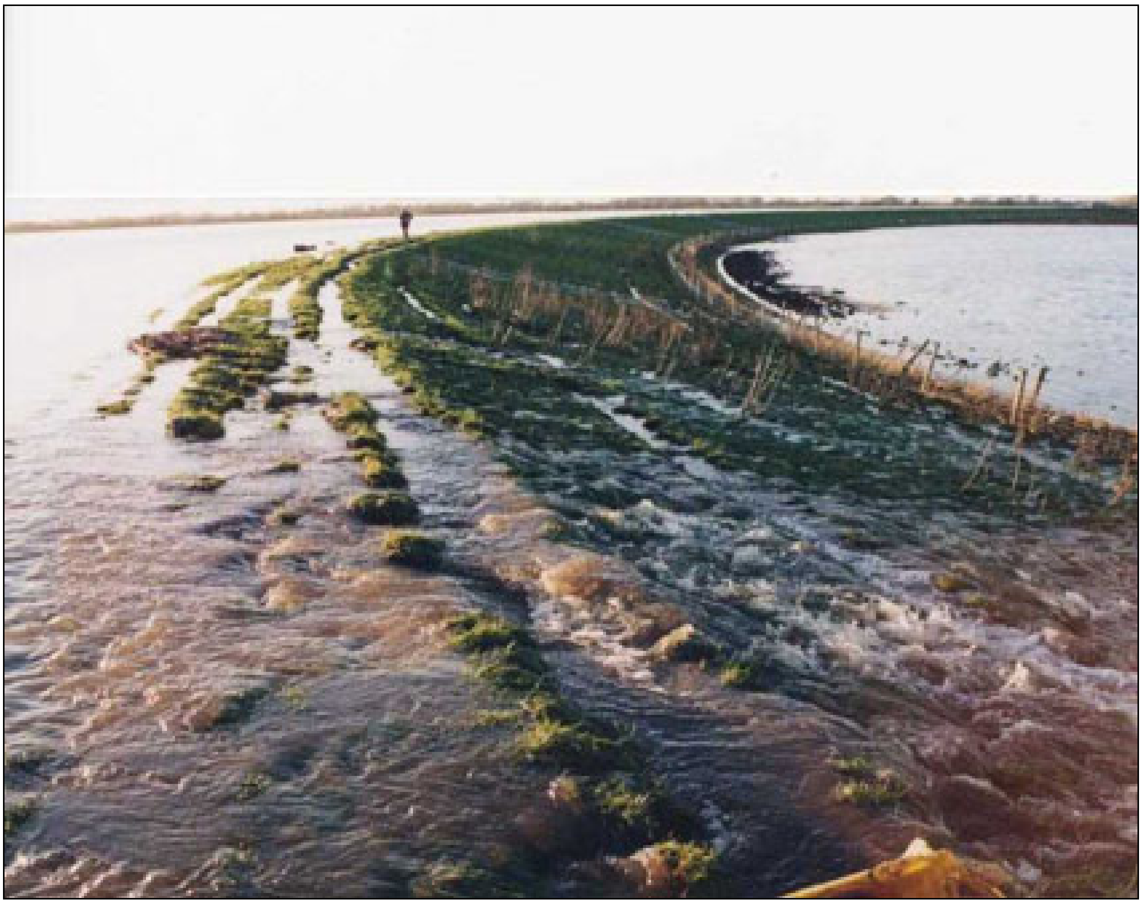


Plate B3.1 Localised overtopping showing dip in embankment crest level

Plate B3.2 Localised overtopping showing dip in embankment crest level

B3.3.3 Deep rotational failure

<u>Overview</u>
Deep rotational failures are typically initiated by changes to an existing situation such as the construction of a new embankment or raising of an existing embankment. Deep rotational failure will usually manifest itself as cracking and downward displacement of part of the crest, bulging of the embankment slope, particularly the base, and heave of the ground in front of the toe. It results in a softening of the embankment fill and a weakening of the foundation soils. If it does not trigger a breach in itself, this may quickly follow unless immediate repairs are carried out.

<u>Problem indicators</u>
Indicative signs of deep rotational failure include:

- Longitudinal cracking along the crest
- Downward displacment of the crest
- Bulging of outward slope and slumping at toe
- Heave of ground in front of toe

See Chapter D5 for more information on deep rotational failure.

<u>Failure mechanisms</u>
Figure B3.4 shows how deep rotational failure can occur as a result of excessive hydraulic uplift or weak foundation material. Plates B3.3 to B3.6 show examples of these processes. Failure may also be prompted by excavation (of drainage ditches) close to the embankment and / or rapid drawdown of water levels in the drainage ditch or against the embankment.

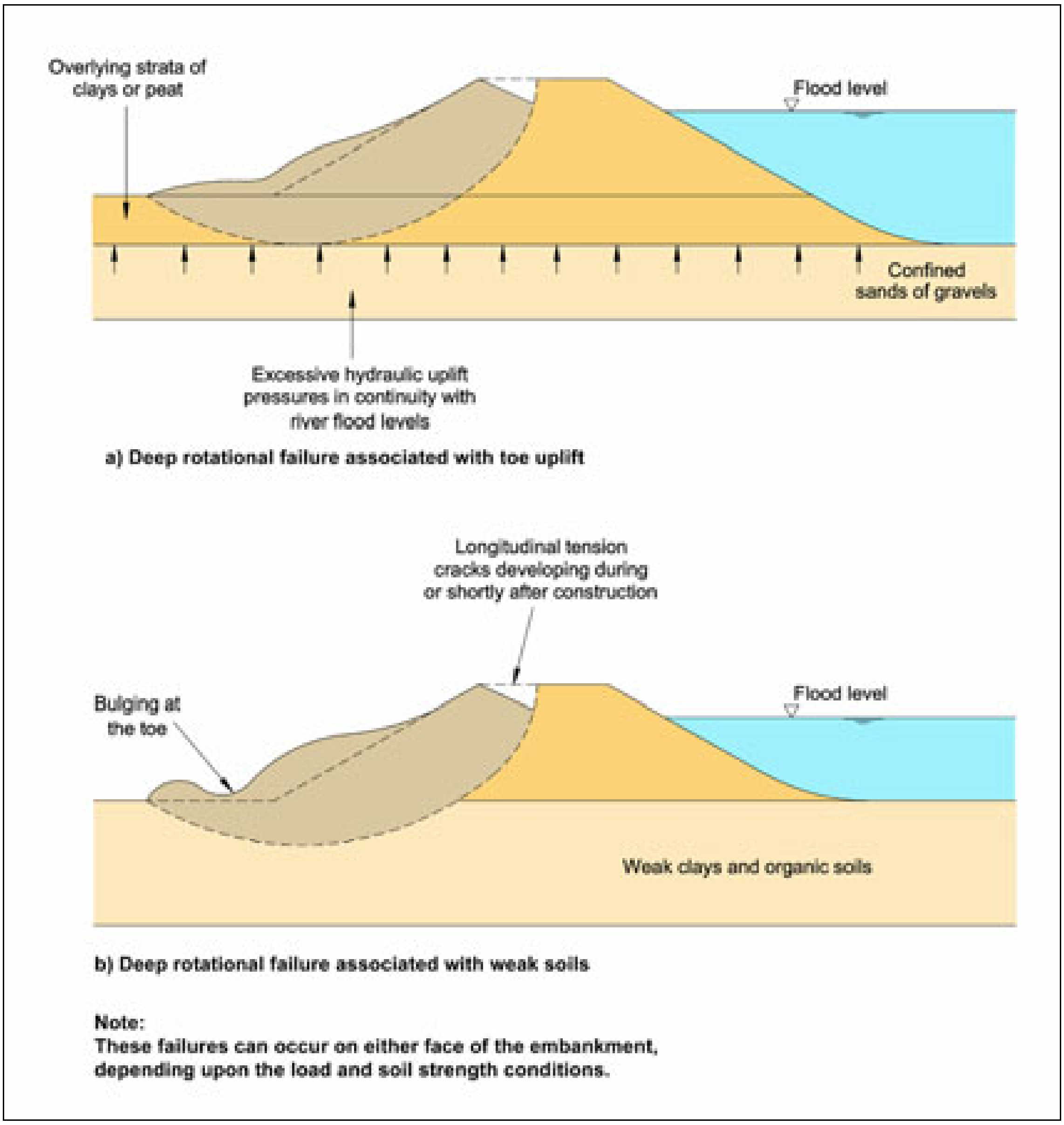


Figure B3.4 Deep rotational failure – process and indicators

Plate B3.3 Rotational failure through inward face of embankment

Plate B3.4 Rotational failure through inward face of embankment

Plate B3.5 Cracking through embankment crest due to rotational failure

Plate B3.6 Cracking through embankment crest indicating rotational failure

B3.3.4 Seepage and piping

Overview

Seepage through an embankment is generally caused by the presence of a permeable layer within the fill or by the existence of cracks or fine fissures. Seepage beneath an embankment is most likely to be caused by a permeable layer (sand, gravel or possibly peat) within the foundation soils. The occurrence of seepage will usually be indicated by areas of standing or flowing water, by damp patches on the ground in front of or on the side slopes of the embankment or by variations in the type or condition of vegetation. Seepage may not always be apparent; in some cases it will only be noticeable during conditions of high water levels or flooding. If left untreated, finer particles of soil will be washed out of the embankment or its foundation by the flow.

Problem indicators

Indicative signs of seepage and piping include

- Areas of standing or flowing water
- Damp patches on the ground in front of the embankment or on its side slopes
- Variation in the type or condition of vegetation
- Wash-out of finer particles of soil
- Sink holes on outward face
- Settlement of embankment crest

See Chapter D8 for more information on seepage and piping.

Failure mechanisms

Figure B3.5 shows a range of mechanisms through which seepage and piping may occur. Plates B3.7 to B3.9 show seepage, piping in action and a breach caused through piping.

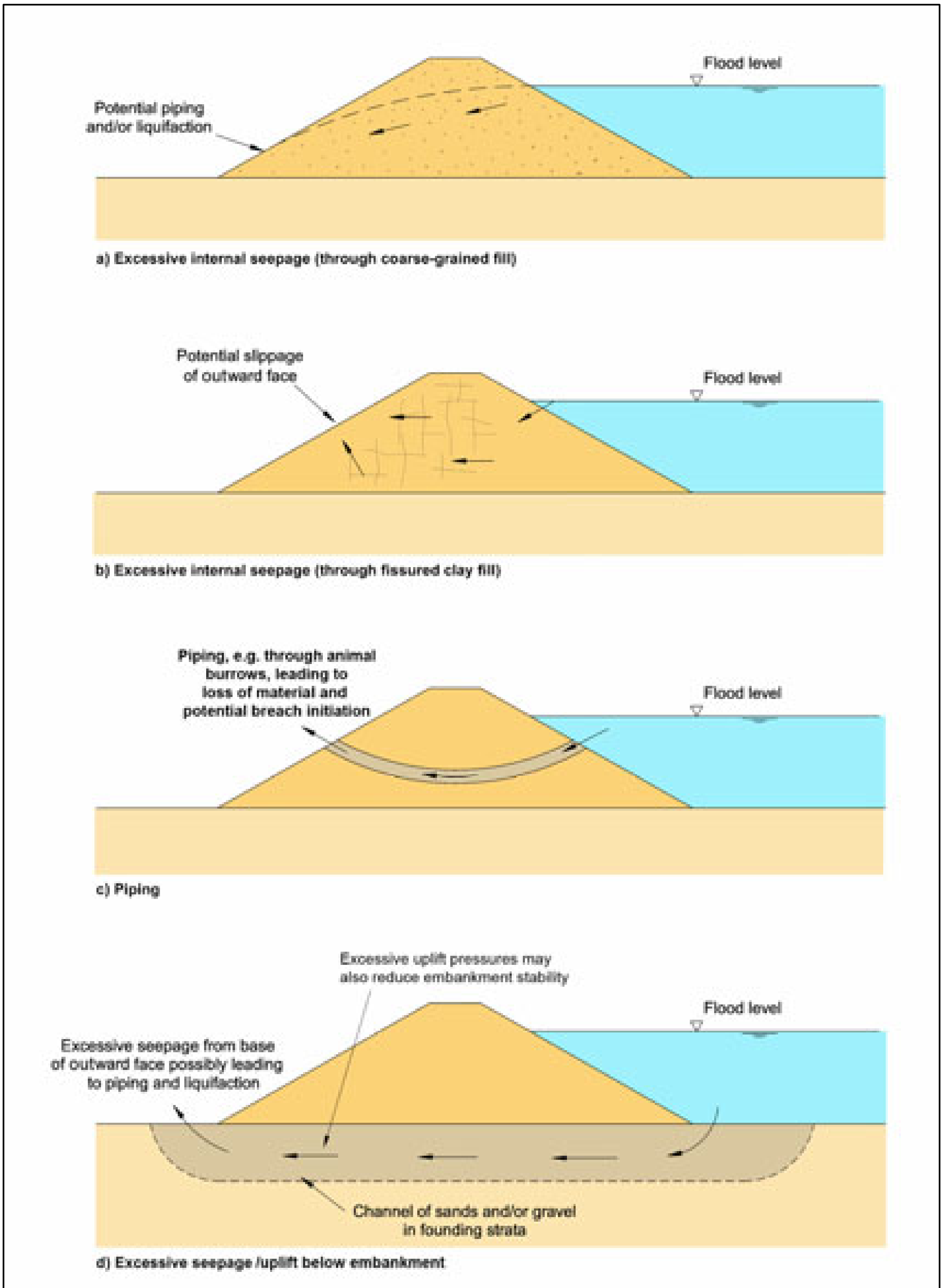


Figure B3.5 Seepage and piping: Process and indicators

Plate B3.7 Seepage through embankment

Plate B3.8 Piping through embankment

Plate B3.9 Breached embankment on the River Alde (remains of pipe can be seen in centre)

B3.3.5 Shallow slope instability (and softening)

<u>Overview</u>
Most flood embankments have been constructed over a period of many years with locally won clayey soils. Over a period of time some soils will weather and soften from the surface down. This effect will be aggravated by seasonal variations; the embankment will dry and possibly crack over the summer months and these cracks will then form a pathway for water in the autumn or winter (by infiltration of rain or seepage of floodwater). For steep sided embankments, this softening process will reduce the factor of safety against shallow slip failure, potentially to a point where surface slumping occurs.

<u>Problem indicators</u>
Indicative signs of shallow slope instability include:

- Furrowing or ridging of the surface of the side slopes
- Areas of exposed soil

See Chapter D6 for more information on shallow slope instability.

<u>Failure mechanisms</u>
Figure B3.6 shows how shallow slope instability can occur. Plates B3.10 to B3.12 show examples of this process.

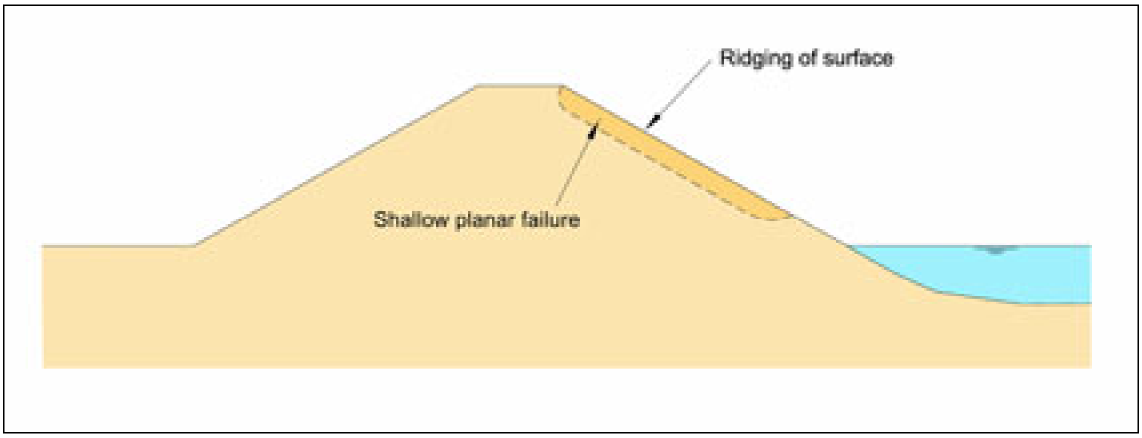


Figure B3.6 Shallow slope instability: Process and indicators

Plate B3.10 Inward face instability (due to undercutting of embankment toe)

Plate B3.11 Inward face instability due to undercutting and surface failure

Plate B3.12 Inward face instability due to undercutting and surface failure

B3.3.6 Erosion

Overview

Surface erosion of an embankment can be caused by several factors such as severe animal grazing and the erosive action of water. Erosion of the inward face can be caused by wave action, propeller wash from vessels using the river or high velocity flow on the outside of a meander. In contrast erosion of the outward face is generally caused by overflow of flood water across the crest. It can also be a part of the failure process caused by seepage and excessive internal erosion leading to a wash out of fine soil, voiding and settlement of the crest or the onset of piping as the flows increase with time.

Problem indicators

Indicative signs of surface erosion include:

- Bare patches along embankment slopes and around secondary structures
- Wash out of fine soil and the onset of piping as the flows increase with time
- Voiding and settlement of the crest
- Shallow slumping of inward face (erosion of toe)
- Channelling across crest and over outward face

See Chapter D10 for more information on erosion and surface protection.

Failure mechanisms

Figure B3.7 shows how erosion can occur as a result of water overflowing an embankment. Plates B3.13 to B3.17 show examples of this process.

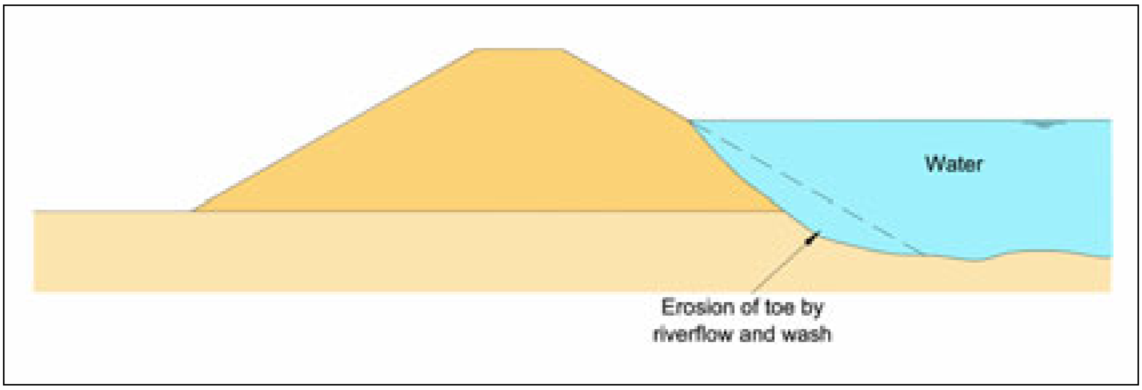


Figure B3.7a Erosion of inward face / toe

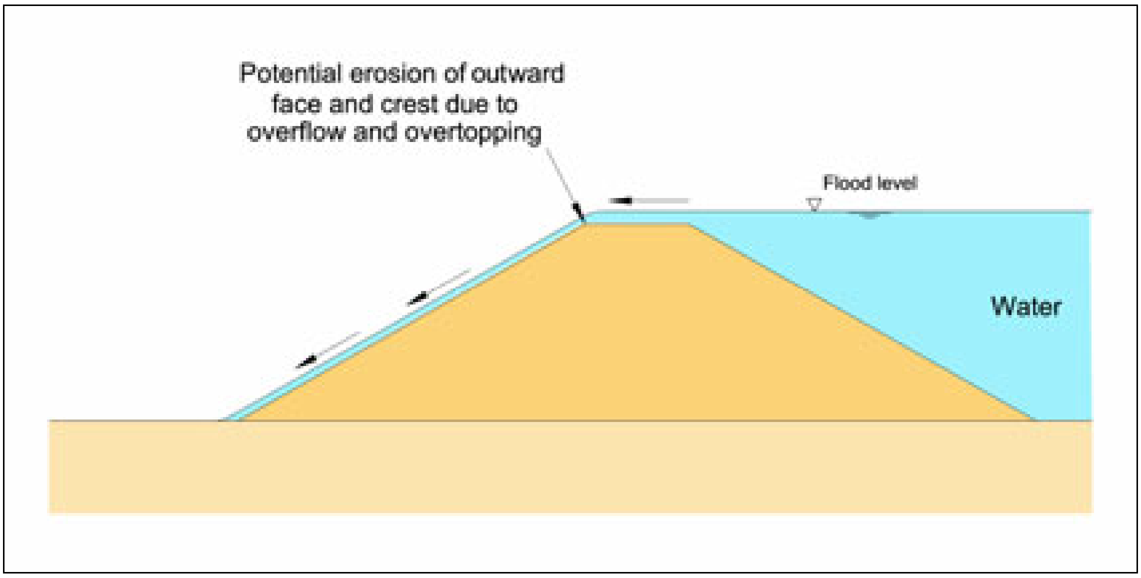


Figure B3.7b Erosion process – overflow

Plate B3.13 Erosion of outward face due to overtopping

Plate B3.14 Erosion of outward face due to overtopping

Plate B3.15 Erosion of inward face by river flow

Plate B3.16 Erosion of inward face due to wave action

Plate B3.17 Erosion of face due to animal activity / surface instability

B3.3.7 Translational sliding

Overview

The presence of very weak surface layers of peats and clays in the foundation can result in a horizontal block movement of an embankment when the undrained shear strength of the surface layer is insufficient to resist the hydraulic forces created by the flood waters acting on the embankment.

Problem indicators

Indicative signs of translational sliding include:

- Bulging of the inward slope
- Transverse and other tension cracks surrounding block movement

Failure mechanisms

Figure B3.8 shows how a translational failure may occur where a weak surface exists between embankment body and foundation material. Plates B3.18 and B3.19 show examples of this process.

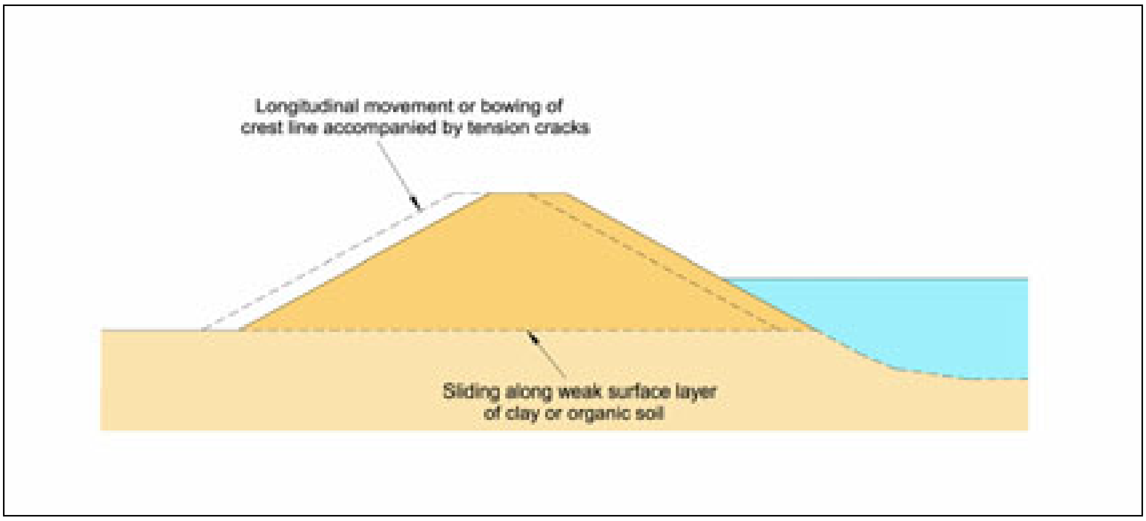


Figure B3.8 Translational sliding - process and indicators

Plate B3.18 Translational block failure of embankment

Plate B3.19 Translational block failure of embankment

B3.4 Improved prioritisation of inspection and assessment

Given the extent of flood embankments within most asset systems inspections need to be prioritised such that known problem embankments, critical defended areas or lengths of newly constructed embankment are inspected on a more frequent basis. Methods for prioritisation of inspections in this manner are an essential part of risk / performance-based asset management, and are being progressively introduced within the EA's asset management process.

A rational approach is to vary embankment (or asset) inspection frequency according to the findings of earlier inspections (i.e. embankments found to be in a poor condition are re-inspected more frequently than those found to be in a good condition). Actions such as the triggering of non-routine maintenance and repair works may also be integrated into such a condition-based system.

Prioritisation must also be linked to the consequence of failure of the asset. As the inspection process is aimed at maintaining performance standards, inspection frequency should ideally be linked to risk (i.e. the probability of embankment failure multiplied by the consequences of failure; see Part C). In this manner, embankments identified as high risk (e.g. high probability of failure and high consequence) will be prioritised above those identified as low risk. Some methods currently in use by the Environment Agency are described in brief in Section D2.3 of this report; furthermore, a current EA research and development project addressing this subject (PAMS) is also described in that section and in Section A4.4.

Within other infrastructure organisations (such as Network Rail and the Highways Agency), such performance-based systems have been developed that include:

- A scoring system based upon different parameters observed in the field (e.g. visual observations of condition indicators and consequence of failure)
- A process for combining and weighting these parameters to provide a single value (e.g. a Performance Indicator on a scale of 1-100)

To operate such a performance-based system, the flood risk reduction attributable to any specific length of embankment must be identified. In the past, this has been done in general terms through the estimation of the number of residential properties (or, in greater detail, through house equivalents as in the FDMM) at risk from failure of the asset. However, when dealing with prioritisation within more complex flood defence systems, estimation of assets at risk is done in a more robust manner. With the RASP-based approach (see Section A4.4.2) potential flood damages are calculated and attributed back to individual embankment lengths. Application of this approach is enabling a risk and performance-based approach to be progressively introduced for prioritising interventions for managing the condition and performance of flood embankments.

Finally, in order to implement a risk and performance-based system for inspection and assessment (correctly prioritising embankments responding under a range of load conditions), the indicators or parameters observed in the field during inspection and used in the assessment system must relate directly to the mechanisms affecting performance. A simple example of this is of embankment performance with regards to overflowing of water (i.e. maximum flood defence level). Performance in this respect can only be determined if the crest level of the embankment is known.

Identification of key indicators and parameters for assessing performance is being undertaken as part of the PAMS project. For embankments, initial basic parameters have been identified (e.g. crest level, embankment material etc.). Basic problem performance indicators are also listed under Section B3.3 in relation to various embankment failure mechanisms. A separate project (see Report 2: Framework for action), parallel to PAMS, is being carried out to provide the best practicable representation of geotechnical processes for flood embankment management. It is likely that improved indicators and parameters will be identified for inspection and assessment in the future as our knowledge and understanding of embankment behaviour improves.

Asset information is currently being stored in the NFCDD and the scope of the embankment parameters being recorded there is also likely to be expanded in time. At the present time it is only possible to record relatively basic data such as:

- Embankment crest level
- Simple description of embankment material on crest and slopes

In the future it is expected that the additional information will also be recorded, perhaps including a more detailed description of embankment and foundation materials and key parameters reflecting such material response, behaviour etc.

(For further information on the development of risk based management tools, see Section A4.4).

B4 EMBANKMENT RAISING AND REPAIR

B4.1 Assessing the need for embankment raising or repair

Previous chapters of this report have addressed the issues of embankment performance and risk assessment; this chapter focuses on the procedures to be followed once improvement works are judged necessary. It includes a review of the options available for embankment improvement works and gives consideration to the engineering implications and limitations of embankment raising and repair. Amongst other things, this chapter also addresses the extent of appropriate ground investigations and outlines relevant design techniques. Finally, this chapter discusses important construction and monitoring issues.

As already discussed, the need for embankment raising should be based on condition surveys, performance assessments and a consideration of the consequences of embankment failure. The guidance in this chapter assumes that such studies and assessments have already been carried out. It must however be stressed that a decision to raise the level of river embankments at a particular location must be taken as part of an overall strategy and asset system management plan for that catchment / asset system; the consequences of local improvement or raising works on the rest of the catchment (both upstream and downstream) must be considered.

This chapter only addresses alterations to existing embankments. While the issues discussed are similar for both the construction of new flood embankments and embankment raising, new embankments will generally have a much more pronounced impact in terms of settlement and stability. They are not therefore considered within the scope of this report. All new flood embankments should be designed by appropriately qualified and experienced geotechnical engineers (as indeed should any major raising or repair of existing embankments).

B4.2 Options for embankment raising

B4.2.1 Additional earthworks on crest

When an embankment is insufficiently high to retain the design level of flood water, consideration will obviously be given to increasing its crest level. The most straightforward way to do this is by placing and compacting new fill material on the embankment crest. However, as illustrated by Figures B4.1 and B4.2, this can have the effect of narrowing the width of the embankment crest considerably. The Environment Agency’s normal requirement is for a minimum embankment crest width of 3.0 metres in order to accommodate the type of plant (excavators, mowers etc) that needs periodic access. As an increased embankment height of 0.5 metres with side-slopes of 2 horizontal to 1 vertical will reduce the crest width by 2.0 metres, it is unlikely that simple crest works will be an acceptable means of embankment raising.

