WP 3: Reliability of Urban Flood Defences

Structure Transitions

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Disclaimer

Summary

This report details work undertaken to investigate and clarify the role that transitions within and between structures have on overall structure performance. Overall conclusions from this work can be found both in this report and in FloodProBE Report D3.1 Guidance on improved performance of urban flood defences (FloodProBE Report No. WP3-01-12-11); this report provides a more detailed assessment of transitions, which underpins those wider conclusions.

Historically, much attention has been paid to analysing the performance of flood defences, and in more recent years numerical modelling has provided a tool for the analysis of overall flood risk (system risk analysis) arising from the simulation of complex river channels and flood defence structure performance. However, whilst these models incorporate measures of flood defence structure performance, they rarely consider the risks to overall performance posed by transitions between and within the flood defence structures. This report highlights that these risks are varied in nature and can be a significant factor contributing to failure.

This report initially provides an introduction to the problem of transitions, followed by a wide range of examples from both within the EU and wider internationally. A typology is then presented, providing a means for describing any and all types of transition structure. This is followed by a series of 9 templates – each describing a different type of transition, highlighting the physical processes, problems caused, potential solutions and case study examples. Finally, conclusions as to the current understanding and state of knowledge and practice regarding transitions are provided, along with recommendations for the focus of future research to address our current gaps in knowledge and practice.

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1 Problems linked to structure transitions

1.1 Introduction

Most levee failures that are not caused by overtopping or overflowing are related to internal erosion, in one form or another (see FloodProBE Task 3.1.1 and chapter 3 of this report). It can be estimated, that more than half of these internal erosion problems are linked to some form of transition in the levee. This has been demonstrated through the analysis of various flood event case studies.

Other problems possibly leading to failure can also be related to transitions, as shall be seen later in this document.

It can also bee seen that it is invariably difficult to analyse the causes of a breach after the event, given the typical level of destruction of the area. Furthermore, most reports and analyses about past events tend to categorize the cause of breaches in a limited way, generally through a list of mechanisms, while a more modern and analytical approach to the analysis of levee breaches (ref. ILH) examines breaches as the consequences of a chain of mechanisms; these chains can be referred to as scenarios. As more than one mechanism is typically at work during a breach, it is possible that the same breach could arise from different "causes": one mechanism can hide another one. Hence, some problems caused by internal erosion or other transition related problems may have been attributed to other causes, and in particular to overflowing (see the River Aude case study).

Whilst we refer to problems arising at transitions, it should be recognised that the specific mechanisms (particularly the different types of internal erosion) can occur on one or other side of the transition, as well as specifically at the transition point.

Hence, the subject of transitions is of particular importance for levee systems. It is even more relevant in urban flood defence systems, as it is more common to find frequent variations in flood defence structures in urban areas and specific structures in or near levees in urban areas that are not directly linked to the levee or flood protection structure.

Structures associated with levees can also cause risk and asset management problems since the owner/manager of a structure can be different from the levee owner/manager. In this case the structure is called an ENCROACHMENT. This situation can cause problems for efficient inspection and maintenance, and hence can restrict effective assessment and management of the levee safety.

Transitions can be studied and described in terms of:

- the failure modes they can be related to,
- if possible, the limit state equations, fragility curves, performance curves or indicators linked to these failure modes,
- the geotechnical problems linked to these transition types or failure modes, in order to be able to propose mitigation and/or remedial measures,

- the possible means of detection of unknown transitions,
- the possible means of detection of a problem occurring,
- the characterization of the structure,
- the characterization of the transition.

Solutions for improving the management of transitions can be proposed in terms of:

- management of the encroachments: organisation (coordination) of the management of the levee AND the structure,
- inspections (pre, during or post flood),
- assessment methods (in some cases this may lead to a need for further research, as we might not have a complete knowledge of the processes involved),
- improvement works (decide between rebuild/remove/act on the soil or act on the structure, propose technical options).

1.2 Typical problems linked to transitions

Processes that are usually called "failure modes" for a levee are in fact scenarios. In these, different physical mechanisms, affecting one or more parts (components) of a levee, follow each other, causing degradation or destruction of one or more components, and so the failure of one or more of the elementary functions of the levee. Finally, the levee itself fails, by breaching or by letting uncontrolled water into the protected area. Failure modes are commonly named from the leading or originating mechanism; for example, overtopping, external erosion, sliding etc.

This process is shown schematically in Figure 1.1 below which illustrates failure scenarios as chains of events including mechanisms, deteriorations and degradation/failure of functions.

This shows that the first mechanisms of a failure scenario are initiated by external conditions or actions on the levee. A mechanism can then result in the deterioration or damage of one or more components. Subsequently, component deterioration or damage results in the degradation or failure of one or more functions, associated to the said component(s). Degradation or failure of a function then leads to an unwanted mechanism appearing or being aggravated.

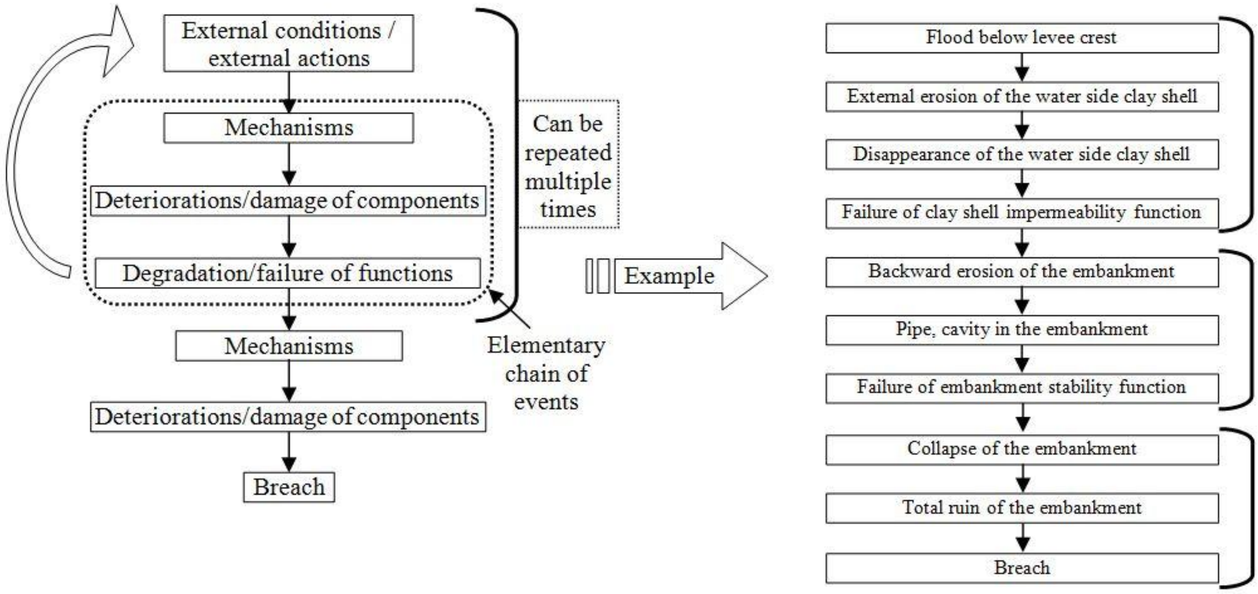


Figure 1.1 Breach scenarios (International Levee Handbook, Rémy Tourment)

The main family of mechanisms that may lead to failure seems to be erosion at a transition area (embankment / "hard" structure or embankment / embankment interface). Very often the mechanism will be internal erosion, but also in some cases it can be through external erosion.

In the case of internal erosion, this is because the contact zone is a preferred seepage area, where erosion can be initiated and develop. This contact between the different zones can be "rough" or "smooth" or even "loose", allowing more or less water flow and so more or less erosion. At this time, the physics of the phenomenon are not known well at the microscopic scale, or characterised well by means of numerical models. The physics of contact erosion probably differ in the case of a transition between a hard structure and an embankment or in the case of a transition between two embankments, for instance at the limit of two stretches of the same levee, with different geotechnical cross sections.

In the case of external erosion occurring at the surface of a transition area, it can be caused either by contact erosion occurring inside, or by an external cause, such as turbulence caused by a difference in roughness coefficient across a transition between two materials. In addition, a simple geometric irregularity can also lead to turbulence and external erosion.

Sometimes the function of the structure or the way it has been built can cause specific erosion problems:

- leakage from pipes (or into pipes),
- poor levee soil conditions around a good condition structure (e.g. sand around a pipe through a levee).

Both of these conditions can initiate or facilitate internal erosion. As pipes are the most common type of "hard" structures found in a levee (see Orleans analysis, in the Loire case study), it is particularly important to consider this specific case. It should be noted that these problems could be avoided or detected through close cooperation between the levee managing organisation, and the pipe managing organisation.

Another type of problem is related to settlement under or near a hard structure, causing a preferred area for flow, which will then result in erosion or increased internal pressures leading to uplift or sliding.

In some cases, the presence of a structure or a transition can also induce sliding (shear), because of additional forces not taken into account in the initial stability analysis.

The failure and collapse of an included structure may lead to either settlement in the levee, a potential overflow, or a loss of cohesion of the levee material in the structure area and hence internal erosion during a flood. Due to the presence of the structure, or because of its failure, mechanical failure (collapse, sliding …) may also happen.

Hence, the typical mechanisms that might occur, alone or as part of a process (or scenario) at structure transitions are (in no particular order of importance):

- external erosion,
- instabilities (sliding, collapsing, settlement)
- contact erosion between soil and hard structure,
- contact erosion between two different soils, or constructed soil interfaces,
- backwards erosion along a decompressed contact area (or along a pipe),
- concentrated leak erosion (generally the final mechanism in an internal erosion scenario, and not the initiating one),

From a geometrical point of view, a transition between a levee and a structure can be seen externally (a line) or internally (as a surface). An included structure that is visible from the outside has both an internal contact surface, and an outside line of limit. An included structure can also be completely hidden, buried within the levee or its foundation.

Erosion may occur both, together or exclusively:

- Internally (for example, internal erosion at the contact surface),
- Externally (for example, external erosion facilitated and starting at the limit).

Erosion may also develop in an embankment behind a protection structure if there are insufficient filtration measures:

- in cracked masonry joints,
- between concrete slabs,

- underneath rip-rap.

In this case the protection structure HIDES erosion instead of avoiding it (Fig 1.1). In a second phase, when the eroded space underneath the protection structure becomes large enough, then the protection structure suddenly fails (through block failure or via whatever units the structure is constructed from).

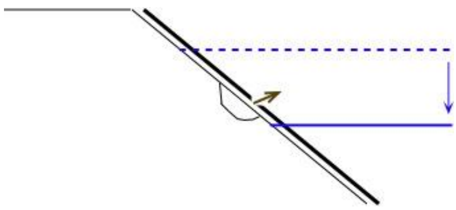


Figure 1.2 Erosion of the embankment hidden by the protection structure

For the situation with a buried structure spanning from the water side to the landward side of the levee (either within the levee or within the foundation), the transition is AROUND and ALONG the structure.

In the case where the transition is between two very different stretches (segments) of a dike (upstream/downstream), the transition is LATERAL to the structure (or levee).

In the case of a transition between layers (surface protection, road, spillway etc.): the transition is BEHIND (or under) the structure.

1.3 Structure of this document

This report provides an assessment of the different types of structure transition, the processes that might occur at transitions and recommendations as to how such transitions should be managed, assessed, designed and repaired to limit flood risk.

Chapter 2 provides an overview of hydraulic loading and erosion mechanisms that can occur and which will affect failure modes at transitions. Chapter 3 then provides some case study examples where transitions have failed in different situations. Lessons can be learnt from these reviews.

Chapter 4 presents a typology of the transition structures. A systematic approach to the determination of the typology of transitions is provided, taking into account both type of structure and geometry. The more important transition types are then described within structured templates, in Chapter 5, including details in connection with their management, assessment, design or repair.

Chapter 6 reviews how structure transitions are now, and could and should be incorporated into the performance assessment of flood defences structures, and in particular for flood system risk analysis.

Chapter 7 provides a summary of key conclusions from the review and identifies issues that require further study in order to improve knowledge about the transitions and hence help manage flood risk attributable to transitions.

2 Hydraulic loading and erosion mechanisms

Whilst a transition structure poses a hazard, the potential flood risk is not realised without some form of hydraulic loading and one or more failure mechanisms. As such, it is important to understand how transitions respond under different hydraulic load conditions and how different erosion mechanisms may develop.

2.1 Hydraulic loading: Structure position versus water loading

The following hydraulic parameters are important for determining the possibility and intensity of erosion:

- velocity and direction of the water flow (relative to the transition direction) and including possible sediment transport,
- water level and its dynamic change, including wave characteristics,
- the resulting hydraulic head along the transition zone,

The **hydraulic gradient** and or hydraulic head (Fig. 2.1) has to be considered in the case of seepage or flow through the embankment. It is strongly linked to the risk of various forms of internal erosion.

The **uplift-pressure** (or interstitial water pressure) is involved in all mechanisms regarding overall stability. It should be calculated by a hydraulic model in transient or steady conditions, depending upon the duration of the hydraulic head.

The **water energy** in the river, specifically along the levee face or toe, should be considered when surface erosion is a possible failure mechanism. Associated to water velocity and wave characteristics, local **turbulence** is often the initiating cause of erosion at an interface between two different revetments on the water side of the embankment.

