

Internal Erosion at Existing Dams: an Outline of a Proposed ICOLD Bulletin

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SYNOPSIS. The improved understanding and investigations on-going at dams and levees in Europe and elsewhere (notably Australia, Canada, Australia and USA) has led to a proposal to draft an ICOLD bulletin on assessing the vulnerability of existing dams without filters to internal erosion and how to deal with any deficiencies. The paper is an early version of the proposed bulletin.

INTRODUCTION

Internal erosion is one of the major causes of dam failure. When constructing new dams protection against internal erosion is provided by filters (ICOLD Bulletin No. 95, 1994), however, many older existing dams do not have filters and may therefore be vulnerable to internal erosion. This paper sets out the structure of a new ICOLD Bulletin (Bridle, 2009) and includes some examples of the content.

The purpose of the paper is to raise awareness of developments in Europe and to encourage UK inputs into the Bulletin in terms of case histories, current practice and other evidence to improve the quality of the Bulletin.

STRUCTURE OF BULLETIN

The Bulletin will be structured as follows:

- A statement of the problem;
- Description of the processes that lead to a failure through internal erosion;
- The tools and techniques that can be used to assess the vulnerability of existing dams to internal erosion;
- Methods of detection of serious progressive internal erosion;
- What interventions might be made to protect vulnerable dams;
- Criteria that can be used to assess the risks if works are not carried out, and thus when and what level of investment is appropriate;

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- Bibliography of recent and key papers relating to internal erosion.

It will include case histories and flowcharts to take practitioners through the process to establish vulnerability to erosion and how to deal with it. These will be supported as far as practicable by appendices with more detailed guidance and summaries of research results on individual issues.

STATEMENT OF PROBLEM

Most failures through internal erosion occur during first filling of the reservoir. Examples of failure by internal erosion in the long term are few but there are many records of internal erosion incidents where erosion did not lead to failure, but was detected before failure occurred. It is estimated that in the United Kingdom's population of about 2,500 dams registered under the Reservoirs Act, there are about 1,600 incidents for every recorded failure. About 60% of the incidents appear to be related to internal erosion, with typically two serious erosion incidents a year (Brown & Gosden, 2008). However in France's population of about 10,000 dams and 9,500 km of canals or dykes, about one failure per year of a small dam or dyke is reported. This has led to the question: "Why is there such a difference in the number of failures of water retaining structures through internal erosion between the two countries?" Although we do not yet have the answer, our understanding of the factors determining internal erosion has developed significantly in recent years. This includes a realisation that internal erosion can occur only when material properties, hydrodynamic properties and stress state of the materials in the dam are such that erosion of small particles can be initiated and continued to carry them through the dam to cause failure.

While there may be few long term failures caused by internal erosion, it should be remembered that failure can cause multiple deaths. The 2009 failure of Situ Gintung dam in Jakarta, Indonesia, many years after construction, may have resulted from internal erosion, and caused at least 58 deaths. The Dale Dyke failure in Great Britain in 1864 caused over 250 deaths and the Teton Dam failure in the USA in 1976 caused 11 deaths. Both were from internal erosion on first filling of the reservoir.

Internal erosion is commonly described as 'internal erosion and piping' but piping is actually the culmination of a process of erosion in which a number of steps must occur and be sustained in order that a 'pipe' develops through the dam and allows the passage of considerable quantities of water which cause erosion leading to a breach. Piping is the major concern about internal erosion but, in the long term, many erosion processes, other than piping, occur and must be detected to prevent piping. They may be triggered by ageing or extreme loadings. During the ageing process the

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gradual erosion of material from the dam may occur eventually leading to sufficient loss to cause the crest to collapse, the slope to slide or washout alongside a culvert or a spillway. Under extreme loading conditions, during an earthquake for example, when the load is redistributed within the dam, openings may occur allowing water to rush in and initiate and continue erosion. Perhaps the most severe loading conditions, however, are when extreme floods are experienced or flooding continues over a long period. In these circumstances the water level, the seepage gradient and the seepage velocities are higher than previously experienced in the dam and this may provide sufficient energy to complete the process of erosion through the various stages that must occur if erosion is to lead to the breach of a dam.

THE PROCESSES INVOLVED IN INTERNAL EROSION

In proposing a framework for risk assessment, Fry (2007) suggests that there are eight steps in an erosion process, shown in Table 1 of Brown and Bridle (2008) and described below:

Step 1 - Loading

All the loading conditions need to be considered. The main loads exerted on dams are hydrostatic and seismic loads. However, other potential loads should not to be forgotten: environmental (animal holes, desiccation cracks, tree roots) and human loads (explosion, acts of terrorism, vandalism or accidents). The most dangerous are sudden extreme loadings, such as earthquake loadings, or exceptional loads imposed over a long period, for example, by sustained high water levels during long periods of flooding.