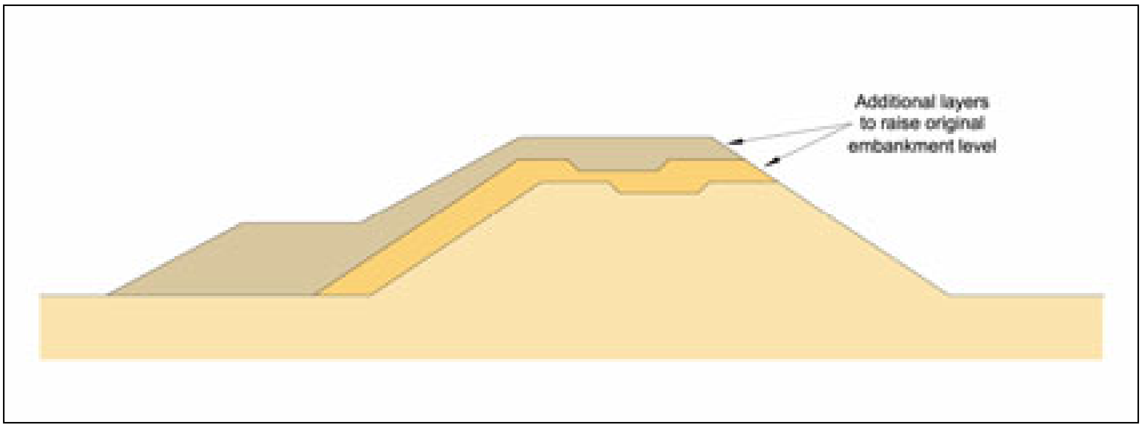


Figure B4.1 Raising embankments in layers

When embankment raising is carried out, the consequences of this work must be considered. In particular, the fill material must be selected to be sufficiently impermeable and compactable without being prone to fine fissuring. It must also be placed in such a way that the interface with the original embankment fill is neither a preferential drainage path nor a plane of weakness. This may involve the removal of topsoil and the careful preparation (by scarifying etc) of the underlying fill. In addition, embankment raising may initiate additional settlement of both the embankment and the underlying soils (which in many cases will be soft clays or peats). It will also reduce the factor of safety against embankment failure. These issues all need to be addressed as part of the design process; they are considered further in the following sections.

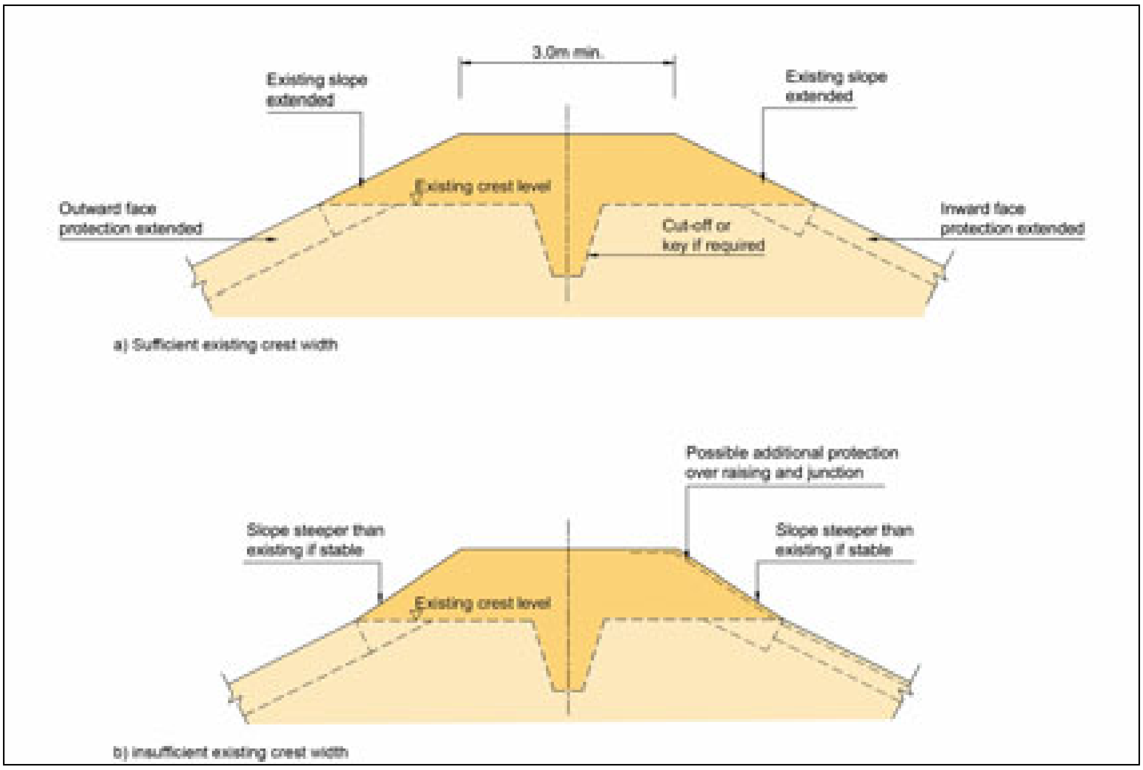


Figure B4.2 Raising the embankment crest elevation

B4.2.2 Additional earthworks on crest and face

If simple crest raising causes the crest width to be reduced by an unacceptable amount, then the embankment may be enlarged as shown in Figure B4.3. It is clear from this figure that not only is the amount of additional fill material considerably increased but also, additional land is required in front of the embankment, particularly if a new drainage ditch ("soke" ditch or "Delph" ditch) is required.

The earthworks must be properly designed both to accommodate the magnitude of anticipated settlement and to ensure stability at all stages of construction as well as in the long term. In order to maintain stability it may be necessary to raise the embankment in stages with pauses for consolidation. Berms to increase toe weighting and / or seepage length or flatter side slopes may also be required for stability.

Placing large volumes of additional fill material makes the raised embankment more susceptible to further settlement, particularly beneath the outward face of the embankment where the newly placed fill material applies proportionally higher pressures on the foundation soils (see Figure B4.3). In addition, the interface between the old embankment and the newly placed fill can become a plane of weakness (the new fill can slide down over the old).

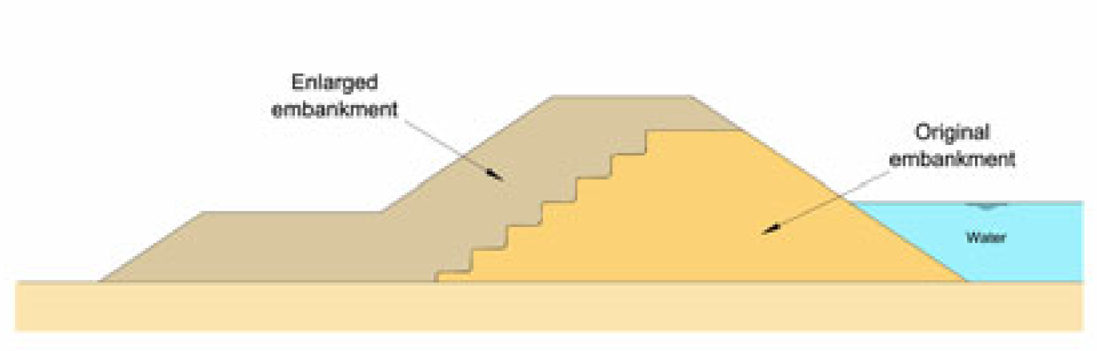


Figure B4.3 Enlarged embankment

B4.2.3 Embedded steel sheet pile walls

In some instances, embankment raising by the deposition of additional earthworks material will not be technically or economically viable. Perhaps no land is available for extending the embankment or perhaps the additional settlement initiated by the filling might adversely affect adjacent structures. In these cases, alternative solutions must be found. One commonly used approach when earthworks have been rejected is the use of embedded retaining walls.

An embedded retaining wall will extend vertically from the existing embankment. As such, if no supporting fill is needed, it applies virtually no additional vertical load on the embankment foundation and therefore does not initiate significant further settlement. It will also avoid the need to purchase additional land adjacent to the embankment.

For embankment raising (as distinct from embankment repair) it is usual to drive or jack the sheet piles through the crest of the embankment, leaving a sufficient length protruding from the surface to raise the flood protection level. From considerations of stability of the sheet pile wall, it is often better to install the sheet pile in the centre of the embankment to optimise the passive resistance against movement of the wall in any direction. However, such a location generally interferes with embankment maintenance (especially mowing). The sheet piling is therefore usually positioned close to the outward or inward edges of the crest. The required length and cross sectional wall thickness of the sheet piling can vary dramatically depending on the position of the wall and the design assumptions about the reliability of any passive support provided by the embankment adjacent to the sheet piling, as well as the amount of any additional fill (Figure B4.4).

B4.2.4 Reinforced concrete walls

Reinforced concrete walls can be installed on the crest of embankments to raise the effective crest level (Figure B4.4). As with embedded retaining walls, they allow flood defence levels to be raised vertically. However, because of their weight (and the weight of any additional retained fill), they impose a vertical loading that can trigger additional settlement. Their performance as flood defence walls is also dependent on the joints between the individual bays or pre-cast units. As and when this deteriorates with age or as a result of settlement, then the water retention capability can be compromised.

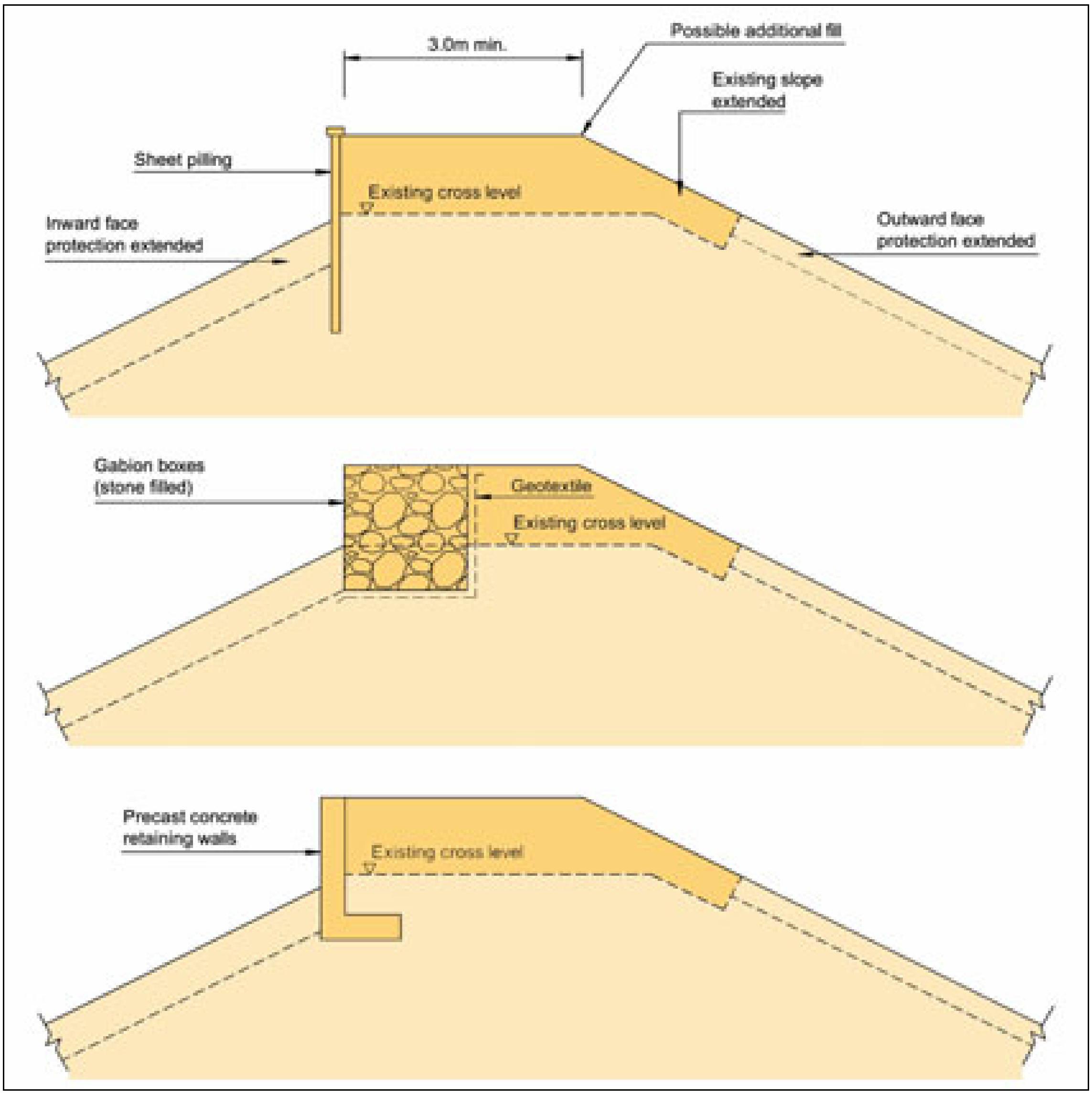


Figure B4.4 Additional design options for raising embankment crest level

Alternative methods such as inverted reinforced concrete U sections and lightweight fill have been used in the past to raise crest levels without significantly increasing embankment load. However, as is the case with any lightweight option, there is a danger that there will be insufficient resistance to horizontal sliding under the applied hydrostatic loads. Checks for this potential failure mechanism must be carried out as part of the design stage.

B4.2.5 Temporary and demountable barriers

Issues relating to the design and use of temporary and demountable barriers to raise temporarily the crest level are covered in a separate Defra/Environment Agency (2001) report (Temporary and Demountable Flood Protection: Appendices to Interim Guidance – Part 1, Draft R&D Publication 130/2). They will not therefore be covered further herein.

B4.2.6 Innovative techniques

Proprietary reinforced earth/geotextile systems
Recent years have seen the increasing use of proprietary systems such as gabion walls, reno mattresses, geotextiles and reinforced earth for embankment raising, embankment steepening and surface protection purposes.

One particular advantage of some proprietary systems is that embankment side slopes can be steepened so reducing land take. They can also greatly enhance erosion resistance in a way that is sympathetic with the surrounding environment. However, they may require special techniques for installation and can have high whole-life costs. Geogrids used for horizontal reinforcement can also act as drainage paths through an embankment so great care is needed if such options are considered.

Light-weight fill
The use of light-weight fill is becoming increasingly common for the construction of road embankments where these embankments are built on weak foundations (as is often the case with alluvial plains and flood embankments). The options for light-weight fill range from low density artificial soils such as PFA (pulverised fuel ash) which, when compacted, is 20% to 30% lighter than most natural soils available in the UK to polystyrene blocks which are considerably lighter than water. None of these materials are without problems; concerns are often raised about PFA's chemical characteristics and the very lightness of polystyrene makes it difficult to hold down when submerged. Similarly, the impermeability of artificial materials is often questionable. For these reasons, it is recommended that these materials are only used following evaluation with carefully planned trials.

Recycled tyres
The use of recycled tyres is currently being examined in some detail as a cheap and environmentally-friendly option for embankment raising/repair, which also offer reduced bearing pressures on the subsoil and increases in embankment shear strength. Two main options appear to be available: (a) using individual tyres to reinforce the soil, and (b) tyre bales.

Individual tyres as soil reinforcement
Tyres can be linked together by strapping to form a grid of rubber; within soil fill these form a reinforced earth system. Embankments of some height have been constructed in this way – for example as described with an embankment in Brazil reported by Sayao, A. S. F. J et al. (2002). Using tyres as soil reinforcement is more common in lower risk land forming and road construction. There are some examples of embankment-type structures which have been built without even linking the individual tyres together – see Figure B4.5 below. In all these uses, careful and well informed evaluation is needed.

Use of tyre bales
Tyre bales have a low density of the order 600 to 650kg/m3, which means they are able to significantly reduce ground pressures whilst having a reasonably high inter-bale shear coefficient (μ = 0.7). They do of course have a high

porosity (about 50%) and a permeability equivalent to that of gravel. Hence where the bales form the core of the flood embankment, there needs to be some impermeable surrounding to the bales in order to keep leakage down to an acceptable value.

The use of tyre bales has been investigated at present in a DTI/EA funded project "Sustainable reuse of tyres in port coastal and river engineering." As part of this project, a major pilot was conducted on the River Witham near Lincoln where some 4000 bales (400,000 tyres) were successfully used by the Environment Agency in stabilising a 1km, length of flood embankment.

The main attraction for using tyre bales at this site relates to the low strength peat foundation. Because of the relative weakness of the peat base, a shallower bank was needed to stabilise the embankment and prevent the weight of conventional clay fill from causing a slip/s. To reprofile the bank to 1:4 would have meant moving a powerline and soke dyke (see Figure B4.6). Such an exercise would have been very disruptive to the local environment, time consuming and expensive.

By using tyre bales as fill, the embankment shoulder was able to be steepened (see Figure B4.7). Less material was used because the tyre bales were much less dense than clay. The stability issues arising from reprofiling the embankment to 1:4 were also overcome. There were no problems of leachate from the tyres, nor any adverse environmental impact. See Plate B4.1 and B4.2 for construction works.

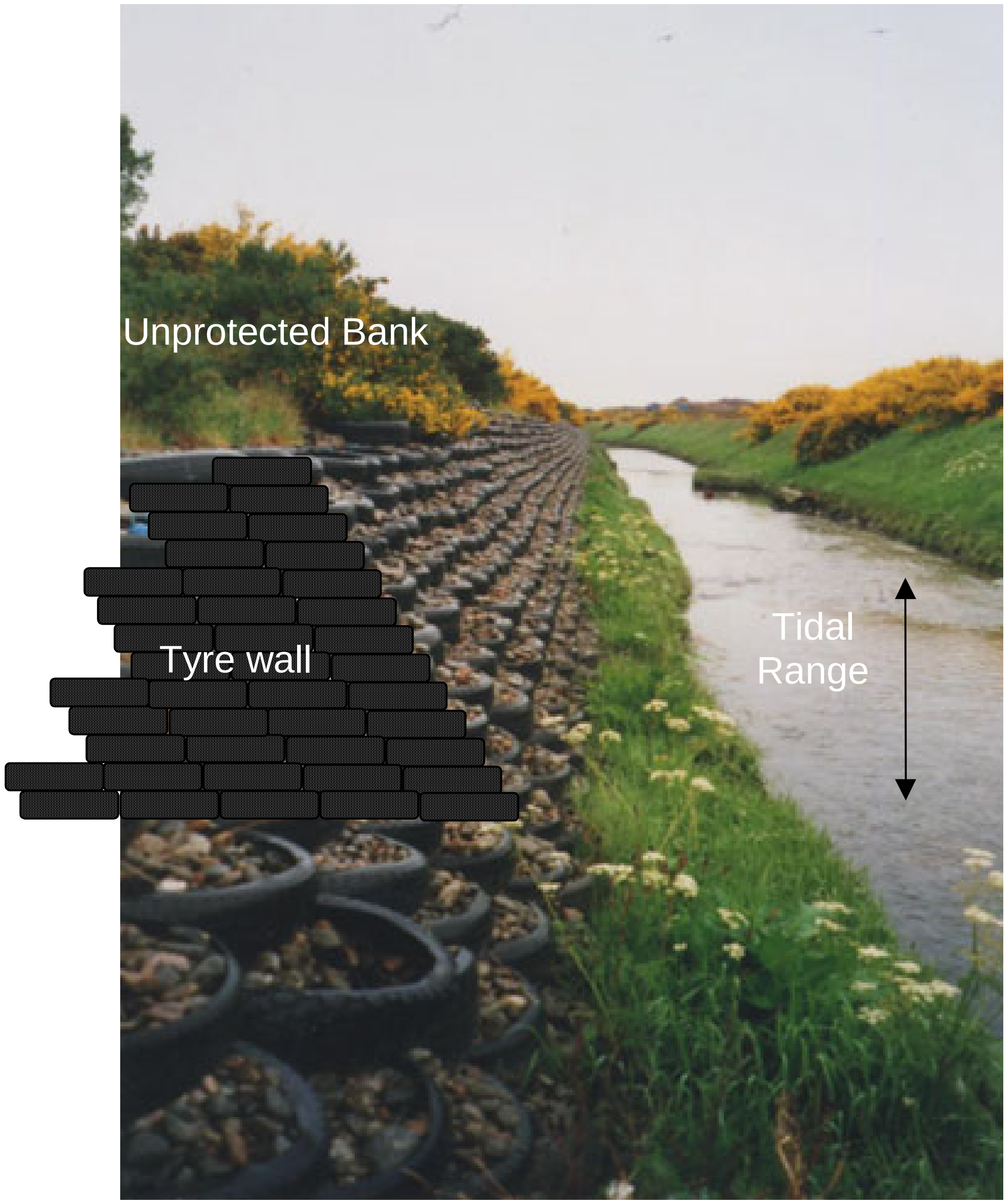


Figure B4.5 Example of a tyre wall reinforcement to embankment face

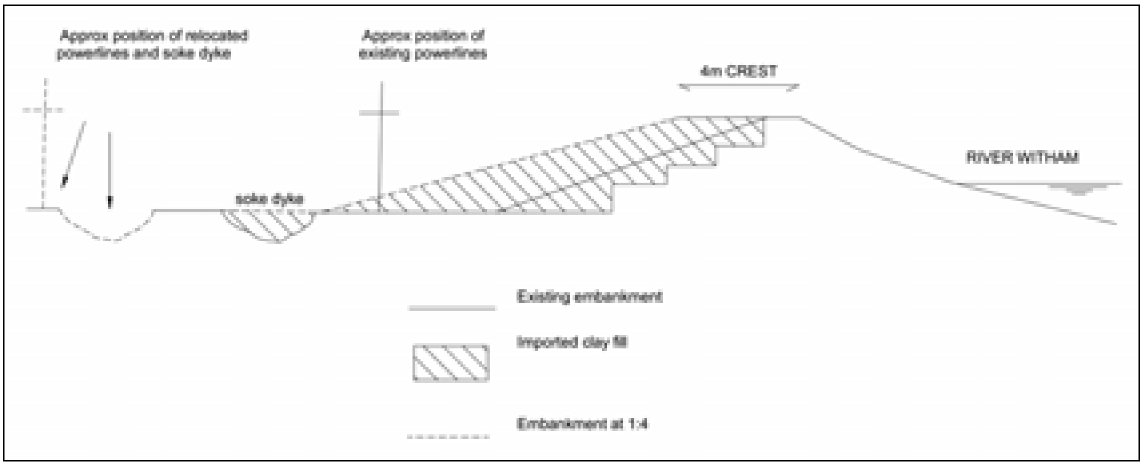


Figure B4.6 **Unacceptable clay fill improvements to R. Witham embankment**

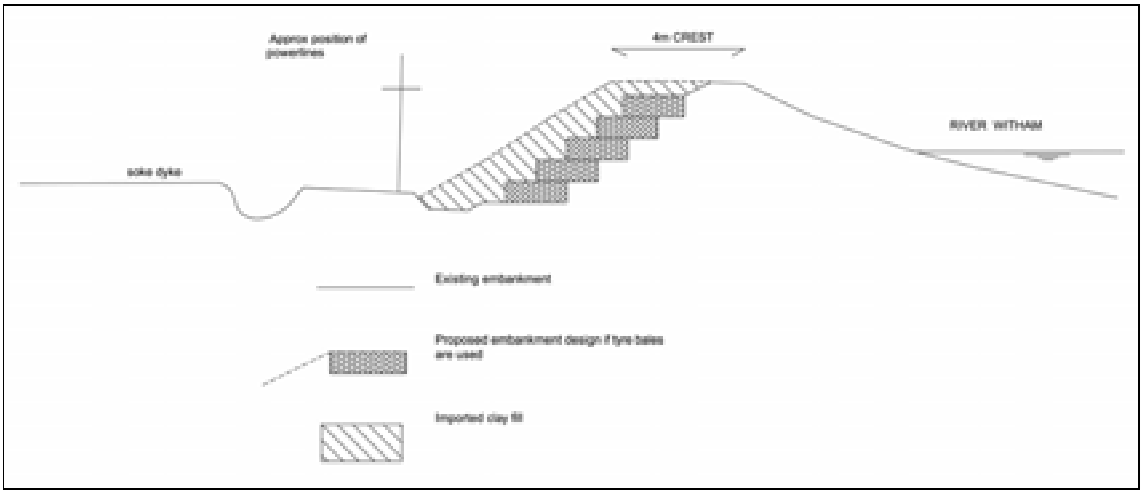


Figure B4.7 **As-built tyre bale improvements to R. Witham embankment**

Plate B4.1 Excavation and placing of tyre bales

Plate B4.2 Embankment face covering tyre bales

INSIDE (INnovations on Stability Improvement enabling Dike Elevations)
INSIDE is a Dutch initiative which aims to achieve European-wide co-operation and knowledge transfer for the purpose of identifying alternative ways of raising flood embankments on weak soil foundations. The initiative is co-sponsored by the Rijkswaterstaat (www.verkeerenwaterstaat.nl/english/) and CUR, the Dutch equivalent to CIRIA.

The issue of dike raising is of considerable interest in the Netherlands as many buildings have been constructed at, or even into, the embankment toe. Raising the level of the flood embankment using the traditional method of berm construction would require the demolition of these structures and hence alternative strengthening schemes need to be considered. The research programme has focussed in particular on methods such as deep cement mixing which strengthen the foundation soil in situ.

B4.3 Options for embankment repair

The discussion above has focussed on the requirement for embankment raising as a response to increase in flood water levels. However, embankment improvement works may also be required as a result of deterioration in embankment performance with time. One or more engineering solutions will need to be adopted to deal with specific problems. The guidance given in this section simply identifies the nature of the available options. This document is not a design guide; detailed assessment or design work should be carried out by suitably qualified and experienced geotechnical engineers.

As a general rule, when a problem with an embankment manifests itself, good practise requires the cause of the problem to be established before remedial works are undertaken. The exception to this is where a breach has occurred or failure appears to be imminent. In this case, emergency action should be taken to deal with the incident as a matter of urgency. Any necessary long-term repairs should be carried out after the breach or potential failure has been stabilised and the cause identified.

In order to confirm the underlying causes of any significant problems, a detailed inspection must be carried out by a suitably experienced and qualified geotechnical engineer. Ground investigation works may then be required to identify the root causes. The methodology for carrying out ground investigations is outlined in BS 5930: Code of Practice for Site Investigation. BS 5930 stresses the need to carry out a desk study as an initial stage of any site investigation. This involves the collation of existing available data such as geological maps and memoirs, borehole logs etc.

A desk study will usually give a good indication of likely ground conditions at a given site; this will form the basis for any subsequent site investigation. The site investigation techniques adopted for the assessment of embankment raising or repairs need to be determined on a site by site basis; they must be targeted towards the cause of the problem as well as the likely remedial works. For any detailed design work, it is likely that the ground investigations will be intrusive, however, the precise scope will depend on individual circumstances. All ground investigations should be designed, specified, supervised and interpreted by suitably qualified and experienced geotechnical engineers.

In the following sections, options for dealing with the more common failure mechanisms are discussed. The solutions tend towards the simple and the robust. However, it is important to appreciate that these options are not exhaustive and in some cases, innovative solutions or combinations of solutions may well be the best way forward. The information provided below is given to provide an indication of suitable preventative or remedial options; site-specific assessment and design will still be required in most cases.

B4.3.1 Settlement

Prevention

As no foundation material or fill is incompressible, it is an engineering fact that the application of load associated with embankment management will result in settlement to varying degrees. For embankments built on soft clays or peats, the settlements initiated by embankment raising can be significant in magnitude and may occur over an extended period of time. These settlements cannot be prevented unless crest raising can be carried out without the deposition of additional fill material (such as through the use of a steel sheet pile solution). Alternatively, the settlements can be mitigated through the use of light-weight fill materials, for example, polystyrene blocks, PFA or the use of tyre bales.

The use of steel sheet piles can be an expensive option, particularly if the piles have to penetrate through thick layers of soft alluvium. The installation of steel sheet piles may also create construction problems such as access for the piling rigs or damage to adjacent structures as a result of pile driving. This option is also unattractive environmentally and visually.

The use of light-weight fill materials will help to minimise the magnitude of settlement initiated by embankment raising. However, such materials are not routinely used for a number of reasons. Firstly, it is likely that the special materials will need to be imported to the site instead of using local soils. Secondly, being light-weight materials, they may generate insufficient resistance to horizontal shearing. It may also prove difficult to inhibit seepage. Finally, some light-weight materials such as PFA may have an adverse impact on the local environment.

Remediation

Embankment raising is required where settlement has occurred or where embankment crest levels are too low. As explained, the deposition of additional fill material will trigger more settlement and reduce the factor of safety against instability. Thus, steps must be taken to overcome this problem. The easiest way to deal with settlement is to anticipate the magnitude of the settlement and then raise the embankment further to provide a “settlement allowance” in compensation. All this can prove costly in terms of the additional fill material and land-take needed to achieve a stable configuration. However, other options such as foundation treatment (stone columns, deep cement mixing etc) may be prohibitively expensive and may have detrimental side effects such as a reduced resistance to seepage.

When raising an embankment, it is important to select suitable fill material. Again, this will be a compromise between material availability and the characteristics that control permeability, shear strength and resistance to crack formation. The design will need to address issues of embankment stability (both short term and long term) and settlement. Construction details will be important: amongst other things, the design and specification must address issues such as the placing and compaction of the fill and the detail of the interface between the existing fill and the new material (e.g. should the new fill be “stepped” into the existing? are filter materials required between different soil types? etc). In some cases, monitoring of the new construction will be required to ensure that observed performance matches that anticipated in the design.

See Chapter D4 for more information.

B4.3.2 Deep rotational failure

<u>Prevention</u>
Deep rotational failures are best prevented by the application of sound geotechnical engineering design principles and good control of construction on site. Deep rotational failures tend to be initiated by changes such as embankment raising, additional applied loading or excavation adjacent to the embankment toe so if such changes are anticipated then their impact on stability must be assessed. The calculation of factors of safety against rotational failure requires an understanding of ground conditions beneath the embankments as well as knowledge of the condition of the embankment itself. Thus desk studies and ground investigations will be required in order to assess stability.

<u>Remediation</u>
The usual solution for dealing with a deep rotational failure once it has occurred is to excavate and replace the failed material (both the fill and the foundation soils), taking care to “step” the new fill into the undamaged part of the old embankment. Any repair, however, must include adequate measures to ensure that the failure is not repeated. The designer must therefore clearly identify and understand the root cause of the original failure.

The choice of replacement fill material is of crucial importance. When compacted, the material must be sufficiently impermeable, have sufficient shear strength and not be prone to fine fissuring. These requirements can be somewhat conflicting as soils with high clay contents will generally be highly impermeable but will also be prone to fissuring and having low frictional strength characteristics whilst soils with low clay contents will demonstrate higher frictional strengths and be less prone to cracking but will be more permeable. If a single material cannot meet all of the design requirements then a composite embankment (e.g. clay core with more coarsely grained shoulders) may be required as is commonly used in dam construction. Where a combination of material types is utilised within one embankment, a system of granular or geotextile filters may be required to ensure that soil particles are not washed from one soil type to another.