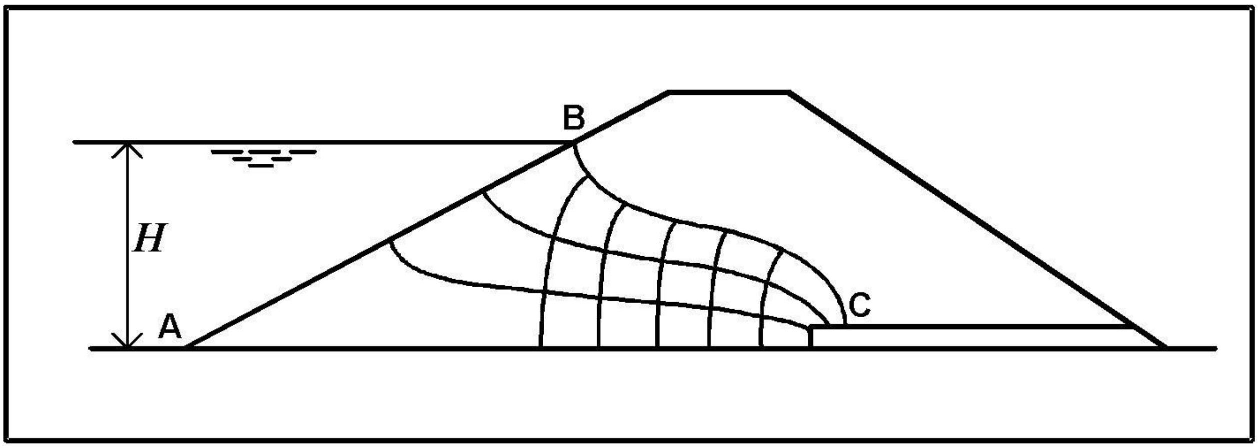


Figure 2.1 Illustration of internal flow and hydraulic gradient (H) through a levee

2.2 Erosion mechanisms

Erosion in relation to transition structures may be divided broadly into surface erosion and internal erosion. Surface erosion processes are more clearly understood, not least because they can be easily observed and attributed to specific physical processes. Typical surface erosion processes related to transition structures can include:

- Surface erosion and gullying as a result of surface water runoff being focussed at the interface between a structure and a levee
- Surface erosion at the transition due to local flow turbulence caused by structure geometry or roughness variations

There are many forms and permutations of the above processes in conjunction with different types of transition structure and hydraulic load.

Less is known about internal erosion processes, since they are, by their nature, hidden until the erosion reaches such an extent that partial or complete collapse of the levee occurs. Indicators of internal erosion, such as seepage flow, may be visible before collapse, but this is not always the case.

Research under FloodProBE WP3.1.1 (see FloodProBE Report WP03-01-12-11) has helped to advance knowledge and understanding in this area. This starts with a clear definition of internal erosion and the various forms that can develop.

Internal erosion is related to all processes which involve the detachment of soil particles and transport by seepage flow within the dam or levee, or its foundation. A consensual view in the water community is that four different basic processes can be identified within the general definition of internal erosion (see ICOLD, 2012). These mechanisms are: backward erosion; concentrated leak erosion; suffusion; and contact erosion. The general definitions of these processes are:

- *Backward erosion (Figure 2-2)*: Detachment of soil particles when the seepage exits to an unfiltered surface and leading to retrogressively growing pipes and sand boils;
- *Concentrated leak erosion (Figure 2-3)*: Detachment of soil particles through a pre-existing path in the embankment or foundation;
- *Suffusion (Figure 2-4)*: Selective erosion of the fine particles from the matrix of coarse particles;
- *Contact erosion (Figure 2-5)*: Selective erosion of the fine particles from the contact with a coarser layer.

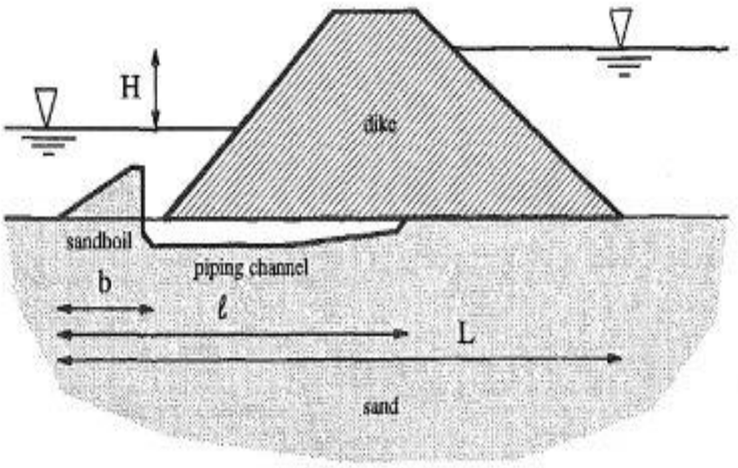


Figure 2.2 Typical example of backward erosion in a sandy layer (Koenders and Sellmeijer, 1992).

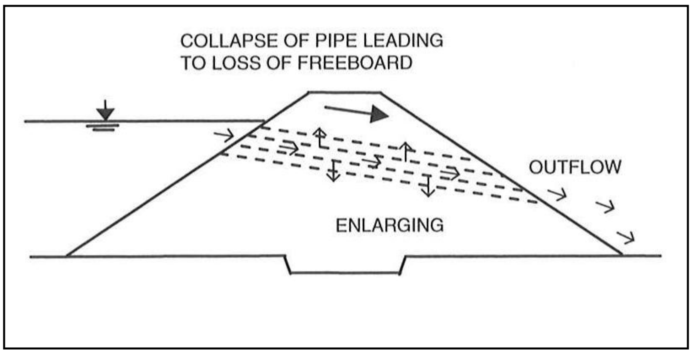


Figure 2.3 Typical example of concentrated leak erosion (Fell and Fry, 2007)

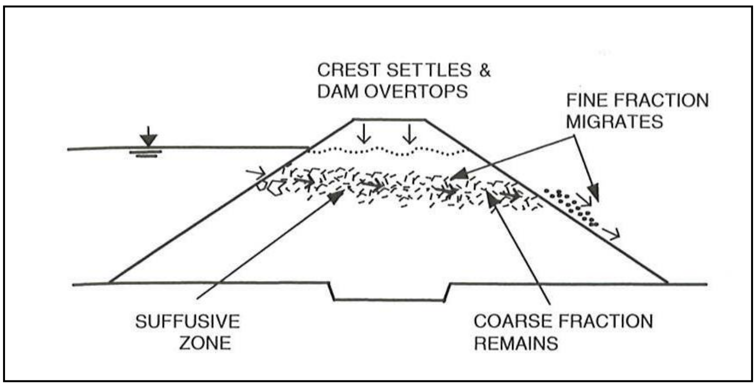


Figure 2.4 Typical example of suffusion (Fell and Fry, 2007)

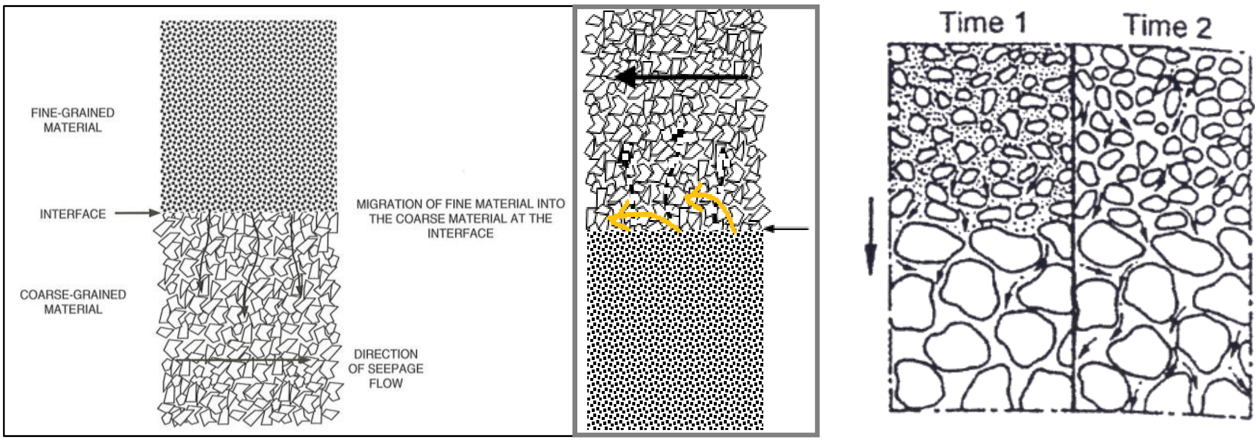


Figure 2.5 Sketch of contact erosion with parallel flow (left) after Fell and Fry (2007) and with transverse flow (right) after Ziems (1969).

Note that the term "piping" can be confusing since it has often been used to describe either backward erosion, concentrated leak, or internal erosion as a whole. Consequently, it has not been used here (as also proposed by ICOLD (ICOLD, 2012)).

It is also noteworthy that, until now, only levee configurations of a completely homogeneous material or composed of homogeneous layers have been studied and described. To account for heterogeneities within a dike, more research is needed, both from a theoretical/conceptual perspective and from an experimental one. Research work on these aspects is only just beginning. In the meantime, our understanding of these processes in relation to homogeneous or layered structures may be considered in relation to transition structures. The following summaries relate to internal erosion through soils.

Two conditions should be fulfilled for internal erosion to occur through a soil:

- Fundamentally, the first condition is that particles can be detached, i.e. that hydraulic shear stresses are larger than resistant contact forces. To reach this hydro-mechanical criterion, water seeping through the flood defence must have sufficient velocity to provide the energy needed to detach particles from the soil structure.
- The second condition is that detached particles can be transported through the soil. Two criteria should be fulfilled. First, a hydro-mechanical criterion: flow is sufficient to carry the eroded particles. Second, a geometric criterion (which is specific to internal erosion): voids exist in the soils within the flood defence that are large enough for detached particles to pass through them. This void is either a pipe inside the soil, as in backward erosion or concentrated leak erosion, or pore space within the grains of a coarse layer, as observed in suffusion and contact erosion.

The nature of the soil in the embankment determines its vulnerability to erosion. Two main classes can be distinguished:

- Granular non-cohesive soils: erosion resistance is related to the particle buoyant weight and friction; hydro-mechanical transport criterion is linked to rolling and sliding resistance of the grains.
- Cohesive soils: erosion resistance is mainly related to the attractive contact forces in between soil particles; the main transport mode is suspension flow.

The specific properties of cohesion or particle size (related to permeability) may be required for several of the mechanisms of internal erosion to occur.

The process of internal erosion of embankment dams or levees and their foundations (rather than type of internal erosion summarised above) can be represented by four phases. This applies for all types of internal erosion:

1. *Initiation*: first phase of internal erosion, when one of the phenomena of detachment of particles occurs.
2. *Continuation*: phase where the relationship of the particle size distribution between the base (core) material and the filter controls whether or not erosion will continue.
3. *Progression*: phase of internal erosion, where hydraulic shear stresses within the eroding soil may or may not lead to the erosion process being on-going and in case of backward and concentrated leak erosion to formation of a pipe. The main issues are whether the pipe will collapse, or whether upstream zones may control the erosion process by flow limitation.
4. *Breach*: final phase of internal erosion. It may occur by one of the following five phenomena (listed below in order of their observed frequency of occurrence).

    1. Gross enlargement of the pipe (which may include the development of a sinkhole from the pipe to the crest of the embankment).

    2. Slope instability of the downstream slope.

    3. Static liquefaction (which may include increase of pore pressure and sudden collapse in eroded zone).

    4. Unravelling of the downstream face.

    5. Overtopping (e.g. due to settlement of the crest from suffusion and/or due to the formation of a sinkhole from a pipe in the embankment).

Invariably, when considering internal erosion processes in relation to transition structures, these processes will vary as they interact with hard and soft structure interfaces. Nevertheless, the descriptive framework above provides a good basis to consider how transition structures might help initiate and support internal erosion processes.

A more detailed description of these internal erosion processes and how they may be analysed is provided in FloodProBE Report WP3-01-12-05.

3 Case study examples

The significance of transitions as points of weakness within flood defence systems can be clearly demonstrated by reviewing a number of historic flood events, and looking more closely at the locations and mechanisms of failure where breaches or defence failures occurred.

Case study examples have been drawn from the following flood events:

France:

- Rhône River, 1993-94
- Xynthia Storm, 2010
- Loire River, 19th Century
- Agly River, 1999

USA:

- Hurricane Katrina (New Orleans)

Thailand:

- Lower Chao Phraya River Basin (Inc Bangkok), 2011

In addition, a review of typical flood defence transitions has been undertaken using aerial photos:

UK:

- Humber Estuary (2011)

3.1 Case studies from France

3.1.1 Rhône (France), 1993-94

In France, during the two winter floods of 1993-94 the southern Rhone River flooded the Camargue delta. However, no overtopping or overflowing occurred; internal erosion has undoubtedly been the cause of most of (even all of) the breaches and of the major damages to the levees. An initial analysis was produced at the time of the events relying on local witnesses [Bonnefoy, R. and Royet, P. (1994)] which attributed most of these failures (13 of 16 in total) to animal burrows and some of them (3 of the total of 16) to pipes, with a possible involvement of tree roots. Since this original work, it has been suggested that the responsibility of animals could have been over stated and may have hidden other more complex mechanisms, all related in some way to forms of internal erosion.

A lot of pipes existed in these old levees, most of them for individual uses such as the irrigation and drainage of agricultural land. A lot of them were poorly maintained or, in some cases even forgotten. The levees were typically built, raised and reinforced over the years and consequently included many transition zones between different types of soils.

Lesson learned from this case study: in old levees there can be many crossing pipes, some of them even forgotten and not maintained, which can be the cause of breaches during floods.

3.1.2 Xynthia (France), 2010

A lot of damage occurred to French coastal levees during the Xynthia storm, mainly in the two departments of Charente Maritime and Vendée. A lot of this damage was caused by overtopping or possibly even by overflowing, due to the unusually high level of loading on the levees; the direction of the waves was also unusual so that some locations which had overtopped during other events were not during this one and vice versa.

Nonetheless, many damages were related to transitions of the "levee" with its protection revetment. The mechanisms and scenarios involved were:

- undermining of the lower part of the sea-side revetment, and subsequently eroding internal parts of the levee (sand, earth);
- varying pressure under the revetment (caused by defects on joints and high pressures caused by the wave impact) either on the sea side or on the crest, leading to a revetment failure, then erosion of the levee body;
- failure of the protection revetment itself then formation of cavities under the revetment, and finally collapse of the revetment.

These mechanisms involving transition between the levee, its foundation and the protection revetment had been previously identified and described (BRLi, 2006) and regularly happen during any storm loading these sea levees. In the same report, another mechanism involving the revetment is described but involves a first step of erosion on the land side by overflowing/overtopping before failure of the revetment.

Lessons learned from this case study: in coastal levees, the protection revetment is essential for the levee safety, and must be properly maintained. The transitions between the revetment and the rest of the levee and its foundation must be designed and constructed in such a way as to avoid erosion of both the levee and its foundation.

3.1.3 Loire river (France), XIXth century major floods and recent history

(Written with the contribution of Jean Maurin, head of the Studies and Works on the Loire Department in DREAL Centre)

In the city of Orléans, the levee system (a pilot site of the FloodProBE project), is 52 kms long and represents about 10% of the length of levees managed on the Loire river by the French State. A recent survey identified 50 linear crossing structures (pipes or cables, including cables in sheaths), 2 non linear crossing structures (a pumping station and a gate) and 35 non linear non crossing included structures (houses, utility buildings). This gives an indication of the extent of the problem of transitions for the levee management organisation; an average of 1.7 transition structures per km in this case.

