Environment Agency

Assessing and managing risks with transitions in flood defence infrastructure

Design and management guide for fixing transitions

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Email: enquiries@environment-agency.gov.uk

Author(s):
Jaap Flikweert, Eva van Maren, Nigel Baker

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Research contractor:
Royal Haskoning DHV

Research collaborator(s):

HR Wallingford, Deltares, IRSTEA, US Army Corps Engineers (USACE), Electricité de France (EDF)

Environment Agency Project Manager:
Dr Sarah Twohig

Environment Agency Project Executive:
Matthew Arthur

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Dr Robert Bradburne
Chief Scientist

Foreword

This guide signposts potentially relevant considerations for practitioners when managing portfolios of flood risk assets with transitions. It is not intended to be, and should not be read as, prescriptive, exhaustive, or a statement of best practice.

The research findings presented in this guide were commissioned by the Environment Agency for this project. This document is one of four outputs from this project and must be read alongside those other research outputs, rather than considered in isolation.

The outputs from this project are being used by the Environment Agency to review and improve our internal management processes. We apply a risk-based approach to all our activities, ensuring public money is targeted in a way to achieve the most benefit. This means that we may conclude that some of the techniques set out in this document are not appropriate for the Environment Agency to use.

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1.1 Project overview

Transitions between flood defence assets and components introduce irregularities which increase the chance of failure, as seen in many historic flood events. Current guidance in England and Wales on the visual inspection of flood defence assets to determine condition does not explicitly account for the potential effects of transitions on defence performance. As such, where transitions do increase the probability of defence failure above that of the adjoining defence assets, the associated risks are missed from local, regional and national flood risk assessments. This research supports identifying, prioritising and assessing flood defence asset transitions to determine if they form a weak spot compared to the neighbouring assets and therefore could lead to increased flood risk. Quantifying the increased failure risk due to the transitions then feed into a next step of prioritisation for improvement works.

The aims of the project are to:

- consider the presence of transitions when assessing flood defence condition
- quantify the effects of transitions on defence performance (fragility) and flood risk
- manage the risk of transitions with improved design and retrofitted solutions for existing defences

The research outputs have been divided into 4 reports. Each report focuses on a different stage of managing assets at transitions (Figure 1-1). This report focuses on step Design of the improvement of transitions for improved operation and maintenance.

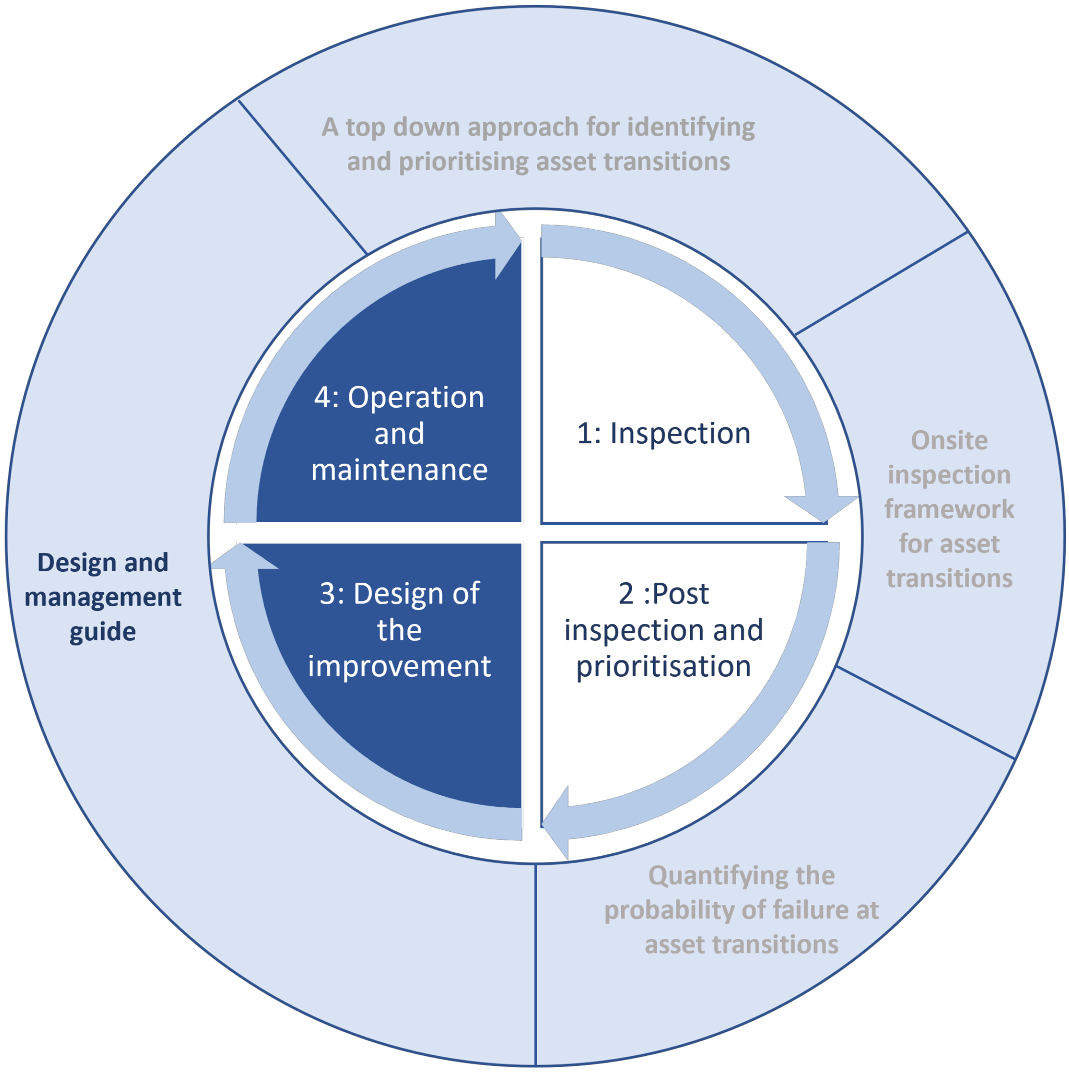


Figure 1.1 Project overview

1.2 Scope of report

The final scope for this report was to deliver guidance on the importance of transitions and their key performance parameters, the assessment and prioritisation of transitions, and basic rule of thumb/engineering judgement type guidance on retrofitting works to address the problems where transitions are considered to pose an increased risk compared to the wider defence.

The developed guide focuses on the improvement of transitions. In many instances, the improvement methods and design approaches are strongly linked to, and very similar to those for regular flood defence embankments and structures. The transition design guide does not provide a step by step process with detailed instructions for addressing transition impacts. Instead it focuses on the principles (how transitions can influence performance), highlights the issues with managing transitions, and presents methods for addressing the impacts. The design methods are typically not discussed in detail, because these are often very similar to methods for design and management of flood defences in general. The intention throughout is that the guide is used alongside the existing guidance and standards, notably the International Levee Handbook (CIRIA (2013)).

1.3 Who is this report for?

The envisaged users are the teams responsible for designing flood defence improvements, particularly the senior engineers in any flood defence asset management organisation. In the specific context of the Environment Agency, this would be the catchment engineers and the Asset Performance Teams and possibly their consultants as well. Many of the potential measures set out in this guide also include maintenance aspects, which may require involvement from other people and teams. It is important however that the senior engineer ensures coordination between design and maintenance improvements.

1.4 Using this report

This guide focuses on the improvement of existing transitions that have been identified as a point of weakness and prioritised for improvement (see section 2.1). However, the issues and principles set out in this guide apply equally to the design of new transitions. More detailed information on the design of new flood defence structures can be found in guidance such as the International Levee Handbook (CIRIA 2013) (see also Text box 1-2).

In many instances, the improvement methods and design approaches in this guide are linked to, and similar to those for regular flood defence embankments and structures. Because of this, the guide does not intend to repeat the existing guidance and standards for flood defence design, which the user is expected to be familiar with and already be applying. Instead, this guide focuses on the 'principles' of how transitions can influence performance, the 'issues' associated with the behaviour of transitions, and the 'methods' for addressing the transition impacts. Overall, it is intended that this guide is used alongside the existing guidance and standards rather than as a replacement for these other sources of information and guidance.

Issues with transition failures can require emergency response. The guide does not address that situation specifically, but the principles apply to emergency repairs as well.

The focus of this guide is on embankment-related transitions, that is, those between embankments and hard(er) structures, including walls, crossing infrastructure and revetments. Embankment-related transitions account for a large share of all flood defence transitions. They are also more likely to be vulnerable to the impact of transitions than situations involving only 'hard' structural materials such as concrete and steel.

This guide considers the 4 transition types illustrated in Figure 1-2, which are discussed and described in more detail in section 3. Transitions between 2 different embankment sections are not addressed specifically, but the principles of the guide apply to those cases too.

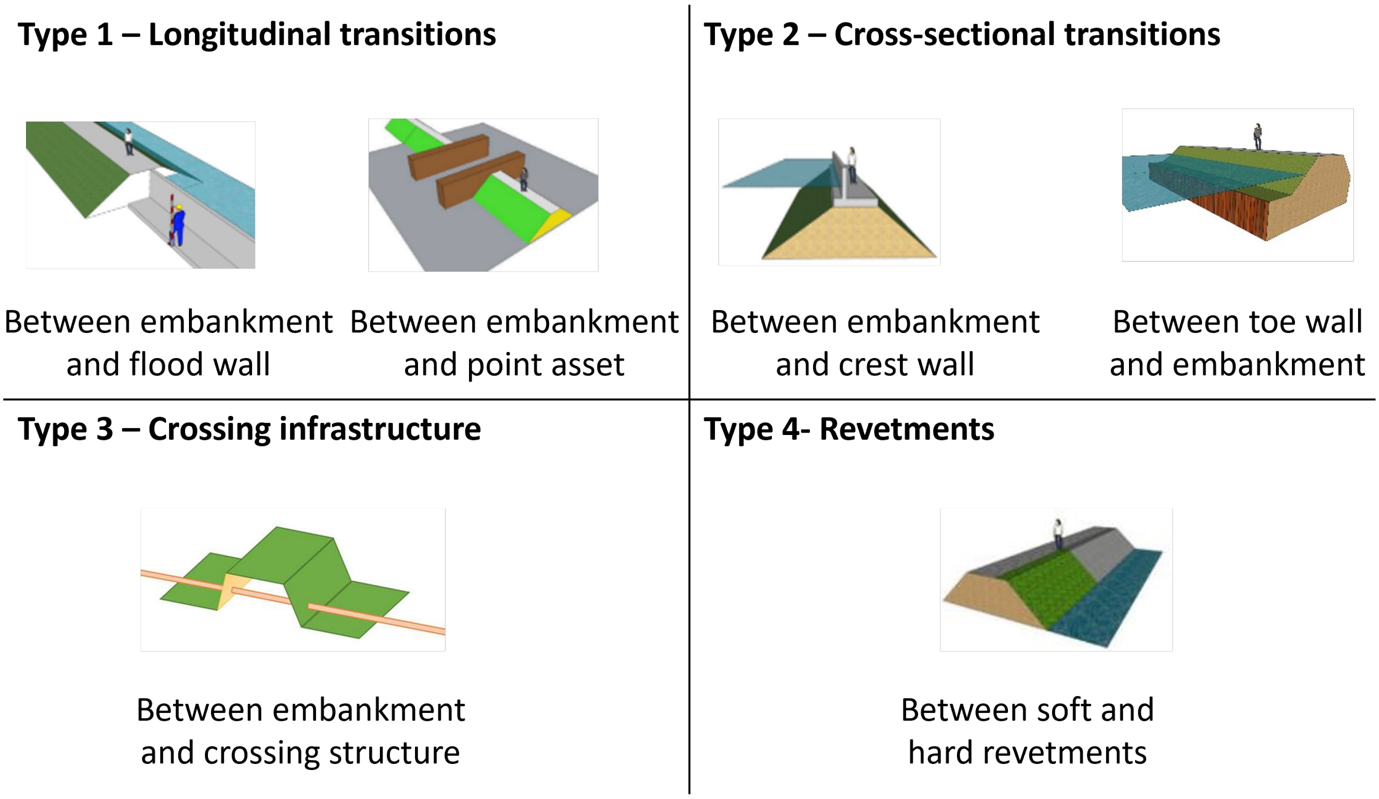


Figure 1.2 Types of transition considered in this guide

This guide is primarily intended to use on fluvial flood defence assets. It is however expected to be useful and broadly applicable for other flood defences too. There are particular differences in emphasis:

- For coastal defences: transition impacts related to wave loading are more prevalent: those related to type 4 (revetments) and failure mechanism ‘backfill washout’.
- For flood storage assets: hydraulic loading is sometimes permanent, which places more emphasis on seepage-related transition impacts. In addition, the legal status of flood reservoirs influences how some flood storage assets are designed and managed.

Examples are very important for a guide of this nature, and, where available, these have been included throughout.

1.5 Report structure

The guide consists of 2 parts. Sections 1 to 5 provide background and context. Section 6 provides focused guidance for designing transition improvements and associated management. The overall structure of the guide is as follows:

- Section 2 Context
  - Flood resilience, flood defence asset management, design process
  - Design principles for transitions
- Section 3 Transition types

- Definition and illustration of the 4 types distinguished in this guide
- Section 4 The impact of transitions on performance
  - How transitions can reduce strength and increase loading: the transition impacts
  - Relationship with deterioration, damage and failure
- Section 5 Types of improvement measures
  - Short overview of broad types of improvement methods
- Section 6 Guidance for addressing each transition impact
  - The main part of the guide, providing methods for design and management
  - Structured by the 10 identified transition impacts

The detailed guidance in section 6 is structured on the basis of how users will typically interact with it. Their starting point will normally be a particular transition that has been selected through the identification and prioritisation process, based on an understanding of the transition's potential impacts on flood defence performance. For this reason, section 6 is organised by the transition impacts: it contains a sub-section with guidance for addressing each 'transition impact'. Where there are nuances relating to specific transition 'types' or particular 'failure mechanisms', these are highlighted within those sections.

1.6 Background and aim

Transitions between flood defence assets and other components introduce irregularities which can increase the risk of damage or breach during a flood. This has been observed in many historic flood events (see text box 1-1).

This guide supports the design of improvements to flood defence transitions with a view to reducing their vulnerability. The design of improvements is part of an asset management process (see Figure 1-3) that starts with 'identifying' transitions that cause potential weak points in the flood defence system (where a transition may reduce strength and/or increase loading). Step 2 of the process confirms the need to improve the transition through 'performance and risk assessment'. Step 3 is then to design the improvement, which is followed by 'implementation' and ongoing 'operation and maintenance' of the flood defence. 'Improvement' in this context can include structural improvement works, but also changes to the maintenance regime, and also (even preferably) removing the transition to avoid its impact.

The envisaged use of this guide starts from the outcome of step 2: the guide is intended for designing improvements to existing transitions, with the aim of achieving a situation where the transition is no longer the weakest point. The principles of the guide apply however to the design of new assets too. The guide also covers how the subsequent stages of implementation and of operation and maintenance should be considered as part of the design.

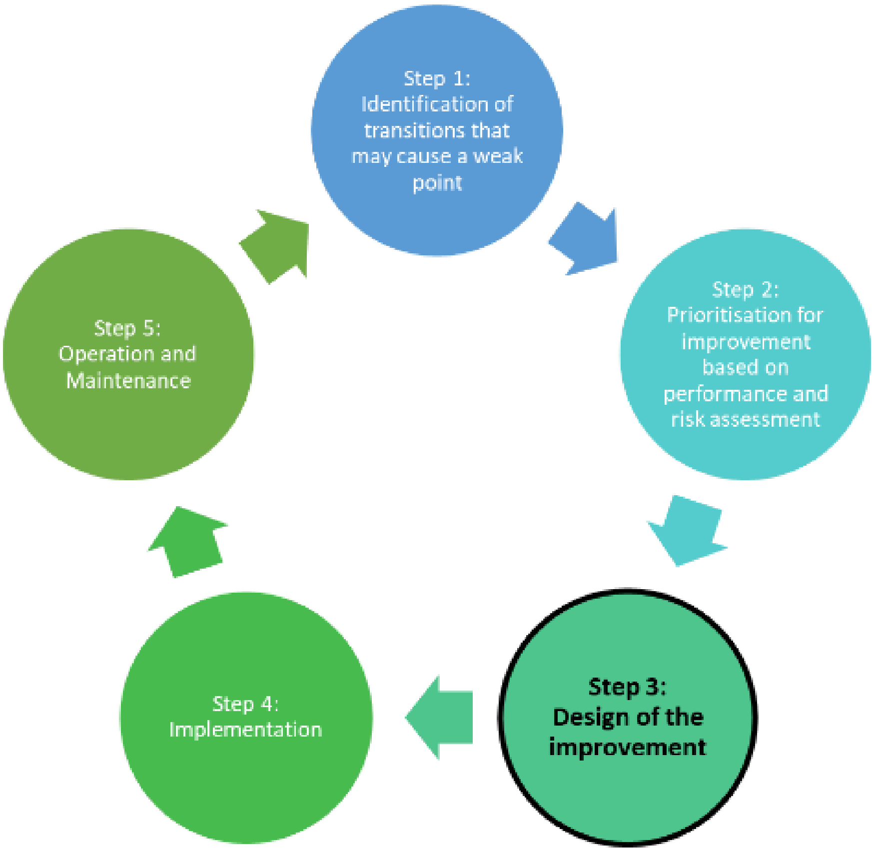


Figure 1.3: Focus of the guide is on designing transition improvements

Section 2 describes the context in which this guide fits, in terms of flood defence asset management and flood defence design.

Text box 1-1: Transitions - an important cause of flooding

Local irregularities and transitions play a role in many historical flood defence breaches. Commonly, transitions have been identified as a contributory factor in a complex chain of mechanisms and events that has ultimately led to damage or breach. Transitions between walls and embankments were identified as an important contributory factor leading to the breaches during Hurricane Katrina in New Orleans. Similarly, the series of assessments of defence performance during floods in England since 2007 has consistently identified local irregularities as the main overall contributing factor leading to damage or breach (see, for example, Royal Haskoning (2008), Royal Haskoning (2010) and Royal HaskoningDHV (2016). In some cases, asset transitions have been explicitly identified as the main cause of failure, such as near Corbridge on the River Tyne in 2015 (see Figure 1-4).

Figure 1.4 Dilston Haughs, Near Corbridge, River Tyne, 2015

This performance of this defence during ‘Storm Desmond’ (December 2015) was analysed in Royal HaskoningDHV (2016). The damage shown here occurred at a longitudinal transition between an earth embankment (downstream) and a composite structure consisting of a masonry wall on the landward side and an earth embankment on the riverward side (upstream; visible at the yellow arrow). The occurrence of the damage was not observed, but it is clear that overflow played a role. Local wrack lines suggest around 0.4m of overflow depth. There was widespread overflow in the area, but this was the only significant damage. The diagnosis identified that the damage will have been caused by a number of transition impacts: locally irregular geometry and steep slope will have increased the turbulence of the overflowing water, while it may also have reduced the strength as a result of restricted access for fill compaction around the wall or grass maintenance.

1.7 Link with International Levee Handbook

The International Levee Handbook (ILH - CIRIA, Ministry of Ecology, USACE, 2013) is the authoritative guide for assessing, maintaining and designing flood defence embankments. The ILH includes specific guidance on designing and maintaining transitions. This transitions guide is a stand-alone document that can be used without reference to the ILH. However, where possible, the methods presented in this guide follow the principles of the ILH and fit within the broad context of the ILH’s levee management and design procedures. This guide therefore contains many references to the ILH, and text box 1-2 summarises where the ILH discusses transitions.

Text box 1-2: Transitions in the International Levee Handbook (CIRIA, Ministry of Ecology, USACE, 2013)

The ILH is an important global reference for levee management and design. It recognises the importance of transitions as a cause of failure and flooding. Its Chapter 3 explains how transitions can increase the chance of failure processes occurring. Chapter 9 of the ILH covers design; its section 9.11 focuses on transitions and introduces 4 types of transitions. Following the ILH's general structure, it discusses general principles of transition design, and outlines issues and methods, illustrated by examples, for 3 failure processes that could be caused by transitions:

- differential settlement: a text box (ILH Box 9.42) that sets out a broad risk management approach (avoid – mitigate – transfer – adapt)
- external erosion (ILH 9.11.2): Issues (typical processes), methods (for calculating loading and solutions) and one example in New Orleans

Internal erosion (ILH 9.11.3): Issues (difficult to observe), methods (measures rather than calculation methods) and 2 examples in France.

2 Context

2.1 What are transitions and how do they influence flood risk?

A transition is a single point or a zone in a flood defence structure where characteristics such as structure type, material, geometry, subsoil or orientation change in a way that can materially affect the performance or integrity of the structure during a flood. Examples are connections between structural flood walls and earthen embankments and crossings of utility infrastructure such as culverts or pipes through or under a flood defence.

Changes of construction characteristics at transitions can have an impact on flood defence performance by locally reducing resistance (strength) or by attracting increased loading. This guide identifies a range of 'transition impacts' and provides principles and example measures for dealing with each of these. The transition impacts are introduced in section 4 of this guide, which describes how each can affect strength and loading, and how the impacts relate to failure mechanisms. Four groups of transition impacts are distinguished in this guide:

- geometry
- differential behaviour of structures/materials
- impediments for construction or maintenance
- preferential traffic paths causing deterioration

The size of a transition zone cannot easily be defined in general terms. It extends as far as the potential impact of the transition on the performance of the flood defence, that is, the full zone where the transition reduces strength below that of the main assets and/or increases the loading. This is sometimes called the 'Influence Zone' and is illustrated in Figure 2-1.

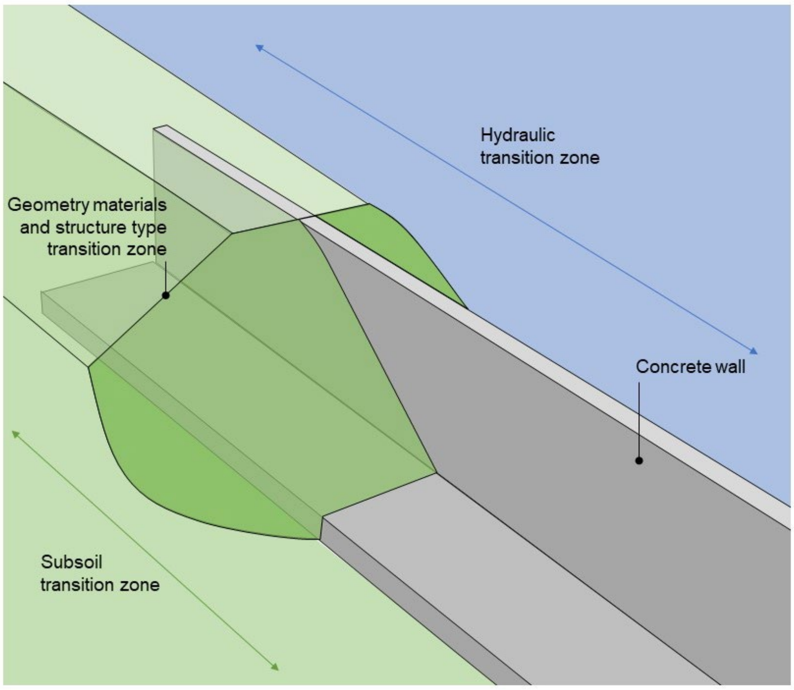


Figure 2.1: Transition zone from different perspectives (for illustration only)

2.2 Place of design in overall flood resilience and asset management

The Flood Risk Asset Management (FRAM) Propeller in Figure 2-2 illustrates how different activities contribute to maximising the level of flood risk reduction of flood defences given the limited resources that are available. This is in line with the Environment Agency's FCRM Asset Management Strategy (Environment Agency, 2017) and supports the National Flood and Coastal Erosion Risk Management Strategy's overall vision of a nation ready for, and resilient to, flooding, now and into the future.

The design of improvements, as discussed in this guide, is informed by a process that starts by inspection (identifying potential weak points where a transition may reduce strength or increase loading); followed by the assessment of each weak point to determine if it significantly reduces flood defence performance and thereby increases flood risk to an unacceptable level.