The excavation and replacement of the failed material may be problematic. Although a failure of part of an embankment may have occurred, a breach may not yet have been initiated. In such a case, repairs should be carried out quickly but in a manner that does not threaten the stability of the remaining embankment or compromise the health and safety of those working on the repair. Very careful consideration should be given to the temporary works for such repairs as removal of failed material could in itself trigger further collapse. These works must be devised and supervised by competent geotechnical engineers. Suitable temporary works may consist of executing the repair in a series of narrow strips to limit the length of exposed embankment. Alternatively, sheet pile retaining walls may be used to provide temporary support.

See Chapter D5 for further information.

B4.3.3 Seepage and piping

Prevention

Options for prevention will only be relevant to the design of new embankments or works which involve substantial embankment raising. In these cases the potential for seepage beneath or through the embankment should be assessed by suitably experienced and qualified geotechnical engineers. If seepage through permeable strata beneath an embankment is a possibility then it may be necessary to install a cut-off (for example a clay filled trench or steel sheet piling) or extend the length of the seepage path horizontally to control the seepage. The design of such measures should be based on seepage calculations and limiting the hydraulic gradient.

Remediation

Where seepage beneath or through an existing embankment is apparent, the need for, and extent of, remedial works must be assessed by a geotechnical engineer who will be able to establish the impact of the seepage on embankment stability and long term performance. The cause of the seepage should be established before remedial measures are designed. For example, is the seepage a result of animal burrows or permeable strata?

The extent of any remedial works will depend largely on the assigned level of risk. It may be sufficient just to manage the seepage by channelling water away through an appropriate method of drainage. Alternatively, it may be necessary to inhibit or control the seepage by installing, for example, a steel sheet pile or a bentonite cement cut-off. These solutions will be costly and hence their use needs to be prioritised using a risk-based approach. In any case, if the seepage through an embankment is allowed to continue, it must be periodically inspected to ensure that the situation is not deteriorating.

See Chapter D8 for more information

B4.3.4 Fine fissuring and cracking

Prevention

With fine fissuring, prevention is better than cure; it is better to build embankments out of materials which are not prone to such cracking rather than to have to treat long lengths of problem embankment. However, it is recognised that most existing embankments have been built with whatever material was close to hand. For existing embankments, it is therefore important that the existence and, if possible, the depth of cracking be identified. The requirement for remediation or ongoing maintenance should then be decided on the basis of the perceived risk and consequence of failure.

Remediation

Treatment options for cracking or fine fissuring can be expensive (consisting largely of replacement or the use of steel sheet pile cut-offs). With many embankments needing to be raised over the coming decades, there is an opportunity to use well selected and engineered fill material for this purpose in order to reduce the scale of the problem and management costs. However, it should be appreciated that works with such fill material will be likely to have a higher initial cost.

Whilst fine fissuring is a well reported phenomenon, it is not well understood. Research is currently underway to establish the scale of the problem and develop cost effective solutions for existing embankments. As explained above, the design of all new embankments and embankment raising should address the problem of fine fissuring through the use of suitable fill materials. Generally material containing not less than 15% not more than 30% of clay are suitable for homogenous embankments or clay cores. Material with clay content greater than 30% should not be placed in surface zones of embankments.

The formation of large tension cracks more than 5mm wide may be indicative of more immediate problems (deep-seated slip failure or differential settlement caused by embankment raising). If left untreated, such cracks will lead to further deterioration. However, the underlying cause of the cracking must be established before the cracks themselves are treated or the cracks will just re-appear.

See Chapter D7 for more information.

B4.3.5 Softening / shallow failure

Prevention

In general, the overriding cause of shallow slippage will be over-steepness of the embankment side slopes in relation to the intrinsic strength of the fill materials (the occurrence of rainfall and high water levels within the river is accepted). Many factors will influence the factor of safety against shallow slippage. These include the effective stress strength characteristics of the soil on the side slopes, the slope angle, the ground water conditions (particularly the impact of wetting fronts due to inundation and the occurrence of rapid drawdown conditions on the outward face of the embankment) and the effects of any vegetation on the slopes. All of these factors need to be taken into account as part of the embankment design if shallow slippage is to be avoided.

Remediation

Shallow slippage can be overcome by flattening the embankment side slopes or by placing a suitable material with higher frictional shear strength (for example, angular gravel or possibly hogging) over the shoulders of the embankment. Alternatively, it may be possible to use geotextiles or encourage the growth of certain types of vegetation root reinforcement of soil.

Even with such an apparently straight forward modification, the design considerations are complex:

- By how much should the side slopes be flattened to achieve a stable configuration?
- How much settlement will the additional material induce?
- What materials should be specified for the new fill?
- What specification of placing and compaction is required for the new fill?
- What are the details of the interface between the embankment and the new fill?

Because of these technical details, it is recommended that the design of remedial works should be undertaken by suitably qualified and experienced geotechnical engineers.

See Chapter D6 for more information.

B4.3.6 Erosion

Prevention

Again, as is often the case with embankment performance issues, prevention is better than cure; focussed preventative measures tend to have lower whole life costs as well as involving less risk in the long term. If erosion of a section of riverbank adjacent to a flood embankment is observed, it is best to address this at an early stage as this will deal with the problem directly rather than waiting for a major failure to occur. For example, the use of toe reinforcement such as rip-rap armour, gabions or the installation of steel sheet pile walls (see Figure B4.8) may stop toe erosion at an early stage and thus avoid the occurrence of undermining and slip failure. The use of small flow deflection groynes may also be considered.

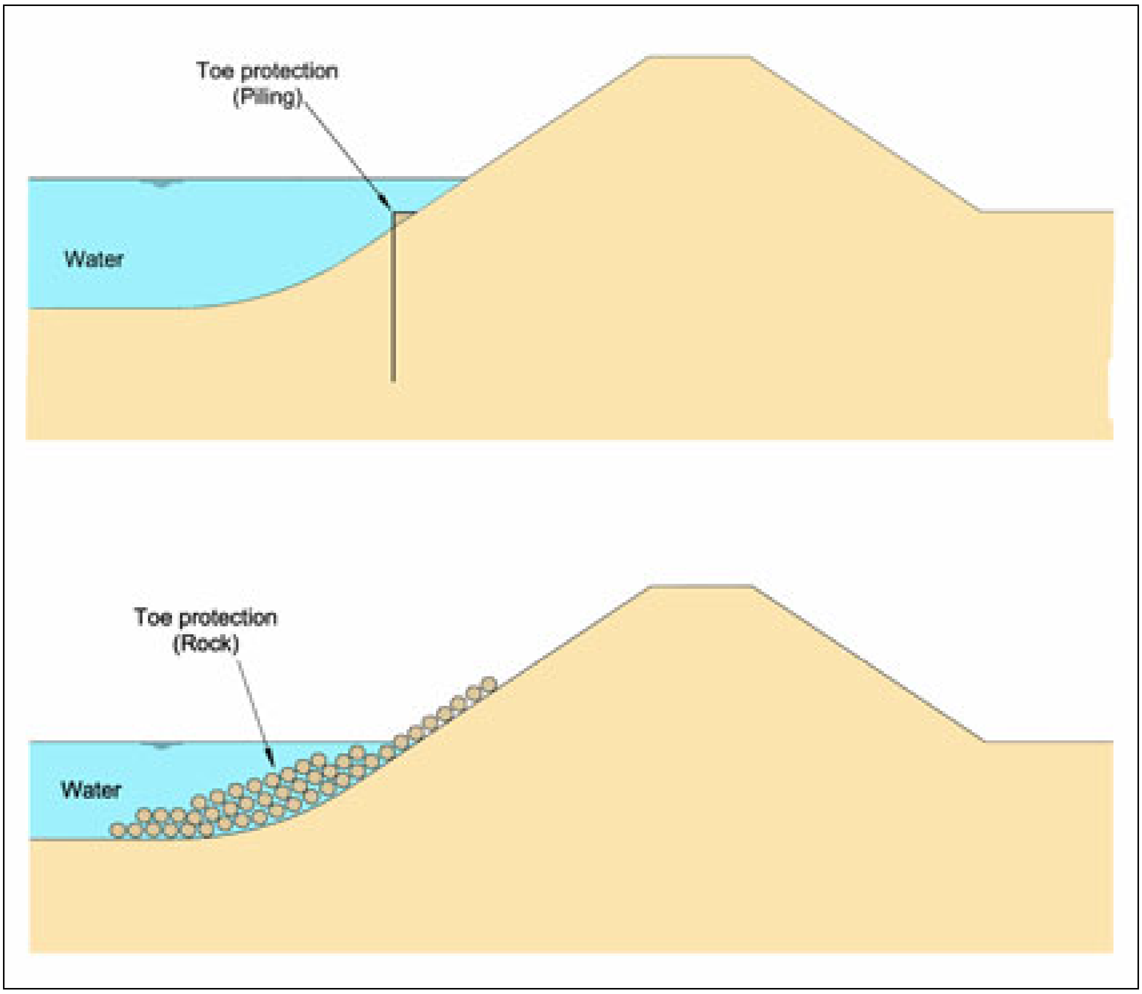


Figure B4.8 Possible solutions for dealing with toe erosion

Remediation

If the erosion is severe, it may be necessary to undertake significant reconstruction works. This may include realignment of the embankment if the erosion stems from the movement of the main river channel. Channel movement, and hence bank erosion, can to some extent be controlled by the construction of small groynes to deflect flow away from the embankment or by controlling the extent and location of pool and riffle sequences within a channel. However, any modifications to the channel must take into account its morphology. Changes that may prove beneficial at one location may trigger further problems elsewhere. Expert advice should be sought when proposing such modifications.

Toe reinforcement is often installed on the basis of engineering judgement rather than by rational design, it often being considered that proper designs in accordance with standard codes of practice result in an over-conservative design. For example, a sheet pile wall installed for the purpose of just providing a degree of resistance to wave attack will be considerably shorter and of smaller cross-sectional thickness than a sheet pile wall designed to support the embankment behind as well. In all situations, it is important to clearly define the design requirements and criteria for long-term functionality. For example, will it matter if a sheet pile wall deflects outwards over a period of years as the embankment creeps? Will periodic replacement provide cheaper whole life costs than a structure designed for a prolonged service life?

See Chapter D10 for further information on external erosion and protection measures.

B4.3.7 Translational sliding

Prevention

Translational sliding occurs when a complete block of embankment is pushed in a landward direction by high water pressures. The mechanism requires high river levels and low shear strengths of materials beneath the embankment. The risk of such a failure occurring is enhanced if the mass of the embankment is able to be reduced by a prolonged period of dry weather (for example if the embankment has a high peat content) or if the strength of the underlying ground is adversely influenced by high water pressures. This mechanism is therefore best prevented by identification of the relevant factors and appropriate adaptation of the design (for example by lengthening the base width of the embankment).

The factor of safety against translational sliding should also be determined as part of any embankment design or assessment as a matter of course.

Remediation

The consequence of a translational slide occurring is likely to be a severe breach, particularly as the failure will probably have been triggered by high water levels in the river. Remedial works are likely to consist of wholesale reconstruction and perhaps realignment of the river bank and / or flood embankment. This will necessitate detailed intrusive ground investigation and careful design.

See Chapter D5 for further information on translational sliding.

B4.4 Design procedures

If a length of embankment has been shown to be deficient or sub-standard, this will not necessarily mean that improvement works will provide value for money. Any potential improvement programme, including non-recurrent maintenance must be based on a viable flood management system. If they are not viable, existing Flood Defence assets may be disposed of. This first phase of planning improvement works is often called the Feasibility Design Stage. Its purpose is to identify constraints and evaluate the likely cost of a number of options for remediation (including a “Do Nothing Option”) in order to ensure best value. Once the benefit of improvement works has been established and a decision to proceed has been taken, a Detailed Design Stage is initiated. As with the feasibility stage, the detailed design will normally be carried out by a consulting engineer who specialises in the design of the relevant flood management works.

On completion of the Detailed Design Stage, contract documents for the construction phase will be issued for tender to selected contractors. The contract documents will usually consist of a specification, drawings, conditions of contract and tender information (form of tender, appendix to the form of tender etc). A range of standard contract conditions is available and the approach to procurement will profoundly affect the allocation of responsibility for the work to be undertaken. However, the selection of any particular contractual or procurement option is beyond the scope of this report. What follows assumes that a “traditional” contract is adopted for the improvement works; adjustments to the allocation of responsibilities and resources will be necessary if other procurement routes are adopted.

The contract for the construction works will be awarded to a selected tenderer following the production of a tender assessment report. The construction of the works should be supervised on site to ensure compliance with the contract documents. Monitoring of the works may also be required to validate design assumptions.

Further explanations of the above stages relevant to flood embankments are given below:

B4.4.1 Feasibility design stage

The purpose of the Feasibility Design Stage is to evaluate a range of possible options for the improvement works including estimating the cost to within a given percentage of the final out-turn cost. A civil engineering consultant will usually be appointed to carry out this work. The consultant is usually under pressure to carry out this phase of work as cheaply and as quickly as possible. However, the reliability of the cost estimate will usually be proportional to the resources allocated to producing it, particularly with embankments where proper assessment of soil and ground conditions is so important.

A feasibility study will normally incorporate the following elements:

<u>Physical characteristics</u>
A topographical survey will be needed to ascertain the physical characteristics of the embankment as the additional height required at any location may well control the final size of the embankment and hence the amount of land that needs to be purchased to accommodate the remedial works.

<u>Identification of constraints</u>
It is important to establish the constraints on improvement works at an early stage as these can have major impact on overall cost. Particular issues to consider include the availability of space for new construction (will additional land need to be purchased?), access routes (is there space for a haul road? etc), and environmental concerns (will trees need to be felled? will construction be limited to particular seasons? etc). A walkover survey will be of great value at this stage of a project.

Desk study

A desk study is normally a cost effective way of gathering information about a site. It can include a review of local geology through a study of geological maps, memoirs and borehole logs. The desk study can also gather historical information (including known pollution and contamination events) through Environment Agency records, inspection reports, old Ordnance Survey maps and data provided by utility service providers. Aerial photographs will also provide useful information, particularly on flood plains where subtle changes in vegetation or topography may indicate changes in ground conditions. Through the geological maps, desk studies can also be used to identify potential local sources of fill material. A desk study will usually define the extent of any further ground investigation required for either the feasibility design stage or the detailed design stage. It is essential that all relevant staff involved in the operation and management of the asset system are asked to contribute information. Verbal reports on performance, particularly how condition changes, or has changed with time can be very helpful to geotechnical understanding.

Initial ground investigation

The desk study will generally allow a qualitative assessment of site conditions to be established at a low cost. If no site specific data is available (for example, boreholes from other investigations etc), further intrusive investigation will probably be required at this stage to validate the assumptions made. The extent and layout of any investigation (intrusive or otherwise) will depend on the findings of the desk study and the required reliability of the feasibility stage design and cost estimate. The ground investigation will usually be carried out by a specialist ground investigation contractor under a contract document prepared by the consulting engineer. All ground investigations should be carried out in accordance with the relevant British Standards, particularly BS1377, BS5930 and BS10175. General guidance on designing, specifying, procuring, supervising and controlling ground investigations can be found in the suite of Site Investigation Steering Group (SISG) documents published by Thomas Telford Ltd in 1993.

It is recommended that all ground investigations are supervised and directed on site by experienced individuals, partly to ensure compliance with the ground investigation contract and its objectives and partly to react to the ground conditions encountered in a flexible manner so that appropriate changes are made to the sampling and testing procedures if unexpected ground conditions are encountered.

The ground investigation contractor will usually produce a factual report, which either he, or preferably the consulting engineer, will interpret to establish a geological model and evaluate geotechnical parameters for use in the design process. It is important that the individual responsible for determining the design parameters is familiar with the design and performance of embankments, particularly as geotechnical parameters are often dependent on the characteristics of the applied loads and the anticipated failure mechanisms.

If the root cause of any problem with the existing embankment has not clearly been established before the initial ground investigation is carried out, then it may be necessary to monitor the embankment's performance over a period of time through instrumentation (for example, piezometers, settlement plates or inclinometers) installed as part of the investigation. The type of any such monitoring will depend on the nature and scale of the particular problem.

<u>Option selection</u>
A number of options (including the "Do Nothing" option) will need to be considered before the preferred option is decided. It is of crucial importance that the selected options deal with the cause of the problem rather than just treating the symptoms. For example, if an embankment crest is settling as a result of overall instability, the deposition of additional fill material on the crest will temporarily raise the embankment to the required height. However, the placement of additional fill may also initiate further rotational movement and hence further settlement. Thus the feasibility study must get to the root cause of any problem and potential constraints before establishing a methodology for dealing with these.

It is good practice at this stage for the consulting engineer to establish a register of risks associated with the remedial works. The purpose of this register is to ensure that risks identified as part of any initial "brainstorming" session are not forgotten at later stages. A risk register should be established once the options for the improvement works have been established; it should thereafter be maintained throughout the design and construction process. Further information on risk registers is available from the Institution of Civil Engineers in their publication "Managing Ground Risks".

The selected options for embankment improvement should be of clearly different natures at this stage, including for example, deposition of additional fill material, the use of steel sheet pile walls or other retaining systems, alternative ground treatment schemes etc.

<u>Cost estimation</u>
Each of the scheme options needs to be developed to such a state that costs associated with a scheme can be estimated to a sufficient level of accuracy (typically +/- 10 to 20%). It is clearly important to get the principles correct and consistent rather than the detail at this stage; for example, careful honing of embankment side slopes to the nearest degree will be to no avail if the works cannot be constructed because of insufficient undrained shear strength of the foundation soils.

The cost estimates prepared by the consulting engineers should be based on the experience of similar construction projects and, if available, standard rates provided by quantity surveyors. In some cases, particularly if specialist techniques or proprietary materials are used, there may be a benefit in involving a contractor with the cost-estimation process.

In many cases, embankment raising works will require the use of significant quantities of fill material. This material will often be carefully specified and this specification may effectively disallow the use of local soils. It should be appreciated that any cost estimate which is not based on the use of compliant material is likely to be flawed and unreliable.

B4.4.2 Detailed design stage

Assuming that the “Do Nothing” option is deemed to be unacceptable on the basis of risk or value, a preferred design option will normally be adopted for development at the end of the feasibility stage. The purpose of the detailed design stage is to design the works through a process of assumptions, engineering calculations and experience and to communicate the final product to the contractor who will construct the works through drawings, a specification and bills of quantities. All of the details necessary for a contractor to complete the construction process need to be committed to paper in a standard format and issued for tender.

If a “traditional” route is to be followed for contract procurement then a consulting engineer will normally be responsible for carrying out the detailed design and compiling the construction contract. If other routes are to be followed the design development might be carried out by the contractor or by another consulting engineer acting on behalf of the contractor.

The first action to be taken at the start of the detailed design stage will normally be to carry out the main ground investigation (assuming that a desk study was carried out as part of the feasibility study). This will be followed by a process of interpretation, which should be carried out by appropriately experienced geotechnical engineers who are familiar with the design process, and then the design itself. Each part of the design should be carried out by appropriately qualified and experienced individuals. Given that most of the work involved with embankment repair or raising is likely to involve the design of earthworks or retaining walls, it would be expected that geotechnical engineers should be involved throughout the design process.

Main ground investigation
The scope of the main ground investigation should be decided at an early stage in the detail design programme. It will depend on the anticipated ground conditions (as established by the desk study and any preliminary investigations carried out as part of the feasibility stage) and the nature of the anticipated construction works. The procedures for specifying, procuring and controlling the main ground investigation are similar to those set out for the feasibility stage ground investigation in Section B4.4.1; the main difference is one of scope. In reality, the responsibility for establishing the extent of the main ground investigation will lie with the designer of the improvement works. Frequently, a main ground investigation will require boreholes along both the embankment crest and the toe of the target embankment at given intervals with intrusive tests such as cone penetration tests carried out at intervening locations. However, the potential range of options is so great that it should be appreciated that there is no such thing as a standard ground investigation.

The ground investigation contractor for the main investigation will produce a factual report that will be used by the scheme designer to produce an interpretative report. In some instances the ground investigation contractor may produce the interpretative report although this is discouraged for major investigations as the contractor will not usually have sufficient design experience.

Detailed design

The purpose of the detailed design stage is to put the flesh on the bones of the feasibility stage concepts. The starting points are the feasibility stage design, a set of design criteria (geotechnical design parameters, critical applied loads, return periods for design water levels and overtopping conditions etc) and the risk register initiated at the desk study stage. These initial elements are usually agreed between the client and the designer before the design is commenced. These will include any functional requirements for multiple use – e.g. recreational access.

Many elements of the works will require that design calculations are carried out. These might include calculations of sheet pile wall lengths and thicknesses, determination of factors of safety for embankment slopes, estimates of seepage volumes or the magnitude of settlements. Calculations may also be required to size channels or culverts, design the amount of reinforcing steel required for a reinforced concrete control structure or the like. The end result of these calculations and the associated engineering judgement is the contract document for the construction of the works. As already discussed, this document can take many forms but most will include conditions of contract, drawings, a specification for the works, bills of quantities and the tender details. These documents will be issued for tender and the contract for the construction works will be awarded to a selected tenderer following the production of a tender assessment report.

B4.5 Construction and monitoring

As has already been stated, both the selection of approach to procurement and the arrangements for site supervision are beyond the scope of this report. However, a number of pertinent issues need to be stressed. In particular, it should be remembered that flood embankments are long linear features; there is always a chance that local variations in ground conditions which had not been identified by the ground investigation process described above might require adaptations or changes to be made to the design at the construction stage. Similarly, the design might have anticipated construction problems in some areas and consequently incorporated a system of instrumentation and monitoring together with options for remedial works. In order to deal with these issues on site, the site establishment for the main construction works should include individuals with geotechnical experience. Additional factors which may affect construction include the discovery of archaeological features or more modern items such as services built into the embankment or immediately adjacent to the embankment, or major variations in expected ground or fill conditions.

Obviously the improved embankment will still require regular inspection in line with the managed framework (Section A.3.2). On the completion of construction, the consulting engineer and site staff will provide record drawings and associated documentation recording the as-built asset. They will also make recommendations for any specific features, over and above the routine condition assessment, that require monitoring. This will include surveys to check on post-construction settlement.

PART C:

RISK AND RISK MANAGEMENT

C1 RISK AND RISK MANAGEMENT

C1.1 General

The need for a risk and performance-based approach to the management of flood embankments was introduced in Part A of this report. In order to understand and apply this effectively, it is important to appreciate the various concepts of risk and performance that are now underpinned by the Environment Agency's Strategy for Flood Risk Management (2003).

This chapter introduces the generic concepts of risk and how risk may be presented in relation to flood embankments. The concepts of probability and consequence are introduced in order to provide a framework for considering the role of embankments under normal and extreme conditions. Various aspects of managing and reducing risk are then introduced, followed by the concept of 'system' risk and reviewing embankment performance through the analysis of Cause-Consequence and Source-Pathway-Receptor diagrams.

Note that as the concepts of Incident and Flood Risk Management (IFRM) are now being widely disseminated within the Environment Agency, and those organisations that work with it in flood risk management, this part of the review is separate from other sections, and will already be familiar to some readers.

> ⓘ**Good practice**
> The concepts of risk presented below have been edited and developed from the Defra / Environment Agency review of risk, performance and uncertainty in flood and coastal defence. This document provides an overview and introduction to these concepts, with the aim of providing a consistent basis for future work and communication with the public and flood and coastal defence community with regards to application of risk concepts.
> - Risk, Performance and Uncertainty in Flood and Coastal Defence – A Review. Report No. FD2302/TR1 / HR Wallingford Report SR587 September 2002

C1.2 An introduction to risk

Flooding and coastal erosion both cause direct damage to property and infrastructure as well as human anxiety and disruption to normal life. Flooding and erosion can also threaten sites of valuable environmental, amenity and archaeological interest. Flood and coastal management systems seek to manage the risk of these undesirable outcomes in the following ways:

- They reduce or manage the source of risk by, for example, promotion of sustainable drainage which restricts runoff from new developments
- They reduce or manage the likelihood of flooding and erosion by building, operating and maintaining flood and coastal management systems (e.g. flood embankments)
- They reduce the impacts should flooding occur by flood forecasting and warning, and emergency planning and response

- They manage the impacts of flooding by controlling land use, particularly avoiding inappropriate development in the flood plain and erosion prone areas, and by avoiding development which could increase flood risk elsewhere
- They raise awareness through publicity campaigns and provision of information on flood and erosion hazards

The risk to individual properties is also managed by household insurance - a form of risk transfer. Flood risk is generally managed by a combination of the above measures. For example a Flood Defence scheme cannot eliminate the possibility of flooding due to exceptional events and so development control and flood warning systems may need to be provided to manage the 'residual' risk which remains.

Concepts of risk assessment and management provide the basis for decision-making over both individual risk management measures, such as a flood embankment, and also over a whole, integrated, programme of measures. They enable the following key questions to be addressed when determining policy, strategic planning, design or construction decisions (MAFF, 2000):

- What might happen in the future?
- What are the possible consequences and impacts?
- How possible or likely are different consequences and impacts?
- How can the risks be managed?

Now consider how these questions relate to flood embankments.

A risk and performance-based approach entails consideration of embankment performance over the entire range of possible loading, with asset management decisions based upon acceptable levels of risk (usually expressed as average annual damages) that the embankment provides to property, people and the environment under a selected design, maintenance and operational regime. This changes the management approach from a more deterministic approach with a specific design standard (i.e. 50 or 100 year return period standard of protection) to acceptable performance over a range of loading conditions (i.e. probability of failure is…).

The first and important step in moving towards this approach is to recognise that an embankment is required to perform predictably over a wide range of conditions. These will vary from no loading through to extreme conditions (Figure C1.1) where the embankment will most likely be overtopped and potentially fail. It is important to recognise that for any practical embankment design, there will always be a finite chance of failure under normal load conditions, as well as a finite chance that flood water levels will overtop the bank.

To assess flood risk, it is therefore necessary to understand how the embankment may behave under a range of conditions. This differs from the current approach, which tends more towards the concept that an embankment is either working well (i.e. stable and retaining all flood water up to the design standard) or has failed (i.e. physically disrupted). Figure C1.2 shows a 'Fragility Curve' for an embankment that describes the probability of failure under a range of loading conditions. Below a certain load condition we can be certain that the probability of failure is at or extremely close to zero. Equally, above a certain load condition we can be sure that failure will occur. The distribution between these limits represents the embankment behaviour under intermediate loading conditions.

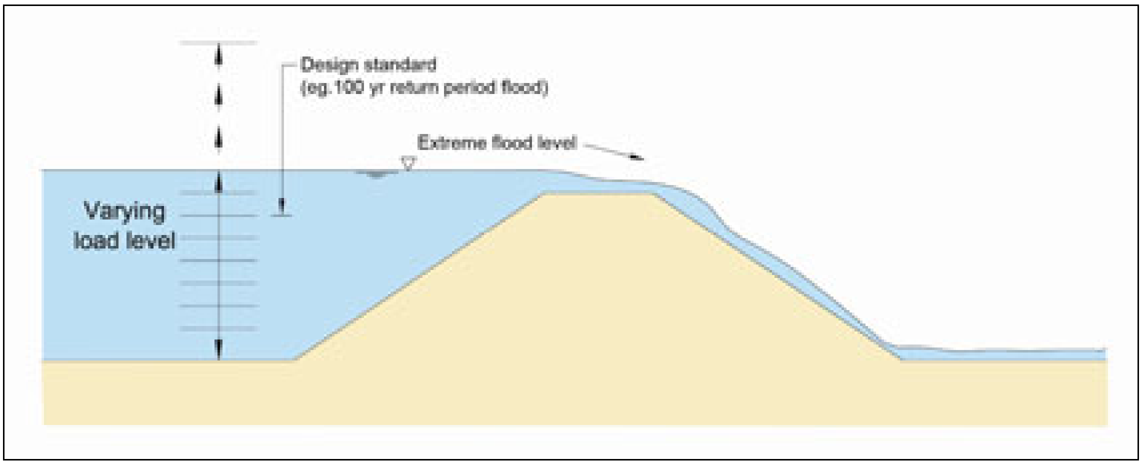


Figure C1.1 Range of loading on an embankment

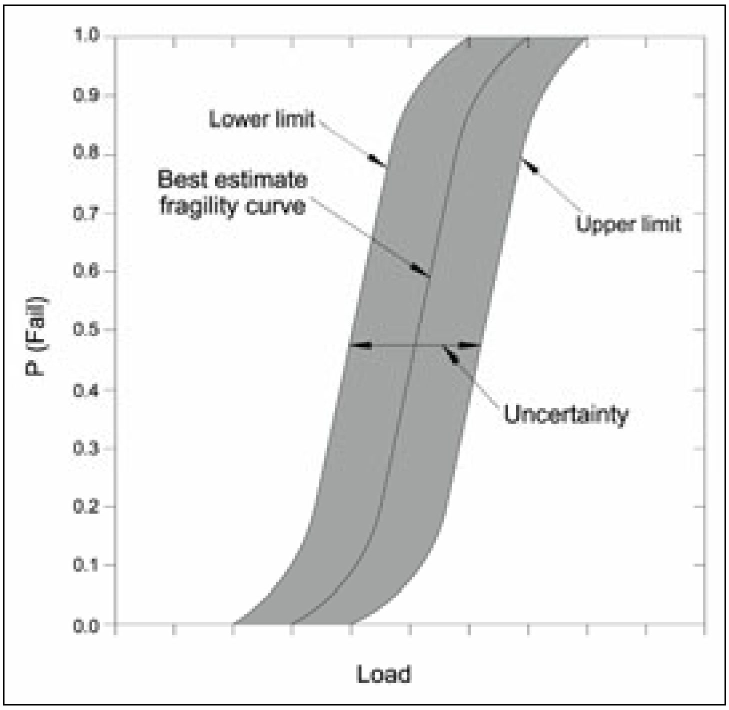


Figure C1.2 Example fragility curves

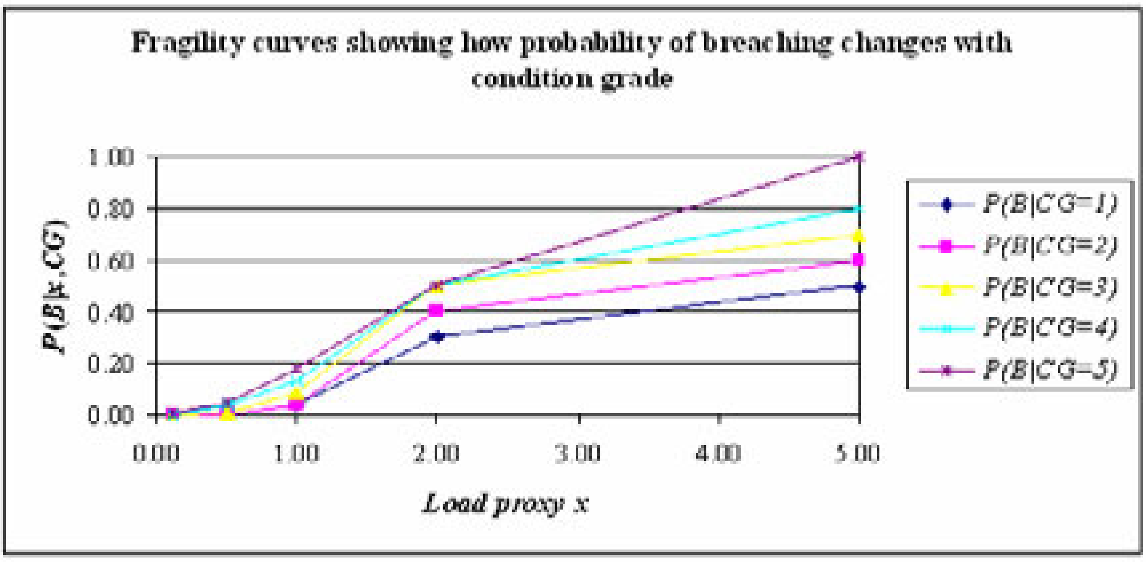


Figure C1.3 Example fragility curves showing probability of embankment breaching relative to standard of embankment defence protection and condition grade

Whilst Figure C1.2 shows a simple relationship between load and probability of failure, the factors that combine to give this relationship are varied and their interaction is complex. The performance of an embankment under a given load will depend, for example, on the condition of material, surface protection measures, vegetation growth etc. Each of these and many other factors must be combined into a single or set of fragility curves. Figure C1.3 shows an example of 5 curves representing the performance of 5 different condition graded (CG) embankments. This shows that whilst the probability of failure of a CG 5 embankment is 1.0 under a load of 5, the probability of failure of a CG1 embankment under the same loading is only 0.5.