Step 2 - Location

Foster, Fell & Spannagle (2000) give international examples of incidents and failures. They distinguish internal erosion failures occurring through the body of embankment dams, through strata in the foundations of dams and through the dam to the foundation. This requires the identification of zones in the dam, or local variations in the dam or the foundations which create conditions in which seepage occurs and may be a site for erosion. Dealing in turn with some failures caused by ageing:

Piping through embankment

The interfaces between dam fill and structures through dams, such as spillways, pipes and culverts, are locations where erosion may occur. Piping initiated around or near conduits in 66% of the known causes of failure. A major reason why conduits passing through dams are so often the site of piping incidents is deterioration of the conduit inducing leaks into or alongside the culvert, particularly where conduits are very old and their location uncertain. The Kantalay dam built in Sri-Lanka in 612 failed in 1986 by piping along the outlet installed in 1875. The 300 year old Saint-

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Ferreol dam (1685) was repaired by diaphragm wall, after piping exiting through the masonry galleries. Les Houches dam failed after 160 years by piping along a wooden conduit.

Piping through foundation

The ratio of the number of incidents to the number of failures by piping through the foundation (77 incidents and 19 failures) is significantly higher than the ratio for piping through the embankment, suggesting that this mode of piping is easier to detect by monitoring. As would be expected, dams with partially penetrating cut-offs seem to be much more likely to experience foundation piping incidents than dams with fully penetrating cut-offs. Based on the ratios of the percentages of piping incidents to those of the population, dams with partially penetrating cut-offs are 15 times more likely to experience foundation piping failures than dams with fully penetrating cut-offs to rock. Many incidents occur along the sides or below the bottom of partially penetrating cut-offs. Internal instability of suffusive soils in foundations, in alluvium for example, may develop over centuries. Several leaks caused by suffusion and contact erosion were detected recently on the 100-year old Cusset dyke. Generally, levees on alluvial soils, deposited by large rivers like the Rhine, Danube, Rhone or Mississippi, have experienced the highest number of piping incidents, but foundation piping incidents are also common in the dam population. Dams founded on glacial and colluvial soils seem more likely to experience piping accidents than other dams, but are less likely to experience piping failures. It is apparent that these soils are susceptible to suffusion and contact erosion, and as these types of erosion proceed slowly they are detected by good surveillance, making breaching very rare.

Piping from embankment to foundation

Dams founded on rock with continuous, open joints require careful surveillance, because piping of embankment materials into the openings in the rock is likely. Dams founded on glacial soils are about 2.5 times more likely than the average dam to experience piping incidents, and for dams on colluvial soils this is 5 times more likely.

Step 3 - Initiation and types of erosion

Fundamentally, the first condition for erosion to occur is particle detachment. Water seeping through the dam must be doing so with sufficient velocity to provide sufficient energy to detach particles from the soil structure. The nature of the soil in the dam determines its vulnerability to erosion. Two classes have to be distinguished:

1. Fine non-cohesive silt soils collapse when saturated under flooding, and are easily eroded and dispersive; as non-cohesive materials become

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coarser through sands, gravels and cobbles then progressively require more energy to initiate erosion. Erosion resistance is related to particle weight.

2. Cohesive clay soils are resistant to erosion. They swell when saturated. High energy is required to pluck cohesive particles from openings within a cohesive fill but the particles thus removed are small and easily carried through coarser fill. Erosion resistance is mainly related to contact forces.

Cohesive soils can sustain openings, but non-cohesive soils cannot sustain openings when saturated. Consequently, erosion below the phreatic surface in non-cohesive materials must occur by the passage of fine particles through coarser particles, the process known as suffusion. Four types of erosion are considered below:

Suffusion

Suffusion occurs when water flows through widely graded materials, such as colluvium in the bed of rivers in mountainous areas, and small particles of non-cohesive fill are transported by the seepage waters through the pores of the coarser particles. This requires that not all the particles are structurally involved, i.e. the effective stresses are transferred through a matrix of the coarser particles. Suffusion is less likely to occur as the percentage of fines increases, i.e. the effective stresses are transferred from only the coarser particles through to being transferred through all the particles. Widely graded and gap graded materials which are vulnerable to suffusion are said to be not internally stable (Kenney & Lau, 1985). The limits of the range of circumstances are referred to as 'under filled' and 'over filled' fill (Vaughan, 1994; ICOLD, 2008). Suffusion is driven by water seeping through fill, which leads to an increase in permeability, greater seepage velocities, and higher hydraulic gradients, possibly accelerating the rate of suffusion and generating instability. Stable situations may be reached such that the stability of the embankment is not threatened, but suffusion may re-commence during periods of high reservoir water level. High water levels also decrease the effective stress, open pore spaces so increasing permeability, and allow fine particles to pass through them, thereby further compounding the rate of suffusion.

