

# Internal erosion in dams and dikes: a comparison

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**Abstract:** Dams and dikes are both water-retaining earth embankments. These are vulnerable to internal erosion but specific differences lead to varying vulnerabilities to different types of internal erosion:

- Dams are usually zoned, with potential filtering capability to arrest piping if it is initiated, while dikes are more commonly unzoned and incapable of arresting erosion.
- Dams are usually higher than dikes, therefore the pressures are higher and leakages are more damaging.
- Dams have usually been built to their present height in one stage, dikes have often been improved over time, with a present crest height considerably higher than the initial height. In case of a significant raise, the original design assumptions no longer apply and modifications to the existing structure to provide sufficient safety may be costly.
- Dams have a limited crest length, while dikes may extend for hundreds of kilometres. This poses quite different possibilities and challenges for inspection and monitoring.
- Dams are built across a stream to block it, while dikes are built along it and only guide the stream. For the design and construction of dams the flow must be sufficiently blocked, including through the foundation. Many dikes on untreated sandy foundations are vulnerable to backward erosion.
- Dams always require provisions to pass the flow, for dikes this is rare. Concentrated leak erosion along culverts and spillways often poses a threat to dams but rarely to dikes.

Each of the above points will be illustrated by practical cases, focusing on the various mechanisms of internal erosion which are dealt with first.

Keywords: Internal erosion; dams; dikes, levees, flood and canal embankments; case histories; monitoring; remediation.

## 1 INTRODUCTION

The recent publication of ICOLD (International Commission on Large Dams) Bulletin 164 on internal erosion in existing dams, dikes and levees and their foundations (ICOLD 2016, 2015) has brought together knowledge and experience from research and practice to provide guidance on the causes of internal erosion and how to investigate, analyze, remediate and monitor earth water-retaining embankments to protect them against failure by internal erosion. ICOLD Bulletin 164 is referred to as 'the Bulletin' in this paper.

The ICOLD European Club Working Group on Internal Erosion (EWGIE) has played a central role in bringing this knowledge together. At its heart is the major advance in understanding of the mechanisms of internal erosion, an issue which has previously been dealt with by disconnected research programs, and approached in practice by qualitative and quantitative risk assessment. The mechanics of internal erosion, which apply to all types of earth water-retaining embankments, are described in the following section. Subsequent sections compare how internal erosion affects, and is dealt with, in dikes and embankment dams.

## **2 INTERNAL EROSION MECHANICS**

### **2.1 Internal erosion occurs when hydraulic forces exceed resistance**

Recent advances in understanding show that internal erosion occurs in earth water-retaining embankments when the hydraulic forces imposed by water flowing through openings or seeping through pore spaces exceed the ability of the soils in the embankments or their foundations to resist them.

### **2.2 Four mechanisms of initiation of internal erosion**

As detailed in the Bulletin, internal erosion is initiated by one of the following four mechanisms:

1. Concentrated leak erosion in which water flowing through cracks or openings erodes soil particles from the walls of the cracks or openings.
2. Contact erosion which occurs at the interface of coarse and fine soil layers when the velocity of water flowing through the coarse layer is sufficient to erode soil particles from the fine layer.
3. Suffusion in which water flowing through the pores in gap-graded soils erodes fine particles through the pore spaces in the matrix of coarse particles.
4. Backward erosion which occurs in sandy foundations below earth embankments able to ‘hold a roof’ above backward erosion pipes that initiate in the foundation sand at the downstream toe of the embankment and progress upstream (‘backwards’), eventually breaking through into the reservoir or waterway retained by the embankment.

The Bulletin makes it possible to estimate the hydraulic load, usually expressed as the water level in the reservoir or waterway, at which internal erosion will initiate. The highest hydraulic loads usually occur during floods.

### **2.3 Four phases to failure by internal erosion**

Internal erosion proceeds towards failure in four phases, as follows:

1. Initiation by one of the four initiating mechanisms listed above when the hydraulic load, usually expressed as hydraulic gradient and water level, exceeds the ability of soils in the embankment to resist it
2. Continuation as eroded particles continue to move after erosion is initiated. Erosion may be arrested at this phase if there are effective filters or fill capable of filtering downstream of the eroding zone, usually the core in a zoned earth embankment. In unzoned embankments (often called ‘homogeneous’ dams or embankments) no other zones are present; consequently unzoned embankments are markedly more vulnerable to internal erosion failure than zoned embankments.
3. Progression, as the erosion forms erosion pipes or enlarges cracks or openings
4. Breach, when collapse of the embankment occurs as erosion pipes enlarge, or excess flow causes collapse of the crest or instability of the downstream slope.