It is also important to appreciate that the fragility curves represent a 'snapshot' at a particular time; deterioration or settlement of an embankment with time will alter the shape of the curve. All of these aspects are being considered within the Defra / EA research programme in developing an appropriate approach to representing the fragility of **actual** assets within the asset systems management process.

C1.3 The meaning of risk

A better understanding has now been developed (based on accepted generic risk management concepts) as to what 'risk' means and how an understanding of risk can help provide better decision-making in flood and coastal erosion management. This section provides an introduction to the key concepts and issues surrounding flood risk management.

Defining risk
Risk may be defined to suit the management of a wide range of environmental, social, economic and technological hazards. It describes both the probability and consequences of harm (or damage) associated with a particular hazard.

This definition has for many years formed the basis for economic appraisal and is now also used for assessing “risk to people”.

For flood management, and for embankments in particular, the hazard is typically the existence of water above adjacent, but as yet unflooded, ground level. The probability of failure will depend upon the loading and embankment condition, although other factors may also influence this. The consequences of flooding, and therefore of asset system failure, may include flood damage to property, the environment and people.

The magnitude of risk is a function of probability and consequence, and is usually assessed by integrating probability times the consequences.

The consequence of an event may be either desirable or undesirable. Generally, however, the flood management community is concerned with protecting society and hence a *risk* is typically concerned with the likelihood of an undesirable consequence and our ability to manage or prevent it. Therefore, in some, but not all cases, a convenient single measure of the importance of a risk is given by:

$$\text{Risk} = \text{Probability} \times \text{Consequence.}$$

where:

- Probability - refers to the chance of a particular *consequence* occurring
- Consequence - refers to the undesirable outcome should a *risk* be realised. It could refer to economic, social or environmental impacts following failure of an embankment. Average Annual Damages (£m/annum) is often used for economic appraisal. Damage per square kilometre or per unit length of flood defence or bank may also be used. Risk to people usually depends on the degree of harm, such as mild or serious health effects. The geographical scale of the consequence will typically extend beyond the local source of the hazard (e.g. rainfall, waves).

This definition is accepted for flood risk management at present, but does not necessarily present the whole answer. Different decision-makers have different concerns and these may need to be reflected in the precise way that risk is defined in future.

<u>Risk management generally</u>

Three broad areas of risk management are identified by Cabinet Office guidelines on the government's capacity to handle risk.

- The **stewardship** role to manage risks from natural hazards. (A priority for the Environment Agency which is concerned with flood risk assessment and management)
- The **regulatory** role to control risks from activities of businesses and individuals
- The **management** role - relating to risks to business, delivery and operations.

These areas overlap. The Environment Agency assesses and manages risk in all of these areas, and uses the same basic definition of probability and consequences. The precise meaning of risk changes to reflect the objectives that are being pursued. For managing risks to projects, for example, the risk will generally be defined in terms of probability (during the life of the construction project) and consequences in terms of time delay, cost (over-run) and quality.

Scale of flood risk

Flood risk is managed at all scales. National flood risk may be summed from risks in all flood risk areas and expressed in terms of average annual damage and subsequently used to support overall government funding and policy. Flood risk in a catchment or coastal cell is also considered in Catchment Flood and Shoreline Management Plans, as well as the risk in smaller "cells" such as per km^2 of the Indicative Floodplain. These may be used to establish catchment and shoreline flood management policies. Flood management strategies and schemes, asset systems management plans, local flood protection and flood warning are all supported by specific risk assessments of smaller areas within a catchment or coastal cell.

At a national scale, the National Flood Risk Assessment (NFRA) provides an indication of current flood risk. Potential long-term changes to risk have been investigated through the *Foresight* Future Flooding project. Predictions of future changes can then be used to measure the reduction in risk achieved through various different scales of government investment, and should also help strategies for future flood risk management to be identified.

Tiered decision support systems are currently being developed such that data used or generated within each level of risk assessment (national; catchment; asset system) can feed up or down into other scale risk assessments. This helps to ensure longer-term consistency between different levels at which risk and management intervention is identified and funded.

Presenting risk

As discussed, risk is generally calculated by multiplying probability and consequence. This may be made up of many (frequent) low-consequence events or rare (low probability) events with catastrophic consequences. In terms of flood embankments, such scenarios may perhaps relate to periodic overtopping and local flooding of embankments in comparison to the single failure of a large embankment or embankment dam. Obviously the nature of the risks with any particular asset management system should be properly understood in planning any management intervention.

Managing risk

As discussed in Section C1.2, a combination of measures might be adopted to manage a particular flood risk, and the way in which these are planned together is an important part of *integrated* flood risk management.

Integrated flood risk management may be considered as a co-ordinated approach for developing and implementing an appropriate "basket" of activities to manage flood risk in a particular catchment or cell. The “Source - Pathway (or barrier) – Receptor” model (see Figures C1.4 and C1.5) provides a robust framework for looking at various options for managing risk, each of which will have different advantages or disadvantages.

Assessing risk in practice

Risk cannot be measured directly. Risk assessments are often supported by historical event data, and there is almost always an element of modelling for assessing present day and future risk. This is often structured around the “Source - Pathway – Receptor” concept. For many assessments, existing hydrological, hydraulic, engineering and economic models can be used to assess the contributing elements – see Figure C1.8. This includes the use of “fragility curves” for addressing the performance of the flood embankment through water loading. Modelling is also helpful for supporting asset management decisions by predicting the effects of interventions. This is essentially how the future PAMS is intended to support the planning and prioritisation of asset management interventions (see Section A4.4.4).

C1.4 The Source–Pathway–Receptor framework

To understand the linkage between hazard and consequence it is useful to consider the Source-Pathway-Receptor (S-P-R) or Source-Pathway-Receptor-Consequence (S-P-R-C) approach. This is a simple generic conceptual model for considering risk within systems and processes. For a risk to arise there must be hazard that consists of a 'source' or initiator event (i.e. high rainfall); a 'receptor' (e.g. flood plain properties); and a pathway between the source and the receptor (i.e. flood routes including embankment overtopping and flood plain inundation). See Figure C1.4.

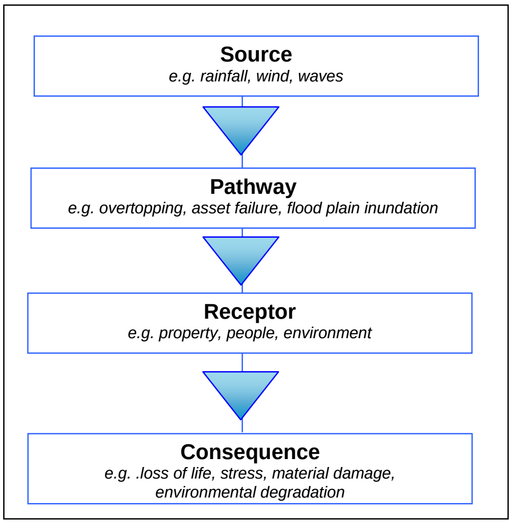


Figure C1.4 Simple conceptual model for considering risk management within systems - Source-Pathway-Receptor-Consequence

Figure C1.5 illustrates this concept applied across the entire flooding system.

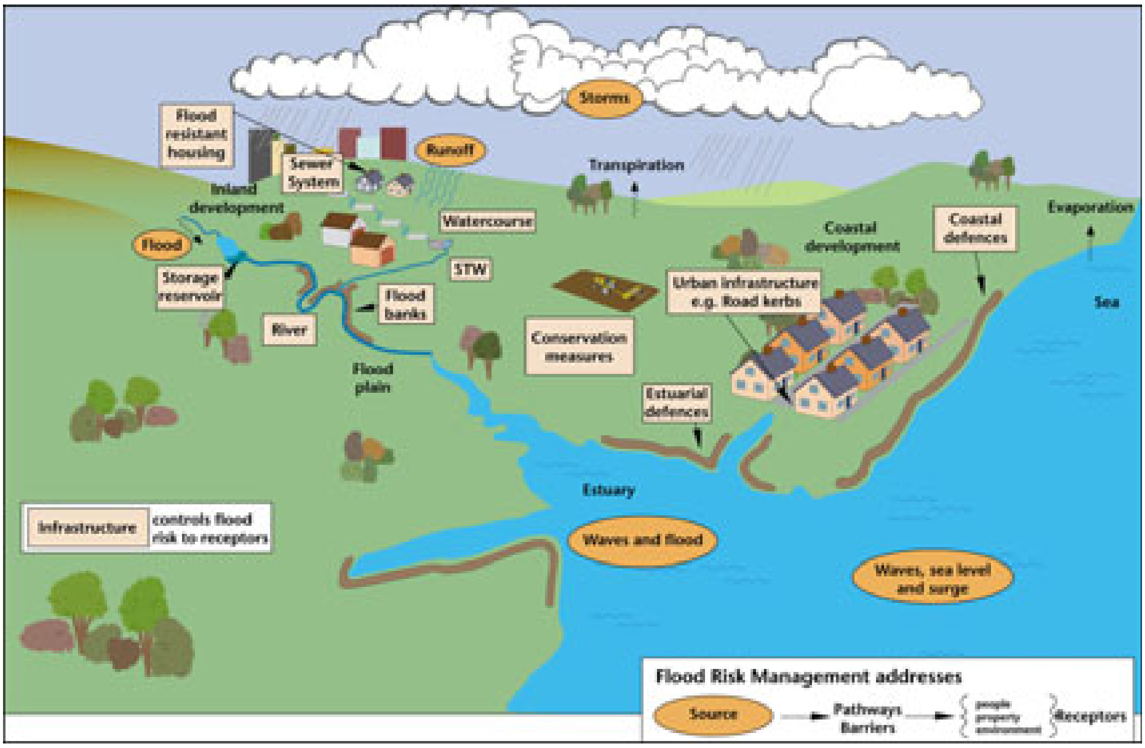


Figure C1.5 **Overall flooding system showing sources, pathways and receptors**

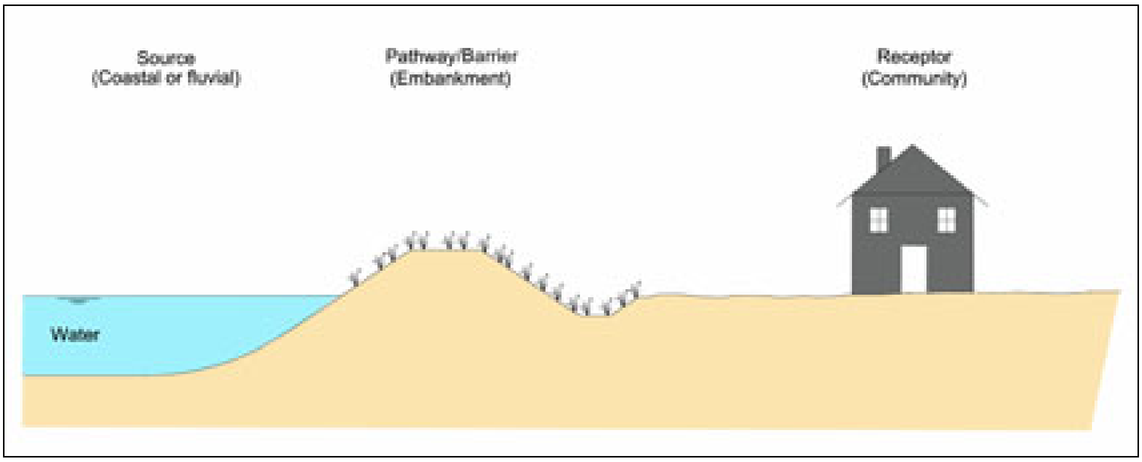


Figure C1.6 **Source-Pathway-Receptor representation of a flood embankment**

If we now consider the position of a flood embankment within the Source-Pathway-Receptor model, the source comprises water at high elevation, whether fluvial, coastal or local runoff, the receptor is typically property and land that we do not wish to flood (towns, farmland etc) and the embankment forms the pathway / barrier between the source and receptor (Figure C1.6).

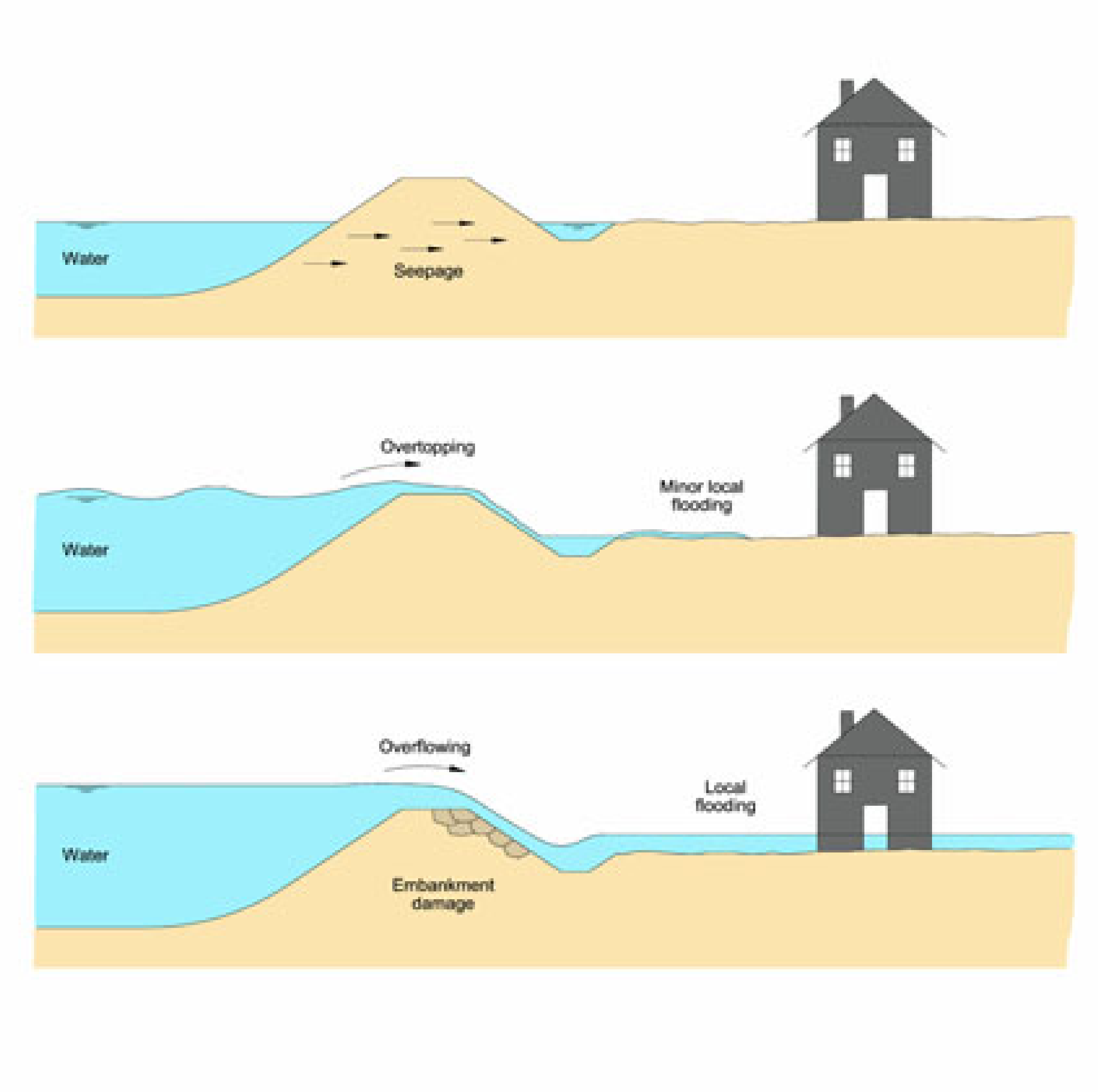


Figure C1.7 Various mechanisms for flood flow past an embankment

Considering flood embankments specifically, it can be seen that the embankment acts as a barrier against the passage of flood water. There are several mechanisms through which water may pass through or over the barrier, and varying orders of magnitude of water flow that could occur. When assessing levels of risk, some may be considered acceptable and others unacceptable (see Figure C1.7 - note that these orders of magnitude are illustrative only and each particular embankment needs to be considered to establish the most important mechanisms). Part B of this report reviews these various mechanisms in more detail.

Box C1.1 Flood embankment performance using risk based techniques

Figures C1.2 and C1.3 show how the performance of a flood embankment may be represented for varying load conditions. Figure C1.8 shows how this information fits within an overall risk based approach to flood management – more specifically calculation of flood risk (in terms of average annual damages). Four curves are shown. The first (source) represents the probability of water loading. This drives a system model that incorporates embankment fragility (pathway - see Figure C1.2) and the flow depth relationship for the floodplain, and produces a loss probability curve for the receptors. Integration of this curve allows calculation of expected damages.

Having established a risk based tool such as this, then the impact of varying the embankment fragility on expected flood damages may be assessed. By linking aspects of embankment design, operation and maintenance to fragility, each of these management intervention processes may then be optimised to reduce flood risk and achieve best value for money.

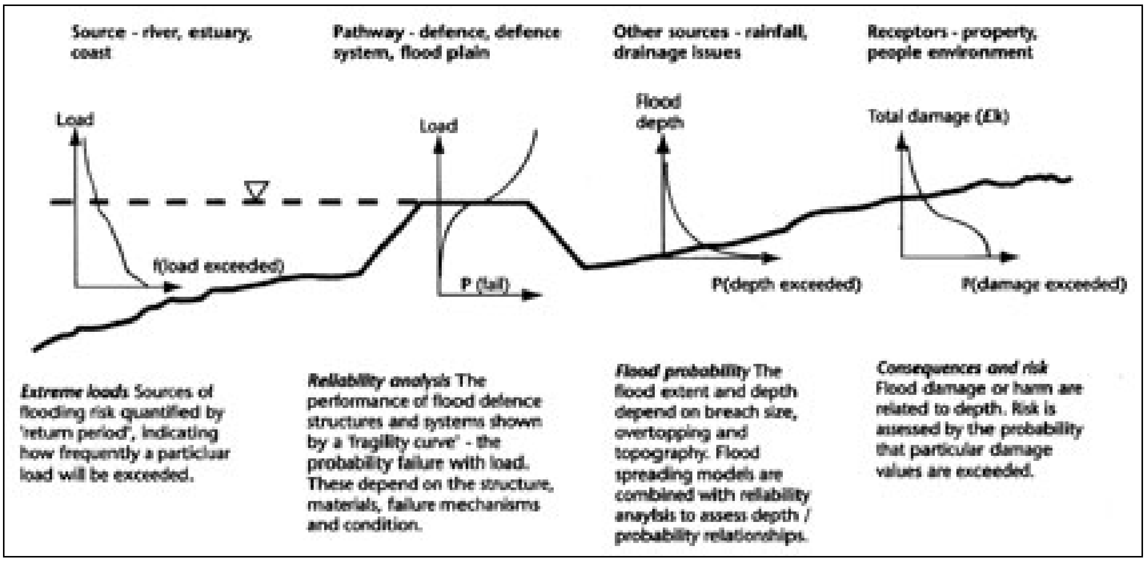


Figure C1.8 Flood embankment performance using risk based techniques

C1.5 What are the units of risk?

The units of risk depend on how the probability and consequence are defined. Probability describes how likely a particular event is to occur. Frequency is often confused with probability, and is no longer used by the Environment Agency for describing flood risk. It is important to understand the difference between these terms:

- **Probability -** may be defined as the chance of occurrence of one event compared to the population of all events. Therefore, probability is dimensionless – it can be expressed as a decimal or a percentage and is often referenced to a specific time frame, for example as an annual exceedence probability or lifetime exceedence probability.

- **Frequency** - defines the expected number of occurrences of a particular extreme event within a specific timeframe (in the special case of Return Period this is usually expressed in years)
- **Consequence –** represents an impact such as economic, social or environmental damage/improvement, and may be expressed quantitatively (e.g. monetary value), by category (e.g. High, Medium, Low) or descriptively

Mathematical formulae are available for relating the probability and frequency of defined events. Formulae are also available for relating, for example, an annual probability to a probability in different time periods such as 25 years. This is discussed in more detail in the Defra / Environment Agency Report FD2302/TR1 (HR Wallingford, 2002).

To give two brief examples:

- In order for an embankment to have a 1% chance of being subjected to its design load, within a 100 year design lifetime, it would need to be designed to withstand a 1 in 10,000 year loading
- A defence with a scheme life of 100 years and designed to a 100-year return period standard may sound ‘safe’. However, there is a 63% chance that the design standard will be equalled or exceeded during scheme life

This type of simple assessment makes a number of assumptions, such as no change in load climate, and these need to be carefully reviewed.

C1.6 How does risk change in time?

Risk is unlikely to remain constant in time and it is often necessary to predict changes in risk in the future, to make better decisions. Some causes of change are well recognised for example:

- Climate (natural variability, greenhouse-gas induced climate change)
- Assets (deterioration, maintenance, improvement works)
- Flood damage / harm (new development, increased vulnerability)
- Erosion rates (changing geological exposures and beach health)
- Changing value of assets at risk
- Improved flood warning / response
- Land use

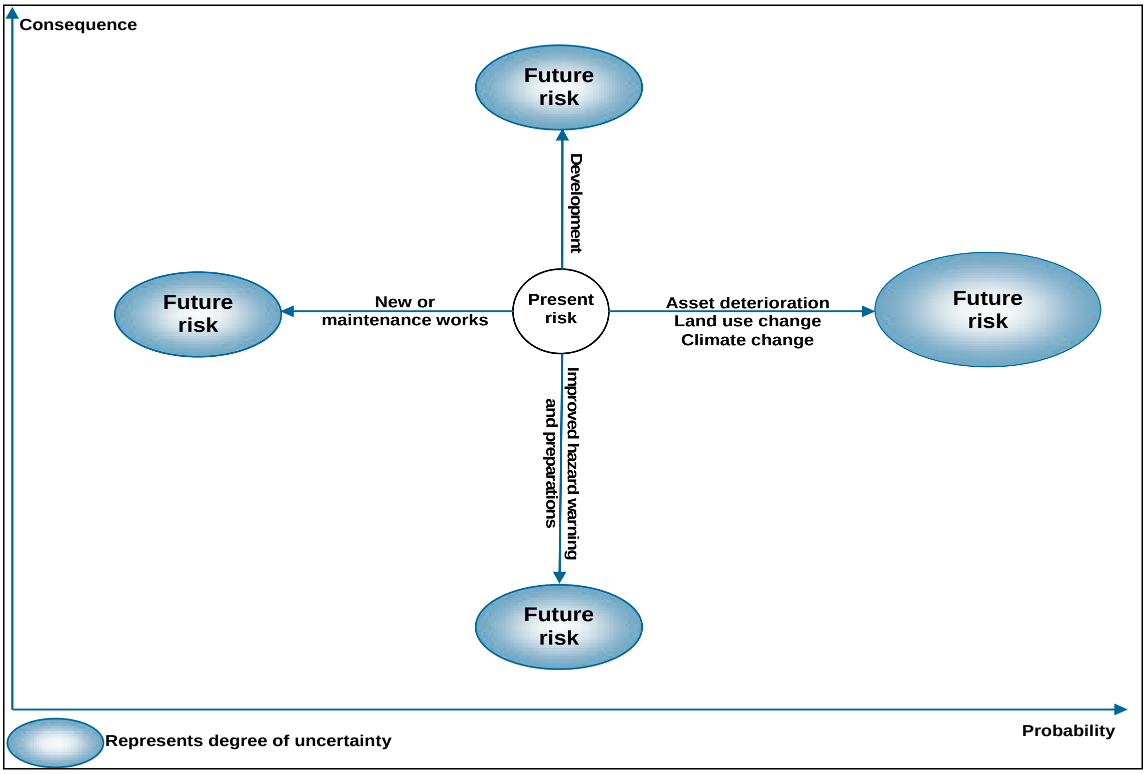


Figure C1.9 Some of the factors that influence future risk

As a result, risk changes in time and our management response to such changes must be integrated and capable of adaptation. An attempt to show the *dynamics of risk* is provided in Figure C1.9.

Each of these causes of change in risk can be considered in relation to flood embankments:

- Climate (Effect of increased water levels, increased duration of flooding, varying climatic conditions (moisture etc.))
- Condition (Embankment deterioration, maintenance, improvement works)
- Flood damage / harm (varying development on floodplain)
- Erosion rates (changing exposure of the embankment)
- Changing value of assets at risk (includes land use)
- Improved flood warning / response (response associated with performance of a particular embankment)

Some management responses for embankments will be routine maintenance; others will entail a more detailed risk assessment and specific responses.

C1.7 How does risk vary in space?

Likelihood, depth and severity of flooding varies across the flood plain and erosion rates vary along the coast or river with geology and exposure. The indicative floodplain defines an envelope of nominally 1% (for fluvial) and 0.5% (for tidal) annual probability. This probability only applies to the limit of the flood plain envelope and assumes defences to be absent.

The presence of defence systems obviously has a major effect on the distribution of flood risk across the flood plain. The distribution of risk will depend upon the properties of defences (e.g. their performance and failure modes under a range of loads) and these may vary along the length of an embankment. The situation becomes particularly complex when a given flood plain is not divided into discrete ‘cells’ by high ground or compartmentalised by embankments. In this situation we need to know:

- What area will flood as a result of water crossing a particular embankment at a particular location
- Which embankments, within an asset system (see Section C1.8 below), provide protection to a given location and how important or critical is each asset to a particular area

These issues of risk attribution are addressed by the RASP methodology (see Section A4.4).

C1.8 Understanding ‘system’ risk

In the broadest terms, a ‘system’ may be described as the social and physical domain within which risks arise and are managed. For the flooding system (see Figure C1.5) this includes the physical process of flooding, the inhabitants of floodplains, their infrastructures and habitats, and the organisations in the public and private sector that influence flooding and its impacts. For example, the key elements of the flooding system are:

- The physical aspects of the water cycle *i.e*. the processes of rainfall and marine storms that lead to fluvial and coastal flooding; runoff from the land; and flood inundation in fluvial floodplains and coastal lowlands
- The man-made flood management assets that are intended to resist or control inundation of floodplains
- The economic, social and environmental assets that are located in floodplains and are impacted upon by flooding and/or have an impact on the flooding process
- The organisations with a statutory responsibility for managing risk and implementing warnings, carrying out real-time interventions such as operating flood barriers, and ensuring preparedness of the people at risk
- Insurers, who provide cover for flood risks
- Broader stakeholder groups with an interest or role in the impacts (both positive and negative) of flooding and actions that may be taken to manage flooding

In determining risk, and the acceptability of that risk, managers, engineers and decision makers are concerned with the way 'systems' behave. Clearly understanding the behaviour of a system and, in particular, the mechanisms by which it may fail based on an understanding of the sources-pathways-receptors-consequences is an essential aspect of understanding risk. This is true for organisational systems, like the provision of flood warnings, as well as for more physical systems, such a series of asset systems protecting a flood plain (see Chapter A4). Once the behaviour of the system is understood, through the use of structured risk tools, the dependent and independent activities and issues contributing to flood risk management can be identified, and risk management options can be assessed and prioritised.

In seeking to understand such a diverse behaviour, risk analysts have recognised the importance of "tiered" approaches, as a way of managing the complexity in many risk issues and carrying analysis to a level of detail appropriate to the decision. These tiered "scales" as applied to flood risk management are discussed in Section C1.2 and illustrated below.