Contact erosion

Contact erosion occurs where a coarse material is in contact with a fine one, for example, in alluvium in the foundations of dams. Flow through gravels may erode the base of an overlying silt layer, for example.

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Backward erosion

Backward erosion occurs where critically high hydraulic gradients at the toe of a clayey (or concrete) dam erode particles upwards and backwards below the dam through erosion pipes, sometimes called 'worm-holes', and sand boils form on the surface. In critical circumstances, such as floods, the head difference increases, these pipes may grow progressively from the area with a lower hydraulic head towards the higher head, hence the name 'backward erosion'. The erosion shortens the seepage path and increases the gradient leading to higher flow velocities causing further backward erosion, increasing the length of the worm-hole, and causing failure when the worm-hole extends backwards to greater than half the width of the dam base.

Concentrated leaks

Where there is an opening through which concentrated leakage occurs, the sides of the opening may be eroded by the leaking water. Such concentrated leaks may occur through a crack caused by settlement or hydraulic fracture in a cohesive clay core, for example, or through desiccation and tension cracks at high level in fill. In some circumstances these openings may be sustained by the presence of structural elements such as spillways and pipes, or by the presence of cohesive materials able to 'hold a roof', as it is described, below which an opening is sustained, the periphery of which is eroded.

Step 4 - Filtration

Erosion once initiated will continue unless circumstances change or the passage of the eroded particles is impeded in some way. For example, they may pass into materials where the pore spaces are of a size that will filter, or trap, the eroded particles and thereby prevent the process from continuing. That is the geometric retention condition criterion. Depending on the ratio of particle particles and pore sizes, the erosion will stop quickly, after a short time (some erosion), will not stop completely (excessive erosion) or will continue (continuing erosion).

Step 5 - Progression

Progression is the phase of internal erosion where the enlargement of the pipe, the increase of seepage, or the increase of pore pressure occurs. Erosion will progress under two conditions: an hydraulic condition and a mechanical condition.

Hydraulic condition

For erosion to progress hydraulic conditions must be suitable. Water seeping through the dam must be doing so with sufficient velocity to provide sufficient energy or drag force to transport particles along openings and off the external surfaces of the dam in a continuous process.

Mechanical condition

The main mechanical condition is whether the pipe or the cavity through which eroded particles are being transported will collapse. Partially saturated non-cohesive materials, silts, sands, gravels, can sustain openings by arching, but when they become saturated the arches collapse. The consequence of this phenomenon is that there can be arched openings at the phreatic surface in an embankment dam along which water flows freely eroding fill particles from the floor of the opening. The phreatic surface is a very vulnerable location for erosion in non-cohesive fill.

Step 6 - Detection

Internal erosion is classically detected by the emergence of dirty water, water containing eroded particles, at the toe of the dam. However, sometimes visual inspection is too late and cannot prevent the failure. Many new less direct means of detecting seepage are now available. The most promising tool is fibre optic cables used to measure temperature which can be used to infer localised flow. Sophisticated remote sensing options offer great potential in detecting whether the seepage has caused erosion.

Step 7 - Intervention

The simplest intervention in an internal erosion situation is to lower the reservoir water level. This increases effective stress, decreases permeability and reduces seepage gradients and may inhibit the process. The lower water level also often passes below the level of concentrated leaks or openings at the phreatic surface and leakage reduces and erosion ceases. Other interventions such as installing filter blankets or filtered drains at seepage points may inhibit erosion and control the situation and prevent it from continuing towards breach. Emergency plans should include warnings to communities downstream prior to attempts to make interventions to inhibit erosion.

Step 8 - Breach

In these circumstances, the entire process, the chain, of internal erosion has been concluded and the dam is on the verge of being breached by one or a combination of the following four mechanisms:

- Gross enlargement of the erosion pipe.
- Slope instability of the downstream slope.
- Unravelling of the downstream face.
- Overtopping (e.g. due to settlement of the crest).