Figure 3.1 Jargeau's gate

However, in recent history there has only been one levee failure attributable to a transition. This was in Montlouis in 2003 during a flood with a 10 years return period.

There were historic floods of the XIXth century when 3 floods occurred in 1846, 1856 and having a return period of around 100 years. It is alleged that crossing structures caused no or damage, as at this time none was present in the levees. A majority (66%) of the problems (breaches or major damages) were caused by overflowing, but a huge number of the problems (15.4% of the total, so 45% of the remaining) were attributed to the presence of "banquettes" on the top of the levee (see Figure 3.2 and

Figure 3.3). These "banquettes" are small (50cm-1m) embankment structures either at the limit of the crest and the river side slope or at the limit of the crest and the land side slope or at both of these limits. The banquettes can be either made of earth or rocks, with earthen banquettes being sometimes covered with armour stone.

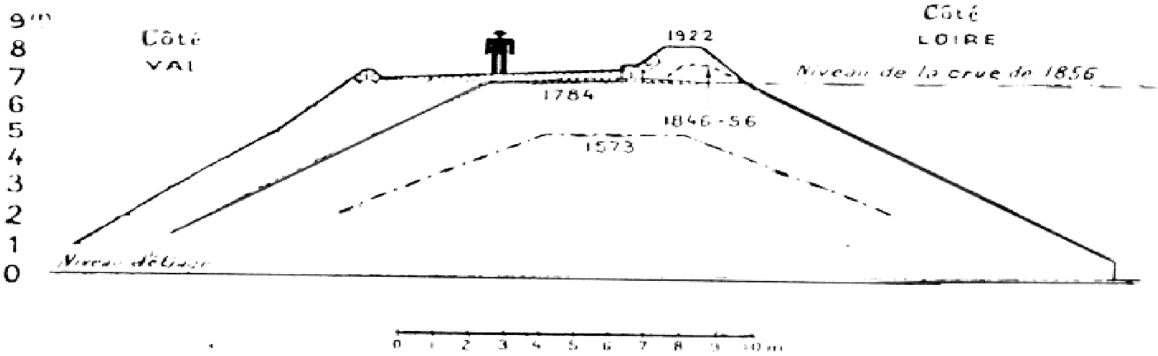


Figure 3.2 A typical cross section of the historic reinforcement of Loire levees

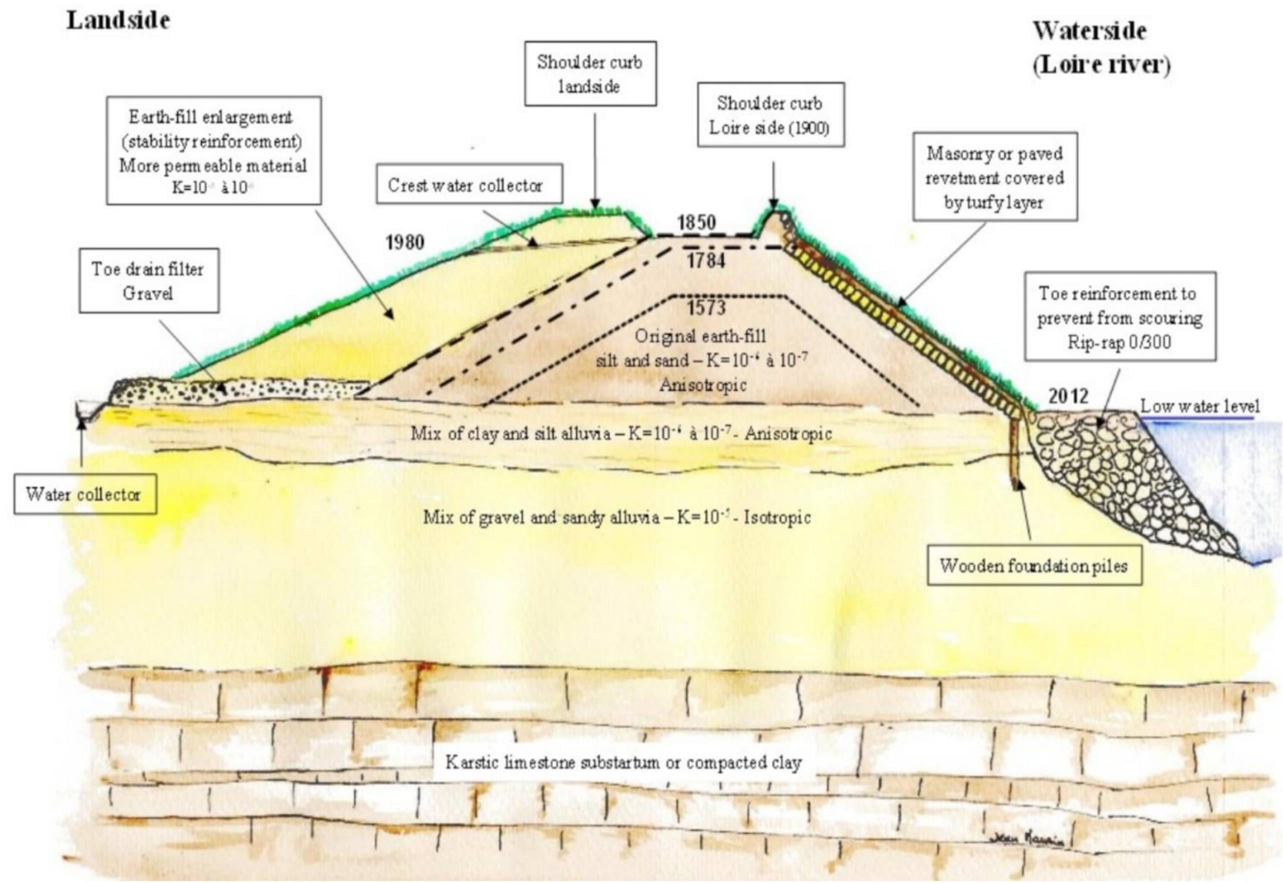


Figure 3.3 A typical Loire levee cross section in the Orléans area (source Jean Maurin)

The problems in relation to the banquettes were caused by internal erosion at the limit of the levee and the banquette (i.e. contact erosion between two soil layers), erosion inside the banquette (i.e. suffusion), or by drainage structures crossing the banquettes (i.e. contact erosion between a soil layer and a hard structure). Banquettes also had a detrimental effect in the situation of overflowing, as they allowed an increase in hydraulic head without offering the same erosion resistance as a full width levee section.

The Loire River offers one of the only documented cases of a failure caused by an included structure. This was during the XIXth century and caused by a house in La Chapelle sur Loire.

Lessons learned from this case study: there can be many pipe crossings in old levees that are weak points, especially as they have been installed through existing levees. Other types of transition can also exist and cause problems, particularly crest level raising structures and embedded buildings.

3.1.4 Agly river (France), November 1999

This case study was edited from Appendix 4 of Surveillance, maintenance and diagnosis of flood protection dikes. A practical handbook for owners and operators (Mériaux, P. and Royet, P., (2007)).

A flood, with a peak discharge of about 2000m^3/s, occurred along the Agly River, in the South of France, in November 1999. The river has levees on both sides of the main river channel along a length of 13.2kms. Overflowing occurred along many kilometres of levees, and caused major damage to 550m of levee sections. One breach (only…) occurred, just in front of the sewage treatment plant; at the time this was attributed to overflowing. However, given the presence of the plant discharge pipe it is highly likely that the location of the breach was facilitated by this pipe and that more than one single mechanism caused the breach.

Lessons learned from this case study: the presence of included structures can facilitate breaches, including via mechanisms not necessarily based on the transition itself, such as through overflowing.

3.2 Case studies from the USA

3.2.1 Hurricane Katrina – New Orleans

Hurricane Katrina caused extensive damage to New Orleans and Southeast Louisiana through extensive breaching of levees and flood defences. Many of the bre aches that occurred, did so at points of transition.

The Interagency Performance Evaluation Taskforce (IPET) undertook extensive studies to understand what happened and to support a programme of defence reconstruction. A series of reports detailing their work is available online.

An example failure mechanism is shown below, along with a copy of the report conclusions on transitions. [Material copied from IPET Volume V. The Performance – Levees and Floodwalls].

Transitions

A common problem observed throughout the flood protection system was the scour and washout found at the transition between structural features and earthen levees. In many cases, the structural features were at higher elevations than the adjacent earthen levee, resulting in scour and washout of the levee at the end of the structural feature. At these locations, the dissimilar geometry concentrates the flow of water at the intersection of the levee with the structure, causing high flow velocities and turbulence that resulted in the erosion of the levee soil. The performance at transitions could be improved by fully embedding the structural walls within the levee fill, and using the levee to transition the difference in elevation from the structure to the main section of the levee. In a few cases, observations indicated that this type of transition performed successfully. The embedded area and the transition to the main section of the levee should have erosion protection such as grouted rip-rap or concrete erosion mats. In some cases, the structures were lower than the connecting earthen levees. At these sites, the flow of the water is channeled over the structural feature, causing erosion of soil on the protected side of the structure. The performance in these cases can be improved by providing erosion protection on the protected side of the structures and along the transition section.

Figure: Scour and Erosion on the Protected Side of the IHNC Adjacent to the 9th Ward in the Vicinity of the South Breach

3.3 Case studies from Thailand

3.3.1 Flooding in the Lower Chao Phraya River Basin (Bangkok)

The following case study has been edited directly from a report organised by ENW, entitled "Post-flood field investigation in the Lower Chao Phraya River Basin (23-27th January 2012). Findings of the Thai – Dutch reconnaissance team. Some additional content sourced via the web has been added to enhance the case study.

Large parts of central Thailand have experienced severe flooding during the second half of the year 2011. The economic and societal damage is enormous: more than 800 fatalities and more than US $ 45 billion (Sources: Wikipedia, Worldbank), making it one of the most costly disasters at a global scale ever.

The flooding in Thailand has been characterized by a number of failures of dykes and structures around the large industrial estate areas, the Chao Phraya river dykes and adjacent irrigation canal dykes. An investigation was organized to investigate the dyke failures and performance of various systems. There are three primary areas of interest:

1. Dykes around industrial estates near Bangkok;
2. The system in the Lower Chao Phraya river Basin (north of Bangkok);
3. King's dyke, i.e. the ring dyke for the protection of Bangkok.

In addition, some historical sites at Ayutthaya (north of Bangkok) were visited

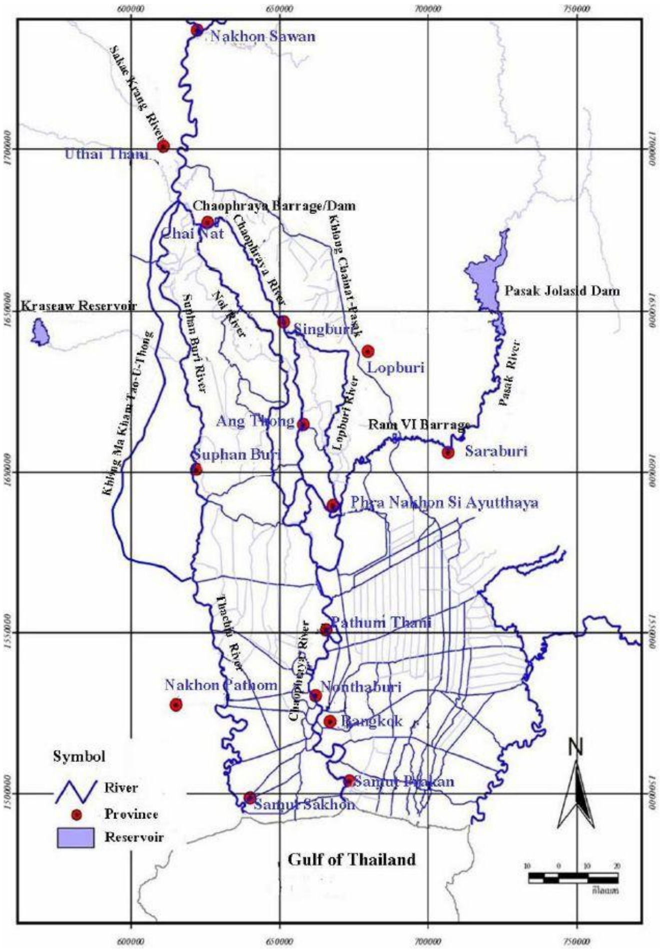


Figure 3.4 River network of the Lower Chao Phraya River basin (UNESCAP)

The Lower Chao Phraya river basin is a complex network of rivers, canals and streams (Figure 3.4). The maximum discharge capacity in the lower part of the basin ranges from 2750 m3/s to 3500 m3/s. During the 2011 floods Thailand was struck by one of the most devastating natural disasters in Thailand's modern history. Sixty five out of seventy seven Thai provinces were subject to flooding along the Mekong and the Chao Phraya river basins. The flooding persisted in some areas for months and resulted in more than 800 deaths and 13.6 million people being directly affected (Figure 3.5).

Figure 3.5 (i) Flood evacuation; (ii) Historical sites flooded; (iii) Temporary flood defences; (iv) Widespread flooding

<u>Failure Mechanisms</u>

An extract from the report introductory summary states the following:

"...Several large breaches occurred in the canal dykes in the Lower Chao Phraya river basin mainly due to overflow and consequent erosion of the dyke body that consisted of clay. Most breaches occurred at weak spots in the system (lower parts of the dyke, connections with structures and at obstructions). Three hydraulic structures were visited that all failed at the connection between the structure and the earthen dyke. This illustrates the importance of a robust design of these transitions..."