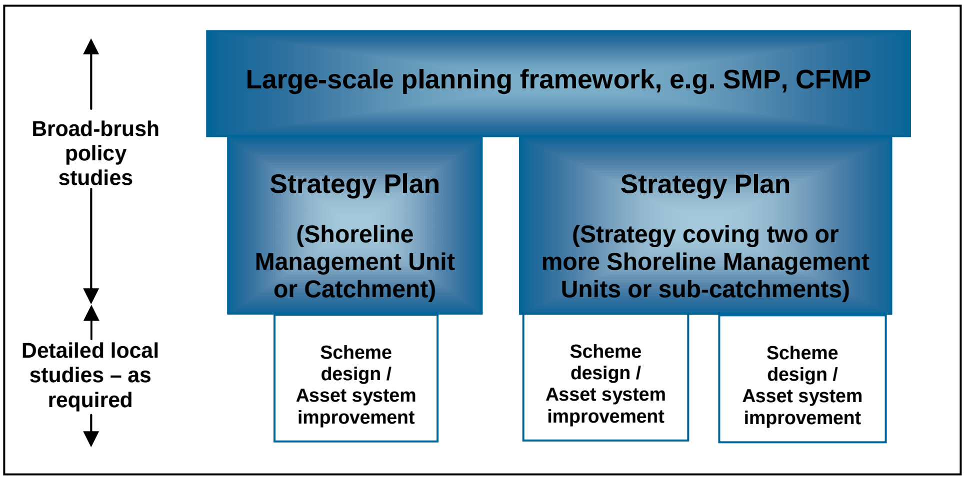


Figure C1.10 Tiered approach to decision-making

C1.9 Summary of key points in Chapter C1

Summary of key points in Chapter C1:

- Risk is a combination of the probability of an event occurring and the consequences of that event
- Risk has different meanings for different stakeholders within society. For flood embankments, flood risk is assessed as the average annual damages to receptors attributed to that particular embankment
- Risk management options include reducing the source of flood risk (water level), likelihood of occurrence (failure or overtopping of embankment), consequence of failure (impact, flood warning, awareness) and also through risk transfer (insurance)
- The Source-Pathway-Receptor (S-P-R) model demonstrates the link (and difference) between hazard and consequence and provides a useful basis for considering flood risk management options
- By representing loading (flood levels etc) and system response (embankment fragility curves) as probability distributions and combining with depth damage relationships, a flood damage-probability curve may be generated. This permits calculation of expected damages (measure of risk). Embankment performance, represented through a fragility curve, may therefore be directly linked to flood risk. The benefits of improved performance, as represented by changes in the fragility curve, may therefore be considered and optimised
- Risk typically changes in time and space and will be dependent upon a number of parameters such as climate, embankment condition and deterioration, land use, etc
- It is important to understand how a particular embankment contributes to flood management within its overall relevant asset system. The risk attributed to the performance of a specific flood embankment may be significantly different from estimates made from simple observation in the field

PART D:

GOOD PRACTICE REFERENCE

D1 INTRODUCTION

D1.1 General

The objective of this part of the document is to provide a reference to current good practice in each area related to aspects of embankment performance. This part of the document may be accessed directly or via references from related sections found under Parts A, B and C.

D1.2 Scope and contents

The information presented under Part D is set out in the following chapters, which are based upon needs and issues identified during industry consultation, undertaken as part of this project.

Chapter D2: Condition assessment
Chapter D3: Vegetation
Chapter D4: Settlement
Chapter D5: Global instability (rotational and translational failures)
Chapter D6: Shallow instability (surface failure)
Chapter D7: Cracking and fissuring
Chapter D8: Seepage and piping
Chapter D9: Overtopping
Chapter D10: External erosion / protection
Chapter D11: Breach formation and emergency action

D1.3 Format of information

Each chapter in Part D presents information in the following format:

- Scope of Guidance: *A bullet point summary of the main issues covered within the chapter*
- An overview of key issues
- Current knowledge and understanding (including consideration of relevant processes and indicators)
- Recommended actions
- Good practice guidance (references)

D1.4 General good practice guidance documents

There are a number of documents that have been identified as offering good practice across a wide range of issues relating to embankments. Those considered best are listed below:

Infrastructure embankments – condition appraisal and remedial treatment
Perry, J., Pedley, M., and Reid, M. 2001. CIRIA Report C550. ISBN 0 86017 5502
This report provides guidance on the maintenance, condition appraisal and repair of infrastructure embankments. It is based on a review of published literature, expert consultation and case studies demonstrating good practice. Whilst the text focuses mainly upon road and rail embankments, there is useful guidance of relevance to flood embankments.

Dikes and revetments. Design, maintenance and safety assessment
Pilarczyk, K W. (ed) 1998. ISBN 9054104554
This book provides extensive guidance on a wide range of aspects relating to fluvial and coastal flood embankments. Design guidance is offered for problems such as embankment stability, wave impact / run up and protection design. Discussion includes embankment failure mechanisms, risk management, operation and maintenance.

An engineering guide to the safety of embankment dams in the United Kingdom
Johnston T.A., Millmore J.P., and Charles J.A., 1999. ISBN 1 86081 2724
Whilst developed for the UK dams industry, this guide provides practical information on the behaviour of embankments, including load-response, performance indicators, mechanisms of deterioration and failure, surveillance, investigation and monitoring.

Investigating embankment dams: A guide to the identification and repair of defects
Charles, J.A., Tedd, P., Hughes, A.K. and Lovenbury, H.T., 1996. ISBN 1 86081 0691
The guide provides a comprehensive overview of techniques used to identify defects in embankment dams. Scope includes field observations, a general approach to investigating defects, sampling, in situ testing, monitoring, leakage investigation and geophysical testing. Case study applications are also reviewed.

Small embankment reservoirs: a comprehensive guide to the planning, design and construction of small embankment reservoirs for water supply and amenity use
Kennard, M.F., Hoskins, C.G. and Fletcher, M. 1996. CIRIA Report 161, Butterworth-Heinemann, London
Covers, amongst other things, geotechnical assessment, ground investigation techniques, embankment design procedures and earthworks design and construction.

Waterway bank protection: A guide to erosion assessment and management

Environment Agency, 1999. R&D Publication 11. Version 1.0

This report provides practical guidance on the erosion assessment and management of waterway banks. Whilst the scope of work does not directly include flood embankments, many of the concepts and solutions are directly relevant and applicable. The guide presents an initial assessment of bank erosion problems, guidance on selecting the most appropriate protection strategy and subsequently guidance on engineering and non-engineering solutions.

Protection of river and canal banks

Hemphill, R.W. and Bramley, M.E. 1989. CIRIA Report. Butterworths. ISBN 0408039450

This publication provides a useful overview on a wide range of aspects relating to river and canal bank protection. Text covers failure processes, the design process and options for bank protection including use of natural materials, vertical bank protection and revetments.

River and channel revetments – A design manual

Escarameia, M. 1998. Thomas Telford. ISBN 0727726919

This design manual first considers the issues of geotechnical stability and hydraulic loading on channel beds and banks, followed by a review of types of revetment and their design. This includes use of rip rap, block stone, gabions, mattresses etc. Consideration is also given to construction issues and maintenance requirements.

The Earth Manual

United States Bureau of Reclamation, 1998

This guidance manual divides into three sections addressing properties of soils, investigation of soils and control of earth construction. The first two sections provide detailed technical guidance on specific tools and techniques for assessing soil condition and behaviour. The third chapter provides more practical construction advice covering a range of earth and earth related structures including the construction of embankments and canals. A useful reference document for more detailed technical information relating to geotechnical issues.

Available via internet at www.usbr.gov/tcg/earth

Embankments on soft clays

Leroueil, S., Magnan, J-P. and Tavenas, F. 1990. Ellis Horwood, London, 360pp

This book reviews soil mechanics theory and practice for the design and construction of embankments built on the soft clays which often underlie the flood plains on which flood embankments are constructed.

Embankments on Soft Clays

Edited by The Public Works Research Centre of Greece; Major contributors: Jardine, R.J. and Hight, D.W. 1987. Athens

This work brought together much of the then current (but still very relevant) "state of the art" theory and practice into one publication, giving summaries on engineering geology, engineering behaviour, field and lab investigatory methods, construction and remediation techniques.

D1.5 Context of guidance

Attention is drawn to the "Statement of Use" on the inside front page. This Part D is intended to act as an index for good practice, particularly to provide the non-specialist engineer or technician with an overview of practice, and to help them to understand the broad areas in which specialist advice is needed. It does not reproduce specific, detailed guidance that has been published elsewhere, and it should not be regarded as a definitive asset management manual.

In general, it is expected that work on assessment, design and management of flood embankments will be carried out with the appropriate involvement of an experienced geotechnical engineer.

Some of the issues covered in this guide are supported by tools being developed under the EA's PAMS (Performance-based Asset Management System) project. Users should seek to maintain awareness of the tools and guidance that have been produced under that project through Defra / EA Research News. This can be downloaded from the Research Newsletter section of the R&D pages of the Defra Flood Management website (www.defra.gov.uk/environ/fcd).

D2 CONDITION ASSESSMENT

D2.1 Condition assessment – Scope of guidance

This chapter contains information and guidance on the following topics:

- Inspection processes / Site investigations
- Assessing embankment integrity

Historically, river flood embankments in the UK have often been built in stages from whatever fill material was freely and locally available. In many cases, the source of material was the ‘soke’ or ‘delph’ ditch immediately adjacent to the bank. The embankments have been built to a variety of geometries, usually incorporating the steepest side slopes that could stand up at the time of construction. Almost by definition, these flood embankments have been built on flat alluvial plains which are frequently underlain by soft organic clays or peats. Over the years, some of these embankments have suffered failures or been breached and then repaired, others have been raised periodically to retain higher water levels or to overcome settlement. As a result of their evolution (in some cases over many years, many embankments are of irregular shape and heterogeneous composition. Moreover, few embankments could be considered to be “well engineered”; in particular their stability would often be considered to be marginal by present day standards.

The evolutionary nature of many flood embankments has meant that they do not have well documented construction histories in the way that many other major civil engineering structures do. As a result, asset managers charged with managing the embankment’s performance are often not fully aware of the nature of either the internal structure of the embankment or of its foundations.

D2.2 Condition assessment – Key issues

Key issues relating to the inspection processes include:

- It is not practicable to apply the same level of inspection across all flood embankments as this would require excessive resources and also result in an inefficient approach. The inspection process should be tiered in order to focus resources on more critical areas. This is the rationale behind the risk-based approach suggested herein
- There is currently no thorough guidance for the complete management process (inspection, identification of problem areas, risk assessment and prioritisation of improvements, ground investigation, geotechnical interpretation and design, construction, performance monitoring etc). However, leading authorities, including the Environment Agency, are progressively developing such systems (see Section A4.4)
- At present, the majority of routine inspections are visual, with ground investigations only being undertaken when serious problems are suspected or when remedial or improvement works are to be carried out

- Inspection staff should have an understanding of both the indicators and processes associated with deterioration of embankments. An understanding of the link between indicators of distress and failure modes is desirable. Initial guidance on the inspection methodology has been given in Part B, Section B3.3 of this document. It is important to ensure that inspections are undertaken on a routine basis

Key issues relating to assessment of embankment integrity include:

- Is the embankment currently fit for purpose?
  - Is the embankment sufficiently high?
  - Is the embankment sufficiently impermeable?
  - Is the embankment sufficiently resistant to erosion from scour, wave attack, overtopping and overflowing?
  - Is the embankment adequate for a navigable waterway (if appropriate)
  - Is the embankment accessible for recreation (e.g. pedestrian access - secondary function)
- How does the condition of the embankment appear to be changing?
  - Are natural processes or human activity likely to compromise performance?
  - Is the embankment settling, cracking or slipping?
  - How is the vegetation affecting embankment performance?
- What information should an assessor or inspector attempt to collect and how often?
- What inspection/investigation techniques are available and what information do they provide?

When considering these issues, it is important to recognise what the purpose and objectives of the assessment are in order to determine the most appropriate approach.

D2.3 Condition assessment – Current knowledge and understanding

The prioritisation of embankment inspections has often been based on experience and judgement. Approaches have varied between organisations. Generally the decision to prioritise resources is based upon a perceived risk and consequence of failure, based upon expert knowledge of the local area.

The Environment Agency is undertaking research into development of a more formalised Performance Based Asset Management System (PAMS) which will provide a framework for inspection and prioritisation of embankments (as part of all flood asset systems). (See Section A4.4).

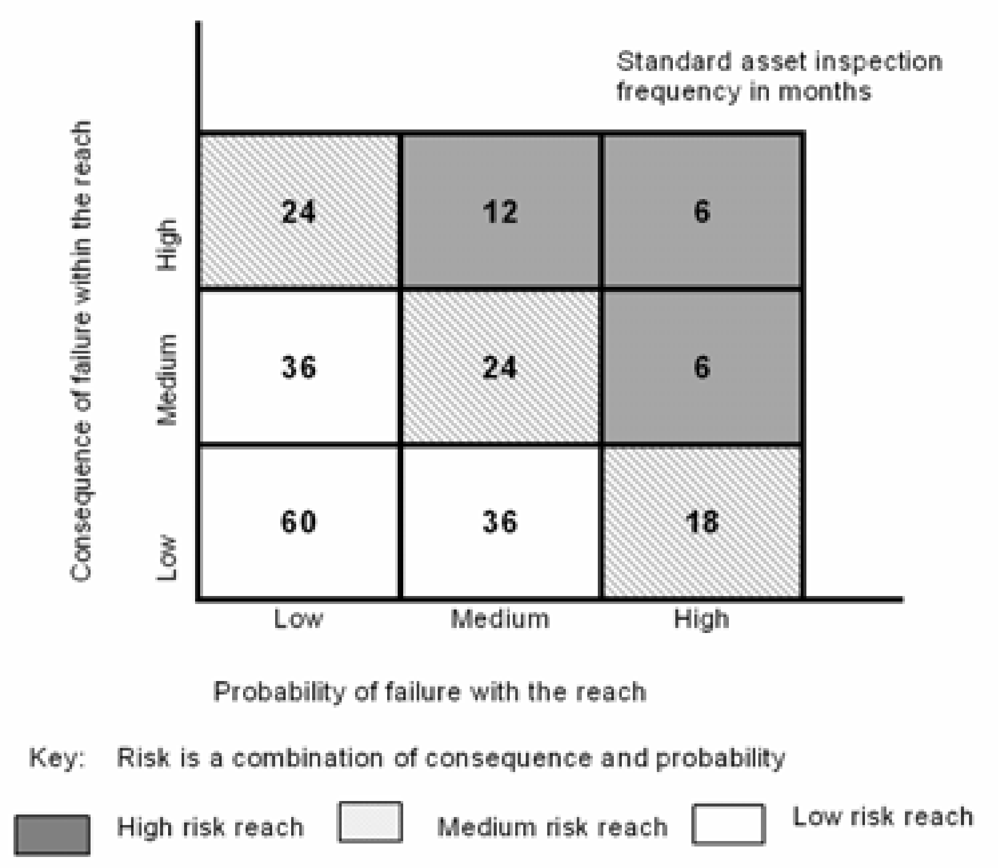
Current guidance on inspection frequency provided by the Environment Agency uses a risk-based approach to set performance standards for (a) rating each asset system as having High, Medium or Low overall consequence of failure, and (b) setting the target condition of each asset and the recommended frequency of visual inspections. Minimum condition grades for “raised defences” (which includes flood embankments) are 2 (Good) or 3 (Fair) for High and

Medium consequence systems respectively. The EA officer responsible for the system may increase or reduce this target condition for specific assets based on local knowledge, engineering judgement (including historical performance), and/or consideration of risk attributable to that asset.

The river or estuary reach or the frontage unit on the coastline is currently used as the geographic unit for setting the inspection frequency. This enables different inspection frequencies to be used within an asset system, appropriate to the differing levels of risk within it. The methodology for determining the inspection frequency applies the following guiding principles:

- The risk-based approach provides decision support to the judgement of competent professionals who make the decision on inspection frequency
- Risk is interpreted as a combination of the consequence of failure (High / Medium / Low) and the probability of failure (High / Medium / Low) within the reach or frontage. The matrix in Table D.2.1 indicates the inspection frequency
- Generally, the higher the risk, the shorter the inspection frequency and vice versa. However, the matrix is not symmetrical and the inspection frequency is always higher if the likelihood of failure is high; and
- Where the risk within a reach or frontage is highly influenced by a single asset or group of assets, these may determine the inspection frequency for the whole reach

Table D2.1 Risk based matrix for frequency of visual asset inspection (from EA Work Instruction)



In addition the responsible officer may require additional visual inspections to be undertaken at any time, particularly following a significant flood or other incident that could affect asset condition. It is emphasised that visual inspection is the first level in a hierarchy of inspections, surveys and testing.

Visual inspection:

- Covers relatively long lengths of embankment, typically 4 to 7km reach / frontage
- Depends upon the training and experience of the inspector
- Does not provide information on internal state of embankment / foundations
- Relies on identification of indicators linked to potential embankment performance

The current guidance on visual inspection of embankments given in the Condition Assessment Manual (see Figure B3.1) is worded so as to provide a good link to observed features and the hazards listed in Table D2.2.

Topographic survey:

The visual inspection should be supported by a survey of embankment crest levels. However, this practice is not yet consistently adopted across the UK.

Collection of survey data for embankments is a key issue for future operation and maintenance. Without knowing the crest level, or having a record of level variation over time, it is impossible to determine the standard of protection offered by the embankment and difficult to determine if settlement or other movement is affecting the embankment.

Traditional terrestrial survey techniques may be appropriate for surveying specific sections of embankment but this becomes expensive when long lengths are embankment are to be assessed. Remote sensing techniques, such as LIDAR, then become attractive. Current levels of accuracy for monitoring embankment crest levels are ±80mm.

Regional developments

Recognising the need to develop more detailed risk based approaches to assessing and prioritising embankment performance, some Environment Agency regions have initiated and employed some more detailed approaches. Such projects serve as examples that can contribute ideas and field experience towards development of a national framework. They also provide an immediate methodology for use in the field. As an example, in North East Region the likelihood of embankment failure is based on an assessment of bank stability through analysis of embankment geometry, body and foundation material and material stratification. The reliability of this approach has still to be assessed through comparison of predictions against observations or other assessment techniques. A key issue in developing any such approach is the identification of parameters that both reflect the likely performance of an embankment and are reasonably viable for collection or analysis.

Dutch approach
The Dutch approach to condition assessment is outlined in the Technical Advisory Committee on Flood Defence (TAW, 2002) publication “Management and maintenance of dikes and banks”. The system is based on an initial collection and collation of basic data that only needs to be gathered once (location, topography, sub-soil characteristics, structure and geometry of dike body, associated structures, fence lines etc) followed by a periodic inspection of aspects prone to change (crest elevation, condition of slopes, vegetation cover etc). The frequency and extent of inspections is related to flood risk and, importantly, the inspections can be changed as deterioration is observed.

The Dutch system relies on the experience and engineering judgement of the inspectors in relating observations to critical conditions leading to failure.

D2.4 Condition assessment – Recommended actions

It is intended that the PAMS project and a future design guide will provide a best practice approach for inspection and improvement of flood embankments (see Section A4.4). Until this, the following tiered approach and stages of investigation are recommended for assessing embankment integrity:

Stage 1: Visual inspection and topographic survey
This should be similar to the current visual inspection regime but with increased attention to factors that are likely to control embankment stability. In particular, there is a need to relate physical observations to geotechnical processes using Table D2.2 (after Table B2.1). Review of topographic data over a period of time plus assessment of local soil conditions will help to identify settlement or instability issues. This process of review should be formalised using a standardised reporting system to ensure a consistent assessment by different inspectors and that the changes of embankment condition between inspections are highlighted.

Stage 2: Formal risk assessment
The formal risk assessment should be carried out on the basis of the visual inspection and the physical characteristics of the embankment, as well as a consideration of the consequences of failure and historical performance. A decision on the need for further investigation should be made on the basis of the formal risk assessment.

Stage 3: Desk study
All relevant and available historical, topographical, geological, hydrological and geotechnical data is collected and collated during this stage. Consideration should also be given to collection of all desk study information into a standardised national database so as to improve overall knowledge. [Note however that historical geotechnical data should be viewed with care and only used when a good ‘provenance’ can be established. The validity and applicability of any earlier soil analysis needs to be ensured. Similarly, use of empirical correlations requires care in practice as the underlying source data is not always available to validate the relationships].

Table D2.2 Geotechnical factors

Element	Hazard	Field observations	Risk	Geotechnical process	Ground conditions to consider / investigate
Founding strata	Settlement	Low crest levels	Low crest levels leading to overtopping	Consolidation of underlying strata (including dissipation of excess pore pressures) or embankment fill material	Consolidation and compression characteristics of underlying soils. Secondary consolidation and creep of soils and fill. Differences in horizontal and vertical permeability of foundation material
	Deep rotational failure	Tension cracks on embankment crest. Settlement of part of crest. Lateral displacement of embankment toe. Heave of ground in front of toe	Catastrophic failure of embankment	Shear failure during construction or embankment raising	Shear strength of fill and foundation soils, in particular undrained shear strength of clays. Possible longer term gain in strength due to consolidation
	Translational sliding	Distortion of embankment crest leading to bulging along outward face	Catastrophic failure of embankment	Lateral hydraulic force exceeds shear resistance of founding strata along base of embankment or desiccation of organic fill leading to a reduction in dead weight	Shear strength of soft clays and organic soils directly beneath the embankment. Desiccation of peat and organic fills leading to a reduction in dead-weight
	Seepage and piping	Seepage or ponding of water in front of embankment	Seepage causing internal erosion and piping	Under-flow of flood water leading to erosion and slope instability	Presence of highly permeable strata beneath embankment either leading to excessive seepage
	Uplift pressures	Heave of embankment toe	High pore pressures causing instability	Build up of uplift pressures in confined permeable strata due to hydraulic continuity with flood or high water load on inward face	Presence of highly permeable strata beneath embankment leading to build up of pore pressures due to confinement
Embankment structure	Shallow slope instability	Shallow translational slumping or slippage of embankment side slopes. Possible tension cracks on embankment crest, settlement of crest, lateral displacement of embankment toe or heave of ground in front of toe	Damage to outward and inward faces of embankment leading to a loss of integrity or a reduced resistance to seepage or overtopping	Instability during rapid drawdown after flood or high water load on inward face. Longer term slippage of slopes due to pore pressure equalisation, reduction in soil suction or progressive failure. Erosion of toe along outward face due to river migration	Compaction of fill material in relation to moisture content. Build up of pore pressures after lengthy period of high water load resulting in saturation of fill material or leading to uplift. Swelling of over-consolidated clay fill leading to shallow slips. Repeated shrinkage and swelling of clay fills leading to progressive failure. Reduction in soil suction pressures in partially saturated soils following infiltration of rain and/or high water load
	Internal seepage and erosion	Cracking within embankment body. Visible seepage on outward face of embankment, particularly during “bank full” conditions. Sediment in water. Animal burrows. Local variations in growth of vegetation	Washout of embankment fill material leading to local settlement, preferential seepage paths, piping and eventually breach	Excessive seepage caused by desiccation and fine fissuring. Excessive seepage due to highly permeable fill material. Loss of embankment material through burrowing or washout of fines	Shrinkage of medium and highly plastic clay leading to fine fissuring. Excessive seepage through coarse-grained fill leading to piping at critical hydraulic gradients
	Erosion of inward face and toe	Bare soil, loss of material visible Undercutting at base of slope	Increased risk of seepage or instability	Erosion of inward face and toe due to river / coastal migration or wave erosion	Shear strength and grading of embankment material. Geomorphological assessment of long term river or coastal migration
	Erosion of outward face	Bare soil, loss of vegetation	Reduced resistance to overtopping	Erosion of outward face due to over flow	Selection of suitable topography, topsoil and vegetation. Possible use of geotextiles

Stage 4: Initial analysis

This includes the analysis of readily available data as well as the results of the visual inspections: A preliminary assessment of potential problems and unknowns is carried out by an expert advisor who produces a specification for further data requirements.

Stage 5: Detailed ground investigations

The need for new ground investigation to confirm the geological setting and to determine geotechnical parameters for analysis and design should be considered by a suitably experienced geotechnical engineer, familiar with the design and assessment of flood embankments. The scope of the ground investigation will depend on the nature of perceived issues and potential solutions, having particular regard to the site conditions. Table D2.3 lists some in-situ test methods and their perceived applicability to various soil parameters and ground conditions.

Table D2.3 In-situ test methods and their perceived applicability
(Pilarczyk, 1998)

	Site-investigation methods												
	Geophysical methods				Penetration methods				Borings				
	Seismic	Electr. resist.	Electro-magnetic	nuclear	Cone penetr. test (CPT)	Piezo cone test (CPTU)	Stand. penetr. test (SPT)	Field vane test (VST)	Press. meter test (PMT)	Dilato meter test (DMT)	Dist. samples	Undist. samples + Lab. tests	Moni-ring wells
Soil profile	C	C	C	-	A	A	A	B	B	A	A	A	-
Classification	-	-	-	-	B	B	B	B	B	B	A	A	-
Piezometric pressure	-	-	-	-	-	A	-	-	B	-	-	-	A
Permeability	-	-	-	-	-	B	-	-	B	-	C	A	C
Dry/wet density	-	-	-	A	C	C	C	-	-	-	C	A	-
Relative/density	-	-	-	-	B	B	B	-	C	C	-	A	-
Friction angle	-	-	-	-	B	B	B	C	C	C	-	A	-
Undr. shear strength	-	-	-	-	B	B	C	A	B	B	-	A	-
Compressibility	-	-	-	-	C	C	-	-	C	C	-	A	-
Rate of consolidation	-	-	-	-	-	A	-	-	A	-	-	A	C
Moduli of elasticity	A	-	-	-	B	B	B	B	B	B	-	A	-
In-situ stress	-	-	-	-	C	C	-	C	B	B	-	A	-
Stress history OCR	-	-	-	-	C	C	C	B	B	B	-	A	-
Stress/strain curve	-	-	-	-	-	C	-	B	B	C	-	A	-
Ground conditions													
Hard rock	A	-	A	A	-	-	-	-	A	-	A	A	C
Soft rock-till, etc.	A	-	A	A	C	C	C	-	A	C	A	A	A
Gravel	A	B	A	A	C	C	B	-	B	-	A	C	A
Sand	A	A	A	A	A	A	A	-	B	A	A	C	A
Silt	A	A	A	A	A	A	B	B	B	A	A	A	A
Clay	A	A	A	A	A	A	C	A	A	A	A	A	A
Peat-organics	C	A	A	A	A	A	C	B	B	A	A	A	A

A: High applicability B: moderate applicability C: Limited applicability

The range of investigatory techniques available to geotechnical practitioners includes detailed inspection, non-intrusive methods (geophysical, etc) and intrusive methods. The intrusive techniques may be sub-divided into 'simple' methods (trial pits, window samples, etc), 'standard' methods (boreholes, cone penetration tests, etc), 'complex' methods (pressuremeter tests, dilatometer tests, etc) and monitoring techniques (piezometer, settlement plates, inclinometers etc). In addition to the above, laboratory tests can be carried out on samples recovered from any of the intrusive techniques. The experienced geotechnical engineer will select appropriate methods in order to be able to characterise the ground and/or fill conditions.

The resulting ground model will of necessity be an interpretation as, in common with most ground investigations, perhaps only one part per million of the embankment and its foundation is actually sampled or tested.

Stage 6: Detailed reliability assessment and/or design of improvements
Having first identified a problem / issue through risk-based inspection, subsequently undertaken initial analysis and more detailed investigation, there should now be sufficient information to carry out a further assessment of reliability of the flood embankment and/or the design of appropriate improvements.

D2.5 Condition assessment – Good practice guidance

Good practice guidance which can inform the assessment of embankment integrity can be found in:

Flood Defence Management Manual (FDMM)
Environment Agency, 1995
This provides the current framework for embankment inspection. Identification of house equivalents at risk from defence failure allows some prioritisation of defences based upon risk. (Note: Current Agency initiative RASP will provide a more extensive risk based framework for this – see Report 2)

Infrastructure embankments – condition appraisal and remedial treatment
Perry, J., Pedley, M. and Reid, M. 2001. CIRIA Report C550
This report provides guidance on the maintenance, condition appraisal and repair of infrastructure embankments. It is based on a review of published literature, expert consultation and case studies demonstrating good practice. Whilst the text focuses mainly upon road and rail embankments, there is useful guidance of relevance to flood defence embankments.

Investigating embankment dams: A guide to the identification and repair of defects
Charles. J. et al, 1996. BRE Report 303
The guide provides a comprehensive overview of techniques used to identify defects in embankment dams. Scope includes field observations, a general approach to investigating defects, sampling, in situ testing, monitoring, leakage investigation and geophysical testing. Case study applications are also reviewed.

An engineering guide to the safety of embankment dams in the United Kingdom
Johnston et al, 1999
Whilst developed for the UK dams industry, this guide provides practical information on the behaviour of embankments, including load-response,

performance indicators, mechanisms of deterioration and failure, surveillance, investigation and monitoring.

Engineering inspection techniques using non-destructive testing
Report for Environment Agency (2001)

Dikes and revetments. Design, maintenance and safety assessment
Pilarczyk, K.W. (ed) 1998. ISBN 9054104554
This book provides extensive guidance on a wide range of aspects relating to fluvial and coastal flood defence embankments. Design guidance is offered for problems such as embankment stability, wave impact / run up and protection design. Discussion includes embankment failure mechanisms, risk management, operation and maintenance.

Management and maintenance of dikes and banks
Technical Advisory Committee on Flood Defence (TAW), Netherlands, 2002, pp20

Responsibility in site investigation
Uff, J.F., and Clayton, C.R.I., 1991. CIRIA Special Publication 73, pp42

Site investigations
Clayton, CRI, Matthews, M.C., Simons, N.E., 1995. Blackwell Science, Oxford, pp584

Waterway bank protection: A guide to erosion assessment and management
Environment Agency, (1999). R&D Publication 11. Version 1.0
This report provides practical guidance on the erosion assessment and management of waterway banks. Whilst the scope of work does not directly include flood embankments, many of the concepts and solutions are directly relevant and applicable. The guide presents an initial assessment of bank erosion problems, guidance on selecting the most appropriate protection strategy and subsequently guidance on engineering and non-engineering solutions.

Cone penetration testing in geotechnical practice
Lunne, T., Robertson, P.K. and Powell, J.J.M. 1997
This book provides extensive guidance on the specification, performance, use and interpretation of the Electronic Cone Penetration Test (CPT) and in particular the Cone Penetration Test with pore pressure measurement (CPTU).