### **2.4 Filtering capabilities of fills in zoned embankments**

Chapter 7 in Volume 1 of the Bulletin explains how to assess whether the fills and filters, if any, in zoned embankments would be capable of filtering eroded particles, and thereby arresting erosion and preventing continuation towards failure. The ‘filter erosion boundaries’ concept (Foster, 2007) can be applied to determine whether the fills in the zones downstream of the eroding zone, usually the core, are no-, some- or excessive-erosion filters, arresting erosion after increasing amounts of sediment-laden leakage and damage, including sinkholes in excessive-erosion ‘filters’. Fills or filters coarser than excessive-erosion filters cannot arrest erosion, and erosion if initiated would continue unchecked towards failure.

The Bulletin includes an example of an investigation to examine if the glacial till shoulder fill of a typical British dam would filter and arrest erosion of particles from the puddled clay core.

The capability of filters in embankments constructed with filter zones before reliable filter criteria (e.g. Sherard and Dunnigan, 1989) became available should be examined using the filter erosion

boundaries approach. The Bulletin includes an example of ineffective widely graded filters at Churchill Falls Dike, which allowed erosion to continue, at normal water levels (i.e. at low hydraulic loads), to the extent that sinkholes formed. Water levels were drawn down before failure occurred, but the filters were at best excessive-erosion filters, or more likely were so coarse that erosion would have continued to failure if the water level had not been drawn down.

Most dikes were built long before filters were applied. With increasing water levels, effects of subsidence and higher demands on flood safety, major improvement works on existing dikes may be needed to address issues resulting from the lack of a proper filter in the embankment and its foundation. The International Levee Handbook provides extensive advice with practical examples, like the Natomas Levee near Sacramento, USA (CIRIA, 2013:1028-1030, 1056-1058).

## 2.5 No filtering capability in unzoned ('homogeneous') embankments

Unzoned dams have no filtering capacity because there are no more-or-less vertical zones downstream of an eroding zone which might provide some kind of filter. This is illustrated in Figure 1 where the concern is contact erosion (CE) at the interface between more-or-less horizontal layers of coarse and fine fills in an unzoned dam. If contact erosion initiated, eroded particles from the fine layer would be carried through the coarse layer to the downstream face, possibly leading to settlement, overtopping and collapse.

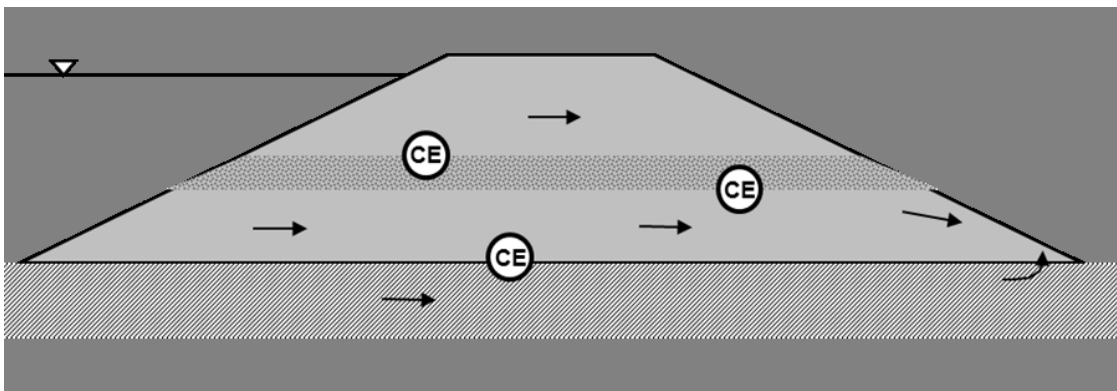


Figure 1. Showing vulnerability of an unzoned dam to contact erosion (CE) at the interfaces between coarse and fine layers. Eroded fine particles could be carried to the downstream face, possibly resulting in crest settlement, overtopping and collapse (from Beguin et al, 2009).