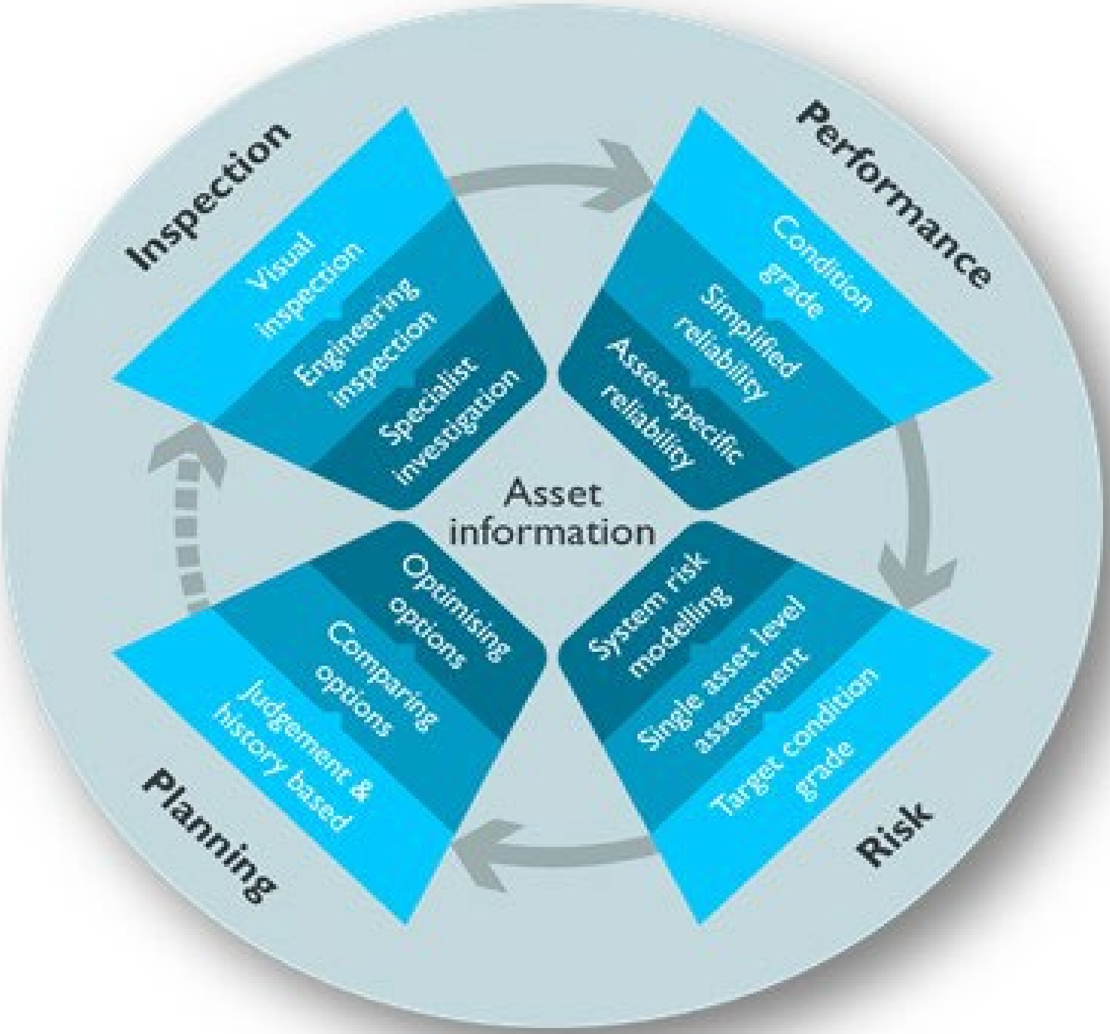


Figure 2.2: Flood risk asset management propeller

The planning step from the FRAM propeller includes design actions as well as a range of other activities such as securing funding and consent for any intervention. This guide focuses on the technical design activity, but also discusses the role of monitoring in addressing ongoing deterioration.

The following sub-sections of this guide describe how transition improvement design works in practice for aspects of the FRAM propeller:

- Design is informed by the preceding steps of inspection and performance/risk assessment.
- Design interacts with the Asset Information System (in the centre of the propeller).

2.2.1 Design is informed by identification and performance/risk assessment

Design is only required for those transitions that form a weak link that increases flood risk to the extent that investment in improvement is justified. This requires a process of identifying potential weak links in the flood defence chain, and a process of assessment that will help to justify and prioritise remedial actions. For example, improvement may not be justified if a transition impact creates a weak landward slope but the crest has excess height; or if the consequences of flooding are very low. These processes of inspection and assessment will also produce information that will be needed as input for the design.

This guide does not discuss the identification and assessment processes in more detail, but it does provide references to relevant sources of further information. The Transitions R&D Project that produced this guide also developed procedures for appropriate inspection and assessment activities specifically for transitions (Environment Agency, 2022b). These were developed specifically for use in the Environment Agency (see text box 2-1), but the broad approaches and concepts can also be used in other flood defence asset management organisations.

Text box 2-1: Processes for identifying and assessing transitions developed for the Environment Agency

The Transitions R&D Project developed procedures for identifying and assessing transitions that need to be addressed, (see Environment Agency, 2022b). The aim of the identification process is to find transitions that form a weak link because they cause a reduction in strength or an increase in loading compared to the adjacent or surrounding embankment, and lead to unacceptable flood risk. The process also collates and produces information that supports the subsequent prioritisation and design processes. The identification process follows a tiered approach as illustrated in Figure 2-2 . Tier 0 is preceded by identifying all the transitions using information from the Environment Agency's AIMS system. This process was developed to run alongside the Environment Agency's regular, well-embedded processes for identifying, prioritising and improving asset performance issues, including the Condition Assessment Manual (Environment Agency, 2012) and the associated 'T98' training programme.

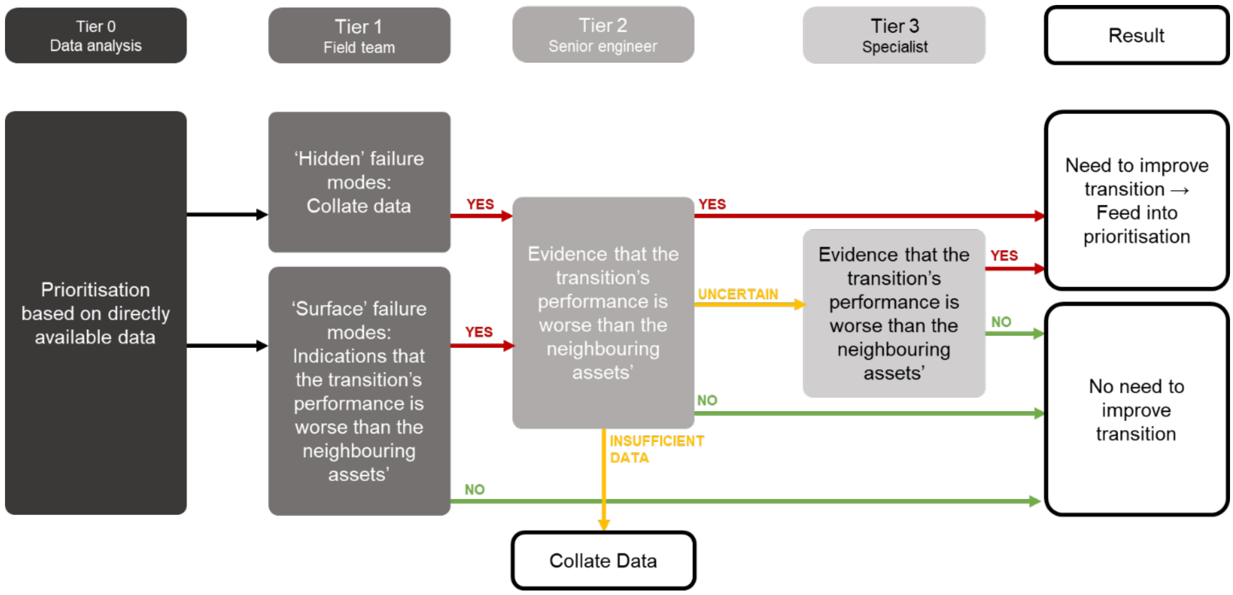


Figure 2.3: Identification process of transition weak links (Environment Agency, 2021)

The identification process provides the following information as a starting point for design:

- directly available data from desk study
- visual observations and basic measurements from field team inspection
- analysis and judgement from engineering assessment by senior engineer
- identifying the transition impact that is causing a weak link in the flood defence system

This is described in more detail for each transition impact in section 6.

There is also useful background information in chapter 5 of the ILH which covers levee inspection, assessment and risk attribution, and provides general principles for these processes.

2.2.2 Design interacts with Asset Information System

The design process is informed by the information available in the Asset Information System (which could be in an IT system such as the Environment Agency's AIMS, but also in other databases and archives). In practice, much of this information will also inform the inspection and assessment processes, and feed through into the design process. The results of the design (changes to basic variables, design documentation) need to be fed back as appropriate into the Asset Information System after any changes have been made.

2.3 Design process

The suggested design process for addressing transitions is shown in Figure 2-4. This translates existing generic embankment design processes into the specific objectives covered by this guide. As described in section 2.1, the focus will be on the changes necessary for addressing existing transitions that have been identified and prioritised. At this level, the transitions design process is very similar to that for flood defence improvements in general. It is based on the ILH section 9.2 and the refinements from CIRIA's guidance to the application of Eurocode 7 to embankments (CIRIA, 2014). The level of detail of each step has to be appropriate to the risk of flooding and the expected value of the intervention.

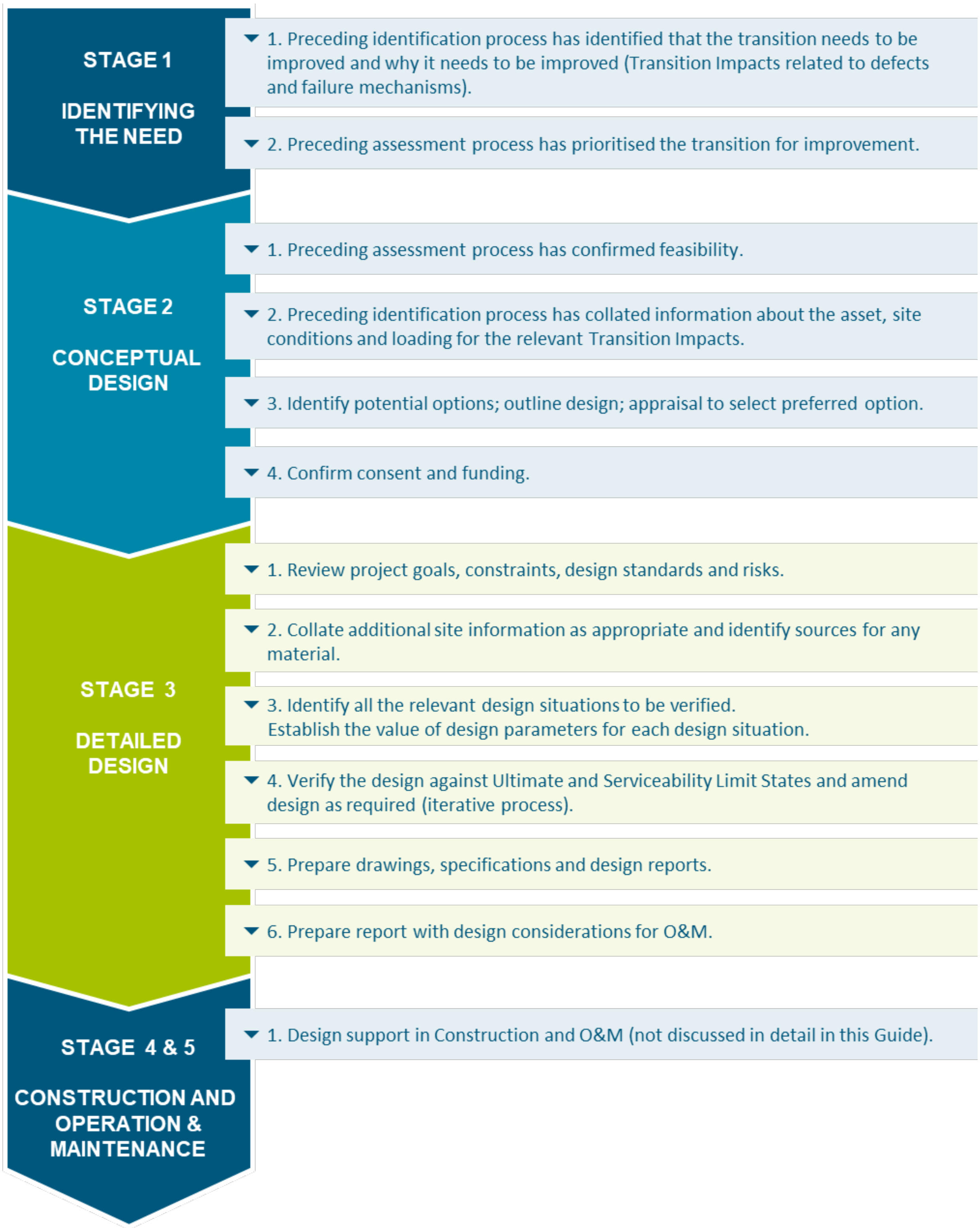


Figure 2.4: Transitions design process, (Royal Haskoning DHV)

2.3.1 Stage 1 Identifying the need

For the typical situation addressed in this guide, the need for improvement will be clear and will have been determined as a result of an inspection process (see section 2.1). After identifying the transition as a weak link, a performance/risk assessment process will have confirmed the need to address it.

This assessment process will have identified why the transition needs to be improved: which transition impacts are causing the weak link, and how this relates to defects, weaknesses and deterioration processes that may lead to failure. This information is an important starting point for the design process, so it is important that the relevant information is well documented.

2.3.2 Stage 2 Conceptual design stage

The aim of this stage is to identify the preferred option and to confirm consent and funding. This requires an outline design that provides enough detail to meaningfully compare benefits, costs and impacts. These appraisal and confirmation processes are outside the scope of this guide, but the preparation of the supporting outline design is included.

The feasibility of the improvement will normally have been confirmed in the preceding inspection and assessment processes. These processes will also have collated much of the information required to start the conceptual design stage (although this may need to be complemented by investigations at this stage):

- geometry, materials and geotechnical characteristics for the transition itself and the 2 assets that it connects
- water levels, waves, turbulence and other factors that constitute the loading
- failure mechanisms for which the transition was identified, with associated damages and deterioration mechanisms that will need to be addressed
- other functions (for example, related to human use or environment) and associated design requirements

The preceding processes may also already have identified potential options for improvement, which can serve as a starting point for identifying options. The first option to consider should be removing the transition (see principle 1 in section 2.4). Although there is a risk that the transition may be relocated with problems still remaining. If that is not possible, then measures for addressing the transition could consist both of structural improvement, but also a change in maintenance regime. The available options for transition improvements are discussed in general terms in section 5, and in more detail for each transition impact in section 6.

The purpose of the design at this stage (called outline or feasibility design in the International Levee Handbook (ILH)) is to identify options that are effective and constructible. Because the design at this stage forms the basis for appraisal and selecting the preferred option, it needs considering adequately in order to prevent significant changes at detailed design stage, which is undesirable. For transitions, much of the work at this stage is similar to the design of flood defence embankments in general. However, there is a need to focus on the specific challenges associated with the detailing of transitions, in particular, the importance of understanding 3-dimensional geometry, differential material behaviour and impediments to construction and maintenance (see transition impacts introduced in section 4.2). Section 2.4 presents the specific principles to follow when designing transitions.

The methods for option appraisal and selecting the preferred option must be proportionate to the scale of the projects and include other considerations such as using sustainable materials. The Environment Agency uses its post-inspection process to identify the appropriate method for option appraisal. For appraising significant investments, both the Environment Agency's post-inspection process and this guide make reference to the FCERM appraisal guidance (Environment Agency, 2010). For lower-cost improvements, simpler judgement-based approaches are appropriate.

The outline design forms the basis for meeting any requirements for consent, typically through an Environmental Impact Assessment (EIA), and for confirming funding, typically through a business case that runs in parallel to, or even integrates with the EIA. If the transition improvement is part of a wider project or programme, then consent and funding will be addressed at that broader level.

2.3.3 Stage 3 Detailed design stage

The objective of the detailed design is to develop the preferred solution in a way that it continues to meet the design and cost requirements and contains enough information for it to be constructed effectively and safely.

As is the case for the conceptual design stage, improvement methods and associated design approaches are similar to flood defence embankments in general. However, there is a need to focus on the specific challenges associated with transitions (see section 4.2). For transitions, the 'project goal' will often be to ensure that the transition is no longer the weak link. This can create a problem for the designer, particularly in situations where old assets are involved (as these may not fully comply with modern design methodologies and criteria - see principle 2 in section 2.4).

Usually, the designer is directly responsible for producing the specifications and drawings. If these are developed by different individuals or groups, then it is important to involve the designer in producing these documents to maintain continuity. This could take the form of a review role and can help to avoid a situation where the design is misunderstood by the organisation responsible for the contract documentation.

It is important that the designer also provides clear guidance for the Operations and Maintenance (O&M) stage which, for transitions, may require specific attention due to poor or limited access routes to the site (see group 3 of the transition impacts in section 4.2). A good working knowledge of the type of equipment available or limitations imposed on operatives who are responsible for maintaining and managing the assets is required. It is good practice for the designer to develop an O&M manual, which is then used as a ‘living document’, updated after construction and then passed on to the flood defence manager.

2.3.4 Stage 4 and 5 Construction and operation and maintenance

The reports from stage 3 should, in principle, provide all the information about the design to build and operate the asset. However, in practice, there is often a need for design input when the improvement is being:

- constructed, to advise on alternative proposals or interpret unforeseen ground conditions or monitoring data
- operated, to help address poor performance and designing subsequent improvements

The processes for this are not discussed in any detail in this guide but, from a technical perspective, this will be based on the same considerations as for the initial design of the improvement.

2.4 Principles for design

An initial set of principles for designing transitions is presented in section 9.11.1 of the International Levee Handbook; these are restated here, in the bullets below. Additional principles were established in developing this guide, and these are listed here, numbered 1 to 8 (in next section 2.4.1). The principles are referenced throughout section 6, where they are applied to the methods for addressing each of the transition impacts.

Principles developed from the International Levee Handbook:

- Historical failures show that great care must be taken in designing ‘transition detailing’:
  - the detail must be considered in 3 dimensions (not just in plan or in cross-section);
  - the magnitude and characteristics of hydraulic loads and external actions must be considered
  - design has to relate to the potential failure mechanisms (see section 4)
  - design solutions should be appropriately robust
- A range of loading scenarios should be considered including:
  - normal operating conditions
  - design flood events (sometimes called ‘resistance’)
  - extreme events that exceed the design event (sometimes called ‘resilience’)
- The following hydraulic parameters need to be considered:
  - velocity and direction of flow, including turbulence and possible sediment transport
  - water level changes, including any waves and their characteristics
  - hydraulic head along and across the transition and the resulting potential for hydraulic separation (see section 6.5) and uplift

- The design process should consider deterioration processes that could compromise performance over time. For example, seasonal shrinkage/swelling of clayey soils leading to desiccation cracking, seepage and/or hydraulic separation or local settlement leading to the possibility of localised overtopping flow.

2.4.1 Additional principles introduced in this guide

1. Avoid transitions altogether if possible.

The best approach for preventing transition impacts is to avoid transitions altogether. In some cases, it may be possible to remove existing transitions rather than trying to control or address their impacts. Alternatively, a transition could be relocated to reduce loading or improve resilience. This is a very important principle: avoiding transitions should always be the first option to consider. Section 5 discusses this for each transition type.

2. Make sure the transition is not the weakest link.

The design objective should be to ensure the transition is not the weak link (in other words, it is not more likely to fail than neighbouring structures). This is recommended as a generic ‘rule of thumb’ for designing transitions.

In line with principle ‘d’ from the ILH, this needs to be considered for the whole life of the transition and neighbouring assets, taking account of differing deterioration rates.

3. Err on the side of caution.

If there is uncertainty about required dimensions (for example, the length of an overlap or the strength of materials), err on the side of caution in order to produce a robust transition. Transitions are more likely to contain unknown irregularities which may be hidden from view. These may introduce additional uncertainties relating to strength and/or loading. As a result, there is a higher than normal likelihood that performance at a transition will be poorer than calculated. With reference to principle 2, it may be appropriate to aim for a slightly better performance than the neighbouring structures by erring on the side of caution. This needs a careful balance, because it is also undesirable that the transition becomes a significant ‘strong point’ which may create new transition impacts for the neighbouring structures (see principle 5).

4. Transitions should be gradual.

Transitions should be as gradual as reasonably possible, both in terms of external geometry and also materials and structure types. This can be achieved by providing sufficient overlap and avoiding abrupt changes.

5. Improvements can introduce new transitions.

Improving existing transitions can introduce new transitions, which will have their own impacts on performance. Designers need to consider these impacts, for example, by avoiding abrupt changes or moving the transition to a less vulnerable location.

6. Improvements can create other impacts.

When addressing a particular transition impact, the full set of other transition impacts (see section 4.2) and their associated failure mechanisms should be considered. This should include an assessment of the possibility that solving one issue may create other problems.

7. If standards cannot be met, then manage the associated risks.

If the adjacent flood defences do not meet current design requirements, then it may not be possible, affordable or sensible to design the transition improvement fully to the current standards. If this is the case, then the designer needs to discuss this issue openly and clearly with the asset owner in order to decide how to proceed (for example, by risk assessment, increased inspection and monitoring and enhanced emergency planning).

8. Manage any short-term performance reduction.

Many of the improvement methods include disturbing the existing flood defence structure. This may cause a short-term reduction in performance, for example, until grass cover has re-established, and the ground consolidated, this may take some time. This issue is not specific to transitions but needs to be acknowledged. The asset manager needs to plan for mitigation if a flood event occurs in the short-term period before the repaired structure has fully re-established itself.

3 Transition types

The focus of this guide is on embankment-related transitions. The guide covers the 4 types of transition shown in Figure 3-1 (which is the same as Figure 1-2). Note that transitions between embankments and dunes, and between 2 embankment assets are not covered explicitly, although the principles apply to those cases too. Each transition type is described and illustrated in greater detail in individual sub-sections.

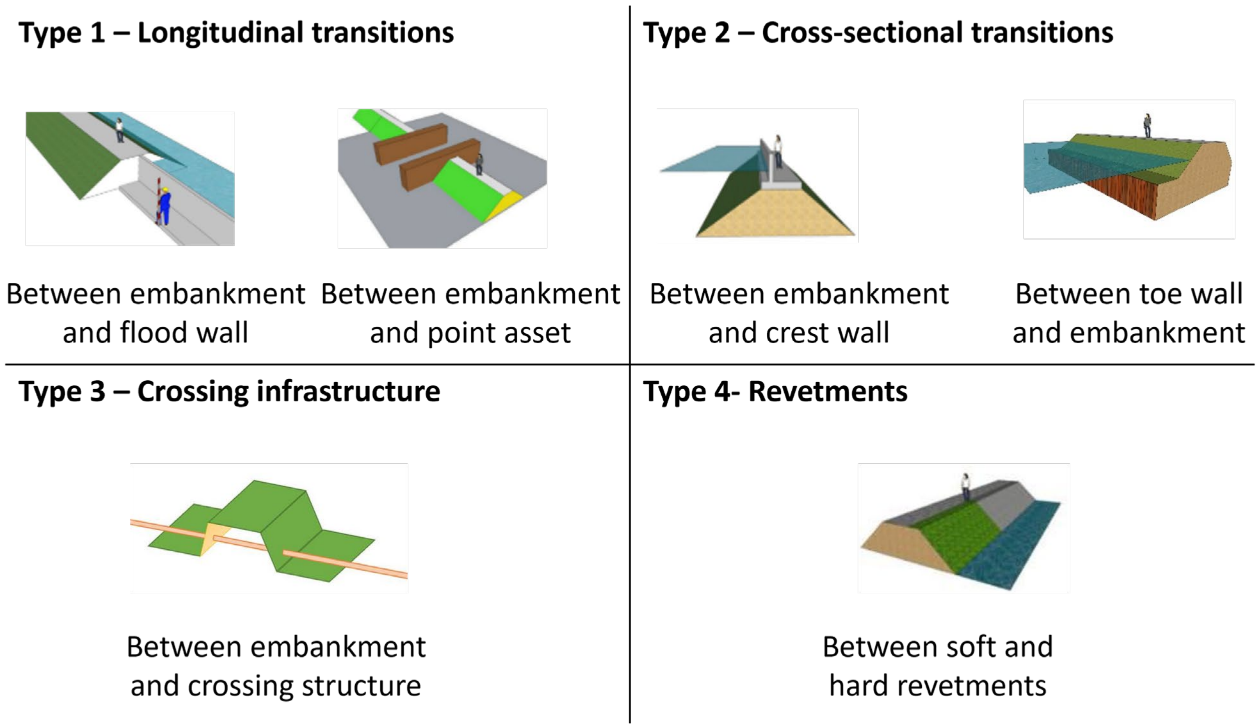


Figure 3.1 The 4 types of transition considered in this guide

When considering how to improve transitions, the type of transition often plays only a limited role. More important is the nature of the transition impact, and how this reduces strength and increases loading in terms of deterioration and failure mechanisms (see section 4). For this reason, the guidance for improvements is structured by the transition impacts, with reference to the transition types in the few cases where this is relevant.