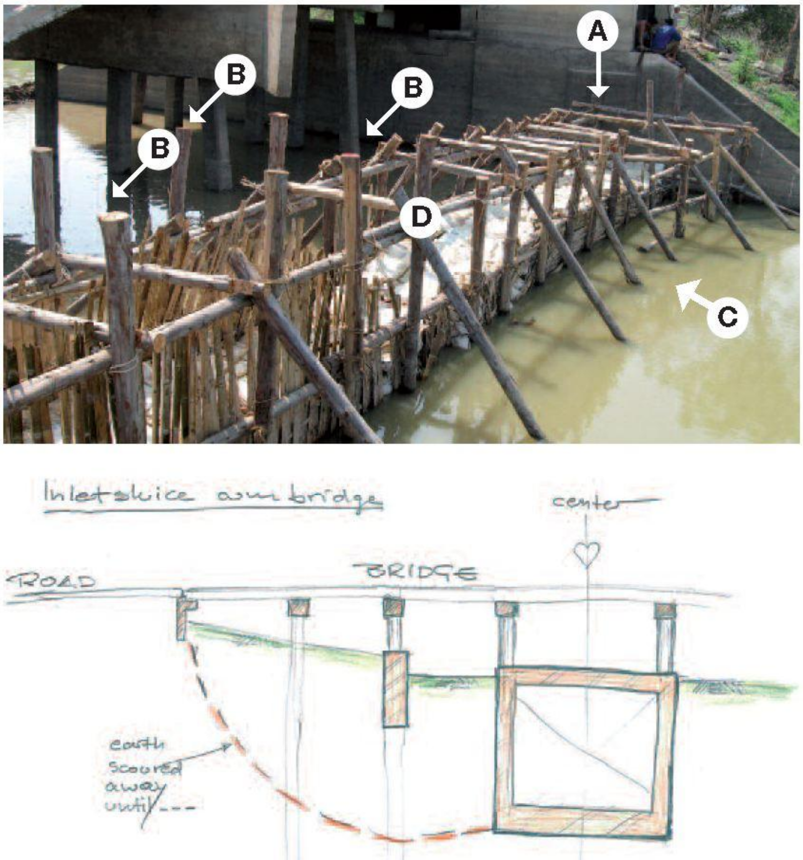
Some examples of the breaches arising from transition failures include:

<u>Layers within the Dyke</u>

There was one occasion of a breach in a dyke near Bang Chrom Sri floodgate, where the local RID officers that breaching may have been caused by seepage through the dyke. At the time of the visit some flow of water and sand through the dyke was observed. One of the reasons could be that a road had been constructed on the old dyke. Sand layers that were used as part of the road foundation thereby became part of the dyke body, thus creating a potential weak spot for seepage.

<u>Hydraulic Structures in the Lower Chao Phraya Basin</u>

All of the structures that were visited failed at the connection of the structure and the earthen dyke. This indicated how vulnerable these connections are. It was noted that similar observations were made in New Orleans after hurricane Katrina. Since the structures were mainly designed for irrigation purposes with small water heads, provisions to prevent seepage / piping during floods seem to be limited, especially on the connection with the adjoining dykes or dam. Therefore scouring and breaching could occur besides the structures. This is illustrated in Figure 3.6 (Klong Ta Nueng floodgate) and Figure 3.7 (Pra Ngam floodgate), which show a photo of the situation and a sketch of the failure.



Klong Ta Nueng floodgate

- **A** *connection of front wall*
- **B** *soil washed away*
- **C** *flow during flooding*
- **D** *temporary coffer dam*

Figure 3.6 Failure of the Klong Ta Nueng floodgate

Pra Ngam floodgate

- Ⓐ *sand fill at the original breach*
- Ⓑ *regular flow*
- Ⓒ *flow during flooding*

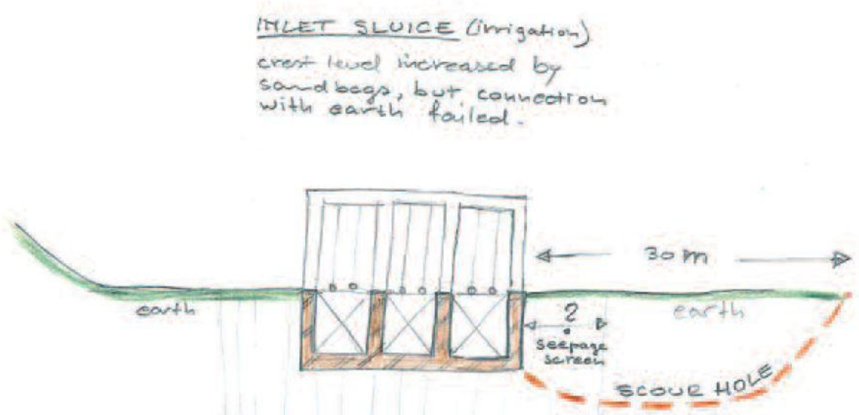


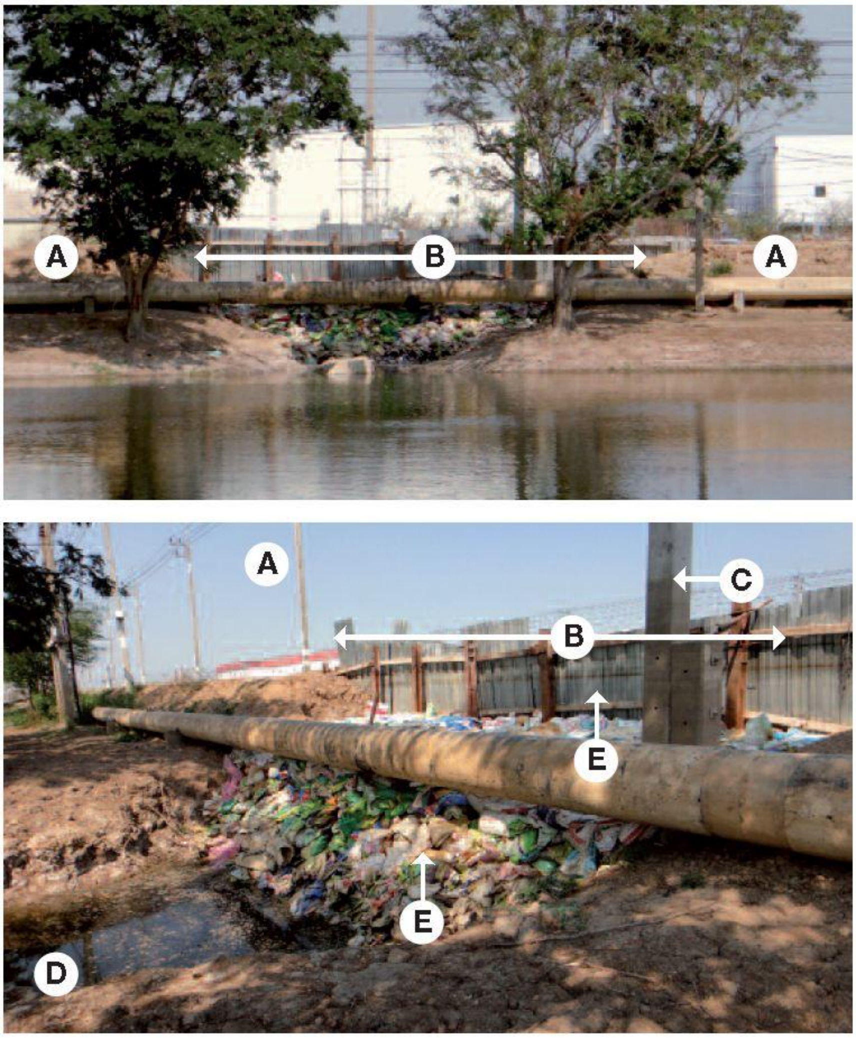
Figure 3.7 Failure of the Pra Ngam floodgate

<u>Rojana Industrial Estate</u>

The Rojana industrial estate which was developed 23 years ago (in 1989). It is located north of Bangkok near the city of Ayutthaya. It is protected by about 70km of dykes and the estate in fact consists of multiple “dyke rings”. The area is protected by dykes with a height of about 4.5m.

Two breaches were visited. The first breach was caused by overtopping and it had a width of about 20m. The canal levee had been raised as flood fighting measure by 0.5m with a backhoe. Still, the final flood levels exceeded the crest level by far (0.8 ~ 1.0m). The pipe along the slope and the columns on the protected area side may be speculated to have contributed to the erosion failure. The failure had occurred after no more than 6 hours after the levee started being overtopped. (See Figure 3.8).

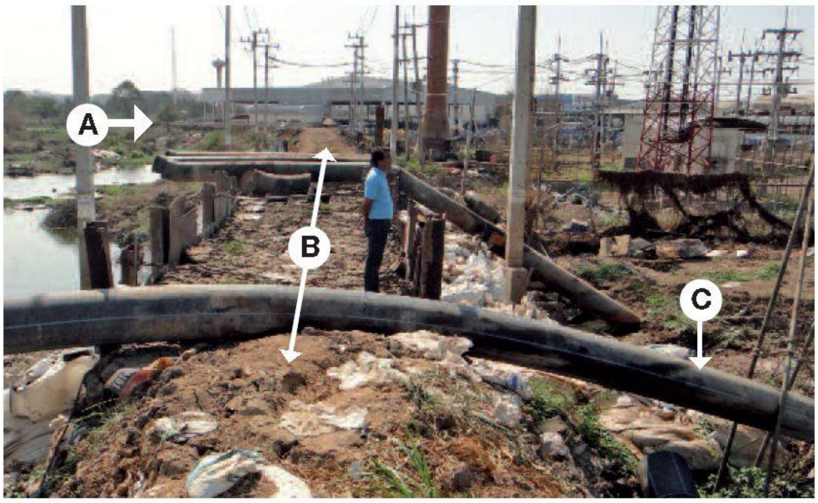
The second breach that was visited occurred at a pipe in the dyke, which was not protected by seepage screens. At this location the failure started with seepage along a pipe through the levee (no seepage screen) and failure progression accelerated when it was also overtopped. According to eye witnesses it took about 2 hours to form the 30 wide breach. The levee was rather new and built after floods in 1999. (See Figure 3.9).



A earthen dyke
B breach and emergency repair

A canal side
B breach width ~20m
C water mark
D protected area
E temporary repairs

Figure 3.8 Breach from overtopping; the pipe along the crest may have contributed to the failure



A overflow direction
B breach width ~30m
C relocated pipe (through levee without seepage screen before)

Figure 3.9 Breach through seepage initiated along a pipe passing through the dyke

Lessons Learnt from this case study:

The report concludes with a series of key points. Amongst the lessons learnt was the following statement regarding transitions:

Transitions between hydraulic structures and (earthen) dykes again proved to be weak spots, but these transitions receive limited attention in current methods for design and safety assessment in the Netherlands and other countries. Design guidance is needed to ensure the safety of these connections. As part of the safety assessment or periodic inspections a number of principles, checks and simple design rules should be developed to be able to assess the safety of these connections. As a general rule, transitions should be designed to be more reliable than the adjacent “standard” elements (e.g. dike reaches).

3.4 Case studies from the UK

3.4.1 River Humber Estuary, UK

The Humber Estuary (UK) is located on the north east coast of England (Figure 3.10). Flood defences within the estuary need to cope with fluvial floods, tidal variations, wave action and coastal surges which occur along the North Sea coast. More information on the Humber Estuary can be found at www.riverhumber.com and the Humber River Basin Management Plan through the Uk Environment Agency website (at the time of writing at http://www.environment-agency.gov.uk/research/planning/124803.aspx).

Figure 3.10 The Humber Estuary – North east coast of England

The defences in the estuary protect a wide variety of property and land use. The City of Hull is on the estuary, and has suffered extensive flooding during flood events over the past decade. Other areas along the estuary are rural, but there are also active industrial areas that benefit from flood protection.

The bulk of the flood defences along the estuary are earth embankments, but with varying degrees of revetment protection and added structures (see below). Typical problems for managing the defences include erosion and seepage (see Figures 3.11, 3.12, 3.14). The tidal range can be very large, resulting in occasions where the flood defences appear set back from the water by a considerable distance (Figure 3.15).

Figure 3.11 Bare soil on the embankment crest

Figure 3.12 High tide water in Winteringham site

Figure 3.13 Seepage at two locations along the embankment in Winteringham

Figure 3.14 Remnants of high tide water in front of the embankment

A review of one stretch of flood defences along the estuary was undertaken in order to catalogue the types of transition that can be found, and as a means of cross checking that the typology developed within this report is comprehensive. The area studied has not suffered a major breach recently, but does require routine maintenance (as with all flood defences) and has also been used for assessment of the geophysical investigation work (FloodProBE WP3.2).

The review was undertaken using Bing Maps with Birds Eye View enabled (see Figures S1-S31). Subsequently, this process has been automated such that when a user pans in to an area, a perspective view is provided. The quality and detail of these images – at least for the area studied – is very good, considering the data and mapping tool is freely available. This resolution is sufficient to scan and identify most areas where a transition (that can be seen externally) exists.

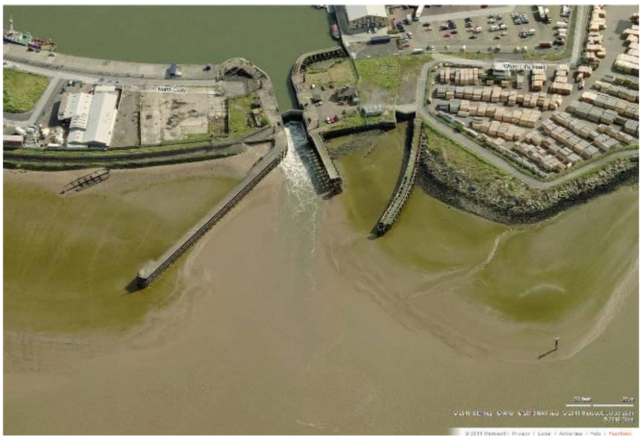


Figure S1

Figure S2

Figure S3

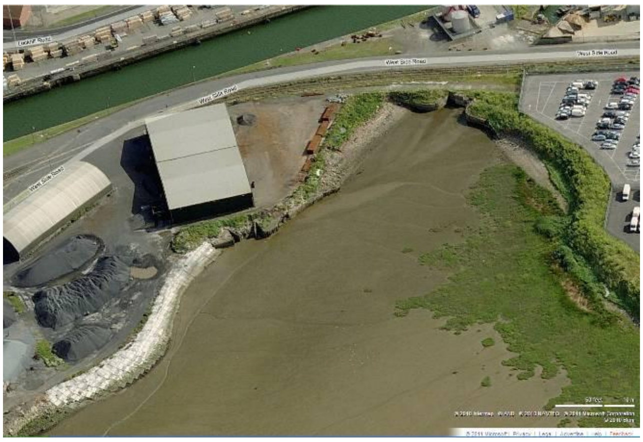


Figure S4

Figure S5

Figure S6

Figure S7

Figure S8

Figure S9

Figure S10

Figure S11

Figure S12

Figure S13

Figure S14

Figure S15

Figure S16

Figure S17

Figure S18

Figure S19

Figure S20

Figure S21

Figure S22

Figure S23

Figure S24

Figure S25

Figure S26

Figure S27

Figure S28

Figure S29

Figure S30

Figure S31

4 Structures and transitions typology

This section provides an overview of the different types of transition structures culminating in a flow chart to assist in identifying different types of transition and problems associated with these transitions (Figure 3-1).