## 3 PROTECTING UNZONED EMBANKMENTS AGAINST INTERNAL EROSION

Many waterway embankments and older dams are unzoned, often with variable heterogeneous fill, sometimes with layers of widely differing grading. Volume 2 of the Bulletin includes examples of unzoned canal embankments where unchecked suffusion caused increased leakage at Jonage Dike and settlement at Kelms Dike. The increasing leakage was identified by routine measurements of drainage flow and the settlement by routine leveling along the crest. The embankments were remediated by grouting over the lengths affected.

Remediation is dealt with in Chapter 10 of Volume 1 and Chapter 5 of Volume 2 of the Bulletin. Alternatives to grouting include 'barriers' – sheet piles, diaphragm walls and secant piles – or filters – usually within filtered berms constructed over the full height of the downstream slope of unzoned dams and embankments to filter eroded particles there.

Barriers are often a convenient alternative where the foundations are also vulnerable to internal erosion. Examples from Volume 2 of the Bulletin include Shikwamkwa replacement dam where a deep plastic concrete cut-off wall through the foundation and the lower fill linked to the fine silty sand core.

The 70 km of the Feather River flood management embankments in California, USA, were remediated by various combinations of embankment core and cut-offs through lower fill and into the foundations. At many dams and embankments, short barriers are installed along the crest to block cracks formed by desiccation or differential settlement.

In addition to providing previously unzoned embankments with filtering capacity, filtered berms also reduce seepage velocity in coarser layers, thereby reducing the hydraulic load imposed, possibly below that required to initiate erosion. However the downstream filters may restrict drainage capacity and thereby increase pore pressure in the embankments. This may adversely affect their stability. Also, eroded particles accumulated on the inner filter impose hydraulic pressure on the berm, which must be designed as a 'weighted' berm providing sufficient resistance against the hydraulic forces to prevent fracture or uplift of the berm.

Volume 2 of the Bulletin describes the filtered berm added to Matahina Dam in New Zealand. This berm was particularly carefully designed because it is to continue to provide filtering capability in the event of cracking of the fill when movement occurs along an active fault during earthquakes. The filter materials were selected to be incapable of holding cracks and thereby remain effective when such movement and cracking occurs.

## **4 INFLUENCE OF HEIGHT ON INTERNAL EROSION POTENTIAL**

### **4.1 Height and consequences of failures of dams and dikes**

The most significant consequence of the height of dams and dikes is that if failure occurs, the flood wave from high structures will be deep and likely to cause loss of life in the floodplain downstream; casualties are less likely to occur in the shallow flood wave from low structures. It is the custom to design dams to high safety standards intended to impose a very low probability of loss of life downstream. Many flood management dikes are designed to cost-benefit criteria. However, loss of life from failures of non-dam embankments, at New Orleans for example after the Hurricane Katrina embankment failures, is leading to a change and in USA the 'loss of life' criterion is now being applied to these situations too.

In France there was loss of life during floods from failures in the 200 km of flood embankments in Rhone delta. The situation has been examined by Mallet et al. (2014) and Mallet and Fry (2016) by quantitative risk analysis using the mechanics detailed in the Bulletin to identify probability of failure by concentrated leak erosion, particularly at incompletely sealed badger burrows, and by backward erosion on lengths of embankments on sandy foundations. In places there was an unacceptably high probability of failure. Remedial work is progressing to reduce the annual probability of failure to 1 in 10,000-years or lower, a high standard as demanded by the potential of failures to cause fatalities.

### **4.2 Height and hydraulic loads causing internal erosion**

The hydraulic loads that initiate internal erosion, other than suffusion, can be estimated from the methods given in the Bulletin, verified if appropriate by laboratory testing. The hydraulic load initiating suffusion must be determined by testing. The loads are expressed as hydraulic gradient ( $H/L$ ), and  $L$ , the width of the embankment, is normally known, allowing  $H$ , the water level that would initiate internal erosion, to be readily determined.

High dams and low dikes are both subject to the hydraulic loads, particularly when water level is high during floods, that may initiate erosion. However high dams often include narrow cores, low permeability zones, supported by wide high permeability zones in the shoulder fills. This subjects the cores to high gradients, which may become 'critical', sufficient to initiate erosion during extreme floods, and unless they are protected by effective filters, the erosive forces may rapidly enlarge cracks, accelerate suffusion, erode fine materials from coarse to fine interfaces, or form continuous backward erosion pipes, leading to rapid failure.