EA AMS (Agency Management System) Work Instructions
These documents provide consistent instruction for Flood Risk Management activity across all operqtional Areas of the Environment Agency. This relates both to the process of activities and to recommended practice. These documents are available only on the EA's Intranet and to its contractors and consultants. Others will need to request them from EA Flood Risk Management at Head Office. Relevant Work Instructions include:

- *Production of performance specification for Flood Risk Management systems and major assets (148_05)*
- *Assessing the risk-based frequency of Flood Risk Management system visual inspections (160_02)*
- *Flood defence asset condition reporting (166_03)*
- *Identification of Flood Risk Management systems (358_04)*

D3 VEGETATION

D3.1 Vegetation – Scope of guidance

Guidance under this chapter includes:

- Effects of vegetation on the function of flood embankments
- Implications for management and maintenance
- Current actions and initiatives

D3.2 Vegetation – The key issues

Vegetation affects many aspects of embankment performance. Vegetation can protect an embankment, control moisture content within an embankment or physically damage an embankment. Some key issues include:

- How does vegetation affect the stability of an embankment both in the shallow surface layer and at depth?
- How does vegetation protect the various faces of an embankment under different load conditions?
- How does vegetation affect wildlife in the area, and in particular does it hide animal burrows?
- How does vegetation affect access, inspection, third party use, environmental value?
- How do differing maintenance programmes affect the quality of vegetation and hence embankment performance?
- How do different weather conditions (dry summer, wet winter) affect vegetation and subsequently the embankment?
- Differing management approaches to maintenance in the various catchment or asset systems results in different standards of vegetation cover. This can occur on the same river catchment.

D3.2.1 Direct impact on flood management function

Embankment failure may occur through a combination of processes. Vegetation can play a significant role in a number of these processes, specifically by:

- Providing an above-ground layer of surface protection against soil erosion by shielding the soil surface from overtopping flow, intercepting and cushioning the effect of direct precipitation (rainfall, hailstones etc.), reducing surface water run-off volume/velocity, reducing the effect of trampling, vehicle wheel loads and wind erosion. Vegetation may also be combined with other materials such as geo-textiles, timber, concrete and stone to form composite systems for enhanced erosion protection
- Providing a below-ground mesh of roots which may enhance **or** reduce embankment integrity through:
    - Root mesh providing a network of reinforcement and protection to the soil which improves resistance to erosion

- Excessive root growth fracturing the embankment body or interface with other structures and providing a preferential route for seepage flow or failure paths through the embankment

- Increasing **or** reducing the moisture content of the embankment. This naturally affects the upper levels of the embankment which are required to operate under extreme conditions:
  - Vegetation cover can maintain a level of moisture within the soil and help to prevent or minimise drying and cracking of the embankment
  - Vegetation cover can draw moisture from the embankment and hence aid and enhance drying and cracking of the embankment
- Large trees can result in the transmission of the dynamic effects of heavy wind onto embankments, leading to movement/failures
- Dying roots of trees within embankments can leave behind pore spaces providing flow/seepage/failure paths and cause settlement. In addition large roots tend to hold together their area of influence only, leading to non-uniform erosion resistance

Where trees have grown into an embankment but cannot be removed (TPOs, designated areas etc.) then it is essential that the trees are managed (i.e. coppicing, pollarding).

D3.2.2 Impact of vegetation on management and operation

The choice and condition of vegetation on an embankment directly affects the management and operation of embankments by affecting:

- The performance of the embankment (as outlined above)
- The ease and effectiveness with which inspection and maintenance works can be undertaken:
  - Inspection of an embankment becomes difficult and unsafe when vegetation is excessive
  - Managed vegetation exposes (or allows inspection of) indicators for seepage and instability (e.g. wet patches encourage different or increased vegetation growth)
  - Managed vegetation can encourage or hinder access (through selective use of brambles, prickly vegetation etc)
- The frequency and nature of management (vegetation management is predominantly cutting, but could include chemical treatments e.g growth retarders/weed killers, tree pollarding/coppicing etc)

Traditionally, different areas within the Environment Agency have established their own standard of vegetation management through balancing allocation of resources against perceived importance. Long-term management trials to observe the effect of cutting regime on the vegetation sward are underway to help inform a more rational planning of cutting regime.

Type and location of vegetation may also affect its overall condition. For example:

- Trees on or near embankments may give strong shade cover resulting in poor quality of vegetation cover underneath
- Trees or fencing may encourage cattle to gather in, or traffic, one particular location, resulting in surface erosion and poor ground conditions
- Grazing may be beneficial to vegetation management between April and October

D3.2.3 Impact on secondary functions

Vegetation management can significantly affect each of the secondary functions of embankments outlined in Section A2.3:

<u>Access</u>
Access may be encouraged or restricted through frequency of maintenance and choice of vegetation (e.g. cut grass encourages walkers onto an embankment, brambles along the toe or inward face discourages access). Restricting access may also affect the ease with which maintenance work may be undertaken.

<u>Recreation</u>
Key users of embankments include walkers, anglers and cyclists. Vegetation that provides easy access for any of these will encourage use.

<u>Environmental</u>
A balance is required between maintaining a uniform vegetation cover for maximum protection against erosion, and encouraging natural growth of indigenous vegetation that would minimise visual impact of the embankment and encourage local wildlife. Priority should be given to ensuring that the standard of vegetation supports the primary flood risk management function of the embankment. However, the overall management process should, as far as possible, use methods that enhance the environment and minimise detrimental impacts on local habitats and visual appearance, recreation etc.

The type of vegetation on an embankment may influence the type of wildlife in the area by encouraging a friendly or hostile environment (both food and habitat). Discouraging burrowing or dangerous / unwelcome animals through the use of vegetation is to be encouraged – although guidance on this aspect is limited.

<u>Health and Safety</u>
Poisonous plants: management of poisonous plants (e.g. giant hogweed) or invasive plants are a legal requirement for some species.

Visibility: the masking of edges or slips in embankments due to excessive vegetation can lead to falls or overturning of vehicles.

Table D3.1 Vegetation: Likely indicators and problems

Indicator	Potential causes	Potential consequences	Suggested actions
Patchy vegetation on inward face of embankment	Poor maintenance Erosive flow greater than protection offered by vegetation Damaging third party use (e.g. fishermen, dumped weed or cuttings) Unstable embankment slopes Inadequate nutrients in top soil High levels of vermin infestation High levels of shade (from trees)	Embankment face vulnerable to erosion under high channel flow conditions. Duration of flow resistance limited	Assess direct cause through review of: - embankment use - maintenance programme - bank stability (slope, moisture, material) Consider improving soil quality or replacing top soil Consider use of alternative protection measures
Vegetation eroded on crest	Overtopping Third party use Vegetation inhibited through maintenance action (dumped weed or cuttings)	Embankment vulnerable to erosion during overtopping Lowered crest sections may focus overtopping flow during an extreme event	Repair crest If overtopping is acceptable, consider increasing standard of bank protection Review maintenance practice
Vegetation bare or eroded on outward face	Embankment instability Third party use Leachate from contaminated fill	Reduced resistance to overtopping Reduced embankment stability Contamination of downstream watercourses	Review embankment use and stability to identify cause. Limit third party action (human or animals) Remove upper zone of contaminated fill and cap the remainder with at least 0.5m of approved fill
Increased vegetation growth in specific areas	Seepage flow	Bank instability Pipe formation - breach	Investigate source of moisture

D3.3 Vegetation – Current knowledge and understanding

Whilst some guidance is available on various aspects of vegetation management, there is limited guidance on how to achieve specific performance targets (e.g. embankment resistance to overflow, animal activity, fissuring etc.). The limited guidance available is referenced later in this section. Industry needs are outlined below, which indicate the lack of guidance in specific areas.

<u>Immediate / Short term measures</u>

- Ensure that vegetation establishment, and short and long term management are considered as part of the embankment design or assessment process
- Utilise new Conveyance Estimation System (CES) to assess the effects of channel vegetation management and dredging on river flood conveyance (including seasonal effects) and flood water level adjacent to embankment

<u>Industry needs / Longer term measures</u>

- Consider embankment vegetation as a whole life issue, rather than simply a maintenance issue
- Specific research and better guidance is required to establish how vegetation type affects performance of embankments (both in terms of surface protection, but also in terms of the other factors such as stability, wildlife, third party use, visual impact, impact upon inspection etc.)
- Where a significant change in vegetation cover is proposed, short-term management measures may be needed whilst changing from an established vegetation to a desired one
- Better guidance is needed on the most effective balance for vegetation management, taking into consideration the effects of maintenance on a range of issues including performance of the embankment, conveyance of the channel, environmental impact, ease of inspection etc. This includes encouraging best use of appropriate, local species to achieve appropriate performance standards

<u>Current actions and initiatives</u>

Bank vegetation maintenance trials

The Environment Agency is carrying out a series of trials investigating the effects of varying maintenance procedures on vegetation growth and quality. The trials are located on service embankments in Lincolnshire and Cambridgeshire. Research is looking at the effects of cutting frequency, management of arising from the cuts, effect of dumping aquatic weed-cutting on the embankments and chemical treatments (e.g. growth retarders weed killers/wipes).

Performance based asset management system for flood defences (PAMS)

See Section A4.4 for more information.

D3.4 Vegetation – Recommended actions

Appropriate and well-maintained vegetation will provide a valuable surface protection layer for embankments, which can reduce or prevent slope erosion and prolong the resistance of an embankment to deeper erosion and breaching, even during extreme overtopping or overflowing events. It is generally considered good practice to maintain the embankment clear from trees and bushes, with a good sward of grass or short vegetation. Trees and bushes can lead to destruction of the embankment body through root growth and may provide a focal point for local scour during extreme flood conditions. Once the surface vegetation has been broken at one location, the integrity of the whole layer and hence embankment can be compromised.

When considering how to improve the condition of an embankment upon which vegetation has grown excessively, it is important to assess first the risk to the embankment before clearing the vegetation. Issues to consider include:

- Will clearing the vegetation leave a stable grass cover, or leave the bank exposed. If exposed, what is the risk of erosion before stable vegetation cover can be re-established?
- Will the removal of large bushes / trees cause more damage to the embankment than their continuing presence? What will be the effect of change in root water absorption and decay over time on the embankment structure and stability if the decision is made to remove large trees or shrubs from an embankment?

Where vegetation cover is poor or variable the following questions should be considered prior to action:

- What are the reasons for the variable nature of growth?
    - Is the vegetation condition indicative of surface erosion, embankment use (or mis-use) or symptomatic of internal problems (e.g. seepage leading to patchy growth)
    - Is the quality of topsoil and / or subsoil sufficient to promote good growth?
    - Does the embankment contain contaminated materials with subsequent leachate affecting growth?
    - How does the existing management programme influence condition?
- Is the type of vegetation cover local or purpose-planted? If the latter, is it the most appropriate type for the local environmental conditions? (Look at other local embankments and assess the most successful vegetation type)

Detailed guidance on the use of vegetation to optimise performance and minimise maintenance is limited, research is ongoing. The reader is advised to follow progress on the current Environment Agency project assessing the effectiveness of varying vegetation maintenance regimes, and to look carefully at the results of local maintenance regimes.

D3.5 Vegetation – Good practice guidance

The following documents provide current best practice relating embankment performance and vegetation:

Overview of embankment / vegetation issues
Infrastructure embankments
Perry J., Pedley M. and Reid M. 2001. CIRIA Report C550. Pp176-179
This provides an overview of some issues relating to vegetation impacts on embankments. Reference is made to guidance for landscaping, control and management of vegetation by London Underground Ltd (LUL, 1998a, 1998b) as well as work being undertaken by the Highways Agency.

Use of vegetation in civil engineering
Coppin N.J. and Richards I.G. 1990. CIRIA / Butterworths

Surface protection and vegetation
Design of reinforced grass waterways
Hewlett H.W.M., Boorman L.A. and Bramley M.E. 1987. CIRIA Report 116

Control of invasive plants
Environment Agency information leaflet
"Guidance for control of invasive plants near watercourses". Particularly addressing Japanese Hogweed, Himalayan Balsam and Giant Hogweed.

Control of Invasive Riparian and Aquatic Weeds
Environment Agency R&D Note 233

Waterway bank protection: A guide to erosion assessment and management
Environment Agency, 1999. R&D Publication 11. Version 1.0
This report provides practical guidance on the erosion assessment and management of waterway banks. Whilst the scope of work does not directly include flood defence embankments, many of the concepts and solutions are directly relevant and applicable. The guide presents an initial assessment of bank erosion problems, guidance on selecting the most appropriate protection strategy and subsequently guidance on engineering and non-engineering solutions.

Condition grading and assessment
Environment Agency Condition Assessment Manual
This provides example photos of different embankment conditions for each of five different condition grades. Implicitly, this shows varying conditions of embankment surface vegetation. As the overall embankment condition degrades, so does the typical quality of surface protection / vegetation. See Plates B1.1 and B.1.2.

Controlling embankment stability through vegetation (Research)

Bioengineering – the Lougham Wood Cutting field trial

Greenwood J., Morgan R.P.C. and Short J. 2001. CIRIA Project Report PR81

Shallow slip failures on embankments and cuttings are more likely to occur in heavy cohesive materials such as Gault Clay. Reinstatement of such shallow failures can be costly and it is thought that the risk of slips occurring might be reduced by the use of selected vegetation. Long-term monitoring of an instrumented, vegetated Gault Clay slope on the M20 will provide information on the performance of the slope over a period of 5 years from construction. Information on the application of vegetative techniques for the prevention of shallow slips will be implemented through Advice Note: The long-term monitoring was completed during the winter of 1998. Some destructive testing will be carried out on selected areas of planting to investigate root growth. Status reports have been prepared annually throughout the life of the project.

D4 SETTLEMENT

D4.1 Settlement – Scope of guidance

The following topics are addressed in this chapter:

- What are the causes of settlement?
- What approach should be adopted to identify the root cause of the settlement?
- How can settlement be treated?

The purpose of this chapter is to describe briefly the process of consolidation and settlement, to identify the key issues and to provide some references to basic technical literature.

Almost by definition, most flood embankments have been constructed on flood plains. Many will therefore have been built on foundations of which contain layers of soft clay or peat. It is a characteristic of these materials that they undergo relatively large time-dependent settlements as they consolidate under an imposed load. This is particularly the case for larger embankments of over two metres height. For riverbanks which have been built up over the centuries, much of this settlement will already have occurred and possibly been obscured by subsequent filling. In contrast, newer embankments constructed to full height in one lift may be prone to large ongoing settlements of perhaps hundreds of millimetres. The process of embankment raising will often trigger additional settlement, especially where additional fill is placed over the side slopes and toe of an embankment.

The obvious problem caused by settlement is that the embankment may not achieve its primary purpose of providing an impermeable barrier to a required level. One issue of particular concern is the time dependency of the consolidation process; an embankment which meets its height requirements for a certain level of protection one year will not necessarily meet those objectives in subsequent years. Another problem caused by settlement is distortion induced cracking of the potentially brittle fill material. This will make the embankment more permeable as well as being more prone to erosion damage and possibly breach as a result of overtopping (which will be more likely as a result of the settlement).

In addition to movements deriving from a consolidation of soft soils beneath an embankment, settlement may result from a number of other causes which may be indicative of more severe problems. In particular, problems such as the ongoing consolidation of embankment fill materials, global instability, the burrowing of animals or internal erosion through seepage can all manifest themselves as settlement in one way or other.

This section addresses the issue of consolidation related settlement (in other words, settlement which derives from changes in volume of the embankment fill material or the underlying soil). Other sections address the issues of instability and erosion.

D4.2 Settlement – Key issues

The thickness of most materials reduces when subject to an externally applied load. For most engineering materials working within their allowable stress ranges, this compression will be elastic (recoverable if the load is removed) and instantaneous. Soils, however, contain free water, some of which will be squeezed out by the application of an external load. As this water is squeezed out, the volume of the soil changes and hence settlement occurs. This process is termed “consolidation”; the rate at which it occurs is dependent on the compressibility and the permeability of the soil. For a flood embankment this process can take many tens of years to complete.

Where embankments are constructed on subsoil of high compressibility and low undrained shear strength, there is a risk of excessive settlement and deformation.

Settlement has two major detrimental effects. Firstly, crest levels may fall below the levels required for the standard of protection against the design flood events. Secondly severe cracking may occur as the embankment deforms over a period of time leading to an increased rate of seepage and a reduced resistance to scour and overtopping.

When settlement is perceived to be a problem, the following issues need to be addressed:

- Identifying the nature of the problem
  - Has the embankment settled?
  - Is the settlement a result of consolidation or has it been caused by other factors ?
  - Is the settlement continuing to occur?
  - How much more settlement is likely to occur and over what time period?
- Investigation and instrumentation
  - What investigation is required to confirm the nature of the settlement?
  - What instrumentation or techniques can be used to monitor settlement?
  - Is monitoring required for long periods, and what expertise is needed to do this?
- Dealing with settlement
  - How can the settlement be dealt with so that the embankment achieves its flood management purpose?
  - Will remedial works such as embankment raising trigger more settlement?
  - What materials and methods might be used?

D4.3 Settlement – Current knowledge and understanding

Correctly identifying the cause of embankment settlement is crucial if appropriate remedial measures are to be designed. This process requires an understanding of the geological setting, soil properties, geotechnical processes and the embankment's construction history. As is the case whenever engineering assumptions have been made, monitoring of embankment performance can be used to validate the approach adopted. It is important that any such monitoring reflects the design / remedial assumptions and measures the relevant aspects of embankment performance. For example, monitoring embankment crest level will indicate whether settlement is occurring but will not give any indication of whether the settlement is a function of consolidation or rotational failure. If rotational failure is a possibility then the use of inclinometers or tell-tales (various systems to highlight progressive embankment movement), installed at the embankment toe, will provide better feedback on the nature of the overall deformations.

Predicting the rate and magnitude of future settlement accurately is difficult because of the large number of variables and the uncertain boundary conditions. Whilst the advent of three-dimensional finite element analysis computer programs and the development of ever faster processing units has improved the engineer's ability to model complex construction situations, the reliability of such methods is still very dependent on the quality of the ground investigation data and the assumptions, particularly with regard to soil properties, made by the design engineer. In general, straightforward calculations made on the basis of simplifying assumptions by an experienced geotechnical engineer may well be more accurate than predictions produced by extended but potentially inappropriate computational analyses.

Having established the cause of the settlement together with its anticipated magnitude and duration, remedial measures can be designed. A number of options are available ranging from simple crest-filling to complex methods such as deep cement mixing with foundation soil as an attempt to arrest the process of consolidation.

D4.4 Settlement – Recommended actions

Where settlement of an embankment is suspected, or needs to be addressed, the following actions are recommended. As stated elsewhere, it is essential to obtain the advice from a suitably qualified and experienced geotechnical engineer:

- Inspect the site and carry out a desk study using any appropriate existing records to conform or establish potential causes of the settlement
- Confirm extent of settlement by undertaking a detailed survey of embankment crest and toe levels and some section profiles. The survey should extend beyond the area of suspected settlement. The observed crest levels should be compared with historic data and, if necessary, records should be taken over a period of time to establish the rate of settlement

- If necessary, carry out an intrusive ground investigation to confirm the geological model and establish geotechnical design parameters
- Identify the causes of the settlement and establish remedial measures if necessary
- Carry out the repair but continue to monitor crest and toe levels to validate the assumptions made

D4.5 Settlement – Good practice guidance

Embankments on soft clays

Leroueil, S., Magnan, J-P. and Tavenas, F. 1990. Ellis Horwood, London

This book reviews soil mechanics theory and practice for the design and construction of embankments built on the soft clays which often underlie the flood plains on which flood embankments are constructed.

Embankments on soft clays

Edited by The Public Works Research Centre of Greece (major contributors: Jardine, R.J. and Hight, D.W. 1987. Athens

This work brought together much of the then current (but still very relevant) "state of the art" theory and practice into one publication, giving summaries on engineering geology, engineering behaviour, field and lab investigatory methods, construction and remediation techniques.

Guidelines on sea and land dikes

TAW (Technical Advisory Committee for Flood Defence in The Netherlands) (1999) The Hague

This report covers general procedures for planning, investigating, designing, constructing and maintaining sea and lake dikes dams, separation embankments and compartment dikes.

Water retaining soil structures

TAW (Technical Advisory Committee for Flood Defence in The Netherlands) Technical Report (2000) The Hague

This technical report covers geotechnical aspects of design, construction and maintenance of earth embankments for water retention purposes.

Dikes and revetments. Design, maintenance and safety assessment

Edited by Pilarczyk, K.W. 1998. ISBN 9054104554)

This book provides extensive guidance on a wide range of aspects relating to fluvial and coastal flood defence embankments. Design guidance is offered for problems such as embankment stability, wave impact / run up and protection design. Discussion includes embankment failure mechanisms, risk management, operation and maintenance.

Code of practice for earthworks. BS 6031: 1981

This British Standard deals primarily with earthworks for highways, railways and airfields and specifically excludes earthworks for dams, reservoirs, canals, river training and sea defences. However, many of the issues covered by the standard are of relevance to river embankment design.

The Earth Manual

United States Bureau of Reclamation (Current edition)

This guidance manual divides into three sections addressing properties of soils, investigation of soils and control of earth construction. The first two sections provide detailed technical guidance on specific tools and techniques for assessing soil condition and behaviour. The third section provides more practical construction advice covering a range of earth and earth related structures including the construction of embankments and canals. A useful reference document for more detailed technical information relating to geotechnical issues.

Available via internet at [*www.usbr.gov/tcg/earth*](www.usbr.gov/tcg/earth)

An engineering guide to the safety of embankment dams in the United Kingdom

(Johnston et al, 1999)

Whilst developed for the UK dams industry, this guide provides practical information on the behaviour of embankments, including load-response, performance indicators, mechanisms of deterioration and failure, surveillance, investigation and monitoring.

Infrastructure embankments – condition appraisal and remedial treatment

Perry, J., Pedley, M. and Reid, M. (2001). CIRIA Report C550

This report provides guidance on the maintenance, condition appraisal and repair of infrastructure embankments. It is based on a review of published literature, expert consultation and case studies demonstrating good practice. Whilst the text focuses mainly on road, rail and canal embankments, the report contains some guidance which can be applied to flood defence embankments.

Investigating embankment dams: A guide to the identification and repair of defects

Charles et al, (1996)

The guide provides a comprehensive overview of techniques used to identify defects in embankment dams. The report covers field observations, a general approach to investigating defects, sampling, in situ testing, monitoring, leakage investigation and geophysical testing. Case study applications are also reviewed.

Small embankment reservoirs: A comprehensive guide to the planning, design and construction of small embankment reservoirs for water supply and amenity use

Kennard, M.F., Hoskins, C.G. and Fletcher, M. 1996. CIRIA Report 161, Butterworth-Heinemann, London

Covers, amongst other things, geotechnical assessment, ground investigation techniques, embankment design procedures and earthworks design and construction.

D5 GLOBAL INSTABILITY (ROTATIONAL AND TRANSLATIONAL FAILURES)

D5.1 Global instability – Scope of guidance

The following topics are addressed in this chapter:

- What are the causes of global stability?
- How can global instability be avoided?
- What are the symptoms of global instability?
- What are the options for dealing with global instability?

This chapter addresses the issue of global instability by briefly describing the phenomenon, identifying the key issues and providing some references to basic technical literature.

For the purposes of this review, the term ‘Global Instability’ is taken to mean the complete failure of a section of embankment either by deep rotational failure or by translational failure. In either case the loss of integrity will mean that in many cases the embankment is no longer able to retain water. Flooding will usually be a consequence of global instability.

Deep rotational failures will tend to be initiated by changes to an existing situation. Examples of causes include the construction of a new embankment or an existing embankment being raised, a high load being applied to the crest, an unusually high water level in the river or the excavation of a ditch at the toe of the embankment. One particular form of deep rotational failure is triggered by high groundwater pressures acting in a permeable layer beneath the embankment.

<u>Deep rotational failures</u>
Deep rotational failure will usually manifest themselves as cracking and downward displacement of part of the crest, bulging of the embankment slope, particularly the base, and heave of the ground in front of the toe. In some cases, however, it can be difficult to distinguish between settlement and global instability, particularly if embankment raising has concentrated settlement onto just the outward side of the embankment. A deep seated failure will result in a softening of the affected embankment fill and a weakening of the foundation soils. If the failure does not trigger a breach itself, this may quickly follow as a result of overtopping or seepage unless immediate repairs are carried out.

<u>Translational failures</u>
Translational failures involve the displacement of the embankment bodily sideways, usually along a weak layer. The failed length of embankment shears off at either end but can otherwise stay relatively intact despite being displaced sidewards by perhaps many metres. For translational failures to occur, a weak layer must exist at a shallow depth beneath the embankment. As a failure mechanism, it is most likely to occur when high river levels follow a protracted dry period during which the embankment may have dried out. This is particularly

the case if the embankment has been constructed out of soils which contain a high proportion of organic or peaty material.

D5.2 Global instability – The key issues

The construction of an earth embankment increases the shear stresses within the foundation soils. If the embankment is poorly designed or the construction process is not appropriately managed, these shear stresses may exceed the available strength of the fill and the underlying soils so that a failure is initiated. This failure mechanism is particularly likely where embankments are built on soft clays and peats found in alluvial plains. If the embankment fill material and the foundations soils are homogeneous, the failure surface will tend to be circular as this represents the most kinematically efficient mechanism. When this occurs, the soil within the failed mass moves downward and outwards. Alternatively, if discrete layers of soft material exist within the ground beneath the embankment then the failure surface may pass horizontally along these layers.

Global instability will tend to be triggered by change. For example, the most likely cause is the initial construction, particularly if the embankment is built in one lift to heights in excess of three metres. Alternative triggers might include embankment raising, excavation of a toe ditch or deepening of the river channel, high applied loads such as excavators or stockpiled dredgings, high river levels or high seepage induced pore pressures.

The characteristic symptoms of global instability are tension cracks around the perimeter of the failure, particularly on the embankment crest or failure periphery, bulging of the embankment or heave of the underlying ground at the embankment toe as well as distortion and cracking of the failed mass of material. If rotational movement is pronounced, a back scarp may form on the embankment crest.

Key issues include:

- Identifying the nature of the problem
  - Has the crest of the embankment settled?
  - Is there evidence of any dislocation of the embankment crest or sideways movement of the body of the embankment?
  - Is there evidence of tension cracking or scarp formation on the crest?
  - Are there any signs of bulging or heave at the embankment toe?
  - Is any seepage evident?
- Investigation and instrumentation
  - What investigation is required to confirm the failure mechanism?
  - What geotechnical data is required to design remedial works?
- Dealing with global instability
  - Are emergency actions required to repair the embankment or close a breach?
  - Will emergency actions compromise the scope of permanent remedial works?
  - How much disturbed material will need to be excavated and removed?

- Will stabilising berms or flatter side slopes be required? If so will additional land be needed?
- Will the improvement works initiate further settlement?

D5.3 Global instability – Current knowledge and understanding

Computer programs are now available to carry out slope stability analyses and predict a factor of safety against rotational or translational failure. These programs work by hypothesising a large number of failure mechanisms (circular, non-circular or wedge type) and calculating for each the driving forces and the resistance provided by the shear strengths of the soils. The critical factor of safety is the lowest calculated ratio of the resisting forces (or moments) to the driving forces (or moments). The quality of the analysis is highly dependent on the program operator, particularly in respect of the choice of the critical mechanisms analysed and the selection of the shear strengths mobilised by the failure. For this reason, it is recommended that slope stability calculations are carried out by suitably qualified and experienced geotechnical engineers.

It is far better to anticipate the possibility of global instability and take steps to avoid the situation rather than having to deal with the situation after a failure has occurred. Global instability is a particular threat to embankment integrity as it can affect a large part of an embankment; failure to deal with such an event quickly may result in the initiation of a breach.

The usual solution for dealing with global instability is to remove the cause of the instability and to excavate and replace the failed material (both the fill and the foundation soils), taking care to "step" the new fill into the undamaged part of the old embankment. The removal of the cause of the instability may involve excavation of stockpiled material or it may involve a reduction of shear stress levels in the embankment foundations by construction of berms or a flatter side slopes as indicated by the slope stability analysis.

The choice of replacement fill material is of crucial importance. When compacted, the material must be sufficiently impermeable, have sufficient shear strength and not be prone to fine fissuring. These requirements can be somewhat conflicting as soils with high clay contents will generally be highly impermeable but will also be prone to fissuring and having low frictional strength characteristics. On the other hand, soils with low clay contents will demonstrate higher frictional strengths and be less prone to cracking but will be more permeable. If a single material cannot meet all of the design requirements then a composite embankment (e.g. clay core with granular side slopes) may be required. Where a combination of material types is utilised within one embankment, a system of granular or geotextile filters may be required to ensure that soil particles do not migrate from one soil type to another under hydraulic load.

The excavation and replacement of the failed material may be problematic. Although a failure of part of an embankment may have occurred, a breach will not always have been initiated. In such a case, repairs should be carried out quickly but in a manner which does not threaten the stability of the remaining embankment or compromise the health and safety of those working on the repair. Very careful consideration should be given to the temporary works for such repairs as removal of failed material could in itself trigger further collapse. These works must be devised and supervised by competent geotechnical engineers. Suitable temporary works may consist of executing the repair in a series of narrow strips to limit the length of exposed embankment. Alternatively, sheet pile retaining walls may be required to provide temporary support

D5.4 Global instability – Recommended actions

It is obviously better to anticipate a global instability and take avoiding action than it is to have to carry out repairs. Seek the advice of a suitably qualified and experienced geotechnical engineer if problems are suspected, and before initiating changes to an existing embankment.

- In the case of a failure, contact an experienced geotechnical engineer immediately and prepare to take emergency action taking his / her advice into account
- Carry out a desk study, making full use of any relevant existing records, and inspect the site to establish potential causes of the failure. Identify if any adjacent areas are at risk
- Confirm embankment layout and the extent of the failure by undertaking a detailed survey of embankment crest and toe levels and some section profiles. The survey should extend beyond the area of the suspected failure
- Carry out an intrusive ground investigation to confirm the geological model and establish geotechnical design / remedial parameters
- Identify the causes of the failure and establish remedial measures as necessary (these might include a repair of the failed zone and the construction of berms or flatter side slopes etc) along any length of embankment found to be at risk
- Carry out the repair and continue to monitor crest levels and horizontal movements of the toe to validate the performance of the remedial works

D5.5 Global instability – Good practice guidance

Embankments on soft clays
Leroueil, S., Magnan, J-P. and Tavenas, F. 1990. Ellis Horwood, London.
This book reviews soil mechanics theory and practice for the design and construction of embankments built on the soft clays which often underlie the flood plains on which flood embankments are constructed.