3.1 Type 1: Longitudinal transition: embankment to hard structure

Type 1 concerns transitions along the length of the flood defence. Type 1 transitions can take the form of overlaps between earth embankments and any hard (non-earthen) structure that occupies all or much of the flood defence cross-section. This hard structure could be a flood wall or a local point structure, such as a gate or sluice. The transition could be between 2 different flood defence structures, but could also be a third-party, non-flood defence asset such as a building or a bridge abutment or a privately-owned property such as a house. Figure 3-2 provides some examples of type 1 transitions; also illustrating that many transitions combine aspects of multiple types.

Figure 3.2: Type 1 transition examples: 3 embankment-wall transitions near East Ferry (Tidal River Trent). The bottom right picture shows a transition between an embankment and a concrete outfall structure (flood storage reservoir at Northenden Riverside Park, River Mersey)

3.2 Type 2: Cross-sectional transitions: wall on crest or at toe of embankment

Type 2 concerns transitions across the flood defence. This typically covers the transition between the elements of a composite flood defence: a retaining wall on top of an embankment or a sheet pile structure at the toe of an embankment. The hard structure can also be a third party, non-flood defence asset such as a building or a bridge abutment. Figure 3-3 provides some examples of type 2 transitions.

It should be noted that this guide (and the overall design process described in section 2.1) only addresses the local impact of the transition on defence performance. While the guide does address local surface erosion around type 2 transitions and seepage/piping along or between hard and soft elements of a type 2 transition, it does not address global instability and settlement of the whole composite flood defence. This is because these parts of design are needed for, and inherent in, the design of the whole composite structure, not just the interfaces between elements. For the design of composite flood defences, reference is made to embankment design guidance such as the ILH and CIRIA's report C749 on the application of Eurocode 7 to flood embankments (CIRIA, 2014).

The issue of stiffness incompatibility, which caused the catastrophic failures of I-walls in New Orleans during Hurricane Katrina is a grey area. It relates to global instability and is inherent in the design of composite structures, but it is also closely linked to the direct interface between hard structure and embankment. It is discussed in more detail in text box 6-5, along with the related phenomenon of hydraulic separation.

Figure 3.3: Type 2 transition examples (at south of Scunthorpe and East Butterwick (Tidal River Trent), 2020

3.3 Type 3: Crossing infrastructure

Type 3 concerns transitions between crossing infrastructure such as outfalls, pipes, culverts and cables, and the body of the embankment that surrounds them. Figure 3-4 provides some examples of type 3 transitions.

Failure of crossing infrastructure, such as pipelines, causes an obvious risk to flood defence performance, and this needs to be addressed in the design of the infrastructure, for example, for strength and water tightness. This guide does not address the design of the crossing infrastructure itself, but only the interaction with the surrounding embankment.

Figure 3.4: Type 3 transition examples of outfall structures (pipe crossings), Partington (left), Butt’s Bridge, Leominster (right)

3.4 Type 4: Revetments

Type 4 concerns transitions between hard and soft embankment revetments. A ‘soft’ revetment might typically be covered by grass, while cast-in-situ concrete, rock armour or other scour protection materials might be used to form the surface of a ‘hard’ revetment. However, this guide applies to any transition between revetments of different types, even between weaker and stronger revetments of the same type. The guide applies to hard revetments that were placed expressly for the purpose of hydraulic erosion protection. However, it can also be applied to revetments with other primary functions such as road surfacing. Note that the guide does not apply to the larger scale design of the revetment away from the transition.

Figure 3-5 provides some examples of type 4 transitions.

Figure 3.5: Type 4 transition example, M180 crossing along Tidal River Trent, 2020

4 The impact of transitions on performance

4.1 Deterioration, damage and failure

Transitions often form weak links in flood defence systems because they reduce the resistance against failure of the defence, and/or because they increase the loading on the defence. This has to be understood in the context of failure mechanisms, which are described by the International Levee Handbook (ILH) as deterioration and damage processes that can (individually, or combined into failure scenarios) ultimately lead to flooding through or over a flood defence. For background purposes Text Box 4-1 introduces the ILH's thorough analysis of embankment failure.

Text box 4-1: Failure mechanisms

Section 3.5 of the ILH explains the main concepts around flood defence failure, in the context of the functions and forms of embankments.

Flood defence failure is defined as the state in which the flood defence is not able to achieve its defined performance. Failure can be structural (breach) or hydraulic (water ingress through or over the defence before the planned protection level is reached).

4.2 Transition impacts

This guide introduces the concept of 'transition impacts': the various ways in which transitions can cause a weak link in the flood defence system by reducing the strength or increasing the loading. Understanding the transition impacts is essential for identifying weaknesses, but also for remediating them, and therefore the design methods in section 6 are structured by the transition impacts. The guide distinguishes between types of transition impacts and provides guidance for dealing with the related issues (noting that this list may not be exhaustive, and that the designer should always consider how a particular transition might affect performance):

- Geometry:
  - shorter seepage paths
  - steeper slopes
  - irregular geometry causing turbulence
- Difference in behaviour of materials
  - hydraulic separation
  - impeded root formation and shading
  - gaps in filter structures
- Impediments to construction and maintenance
  - poor compaction around transition elements

- impeded maintenance due to poor access and visibility

- Preferential traffic paths causing deterioration
  - rutting and furrowing
  - animal burrows

Section 6 contains a sub-section for each of these 10 transition impacts, describing and illustrating the physical process, the relation with failure mechanisms, principles for design, improvement methods, design approach and examples. In practice, a transition often has more than one of these impacts, which all need to be addressed (see section 6.1).

The identification process (see section 2.1) will have identified that one or more of these transition impacts apply. Transition impacts can be identified in 2 ways:

- observable damage, which directly affects performance but can also be a sign of reduced strength or increased loading. This is typically identified through field inspection
- an inherent issue: insufficient strength or increased loading that has not yet caused visible damage but is likely to do so under design conditions. This is typically identified through engineering assessment. Identification of low spots is an exception to this rule

4.3 Relation to failure mechanisms and deterioration

All transition impacts are related to at least one, but typically to multiple failure mechanisms. The 5 most relevant failure mechanisms for transitions are shown in Figure 4-1.

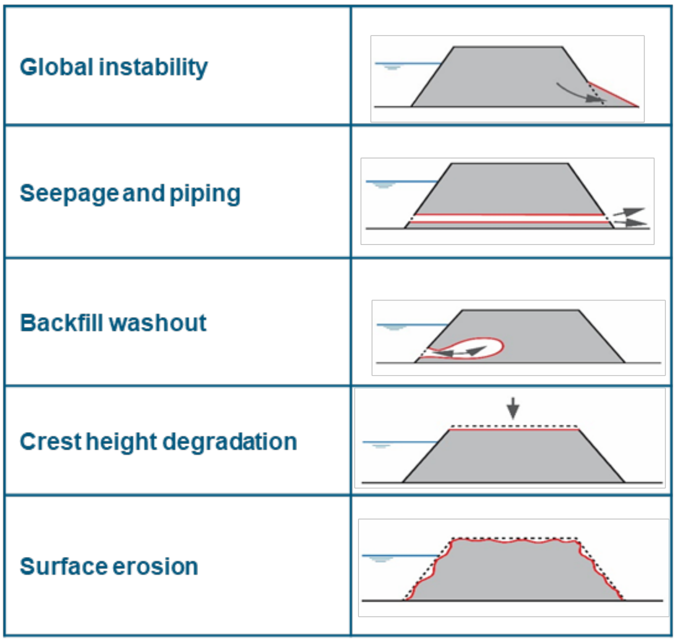


Figure 4.1: Embankment failure mechanisms that can be affected by transitions

The identification process may have determined one dominant failure mechanism, but the designer will still need to check against all relevant failure mechanisms. Note also that failure is often a complex sequence where one process triggers the next.

Once an embankment is constructed, when failures occur during flood events, they are commonly triggered by hydraulic actions such as external erosion (including overtopping flow which may be the result of embankment settlement) or seepage causing internal erosion, softening or uplift, all of which can lead to instability, collapse and then breach. These mechanisms can be characterised as geotechnical failures resulting from hydraulic actions. Failure directly caused by global instability (without any hydraulic load) is less likely once the embankment has been constructed, but all relevant failure mechanisms still need to be considered, particularly for the specific case of transitions.

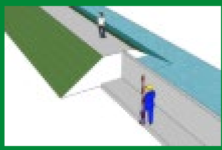
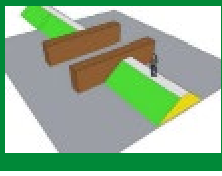
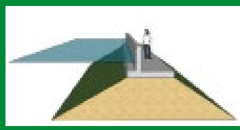
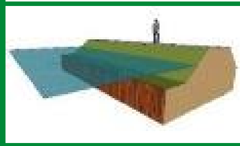
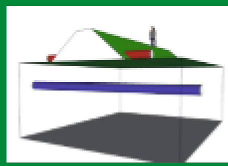
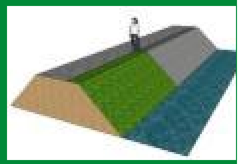
Some of the transition impacts constitute, or relate directly to, deterioration processes that could ultimately lead to one or more of the failure mechanisms in Figure 4-1. This is the case for:

- progressive internal erosion caused by multiple flooding events
- impeded root formation and shading, leading to grass deterioration
- gaps in granular or geotextile filter structures, leading to internal erosion
- impeded maintenance, leading to grass deterioration
- traffic of people, animals or vehicles, concentrated along the edge of hard structures or linear features such as fence lines, leading to rutting and grass deterioration
- animal burrowing which might create flow paths through the embankment or trigger crest settlements, leading to preferential overtopping flow

4.4 Transition impacts per failure mechanism and transition type

The matrix in Table 4-1 gives an overview of the transition impacts addressed by this guide. It shows, for each transition impact, the failure mechanisms that it can cause. These are direct impacts, which typically can then trigger other failure mechanisms; those secondary impacts are not shown in this table. Green cells concern a reduction in strength, orange cells an increase in loading. The matrix also shows the transition types that each transition impact is most likely to apply to. Note that this table may not be exhaustive.

Table 4-1: Transition impacts, failure mechanisms and transition types

Transition Impact	Longitudinal  	Cross-sectional  	Crossing infrastructure 	Revetments 
1) **Geometry**				
a. Shorter seepage paths	SP		SP	
b. Steeper slope angles	GI, SE			
c. Irregular geometry causing turbulence	SE	SE	SE	SE
2) Difference in behaviour of materials				
a. Hydraulic separation along hard/soft interfaces	SP	SP	SP	
b. Impeded root formation and shading	SE	SE		SE
c. Gaps in filter structure			BW	BW
3) **Impediments to construction and maintenance**				
a. Poor compaction	GI, SP, CH		GI, SP, SE,CH	CH
b. Poor maintenance due to poor access and visibility	SE	SE	SE	SE
4) Preferential traffic paths causing deterioration				
a. Surface (vehicles, pedestrians, animals)	CH, SE	SE	SE	SE, CH
b. Animal burrows	CH		CH	CH

Key:

- GI: Global instability
- SP: Seepage and piping
- BW: Backfill washout
- CH: Crest height degradation
- SE: Surface erosion

The relationship of the transition impacts with deterioration processes and failure mechanisms is complex, and this is discussed in more detail at the start of each subsection in section 6.

Table 4-1 includes a number of gaps; these indicate combinations of transition type and impact that are not addressed in this guide, for the following reasons:

It is possible that a transition will have an adverse impact on the hard structure as well as the embankment, although typically the impact on the embankment will be more significant. For example, there could be cases where the hard structure relies on passive resistance from the embankment, so there could be a knock-on effect if the embankment is subject to erosion or softening. This situation is not discussed in detail in this guide because of the focus on embankments. However, it emphasises the general requirement for designers to look at issues in their context.

Cross-sectional transitions (type 2) are typically composite flood defences. There is an obvious potential for global instability and crest degradation issues with this type of defence, but this guide does not address these issues because they are fully inherent in the design of composite defences. As a result, the guide only addresses issues that can be caused directly by the transition between the components, that is, seepage/piping and surface erosion.

Revetment transitions are covered for their impact on surface erosion, but they are normally not heavy enough to influence global stability or crest height, and too superficial to influence seepage. In a coastal setting, there are known issues where the transition between revetment types can locally increase upward pressure under wave loading, causing top layer instability. This could require detailed analysis and particular design interventions which are not discussed in this guide.

5 Types of improvement measures

There is a wide range of methods available for addressing transition impacts, both in terms of design and maintenance. As mentioned in section 1.2, these methods are often strongly linked to those for regular flood defences, and this guide focuses on the transition specific aspects of those methods.

Specific methods for each transition impact are presented in section 6. It should be noted that section 6 does not provide an exhaustive list of potential options. Designers must consider other suitable options during the design process.

The methods can be broadly structured in the following 4 types:

5.1 Relocate transition

As indicated in principle 1 in section 2.4, the best way of reducing transition impacts is to avoid a transition or to relocate it to a less exposed location. This is often not possible or practical. However, this approach should be considered as part of any design or management plan for transitions, not least because it might generate some new ideas for ways of managing problems associated with the transition.

- For type 1 (longitudinal), there may be cases where it is possible to remove short sections of wall or embankment, perhaps originally constructed to work around constraints that no longer exist. If the hard structure concerns a point asset such as a flood gate for a road, it may be possible to realign the road so that it runs over the crest. Note that this may introduce new revetment transitions with their own impacts, and these will have to be considered and addressed.
- For type 2 (cross-sectional), removing the hard component of a composite asset may be possible if there is enough space, on the waterside and/or the landside of the defence, to accommodate the larger footprint of an embankment.
- For type 3 (crossing infrastructure) it may be possible to realign the route of the crossing so that it crosses over the crest of the embankment body instead of through it. Note that this may introduce new transitions around any support structures, with their own impacts, and these will have to be considered and addressed.
- For type 4 (revetments), there may be cases of ‘patchwork revetments’, often extended over time, which could be rationalised into a single revetment.

These approaches require proper design according to good practice and guidance for flood defences, considering all failure mechanisms and other impacts. This is generic to flood defence design and not discussed in further detail in this guide.

5.2 Observational approach

For a number of the identified transition impacts, the direct effect is to cause deterioration and/or damage. Over time, this process can reduce the strength of an asset to an unacceptable level. If the performance of the asset has deteriorated but not yet to an unacceptable level, then the preferred method could be to identify a trigger for intervention and to monitor how the transition's condition changes over time. An example would be the deterioration of grass quality next to a transition, through impeded root formation, shading or impeded maintenance.

However, it should be remembered that because the transition has not yet failed, this does not mean it is not a weak link, as it may not have experienced any significant (e.g. design) flood events. Similarly, it does not mean that any ongoing deterioration will continue at the same (potentially slow) rate as experienced up to the time of the assessment. Designers should carefully consider the risks associated with the observational approach. In many cases, it may be necessary to carry out additional maintenance or repair work to delay the deterioration (as set out directly below).

5.3 Address the symptoms

Transitions will often have been identified and prioritised for improvement because the transition impacts have already caused some damage. If improvement works only repair the damage but do not address the cause, then the transition will remain a weak link. While this is not usually the preferred approach, in some cases it may be an acceptable method. For example, a sacrificial element could be incorporated into the design and while this would be expected to be lost over time, this might still be a cost-effective solution.

An example would be a situation where animal traffic next to a transition causes rutting that reduces the crest height. It could be appropriate to raise the crest with a surplus without taking measures to reduce animal traffic, as long as this is combined with monitoring and a plan to review and intervene again when needed (and the associated ongoing cost and effort is accepted). However, even in this case, resilience should be considered. For example, if the surplus fill is of poor quality such that it is easily erodible, it may be washed away quickly in the event of overtopping flow. In this case, the additional fill material would be ineffective.

5.4 Address the cause

In many cases this will be the preferred approach (in addition to repairing any damage). This proactive approach is therefore the main focus of the improvement methods presented in section 6. Some of the methods are focused on improving the strength of the transition, others aim to reduce the loading.

6 Guidance for addressing each transition impact

6.1 Addressing transition impacts

This section is organised by the transition impacts as introduced in section 4.2:

- Geometry:
  - shorter seepage paths (section 6.2)
  - steeper slopes (section 6.3)
  - irregular geometry causing turbulence (section 6.4)
- Difference in behaviour of materials
  - hydraulic separation (section 6.5)
  - impeded root formation and shading (section 6.6)
  - gaps in filter structures (section 6.7)
- Impediments to construction and maintenance
  - poor compaction around transition elements (section 6.8)
  - impeded maintenance due to poor access and visibility (section 6.9)
- Preferential traffic paths causing deterioration
  - rutting and furrowing (section 6.10)
  - animal burrows (section 6.11)

Each transition impact is discussed in its own section, each with the following sub-sections:

- How does the transition impact work and how can it lead to failure?
- Principles for design
- Improvement methods and design approach

In practice, a transition can be subject to more than one of these impacts. In this case, all of the identified impacts will need to be addressed. If one impact is clearly dominant, you should refer to the appropriate sub-section to select a remedial measure (and then check that any other transition impacts are addressed by this approach). If multiple impacts are of similar significance, then it may be necessary to consider each of them in parallel and design combined methods to address them all.

Measures to address one transition impact can sometimes create other transitions. For example, installing surface protection to protect against increased turbulence can create a type 4 transition (revetment), with its own impacts.

6.2 Geometry – shorter seepage paths

6.2.1 How does it work and how can it lead to failure?

Why is it a typical transition issue?

The complex geometry encountered in some transitions can create situations where seepage is more likely than at neighbouring defences as a result of shorter seepage distances (and therefore higher hydraulic gradients). This can lead to various seepage-related problems discussed further here. As a result, transitions can be particularly vulnerable if seepage paths have not been well considered (in particular, missing the 3-dimensional perspective) or if they are poorly detailed, poorly constructed or if they have deteriorated since construction.

Shorter seepage paths can also be caused by leaks into or out of crossing infrastructure such as pipelines. This guide does not address structural design of crossing infrastructure, but the principles and measures in this section can apply to that situation too.

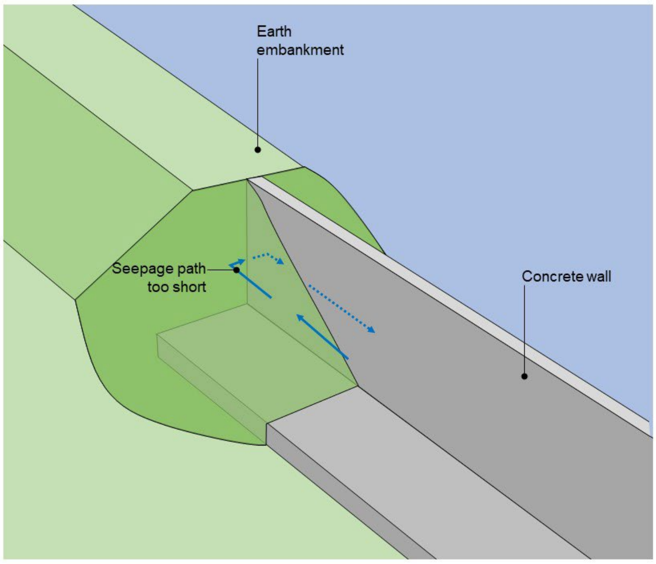


Figure 6.1: Shorter seepage paths

How can it lead to failure?

In situations where a transition results in the shortening of seepage paths, this can lead to increased hydraulic gradients and these, in turn, can lead to an increased risk of uplift or hydraulic separation between a hard structure and the embankment fill material. It can also lead to internal erosion through suffusion (loss of mass without collapse), suffosion, (loss of mass that does include collapse), contact erosion and associated concentrated leak erosion, or backwards erosion (piping). Internal erosion can create a downwards spiral of deterioration, leading to increased permeability, further increased rates of seepage and the formation of preferential seepage paths. In UK conditions, seepage can go undetected for extended periods because it mainly occurs in short periods of flood when water levels are high and surfaces are wet already as a result of precipitation.

This process can lead to a direct failure of the embankment (for example, by significant volumes of seepage leading to extensive internal erosion followed by embankment collapse, or by uplift of the landward toe of the embankment causing slope failure and loss of crest). However, it can also lead to settlement of the embankment crest through internal erosion followed by localised overtopping flow and eventually to collapse and breach.

High water pressures in the fill or in the underlying natural ground can increase the risk of uplift and/or slope instability of the landward parts of the structure. The combination of these mechanisms can lead to rapid deterioration and potentially to collapse and breach during flood conditions.

There is a strong link with other seepage-related transition impacts, in particular hydraulic separation (see section 6.5) and poor compaction (section 6.8). The physical impact is different, but the resulting failure process, improvement methods and design approaches can be similar. Specific issues and methods for crossing infrastructure (type 3) are discussed in section 6.5.

To which transition types does this impact apply?

Shorter seepage paths can occur in transition type 1 (longitudinal) and type 2 (cross-sectional).

6.2.2 Principles for design

How can design increase strength and reduce loading?

The best way of addressing transition impacts is to avoid a transition or move it to a less exposed location; section 5 gives suggestions for each transition type.

If avoidance is not possible, then loading can be reduced by reducing the hydraulic gradient. This is done by lengthening the seepage path, by increasing the overlap between embankment and hard structure or by installing structural elements. It is also possible to accept the increased hydraulic gradient but reduce the risk of cracking (by improving the interface between embankment and hard structure) or increase the resistance to internal erosion (by installing filters).

Seepage is a complex mechanism. Each of the relevant seepage related issues should be considered and analysed if necessary. For example:

- how much seepage will occur under design situations if no modifications are made? Will this volume of seepage be sufficient to cause flooding in itself?
- is hydraulic separation, leading to concentrated leak erosion possible (considering that transitions between soil and hard structures are particularly vulnerable)?
- will the seepage cause internal erosion in the fill material or the natural soil?
- can the possibility of internal erosion be managed through suitable filter design?
- will internal erosion caused by seepage trigger collapse settlements in the fill material?

If this assessment indicates that seepage around a transition is likely to be problematic and will reduce resilience during a flood, then remedial measures should be designed so that the transition will be more robust than the adjacent structures. Possible solutions are discussed in section 6.2.3.

Text box 6-1 presents a suggested design process for transitions where seepage is the dominant issue. Particular design issues for transition impact shorter seepage paths include the following:

- geometry of the transition: it is important to consider seepage paths fully in 3 dimensions. This can be facilitated by producing 3D images in appropriate software such as AutoCAD 3D. This will require accurate topographic survey data and as-built information about the transition
- the buildability of any design in the vicinity of the transition should be considered carefully. Potential issues include:
  - working on slopes
  - working around existing structures where space is limited (detail work)
  - working in and around the river system (health and safety issues, environmental issues)

Given these issues, designs of transitions need to be robust and to err on the side of caution (for example, in terms of geometry, safety factors). Clear communication from the designer to the contractor, pointing out the critical points in the design is also essential.

Text box 6-1: Design process for seepage-related transition impacts

Various transition impacts relate to seepage, in particular hydraulic separation (section 6.5) and poor compaction (section 6.8), but it can also play a role for others. The separate sub-sections describe it from the perspective of the specific impact, but there are strong interactions and overlaps in terms of principles and methods. Here we present a suggested design process for transitions where seepage is the dominant issue.