With some caveats regarding seasonal and other changes in cracking in embankments, existing embankments have demonstrated that they are resistant to internal erosion to the highest water level, usually the highest flood level, to which they have ever been subjected.

However, without investigation and analysis using the Bulletin, it is not possible to know, or pre-empt by monitoring and surveillance, the water level that will cause an embankment to fail. Failure will occur during an extreme flood, more severe than any experienced previously, with quantities of flow that cannot be diverted by emptying pipes or similar. Progression to failure will be rapid. In case of an acceptable annual probability of failure in the order of magnitude of 1 in 10,000 years, the flood level will nearly always be higher than any historical flood level. If analysis shows that internal erosion failure will occur at an unacceptably low water level, remediation will be required. A surveillance and monitoring regime can then be deployed to confirm that the remediated embankment remains in the condition that the remediation was designed to achieve.

## 5 HEIGHT INCREASES LEADING TO BACKWARD EROSION

A major difference between dams and dikes is that dams are hardly ever raised after initial completion, and if they are, usually a thorough redesign is made. Dikes on the other hand are often raised, especially in past centuries, when the main concern was with the attained crest height only. As a result, other failure mechanisms have often been neglected. This especially holds for sand layers in the foundation, underneath the original base of the dike. Knowledge about the main cause of internal erosion there was lacking at the time many dikes were built. Besides, the original height of the dike may have been insufficient to cause backward erosion.

After several attempts to describe the phenomenon of backward erosion (e.g. Clibborn and Beresford (1902) and Bligh (1907)) came close, but erred with respect to the influence of the weight of the overlying construction, in 1910 Bligh managed to capture the essence, including a practical rule for the required ratio of  $H/L$  ( $H$ =hydraulic head,  $L$ =horizontal seepage length) to be safe, with coefficients depending on the type of granular material in the foundation. This was based on his (undocumented) experience on masonry weirs in India, but it holds for any granular layer underneath a cohesive layer able to 'hold a roof' above the sandy foundation.

Based upon the forces exerted on individual grains by the seepage flow in an already existing backward erosion pipe, Sellmeijer (1988) showed why sand boils behind pipes of limited length will not lead to failure, provided that a critical head (corresponding to a critical pipe length) is not exceeded. He also showed the dependence on scale: the larger a dike, the smaller the maximum allowable ratio of  $H/L$  becomes for an otherwise given situation. In other words: Bligh's rule is less safe for larger constructions.

Recently, Van Beek (2015) explained the process at the head of the pipe ('primary erosion'), while Sellmeijer focused on the enlarging of a pipe only ('secondary erosion'). Besides, Sellmeijer's theory describes a two-dimensional configuration only – corresponding to a longitudinally uniform outflow situation at the toe of the dam or dike – while in reality three-dimensional situations are often found, e.g. a single outlet through a confining layer of a local depression or a drainage ditch leading away from the structure.

Knowledge of the causes of potential failure helps to devise prevention measures. The large scale field tests ( $L=15$  m) at the IJkdijk in 2009 and supporting laboratory tests (Van Beek et al., 2011) have led to the following measures against backward erosion that were all successfully tested in similar tests at the IJkdijk in 2012, although failure was not reached (Koelewijn, 2014):

- A controllable horizontal drainage tube under the embankment, installed e.g. by horizontal directional drilling, to intercept and drain water, reducing the flow velocity and avoiding erosion;
- A vertically inserted permeable geotextile to block particles without hindering groundwater flow. Pipes will occur as usual but will not pass beyond the geotextile, nor under it;
- A coarse granular filter, meeting all filter criteria with respect to the base soil, covered by an impervious layer. The effectiveness is roughly similar to that of the geotextile.

In the past five years, these techniques have all been developed further. The controllable drainage tube has been applied in a dike rehabilitation project over a length of 100 m at a dike along the IJssel river near Veessen (the Netherlands), as a cost-effective alternative saving an old farmhouse, considered typical for the area from a cultural-historical perspective. The situation is indicated in Figure 2.





Figure 2. Alignment of controllable drainage tube near Veessen

The vertically inserted geotextile has been applied at four different locations in the main dike along the Lek river between Hagestein and Opheusden in the Netherlands. These sections have lengths of 100 to 500 meters (Förster et al., 2015). Field tests have been carried out at a dike of secondary importance to investigate various failure mechanisms associated with this solution (Koelewijn et al., 2017a). Two other applications are in preparation, as well as large-scale tests to determine the critical head of this system.