Embankments on soft clays
Edited by The Public Works Research Centre of Greece (major contributors: Jardine, R.J. and Hight, D.W. 1987. Athens
This work brought together much of the then current (but still very relevant) "state of the art" theory and practice into one publication, giving summaries on engineering geology, engineering behaviour, field and lab investigatory methods, construction and remediation techniques.

Guidelines on sea and land dikes
TAW (Technical Advisory Committee for Flood Defence in The Netherlands) (1999) The Hague
This report covers general procedures for planning, investigating, designing, constructing and maintaining sea and lake dikes dams, separation embankments and compartment dikes.

Water retaining soil structures
TAW (Technical Advisory Committee for Flood Defence in The Netherlands) Technical Report (2000) The Hague
This technical report covers geotechnical aspects of design, construction and maintenance of earth embankments for water retention purposes.

Dikes and revetments. Design, maintenance and safety assessment
Edited by Pilarczyk, K.W. 1998. ISBN 9054104554)
This book provides extensive guidance on a wide range of aspects relating to fluvial and coastal flood defence embankments. Design guidance is offered for problems such as embankment stability, wave impact / run up and protection design. Discussion includes embankment failure mechanisms, risk management, operation and maintenance.

Code of practice for earthworks. BS 6031: 1981
This British Standard deals primarily with earthworks for highways, railways and airfields and specifically excludes earthworks for dams, reservoirs, canals, river training and sea defences. However, many of the issues covered by the standard are of relevance to river embankment design.

The Earth Manual
United States Bureau of Reclamation (Current edition)
This guidance manual divides into three sections addressing properties of soils, investigation of soils and control of earth construction. The first two sections provide detailed technical guidance on specific tools and techniques for assessing soil condition and behaviour. The third section provides more practical construction advice covering a range of earth and earth related structures including the construction of embankments and canals. A useful reference document for more detailed technical information relating to geotechnical issues.

Available via internet at www.usbr.gov/tcg/earth

An engineering guide to the safety of embankment dams in the United Kingdom
(Johnston et al, 1999)
Whilst developed for the UK dams industry, this guide provides practical information on the behaviour of embankments, including load-response, performance indicators, mechanisms of deterioration and failure, surveillance, investigation and monitoring.

Infrastructure embankments – condition appraisal and remedial treatment
Perry, J., Pedley, M. and Reid, M. (2001). CIRIA Report C550
This report provides guidance on the maintenance, condition appraisal and repair of infrastructure embankments. It is based on a review of published literature, expert consultation and case studies demonstrating good practice. Whilst the text focuses mainly on road, rail and canal embankments, the report contains some guidance which can be applied to flood defence embankments.

Investigating embankment dams: A guide to the identification and repair of defects
Charles et al, (1996)
The guide provides a comprehensive overview of techniques used to identify defects in embankment dams. The report covers field observations, a general approach to investigating defects, sampling, in situ testing, monitoring, leakage investigation and geophysical testing. Case study applications are also reviewed.

Small embankment reservoirs: A comprehensive guide to the planning, design and construction of small embankment reservoirs for water supply and amenity use
Kennard, M.F., Hoskins, C.G. and Fletcher, M. 1996. CIRIA Report 161, Butterworth-Heinemann, London
Covers, amongst other things, geotechnical assessment, ground investigation techniques, embankment design procedures and earthworks design and construction.

D6 SHALLOW INSTABILITY (SURFACE FAILURE)

D6.1 Shallow instability – Scope of guidance

The following topics are addressed in this chapter:

- What are the causes of shallow stability?
- What are the tell-tale signs of shallow instability?
- What design methods are available for assessing embankment stability?
- How can shallow instability be treated?

As explained in Chapter D1, most flood embankments in the UK have been constructed over a period of many years with locally won soils, and often without a high level of design or construction control.

When a clayey material is compacted to form a river embankment, its initial shear strength will depend on the characteristics of the constituent soil particles, the soil moisture content and the applied compaction effort. Over a period of time, however, the soil will weather and potentially soften from the surface down. This effect will be aggravated by seasonal variations; the embankment will dry and possibly crack over the summer months and then these cracks will then form a pathway for water in the autumn or winter (by infiltration of rain or seepage of flood-water).

With steep sided embankments, this softening process will reduce the factor of safety against shallow slip failure, potentially to a point where surface slumping occurs. This process will be inhibited to a certain extent by the tendency for vegetation to desiccate and reinforce the soil near the embankment surface. The tendency for slumping is highly dependent on the slope of the embankment sides; many river embankments are over-steep as they were initially constructed with a little fill as was necessary for the embankment to stand up in the short term.

D6.2 Shallow instability – The key issues

Shallow slip failures will usually manifest themselves as a furrowing or ridging of the surface of the side slopes. Where vegetation is effective at strengthening the soil near the surface, there will be a tendency for failure surfaces to be pushed deeper into the embankment. However, shallow failure surfaces will generally not be more than one metre deep. The tendency for shallow slips to form can be exacerbated on the inward face by high river levels over a period of time being followed by a rapid draw-down of flood water level. Shallow failure surfaces will not generally threaten the overall embankment integrity in the short term. However, if they are not dealt with, then the softening front may progress deeper into the embankment. In addition, in a cracked, distorted and furrowed state, the side slopes of the embankment will be more vulnerable to erosion, particularly from overtopping.

In general, the overriding cause of shallow slippage will be over-steepness of the embankment side-slopes in relation to the intrinsic strength of the fill materials given the local soil water regime. This can be overcome by flattening the slope or by placing a suitable material with a higher frictional shear strength and better drainage characteristics (for example, angular gravel) over, or in bands within, the shoulders of the embankment. Alternatively, reinforcement can be provided by means of different vegetation or the use of geotextiles.

- Identifying the nature of the problem
  - Is slumping of the embankment side slopes evident?
  - Over what extent is the disturbance?
  - What is the slope of the sides?
  - From what materials has the embankment, particularly the surface layers, been constructed?
  - Is the slumping on the outward or the inward face?
  - Is any seepage or other sources of softening / wetting the soil evident?
- Investigation and instrumentation
  - What investigation is required to confirm the failure mechanism?
  - What geotechnical data is required to design remedial works?
- Dealing with shallow failure
  - Are emergency actions required?
  - Will emergency actions compromise the scope of permanent remedial works?
  - Will disturbed/slumped material need to be removed and replaced?
  - Will flatter side slopes or berms be required?
  - What materials should be specified for the new fill?
  - Will other reinforcing techniques help?
  - If berms or flatter side slopes are required, how much additional settlement will be induced by this filling?

D6.3 Shallow instability – Current knowledge and understanding

As with deep rotational failure, and more generally for any soil instability problem resulting in a slip, shallow instability occurs when the driving forces along any particular failure surface exceed the available shear strength. Shallow failures tend to be controlled by the frictional strength characteristics of the embankment fill materials. Were it not for the effects of vegetation and the soil cohesion, pore pressures or suctions, the limiting side slope would be the angle of repose of the fill material. The beneficial effect of the vegetation together with some apparent cohesion of the soil means that shallow slumping failure surfaces tend to occur at depths of between 200mm and one metre below the surface of the slope.

Owing to the need to provide a factor of safety, the maximum inclination of the side slopes needs to be flatter than the angle of repose of the fill material. When seepage pressures or the process of rapid drawdown are considered, the design slope angle becomes flatter still, to the point where many existing slopes would be considered to be over-steep. Vegetation and some apparent cohesion keep the slopes stable for much of the time but slumping can occur, particularly during extended periods of heavy rainfall or with a rapid fall in water level following saturation of an embankment by high flood water level.

Slope stability computer programs can be used to assess the factor of safety against shallow failure. However, given the difficulties of assessing geotechnical parameters and establishing boundary conditions (particularly issues relating to pore pressure such as soil suctions, wetting fronts, rapid draw down and seepage), these need to be used with care. For this reason, it is recommended that slope stability calculations are carried out by suitably qualified and experienced geotechnical engineers.

D6.4 Shallow instability – Recommended actions

In the case of any apparent slope failure, seek the advice of an experienced geotechnical engineer immediately. If necessary, carry out emergency action as directed by the geotechnical engineer:

- Carry out a desk study, making full use of any relevant existing records, and inspect the site to establish potential causes of the failure
- Confirm embankment layout and the extent of the failure by undertaking a detailed survey of embankment crest and toe levels and some section profiles. The survey should extend beyond the area of the suspected failure
- Carry out an intrusive ground investigation to confirm the nature of the embankment fill material and any sources of water (e.g. seepage, local drainage). Establish the likely soil water regime
- Identify the causes of the failure and establish remedial measures as necessary (these might include a repair of the failed zone, better surface drainage, and the construction of berms or flatter side slopes etc)
- Carry out the repair and continue to monitor crest levels, the slope movement and horizontal movements of the toe to validate the performance of the remedial works

D6.5 Shallow instability – Good practice guidance

Dikes and revetments. Design, maintenance and safety assessment
Edited by Pilarczyk, K.W. 1998. ISBN 9054104554)
This book provides extensive guidance on a wide range of aspects relating to fluvial and coastal flood defence embankments. Design guidance is offered for problems such as embankment stability, wave impact / run up and protection design. Discussion includes embankment failure mechanisms, risk management, operation and maintenance.

An engineering guide to the safety of embankment dams in the United Kingdom
(Johnston et al, 1999)
Whilst developed for the UK dams industry, this guide provides practical information on the behaviour of embankments, including load-response, performance indicators, mechanisms of deterioration and failure, surveillance, investigation and monitoring.

Infrastructure embankments – condition appraisal and remedial treatment
Perry, J., Pedley, M. and Reid, M. (2001). CIRIA Report C550
This report provides guidance on the maintenance, condition appraisal and repair of infrastructure embankments. It is based on a review of published literature, expert consultation and case studies demonstrating good practice. Whilst the text focuses mainly on road, rail and canal embankments, the report contains some guidance which can be applied to flood defence embankments.

Investigating embankment dams: A guide to the identification and repair of defects
Charles, J.A. et al 1996. BRE Report 303. ISBN 1860810691
The guide provides a comprehensive overview of techniques used to identify defects in embankment dams. The report covers field observations, a general approach to investigating defects, sampling, in situ testing, monitoring, leakage investigation and geophysical testing. Case study applications are also reviewed.

Protection of river and canal banks
Hemphill, R.W. and Bramley, M.E. 1989. CIRIA / Butterworths. ISBN 0408039450
This publication provides a useful overview on a wide range of aspects relating to river and canal bank protection. Text covers failure processes, the design process and options for bank protection including use of natural materials, vertical bank protection and revetments.

River and channel revetments – A design manual
Escarameia, M. 1998. Thomas Telford. ISBN 0727726919
This design manual first considers the issues of geotechnical stability and hydraulic loading on channel beds and banks, followed by a review of types of revetment and their design. This includes use of rip rap, block stone, gabions, mattresses etc. Consideration is also given to construction issues and maintenance requirements.

Bio-engineering – The Longham Wood Cutting field trial
Greenwood, J., Morgan, R.P.C., and Short, J., (2001). Project Report PR 81. CIRIA, London
Shallow slip failures on embankments and cuttings are more likely to occur in heavy cohesive materials such as Gault Clay. Reinstatement of such shallow failures can be costly and it is thought that the risk of slips occurring might be reduced by the use of selected vegetation. Long-term monitoring of an instrumented, vegetated Gault Clay slope on the M20 provided information on the performance of the slope over a period of 5 years from construction.

D7 CRACKING AND FISSURING

D7.1 Cracking and fissuring – Scope of guidance

The following points are covered in this chapter:

- Why is cracking a problem?
- What are the causes of cracking?
- When does cracking need to be dealt with?
- What methods are available for dealing with cracking?

Evidence of cracking in flood embankments can be an indicator of a problem. For example, cracking can be one of the main signs of embankment instability. Alternatively, cracks could be generated by shrinkage of the embankment fill material or by settlement of the foundation soils. However, limited surface cracking in a dry summer will generally close up as the soil moisture returns. In most cases, cracking will lead to accelerated weathering of the embankment and an increased risk of seepage, instability and breach.

D7.2 Cracking and fissuring – The key issues

The identification of potential problems with embankments relies heavily upon visual inspection. Environment Agency guidelines for inspection include assessment of cracking. However, identifying whether and to what extent the degree, style and location of cracking affects the risk of failure of the embankment can be difficult. It is considered that more detailed guidance on the interpretation of cracking needs to be provided to aid visual inspections.

The key issues that need to be considered with cracking include the following:

- How extensive is the cracking, and is there any sign of movement of the embankment?
- To what extent is the cracking seasonal?
- When does cracking constitute a threat to embankment stability?
- What cracking features can be related to specific modes of failure?
- How can cracks be repaired effectively?

Matters to consider when assessing an embankment suffering from cracking include:

- Does the embankment appear stable? Is cracking established but stable? Is rapid action apparently required, or does there appear to be time to undertake a longer term investigation – perhaps through monitoring?
- Can the cause of cracking be established? Has it been caused by drying of the surface layers or is it a symptom of a more deep seated problem? Does vegetation indicate recent slips or opening of cracks?
- Have there been any works undertaken near or on the embankment recently? Are there any external factors that may have affected embankment settlement or stability?

- Has the embankment been subject to prolonged heavy rainfall / high water levels?

Fissuring of clay embankments can extend to depths of more than 1m below the crest level. The cracks may be fine, but can still permit the ingress of water into the embankment body during high flood or rainfall conditions. However, the depth of fissuring can be difficult to identify without careful and potentially damaging intrusive investigations.

When considering the likelihood and potential consequences of cracking and fine fissuring, it is important to consider the following issues:

- When does fissuring significantly affect the performance of an embankment?
- What measures can be taken to repair fissured embankments?
- What measures can be taken to avoid or reduce fissuring?

D7.3 Cracking and fissuring – Current knowledge and understanding

The assessment of embankment behaviour when cracking occurs is a specialist task and should be undertaken by a geotechnical expert. Assessment of the problem is likely to require a review of geotechnical conditions, hydraulic loading and the condition of the embankment. Any analysis of the problem requires a combination of science and judgement.

Fine fissures form as a result of weathering of clay fill (in particular, the annual process of drying in the summer and wetting in the winter). They have the effect of increasing the permeability and decreasing the strength of the clay fill within the embankment. Fine fissures predominate near the surface of embankments in the zones that are not frequently wetted. Fissuring of clay embankments is a recognised issue – although the true contribution of fissuring towards embankment failure has not been quantified. Guidance is available on techniques to minimise fissuring.

The analysis of the failure mechanisms for many of the coastal breaches during the 1953 floods suggest that embankments failed through breaching following water ingress into the fissured crest. Whilst it is a recognised mechanism for water to enter into the body of an embankment and have a destabilising effect as a result of softening and increased pore pressures, the actual contribution of fine fissuring and cracking towards destabilisation of an embankment is yet to be reliably established.

Given these current limitations, best practice is limited to recommended techniques for minimising fissuring, or designing embankments to avoid fissuring. Without a greater understanding of the effect of fissuring on embankment performance, however, it is difficult to establish the cost benefit of such measures.

The remedial option usually preferred for dealing with cracks and fissures is to remove the cracked material and replace with a material such as hoggin (a gravelly, sandy clay or silt) which is less likely to be susceptible to cracking than the original material. The earth embankment fissuring manual (Environment Agency, 1996) provides general guidance on dealing with fine fissuring.

D7.4 Cracking and fissuring – Recommended actions

- Where cracking is first observed, an immediate decision is required on whether this indicates a problem which is developing rapidly, or if the symptoms are representative of a longer-term process. In either case, advise should be sought from a geotechnical expert
- When conditions suggest a slower, longer term problem, a site investigation undertaken to establish material condition, extent and depth of cracking, pore pressures etc is recommended
- Implementing remedial measures before understanding the full nature of the problem may make conditions worse rather than better because the potential destabilisation mechanisms are varied
- The extent of fissuring in an embankment can be influenced by a number of factors including soil type, moisture content, vegetation, weather etc. Where fissuring is recognised to pose a serious threat to embankment performance, it is recommended that works outlined within the earth embankment fissuring manual (see below) are implemented
- Where the cost benefit of such measures is not clear, expert judgement is required

D7.5 Cracking and fissuring – Good practice guidance

Earth embankment fissuring manual
Environment Agency (1996) Technical Report W41 (Environment Agency, 1996)
This report highlights the problems associated with fissuring in clay embankments. Methods for assessing the problems and guidance as to the appropriate remedial actions are considered along with design recommendations and post construction maintenance.

Infrastructure embankments – condition appraisal and remedial treatment
Perry, J., Pedley, M. and Reid, M. (2001). CIRIA Report C550
This report provides guidance on the maintenance, condition appraisal and repair of infrastructure embankments. It is based on a review of published literature, expert consultation and case studies demonstrating good practice. Whilst the text focuses mainly upon road and rail embankments, there is useful guidance of relevance to flood defence embankments.

D8 SEEPAGE AND PIPING

D8.1 Seepage and piping – Scope of guidance

The following points are covered in this chapter:

- Mechanisms of seepage through embankments
- When does seepage/leakage constitute a threat to embankment stability?
- What options are available for dealing with seepage and piping?

On the face of it, seepage through or under an embankment constitutes a failure of a flood embankment to perform its main function of water retention. However, especially in its early stages, the volume of water lost is often relatively small and the integrity of the embankment is not threatened. If left untreated, however, finer particles of soil could well be washed out of the embankment or its foundation by the flow. Thus, the problem is one of progressive deterioration; as the soil becomes more permeable, the flow rates increase and as a result, larger particles of soil are eroded. Seepage will also increase the likelihood of slip failure as a result of altering the phreatic surface and soil / water regime within the embankment, causing a softening of the fill materials or increasing the uplift pressures beneath an embankment.

Seepage through an embankment is generally caused by the presence of a permeable layer within the fill or by the existence of cracks or fine fissures as described above. Seepage beneath an embankment is most likely to be caused by a permeable layer (sand, gravel or possibly peat) within the foundation soils. The occurrence of seepage will usually be indicated by areas of standing or flowing water, by damp patches on the ground in front of the embankment or on the side of the embankment or by changes in the type or condition of vegetation. Seepage may not always be apparent; in some cases it will only be noticeable during conditions of high water level or flood.

See also Section B3.3.4 for illustration and photographs.

D8.2 Seepage and piping – The key issues

Seepage or piping through an embankment, combined with cracking of the embankment, can be indicative of a number of failure processes and can result in embankment failure through a variety of mechanisms. Given this complexity and the potential difficulty in establishing the actual mechanisms and risks of failure at any particular embankment, it is recommended that the investigation is carried out by an experienced geotechnical engineer. The Environment Agency (1996) classified potential seepage mechanisms according to the following five processes:

<u>Seepage beneath embankments</u>

- Seepage beneath the embankment may create excessive uplift pressures or lead to piping where the embankment is constructed upon layers of permeable material and the hydraulic loading on this increases due to flood or high water conditions. Excessive uplift pressures will lead to embankment deformation and possibly failure; piping will ultimately remove material from under the embankment leading either to critical flow, where the whole bank is undermined and eventually breaches, or subsidence of the crest, so reducing the standard of protection and providing a focus for possible overtopping and breach.

Seepage through embankments

Seepage through an embankment may occur through the following routes:

- Seepage near the surface of the embankment via fine fissuring caused through shrinkage of clay material. This is particularly relevant under flood conditions where higher than average water levels will load clay embankments that have tended to remain dry and hence to crack
- Seepage through the main body of the embankment via fine shrinkage fissures in clay fill, localised zones of relatively high permeability fill, or animal burrows or passages created by the roots of (former) vegetation
- Seepage through the main body of the embankment via interfaces between distinct layers or structures (embankments are particularly vulnerable where structures such as outfalls, pipes etc. pass directly through the embankment)
- Seepage through the main body of the embankment in relatively more permeable and homogeneous fill

The management and targeted maintenance of embankments currently relies heavily upon visual inspection. Indicators of problems that may be identified by visual inspection include seepage through embankments. More detailed guidance on the likely effect of seepage needs to be provided to aid visual inspections. At present, the link between failure of an embankment and the degree, style and location of seepage is not well established or disseminated. The key issues include:

- When does seepage constitute a threat to embankment stability?
- What seepage features can be related to specific modes of failure?

Key issues to consider when assessing an embankment suffering from seepage include:

- Does the embankment appear stable? Is seepage condition stable over an extended period of time or is it getting worse? Is rapid action apparently required, or does there appear to be time to undertake a longer term investigation, perhaps through monitoring?
- Has the embankment been subjected to prolonged heavy rainfall / high water levels? How does seepage appear to be driven, if at all, by these?
- What existing records are available of the embankment construction and the foundation conditions?
- Can the route and source of seepage be established? Does local vegetation suggest long term seepage?
- Have there been any works undertaken near or on the embankment recently? Are there any external factors that may have affected embankment condition?

- What are the risks to embankment performance as a result of the seepage?

D8.3 Seepage and piping – Current knowledge and understanding

Assessment of the problem is likely to require a review of geotechnical conditions, hydraulic loading and embankment condition. Analysis of the problem requires a combination of science and judgement to consider potential failure modes and remedial action.

Research into pipe formation processes is being undertaken. More information may be found via the EC IMPACT project, see www.impact-project.net. The conclusions of this research will be presented through the EC FLOODsite task on "*Modellling breach initiation and growth*", see www.floodsite.net.

Plate D8.1 Piping through a test embankment alongside rock abutment (IMPACT Project – Field Test)

D8.4 Seepage and piping – Recommended actions

- Where seepage is first observed, an immediate decision is required on whether this indicates a problem that is developing rapidly, or if the symptoms are representative of a longer-term process. In either case, advice should be sought from a geotechnical expert
- If the seepage is cloudy then it is likely that material is being removed from the embankment body. This is normally indicative of a serious and

immediate problem. Where seepage water is clear and the flow rate is slow, the degree of severity of the situation is extremely difficult to determine since seepage/leakage may occur for months or simply hours before the initiation of a possible failure or slip. In such a situation, a failure may be triggered by progressive deterioration or by a marginal increase in retained river level. If possible, monitor the seepage rate in order to determine whether there is a noticeable increase; if the rate is increasing then the seepage is likely to be progressing towards failure
- If the seepage is significant, consider also the effect that this may have on areas of the embankment that it is wetting and if possible remove excess water from the area
- When conditions suggest a slower, longer term problem, then a site investigation, making full use of any relevant existing records, should be undertaken to establish material condition, pore pressures etc
- The seepage and potential failure mechanisms are varied which means that implementing remedial measures before understanding the full nature of the problem may make conditions worse rather than better

D8.5 Seepage and piping – Good practice guidance

Infrastructure embankments – condition appraisal and remedial treatment
(Perry et al, 2001: CIRIA Report C550)
This report provides guidance on the maintenance, condition appraisal and repair of infrastructure embankments. It is based on a review of published literature, expert consultation and case studies demonstrating good practice. Whilst the text focuses mainly upon road and rail embankments, there is useful guidance of relevance to flood defence embankments.

Guidelines on sea and land dikes
TAW (Technical Advisory Committee for Flood Defence in The Netherlands), 1999. The Hague, pp85
This report covers general procedures for planning, investigating, designing, constructing and maintaining sea and lake dikes dams, separation embankments and compartment dikes.

Water retaining soil structures
TAW (Technical Advisory Committee for Flood Defence in The Netherlands) Technical Report, 2000. The Hague, pp248
This technical report covers geotechnical aspects of design, construction and maintenance of earth embankments for water retention purposes.

Dikes and revetments. Design, maintenance and safety assessment
(Pilarczyk, K W. (ed) 1998. ISBN 9054104554)
This book provides extensive guidance on a wide range of aspects relating to fluvial and coastal flood defence embankments. Design guidance is offered for problems such as embankment stability, wave impact / run up and protection design. Discussion includes embankment failure mechanisms, risk management, operation and maintenance.

An engineering guide to the safety of embankment dams in the United Kingdom
(Johnston et al, 1999)
Whilst developed for the UK dams industry, this guide provides practical information on the behaviour of embankments, including load-response, performance indicators, mechanisms of deterioration and failure, surveillance, investigation and monitoring.

Investigating embankment dams: A guide to the identification and repair of defects
(Charles et al, 1996)
The guide provides a comprehensive overview of techniques used to identify defects in embankment dams. The report covers field observations, a general approach to investigating defects, sampling, in situ testing, monitoring, leakage investigation and geophysical testing. Case study applications are also reviewed.

Small embankment reservoirs: A comprehensive guide to the planning, design and construction of small embankment reservoirs for water supply and amenity use
(Kennard, M.F., Hoskins, C.G. & Fletcher, M. 1996. CIRIA Report 161, Butterworth-Heinemann, London)
Covers, amongst other things, geotechnical assessment, ground investigation techniques, embankment design procedures and earthworks design and construction.

D9 OVERTOPPING

D9.1 Overtopping – Scope of guidance

Overtopping may be as a result of flood water levels overflowing the crest of an embankment, or through wave action resulting in periodic overflowing. Both issues are covered in this chapter, although more detail is given here on wave action, whilst floodwater overflowing (i.e. fluvial overtopping) in covered in more detail in the following Chapter D10.

The following points are covered in the chapter:

- Will the embankment be subject to wave overtopping, and what levels of overtopping might be tolerated?
- How can an embankment be designed to resist or control overtopping?
- Will waves erode / damage the face of the embankment?

D9.2 Overtopping – The key issues

Wave action:
Wind action over any open water area (the fetch) will generate wave action, and even relatively moderate wind speeds over small fetch lengths (perhaps above 1km) can generate waves (perhaps with wave height H_s > 0.4m which will erode unprotected natural materials).

Flood embankments around estuaries or on open coasts will experience wave action and, under any major storm, may be expected to experience some wave overtopping. (It is worth remembering that wave conditions and storm water levels are stochastic variables, and many different combinations of wave and water level may permit some waves in the storm to overtop. It is seldom realistic to expect an embankment to be high enough to give “zero overtopping”.) The purpose of any such coastal flood risk management system is, therefore, to restrict overtopping under defined return period events to given thresholds, and/or to reduce the severity / consequence of any such flood.

Wave overtopping may occur under conditions of high water level and moderate waves, or lower water level and larger waves. Wave energy at the embankment will be reduced by bed friction and wave breaking if it is fronted by a saltmarsh or an adequate beach, in which case the water level will have most effect on the overtopping.

Excessive wave overtopping relative to the standard of protection will damage lightly protected (or unprotected) crests or outward faces. This erosion may then propagate rapidly upwards or forwards to the crest and inward face, leading to sudden breaching.

Wave action on the inward face of an embankment may cause direct erosion of the embankment material, removal of material from beneath protection such as placed rock, concrete, interlocking slabs etc., or (in extreme cases) direct erosion of the protection itself leading to subsequent erosion of bank material. Inward face erosion can propagate rapidly upwards / backwards, leading to sudden breaching.

Direct wave attack may also induce raised pore water pressures within an embankment that may affect mass stability. Unacceptably high pore water pressures may lead to surface or body slips and failures.

Flood overtopping:
A majority of flood embankments are only protected by vegetation and not designed to permit significant overtopping, particularly over more than 12 hours. The effect of overtopping (either prolonged shallower flow or periodic deeper flow) will be the progressive erosion of crest and outward face surface material, followed by more aggressive downcutting and removal of body material, leading to eventual breach of the embankment.

The resistance of an embankment to erosion by overtopping flow will depend upon a number of factors including the:

- Nature of any embankment surface protection material(s)
- Condition of embankment surface protection materials
- Condition of embankment body materials

Surface protection materials may include vegetation, geotextiles, concrete, stone etc. A key factor in the effectiveness of these surface protection measures is their uniformity and condition. Erosion from overtopping flow will typically be initiated at weak points or discontinuities in surface layers. Where protection is given by grass, local irregularities (e.g. clumps of grass) or areas of poor growth or surface damage can provide a focus for erosion. More guidance on surface protection is given in Chapter D10.

Since erosive forces from overtopping increase with the unit discharge (flow/unit length) of water, then any local deficiency in crest level along a length of embankment will lead to a focussing of overtopping flow and subsequent increased risk of erosion at that point.

The risk of erosion will also be increased where the embankment has been saturated by prolonged rainfall, seepage or slight overtopping. Conditions will be worsened where cracking or discontinuities in the embankment permit water to enter the body of the embankment directly.

D9.3 Overtopping – Current knowledge and understanding

Wave action:
Under wave attack during storms, the following processes may occur:

- Direct erosion of the exposed inward face by wave attack
- Wave overtopping and/or overflowing due to surge level, leading to water flowing over the crest and outward face of the embankment during the storm event

- Breaching of the embankment allowing water to flow through the breach, both during and after the storm event

Overtopping may lead to breaching in some cases, but in many practical instances, low degrees of overtopping will be resisted by the structure with little or no damage. High degrees of overtopping may, however, damage the crest or outward slope, leading to the onset of a breach. Once started, wave action may continue to influence the breaching process until the bottom of the breach reaches the level where water level driven flows dominate. Techniques for predicting the magnitude of overtopping flow and how to protect against them are given in Chapter D9.4.

<u>Flood overtopping:</u>
Methods are available for the design of surface protection measures (see Chapter D10). Whilst we may suggest that overtopping leads to erosion, breach formation and failure, the exact mechanisms that occur during the erosion and breach formation stage are not widely understood. These factors particularly affect the speed of erosion and breach growth leading to embankment failure. Also, the effect of fissuring and ingress of water into the body of the embankment under load conditions has not yet been fully quantified.

The design approach is to avoid reaching these conditions. These include:

- Design of an embankment to withstand overtopping
- Design of an embankment to overtop or even breach at a specific location

It is usually too expensive to protect long lengths of embankment against significant overtopping. However, where an embankment crest is known to overtop under certain conditions, it may be advisable to deliberately create a lower section in the embankment crest in order to focus overtopping flow at one location and hence protect other lengths. The lowered section may be designed with protection so as to withstand these overtopping flows (see Chapter A2.5).