4.1 Typology

The following provides a list of different structures and transition types.

Buried structures:

- pipes (metal, plastic, concrete, masonry, …),
- cables.

Part buried, but visible structures:

- culverts,
- gates,
- houses,
- stairs,
- manholes (probably associated with a buried structure or network).

External structures:

- surface protection,
- roads.

Change in type of levee

- contact between the levee and a flood wall (lateral / vertical),
- contact between different levee stretches,
- contact between the levee and natural high ground.

4.2 Main types of transition and related potential problems

The type of transition influences the nature of the problems it may cause.

The main types of transitions are described according to a flowchart presented in figure 4-1.

A transition can be either :

- between two levee segments (including between a levee segment and natural ground and between a levee segment and a flood wall). In these cases the difference between the different segments can be in terms of outside geometry, of protection revetment (slope or crest, road, …), and in terms of internal cross section.
- between a levee segment and its own revetment,
- between a levee and a flood wall above the levee,
- between a levee and a linear structure,
- between a levee and a non-linear structure.

The following flowchart (Figure 4.1) provides a tool to identify the type of transition, and the potential problems that could be encountered with each type of transition, as well as the principles for solutions.

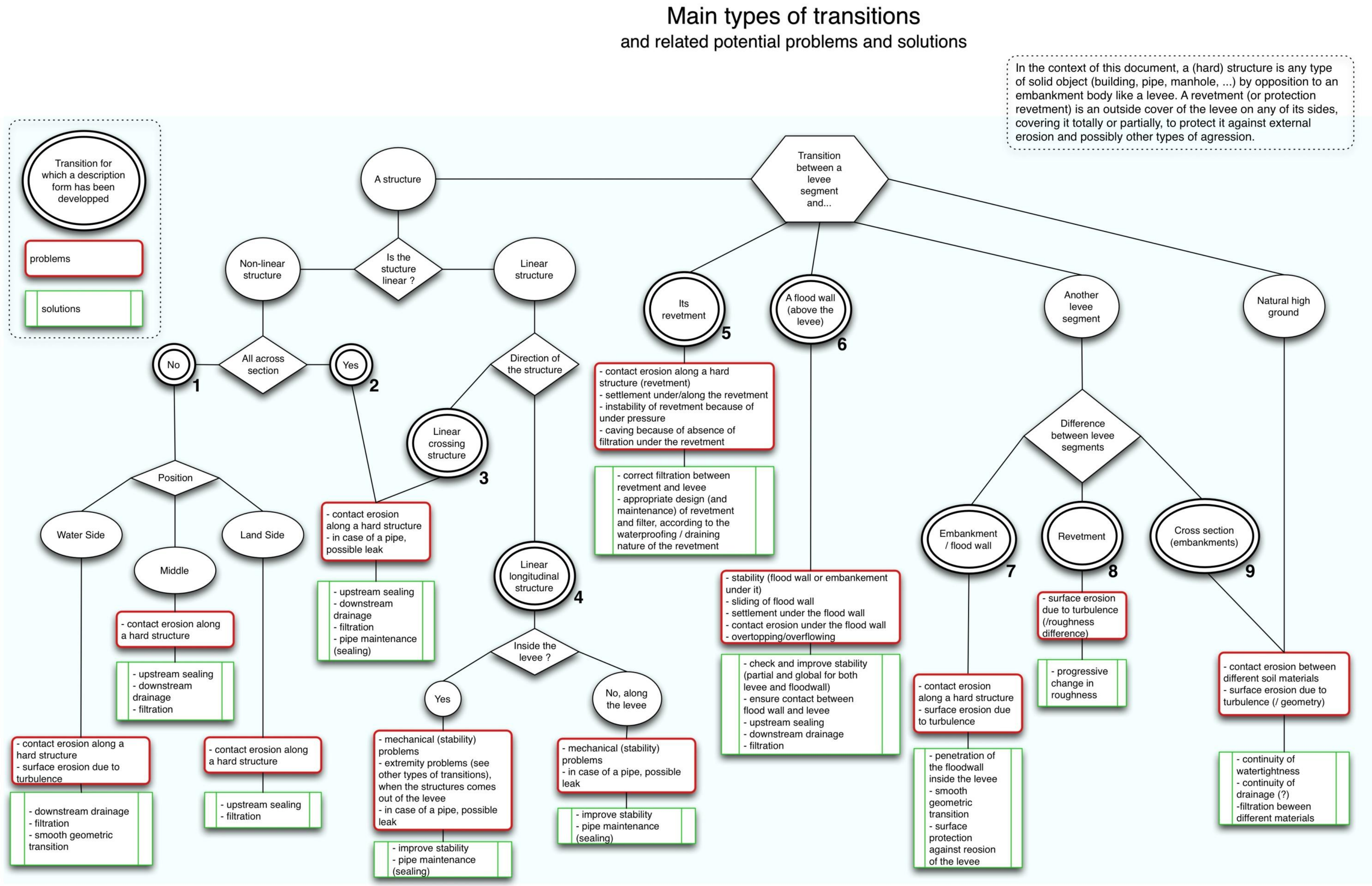


Figure 4.1 Flow chart to identify types of transition and potential associated problems

5 Description forms for structure transitions

This chapter provides a detailed description of the different types of transitions found with levees. A standard form is used for each description. Each form includes a description of:

- the transition type,
- the potential failure modes and mechanisms linked to this type of transition,
- the way(s) to detect this type of transition,
- the way(s) to detect the typical problems associated with the transition,
- best practice to avoid problems in terms of design, maintenance and/or management,
- issues and questions associated with the transition
- case studies and examples

Some specific transition cases may relate to more than one form.

Some generic actions can be considered for all types of transitions, mainly in terms of management, in order to facilitate their assessments and maintenance.

A database of all transitions should be filled and maintained for each transition type, with a specific data collecting form for each transition type. Each specific transition should be referenced, described in this database, as well as inspected both regularly and after and if possible during every loading event (flood or storm).

Specific initialisation of the database filling should be undertaken by the manager, including searching through records and archives, questionnaires to networks (water, sewage, power, communication, etc.) managers and using of specific detection methods.

Structures maintained by other managing organisations (encroachments) should be submitted to authorization and approval of the technical details by the levee-managing organisation in case of building or modification.

5.1 Transition 1: Non-linear, partially included structure

Description :

This type of transition relates to (partially) included structures, which are generally not directly related to the levee flood protection function. Unlike non-linear crossing structures, most of the time these structures are NOT dividing or ending the levee. These cause obvious problems in management, particularly for inspection and maintenance. The risk of erosion at the contact area is promoted, and will be difficult to detect. Furthermore, some buildings can have basements that extend under the levee.

Illustration :

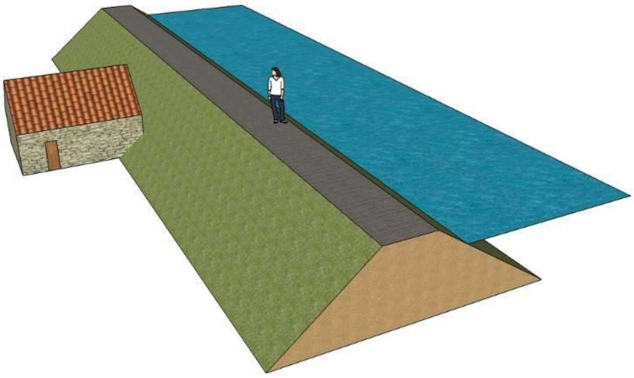


Figure 5.1 Illustration of a non linear partially included structure in the levee

Photos :

Photo 5.1 A house built into a levee on the River Loire.

Main failure modes associated with this type of transition:

- Internal erosion
- External erosion (turbulence on the river side)

Detection of the transition:

- Records, archives
- Visual inspection
- Aerial photographs

Detection of problems:

- Visual inspection

Problem indicators:

- Signs of seepage and internal erosion into and around the included structure
- External erosion around the structure

Best practice to avoid problems at this type of transition:

Design:

- Avoid building unnecessary structures into levees
- Ensure adequate sealing, drainage and filter measures to control seepage and avoid progression of internal erosion
- Ensure smooth geometric transition on the water side

Repair / retrofit:

- Install appropriate sealing, drainage and filter controls to avoid progression of internal erosion

Management:

- Try to implement inspections of the structure, both inside and outside where possible.

5.2 Transition 2: Transition between a levee segment and a non linear crossing structure

Description : *This type of transition relates to structures which are dividing or forming an end stop for the levee. Most of the time, these structures are directly or indirectly related to the flood protection function (i.e. without the levee, these structures would not have been built), examples: spillways, gates, etc.*

Illustration :

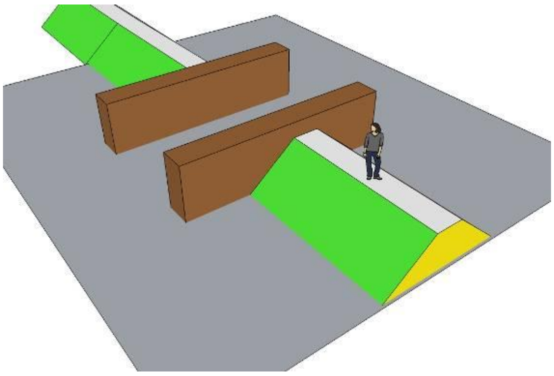


Figure 5.2 Illustration of a transition with a structure across the levee

Photos :

Photo 5.2 A gate in a levee

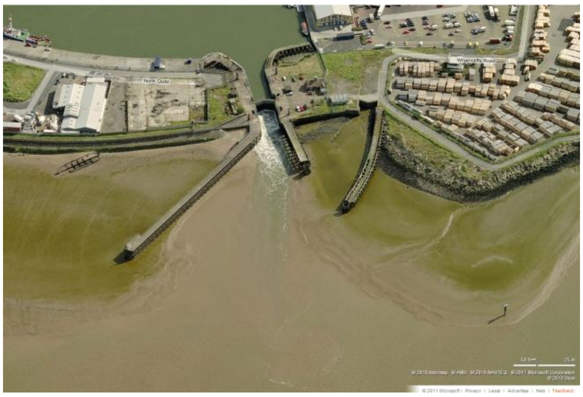


Photo 5.3 Complex mixture of levees, cutoffs, jetties and locks (Humber Estuary, UK)

Main failure modes associated with this type of transition:

- seepage problems at the interface between levee and structure arising from differential settlement,
- internal erosion caused by water seeping along the interface between structure and levee

Detection of the transition:

- records
- visual inspections
- aerial photos
- topography (particularly LIDAR)
- geophysical survey

Detection of problems:

- visual inspections (normal conditions, but mainly during or post flood)
- topographic monitoring

Problem indicators:

- Signs of settlement or distortion of the levee profile
- Signs of seepage along the structure – levee interface
- Signs of distress within the structure (cracking, distortion)

Best practice to avoid problems at this type of transition:

Design:

- Ensure adequate design at levee interface to avoid differential settlement and to prevent paths of preferential seepage

Repair / retrofit:

- Grouting (including Biogrout)

Management:

- nothing specific

Case study example

The following set of pictures illustrates the problems that can occur at the transition between a structure and a levee particularly in terms of contact erosion.

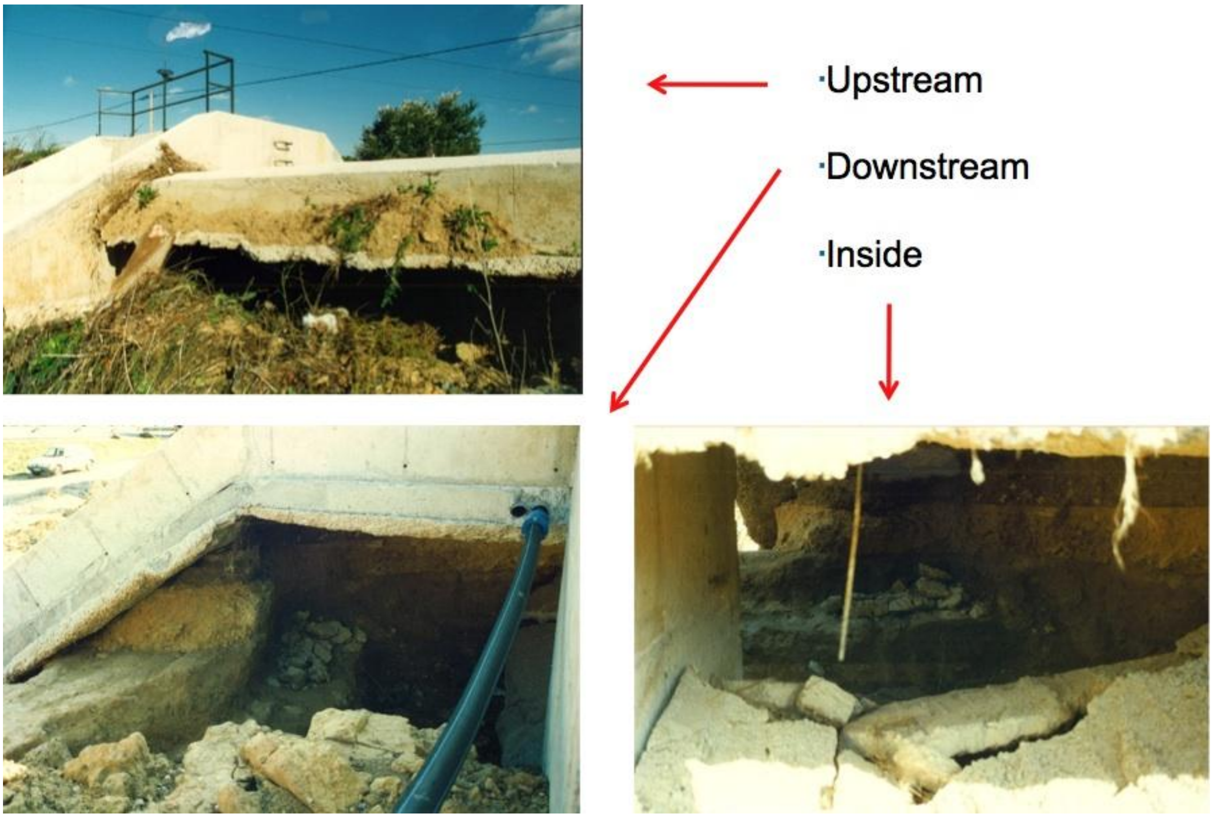


Figure 5.3 Erosion along a safety weir wall, and under its crest (Aix en Provence)

5.3 Transition 3: Linear crossing structure

Description:

Linear crossing structures can be found: across the levee, under the levee (through the foundation) or partially in the levee and its foundation. Sometimes they cross the levee only partially (for instance from the crest to the bottom of one of the slopes).