1) Identify if an additional internal barrier is required.
2) Consider options for geometry (for example, extend barrier into embankment, extend overlap of embankment along wall, deepen barrier).
3) Determine the length and/or depth of the barrier by carrying out seepage analyses through the soil or fill material in the vicinity of the barrier. Evaluate flow velocities and hydraulic gradients and extend the length/depth of the barrier until these are acceptable.
4) Consider the possibility of hydraulic separation or preferential seepage along hard structure. This will involve considering contact stresses, which can be related to the quality of compaction, as well as the permeability of the soil or fill material. The aim should be to achieve a situation where the flow along the interface will be lower than the flow through the soil. Particular consideration should be given to options for improving connectivity between the embankment and the hard structure. For example:

- achieve a good bond between soil and hard structure by casting the wall directly against the soil (for example, diaphragm wall) or compacting the soil against a hard structure with a roughened surface (see section 6.5)
- if installing new structural elements into the ground (such as sheet piles), consider ways of improving bond between soil and sheet pile such as by using surface coatings. Note that the driving of sheet piles may have a harmful effect on adjacent structures, which might create new seepage paths, so you should consider using jacked sheet piles (press-in piles such as Giken or similar).

Check the constructability of the proposed modifications and critically evaluate if these will introduce new weaknesses or transitions.

How to determine acceptable conditions?

Text box 6-1 sets out suggestions for the analysis method for seepage related issues. Analysis should be carried out for flow around, through and under the transition; in practice this may require considerable engineering judgement, because of lack of precise information at the interface, which makes the use of calculation methods and proprietary approved seepage software and hand calculations challenging. The analysis should aim to show that following any remediation, the seepage rates and hydraulic gradients have been reduced to acceptable limits, erring on the side of caution to address the uncertainties (see principle 3 in section 2.4).

6.2.3 Improvement methods and design approach

The methods in this section focus on reducing hydraulic gradient (alongside improving resistance against internal erosion), as these are most directly relevant for addressing the impact of shorter seepage lengths at a transition. As indicated in section 6.2.2, seepage at a transition can also be addressed by improving the interface of the materials between embankment and hard structures. These methods are, however, more relevant for transition impacts hydraulic separation and poor compaction, and are therefore discussed in sections 6.5.2 and 6.8.3.

Potential methods include the following:

1. Extend hard wall further into embankment with hard structure (type 1 transitions).
2. Extend earth embankment further along hard wall (type 1 transitions).
3. Install cut-off wall below a flood wall and into the embankment beneath (type 2 transitions).
4. Install filter on landward face of the transition to reduce seepage rates and effectively lengthen seepage paths.

Method 1: Extend hard wall to lengthen seepage path – type 1

Improvement method

In this method the seepage path is lengthened by installing a solid wall attached to the hard wall structure into the embankment. There are alternative methods for this extension such as forming a grout wall, a diaphragm wall or continuous piled wall.

In all cases, a full seal is required between the existing hard wall and the new extension so that the wall extension does actually lengthen the seepage path. For this type of method, there is an added benefit to driving or jacking sheet piles into the ground, because this will improve soil structure contact by compressing the soil either side of the sheet pile. If the soil is prone to loosening as a result of sheet pile driving, then alternatives such as pile jacking or silent piling should be considered.

The designer should be aware that deterioration may occur after construction (for example, desiccation cracking, seepage erosion). Where possible, steps should be taken to mitigate the problem (for example, using fill material with low volume change potential in low stress areas near ground surface).

One benefit of this method will be that the existing bank will not require extensive excavation. However, some remedial works on the embankment surfaces, particularly the crest, may be required after construction.

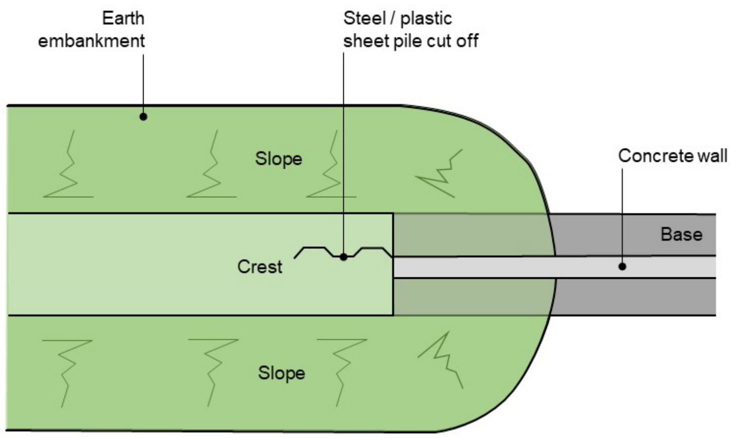


Figure 6.2: Installation of sheet pile to lengthen seepage path – type 1

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects):

- Seepage analysis (with appropriate approved software) to show that the proposed wall extension (toe level and lateral length) is sufficient to reduce or inhibit flow below the toe and around end of wall.
- If jet grouting along a seepage path is considered, it needs to be designed/specified to flow to form the columns without necking or bulging, avoid hydraulic fracturing (partly

design, partly construction related), chemical composition to be suitable for the chemical make-up of the embankment fill, bond to soil and wall and not be damaging to the environment. Note that in current practice it is difficult to control pressures to minimise the risk of environmental contamination.

- The concrete mix design for the secant or diaphragm wall must provide a permeability lower than the surrounding earth embankment, but with properties that allow construction of a quality wall to prevent seepage. This will include all design elements for concrete such as cement and water content, aggregate grade and type, resistance to site conditions, slump measure, cube strength, flexibility, additives and on-site testing.
- If using a diaphragm wall system, careful thought should be given to whether a one-phase or a two-phase construction system is adopted. The benefit of a one-phase system will be that potentially damaging support fluids such as bentonite can be avoided. However, a two-phase system can provide greater flexibility during construction.
- For structural elements such as sheet pile walls, there is a need to check the structural capacity of the system (bending moments/shear forces) in the new wall and to consider how the relatively rigid structure might attract load.
- Consider the effects of the new wall on global stability of the earth embankment and how it may detrimentally change stress concentrations within the earth embankment, leading to potential vulnerabilities and possibly failure that was never originally considered possible. The well-known issues with I-walls in New Orleans provide an example (see ILH box 9.64).
- Decide if grouting is required (or not) between the new and old wall to provide a suitable seal so that the wall extension does actually lengthen the seepage path.

Method 2: Extend earth embankment to lengthen seepage path – type 1

Improvement method

In this method the seepage path is lengthened by extending the earth embankment along the solid wall, both front and back, with the same soil, geometry and vegetation as the existing bank. This will only work for longitudinal transitions with the wall in line with the bank, not across it. When extending the old embankment, surface vegetation and topsoil should be removed from the old embankment and steps should be cut to facilitate compaction of the new fill against the old embankment. Consideration should also be given to roughening up the existing hard wall to facilitate a good bond between the wall and the compacted soil (Figure 6-4).

A main concern for this method is the compaction of the new soil against the existing wall in what is likely to be a confined space working near the water course. The existing bank will require topsoil stripping and the surface to be benched to allow the new soil fill to key in and be placed in layers to achieve suitable compaction. Roughening the exposed wall surface will help adhesion of placed soil. If access is difficult, this will require small compaction plant; see text box 6-7. This issue might even make this method unsuitable.

There may also be a need for a dewatering system to allow work at the toe of the bank where it meets the solid wall base.

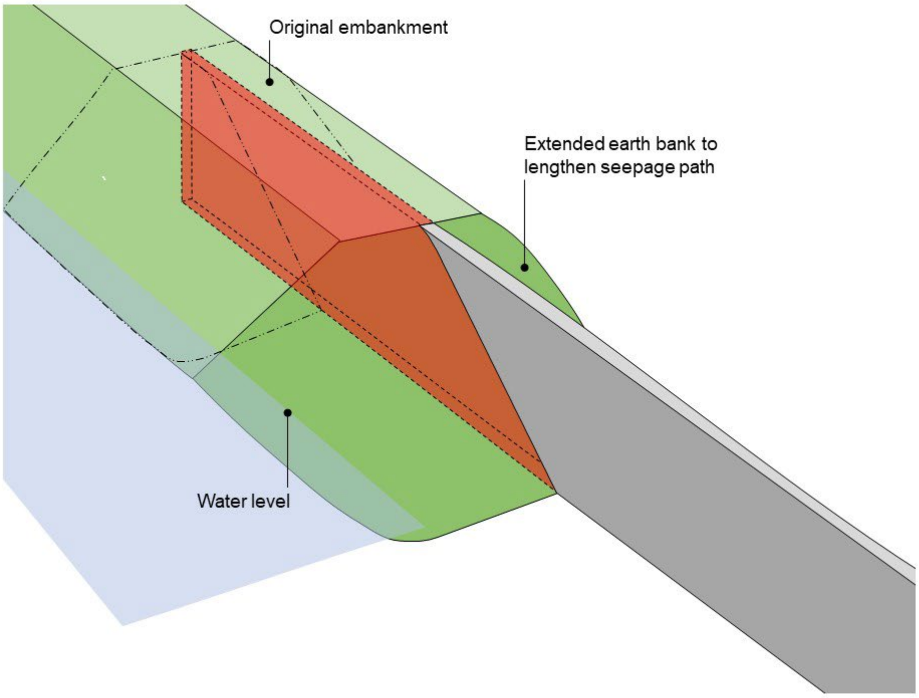


Figure 6.3: Extension of earth embankment to lengthen seepage path – type 1

Figure 6.4: Preparation of the flood wall transition at Comps by roughening up the surface (courtesy of Thibaut Mallet; see ILH Figure 9.66)

Design approach

During the design process, the following elements must be considered specifically for this method (while duly considering all design aspects):

The design should aim to achieve a durable connection that reduces to a minimum the seepage between the soil and the wall for the specified design life with low maintenance. In particular, the likelihood of seepage along the interface between the fill material and the wall should be lower than that of seepage through the fill material itself. Particular steps to be carried out in the design include the following:

1) Analyse the stability of the bank to check that the existing geometry is stable. If it does not meet applicable design standards, then notify the asset owner and decide how to proceed (see principle 7 in section 2.4).
2) The nature and the compaction requirements for the fill material should be carefully specified so as to achieve the design objectives. It is noted that:
    i. soil compacted dry of optimum moisture content (OMC) will be stronger and stiffer than soil compacted wetter of OMC, but its air voids ratio will be higher and so the soil will potentially be prone to collapse settlement and volume change
    ii. if the soil is compacted wetter than OMC, it will be weaker but less prone to collapse on wetting and it will usually form a better connection with the existing wall
3) Consider roughening the existing wall to help adhesion with the soil.
4) The length of the overlap between structure and embankment fill should be assessed using seepage analysis with suitable software to design the characteristics of the wall extension (material type, toe level and length) to check that the overlap is sufficient to reduce flow below the toe and around the end of the wall to acceptable limits.
5) The fill material for the embankment extension should have similar properties to the existing embankment soil for compatibility; if there is a difference, then it is preferable to use soil of lower permeability and with low plasticity and shrinkage potential to avoid future cracking. If suitable material cannot be sourced, then interfaces will be required.
6) Design the required compacted strength and density for seepage control and stability and then produce the specification for its placed properties; compaction needs particular care to achieve good connection with the wall in addition to density and strength. Consider methods for placing and compacting the soil in a reduced space with possibly limited access to achieve the required compaction in safety (text box 6-7). Note that it is better to place and compact fill materials beyond the final surface and then trim back to the final surface rather than trying to compact on a slope.
7) Specify topsoil and revegetation requirements for the embankment extension, considering specific requirements near edges and hard structures (text box 6-6).

Method 3: Demolish wall, install cut-off and rebuild wall – type 2

Improvement method

This solution is relatively invasive and very expensive, so should only be considered if the transition geometry does not allow any of the above solutions to be considered, and if the criticality of the defence justifies the investment. The method involves demolishing the existing flood wall, installing a suitable cut-off through the bank crest and rebuilding the flood wall, making sure a good connection is achieved between wall and cut-off.

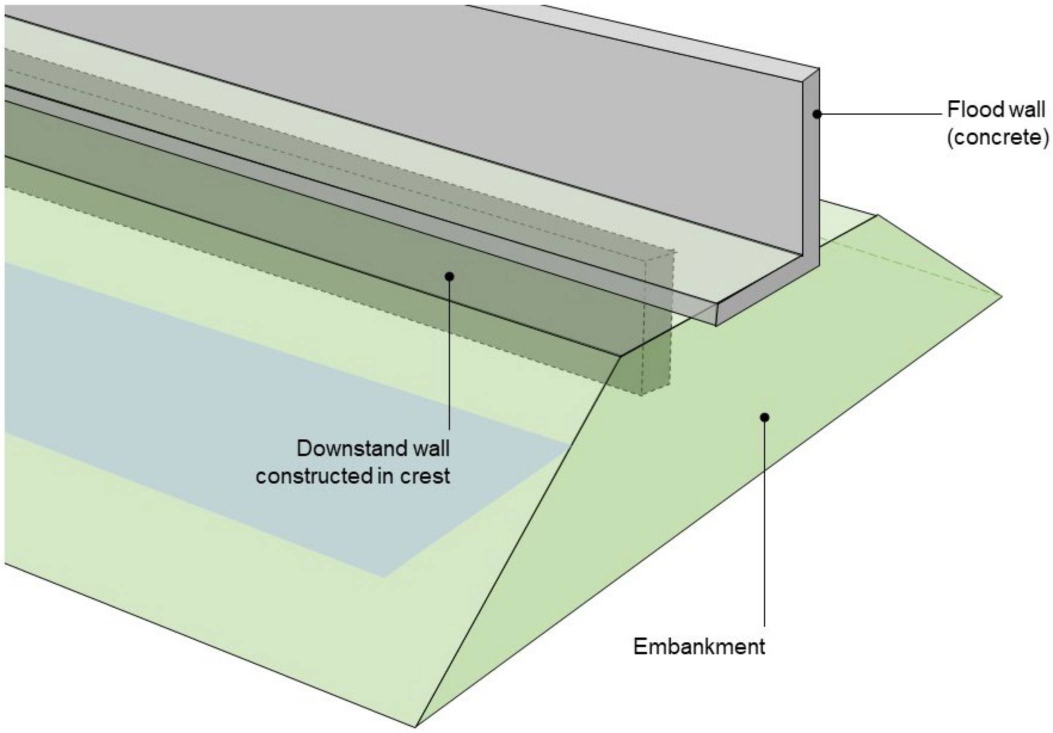


Figure 6.5: Installation of structural downstand – type 2

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects):

- seepage analysis using suitable approved software to check that the downstand wall depth is sufficient to reduce or stop flow below the toe and around the end of the wall
- design demolition process
- design cut-off element to be structurally sound, durable and buildable
- design connection to the hard wall
- design/specify hard wall to be reinstated
- check crest is suitable for cut-off and improve as required

Text box 6-2: Alternative method 3 options – install riverward cut-off at base of wall

This text box describes alternative cheaper and less invasive options compared to method 3. These are only feasible if the crest of the bank is sufficiently wider than the wall base to provide space to install the cut-off on the riverside of the wall. This is required to avoid weakening the top of the bank, which could lead to erosion and a different seepage path without solving the transition impact. This wall could be a diaphragm wall, sheet piles or a contiguous concrete wall and possibly grout/chemical injection. With injection it is difficult to prove sufficient voids have been filled to provide a robust cut-off system, but it may be viable for minor works.

The wall must be connected to the base of the flood wall to prevent a seepage path between the new and old walls. This could be in the form of a concrete capping beam cast around the top of the new wall and dowelled into the existing wall base, but any alternative that seals the seepage path will be suitable.

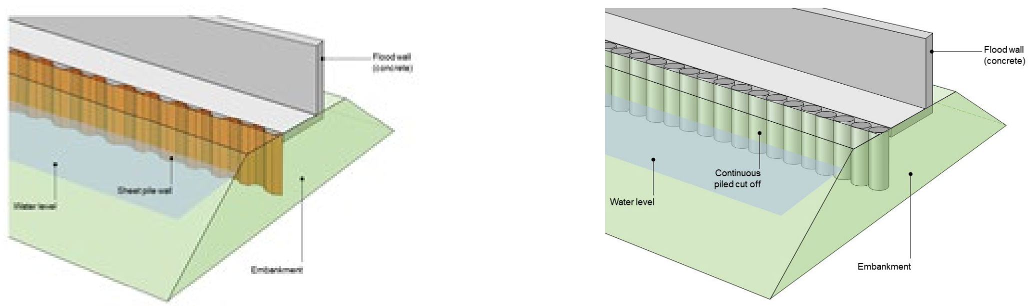


Figure 6.6: Alternative cut-offs – sheet pile wall/contiguous piles

<u>Design approach</u>

The design must account for specifics of seepage under the crest wall (while duly considering all design aspects):

- seepage analysis using suitable approved software to check that the cut-off wall depth is sufficient to reduce or stop flow below the toe and around end of wall
- design cut-off element to be structurally sound, durable and buildable
- design connection to the hard wall base
- check crest is suitable for cut-off and improve as required

Method 4: Install dry side filter – type 1

Improvement method

A filter can be used as a stand-alone solution for transitions with minor issues or if other solutions cannot be used. It can also be used as a secondary method alongside the major solutions described earlier.

The method involves installing a downstream (landward side) filter that can slow or even halt the loss of material from the earth embankment, and so reduce or stop internal erosion and potential failure. The filter can be constructed from modern geofabric filters pinned to the bank surface or the more traditional graded soil layer type filter. The choice will be site-specific when all constraints are considered.

Note that there are caveats for applying filters:

- If filters replace embankment fill they can attract the flow, because they are more permeable than the embankment fill.
- If they are placed externally, they may collect sediment lost through internal erosion, but this will not necessarily stop the internal erosion of the embankment.
- Filters tend to clog up over time so will require monitoring and may require refurbishment or replacement. In particular geofabrics, when clogged up, can lift off the surface.
- In general, filters are difficult to retro-fit to an existing structure.

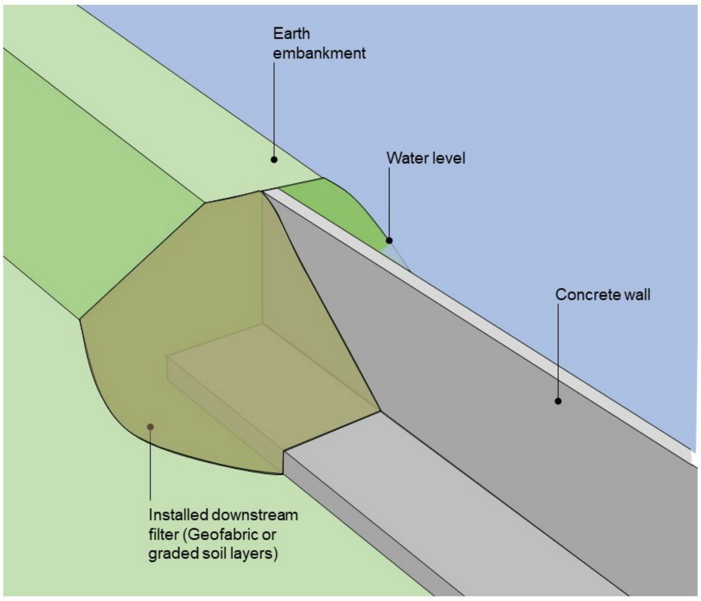


Figure 6.7: Downstream filter – geofabric or graded soil

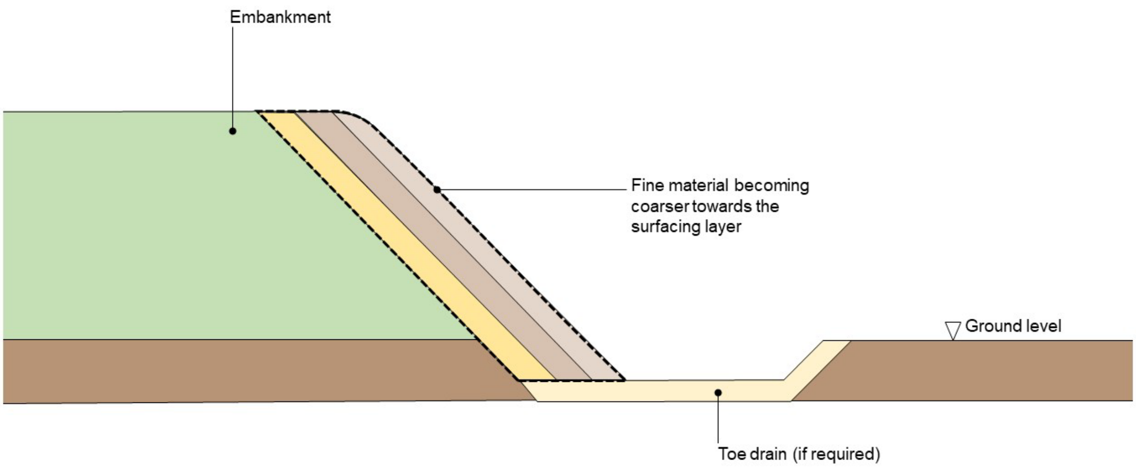


Figure 6.8: Downstream filter cross section - graded soil

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects):

- Filter design to reduce/stop the loss of fines from the downstream (landward) face of the transition. Choice between soil or geofabric filter to be made depending on designer preference, site conditions/constraints and other client/site requirements. The design for a soil filter will need to identify the number of layers, soil grading and layer thickness.
- Consideration of height of filter required to meet all flood levels for the structure's design life and allowing for climate change.
- Consider the need for a downstream toe drain for dealing with any residual seepage through the transition.
- Specify the soil or geofabric identified in the design process and identify method of securing if a geofabric is chosen.
- Specify storage and construction methods to avoid segregation, degradation, mixing and contamination of the individual filter layer soils.

6.3 Geometry – steeper slopes

6.3.1 How does it work and how can it lead to failure?

Why is it a typical transition issue?

Oversteep slopes can occur at transitions due to complex geometry, for example, if the transition has not been considered fully in 3 dimensions. This can cause a situation where slope angles are too steep locally. Transitions are, for example, vulnerable where an earth embankment curves towards a wall, and if poorly detailed or constructed.

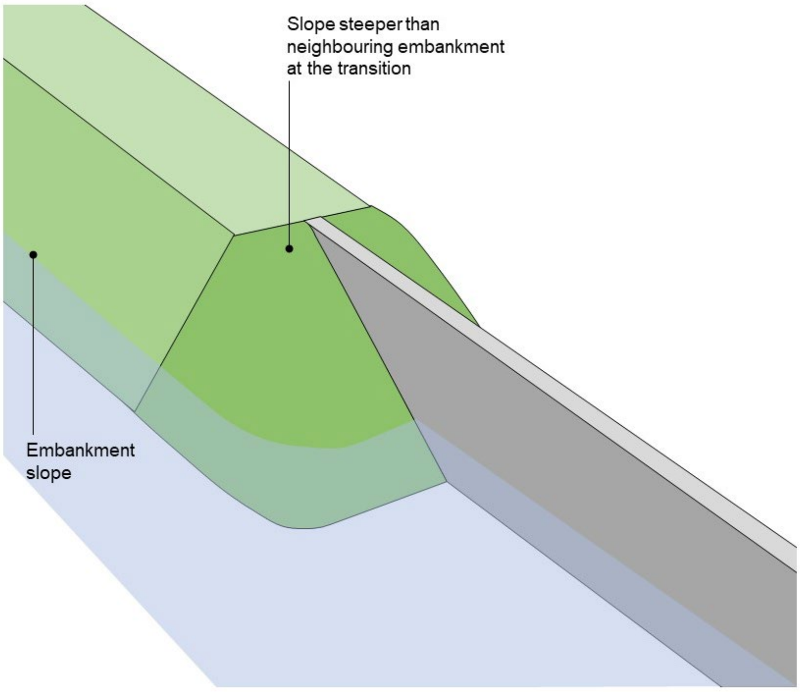


Figure 6.9: Oversteep slopes

How can it lead to failure?

There are 2 ways in which a steeper slope at a transition can cause problems:

Oversteep slopes can lead to surface erosion. This is a risk at both waterward slopes (high flow and waves) and landward slopes (due to overflow, in particular at the toe of the slope). A steeper slope may reduce resistance against erosion but also leads to higher flow velocities, and potentially increased turbulence, which increases the loading. Once the surface has eroded away, the embankment core becomes exposed and this can erode more rapidly, potentially leading to collapse and breach. This has to be considered in combination with the other transition impacts that can cause slope erosion: increase of loading through turbulence caused by irregular geometry (section 6.4), reduced strength caused by impeded root formation (section 6.6), impeded maintenance (section 6.9), rutting (section 6.10) and animal burrows (section 6.11). Surface erosion can also be caused by local rainfall, in which case it acts as a deterioration mechanism. This is normally associated with poor grass swards and/or where surface drainage has not been adequately considered.