For the coarse sand barrier such large-scale tests are part of a thorough test program carried out from Summer 2017 until Autumn 2018, in preparation of applications on real dikes (Koelewijn et al., 2017b).

## 6 INFLUENCES OF THE LENGTH OF DAMS AND DIKES

Long embankments present challenges in investigations to determine foundation conditions and in long-term surveillance and monitoring. While it is feasible to investigate the footprint of a dam in adequate detail to provide sufficient information to design for foundation watertightness and stability, this may not be feasible along long lengths of flood management and waterways embankments. An understanding of the river geomorphology can simplify matters. Figure 3 shows how river meandering and its consequences have formed differing river channels cut into the older alluvium, which have subsequently been infilled with sand and other alluvium, and often covered with a fine-grained soil or clay blanket, usually called ‘the confining layer’, at the surface.

The floodplain deposits of major rivers such as the Mississippi, for example, seem less complex than that in Figure 3, and may be sensibly the same for many miles. Within the older floodplain deposits, the river course has meandered in more recent times, leaving modern alluvium within the remnant channels. Reports of incidents of Mississippi floods in 2011 (Shrewbridge, 2016), and 1993 (Navin, 2016), seem to show that these materials are more vulnerable to backward erosion than the older floodplain deposits. Consequently, identifying the locations of such deposits by geomorphological studies (including from aerial photos, LIDAR, etc) would limit the extent of investigations and concentrate analyses on the vulnerable reaches of long embankments.

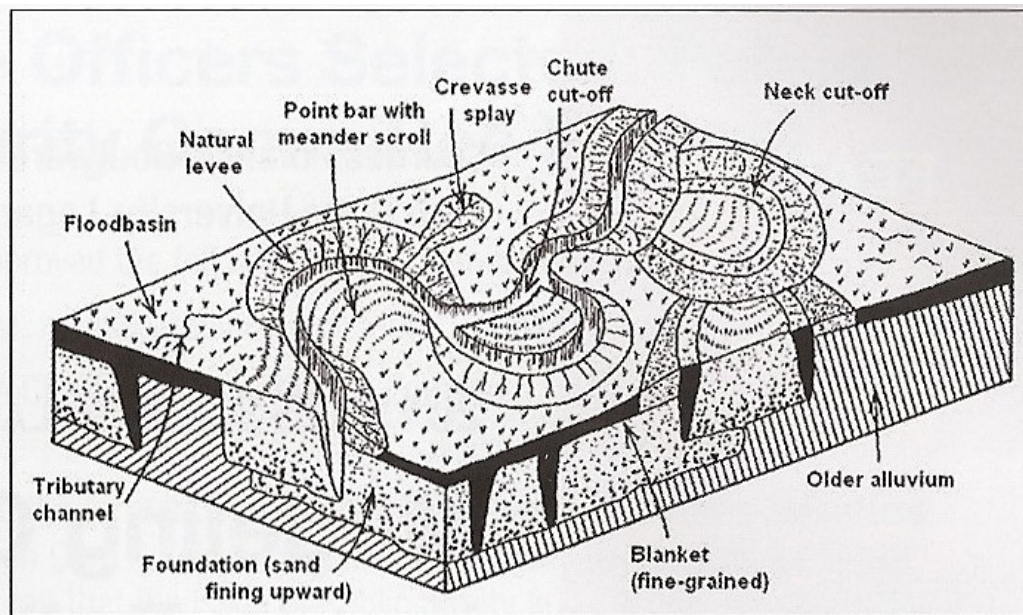


Figure 3. Geomorphic features in meandering river environment (from Polanco-Boulware 2015)

As explained in Bridle (2015) and in Chapter 6 of Volume 2 of the Bulletin, surveillance of long embankments requires regular walkovers by experienced observers at a frequency related to the importance of the embankment and potential for causing loss of life. Optical fibers provide a convenient means of monitoring the performance of long embankments. They are often installed and read by specialists once or twice a year, but this does little to alleviate the responsibility placed on observers to detect malfunction, deformation and leakage, as soon as it occurs. Monitoring by continuous reading of optical fibers would identify new leakages, and if the appropriate fiber is installed, identify new deformations, as they occur.