This type of structure poses specific management issues, as they are often managed by organizations that are different from the levee management organization.

Illustration:

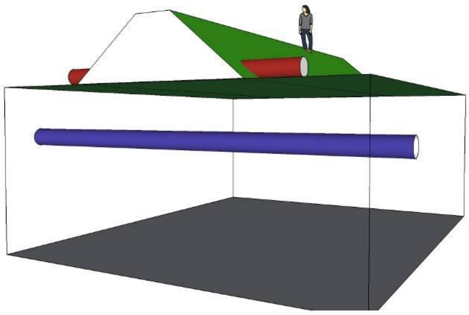


Figure 5.4 Illustration of linear crossing structures, across the levee and under its foundation

Photos :

Photo 5.4 A pipe crossing through and across the water side of a levee (Rhone River)

Photo 5.5 A gate control at the end of a culvert passing through a levee (River Loire)

Main failure modes associated with this type of transition:

- seepage problems at the interface between levee and structure arising from differential settlement,
- internal erosion (with a range of different sub-types) initiated along the structure, caused by seepage
- internal erosion along part of the structure caused by water going into or from a pipe,

Detection of the transition:

- records, archives (not necessary those of the levee manager)
- visual inspections
- aerial photos
- geophysics

Detection of problems:

- visual inspections (normal conditions, but mainly during or post flood)
- camera inspection from inside any pipes
- topographic monitoring

Problem indicators:

- leakage or evidence of internal erosion (moisture, fine soil particles)
- irregular geometry, signs of subsidence

Best practice to avoid problems at this type of transition:

Design:

- Design measures to prevent internal erosion along the structure levee interface
  - after placing pipe/cable in the trench, fill the trench with vibrated concrete
  - place pipe/cables at the upper part of the levee (by means of a siphon, if relevant – Fig 5.7)

Repair / retrofit:

- Ideally, removal, but if not an option then (i) identification of the failure mode induced by the linear structure and subsequently measures to prevent that failure mode (which could relate to structural stability, internal erosion, surface erosion etc)
- Complete excavation and installation of internal erosion protection measures (filters, lengthening of the transition internal line (i.e. reduction of the hydraulic gradient))

- No specific drainage on the land side of the structure if the rest of the levee has no specific drainage, in order not to create a particular location with a higher hydraulic gradient.

Management:

- Agreement between the levee manager and the network manager before starting any work on the crossing structure

Case study examples

The following picture was taken during the 1993-94 floods of the Rhône River in Camargue (see description of this case study in 3.1.1).

Photo 5.6 Levee breach initiated along a pipe crossing (Rhône River). Photo SNRS.

The following set of pictures shows a breach which was probably caused by erosion around some telecommunication cables: in the picture on the right, it can be seen that the cables were put in a trench filled with coarse and non cohesive material which would act as a preferential seepage path. The trench can also be seen on the upper left picture, on the left of the set of cables (just under the house).

Figure set 5.5 Breach initiated along crossing cables (Mosson River, winter 2002-2003).

The following set of pictures shows a pipe which is crossing under the base of a levee with no specific treatment of the contact surface visible, and hence the strong possibility of contact erosion

Figure set 5.6 A pipe crossing at the base of a levee (Dresden)

The next picture presents a solution (adopted as general design by SYMADREM, Rhone River levee management organisation, for retrofitting older pressure pipes), as it lengthens the contact area, and removes most of it at the point of highest gradient.

Photo 5.7 A crossing pipe with " siphon shape" (Rhone River), to minimize the risk of internal erosion along the pipe. Picture of the land side of the levee.

5.4 Transition 4: Linear longitudinal structure

Description : *Linear longitudinal structures can be found: inside the levee, under the levee (in its foundation) or alongside the levee near the foundations*

Illustration :

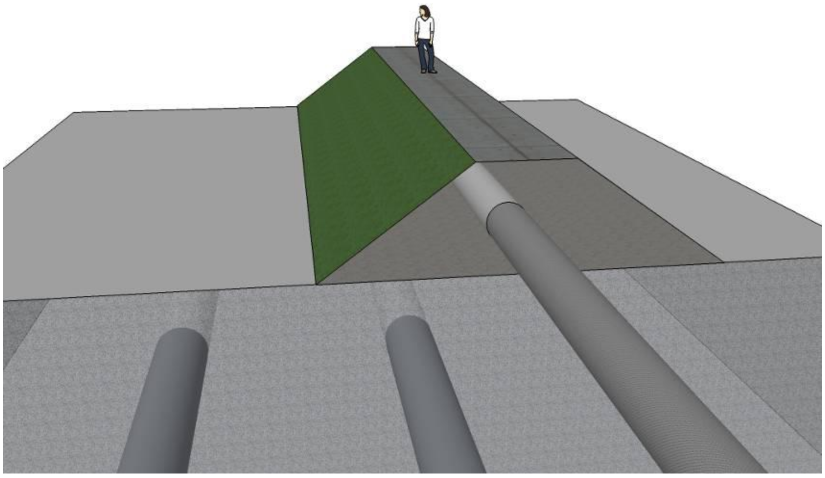


Figure 5.7 Illustration of longitudinal linear structure inside, under and alongside the levee

Photos :

Photo 5.8 Breach of a coastal levee (Vendee, France) exposing a longitudinal pipe

Main failure modes associated with this type of transition:

- internal erosion caused by water going into or out from a pipe,
- stability problems caused by a potential weak point (initiation of a slip surface)

Detection of the transition:

- records, archives (not necessary those of the levee manager)
- visual inspections
- aerial photos
- geophysics

Detection of problems:

- visual inspections (normal conditions, but mainly during or post flood)
- camera inspection from inside any pipes
- topographic monitoring

Problem indicators:

- seepage or internal erosion evidence (moisture, fine soil particles)
- irregular geometry, signs of subsidence

Best practice to avoid problems at this type of transition:

Design:

- taking into consideration the existence of the structure in stability analysis and in possible internal erosion problems (imperviousness, filtration)

Repair / retrofit:

- Ideally, removal, but if not an option then (i) identification of the failure mode induced by the linear structure and subsequently measures to prevent that failure mode (which could relate to structural stability, internal erosion, surface erosion etc)

Management:

- Agreement between the levee manager and the network manager before starting any work on the longitudinal structure
- Good management and inspection of the structure

5.5 Transition 5: Transition between the levee body and a surface revetment

Description : *This transition relates to the interface between the levee body and the revetment on the levee (on the water side, the landward side, or the crest). Most of the issues are more important on the water side, because of more frequent water level variation and higher surface flow speed.*

Illustration :

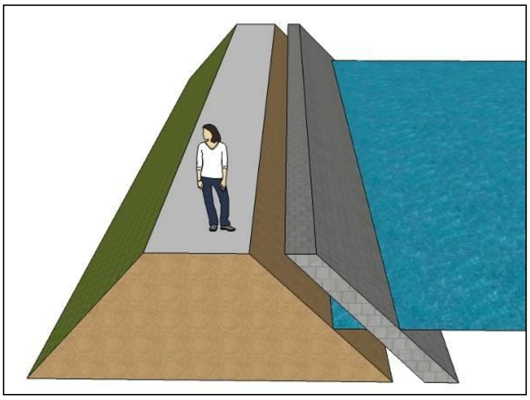


Figure 5.8 Illustration of a transition between the levee body and a surface revetment

Photos :

Photo 5.9 A leak through the joints of a masonry revetment, after a flood. This can lead to erosion behind the masonry (Arles, France).

Photo 5.10 Failure of a levee caused by erosion underneath the revetment followed by the collapse of the revetment (Algiers, New Orleans, USA)

Main failure modes associated with this type of transition:

- erosion of the embankment behind the revetment, worsened by and also worsening revetment damage,
- uplift of the protection can develop when under-pressure (cracks in a solid revetment and waves or rapid flow decrease).

Detection of the transition:

- records, archives, plans for proposed works
- visual inspection

Detection of problems:

- visual inspections (normal conditions, during or post flood):
- topographic monitoring
- geophysical survey

Problem indicators:

- geometric irregularities
- failing integrity of the revetment
- signs of leakage (in both directions)

Best practice to avoid problems at this type of transition:

Design:

- use of appropriate filter design at the levee - revetment interface
- avoid any water flow along the surface underneath the revetment (seepage, rainwater etc).

Repair / retrofit:

- same as design

Management:

- maintain the integrity of the revetment in good condition

5.6 Transition 6: Flood wall above a levee

Description :

This type of transition is related to flood walls built on and into a levee, usually to raise its crest without enlarging the levee at its base.

Illustration :

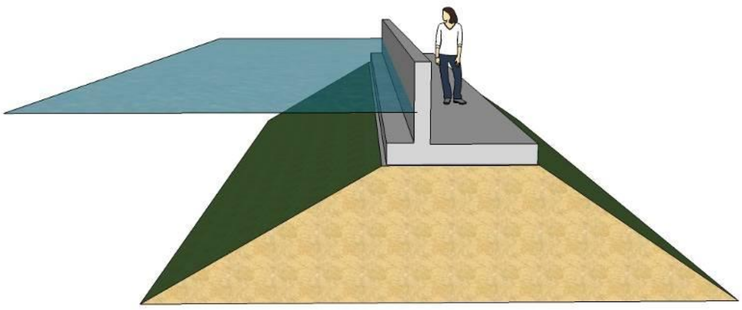


Figure 5.9 A flood wall above a levee

Photos :

Photo 5.11 17th Street Canal levee breach (Hurricane Katrina, New Orleans, USA)

Photo 5.12 Concrete wall on top of levee defences in the River Thames Estuary (UK).

Main failure modes associated with this type of transition:

- contact erosion at the interface, which can then lead to erosion of the levee itself and/or stability failure of the flood wall,
- stability problems related to the flood wall alone (but these are not specific to the transition),
- stability of the embankment, including the foundation, given the higher hydraulic loads, if the wall has been built after the original levee construction,
- erosion of the levee by overflowing or overtopping above the flood wall, which can lead to another failure mechanism and failure of the flood wall..

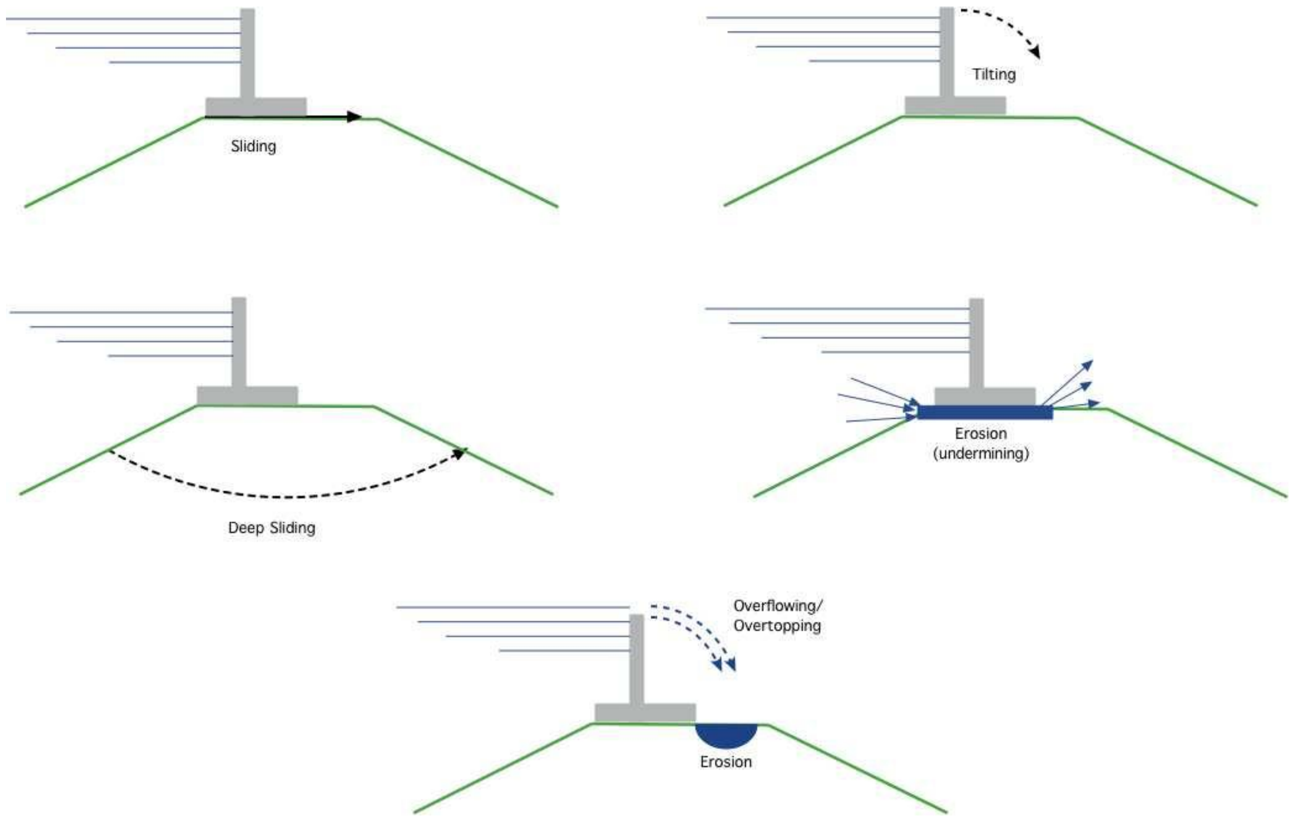


Figure 5.10 Mechanisms involved in the failure of levees including flood walls

Detection of the transition:

- records
- visual inspections
- aerial photos

Detection of problems:

- visual inspections (normal conditions, during or post flood)
- monitoring (displacement)

Problem indicators:

- Signs of settlement or distortion of the levee crest and wall line
- Cracking of the embankment crest or slopes
- Cracking of the wall
- Signs of seepage or erosion (both internal and external) around the levee / wall interface

Best practice to avoid problems at this type of transition:

Design:

- Ensure good contact conditions between the wall and the levee leading to a good water tight surface on the water side of the levee
- Ensure stability of the wall, as well as of the levee, including consideration of full loading on the wall

Repair / retrofit:

- Install measures to prevent seepage
- Install measures to prevent erosion close to the wall on the land side
- Increase structural stability of the wall and adjacent soil

Case study example

When Hurricane Katrina struck New Orleans in August 2005 extensive flooding occurred, with levee breach occurring in a number of places. One of the mechanisms of failure that occurred was the failure of wall sections constructed on top of and integrated into the levees. See Section 3.2 of this report for more details and examples.