A steeper slope can also lead to instability as the upper slope's destabilising force and crest loading exceeds the restoring force of the lower slope. This can cause circular or non-circular failure surfaces to develop within the soil body, potentially leading to collapse and breach. The onset of failure is dependent on the geometry but also the properties of the soil making up the slope. In this case, the possibility of slope instability should be considered, particularly where it can be triggered by hydraulic or geo-hydraulic actions such as overflow and seepage.

To which transition types does this impact apply?

Steeper slopes can occur in transition type 1 (longitudinal) and potentially also type 3 (crossing infrastructure) near the exit/entry point.

6.3.2 Principles for design

How can design increase strength and reduce loading?

The best way of addressing transition impacts is to avoid a transition or move it to a less exposed location; section 5 gives suggestions for each transition type.

If this is not possible, the obvious approach for resolving this transition impact is to slacken the slope. Alternative approaches (possibly in combination) are to increase erosion resistance of the slope and to reduce exposure to flow.

A slacker slope would generally reduce slope instability risk but there may still be factors which might affect the stability of the slope such as seepage or turbulence at the toe of an embankment during overtopping flow. If necessary, residual geotechnical and hydraulic issues can be addressed by reinforcing the toe to resist turbulence, increasing toe weight on the slope, reducing crest load or improving soil strength (developed further in section 6.3.3).

Design issues

Particular design issues for this transition impact include the following:

- Geometry of the transition: It is essential that the slope geometry and its relationship with the hard defence are assessed and fully understood in 3 dimensions, in order to assess the problem and find solutions. 3D images should be produced and this will require detailed and accurate topographic survey data and as-built information about the transition.
- The buildability of a practical design in the area of the transition that is likely to have limited access, slopes and working around the river system, is a challenge. In such cases, the design needs to be robust, erring on the side of caution in terms of geometry and safety factors. Clear communication from the designer before and during the construction stage is also essential, pointing out the critical points in the design.

How to determine acceptable conditions?

Text box 6-1 focuses on accounting for turbulence in hydraulic loading, but also contains references for the generic design methods for slope erosion.

Geotechnical stability needs to be checked in accordance with relevant codes such as EC7, which also provides acceptable Factors of Safety for slopes. This analysis should be carried out for circular and non-circular slips using a proprietary approved software. The analysis must show that safety factors are above the required values in all types of analysis, for example, SLS, ULS1 and ULS2 (see CIRIA, 2014). In the event that the stability of the existing structure is found not to meet existing standards, then the asset owner/manager should be informed and a decision should be made about the way to proceed (see principle 7 in section 2.4).

6.3.3 Improvement methods and design approach

The following potential methods for slope erosion are described below:

1. Slacken slope by removing in situ soils.
2. Slacken slope by placing imported material onto slope.
3. Apply reinforcement locally.

Separate methods are provided in case there is a residual geotechnical instability to address:

4. Reduce crest load.
5. Increase toe weight.

These could be applied individually but also in combination, as identified for each method below.

Most of these methods are largely applicable for flood defence embankments in general. The sections below highlight how to address the specific issues around a transition.

Method 1: Slacken slope by removing in situ soils

Improvement method

In this method soils will be removed from the existing slope to slacken the slope adjacent to the hard defence at the transition and feather into the embankment for a smooth transition.

The slope will need to be revegetated and time to establish the vegetation must be considered in the appraisal of risk and the overall construction process.

This solution is only suitable if:

1. the length of embedded solid wall is sufficient to not affect seepage path lengths

2. the available crest width is sufficient for the slope to be slackened by removal, while maintaining the width required for access

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects).

- Review achievable grass cover quality (considering, for example, access for maintenance) and confirm that this is strong enough for expected loading. Note it is the sub-strait that provides the strength for loading and topsoil provides grass cover.
- Slope stability analysis of remedial option to check that modern codes are complied with for all design cases, for example, SLS, ULS1 and ULS2 and loads, using relevant partial factors in accordance with Eurocode 7 design or equivalent.
- Methods of safely and practically removing soil from the slope suitable for the transition geometry, location, restricted access at transition, working near water. Topsoil should be removed and stored separately and replaced following reprofiling.
- Relay topsoil and revegetate with suitable seed mix and establish grass seed maintenance for effective growth (text box 6-6).

Method 2: Slacken slope by placing imported material onto slope

Improvement method

In this method the existing steep slope adjacent to the hard defence will be stripped of topsoil and benched to allow imported soil to be placed and compacted on the benching at a slacker slope angle. Fill materials will be compacted in suitable layers to a specified improved density and strength compared to existing bank and they should be of similar or better properties to the existing embankment material.

The slope will need to be revegetated. Time to establish the vegetation must be considered in the appraisal and overall construction process.

This option also offers the opportunity to address any seepage and piping issues: the texture of the wall can be changed to improve adhesion with soils as they are placed back on the slope, and water bars could be installed to increase flow paths (see section 6.2).

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects).

- Slope stability analysis of remedial option to check that modern codes are complied with for all design cases, for example, SLS, ULS1 and ULS2 and loads, using relevant partial factors in accordance with Eurocode 7 design or equivalent.
- Methods of safely and practically removing topsoil, importing soil, benching slope and placing/compacting soil suitable for the transition geometry, location, restricted access at transition, working near water.

- Compaction design setting out requirements for smaller plant and possibly hand compaction due to restrictions in space and irregular shaped structures at the transition. The soil classification and required compacted properties need to be defined. See text box 6-7.
- Compacted soils to be feathered into the transition to maintain smooth slopes and curves and avoid any angular corners that may induce excessive turbulence leading to surface erosion (see section 6.4). Note that it is better to place and compact fill materials beyond the final surface and then trim back to the final surface rather than trying to compact on a slope.
- Relay topsoil and revegetate with suitable seed mix (text box 6-6). Note that topsoil should not be compacted.

Method 3: Apply reinforcement locally

Section 6.4.3 describes this method in the context of transition impact 'Turbulence caused by irregular geometry' (Method 4). The method to increase strength is practically the same for these 2 transition impacts, so reference is made to that section.

Method 4: Reduce crest load (to address slope instability)

Improvement method

In this method the crest loading is reduced by a suitable method, such as restricting traffic on the crest, in order to reduce destabilising forces and so improving stability without having to change the slope angle. The exact solution should be defined on a case-by-case basis and should be based on how much improvement in slope stability will actually be achieved.

This method could be combined with other options, in particular additional toe weight.

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects).

- Slope stability analysis of remedial option to check that modern codes are complied with for all design cases, for example, SLS, ULS1 and ULS2 using relevant partial factors in accordance with Eurocode 7 design or equivalent.
- Seed mix for revegetating the slope (text box 6-6).

Method 5: Increase toe weight (to address slope instability)

Improvement method

In this method toe weight is added to increase stabilising forces to improve stability without having to change the slope angle. This could be achieved by adding rock or concrete blocks to the toe. If loss of fines is a concern, a geotextile may need to be added below the rock/concrete. The slope may need to be revegetated if damaged during the works, and the designer needs to consider the impact of making the geometry more irregular.

This method could be combined with other options, in particular slackening the slope by removing embankment material and reducing crest load.

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects).

- Slope stability analysis of remedial option to check that modern codes are complied with for all design cases, for example, SLS, ULS1 and ULS2 and loads, using relevant partial factors in accordance with Eurocode 7 design or equivalent.
- For both rock and concrete, size, type, quantity and source need to be suitable for transition hydraulic conditions (particularly turbulence).
- Methods of safely and practically placing rock/concrete need to be suitable for the transition geometry, location, restricted access at transition, working near water.
- Placement of geotextile should be considered to stop the loss of fines; in addition to normal design requirements, there is a need to consider transition specific issues such as turbulence, restricted working space and lap to neighbouring unprotected slopes.
- Seed mix for revegetating the slope (text box 6-6).

6.4 Geometry – Irregular geometry causing turbulence

6.4.1 How does it work and how can it lead to failure?

Why is it a typical transition issue?

Irregular geometry can occur at transitions and cause turbulence because:

- adjacent hard defences such as walls create hard, angular edges which can cause turbulence, right next to the transition, on the adjacent soft defences
- different assets may have a different geometry and/or the surface is irregular, for example, from a vertical wall to a sloped embankment
- there is often a crest level difference between hard walls and embankments because of different freeboard and/or settlement allowance. If this is an abrupt difference, it will concentrate overflow at the transition

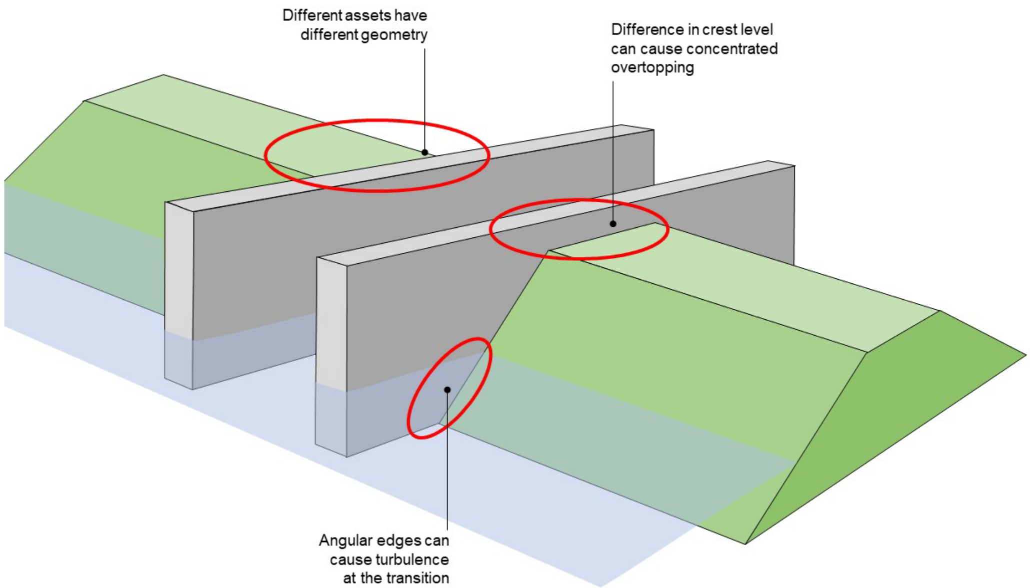


Figure 6.10: Type 1 transition impact areas

Figure 6.11: ILH Figure 9.65 New Orleans levee scour at transition with a flood wall (courtesy USACE)

How can it lead to failure?

An irregular geometry can increase turbulence of local wave/flow action, either along the slope (fluvial flows) or over the crest and onto the landward slope (overtopping flow). If the turbulence increases the loading so that it exceeds a critical level, it can cause external erosion, leading to a loss of embankment material such as scour around a pipe which can then cause instability, damage and eventually breach of the embankment.

To which transition types does this impact apply?

Irregular geometry causing turbulence can occur in all 4 transition types.

Examples

Figure 6.12: Crest level difference that could concentrate overtopping flow onto poor grass near transition, flood storage reservoir at Northenden Riverside Park (River Mersey), 2019

Figure 6.13:Type 1 transition – different assets with different geometries can lead to turbulence, south of Scunthorpe (Tidal River Trent), 2020

Figure 6.14: Gabion baskets applied as toe protection washed away as located at vulnerable point creating irregularities, Butt's Bridge, Leominster 2018

6.4.2 Principles for design

How can design increase strength and reduce loading?

The best way of addressing transition impacts is to avoid a transition or move it to a less exposed location; section 5 gives suggestions for each transition type.

The aim of design is to prevent surface erosion (and potentially resulting slope instability). This means that the flow velocity, including turbulence allowance, has to be lower than the critical value for the surface.

If it is not possible to avoid a transition, there are 2 fundamental approaches for addressing the impact of irregular geometry (developed further in the next section):

- Reducing loading. This can be achieved by reducing the occurrence of turbulence (by reducing irregularity of the geometry) or by reducing the exposure of critical points to turbulence (for example, by moving the transition to a more sheltered location). If the irregular geometry is at the landward side of the defence, then it can be addressed by raising the crest locally to prevent overtopping flow over the irregular geometry.
- Increasing strength: Increase resistance to turbulent flow.

The CIRIA Scour Manual (CIRIA, 2015) provides guidance on erosion due to flowing water and wave action in general.

How to determine acceptable conditions?

Most design methods are based on a normal level of turbulence, such as shown in Figure 6-15. Text box 6-3 gives guidance for taking account of turbulence in design of revetments.

Text box 6-3: Taking account of turbulence in hydraulic loading

ILH section 7.3.7.5 provides guidance on the role of turbulence. It states that many revetment design formulas assume a normal level of turbulence, and where this is exceeded, a velocity correction should be applied as follows:

$u_{eff} = u\ (1+r)$

u_{eff}: calculation value for flow velocity

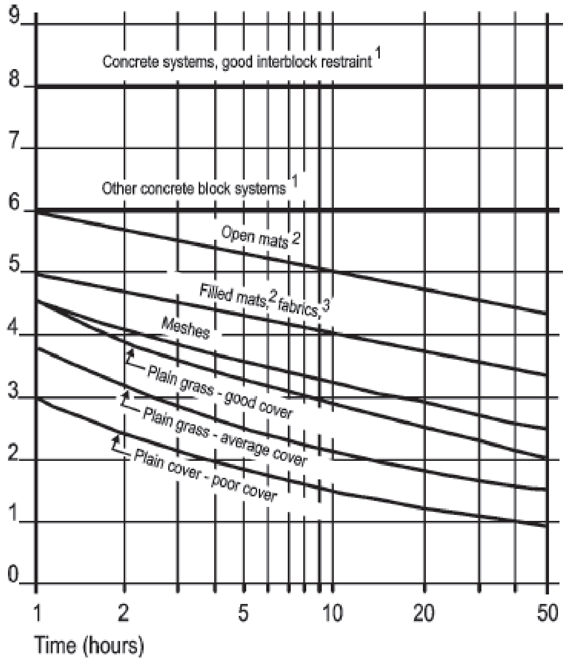
u: local time-averaged flow velocity

r: turbulence intensity

The hydraulic interaction between flow and structures (such as around transitions with complex geometries) leads to a turbulence intensity of 0.15 (15%) as a minimum. ILH does not provide actual values for example geometries. Indicative modelling by HR Wallingford as part of the Transitions R&D project suggests a local velocity increase of 20% to 50% as water flows from an undisturbed channel flow into an overflow between an embankment and a vertical wall.

Figure 6-15 (from CIRIA, 1987) is often used for assessment of erosion resistance of grass slopes. The notes to the graph state that it is based on uni-directional flow; it is not suitable for wave loading or overtopping. Adding 20% to the flow velocity (vertical axis) typically has limited effect on the choice of the option. However if the turbulence intensity is increased by around 50%, then typically stronger options need to be considered.

In rare cases, when the design is very critical and costly, it may be possible to carry out 3D modelling to calculate the turbulence intensity. Normally though, the designer will have to estimate the turbulence intensity based on relatively simple assessments or methodologies; engineering judgement will be critical in these cases. The designer should think through how increased turbulence will affect the performance of the structure in its specific setting and, in doing this, it will often be appropriate to err on the side of caution and select an option at least one level more robust than suggested by standard design graphs (see principle 3 in section 2.4).



Notes

1. Minimum superficial mass 135 kg/m³.
2. Minimum nominal thickness 20mm.
3. Installed within 20 mm of soil surface, or in conjunction with a surface mesh.
4. These graphs should only be used for erosion resistance to unidirectional flow. Values are based on available experience and information contained in Hewlett *et al* (1987).
5. All reinforced grass values assume well-established, good grass cover.
6. Other criteria (such as short-term protection, ease of installation and management, and susceptibility to vandalism) have to be considered in choice of reinforcement.

Figure 6.15: Design graph for revetments, from CIRIA 116 (Design of reinforced grass waterways)

6.4.3 Improvement methods and design approach

Potential methods include:

- reducing loading: reprofile/realign geometry to reduce turbulence
    1. limit exposure to turbulence
    2. remove or alter the structure
    3. reprofile embankment slopes locally by adding or removing fill material
- increasing strength: increase resistance to turbulence
    4. apply reinforcement locally

Method 1: Limit exposure to turbulence

Improvement method

Depending on scale and local setting, it may be appropriate to consider an improvement method that will deal with the cause of the turbulence. This could be achieved by local crest raising; this is discussed in more detail in method 3 of section 6.10.3.

Another option could be to move the transition itself, or the irregular element of it, to a less vulnerable point and therefore have reduced turbulence at the transition. Figure 6-16 shows a case where it would be preferable to move the transition away from under the bridge, so that the soft/hard transition is no longer shaded and it is less exposed to the turbulence caused by the bridge abutments. Figure 6-17 is a case where a long revetment was installed so that its far, downstream end would not be exposed to severe turbulence.

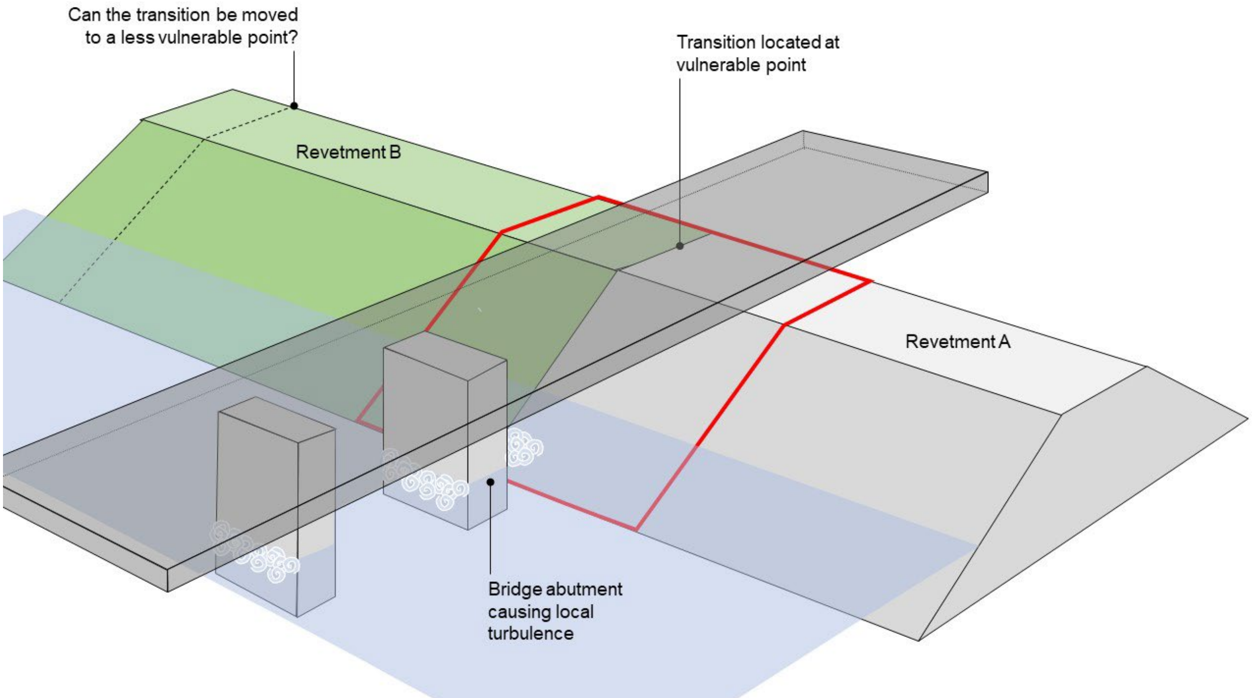


Figure 6.16: Moving the transition to a less vulnerable location

Figure 6.17: Manor Farm, Jubilee River

The irregular geometry could also be prevented by providing a deflector (sheet pile or raised area in front of the embankment) to protect the area that is prone to increased turbulence. When providing a deflector, consideration should be given to the 'new' transition that is being created and any impacts that the proposed solution may cause downstream (for example, on slope stability or surface erosion resistance). Realigning the embankment by partially or fully rebuilding it so that it is not prone to local turbulence could also be considered where the structure affected by scour is critical and/ or expensive to rebuild or, locally protect.

6.4.3.1.1 Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects):

- The expected flow velocity can be estimated through 2-dimensional hydraulic modelling. For more critical, high-value cases, even 3-dimensional hydraulic modelling could be considered.
- Installation method must minimise damage to the existing wall/embankment during construction.
- Consider the effects of the deflector, ensuring that no new weak points or increased loading are introduced locally or elsewhere in the existing flood defence.

Method 2: Remove or alter the structure

Improvement method

It may be possible to remove the geometric irregularity by removing or altering the structure so that it does not cause turbulence. If realistic, the solution would typically involve giving the geometric transition a more regular shape.

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects).

- Assessing the function of the asset that causes the irregularity, and if this function could still be achieved by a more gradual geometry.
- Consider all failure mechanisms when making radical changes to the structure.

Method 3: Reprofile embankment slopes locally by adding or removing fill material

6.4.3.1.2 Improvement method

In some cases, the impact of irregular geometry can be addressed by regrading the slopes of the embankment locally at the transition.

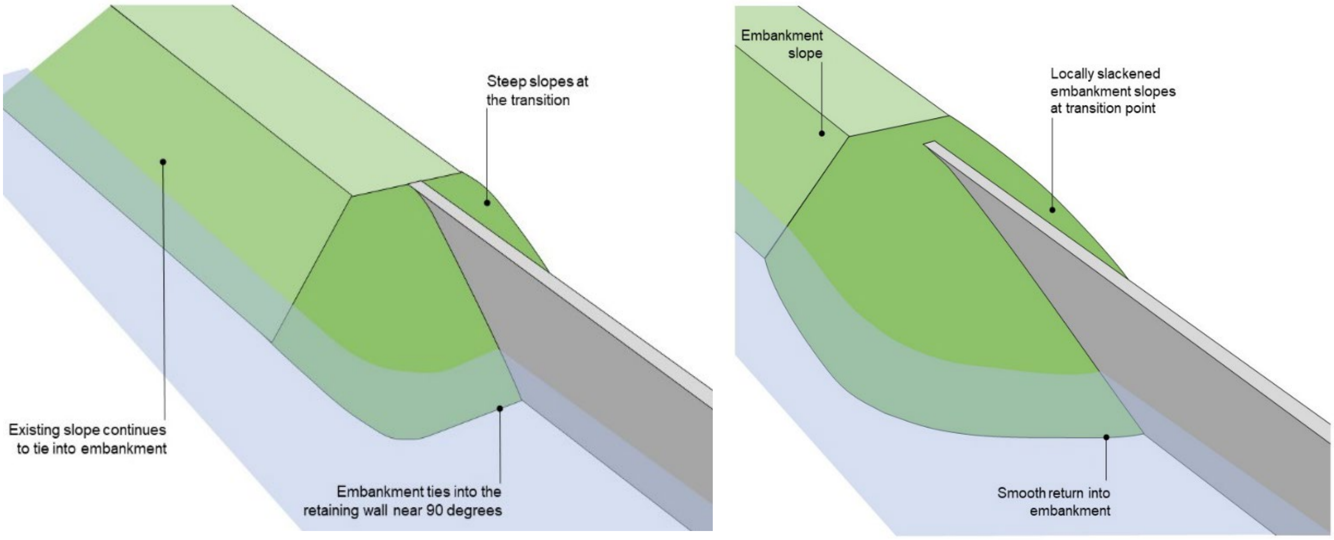


Figure 6.18: Locally slackened slopes at the transition on the right (compared to the left)

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects).

- Assessing the velocity including the turbulence allowance so that the proposed method provides greater resistance values (see text box 6-3).
- Following the approach in principle 7 (section 2.4.1), slope stability analysis of remedial option to check that modern codes are complied with for all design cases, for example, SLS, ULS1 and ULS2 using relevant partial factors.
- Specify soil properties of material to be imported to match or improve on the ground conditions assumed in the slope stability analysis.
- Avoid the streamlining of the embankment profile creating narrow wedges of soil that could be vulnerable to erosion; this could also require local reinforcement (see section 6.4.3).
- Define compaction method and benching requirements to achieve required compaction (see text box 6-7).
- Define placement criteria to achieve required ground conditions from slope stability model.
- Selection of grass seed mix, timing (including time to establish a satisfactory grass sward) and application method (see text box 6-6).

Method 4: Apply reinforcement locally

Improvement method

Where turbulence is likely to remain at the location of the transition or where space is constrained to slacken the slopes of the embankment, local reinforcement of the slope could be considered. Section 6.3.3, method 3 mentions the same method in the context of oversteep slope angles and refers to this section for details.

In some cases, providing a good grass cover could be enough. However, this is typically challenging around transitions (due to shading and impeded root growth (section 6.6) and due to impeded maintenance (section 6.9). This section focuses on additional measures.