Dornstädter (1997) explains how soil temperature probe measurements detect seepage, based on Kappelmeyer (1957). Leakage quantities can be determined by measurement of temperature changes over optical fibers, using analytical techniques developed by Johansson (1997). Johansson and Sjødahl (2007) give examples. Radzicki and Bonelli (2010) developed the impulse response method to eliminate influences of air temperatures from the analyses for a canal dike with a constant water level. Bersan (2015) analyzed temperature measurements from one of the backward erosion experiments at the IJkdijk trial to demonstrate the possibilities of optical fibers.

The advantage of the optical fiber approach is that it can measure for leakage and locate its position to about one meter over long lengths, many kilometers, along a canal, for example, while the costs are not as prohibitive as they would be if monitoring by pore pressure meters was adopted. Fibers can also be installed in locations where direct measurement is not possible, below water level at the toe of a dam, for example. Recently, measurements with both pore pressure meters and optical fiber were obtained for a near-failure situation as reached in a research project carried out in the Willemspolder field laboratory for the vertically inserted geotextile. Here, new ditches were excavated immediately downstream of a dike of secondary importance, where sand boils already occurred occasionally in a ditch some 20 meters behind the dike. Correlations could be made between pore pressure readings, field observations and temperature measurements from two optical fibers (Koelewijn et al., 2017a).

## 7 INVESTIGATION, ANALYSIS AND REMEDIATION TO PROTECT OLD STRUCTURES AGAINST INTERNAL EROSION

### 7.1 Investigations and analyses

Investigations and tests to provide information for analyses are dealt with in Chapter 3 and Chapter 4 of Volume 2 of the Bulletin. Engineering analysis is dealt with in Volume 1; Chapter 9 suggests eight steps for engineering assessment. All analyses require knowledge of the embankment geometry, and the dimensions and materials in the zones, layers and strata in the embankment and foundations. The soil parameters required are summarized in Table 1 (taken from Bridle, 2015):

Table 1: Summary of soil and other parameters needed for internal erosion analyses

Initiating mechanism	Soil properties
Backward erosion	Foundation: Grading, permeability Fill: capable of 'holding a roof' (clay or fine silt)
Contact erosion	Both foundation and fill: Gradings of each layer to check for coarse – fine interfaces. Permeability and hydraulic gradient (and thickness) of coarse layers to estimate Darcy velocity
Suffusion	Fill (usually only, but beware some foundation materials may be suffusive): Grading, tests to estimate gradient at which suffusion will initiate, e.g. Benamar et al. (2012); in some cases tests at measured confining stress and gradient, as Fannin et al. (2008) may be warranted.
Concentrated leaks	Fill, particularly at crest and alongside spillway walls; foundations, particularly near culverts: Grading and Atterberg limits to define soil types. Main challenge is estimating location, depth and width of cracks and openings, but parametric studies may show that crack dimensions could not be eroded. Hydraulic fracture may occur in low stress zones e.g. fill above old river channels or canyons. In zoned dams, downstream fills may arrest erosion by filtering. Consider filter 'collars' to protect at spillways and culverts. Hydraulic gradient across cracks should be estimated from maximum flood level at upstream side. Hydraulic shear strength from tables in Bulletin for first estimates, from Hole Erosion Test (plastic soils) and Jet Erosion Test (non-plastic soils) as necessary.

The challenges in relation to concentrated leak erosion are included in the table. The main challenges in determining soil parameters for the other mechanisms are:

- Collecting full samples from non-plastic soils below water table;
- Measuring in-situ permeability in the relatively coarse soils in which contact erosion and backward erosion occur.

The use of special samplers, e.g. Bishop (1948); or sonic drilling and similar may make it possible to collect full samples below water table.

In-situ permeability is difficult to determine, and may vary locally within strata and change as water level changes. In-situ permeability can be measured directly at the base of advancing boreholes and by piezo-cone adaptations of the Cone Penetration Test. In-situ permeability can also be measured in piezometers. A direct and effective determination of permeability is by back calculation from direct measurement of leakage quantities through known areas of susceptible materials. The simplest means of determining leakage quantities is from direct measurement of discharge from collection systems measured over V-notch weirs, for example. The leakage is visible in ditches and in measurement chambers. If erosion is occurring, the eroded particles will probably be visible. The water level in weir



chambers can be measured automatically and transmitted and read remotely, if required. Leakage quantities can be determined by measurement of temperature changes over optical fibers, as discussed in relation to the influence of the length of dams and dikes.