Photo 5.13 New Orleans, London Avenue Canal (Photo: www.online-utility.org)

5.7 Transition 7: Transition between a levee segment and a flood wall

Description :

Illustration :

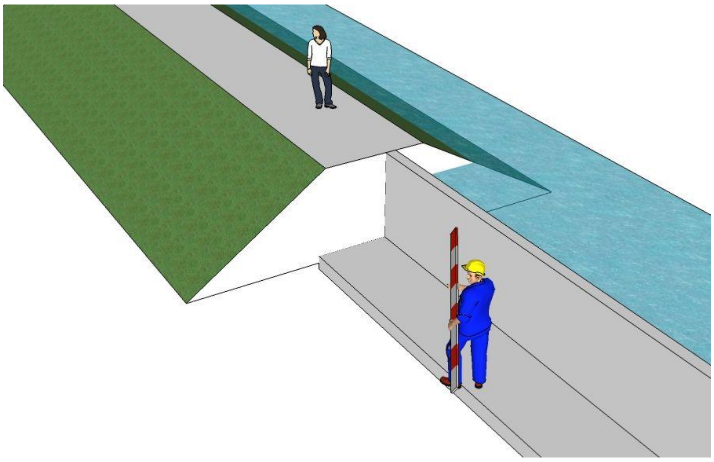


Figure 5.11 transition between a levee and a flood wall

Photos :

Photo 5.14 transition between a flood wall (front, left) and a levee (back) in New Orleans, Louisiana USA (source ILH, USACE)

Photo 5.15 transition between a levee and a flood wall in Cape Girardeau, Missouri, USA (source ILH, USACE)

Main failure modes associated with this type of transition:

- contact erosion along a hard structure

- surface erosion due to turbulence or other specific complex hydraulic action (caused by current and/or waves)

Detection of the transition:

- ➢ records, archives, plans for proposed works
- ➢ visual inspections (normal conditions),
- ➢ aerial photos.

Detection of problems:

- ➢ visual inspections (normal conditions, during or post flood),
- ➢ topographic monitoring,

Problem indicators:

- ➢ changes in profile,
- ➢ signs of external erosion,
- ➢ signs of internal erosion,
- ➢ signs of water flowing at the contact area.

Best practice to avoid problems at this type of transition:

Design:

- ➢ construction of a progressive transition (gradual change in the geometry) rather than an abrupt change, penetration of the floodwall inside the levee,
- ➢ surface protection against erosion of the levee

Repair / retrofit:

- ➢ sealing of the contact between floodwall and levee
- ➢ surface protection against erosion of the levee

Management:

- ➢ nothing specific,

5.8 Transition 8: Transition between two parts of a levee with a different surface revetment

Description :

This transition relates to changes in the form of the outside revetment of the levee, be it on the water side, the land side, or the crest. The outside geometry does not change.

Illustration :

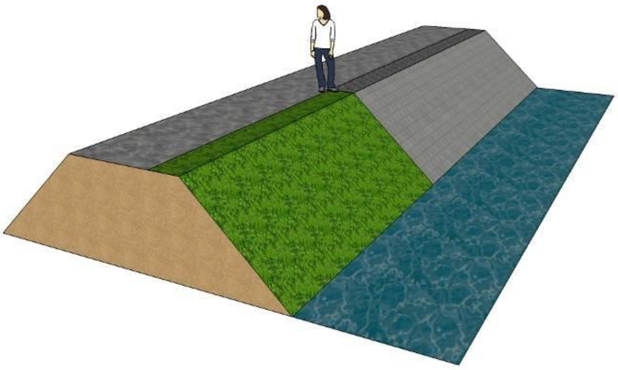


Figure 5.12 Illustration of a transition between different surface revetments

Photos :

Photo 5.16 A stairway on a levee (Loire river). Transition between grass cover and stonework.

Photo 5.17 Runoff water channel on a levee slope. Transition between grass cover and stonework.

Main failure modes associated with this type of transition:

- surface erosion due to turbulence (roughness) from flow along the levee surface,
- surface erosion from a concentration of runoff and/or overflowing down the levee slope,

Detection of the transition:

- records, archives, plans for proposed works
- visual inspections (normal conditions mainly, also during or post flood),
- aerial photos.

Detection of problems:

- visual inspections (normal conditions, during or post flood),
- topographic monitoring,
- geophysical survey (erosion behind revetments)

Problem indicators:

- changes in profile,
- revetment erosion,
- signs of erosion underneath the revetment,
- signs of water flowing through the revetment (in either direction).

Best practice to avoid problems at this type of transition:

Design:

- construction of a progressive transition (gradual change in the roughness of the revetment) rather than an abrupt change
- use of rip-rap with smooth grain size distribution rather than gap-graded,
- use of appropriate filter design, locate the transition farther from the active river bed, hence reduce exposure of the transition to high water speed and stress.

Repair / retrofit:

- same as design

Management:

- nothing specific,

Case study example

During the December 2003 flood in the Southern Rhone area, a small canalised river (the Vigueirat) overflowed in many places, along a length of some kilometres. A single breach occurred, just downstream a rip-rap protected area. No witnesses could confirm the mechanisms involved, but the fact that the breach occurred precisely at this point demonstrates that it was probably a weak point.

5.9 Transition 9: Transition between two parts of a levee with different cross sections

Description :

This transition relates to changes in the internal and / or external cross section of the levee, which is different from one segment to the next one. Usually this happens when there was some historic event (breach or major damage followed by repairs, preventative reinforcements) leading to this difference. The text in this form can also apply to the transition between a levee and natural ground at its extremity.

Illustration :

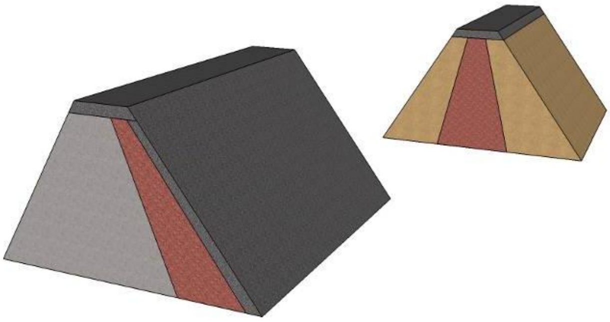


Figure 5.13 Illustration of a transition between different cross sections

Photos :

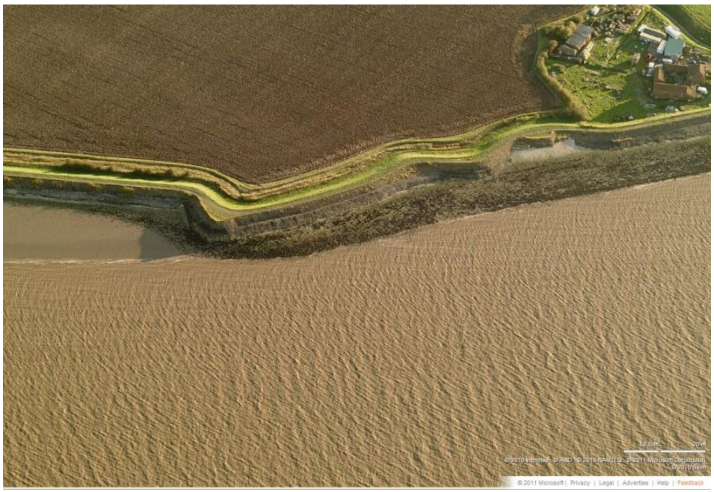


Photo 5.18 Varying section profile of flood levee in the Humber Estuary (UK)

Main failure modes associated with this type of transition:

- contact erosion between different soil materials
- surface erosion due to turbulence or concentrated flow (including waves) (in the case of a transition with a different outside geometry)

Detection of the transition:

- records, archives, plans for proposed works
- geophysics, boreholes
- visual inspection (in the case of a transition with a different outside geometry)

Detection of problems:

- visual inspections (during and post flood)
- topographic monitoring
- geophysical survey

Problem indicators:

- signs of surface erosion
- signs of seepage through the levee
- signs of profile distortion (slips, settlement etc.)

Best practice to avoid problems at this type of transition:

Design:

- continuity of water-tightness
- continuity of drainage (if relevant)
- continuity of filtration between different materials
- no abrupt changes of outside geometry
- continuity or smooth change of surface protection.

Repair / retrofit:

- creation of a watertight barrier on the water side or in the middle of the levee, expanding in both segments
- creation of a filtered draining fill on the land side of the levee, expanding in both segments

Management:

- nothing specific

Case study example

During the 1970s, reinforcements were made to long stretches of levees on the River Loire. Two main approaches to reinforcement were used, both with the objective of avoiding internal erosion. On a majority of the levees, landside fill was put in place, either as draining fill or fill with a drain at the bottom (see the next two figures).

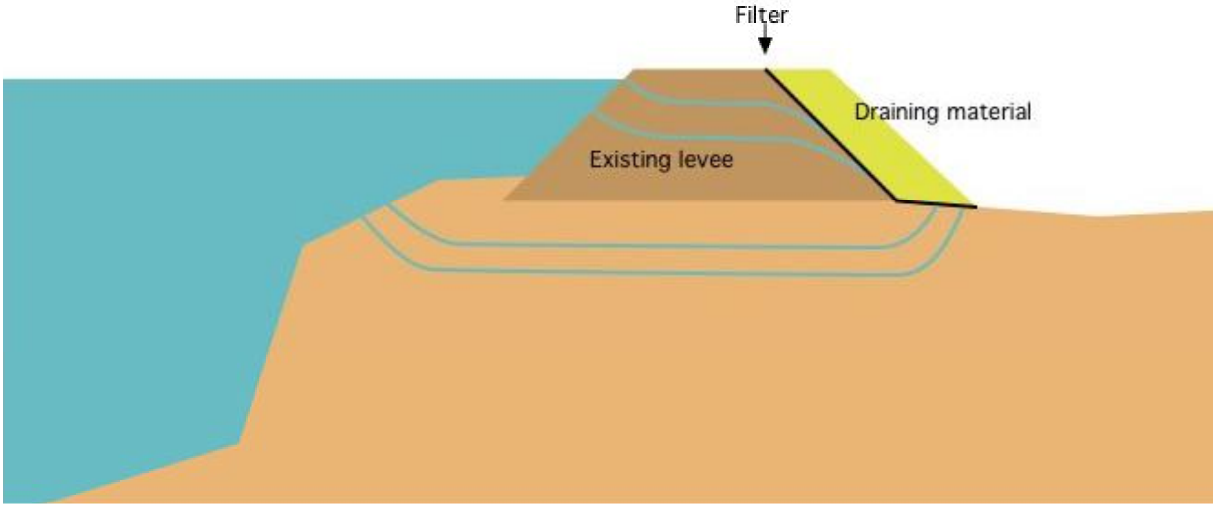


Figure 5.14 Reinforcement with a draining shoulder on the landward side of the levee

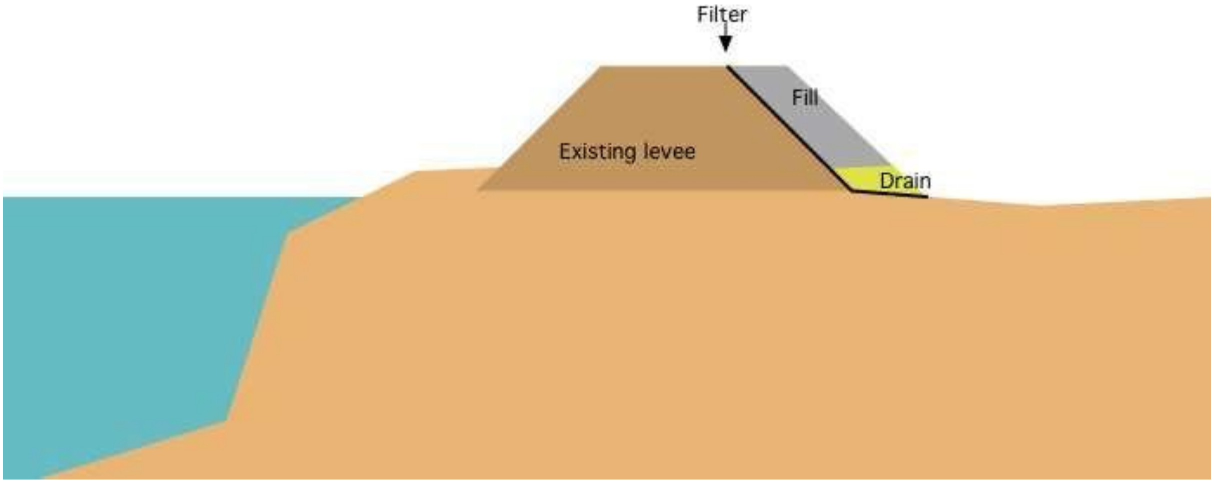


Figure 5.15 Reinforcement with a drained shoulder on the landward side of the levee

When there were land use constraints on the landward side of the levee, another solution was used, such as the use of impervious fill on the river side (see next figure).