Reinforcement options at the toe or along the slope at the transition could comprise (broadly from 'light' to 'heavy'):

- 'soft' reinforcement such as staked willow, faggots and coir rolls
- reinforced grass
- geotextile/matting along the slope of the embankment
- grasscrete blocks along the slope of the embankment
- gabion baskets at the toe of the embankment
- sheet pile at the toe of the embankment
- rip rap at the transition along the slope of the embankment
- rock at the transition at the toe of the embankment
- concrete block revetment along the slope of the embankment
- asphalt along the slope of the embankment

ILH section 9.6 provides further guidance for surface reinforcement measures in general.

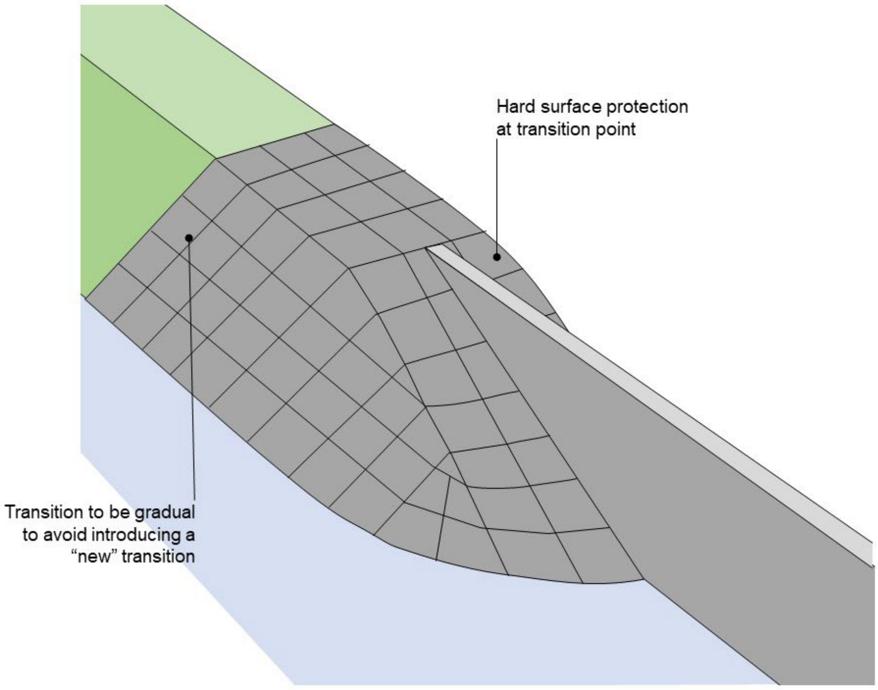


Figure 6.19: Illustration of local reinforcement along toe and slope

Design approach

Text box 6-3 discusses how to take account of turbulence when designing slope reinforcements.

Products are available on the market and should be selected based on the typical considerations for flood defences in general (not discussed in further detail in this guide). For the application at or near transitions with irregular geometry, the following specific considerations apply:

- Products are to be selected depending on the resistance that is required for velocity including turbulence, as discussed in text box 6-3.
- Requirement for a filter should be considered to stop the loss of fines due to turbulence and rapid drawdown. This could be a geotextile, but in some cases, a granular filter is more suitable. The design of the filter will depend on the velocity, including turbulence that it is exposed to, in addition to all normal design considerations for geotextile filters. See section 6.7.
- Buildability in potentially constrained spaces with poor accessibility. This can require a more robust solution (stronger materials, larger overlaps) than on a uniform slope, or pose specific requirements to the flexibility of the materials.
- Maintenance considerations, in particular around constrained spaced with poor access. This can require covering a larger area with the reinforcement so that no mowing is required near hard structures or on complex slopes.
- New/extended surface protection will introduce a new ‘moved’ transition at the end of the reinforcement. The designer needs to consider if this introduces new transition impacts (in principle any of the 11 listed in section 4.2) and address these as required. Solutions with a rougher surface, such as rip rap, rock, gabion baskets, could cause additional local turbulence to neighbouring unprotected slopes. The transition should be gradual. Refer to text box 6-4 for lapping, pinning, tie-in and anchoring considerations for materials such as geotextiles and matting.

Figure 6.20: ILH Figure 3.149 Gradual transition between wide levee and narrow floodwall, New Orleans, Louisiana, USA (courtesy USACE)

Text box 6-4: Geotextile and matting considerations at transitions

The design and placement of geotextiles should follow normal guidance and standards for application on flood defences. This text box sets out specific requirements for the placement of geotextiles at transitions, in particular additional turbulence, placement on slopes with poor access and the need to create gradual, smooth transitions. Note that in some cases, geotextiles are less suitable, and granular filters should be considered (see also section 6.7).

When applying a geotextile, matting or equivalent product significant consideration should be given as to how the materials are being installed, including:

Lap length

Separate rolls (or pieces) of geotextile/mats could have a certain lap length (length that 2 materials overlap). The geotextile lap length/arrangement will be set by the designer based on industry and manufacturers' standards. Lapping geotextiles/matting at transitions should be avoided where possible, as this is the most vulnerable point. If a lap is required at the transition careful consideration should be given to the laps (fully lapped and no gaps), as transitions are generally areas where more stress is anticipated.

Figure 6.21: Insufficient overlap between the geotextiles on toe erosion protection, along north Kent coast, 2020

Pinning pattern

Geotextile or mats usually are to be pinned down to the underlying material. The pinning patterns (frequency and length of pins) will be set by the designer based on industry and manufacturers' standards. The patterns can be influenced by factors such as type of pin, underlying soil material and required pull-out force. At transitions, consideration should be given to an increased frequency of pins to reduce the risk of the geotextile becoming loose.

Tie-in/ anchor detail at the interface

At the end of the geotextiles, they should be anchored into the ground. This is achieved by excavating a trench covering the geotextile sufficiently so that it forms an ‘anchor point’. At the hard defence interface, the common practice is to run the geotextile vertically along the hard structure and bury it in the ground where practicably possible. Specific anchor details for using the products in a flood embankment context should be designed in discussion with the manufacturer, reflecting the specific requirements near a transition (additional turbulence, limited access) and consideration should be given to stronger/ more robust materials at these vulnerable locations.

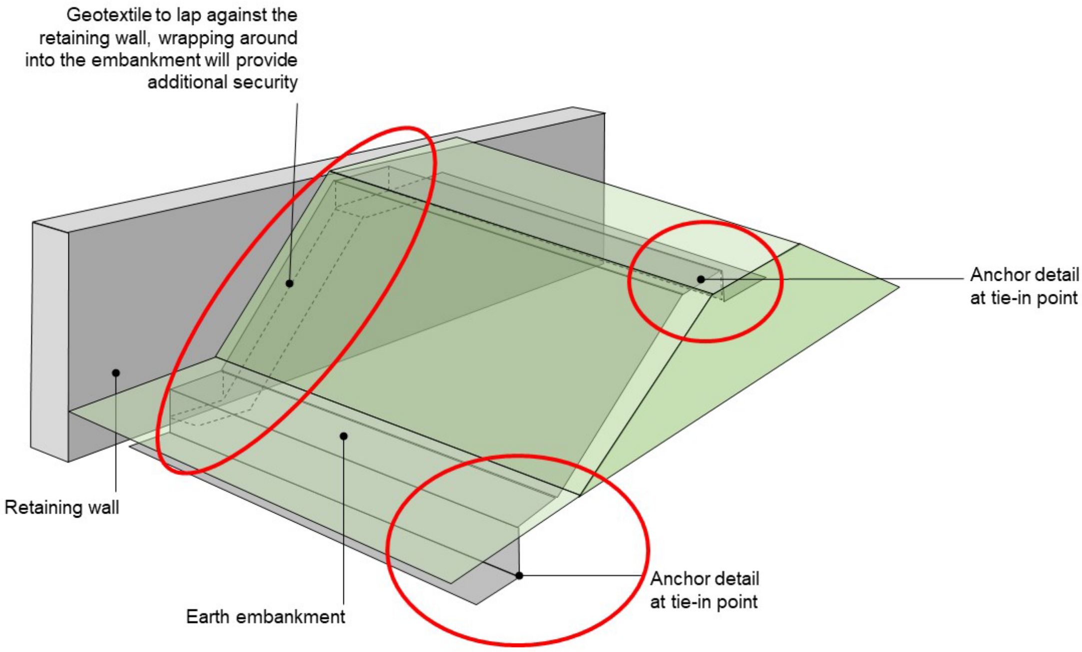


Figure 6.22: Geotextile and anchor points

Tensile strength

It may be useful to consider higher tensile strength geotextile types/materials which will be able to provide more resistance to turbulence.

6.5 Materials behaviour – Hydraulic separation

How does it work and how can it lead to failure?

Why is it a typical transition issue?

Hydraulic separation can occur particularly at transitions where embankment fill materials are placed against a hard structure or where a structure is constructed on the crest of a bank. There is an interaction with stiffness incompatibility (see text box 6-5); the 2 mechanisms are both caused by the difference in characteristics between the 2 materials.

Hydraulic separation can occur when the water pressure at the junction between 2 different materials of low permeability, such as steel and clay, is sufficiently high to separate the 2 bodies; it is a form of hydraulic fracture. This will only occur if the minimum total stress (often horizontal) of the soil acting against the hard wall is exceeded by the water pressure. It can result in the opening up of a hydraulic path around or below the wall section that can then lead to significant seepage and possibly to internal erosion such as concentrated leak erosion.

Text box 6-5: Stiffness incompatibility

The issue of stiffness incompatibility, which caused the catastrophic failures of I-walls in New Orleans during Hurricane Katrina is not discussed fully in this guide in terms of improvement methods, because it is inherent in the design of composite structures. This text box provides some background because it is closely linked to the direct interface between hard structure, and can occur in combination with hydraulic separation.

Stiffness incompatibility is caused by large differences in stiffness between different structural materials, for example, a concrete embedded wall and earth embankment. Under loading, this can lead to a concentration of load on the (higher stiffness) structure and the resulting performance might lead to significant and rapid deterioration. For example, a concrete ‘I’ wall on an embankment crest relies on the passive resistance of the downstream side of the embankment. As illustrated in Figure 6-23, significant displacement may be required to mobilise this passive resistance. This can result in the wall attracting a significant hydraulic load and can trigger instability. An example of stiffness incompatibility concerns the New Orleans I-walls seen in Figure 6-24, where the embedment was insufficient to allow the wall to work efficiently without damaging the bank; this led to seepage washout and failure during Hurricane Katrina in 2005.

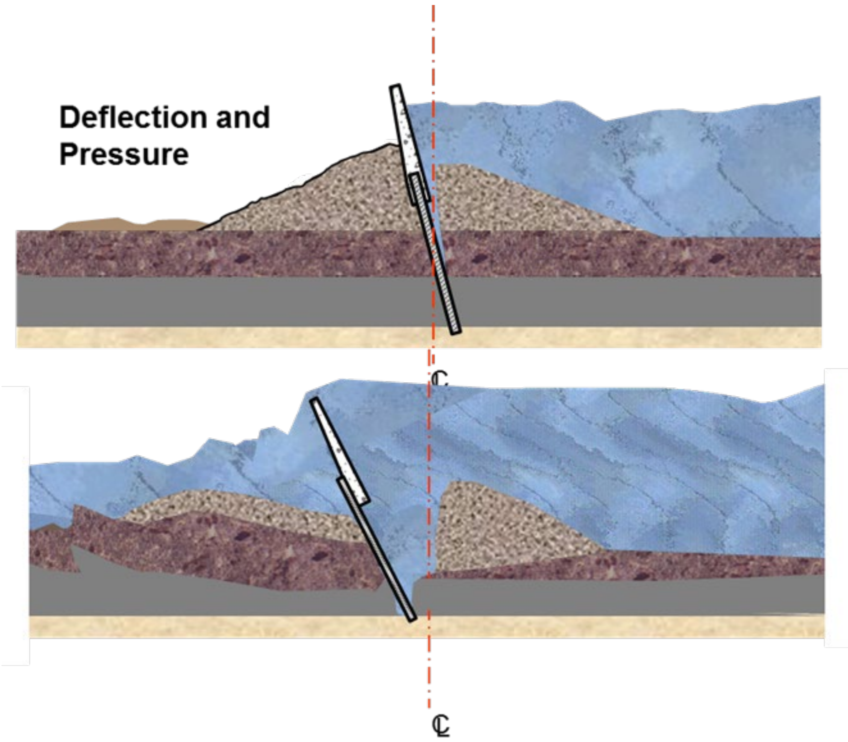


Figure 6.23: Illustration of stiffness incompatibility

Figure 6.24: I-walls failed during Hurricane Katrina due to stiffness incompatibility

How can it lead to failure?

Hydraulic separation shortens seepage paths and this increases the hydraulic gradient that drives seepage. This can lead to failure if other conditions are in place such as high permeability soils and poor compaction. It can lead to excessive flow velocities, which can cause particle movement if a critical hydraulic gradient occurs. This, in turn, can cause internal erosion with possible instability from lowering of soil strength/density. Either of these occurrences can lead to the collapse/breach of a bank.

There is a strong link with transition impact shorter seepage paths (see section 6.2). The physical impact is different, but the resulting failure process, improvement methods and design approaches are very similar.

To which transition types does this impact apply?

Hydraulic separation can affect transition type 1 (longitudinal), type 2 (cross-sectional, wall built on an embankment) and type 3 (infrastructure crossing).

6.5.1 Principles for design

The best way of addressing transition impacts is to avoid a transition or move it to a less exposed location; section 5 gives suggestions for each transition type.

If avoidance is not possible, hydraulic separation can be addressed by the following 2 fundamental approaches (developed further in the next section):

- stop or significantly reduce seepage into the transition
- recompact embankment soils and roughen the wall face (see Figure 6-4) to reduce seepage

Design issues

Text box 6-1 presents a suggested design process for transitions where seepage is the dominant issue. Particular design issues for transition impact hydraulic separation include the following:

- The need to fully understand the transition in 3 dimensions.
- The buildability of a practical design in the area of the transition that is likely to have limited access, slopes and working around the river system, is a challenge. In such cases, the design needs to be robust, erring on the side of caution in terms of geometry and safety factors (see principle 3). Clear communication from the designer to the construction stage is also essential, pointing out the critical points in the design.
- The soil type to be used for methods that require new material must be carefully considered for its particle size, shrinkage potential/plasticity and the maximum dry density versus optimum moisture content relationship.
- The use of a clay plug or grout/resin injection can be considered for this failure mechanism, but this requires careful consideration of the issue of hydraulic separation around the clay plug and proving the injected material has filled sufficient voids to reduce seepage and avoid hydraulic separation.

In particular for type 3 (crossing infrastructure), designers have over the years tried many different solutions, but the issue of hydraulic separation remains a challenge. Applied measures and their challenges are, for example:

- recompacting soils against the infrastructure (with or without flanges) has not always proved to be successful
- putting in baffle plates flanges to increase the seepage path is a challenge because it is difficult to compact the soils satisfactorily in the reduced space
- bitumen which might help to improve the adhesion between embankment fill material and the hard structure can be environmentally damaging
- downstream (landward) filters do not reduce hydraulic fracture on the upstream face

Section 6.5.3 describes a potential measure that uses weaker/softer material to allow ease of compaction which has been used successfully.

How to determine acceptable conditions?

Text box 6-1 sets out the analysis method for seepage related issues. There is little formal analysis that should be carried out for hydraulic separation at a junction, because all that is required from the remedial works is to seal off the possible path for water pressure to overcome the total stress against the hard wall/structure. The seal must be effective because once separation starts, the failure can become progressive and accelerate rapidly.

Analysis of flow around, through and under the transition using a proprietary approved software could be carried out to assess the overall seepage related to the transition and remedial works, but this may not be essential.

6.5.2 Improvement methods and design approach

In general, the methods for this impact are relatively invasive and expensive, which means that the preference for avoiding the transition is an even more important principle in this case (which will then require sealing of the old crossing, see Method 4). Some of the methods for addressing hydraulic separation are the same as for transition impact shorter seepage paths (see section 6.2), because they concern a similar seepage-related failure process.

Potential methods include:

1. Extend the face of the bank (type 1).
2. Install cut-off wall at base of the wall (type 2).
3. Demolish bank and reconstruct with roughened surfaces (type 1 and 3).
4. Excavate to crossing infrastructure and reinstate with clay zone (type 3).
5. Seal crossing infrastructure and divert over bank (type 3).

Method 1 Extend the face of the bank (type 1)

This method is described fully in section 6.2.3.

Method 2 Install cut-off wall at base of wall (type 2)

This method is described fully in text box 6-1 in section 6.2.3.

Method 3 Demolish bank and reconstruct with roughened wall surfaces (type 1 & 3)

Improvement method

In this method hydraulic separation is addressed by demolishing the existing earth embankment, storing/screening the soils ready for reuse, and roughening the hard wall surface at the transition to help adhesion on the rebuilt bank (see Figure 6-4). With the wall surface roughened, the embankment will be rebuilt with the existing soils if suitable or with suitable imported soil, compacted in layers to a specified density, moisture content and safe slope angle. The embankment slope will then require revegetating or other surfacing.

The crest of the transition will be reinstated to its required level.

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects):

- Specify the requirements for the soil to rebuild the bank with low to intermediate plasticity and not prone to shrinkage as this could lead to cracking and further hydraulic separation. This requires soils of suitable plasticity and grading.
- Specify the compaction process suitable for the soil type, transition geometry, limited access and river environment (see text box 6-7).
- System must have sufficient flexibility to cope with the natural movement between the hard and soft elements of the transition.
- Revegetating surface where required due to embankment rebuild (see text box 6-6).

Method 4: Excavate to crossing infrastructure and reinstate with clay zone (type 3)

Improvement method

In this method hydraulic separation is addressed by removing the bank directly around the pipe or other crossing infrastructure for a suitable area to allow a soft to firm clay to be placed around the pipe to form a flexible malleable surround. This surround can then be covered with the general embankment material to rebuild to full height and repair any low spots in the crest.

The soils to be used to seal around the pipeline must be suitable imported soft to firm clays that will allow flexibility but limit settlement above/around the pipeline. The soft to firm clay will need to be placed carefully, probably by hand with small tools to limit compaction, and care then taken to rebuild the bank around the puddled clay material.

The rebuilt section will need to be compacted in layers to a specified density, safe slope angle and condition. The embankment slope will then require revegetation with a suitable fast growing seed mix or other surfacing to minimise erosion at the pipe, match the surrounding area, and transition smoothly into the surrounding embankment face.

The crest of the transition will be reinstated to its required level.

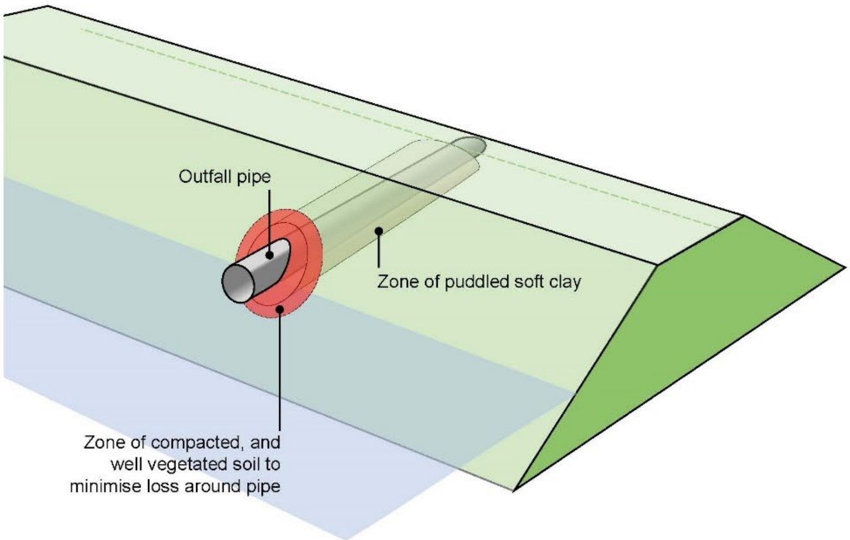


Figure 6.25: Example of soft to firm zone of clay around cross-over

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects):

- Design and specify the puddled clay to provide a material that can be lightly compacted and form a flexible, malleable, low permeability seal of suitable dimensions for the crossing infrastructure. This clay should be intermediate to high plasticity with a suitable moisture content to provide a soft to firm clay. The soil will need sufficient strength to allow compaction and placing of excavated embankment soil above and around it.
- Specify the compaction requirements for the excavated soils to form a stable bank around the soft to firm puddled clay. If the excavated soils are deemed unsatisfactory, then imported fill will be required and this must have suitable low to intermediate plasticity (workable but low crack potential) and grading to reduce the risk of shrinkage that could lead to cracking and further hydraulic separation.
- A trial should be considered to determine the effectiveness of this method and available soils; this is only practical if the area is large enough for a trial to be effective.
- Specify the compaction process suitable for the soil type, transition geometry, limited access and river environment (see text box 6-7).
- Resurface the slope where required due to embankment rebuild. If this includes grass cover (see text box 6-6). This zone must be designed to minimise erosion around the crossing, match adjacent areas and avoid forming another transition zone with risk of associated impacts.

Method 5: Seal crossing infrastructure and divert over bank (type 3)

Improvement method

In this method hydraulic separation is addressed by avoiding the transition; this approach is most relevant for pipelines, in particular for pressurised systems.

It involves the following steps:

- divert the pipe over the bank
- cut back existing pipe or remove completely
- seal internally with a grout or similar fill, allowing flexibility to avoid cracking of the pipe in the future

The bank is rebuilt where the pipe was excavated by placing new embankment material on the front and back face to seal the bank. This zone must be deep enough to provide a seal that is not prone to deterioration or allows excessive seepage to the cut of pipe.

The soils to be used to seal the bank must be suitable imported soil that:

- will avoid shrinkage
- can be compacted in layers to a specified density
- can provide a stable slope angle

The embankment slope will then require revegetation or other surfacing. The crest of the transition will be reinstated to its required level.

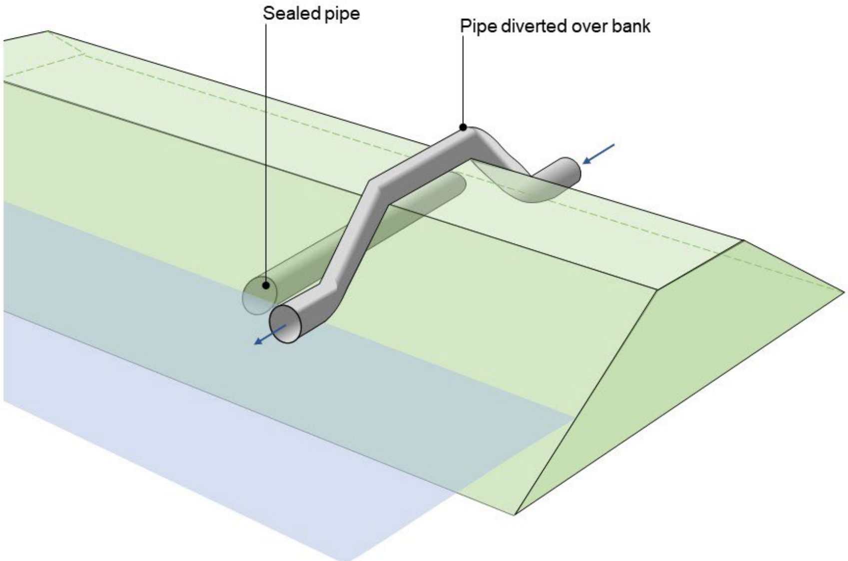


Figure 6.26: Example of cross-over diversion over embankment

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects):

- Design the pipework to extend over the bank taking account of location, operation, maintenance. The location may not allow this solution, so careful consideration is required before choosing this method.
- Specify the soils to rebuild the bank where the pipe has been cut back into the bank, making sure it has suitable low to intermediate plasticity (workable but low crack potential) and grading (not too clayey) to reduce the risk of shrinkage that could lead to cracking and further hydraulic separation.
- Specify the compaction process suitable for the soil type, transition geometry, limited access and river environment (see text box 6-7).
- Revegetating surface where required due to embankment rebuild (see text box 6-6).

6.6 Materials behaviour – Impeded root formation and shading

6.6.1 How does it work and how can it lead to failure?

Why is this a typical transition issue?