Assessing which of the four final steps will occur at a dam failing through internal erosion potentially provides information on breach characteristics. This can assist in preparing emergency plans, particularly by assessing time to failure and maximum peak discharge to provide emergency authorities

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with information on which to base their actions to prevent failure and minimize the consequences in the event of failure or a serious incident.

ASSESSING VULNERABILITY – TOOLS AND TECHNIQUES

Data collection and ground models

How the energy to cause erosion comes to be present is the result of the interaction of all the properties of the dam and reservoir, particularly the geometric, hydraulic and mechanical susceptibilities of the materials in the dam and foundation. This interaction is illustrated by the Venn diagram (Figure 1) below, developed by Steve Garner of BC Hydro during and after the 2009 workshop of the ICOLD European Working Group on Internal Erosion (Garner & Fannin, 2009).

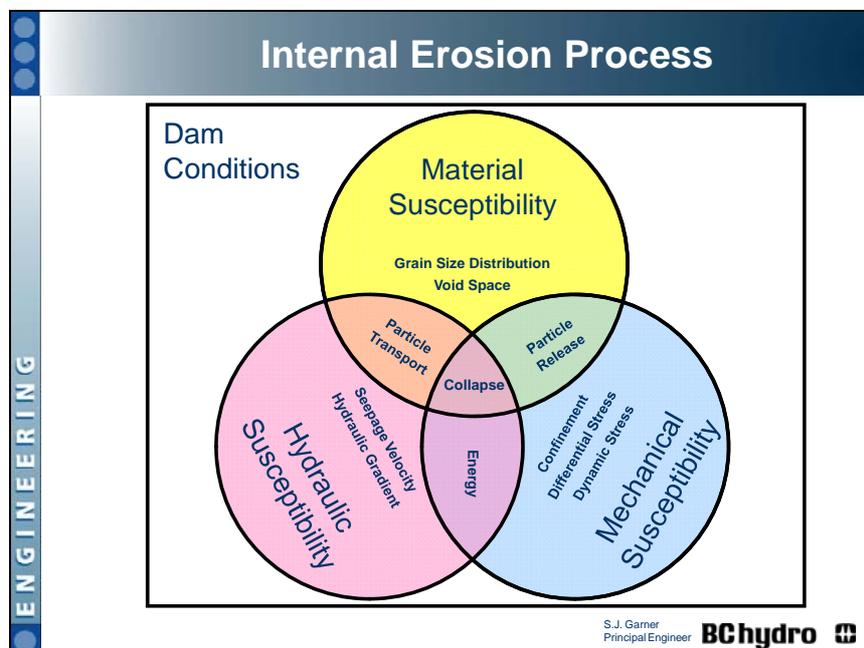


Figure 1. Venn diagram illustrating interaction of geometric, hydraulic and mechanical susceptibilities of soils to internal erosion (courtesy of Garner, Fannin and BC Hydro)

The fundamental requirement for assessing vulnerability of the dam to internal erosion is to accumulate relevant data to develop the following four ground models of the dam and its foundation:

Geometric model

The geometric model compiles the details of the internal geometry of the dam. Is it zoned, and includes the geometric details of the zones and the foundation contact of the fill within the various zones. In heterogeneous

dams it is necessary to examine the dam internally and externally and identify discontinuities.

Geological model

The geological model identifies the most vulnerable locations considering lithology (positions and nature of soft soils, weathered rock and bedrock), structural analysis (tectonic, position of discontinuities: joints, faults, etc) and geological background (earthquake, geomorphology). The susceptibility to erosion of weathered or soft rock and quality of joints (opening and content) are the key factors.

Geomechanical model

The geomechanical model is the compilation of the mechanical properties required for internal erosion assessment and stability analysis, including permeability, bulk density, cohesion, friction angle, modulus and in situ properties such as cone strength value and friction ratio. In situ tests are useful to establish the variability of properties (mean, standard deviation, and autocorrelation parameters).

Hydraulic model

It is fundamental to understand the hydrodynamic situation in the dam. The routes of seepage paths through the dam can be determined from piezometric readings, from seasonal temperature measurements in piezometer tubes or through probes. The state of stress in the dam should be considered as this will affect the permeability. A new CPT test, called Permeafor, may be used to determine continuous vertical profiles of permeability and cone resistance. Seepage and hydraulic gradients through the dam in extreme circumstances should be considered.

Seepage analysis and evaluation of initiation and continuation of erosion

The types of erosion and the vulnerability of the dam to them need to be examined by various means.