## 7.2 Acting on results of internal erosion analyses

It is not possible to know if an embankment is adequately or inadequately resistant to internal erosion without carrying out analyses. The internal erosion analyses will estimate the water level at which internal erosion leading to failure will occur. In some cases this water level will be high enough, and its probability of occurrence low enough, for no remediation to be needed. In such cases, a suitable surveillance and monitoring system will be required to check that the dam's future condition and performance continue to be satisfactory. In other cases remediation will be needed to improve the dam's condition and its ability to resist internal erosion, after which an appropriate surveillance and monitoring scheme must be put in place.

## 7.3 Remediation

The two main remediation options to protect embankments against internal erosion are barriers or filters. The general issues are discussed in Chapter 10 in Volume 1 and more details are given for remediation to address the four modes of internal erosion in Chapter 5 of Volume 2. Some of the case histories in Chapter 2 of Volume 2 include descriptions of remedial measures. Examples of remediation have been mentioned in other sections of this paper.

# 8 INFLUENCES OF CULVERTS AND SPILLWAYS PASSING THROUGH EMBANKMENTS

Culverts and spillways and other conduits (sometimes collectively called 'penetrations' e.g. FEMA (2005)) passing through dams and dikes are commonly the site of failures by internal erosion. Such failures seem to occur in both high dams and low dikes. Some of the failures in the dikes in the Rhone delta mentioned earlier occurred where pipes passed under the dikes.

As reported in Volume 2 of the Bulletin, at Warmwithens dam, about 10 m high, a newly tunneled replacement low level outlet conduit was quickly washed out as the reservoir refilled on completion of the tunneling. This is thought to be the result of hydraulic fracture as the fill above the tunnel, which had been loosened by the 'ground loss' that inevitably occurs as tunneling proceeds, settled slightly as it was wetted up on refilling. Reservoir water rushed into the crack and 'floated' out the fill above the new tunnel, completely emptying the reservoir during a morning. Ferguson et al. (2013) examined the stress conditions around culverts and the potential for hydraulic fracture and cracking.

Dikes rarely have spillways, but the 15 m high unzoned Situ Gintung dam failed at the spillway position as the reservoir refilled rapidly after a drought. This is thought to have been initiated by water entering desiccation cracks below the spillway that remained open during refilling. The resulting uplift from the reservoir water was sufficient to rupture the masonry floor of the spillway allowing water to rush through the cracks and wash out the fill at the spillway position. Between 100 and 200 people were drowned in the sudden onrush of water released by the failure.

The Bulletin in Chapter 5 of Volume 2 makes recommendations on construction details to limit the possibility of washouts at low-level conduits and high level overflows. The principle is to seal by building conduits into the foundation or cut-offs below overflow channels to below the depth of desiccation cracks, for example, but to allow for leaks and arrest erosion by providing filter collars around conduits and overflow structures downstream of the seal. Care must be taken to provide sufficiently large capacity drainage outlets from the filter collars to avoid uplift and rupture from water accumulating at reservoir pressure below conduits or below overflow channel floors. The International Levee Handbook deals with practical design solutions for these issues in Section 9.15.4 (CIRIA, 2013:1165-1179).

## 9 CONCLUSIONS AND RECOMMENDATIONS

In their vulnerability and response to internal erosion dams and dikes have much in common. Both behave in response to the mechanisms of the four modes of internal erosion. Internal erosion initiates when the hydraulic load, usually expressed as water level, exceeds the ability of the soils in the embankment to resist them.

Failures of dams are often considered more dangerous than dike failures, but application of a 'loss of life' criterion may give similar outcomes and seems more appropriate in the light of the tragic loss of life in New Orleans and elsewhere resulting from inundation after dike failures. Higher demands and an increase of knowledge on the failure modes seems to have the largest impact on the oldest structures, often dikes. Remediation measures are more cost-effective if they interrupt failure modes instead of simply applying sufficient volume. The greater extent of dikes as compared to dams makes comprehensive monitoring more of a challenge for the former. The emerging use of the optical fibers may prove very useful in this regard.

Effective remediation of old structures against internal erosion requires proper investigation and analysis of the current situation, as outlined in both volumes of the recent ICOLD Bulletin on internal erosion (ICOLD, 2015, 2016), applicable to both dams and dikes. Penetrations like culverts and spillways provide challenges of their own. In this regard, the Internal Levee Handbook (CIRIA, 2013) may prove its value too.

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