Impeded root formation and shading can affect the grass cover of embankments, leading to the increased risk of external (surface erosion). This is particularly problematic at transitions because this is where the presence of hard elements can limit the growth of grass and thereby limit its erosion resistance. This can sometimes be the result of a type of grass used that is unsuited to its environmental conditions; in other words, the ground is too dry, too wet or too compacted for the grass species chosen. If the management regime has been reduced to only allow infrequent cuts with a flail mower, this can also result in the grass and vegetation being cut and the cuttings being left to lie on top of the cut grass effectively as a mulch. This can lead to the grass sward failing, bare areas of earth forming, an invasion by broad leaved weeds and, in some cases, non-native invasives.

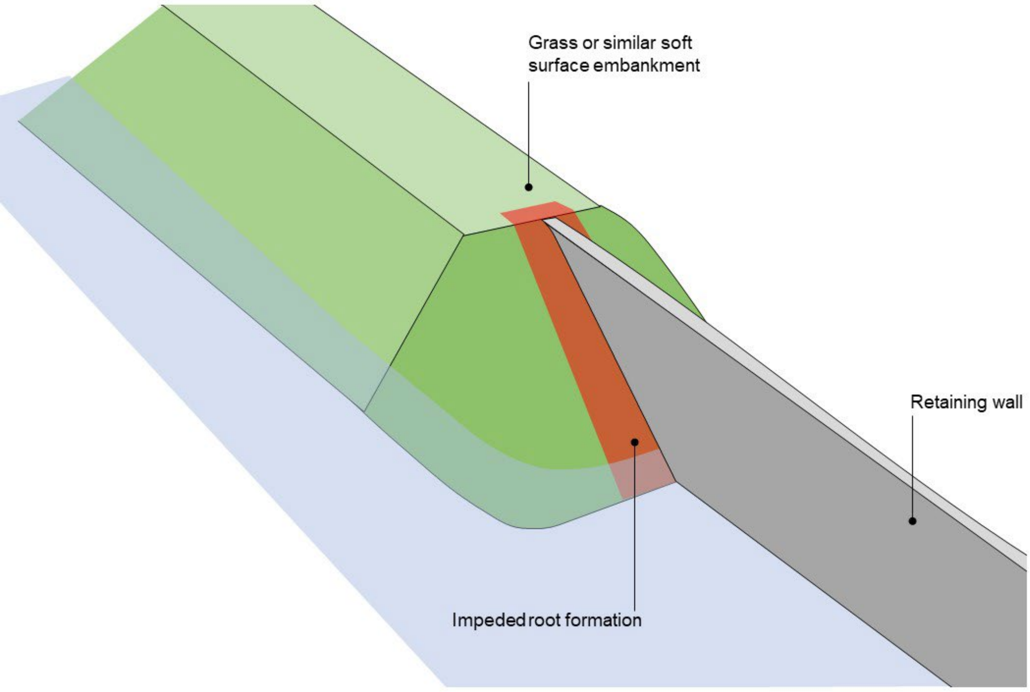


Figure 6.27: Schematic example of impeded root formation at type 3 transition

How can it lead to failure?

Poor vegetation is a deterioration mechanism that can reduce resistance to surface erosion. Transitions are often already more vulnerable due to complex geometries causing turbulence (see section 6.4) and other impacts. Surface erosion can initiate collapse which can ultimately lead to breach of the embankment.

To which transition types does this impact apply?

Impeded root formation and shading can occur in all transition types.

Examples

Figure 6.28: Example of poor grass caused by shading, Alney, 2018

Figure 6.29: Example of poor grass caused by shading and possibly impeded root formation, M180 crossing along Tidal River Trent, 2020

6.6.2 Principles for design

How can design increase strength and reduce loading?

The best way of addressing transition impacts is to avoid a transition or move it to a less exposed location; section 5 gives suggestions for each transition type.

If avoidance is not possible, the issue of root formation and shading can be addressed in various ways (developed further in the next section):

- Reduce the risk of the deterioration mechanism. This is normally best achieved by establishing a bespoke maintenance regime where this issue occurs. In some cases, it may be possible to avoid the need for vegetation management by installing surface protection.
- Reduce the risk of surface erosion during a flood event. This can be achieved by reducing exposure to flow (for example, raising the crest if the transition impact is on the landward side) or by improving the surface's resistance against hydraulic erosion. This also includes repair of any damage that has already occurred.

These methods can be applied individually but also in combination.

How to determine acceptable conditions?

Due to the gradual nature of this impact, the ongoing performance of the improvements should be monitored, with a view to taking further measures if the issue keeps occurring and affecting flood defence performance.

Acceptable conditions of grass for protection against hydraulic erosion are discussed in section 6.3.2.

Text box 6-6: Grass seeding: particular requirements near transitions

A number of transition impacts relate to the loss of grass cover at the transition (caused by shading, impeded root formation, rutting and furrowing), and these can create a vulnerability which could lead to surface erosion in the event of a flood. Maintaining an established grass cover is especially important at transitions because the reduced strength often coincides with potentially increased loading due to turbulence that can be caused by transitions' irregular geometry.

Location and the exposure to these areas should be assessed and it should be determined whether grass-seeding provides the required sustainable long-term solution or whether it is acceptable that a 'monitor' and 're-seed when required' approach is acceptable.

If bare patches at the transitions are being reseeded, the following should be considered:

- area of grass seeding: this needs to include overlap beyond the directly affected areas where the grass is already established
- type of grass seed mix: shade tolerant grass seed mixed will be more suitable to bare patches caused by shading; some seed mixes may be more suitable to certain soil conditions than others
- seeding rate: seeding rate can be increased at vulnerable points such as transitions
- location of the areas to be reseeded and public/animal accessibility (especially where this has been caused by rutting/furrowing or animal burrows at the transition): areas should be fenced off until the grass has re-established, and the asset manager needs to be aware that the soil forms a weak point if a flood event occurs before the grass is established

- if the grass is to establish at an accelerated rate, then different grass seeding methods such as hydroseeding or pre-grown mats or turf could be considered
- timing of the grass-seeding: grass should be seeded when it will establish itself quickest and there is low risk of the grass not growing or being washed away after seeding
- aftercare of the seeded areas: fertilising, over seeding, watering, weed control and cutting are important for the grass to establish itself effectively, and these may need to be strengthened near transitions

To enhance the erosion resistance of plain grass, a geotextile reinforcement can help in protecting/stabilising the surface soil parameters or improve continuity between the grass plants.

Refer to CIRA Design of reinforced grass waterways for further (embankment generic) grass surface design and management guidance (reprint 2003).

6.6.3 Improvement methods and design approach

If the existing damage is not severe, then the preferred method for this gradual deterioration mechanism could be an observational approach: identify a trigger for intervention (for example, size of bare patches) and monitor how the condition develops. Note the warning in section 5 that the designer should carefully consider the risks associated with an observational approach.

Exposure could be reduced by local crest raising if the transition impact is on the landward side; this is discussed in more detail in method 3 in section 6.10.3.

Alternatively, potential methods include:

1. removing the cause of impeded root formation area where possible
2. selecting different types of grass cover
3. changing surface protection material
4. reviewing and amending the maintenance regime

Method 1: Remove or alter the cause of impeded root formation area where possible

Improvement method

If the adjacent structure is affecting grass growth, it will usually not be possible to address this cause. However, there may be exceptions where it is possible to remove or alter the hard structure to avoid this impact. In such a case, there is an obvious need to ensure that the flood defence function of the hard structure is considered in the design.

Design approach

During the design process the following must be considered specifically for this method (while duly considering all design aspects):

- functionality of the hard flood defence structure causing the impeded root formation and whether this can be removed or altered to allow root formation

Method 2: Select different type of grass cover

Improvement method

It may be possible to select a more shade or drought tolerant grass mix to address this issue and re-establish a grass cover that provides protection against surface erosion.

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects):

- selecting the grass mix should be in keeping with and suitable to its surrounding environment
- maintenance is to be considered (including access)

Method 3: Change surface protection material

Improvement method

Grass surfacing at critical transition areas could, for instance, be replaced by local surfacing material that does not rely on its roots to provide cover, such as concrete (blocks) or asphalt. Any alternatives should be able to provide continued protection to surface erosion.

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects):

- Products/materials are to be selected depending on the resistance that is required to be provided when considering other failure impacts (such as turbulence, traffic loading).
- Flexibility of materials is to be considered as the transition is often a complex geometric area (can they be bend/ cut to suit easily?).
- New/extended surface protection will introduce a new ‘moved’ transition at the end of the protection which can influence the behaviour. The designer needs to consider if this introduces new transition impacts (in principle any of the 11 listed in section 4.2) and address these as required. The transition should be gradual.
- Refer to text box 6-4 for lapping, pinning, tie-in and trenching considerations for materials such as geotextiles and matting.
- Maintenance is to be considered (including access).

Method 4: Review and amend maintenance regime

Improvement method

It may be possible to improve grass quality through bespoke vegetation management. For shaded areas this could involve less frequent mowing, keeping the height of cut higher and preferably removing the clippings. Limiting access on the grass may also improve the quality (see section 6.10).

6.7 Materials behaviour – Gaps in filter structure

How does it work and how can it lead to failure?

Why is it a typical transition issue?

Gaps in filters can occur at revetment transitions or on the edge of filters placed at the downstream end of other transitions for managing seepage. The gaps can be caused by differential movement of the revetments or inadequate consideration of the 3-dimensional connection elements, for example, between 2 connecting revetments' filter layers. The impact is more likely to occur in geotextile filters because granular filters do not tend to have hard discrete edges and are less likely to be damaged by impact.

How can it lead to failure?

Gaps in the filter structure can cause loss of fines/fill material or granular filter material from under the top layer. This can cause further movement of facing blocks, and a more progressive failure could start to occur, leading to internal erosion, slope instability and collapse. The loss of filter materials could be described as a deterioration mechanism that causes weaknesses that can ultimately lead to failure.

Gaps in filters can relate to various deterioration and failure mechanisms, influenced by the location on the flood defence and the associated hydraulic loading and function of the revetment:

- On the waterward face, the issues are with wave and current action, seepage into the embankment during a flood and seepage out of the embankment after the flood (rapid drawdown). The surfacing is there to mitigate these effects. The wave and current action can cause facing blocks to be lifted or displaced. It can also damage the filter: lifting/tearing of a geotextile filter, or loss of material from a granular filter. If the filter is damaged, fill material from the underlying embankment can be washed out, leading to localised revetment failure.
- On the landward side of the bank, the facing is there to mitigate the effects of overtopping flow. In addition, it could also be pushed off the embankment surface by seepage pressures during a flood.

To which transition types does this impact apply?

Gaps in filter structure can affect transition type 4 revetments, but also other transition types, where filters are sometimes installed at their landward side for managing seepage.

6.7.1 Principles for design

The best way of addressing transition impacts is to avoid a transition or move it to a less exposed location; section 5 gives suggestions for each transition type.

If avoidance is not possible, then the fundamental approach for addressing the impact of gaps in filter structure is to provide a functioning filter that also prevents loss of soil particles between the revetments. This largely involves following the principles of generic filter design for flood defences. The main principles are that the filter has to retain soil but be sufficiently permeable to avoid excess water pressure build-up. The ILH discusses filter design in its section 9.8.2, with reference to its section 8.5.5 for assessment tools.

Design issues

Particular design issues for this transition impact include the following:

- Identify the issue with the transition, for example, is it loose blocks, loss of soft facing material or just separation of the 2 elements leading to exposure of the underlying filter and/or backfill.
- Design the filter system (geotextile or soil) to be installed below the soft and hard sides of the transition taking particular care that the filter provides the dual functions of preventing the movement of soils from one zone to another within the bank, while allowing some water through to avoid excessive pressure build-up.
- The filter will need a further dual element of design to be compatible with both the hard and soft faced sides of the transition.
- Filters require careful detailing in design, and also much care during placement, and this is even more critical around transitions. The buildability of a practical design in the area of the transition that is likely to have limited access, slopes and working around the river system, is a challenge. In such cases, the design needs to be robust, erring on the side of caution in terms of geometry and safety factors. Clear communication from the designer to the construction stage is also essential, pointing out the critical points in the design.
- Design the front facing across the transition to avoid irregular surfaces with the soil of the soft face level with the top of the blocks on the hard face.
- Filters can be made from geofabrics or from granular material, each with their benefits and disadvantages in terms of cost, layer thickness, durability and functionality.

How to determine acceptable conditions?

The ILH's section 8.5.5 presents assessment methods for soil retention and permeability, covering both granular and geotextile filters.

Once the method and soil properties are defined by the designer, the design will consider the effectiveness of sealing a transition joint against gaps in filter structure by adopting a flexible material in the solution. The acceptable conditions will include the need for an overlap from hard to soft revetments and sealing the edge of the transition to avoid water inflow and potential uplift.

Filter requirements depend on the grain size and nature of the soil that needs to be retained and the exposure of the revetment to hydraulic loading. Around a transition it would be prudent to take a conservative approach for external erosion; however, this is difficult for the filtration properties as this requires a careful balance between the needs of capturing the soil particles while avoiding pressure build-up.

Due to the gradual nature of this impact, the ongoing performance of the improvements should be monitored, with a view to taking further measures if the issue keeps occurring and affecting flood defence performance.

6.7.2 Improvement methods and design approach

If the existing damage is not severe, then the preferred method for gradual loss of fines could be an observational approach: identify a trigger for intervention and monitor how the condition develops. Alternatively, the filter could be improved and reconstructed.

A potential method includes:

1. reconstructing filter to overlap the transition

Method 1: Improve localised filter and seal transition

Improvement method

The gap in the filter structure can be remediated by installing a filter system that will allow water to flow at low velocities but avoid the loss of fines from the revetment backfill. The filter could be granular material or geofabric depending on site conditions.

When the facing blocks from the hard revetment and the soil are removed to carry out remediation, there may be the need to replace any fill material lost due to backfill washout in the localised area. Finally, the soil and blocks are relayed/replaced and with the soil placed over the edge of the blocks to form a suitable localised seal. See Figure 6-30.

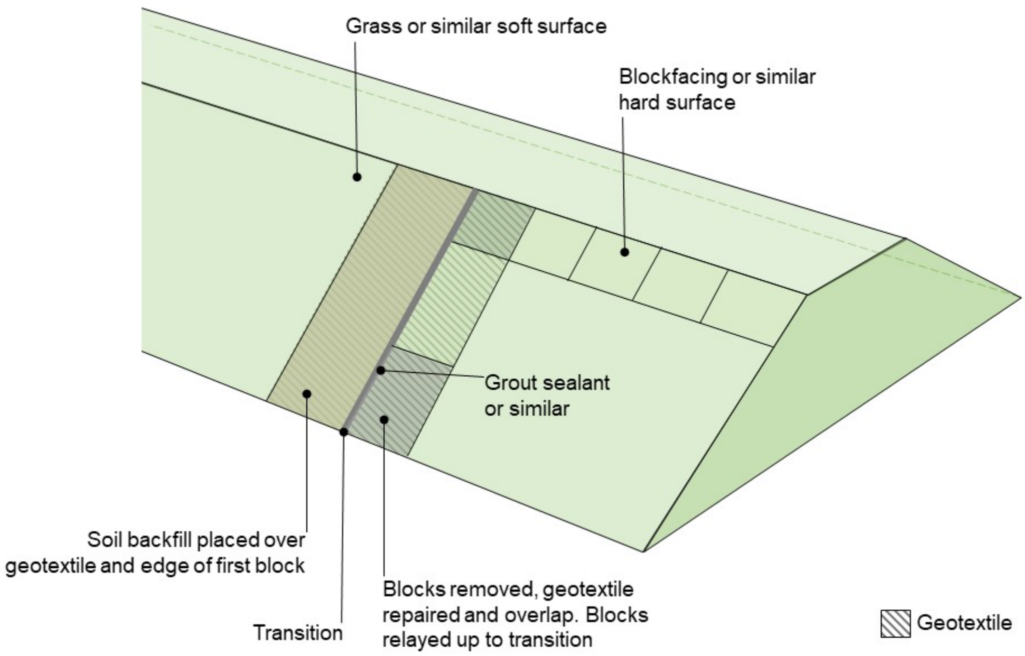


Figure 6.30: Improvement of gap in filter structure for revetments

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects):

- The filter must have sufficient overlap to avoid detrimental water flow but allow low velocity seepage with no loss of fines. The filter must also be flexible enough to deal with differential movement across the transition.
- The filter must have sufficient thickness to address the possibility of loss of soil and exposure of the filter.
- Avoid irregular shapes to reduce turbulence and reduce/remove uplift pressures by setting into the backfill across the transition to obtain an adequate seal.
- Fill should be workable on the slope, considering any access constraints. Specify compaction details for this material (see text box 6-7).

6.8 Construction and maintenance – Poor compaction

6.8.1 How does it work and how can it lead to failure?

Why is it a typical transition issue?

Poor compaction can occur at transitions because the complex geometry requires non-standard approaches, and limits access for plant.

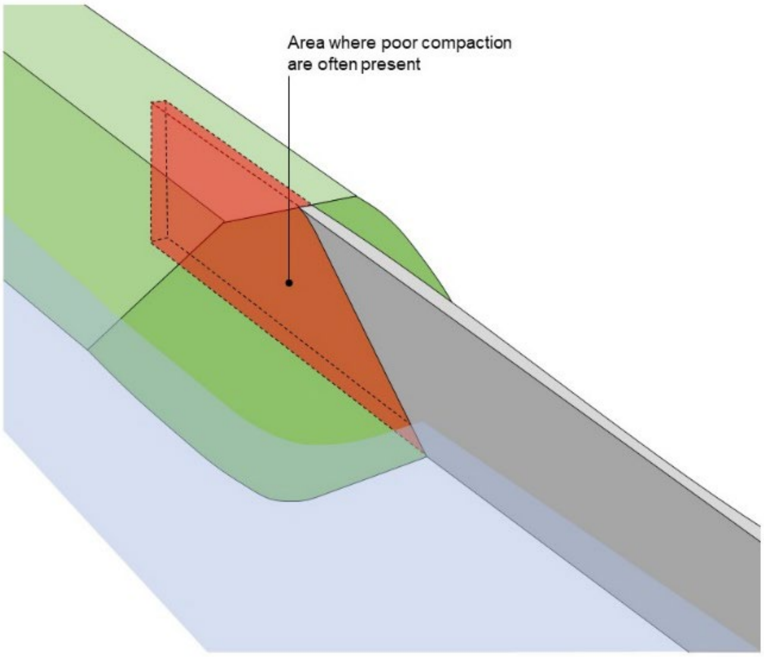


Figure 6.31: Poor compaction at transition

How can it lead to failure?

Poorly compacted soils can be subject to significant volume changes as a result of hydraulic compaction, particularly when the fill material is inundated for the first time. This can lead to localised settlements in the vicinity of the poorly compacted material and potentially to overtopping flow as a result.

Poorly compacted soils can also create pathways for seepage around a hard wall or a pipe/cable, causing an increased risk of internal erosion through suffusion and backwards erosion. This, in turn, can lead to loss of fill material around the structures, settlement of the crest and eventually to collapse and breach. High water pressures in the soil can also increase the risk of uplift or slope instability.

Finally, loosely compacted soil is less resilient to ongoing hydraulic erosion following surface erosion. The combination of these mechanisms can lead to rapid deterioration and potentially to breach during flood conditions.

To which transition types does this impact apply?

Poor compaction around the transition can affect any transition, but in particular types 1, 3 and 4.

Figure 6.32: Embankment collapse (possibly poor compaction coupled with seepage – FEMA

Figure 6.33: Failure due to transition, possibly caused by poor compaction FEMA 484

6.8.2 Principles for design

How can design increase strength and reduce loading?

The best way of addressing transition impacts is to avoid a transition or move it to a less exposed location; section 5 gives suggestions for each transition type.

If avoidance is not possible, the fundamental approach is to improve the compaction, taking special care to consider transition-specific constraints related to access.

Design issues

Text box 6-1 presents a suggested design process for transitions where seepage is the dominant issue. Particular design issues for improving compaction at a transition include the following:

1. For poor compaction the 3D effects of the transition must be carefully considered as limited site access (under structures, steep slopes), irregular shapes, directional changes limiting plant size, slopes and working near water will make compacting to specified densities a challenge during construction.
2. The design should aim to avoid smooth surfaces along the interface with soil where possible, limit placing soils under structures, limit irregular shapes, avoid small areas and try to leave access for different types of plant to complete compaction as required. Production of 3D images will help with this, as will early contractor involvement to discuss types of plant and compaction.
3. The design must set out any benching requirements for the existing embankment that will be in place as the base to build the transition from.
4. Consider other transition impacts related to seepage and take the opportunity to address these if possible; in particular short seepage paths (section 6.2) and hydraulic separation (section 6.5).
5. The buildability of a practical design in the area of the transition that is likely to have limited access, slopes and working around the river system, is a challenge. In such cases, the design needs to be robust, erring on the side of caution in terms of geometry and safety factors. Clear communication from the designer to the construction stage is also essential, pointing out the critical points in the design.

How to determine acceptable conditions?

In principle, for issues such as stability, standards such as EC7 should be followed as appropriate. However, as indicated in section 2.4, in some cases this may not be achievable because the neighbouring structures may not fully comply with current design codes. If this is the case, then the issue should be discussed with the asset owner. In this situation, it may be appropriate to design structures so that the transition is simply less likely to fail than the neighbouring structures.

For compaction, assessment and testing methods are described in text box 6-7.

Text box 6-1 sets out the analysis method for seepage related issues. To set the limits, the hydraulic gradient (hydraulic head/length of seepage path) must be low enough to reduce the inter particle forces so that soil cannot start to move and lead to internal erosion. Therefore, the longer the path the better the solution, but physical site constraints may require a compromise.

Analysis should be carried out for flow around, through and under the transition using a proprietary approved software. Where appropriate, this should be supported by spreadsheets or flow net hand calculations to verify computer output. As stated in text box 6-1, the seepage analyses should be carried out for flow through the soil; the works carried out along the interfaces between structure and soil should be carried out with the objective of making seepage along that interface less likely than that through the soil.

For slope stability, analysis can be carried out in accordance with relevant codes such as EC7, which provides acceptable Factors of Safety for slopes. Analysis should be carried out for circular and non-circular slips using a proprietary approved software. The analysis must show that safety factors are above the required values in all types of analysis, for example, SLS, ULS1 and ULS2. The analysis will require all soil properties relevant to slopes, for example, strength and density, slope geometry, loads and hydraulic conditions.

6.8.3 Improvement methods and design approach

The details of improvement methods will be location specific. In some cases, it will be preferable to use existing embankment soil, while in other cases soil will need to be imported. The design and management will be mostly the same as for flood defence embankments in general, and that is not addressed in this guide. There are, however, transition-specific aspects around compaction, which are summarised in text box 6-7.

A preferred approach in dam engineering is to make sure that the hard surface is battered away from the vertical, so that when the soil is compacted (in layers) against it, the compaction effort tends to facilitate a wedge effect which drives the soil more tightly against the hard surface.

It is important to note that over-compaction can prevent or stunt grass growth, leading to increased erosion risk. This is often because of over-compaction during construction and decompaction measures to a suitable depth and extent not being carried out prior to hand-over of assets. There’s a fine line between preserving the compaction level of the soils on engineering grounds and permitting an adequately open soil structure to permit drainage and root penetration for the formation of a good, dense root system and resulting grass sward.

Text box 6-7: Compaction of soil on embankments against hard structures and complex geometries

It can be difficult to properly compact fill material around complex 3D geometric structures. In this case, careful consideration should be given to the construction sequence; for example, place soil first and then install sheet piles through the fill (which might help compaction see section 6.8), or place a wall first and then place the soil (in which case it should be possible to create surfaces which are amenable to having soil placed and compacted against them). The tools/plant used to achieve the compaction around transitions must also be considered. Layer thicknesses may also need to be adjusted to achieve the required compaction and this may vary at different locations around the transition and will be type dependent. In any case, trials will probably be needed to identify compaction methods that produce appropriately conditioned fill materials.

The tools/plant required may consist of larger rollers as normally adopted for earthworks if space and access allow, but more likely will be the walk-behind vibratory plates (wacker plates), the small vibratory rollers (smooth or sheep's foot) and/or drop weight compactors as described from the Specification for Highway Works (SHW) (see Figure 6-34). To assess the required thickness, plant and passes, a trial around the transition must be considered to help identify the optimum methods for the particular transition type. The trial will need to be at the transition and not remotely as the overall transition geometry will be as important as the plant and passes.