Erodibility resistance to concentrated leaks

Now it is possible to consider the erosion potential at vulnerable positions. The erodibility, shearing resistance, of a cohesive fill can be assessed using the Hole Erosion Test (HET). HET, developed by Wan & Fell (2004), is an improved version of the Pin-Hole Test, delivering a quantitative evaluation of the erodibility resistance. The threshold law is often written as:

$$\frac{dm}{dt} = k_{ER}(\tau - \tau_c) \text{ or } \frac{dV}{dt} = k_D(\tau - \tau_c)$$

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where m and V are respectively the eroded mass and volume, k_{ER} and k_D are respectively the mass and volume erodibility coefficients. The erosion assessment compares the shear force imposed by the seeping water τ to the erodibility resistance τ_C also called the critical shear stress. No erosion occurs where the shear force is lower than the erodibility resistance. The coefficients of erosion and the critical stress are not independent. The critical (threshold) stress, τ_C , increases with the cohesion, the degree of saturation and the homogeneity of the sample. Data measured on different clayey soils from UK and France showed that the resistance of clays from UK (IP=7 and WL=24) is high (99 Pa), but the resistance of alluvial silty clay from France (IP=9 and WL=29) is very low (τ_C negligible). The high number of failures along alluvial dykes in France, referred to in 2 above, may in part come from the very low resistance in alluvial soils. When the soil is sandy or of low cohesion, the HET sample cannot hold the pipe during saturation, and in such circumstances, the JET test is required (Hanson & Cook, 2004, Regazzoni et al, 2008). Initially developed for measuring erodibility resistance during overtopping, the JET test has another advantage: it can be used on site and measure the intact resistance and the huge range of the erodibility at the top of fill.

Worm-hole backward erosion and piping condition

The formation of erosion pipes in a granular layer directly underneath a cohesive layer has been of particular concern in the Netherlands, where sand boils often occur at the toe of dykes protecting the low-lying hinterland. In the early 1970s a research program was started in the Netherlands to develop a sound risk assessment methodology to assess the safety of flood protection embankments prone to sand boils. Two decades later, this research program resulted in Sellmeijer's design rule (Figure 2), which is now commonly used in Dutch engineering practice and included in guidelines [TAW, 1999].

In Figure 2, H is the head difference, L is the flow path length, l is the worm-hole length, κ is the geometric permeability, and d is the effective grain diameter of the sand layer. Note that the geometric permeability, κ , is the (D'Arcy permeability * viscosity of water)/ (density of water * g). Density* g is 9,800, say 10^5 , viscosity is about 10^{-3} , κ is therefore about D'Arcy permeability $k*10^{-8}$. The effective grain size, d , is the d_{15} (in metres) of the sand layer. Using the rule to estimate the wormhole length, l , the increased seepage gradient can be evaluated, and its impact on the stability of the downstream toe assessed.

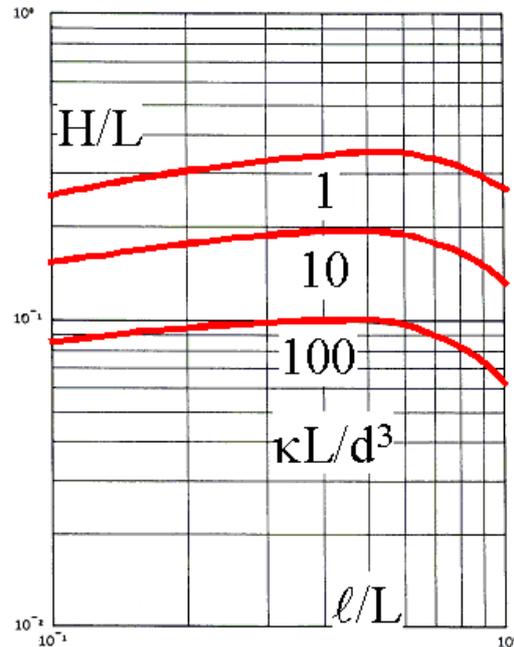


Figure 2. Sellmeijer's design rule

CONCLUDING REMARKS

This paper sets out an early version of the structure of the forthcoming ICOLD Bulletin on assessing the vulnerability of existing dams to internal erosion. During 2010 it will be discussed and reviewed by the ICOLD European Internal Erosion Working Group and the ICOLD Technical Committee on Embankment Dams. During 2011 the second part will be drafted for review by the two groups. It is planned to submit the final draft for ICOLD approval in 2012.

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