This concept is also applied with fuse plug sections into an embankment. These sections are designed to overtop preferentially and subsequently (under extreme conditions) to erode into a breach. This permits floodwater to flow from the river into low value washland (and avoid flooding other higher-value areas) without causing undue damage to the flood embankment. In practice, this approach appears to be used more frequently overseas and on larger rivers in comparison to those in England and Wales.

D9.4 Overtopping – Recommended actions

<u>Wave action:</u>
For any embankment where wave action might be significant, carry out a simple analysis of possible water levels and wave conditions. Calculate overtopping discharges for a range of possible combinations of wave / water level (not simply some “worst” case). Compare predicted overtopping with suggested limits. If these indicate potential problems, seek specialist assistance. The next step will probably require a “joint probability” analysis to test the likely return

period for different combinations of extreme water level and wave condition. In some cases, that study will be sufficient to indicate acceptably low levels of risk. Otherwise, engineering measures to reduce the overtopping (e.g. crest raising), or to reinforce the embankment might be needed.

Analysis of the standard of protection to the embankment crest and / or outward face should use initial guidance in the Environment Agency's Overtopping Manual (Besley, 1999) and/or the Rock Manual (CIRIA, CUR, CETMEF, 2007). The Environment Agency manual is currently being updated via the UK-led EUROTOP project.

Where high overtopping flows are possible, and the standard of protection is insufficient, two courses of action are possible:

- Reduce the overtopping by increasing foreshore levels (and hence reducing wave energy at the embankment), modifying the embankment inward face (e.g. adding a berm, flattening the slope, or increasing wave dissipation in inward face armour), or adding a wave wall to the crest
- Increase the resistance of the crest / inward face, perhaps by strengthening the crest (a concrete or asphalt slab), and/or reinforcing the outward face (perhaps by a flexible concrete blockwork mat, or addition of geogrid reinforcement)

Any overtopping flows should be received into an outward face ditch with potential to drain back to the inward (seaward) side after the tide / storm has reduced. Always remove obstacles to flow on the crest or outward face.

Safe operation of coastal flood embankments under overtopping conditions requires careful assessment of mean overtopping discharges, possibly of peak volumes, flow velocities and depths, and an understanding of acceptable rates of overtopping with regards to surface protection / embankment erosion. Advanced analysis methods are available to predict mean overtopping discharges using empirical equations or numerical models of simplified wave equations. Peak overtopping rates and/or overtopping flow depths / velocities can also be predicted. Advice on levels of mean or peak overtopping that can be tolerated by different embankment / protection types is, however, still very approximate.

Present practice for embankments under threat of significant wave attack is to protect the inward face by revetment armouring preventing erosion of material from the embankment face, see McConnell (1998). The design of such protection under wave loading requires specialist advice, particularly with regard to the relative permeability of the armour and the main body of the embankment. Otherwise hydraulic pressure within the supporting layers can lead to unexpected failures.

Within the embankment, geotechnical stability can be enhanced by appropriate drainage works to prevent build up of pore water pressures, but care must be taken to ensure that pressure gradients remain appropriate over a wide range of different water level and wave conditions.

Flood overtopping:
Where an embankment may be subject to periodic overtopping, three approaches may be taken, namely:

- Raise the flood embankment (See Chapter B4)
- Implement a temporary or demountable defence system
- Assess the extent of overtopping and design appropriate protection measures (including the use of overflow sections and possibly fuseplug sections)

In order to be able to assess the effectiveness of existing surface protection measures, or to design new protection measures, it will be necessary to predict the design flood water level conditions and to have survey data showing, at minimum, the crest levels along the embankment. Appropriate solutions may comprise a combination of crest raising and surface protection, depending upon the nature of the problem. Chapter D10 provides guidance on surface protection measures.

D9.5 Overtopping – Good practice guidance

Wave overtopping:
Wave overtopping may be estimated at a simple level by methods published in two manuals. The "Revetment Manual" by McConnell (1998) gives simple (approximate) procedures to estimate wave conditions, even on restricted fetches. It also outlines simple overtopping prediction methods based on methods by Owen (1980).

The Environment Agency's Overtopping Manual by Besley (1999) gives more detailed overtopping predictions, and lists suggested "tolerable" overtopping limits for different structure types. The user is cautioned that there is relatively little validation of these "tolerable" limits, and no validation data at all for UK embankments / practice. This is currently being updated under the UK-led project (www.overtopping-manual.com) to produce a European Overtopping Manual.

Overtopping of seawalls – design and assessment manual
Besley P. (1999) R & D Technical Report W 178, ISBN 1 85705 069 X, publn. Environment Agency, Bristol

Revetment systems against wave attack: a design manual
McConnell K.J. (1998) ISBN 0-7277-2706-0, Thomas Telford, London

Design of sea walls allowing for wave overtopping
Owen M W (1980) Report EX 924, Hydraulics Research, Wallingford

Flood overtopping:
See Chapter D10 on external erosion and protection.

D10 EXTERNAL EROSION AND PROTECTION

D10.1 External erosion – Scope of guidance

The following points are covered in this chapter:

- Types of external erosion
- Methods for protection
- Typical problems

D10.2 External erosion – The key issues

Embankment erosion can occur for a variety of reasons and may affect any exposed face of the embankment. Each form of erosion can pose a threat to the overall stability of the embankment, either directly or indirectly through related processes, such as breach formation.

Typical sources of erosion may include:

Inward face:
- River flow
- River meandering / morphology (including movement of a flow channel within the main river channel)
- Wave action
- Wash from boats
- Animal / recreational use

Crest:
- (Wave) overtopping
- Overflowing
- Animal / human activity

Outward Face:
- (Wave) overtopping
- Overflowing
- Animal / human activity

Erosion typically occurs when loading (either hydraulic, animal or human) is focussed in a particular area. For example, erosion may occur when:
- River flow impinges directly on an embankment
- Overflowing of water occurs at a low spot along the embankment crest
- Flow across the crest or down the outward face is deflected or concentrated locally (e.g. by a post or clump of grass)
- Repeated use of the embankment for access (crest or banks)

Carrying out effective protection measures does not automatically entail extensive construction works. It is important to first understand the cause of the erosion, then the erosion process itself and subsequently to identify the most appropriate protection measure. These measures may range from modern construction materials (e.g. mass concrete) to the use of traditional methods (e.g. reed beds). Some common types of erosion protection include:

- Concrete / blockwork revetment
- Stone / rip rap
- Gabions / mattresses
- Geotextiles, generally used in conjunction with vegetation
- Wood / timber
- Vegetation, particularly a well-managed grass sward

D10.3 External erosion – Current knowledge and understanding

A good understanding now exists of the various erosion processes that affect embankments. However, quantification of the various processes such that specific design conditions may be 'met' is less well specified.

Design engineers who are not used to working with water often design structures across and adjacent to water with little regard to potential hydraulic action, and the impact that the structure may have on flow conditions. This can result in erosion problems adjacent to the structure as well as difficulties up or downstream from the structure, by affecting river morphology or coastal processes. This invariably appears as some form of bed or bank erosion.

Current design ability with respect to erosion of embankments is summarised below:

<u>Wave action:</u>
Prediction of wave generation over fetch lengths and wave run up on embankments is relatively good.

Prediction of erosion rate / initiation time and location due to wave action is poor.

Note: Chapter D9 provides specific guidance on wave overtopping.

<u>Inward face erosion:</u>
Design methods for hard protection (e.g. rip rap) against specified velocities are relatively good.

Prediction of rate of erosion and deterioration of an unprotected embankment under flow is poor.

Identification of the real cause of erosion can also be overlooked. Whilst the immediate problem may be erosion, the real cause may stem from wider reach-based morphological effects (i.e. flow channel movement, river meandering etc.). Analysis of morphological cause and effect typically requires expert advice.

Crest erosion:
As with the inward face, design guidance is available for the design of rock protection under various flow conditions. Limited guidance is also available on the performance of grassed surfaces under various flow conditions, together with various methods of "reinforcing" grass such as geotextiles or open concrete blocks.

Prediction of the time to potential breach initiation and rate of development of erosion through wave overtopping or overflowing is poor.

General guidance exists on protecting against other types of erosion such as animal or human activities.

Outward face erosion:
The key issue for the protection of the outward face is whether or not the embankment is designed to withstand overtopping waves, or overflowing water. If the embankment is not required to withstand these conditions, any surface protection (typically vegetation) is incidental (but valuable).

Erosion of the outward face is typically through overflow or overtopping. Limited guidance is available on the performance of vegetation as protection. Design guidance is available for hard defences.

Prediction of the rate of erosion development, once initiated, is poor.

D10.4 External erosion – Recommended actions

The protection of an embankment against external erosion should be addressed as a long-term management action for the overall asset system. It is far better to initiate precautionary measures in order to maintain a stable embankment than to take measures in reaction to progressive erosion.

Whilst initial signs of erosion may pose a minor threat to overall embankment performance, surface erosion per se may not pose the greatest threat. For example, discontinuities in the crest or face protection may allow excessive water into the body of the embankment leading to internal erosion and / or instability. Erosion of the crest may create a low spot which would provide a focus for overflowing water. The interaction between surface erosion and potential failure mechanism is complex.

The basic cause of the erosion should be identified. Specifically, whether the erosion is a local feature or indicative of wider morphological activity. Protection measures against the latter may not be successful if the nature of the problem is not fully understood. It should be recognised that works to a river that affect bed gradient, meandering, sediment movement etc. may initiate scour or deposition at other locations hundreds of metres away from the original works.

Prioritisation of any repair works should be undertaken according to a risk based approach. Guidance on these is given in Chapter D2.

D10.5 External erosion – Good practice guidance

Guidance on specific protection measures, their design and implementation may be found in the following references:

Dikes and revetments. Design, maintenance and safety assessment
(Pilarczyk, K W. (ed) 1998. ISBN 9054104554)
This book provides extensive guidance on a wide range of aspects relating to fluvial and coastal flood defence embankments. Design guidance is offered for problems such as embankment stability, wave impact / run up and protection design. Discussion includes embankment failure mechanisms, risk management, operation and maintenance.

Waterway bank protection: A guide to erosion assessment and management
(Environment Agency, 1999. R&D Publication 11. Version 1.0)
This report provides practical guidance on the erosion assessment and management of waterway banks. Whilst the scope of work does not directly include flood defence embankments, many of the concepts and solutions are directly relevant and applicable. The guide presents an initial assessment of bank erosion problems, guidance on selecting the most appropriate protection strategy and subsequently guidance on engineering and non-engineering solutions.

Protection of river and canal banks
Hemphill RW, Bramley ME (1989). CIRIA Report. Butterworths. ISBN 0408039450
This publication provides a useful overview on a wide range of aspects relating to river and canal bank protection. Text covers failure processes, the design process and options for bank protection including use of natural materials, vertical bank protection and revetments.

River and channel revetments – A design manual
Escarameia M (1998). Thomas Telford. ISBN 0727726919
This design manual first considers the issues of geotechnical stability and hydraulic loading on channel beds and banks, followed by a review of types of revetment and their design. This includes use of rip rap, block stone, gabions, mattresses etc. Consideration is also given to construction issues and maintenance requirements.

Revetment systems against wave attack – A design manual
McConnell K (1998). Thomas Telford. ISBN 0727727060

Design of reinforced grass waterways
Hewlett HWM, Boorman LA, Bramley ME (1987). CIRIA

Guidelines on sea and land dikes
TAW (Technical Advisory Committee for Flood Defence in The Netherlands), 1999. The Hague, pp85

This report covers general procedures for planning, investigating, designing, constructing and maintaining sea and lake dikes dams, separation embankments and compartment dikes.

Water retaining soil structures

TAW (Technical Advisory Committee for Flood Defence in The Netherlands) Technical Report, 2000. The Hague, pp248

This technical report covers geotechnical aspects of design, construction and maintenance of earth embankments for water retention purposes.

D11 BREACH FORMATION AND EMERGENCY ACTION

D11.1 Breach formation – Scope of guidance

The following points are covered within this chapter:

- Predicting breach formation – breach growth, breach location
- Emergency action when breaching occurs

Plate D11.1 Breach on River Aire (Gowdall, Autumn 2000)

Plate D11.2 Breaching of flood embankment along the River Conway

D11.2 Breach formation – The key issues

A flood embankment may breach as the result of many different processes (see Figure B2.1). The onset of breaching occurs when seepage through the embankment or flow over the top of the embankment reaches a critical level whereby significant quantities of bank material are being removed. Once this process begins it rapidly becomes more and more difficult to prevent complete failure of the bank.

Piping
Critical conditions resulting from seepage or leakage are, typically, when flow increases to a significant level (i.e. gushing from the outward face of the embankment) and becomes cloudy (i.e. removing sediment from the embankment body). Cracking and removal of sediment and blocks of embankment material from the outward face will occur as erosion of material creates a progressively larger hole through the embankment. Eventual subsidence of the bank material above the 'pipe' and open breaching of the embankment will follow.

Overtopping
Critical conditions from overtopping will occur when flow is sufficient to remove any surface protection material (such as grass) and start to erode embankment material. Erosion of material will typically initiate around inconsistencies in the surface protection and/or local features that deflect and concentrate the flow (e.g. around clumps of grass). Erosion of the outward toe will also develop. Indicators of problems include patches of eroded material or small gullies formed through the crest and outward face by overflowing water.

Where overflow occurs but surface material is not eroded, problems may still occur if the flood water saturates the outward body of the embankment. This can raise pore water pressure and may result in local slips which could in turn lead to full breaching. Cracking in the embankment can aid this process by allowing overtopping water to directly enter the body of the embankment.

Critical indicators include:

- Flow over the embankment crest – progressively more serious as surface protection (vegetation, geotextile, stone, concrete etc.) starts to erode, be undercut or be removed
- Seepage through the embankment showing a flow of water – progressively more serious as water removes sediment (i.e. cloudy water)
- Slipping / slumping of the embankment faces under extreme load conditions

Key challenges for effective flood risk management include how to predict when, where and how an embankment might fail through breach formation and subsequently how to deal with a breach during a flood event. It is far better to prevent such occurrences rather than deal with them during or after the event. However, in order to do so, a better understanding of the causes and failure mechanisms is required. Current knowledge and management (modelling) tools in this area are limited. Some specific issues are considered as follows:

- Predicting breach location before the event is difficult. The mechanisms through which an embankment might fail are complex and varied (See Figure B2.1). Research into breaching processes continues through a number of projects, however a methodology for reliably predicting potential breach location has not yet been established. With a reliable methodology for assessing potential breach location based upon inspection parameters, then a risk based approach to asset management may be adopted. Frameworks for such an approach are being developed by the Agency however current understanding of embankment performance under varying load conditions is limited
- Predicting the time to failure of an embankment is critical for assessing whether an embankment is likely to withstand a flood event and whether flooding as a result of failure might necessitate emergency action for specific areas. Predicting failure when no such failure occurs can also lead to severe disruption when, for example, evacuation procedures are initiated. The need to be able to reliably predict the behaviour of an embankment during failure is, therefore, clear
- Predicting what might happen in the event of embankment failure is an important aspect of flood risk management. Assessment of the rate and ultimate size of a breach directly affects the rate and volume of flood water discharging through the breach. This in turn, determines the extent of damage that might occur and the nature of any emergency action plans that might be developed
- Once an embankment breaches, the rate of flow of water can grow rapidly. Lateral erosion of the embankment can also occur quickly. Depending upon the situation, it may be critical to close the breach as quickly as possible. Predicting the rate of growth, method and time of closure are therefore all key issues in a successful closure

Where breaching of tidal flood embankments has occurred, the bed level through the breach will be an important factor in determining the impact. This must be raised to prevent repeated inundation during subsequent high tides.

D11.3 Breach formation – Current knowledge and understanding

Breach location:
Our current ability to predict breach location is poor.

Fundamental research into breaching processes and factors contributing to these processes is required before we can methodically assess potential location. Where estimates are required, it is recommended that expert judgement is sought, and in particular, use is made of local knowledge to focus inspection around areas traditionally known to suffer stability problems. A risk based approach should always be taken to prioritise effort and resources (i.e. consider likelihood of failure and potential impact of failure).

Time to failure:
Our current ability to predict the time to failure of an embankment is very poor.

Some failure mechanisms are more predictable than others. For example, when severe overtopping of an embankment occurs, it is likely that failure will occur within minutes rather than hours – particularly when it is obvious that surface protection such as grass, stone or concrete are being undermined and removed. However, when the failure process is through seepage or piping and changes to the embankment (appear) to take place very slowly, then prediction becomes much harder. Piping may develop through an embankment over a period of weeks or even years. However, a critical point will be reached where the rate of erosion will accelerate and failure will occur. When flow is turbulent and mixed with sediment it is clear that the latter stage has been reached and failure is probably likely within minutes or hours. Prior to this, failure could occur within hours, weeks or even years.

If prediction of the likely time to failure is required during an event, this is best made through expert judgement by an experienced engineer familiar with construction of flood or dam embankments and relevant hydraulics and geotechnical theory.

<u>Breach formation:</u>
Our ability to predict breach formation through an embankment is basic, but initial modelling tools have been developed and research continues to improve these. The accuracy of current predictions is in the order of $\pm$30% in terms of predicting peak discharge for a simple failure scenario, but worse for other parameters such predicting the width of breach etc. (IMPACT, 2004).

It should be noted that river modelling tools are increasingly advertised as containing ‘breach’ modules for predicting the flood discharge through an embankment. However, care needs to be taken to understand the nature of a given model. Many such models simply predict flow through a breach based upon size and rate of growth – information that the modeller must provide first!

<u>Breach closure:</u>
Experience of closing embankment breaches during a flood event is not well documented. Repairs have typically been undertaken on a site by site basis. Careful consideration of the hydraulics, soil conditions and available access is required to develop an appropriate solution to the problem. An estimate of potential breach size may be correlated with historic storm and failure events in that catchment (IMPACT, 2004) but the site and event specific nature of breach formation means that expert advice should be sought on this issue.

D11.4 Breach formation – Recommended action

<u>Breach location</u>
There are no tools currently available for predicting specific breach location, although risk and performance based methods now being adopted for prioritising asset maintenance implicitly do this to a limited degree (i.e. either by focusing maintenance work in areas known to suffer erosion or slippage etc. or by attributing a higher risk to a particular length of flood embankment).

Where an objective assessment of potential breach location is required across an asset system, the current best approach is to base this on known problem embankments and areas where failures have previously occurred, together with current asset inspection and survey data.

Time to failure
Until our understanding of the fundamental processes involved in embankment breaching improves, it is recommended that prediction of time to failure of an embankment, and the response of an embankment to varying load conditions, is made through expert judgement by engineers highly experienced in the management of flood or dam embankments.

Breach modelling
Whilst breach modelling tools are being developed, best practice is to predict breach formation using a variety of approaches and then to apply expert judgement as to the most likely scenario. The HR BREACH and USDA SIMBA models are currently recommended for estimation of breach growth in earth and clay embankments. More information on breach modelling can be found at the IMPACT project website (www.impact-project.net see work packages 2 and 5) and the FLOODsite project website (www.floodsite.net – see tasks 4 and 6).

Breach repair and closure
For breach repair / closure the following actions are recommended:

- Reduce flow into the breach by placing material upstream of the opening (beware rapid increase in breach width and / or depth). Do not underestimate the strength of flow through the breach. To prevent wash through, any material placed needs to be:
  - placed quickly and precisely
  - preferably blocking the breach in a single action – partial breach blockage can focus flow to one area and increase erosion in this area undermining the partial blockage and increasing lateral erosion
  - take into account the likely development of a scour hole within and immediately downstream of the breach. Material used to block the breach will need to be larger in depth than the height of the embankment to cater for this
- Consider options for reducing flood levels upstream (i.e. diversion, deliberate breaching elsewhere etc)
- Consider engineering works to prevent lateral growth (e.g. placed rock or piling at a distance back from the breach)
- For tidal breach, implement immediate works to raise the breach base level in order to prevent or minimise repeat flooding during later tidal events

Plate D11.3 Breach repair on River Blyth in 1993

Plate D11.3 shows a temporary breach repair using sandbags. Whilst this offers a possible temporary solution after the breach event, use of sandbags is unlikely to be sufficient to close a breach during the event, unless work is undertaken before the breach develops from initial overtopping or piping.

D11.5 Breach formation – Good practice guidance

Good practice guidance is relatively limited and dispersed. The following projects will provide additional information:

The IMPACT Project (www.impact-project.net):
Specific research was undertaken on breach formation processes, modelling breach formation and assessing uncertainty in breach prediction.

A number of researchers around the world have developed models for predicting breach formation, but these are typically limited and often not commercially available (CADAM, 1998). One model (NWS BREACH from the US DAMBRK package) is available for use, but research by HR Wallingford has shown this to be limited and flawed in places. If used, it is recommended that the modeller cross check results from a number of possible scenarios to ensure consistent trends in prediction.

A programme of model development and testing was undertaken as part of the IMPACT project – see www.impact-project.net. Two promising modelling approaches were noted as being offered by:

- The HR BREACH model (HR Wallingford, see Mohamed et al, 2002 and www.hrwallingford.co.uk)
- The SIMBA model (US Dept. Agriculture, Agricultural Research Service, see http://www.ars.usda.gov/main/site_main.htm?modecode=62171000

FLOODsite Project (www.floodsite.net):
The FLOODsite project is a major collaborative European project addressing flood risk management. The research programme is closely aligned with EA research needs, in particular failure modes of flood management structures including embankment breach initiation and formation. Particular focus is being placed upon breach initiation processes due to wave action and the improvement of breach prediction models following the IMPACT project conclusions (see FLOODsite Tasks 4 and 6). Links also exist between FLOODsite research and the UK Flood Risk Management Research Consortium (FRMRC) research programme (www.floodrisk.org), where specific research into fine fissuring of embankments is underway.

RASP and PAMS:
The Agency is currently developing a number of risk and performance based management tools (see Section A4.4). Both RASP (Risk Assessment forflood and coastal System Planning) and PAMS (Performance based Asset Management System) implicitly adopt a methodology for estimating the risk of embankment failure. The assumed breach characteristics will be progressively improved in line with research into embankment performance processes.. For more information on RASP see www.rasp-project.net and for PAMS see www.pams-project.net

REFERENCES

The following provides a summary list of references referred to in this document.

Besley P.,1999. Overtopping of seawalls – design and assessment manual. R & D Technical Report W 178, ISBN 1 85705 069 X, publn. Environment Agency, Bristol

British Standards BS1377: Methods of test for soils for civil engineering purposes

British Standards BS5930: Code of practice for site investigation

British Standards BS 6031: 1981. Code of practice for earthworks

British Standards BS10175: Investigation of potentially contaminated sites – code of practice

CADAM, 1998: Concerted action on dambreak modelling. EC concerted action programme under the 4th framework programme. Proceedings from workshops 1,2,3,4 and on the web. See www.hrwallingford.co.uk website for access

Charles J.A. Tedd P. Hughes A.K. Lovenbury H.T., 1996. Investigating embankment dams: A guide to the identification and repair of defects. BRE Report 303. ISBN 1 86081 0691

CIRIA, 1987. Design of reinforced grass waterways. CIRIA Report 116

CIRIA, 1996. Small embankment reservoirs. CIRIA Report 161, ISBN 0860174611

CIRIA, 1997. Culvert Design Guide. CIRIA Report 168. ISBN 0860174670

CIRIA, CUR, CETMEF, 2007. The Rock Manual. The use of rock in hydraulic engineering. 2nd edition. C683. CIRIA. London

Clayton, C.R.I., Matthews, M.C., Simons, N.E., 1995. Site Investigations, Blackwell Science, Oxford, pp584

Coltrup, J., 1984. Seawall Seepage – Project Team Report, Anglian Water, Colchester Division

Coppin N.J., Richards I.G., 1990. Use of vegetation in civil engineering, CIRIA / Butterworths

Defra/Environment Agency, 2001. Temporary and Demountable Flood Protection: Appendices to Interim Guidance – Part 1, Draft R&D Publication 130/2

Environment Agency. Control of Invasive Riparian and Aquatic Weeds. R&D Note 233

Environment Agency, 1995. Flood Defence Management Manual (FDMM)

Environment Agency, 1996. Project Record W/I724/3 & Technical Report W41. (Frith et al). Earth embankment fissuring manual

Environment Agency, 1996 Geotechnical Performance of Flood Defence Embankments, Scoping Study, R&D Technical Report W35

Environment Agency, 1999. Waterway Bank Protection: A Guide to Erosion Assessment and Management. R&D Publication 11. Version 1.0

Environment Agency, 2001. Engineering Inspection Techniques using Non-Destructive Testing. (Draft report)

Environment Agency, 2003. Strategy for flood risk management 2003-2008

Environment Agency, 2006. Managing Flood Risk, Condition Assessment Manual. Doc. Ref. 166_03_SD01

Escarameia M., 1998. River and Channel Revetments – A Design Manual. Thomas Telford. ISBN 0727726919

Greenwood J, Morgan R.P.C., Short J., 2001. Bio-engineering: a field trial at Longham Wood Cutting, M20 motorway. Special Publication 128. CIRIA, London. [Now published as a project Report CIRIA PR 81, Bioengineering – The Longham Wood Cutting field trial. CIRIA, 2001]

Hemphill R.W., Bramley M.E., 1989. Protection of River and Canal Banks. CIRIA Report. Butterworths. ISBN 0408039450

Hewlett H.W.M., Boorman L.A., Bramley M.E., 1987. Design of Reinforced Grass Waterways. CIRIA Report 116

HR Wallingford, 2002. Risk, Performance and Uncertainty in Flood and Coastal Defence – A Review. Defra/EA Report No. FD2302/TR1 / HR Wallingford Report SR587

ICE, 1996. Floods and reservoir safety. 3rd Edition. Institution of Civil Engineers. ISBN: 0 7277 2503 3

ICE, 2000. A guide to the reservoirs act 1975. Institution of Civil Engineers. ISBN: 0 7277 2851 2

IMPACT, 2004. IMPACT: Investigation of extreme flood processes and uncertainty. Final technical report. EC research project under the 5th framework programme, contract No. EVG1-CT-2001-00037. Proceedings from workshops on CD ROM and web. www.impact-project.net

Johnston T.A., Millmore J.P., Charles J.A., 1999. An Engineering Guide to the Safety of Embankment Dams in the United Kingdom. ISBN 1 86081 2724

Kennard, M.F., Hoskins, C.G. & Fletcher, M., 1996. Small Embankment Reservoirs: A Comprehensive Guide To The Planning, Design And Construction Of Small Embankment Reservoirs For Water Supply And Amenity Use. CIRIA Report 161, Butterworth-Heinemann, London

Leroueil, S., Magnan, J-P., Tavenas, F., 1990. Embankments On Soft Clays. Ellis Horwood, London, 360pp

Lunne, T., Robertson, P.K., Powell J.J.M., 1997. Cone penetration testing in geotechnical practice

MAFF, 2000. Flood and coastal defence project appraisal guidance notes: Approaches to risk. FCDPAG4

Masters N., 2001. Sustainable use of new and recycled material in coastal and fluvial construction – A Guidance Manual. Thomas Telford. ISBN 0727729500

May R., Bromwich B.C., Gasowski Y., Rickard C., 2003. Hydraulic Design of Side Weirs. Thomas Telford. ISBN 072773167X

McConnell K.J., 1998. Revetment systems against wave attack: a design manual. ISBN 0-7277-2706-0, Thomas Telford, London

Mohamed, M.A.A., Samuels, P.G., Morris, M.W., Ghataora, G.S., 2002. Improving the accuracy of prediction of breach formation through embankment dams and flood embankments - Proc. of the Int. Conf. On Fluvial Hydraulics, Louvain-la-Neuve, Belgium, 3-6 Sept. 2002 - River Flow 2002, Bousmar & Zech (editors)

Morris M.W., Simm J., 2000. Construction risk in river and estuary engineering. Thomas Telford. ISBN 0727728628

Owen M.W., 1980. Design of sea walls allowing for wave overtopping. Report EX 924, Hydraulics Research, Wallingford

Perry J., Pedley M., Reid M., 2001. Infrastructure embankments – condition appraisal and remedial treatment. CIRIA Report C550. ISBN 0 86017 5502

Pilarczyk, K.W. (ed.), 1998. Dikes and Revetments. Design, maintenance and safety assessment. Balkema press. ISBN 9054104554

Sayao, A.S.F.J., Medeiros, L.V., Sieira, A.C.C.F., Gerscovich, D.M.S., Garga, V.K., 2002. Proceedings of the Institution of Civil Engineers - Geotechnical Engineering. Vol. 155, no. 4, pp. 217-219. Oct. 2002

SI 1985. No 177. Statutory instruments relating to the Reservoirs Act, 1975. ISBN 0 11 056177 5

Simm J., Cruickshank I., 1998. Construction risk in coastal engineering. Thomas Telford. ISBN 0727726862

Site Investigation Steering Group (SISG), 1993. Site Investigation in Construction, Thomas Telford:

Part 1 – Without ground investigation, ground is a hazard
Part 2 – Planning, procurement and quality planning
Part 3 – Specification for ground investigation
Part 4 – Guidelines for the safe investigation by drilling of landfills and contaminated sites

TAW (Technical Advisory Committee for Flood Defence in The Netherlands), 1999. Guidelines on Sea and Land Dikes. The Hague, pp85

TAW (Technical Advisory Committee for Flood Defence in The Netherlands) Water Retaining Soil Structures. Technical Report, 2000. The Hague, pp248

Technical Advisory Committee on Flood Defence (TAW), 2002. Management and Maintenance of Dikes and Banks. pp20

The Public Works Research Centre of Greece (Ed) (major contributors: Jardine, R.J. and Hight, D.W.). 1987. Embankments On Soft Clays. Athens, 356pp.)

Uff, J.F, Clayton, C.R.I., 1991. Responsibility in site investigation, CIRIA Special Publication 73, pp42

United States Bureau of Reclamation, 1998. The Earth Manual

PB 12171

Ergon House
Horseferry Road
London SW1P 2AL

www.defra.gov.uk

defra
Department for Environment
Food and Rural Affairs