Figure 6.34: Tools for compaction in areas with limited access

The Specification for Highway Works, Clause 612 highlights the following: "Dropping weight compactors are machines in which a dead weight is dropped from a controlled height using a hoist mechanism and they include self-propelled machines with mechanical traversing mechanisms capable of compacting soil in trenches and close to structures."

The rollers/plates must be in motion when the compaction system is engaged to avoid digging in effects when stationary, and local over-densification.

The compaction target levels must be set out by the designer. This includes the need for reference compaction tests identifying the maximum dry density versus optimum moisture content with associated air voids along with the natural moisture content of the proposed soil. The target level of compaction and the moisture content at the time of compaction must be set to achieve the required competence of the fill material, including a suitable target defined as a percentage of the maximum dry density (as standard or modified value) and the required moisture content. For hydraulic structures, it would be usual to compact material on the wet side of the optimum moisture content (OMC) to keep the air voids ratio low (~5%).

In addition, the soil source must be tested for particle size and plasticity to check on shrinkage potential and associated vulnerability to future cracking.

Where areas of the embankment at the transitions are to be rebuilt, it is important to excavate beyond the extent of the transition impact (rutted area, poorly compacted area, eroded surface area) so that the transition impact is not simply moved to the end of the improvement works. It is good practice to create an integrated connection with the existing asset; this can be achieved, for example, by benching into the existing asset (along the slope) or providing a key along the crest and compacting the soil in defined layer thickness (up to 250mm). In addition, an overlap zone from the new to old bank should be included and this should be at least 600mm wide to achieve a competent joint and not inadvertently introduce another weak zone. As placement and compaction are carried out, there should be regular accurate surveys to keep control over geometry and layer thickness.

Similarly, in situ tests should be carried out as the works proceed (for example, field density tests - sand replacement, core cutter or nuclear method) to confirm the required compaction has been achieved. Hand vanes can be used to check undrained shear strength in cohesive soils. At vulnerable areas (such as transitions) consideration should be given to increasing the frequency of in situ testing beyond that which would normally be adopted for earthworks.

Two types of specification are commonly used; performance and method. Each has advantages and disadvantages, but for transitions it would be advisable to use a performance specification to allow more control of the end product, while allowing the contractor to choose the relevant plant for the limitations of the transition site.

6.9 Construction and maintenance – Impeded maintenance

6.9.1 How does it work and how can it lead to failure?

Why is this a typical transition issue?

The presence of transitions can impede maintenance because transitions often have complex geometries and sharp angles that are more difficult to access than uniform slopes and can limit visibility. A change of ownership or asset management responsibility can also cause access issues, and occurs more typically at transitions. This could lead to reduced maintenance causing unacceptable vegetation growth. It can also lead to bare patches.

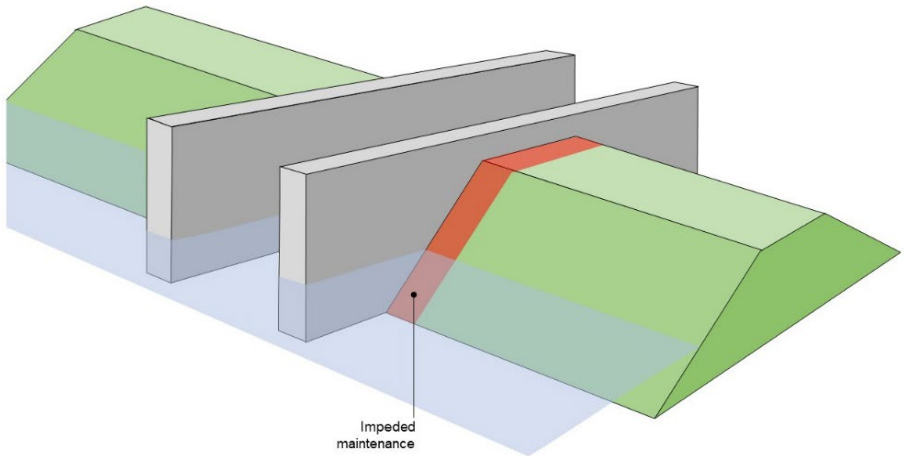


Figure 6.35: Typical area of impeded maintenance

How can it lead to failure?

Impeded maintenance can lead to deterioration mechanisms related to poor vegetation cover, and this reduces resistance to surface erosion. Transitions are often already more vulnerable due to complex geometries causing turbulence (see section 6.4) and other impacts. Surface erosion can initiate collapse which can ultimately lead to breach of the embankment.

To which transition types does this impact apply?

Poor maintenance practices due to access and visibility can occur in all transition types.

Examples

Figure 6-36 and Figure 6-37 provide examples where maintenance plant is unable to get too close to the hard/soft defence interface to control the grass. It is important for the grass growth to be controlled to monitor and inspect the flood defences. In this instance, herbicide was sprayed to maintain the area and while this keeps the vegetation low, it also causes poor grass cover at the hard/ soft interface which poses a risk to the performance of the transition.

Figure 6.36: Example of impeded maintenance causing vulnerability to surface erosion, Victoria Park Warrington, 2019

Figure 6.37: Example of impeded maintenance causing vulnerability to surface erosion, south of East Ferry (Tidal River Trent), 2020

6.9.2 Principles for design

How can design increase strength and reduce loading?

The best way of addressing transition impacts is to avoid a transition or move it to a less exposed location; section 5 gives suggestions for each transition type.

If avoidance is not possible, the issue of impeded maintenance can be addressed in various ways (developed further in the next section):

- Reduce the risk of the deterioration mechanism. This is normally best achieved by establishing a bespoke maintenance regime where this issue occurs. In some cases, it may be possible to reprofile the slope or otherwise change the geometry to improve access, or to avoid the need for vegetation management close to the structure by installing surface protection.
- Reduce the risk of surface erosion during a flood event. This can be achieved by reducing exposure to flow (for example, raising the crest) or by improving the surface's resistance against hydraulic erosion. This also includes repairing any damage that has already occurred.

These methods can be applied individually but also in combination.

How to determine acceptable conditions?

The aim is to design a solution that is practical to maintain, and this requires direct engagement with those responsible for maintaining the defences.

Due to the gradual nature of this impact, the ongoing performance of the improvements should be monitored, with a view to taking further measures if the issue keeps occurring and affecting flood defence performance.

Acceptable conditions for protection against hydraulic erosion is discussed in section 6.3.2.

6.9.3 Improvement methods and design approach

If the existing damage is not severe, then the preferred method for this gradual deterioration mechanism could be an observational approach: identify a trigger for intervention (for example, size of bare patches) and monitor how the slope's condition develops. Note the warning in section 5 that the designer should carefully consider the risks associated with an observational approach.

Alternatively, potential methods include:

1. limiting maintenance - changing surface protection
2. improving and maintaining continued access and visibility at transitions
3. reviewing and amending maintenance regime

Method 1: Limit maintenance - change surface protection

Improvement method

For areas that require maintenance, such as grassed embankments that require frequent mowing, alternative surfacing could be considered that requires no or less maintenance. Any alternatives should provide protection to hydraulic surface erosion and meet specific transition requirements mentioned in the bullet points below:

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects):

- Products/materials are to be selected depending on the resistance that is required to be provided when considering other failure impacts (such as turbulence, traffic loading).
- Flexibility of materials is to be considered as the transition is often a complex geometric area; it may be necessary for the materials to bend easily, and/or be cut to suit.
- New/extended surface protection will introduce a new 'moved' transition at its end. The designer needs to consider if this introduces new transition impacts (in principle any of the 11 listed in section 4.2) and address these as required.
- Refer to text box 6-4 for lapping, pinning, tie-in and anchoring considerations for materials such as geotextiles and matting.
- Produce appropriate maintenance regime with changed surface protection.

Method 2: Improve and maintain continued access and visibility at transitions

Improvement method

Adequate access and visibility at transitions should be created and subsequently sustained at the transition to allow maintenance.

Elements that prevent this should be identified and removed or maintained (cut down/ trimmed) where possible. For instance, where built up vegetation prevents access to the transition, this should be cut down/trimmed and continued to be done on a regular basis to enable continued access. If there are permanent or temporary structures that prevent access, then it should be considered whether these can be moved or changed to allow better access. In some cases, it may be possible and justified to reprofile the slope to improve access – see section 6.3 for design considerations. For instance, setting hard materials slightly below the grass so maintenance equipment has access to all of the grassed surface.

Design approach

During the assessment of maintaining access and visibility at the transition, the following must be considered specifically for this method:

- impact of trimming/removing vegetation on adjacent areas that prevent access for maintenance
- impact of changing/moving structures or reprofiling the embankment slope in order to improve access for maintenance

Method 3: Review and amend maintenance regime

Improvement method

During the pilot carried out as part of this project, a number of areas were identified along the sides of concrete wall stems that were not maintained due to accessibility – where the grass mower could not get close enough to the stem. Instead of grass cutting, spraying was carried out; this prevents excessive growth, but can also kill the vegetation and create bare patches that will be prone to surface erosion. (see Figure 6-37). The following alternatives could be considered:

- smaller grass mower equipment (mower/strimmer), which has better accessibility to areas
- less aggressive herbicide (less concentrated)
- Growth retarders
- Species specific herbicide
- Targeted application (i.e. not spraying)

Design approach

During the assessment of the alternative maintenance regime, the following must be considered specifically for this method:

- for alternative spraying techniques the detrimental impact on the surroundings should be assessed
- ideally, alternative mowing techniques should be considered for the application for the whole asset where possible (to minimise different tool requirements), as long as the duration of the task does not become unacceptably longer

6.10 Preferential traffic paths causing deterioration – Rutting and furrowing

6.10.1 How does it work and how can it lead to failure?

Why is it a typical transition issue?

Traffic of vehicles, people and animals is sometimes more concentrated on embankments at transitions because adjacent hard defences such as walls are often not accessible or fenced off, which can lead to preferential use right next to the transition, on the adjacent soft defences. This also includes areas that are robustly fenced off for health and safety reasons, as illustrated in Figure 6-40. Local rainfall can compound this impact, by preferentially flowing in ruts once they have formed. The resulting loss of grass cover at these locations leads to the surface being more vulnerable to external erosion during overflow events. The presence of fences can also directly cause turbulence and related impacts (see section 6.4).

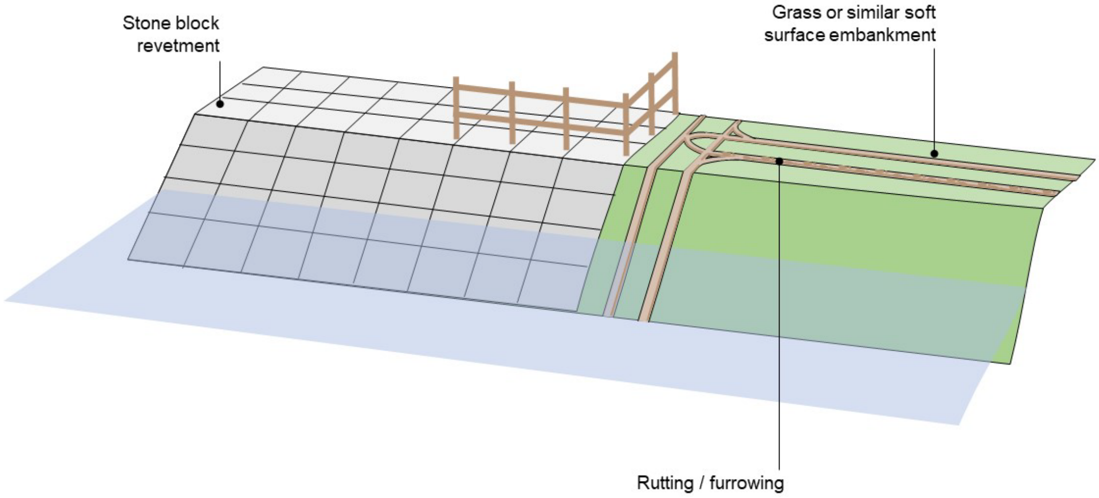


Figure 6.38: Schematic example of rutting and furrowing transition impact

The impacts of rutting on performance or the measures to address it are largely not fundamentally different from flood defence embankments in general. There are a few transition-specific aspects however, which are the focus of this section of the guide:

- increased turbulence affecting design of surface protection
- buildability can be impeded if geometry is complex and space is limited
- need to prevent introducing a new transition at the edge of the improvement

How can it lead to failure?

Preferential paths (or rutting) created by pedestrians, vehicles and animals are a deterioration mechanism that can damage the surface. This can make slopes and crest more vulnerable to surface erosion during flood events, which can ultimately lead to collapse and breach. If damage is at the crest and severe, it can also directly reduce the crest height, increasing the chance of concentrated turbulent overtopping flow during an exceedance event.

To which transition types does this impact apply?

Preferential traffic paths are most likely to occur in transition type 1 (longitudinal) and type 2 (cross-sectional), although they can also occur of type 3 (crossing infrastructure) and type 4 (revetments).

Examples

Figure 6.39: Rutting and furrowing on embankment crest, Leominster (River Lugg), 2017

Figure 6.40: Handrail and restricted access on to the structure has promoted preferential path alongside the steps (likely due to downhill cycling), Fletcher Moss Park (River Mersey), 2019

Figure 6.41: Preferential path alongside landward slope at overgrown transition near Scunthorpe (Tidal River Trent), 2020

Figure 6.42: Preferential path alongside timber post and rail fence and gate, Kirkby Wharfe, 2021

6.10.2 Principles for design

How can design increase strength and reduce loading?

The best way of addressing transition impacts is to avoid a transition or move it to a less exposed location; section 5 gives suggestions for each transition type.

If avoidance is not possible, rutting can be addressed in various ways (not fundamentally different from flood defence embankments in general) as follows:

- reduce the risk of the deterioration mechanism. This can be achieved by reducing exposure to traffic or by improving the surface's resistance against traffic wear

- reduce the risk of surface erosion during a flood event. This can be achieved by reducing exposure to flow (for example, raising the crest locally so that the initial overtopping flow occurs in a more controlled way and in a less vulnerable area, while avoiding this creating new transition impacts) or by improving the surface's resistance against hydraulic erosion. This also includes repairing any damage that has already occurred

These methods can be applied individually but also in combination.

How to determine acceptable conditions?

With regard to minimising deterioration, there are no firm quantitative rules for the relationship between traffic volume and erosion resistance, but the specifications of surface protection products typically do include type and frequency of usage.

Due to the gradual nature of this impact, the ongoing performance of the improvements should be monitored, with a view to taking further measures if rutting keeps occurring and affecting flood defence performance.

Acceptable conditions for protection against hydraulic erosion is discussed in section 6.3.2.

6.10.3 Improvement methods and design approach

If the existing damage is not severe, then the preferred method for this gradual deterioration mechanism could be an observational approach: identify a trigger for intervention (for example, depth and extent of rutting relative to crest height or size of bare patches) and monitor how the condition develops. Note the warning in section 5 that the designer should carefully consider the risks associated with an observational approach.

Alternatively, potential methods include:

- reducing deterioration: reducing/limiting traffic using the crest and the slopes of the embankment
    1. limit traffic using the crest of the embankment
- increasing strength: increase resistance to traffic using the crest and the slopes, and/or to hydraulic erosion
    2. repair depressions and ruts locally
    3. create surplus height on crest or slope (overfilling) (this method can also reduce exposure to overtopping flow)
    4. install surface protection on embankment crest or slope

Method 1: Limit traffic using the crest and slope of the embankment

Improvement method

Depending on scale and local setting, it may be appropriate to consider an improvement method that will deal with the cause of the preferential paths (rutting and furrowing). It may be possible to avoid future rutting and furrowing by limiting or preventing pedestrians, animals and vehicles on the embankment surface (crest and slopes). This can be achieved by installing fences or signage. It may also be possible to avoid concentration of traffic, again by careful use of fences and signage, or by offsetting fencing from the physical transition. It may be more difficult to achieve improvements for 'illicit' traffic than for authorised traffic. Note that in practice, this will often have to be combined with other measures, especially to address any damage already incurred. It is also important to consider the risk that this approach simply moves the rutting to a different location.

Design approach

During the design process the following must be considered specifically for this method (while duly considering all design aspects):

- availability, practicality and acceptability of alternative routes for pedestrians, animals and vehicles

Method 2: Repair depression and ruts locally

Improvement method

This method only deals with the symptoms, so it should normally only be applied in combination with methods that also address the cause (see method 1 above) or a sacrificial buffer should be applied (see method 3 in Section 6.10.3) .

Section 4.8 of the ILH sets out methods for repairing ruts for embankments in general. These also fully apply to transitions.

It is important to ascertain the area and the depth of the ruts so that the mitigation measures fully cover the affected area. It is preferred to over-excavate the area that is affected by rutting (for example, some distance beyond, both in surface area and depth) to ensure that the rutting is sufficiently covered.

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects).

- Fluvial freeboard guidance R&D Technical report W187, AM Kirby and JRV Ash if the crest height levels have to be reviewed in line with the latest water levels, climate change and freeboard allowance. Note that if the neighbouring defences do not meet this guidance, then this needs to be discussed openly with the asset owner, and the design goal may be to ensure that the transition is not the weakest link (see principles 1 and 7 in section 2.4).
- Selection of grass seed mix, timing and application method. Refer to text box 6-6 for grass seeding considerations.

Method 3: Create surplus embankment surface (overfilling) on crest and/or slopes

Improvement method

If the appearance of the grassed surfacing of the embankment is to be maintained, adding sacrificial material to the slopes and/or crest by overfilling slightly (for example, adding sacrificial fill material/topsoil to increase the level and width temporarily to allow for future rutting) could be considered to allow for potential future surface erosion and crest height degradation.

The surplus slope and crest raising should be determined based on exposure and envisaged time until the next intervention.

It is important to avoid this improvement creating new transition impacts. Longitudinally, the sacrificial fill material should be feathered (gradually transitioned) into the adjacent embankment outside of the area that is used by pedestrians/vehicles. Geotextile could be incorporated to provide more resistance.

Any additional sacrificial material on the slopes is likely to result in an increase of embankment footprint.

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects).

- Fluvial freeboard guidance R&D Technical report W187, AM Kirby and JRV Ash if the crest height levels have to be reviewed in line with the latest water levels, climate change and freeboard allowance. Note that if the neighbouring defences do not meet this guidance, then this needs to be discussed openly with the asset owner, and the design goal may be to ensure that the transition is not the weakest link (see principles 1 and 7 in section 2.4).
- Selection of grass seed mix, timing and application method, in particular considering the particular requirements next to a hard structure, and overlap with the adjacent unaffected surface to avoid moving the transition impact on.

Method 4: Install surface protection on embankment surface (crest and/or slopes)

Improvement method

If a more robust measure is needed or insufficient space is available, surface protection could be considered at the crest and/or slopes, at the transition point or for a certain length. This could be a light product (such as grass/turf reinforcement or a ground reinforcement system, for example, cellular paving/paving grid) or a harder option such as concrete blocks, armour stone or asphalt paving. This option should be considered in combination with repairing the depression and ruts. The choice between hard and light surface protection depends on expected hydraulic loading, access requirements (including whether vehicles are expected) and visual requirements.

Any transition into the neighbouring embankment or slopes should be tied into the adjacent asset.

With the installation of any surface protection, it is imperative to consider that it does not introduce a new transition and associated impacts at the end of the reinforcement. If this is not avoidable, the transition should be gradual, and should be 'anchored', lapped and pinned down (depending on the applied product). Refer to text box 6-4 for further information on lapping, pinning and anchoring in of geotextiles.

Design approach

During the design process the following elements must be considered specifically for this method (while duly considering all design aspects).

- Products are to be selected depending on the resistance that is required to be provided for the envisaged loading, including required purpose, frequency of use and type of load (pedestrian or vehicular).
- ILH section 9.6 lists the general characteristics of surface protection systems in table 9.11.
- Flexibility of materials is to be considered as the transition is often a complex geometric area (can they be bent or cut to suit easily?).
- New /extended surface protection will introduce a new 'moved' transition at its end. The designer needs to consider if this introduces new transition impacts (in principle any of the 10 listed in section 4.2) and address these as required. The transition should be gradual.
- Tie-in details should be in accordance with manufacturers' recommendations. These should be gradual, lapped and anchored to avoid introducing a new sharp transition with similar negative impacts, refer to text box 6-4 for geotextile and matting considerations.

6.11 animal burrows

6.11.1 How does it work and how can it lead to failure?

Why is it a typical transition issue?

Animal burrows are sometimes more concentrated in embankments at transitions because adjacent hard defences are generally not accessible for animals. As a result, the density of burrows can be amplified on the adjacent soft defences.

Figure 6.43: Animal burrows at transition with headwall, Tide Mills, Sussex, 2021

The impacts of animal burrows on performance or the measures to address them are not fundamentally different from flood defence embankments in general.

How can it lead to failure?

Animal burrows are a deterioration mechanism that can lead to a range of failure mechanisms: they can cause crest height degradation and they can (a) initiate seepage and internal erosion (b) encourage surface erosion due to the loss of grass cover and (c) increase pore pressures triggering slope/mass instability.

To which transition types does this impact apply?

Animal burrows can occur anywhere, but their density can be increased particularly at type 1 transitions (longitudinal).

6.11.2 Principles for design

The best way of addressing transition impacts is to avoid a transition or move it to a less exposed location; section 5 gives suggestions for each transition type.

If avoidance is not possible, but the existing damage is not severe, then the preferred method for this gradual deterioration mechanism could be an observational approach: identify a trigger for intervention and monitor how the condition develops.

In terms of interventions, addressing animal burrows is not fundamentally different at transitions than in flood defence embankments in general. They can be addressed by reducing the risk of the burrows themselves, or reducing the risk of the associated failure mechanisms, and repairing any damage that has already occurred. The methods and associated design approaches are not transition-specific, and have therefore only briefly been discussed in this guide.

6.11.3 Improvement methods and design approach

If the existing damage is not severe, then the preferred method for this gradual deterioration mechanism could be an observational approach: identify a trigger for intervention (for example, number/density of burrows) and monitor how the slope's condition develops. Note the warning in section 5 that the designer should carefully consider the risks associated with an observational approach.

The ILH (in its section 9.12.3) describes methods for repairing animal burrows and for incorporating barriers to animals. They are generic for flood embankments and therefore not described in detail in this guide, but are applicable for all relevant transition types:

1. limit animals from accessing the embankment
2. fill animal burrows locally
3. partially rebuild the embankment
4. structurally cut-off the burrows (for example, by installing piles to a level below the burrows, or an impassible layer such as a mesh along the slope – only to be applied after backfilling of the borrow)

References

CIRIA, 1987. Design of reinforced grass waterways. CIRIA C116, London, 1987.

CIRIA 2014. *Application of Eurocode 7 to the design of flood embankments*, CIRIA C749, London, 2014

CIRIA, 2015. Manual on scour at bridges and other hydraulic structures, second edition. CIRIA C742, London, 2015.

CIRIA, MINISTRY OF ECOLOGY, USACE, 2013. The International Levee Handbook, CIRIA, London, UK (ISBN: 978-0-86017-734-0). www.ciria.org.

ENVIRONMENT AGENCY, 2009. Fluvial Design Guide. December 2009.

ENVIRONMENT AGENCY, 2012. Condition assessment manual. Managing flood risk. Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2017. Modernising FCRM Asset Management. Our FCRM Asset Management Strategy 2017-2022. LIT10657, 26 April 2017.

ENVIRONMENT AGENCY, 2022b. Transitions in flood defences – Guide to identify need for improvement. May 2021.

ROYAL HASKONING, 2008. Technical analysis of defence failures, Summer floods 2007. 9T0505, 29 April 2008

ROYAL HASKONING, 2010. Cumbria 2009 Floods: Asset Performance Analysis. 9V7718, July 2010

ROYAL HASKONINGDHV, 2016. Technical analysis of defence performance, Winter floods 2015-2016. PB5045, December 2016.

TOURMENT, R., ROYET, P., MORRIS, M., 2015. Comprehensive report on Action 3.1.2: Structure transitions. Report number WP03-01-12-10. 1 FloodProBE (www.floodprobe.eu).

Acronyms

AIMS – Asset Information Management System

EIA – Environmental Impact Assessment

ILH – International Levee Handbook

FCRM – Flood and Coastal Risk Management

FCERM – Flood and Coastal Erosion Risk Management

FRAM – Flood Risk Asset Management

O&M- Operation and Maintenance

OMC – Optimum Moisture Content

SLS- Serviceability Limit State

ULS1 – Ultimate limit state 1

ULS2 - Ultimate limit state 2

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