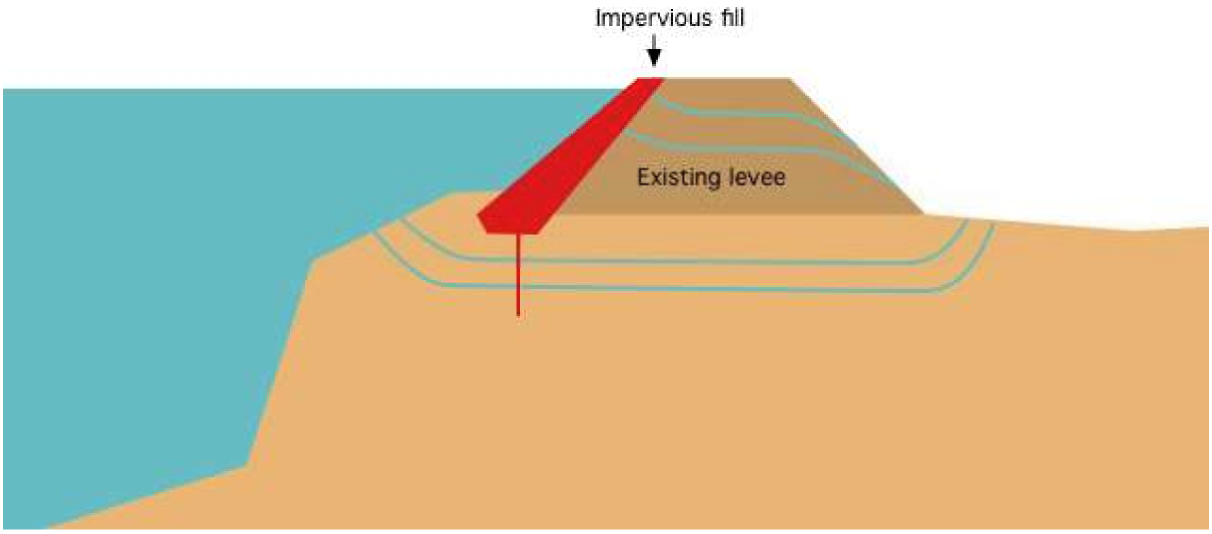


Figure 5.16 Reinforcement with an impervious shoulder on the riverside of the levee

In some specific areas, where the levee was close to the river and there were land use constraints on the landward side, no reinforcement measures were made.

No special design details were used at the junction between two stretches of a levee that were treated differently; this can cause internal erosion problems, as there is no continuity of the main impermeable layer and associated filter components.

Nowadays, levee management organisations are beginning to define reinforcements with detailed consideration of the transitions, both at the junction of two stretches treated differently, as well as for other solutions for the areas that were not originally treated.

6 Including structure transitions within flood risk assessments

Assessment of the performance of a system of flood defences, rather than of an individual flood defence structure, is often required as part of a flood risk assessment. The way in which system performance is assessed varies between countries and according to specific assessment; national policy and cultural approaches have a significant impact on the approaches taken. However, analysis of system performance typically requires the assessment of each component of the system in a methodical manner. Historically, this has evolved by summing the analysis of each of the individual levee segments. In many countries and organisations, little attention has been paid to the formal inclusion and assessment of transition points.

Within England & Wales, and The Netherlands, probabilistic methods are used to analyse system flood risk. Fundamentally, the approach considers how the flood defence structure performs over a range of load conditions and what might happen when failure occurs. The system adopted in England & Wales links potential inundation and impacts arising to the performance of each specific defence structure or length for each load condition considered (Sayers et al., 2004). Hence by summing all of the performance conditions considered, overall flood risk may be calculated, and contributions to this flood risk may also be attributed to specific flood defence structures and lengths. This provides valuable information for prioritisation of asset management activities helping to ensure the most effective use of invariably limited resources.

However, whilst such an approach offers an effective framework for risk analysis and management, the accuracy of the results depends upon the degree to which the overall system response has been simulated. At present, the contribution of transitions to overall system risk is not considered. Analysis of historic events such as at New Orleans (US Army Corps Engineers (USACE), 2007) and in the south of France, for example, on the River Rhone (Bonnefoy and Royet, 1994) suggest that some types of transition provide a focal point for failure mechanisms and hence pose a greater risk than might otherwise have been recognised. Inclusion of transitions within system risk analyses should therefore be undertaken in order to improve the accuracy of risk prediction.

Since considerable work has been undertaken over the past decade to develop system risk models it is important to identify a way in which transitions may be included within the established calculation framework. Two fundamental approaches have recently been identified during research being carried out by HR Wallingford as part of a programme to improve the representation of defence fragility for the UK Environment Agency:

1. Direct identification and analysis of transitions as specific ‘units’ within the system risk model
2. Adjustment of the performance assessment of the defence lengths associated with the structure transition

Each of these two approaches has implications for the analysis work required. Choosing Option 1 - direct identification and analysis of transition structures within the overall analysis framework - requires adaptation of the framework for analysis, along with the development of limit state equations representing the failure modes envisaged for each transition type. Descriptions of the transitions, failure modes and limit state analysis may be summarised through extension of the earlier failure modes work under the EU FLOODsite project (www.floodsite.net) (Allsop et al., 2007). At the time of writing it was not clear whether such analyses would be feasible for the range of transitions and failure modes likely to be typical of flood defence structures.

The second approach offers an easier and quicker solution for analysis, although maybe not as rigorous a solution in the longer term. The approach is to adjust the performance assessment of the defence length(s) associated with the transition to reflect the increased risk of failure. This may be undertaken through integrating analysis of the transition failure process into creation of the fragility curve for the defence length, or by adjusting the 'base' defence length fragility curve using expert judgement. The latter offers the simplest means of including the effects of transitions within the existing analysis framework.

In the longer term is might be foreseen that transitions within and between defence lengths are identified and analysed uniquely (ie. Not recorded and represented as part of an adjacent defence structure). This would be more consistent with the steps required to record, inspect and maintain transitions as part of a range of flood defence structures. Under this approach, individual transition performance analysis (i.e. Option 1) would be a better way to analyse the risks posed.

7 Conclusion and needs for further research

7.1 Working with transitions – problems and solutions

Whilst flood defence asset managers, who routinely inspect and manage defences, are typically aware of the practical risks posed by transitions between structures, these risks are not yet routinely included within system flood risk analyses. A series of flood events such as in New Orleans (USA), Bangkok (Thailand) or on The Rhône (France) have highlighted that such transitions can create weak points within flood defence systems. Hence transitions within flood defence structures need to be routinely identified and managed as part of the overall flood risk management programme.

Research under the FloodProBE project has provided a framework for the definition of transition types. Consideration of what constitutes a transition shows that there are far more conditions where transitions occur than might initially be considered. Structures buried within, built on top of and through levees all create transitions, as do structures that partially encroach into levees, and sometimes into the crest, from either the land or water sides. The FloodProBE work provides definitions and a flow chart for classifying these transitions.

Along with the classification of transitions, the research also provides a series of transition descriptions - one for each type of transition. A standard format has been applied for each description within which the transition is described, along with diagrams and photos. Typical problems associated with the transition type are identified, along with indicators of those problems that might be seen during a visual inspection of the levee. Subsequently, steps towards potential solutions for both the design and post construction stages are provided as guidance for the asset manager. At this stage, the solutions presented are generally generic rather than detailed. It should be recognised, though, that the best solution remains to avoid creating transitions wherever possible.

Rec.1: Transitions invariably create a risk point within a flood defence structure, hence wherever possible the creation of transitions should be avoided. Where avoidance is not possible, then the failure mechanisms involved and hence the risks associated with the transition should be assessed, and the design for building or repair should be tailored accordingly.

7.2 Taking transitions into account

7.2.1 For asset management

The goal in reviewing and developing the information on transitions was to provide guidance on how to identify and manage the risks posed. From a practical perspective, it also became clear that identifying where transitions existed was also a problem. For the situations where transitions arise from interfaces between structures buried within or even under the levee, records do not always exist and a visual inspection does not always show any signs of the transition. In this situation a review of historic records and asset manager’s field experience is probably the only initial method that asset managers could employ in order to develop a long list of transition structures for assessment.

Rec.2: In order to manage transitions it is necessary to identify them and their associated problems. Hence transitions should be recorded as specific items within an asset management database. In this way they will be formally recorded, inspected and managed.

Rec.3: If transitions are formally recorded, inspected and managed, then guidance for visual / routine inspection (as is currently provided for levee and flood defence structure inspection) is required.

7.2.2 For flood risk analyses

Once transition structures have been identified they may be assessed for any problems. The summary information provided tries to identify problem indicators that may be observed in the field, along with potential failure modes and subsequently solutions. However, it is clear that the degree of knowledge around some of the processes that can occur is limited and the subject of ongoing research.

Rec. 4: Since the risks posed by transition structures affects the overall performance of a system of flood defences, these risks should be included within any overall analysis of performance.

Historically, the analysis and inclusion of risks generated from transitions has not been undertaken – at least within the UK and Dutch frameworks for flood risk analysis. Inclusion of transitions within a modelling framework for risk assessment then poses a number of challenges. For a rigorous assessment it is necessary to include transitions as point or individual structures, against which performance data has to be attributed. This requires adaptation of the analysis framework to incorporate such structures plus sufficient knowledge of the potential failure mechanisms as to allow performance curves (fragility curves) to be produced for each transition structure under a range of load conditions. It is clear that current the understanding and characterisation of some of the processes is not at a sufficient stage to provide a reliable numerical representation of the processes (e.g. the various different forms of internal erosion, as reported in WP3.1.1 of the FloodProBE research programme). However, in the absence of numerical models of the failure process, judgement may be used to develop initial estimates of performance based upon field experience.

A simpler approach for the initial inclusion of transitions within flood risk models is to adapt the performance curves of the adjacent flood defence structure(s) to better represent the overall risk posed by the defence length(s) and the transition. Again, this could be achieved numerically or by inclusion of judgement based performance curves.

Rec. 5: The contribution of transitions to overall flood risk should be assessed (within system risk modelling) either through (i) direct identification and analysis of transitions as specific 'units' within the system risk model or (ii) adjustment of the performance assessment of the defence lengths associated with the structure transition.

7.3 Gaps in knowledge and management

Whilst the analysis of transitions is an important issue which would help to improve the accuracy of system risk models, and assist day to day asset and hence flood risk management, there are clearly a number of development tasks and gaps in knowledge that need to be addressed to help in this process.

7.3.1 Building from other FloodProBE Project research actions

The various work actions under FloodProBE WP3 all contribute towards a better understanding of levee performance and management, hence are interlinked. Some actions provide specific knowledge which supports the identification and analysis of transitions.

FloodProBE Task 3.1.1 advances our understanding of internal erosion processes. This knowledge is fundamental to transition failure processes, and is discussed further in Section 7.3.2 below. The knowledge provided improves our ability to analyse the risk on internal erosion at transitions, but there is still a significant lack of knowledge and tools to cover all forms of internal erosion, and those processes initiated at transitions.

FloodProBE task 3.2 addresses the use of geophysics and remote sensing data. The work on geophysics has provided a clear understanding of the different methods and what they can be used for in the assessment of standard levees, but has not gone further than identifying the fact that geophysics techniques are disrupted by some transitions (e.g. reinforcement in hard structures, as shown by the Humber surveys). Hence a further stage of research is now required to build from the transitions typology and to show how the different geophysical techniques may be used (or not) to locate the extent and condition of transitions.

Rec. 6: *R*esearch is required to build from the transitions typology and to show how the different geophysical techniques (FloodProBE Task 3.2) may be used (or not) to locate the extent and condition of specific transition structures.

FloodProBE Task 3.2 also addresses the use of remote sensing data (LIDAR). This has been shown to be excellent for the detailed assessment of the surface features of a levee, and hence for an initial survey of potential transition structures. The Orleans pilot study demonstrates this very well. The Humber transitions case study also shows how use of a tool such as Google Maps can allow a similar process to be undertaken with free publicly available data, but with less precision than from a specified LIDAR survey.

Research under FloodProbe Task 3.3 shows how combining and analysing data of different types and sources can allow you to improve your analysis of levee performance. These concepts also apply to the identification of, and performance assessment of transitions.

7.3.2 Understanding and predicting internal erosion processes

Internal erosion is often a contributory factor to failure modes associated with transition structures; hence a clear understanding of these processes, along with methods for performance assessment is essential. In particular, this relates to the processes that can occur at a soil / structure interface and how to improve resistance to erosion in this area (and hence providing the physical basis for generation of performance curves that underpin any numerical flood risk assessment). The following questions are typically asked:

- What are the physics involved in (internal) contact erosion for both 'soil/soil' and 'soil/structure' interfaces? In particular, if no empty space exists around a pipe or structure crossing, does internal erosion have a greater chance to develop at the transition than in the body of the adjacent soil?
- How do you characterise the 'soil/soil' and 'soil/structure' interface?
- How do you characterise resistance to erosion at the 'soil/soil' and 'soil/structure' interface?
- How do you improve resistance to erosion at the 'soil/soil' and 'soil/structure' interface?
- What is the cause for initiation of contact erosion at the 'soil/soil' and 'soil/structure' interface? The driving force is hydraulic head, but how can we characterize the resistance?

Rec. 7: The various mechanisms of internal erosion are often a contributory factor to failure modes associated with structure transitions; hence a clear understanding of these processes, along with methods for performance assessment are needed.

7.3.3 Quantifying the risks posed by structure transitions

The research here has demonstrated the importance of structure transitions and provided a framework for identification. Methods for risk quantification to allow routine inclusion within flood risk analysis and management procedures are required. Hence, for each transition type, representation of the potential failure process is required. This will then allow integration of the risk contribution from transitions into the existing frameworks for analysis – either as an adjustment to the performance of the adjacent structures or as a unique risk contribution from the transition itself.

Rec. 8: Develop a representation of failure modes for each of the transitions defined within the framework (limit state equation, empirical equation, failure mode analysis based index method etc.). From these representations, develop fragility curve representations for each transition and / or rules for adaptation of existing defence structure assessment methods and fragility curves.

Rec. 9: Include structure transitions into system flood risk analysis models and methods

7.3.4 Improving the design, construction and management process

Having established the significant role that transitions can play on overall flood risk, we need to ensure that the significance of transitions is understood by everyone within the design and construction chain, as well as by flood risk managers. Ultimately this should lead to a reduction in flood risk through improved design and management of transitions.

There are three key aspects to undertaking this process:

1. Raising awareness and providing guidance on the issues associated with transitions, along with potential options for remedial measures or redesign.
2. Provision of specific methods for the performance analysis of each specific type of transition
3. More detailed guidance on potential solutions for problem transitions (moving from the current generic guidance to transition specific solutions)

In order for a levee manager to decide upon the most appropriate measures for dealing with a transition it is necessary to assess the risk between rebuilding and retrofitting a solution. Whilst the direct costs of such work can be easily estimated, the different risks resulting from differing levels of resulting performance require fragility curves (performance curves based upon limit state analyses, expert judgement or a combination) to be produced for each transition, with sufficient detail to differentiate between the transition condition and potential failure modes arising from different design variations and retrofit solutions.

Rec. 10: Building from Recommendations 8 & 9 above, development of more detailed representations of failure modes in support of the risk based assessment of different design and retrofit solutions. An initial step would be to define more detailed, different options for design and retrofit of each transition type.

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