Applying Internal Erosion Mechanics to improve Internal Erosion Risk Assessments

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ABSTRACT

Event tree dam safety risk assessments often include 'expert elicitation' to identify likely internal erosion failure pathways, the probability of occurrence of failure and how rapidly failure will occur. ICOLD Bulletin 164 on internal erosion in existing dams, dikes and levees and their foundations assembled knowledge demonstrating the mechanics of internal erosion in water-retaining earth embankments. This is progressively reducing the need to rely on 'expert elicitation' to cover gaps in knowledge. The Bulletin shows that internal erosion occurs when the hydraulic loads imposed by water seeping through pores or flowing through cracks in the fill and foundations of these embankments exceed the ability of those soils to resist them. It gives methods of estimating the hydraulic erosive loads that will cause internal erosion to failure. The highest erosion loads usually occur when water levels are high as floods pass through reservoirs or waterways. Consequently the probability of occurrence of loads causing failure can be estimated from the flood hydrology to provide, together with the consequences of failure taken from dambreak flood analyses, the two components of the risk equation (risk = probability x consequences). The paper shows how applying this new knowledge will lead to improved risk assessments, particularly in relation to the rapidity at which failure will occur, and how in embankments vulnerable to internal erosion, filter zones or fill zones capable of filtering are crucial to arresting erosion if it has initiated.

INTRODUCTION - ICOLD BULLETIN 164 ON INTERNAL EROSION

ICOLD is the International Commission on Large Dams, founded in 1928, with the principle objective of sharing knowledge to make dams safe, recently re-stated in the World Declaration on Dam Safety (ICOLD, 2019a). Knowledge is shared through Bulletins, the word used by ICOLD for guidance documents.

ICOLD Bulletin 164 (ICOLD 2017, 2016) collects and shares knowledge on internal erosion from experience and research to guide engineers on keeping water-retaining earth dams and levees safe. It is in two volumes as follows:

- ICOLD 2017. Bulletin 164 Internal erosion of existing dams, levees and dikes, and their foundations. Volume 1: Internal erosion processes and engineering assessment.

(Final version in book and electronic form, issued 2017. Publication of final preprint in English and French issued on 19 February 2015, first preprint issued in English, 22 January 2013. All preprints reviewed by ICOLD National Committees and approved for issue by ICOLD Executive at Annual Meetings).

- ICOLD 2016. Bulletin 164 Internal erosion of existing dams, levees and dikes, and their foundations. Volume 2: Case histories, investigations, testing, remediation and surveillance. Final preprint in English only, issued 6 May 2016. Translation to French in progress.

The Bulletin is referred to variously in this paper as: 'the Bulletin', Volume 1; Volume 2; ICOLD, 2017 and ICOLD, 2016.

ICOLD (2019b) and EWGIE27-UBC (2019) provide very accessible summaries and updates of the Bulletin. Bridle (2019 a,b,c) gives more details.

THE THREAT OF INTERNAL EROSION

Internal erosion is a major cause of failure of water-retaining earth embankments – dams and levees. Chapter 1 in Volume 1 gives the statistics. The number of internal erosion failures is similar to those resulting from external surface erosion – caused by scour of the surfaces of the crest and downstream slopes by overflowing water ('white water' flow) or overtopping (intermittent flow from wave overtopping). Together these two causes generate most failures; failure by instability, usually in earthquakes, causes only about 6% of earth embankment dam failures.

Dam failures release a deep flood wave that flows along the river valley downstream at speed, usually causing fatalities and extensive damage.

Levee failures may in some circumstances have similar consequences, more usually levees overtop when floods of greater magnitude than the design standard occur. In major rivers, this can cause fatalities, but more usually levee overflows cause distress and damage by inundation.

A major concern about internal erosion failures is that they can occur rapidly, allowing little or no time to warn people to move to higher ground out of the floodway.

INTERNAL EROSION MECHANICS – THE BASICS

Internal erosion is an erosion process, similar to riverbed erosion and erosion of dam and levee surfaces when overflow occurs. Like other erosion phenomena, the cause of erosion is the force of water eroding soil particles and transporting them downstream. The greater the hydraulic force, the faster the flow, and the larger the particles that will be eroded. In the case of internal erosion, the particles are eroded by flow through the embankment – through pore spaces or through openings, cracks or holes, in the embankments. In the case of water-retaining earth embankments, the highest hydraulic forces occur when water level is high, making the hydraulic gradient across the dam or levee (and its foundation) high. The highest gradients and hydraulic forces occur when floods pass through the reservoir or along the waterway.

The Bulletin provides the means to estimate the hydraulic force, usually expressed as a water level, that will cause internal erosion for the four modes of internal erosion: contact erosion, concentrated leak erosion, suffusion and backward erosion.

The threat posed by internal erosion can be better understood when the water level at which internal erosion will occur is known (even if not precisely). The following points are examples of how water level affects internal erosion potential:

- If it is above the crest of a dam or levee, internal erosion cannot occur, but the embankment may be vulnerable to surface erosion during overflow.
- If it is around normal water level, there may be signs of internal erosion already, and the rate of erosion will rapidly increase when a flood passes by the embankment.
- If it is between normal water level and crest (or overflow level if a spillway is present) erosion will occur during floods of lesser magnitude than the design flood, meaning the embankment is more vulnerable to internal erosion than floods.
- The rate of internal erosion accelerates as water level goes above the water level at which it initiates.
- A further benefit of knowing the water level causing internal erosion is that the annual probability of occurrence of that water level can be derived from the flood hydrology. This can then be used together with the consequences of failure, derived from dambreak analysis, to provide the two components of the risk equation (risk = probability x consequences).

USING THE BULLETIN TO ADDRESS THE RAPIDITY OF INTERNAL EROSION FAILURES

Knowing that internal erosion occurs when hydraulic forces are sufficient to cause it, it is plain that the higher the water level is above the level at which internal erosion initiates the more rapid will be the erosion.

The speed at which an internal erosion failure can occur is illustrated by failures on first filling, such as that at Teton dam in Utah, USA, in 1975 (reported in Volume 2 of the Bulletin). The dam failed in just four hours. The water level was rising as it would during a major flood in a completed dam and reservoir. The water level could not be reduced as the emptying pipes were not complete. Substantial leakage and piping was observed at 8.00 am, accelerating and breaching the dam by noon. The first indications as the reservoir filled occurred two days earlier when clear seeps were seen in the valley side downstream. If it had been possible to stop filling at the first sign of malfunction and use the Bulletin to assess how to stop erosion in future, measures such as foundation grouting, improved filtering downstream of the core and on the downstream foundation (or a cut-off through the core into the grout curtain) would likely have been implemented to make the dam resistant to internal erosion.

Engemoen and Redlinger (2008) reported on internal erosion events in 99 dams in the USBR inventory of 220 dams. Only one dam failed, 53 events involved particle transport and the remainder were excessive seepage or sand boils. Of the 99 events, nine were in the embankments, 70 in the foundations, six from the embankments into a conduit and eleven into toe or under drains. including two that had caused severe damage to the dams. As its significance was not appreciated at that time, there was no record of water levels. Plainly no incidents occurred during floods of any note, most incidents occurred on refilling from snow melt after summer drawdowns for irrigation. The dams are now protected by filters, but whether this was necessary in all cases could have been investigated with present knowledge to justify expenditures more rigorously.

To examine risk and pathways to internal erosion failure, event trees had been developed showing the steps that could lead to breach. Figure 1 shows an example.

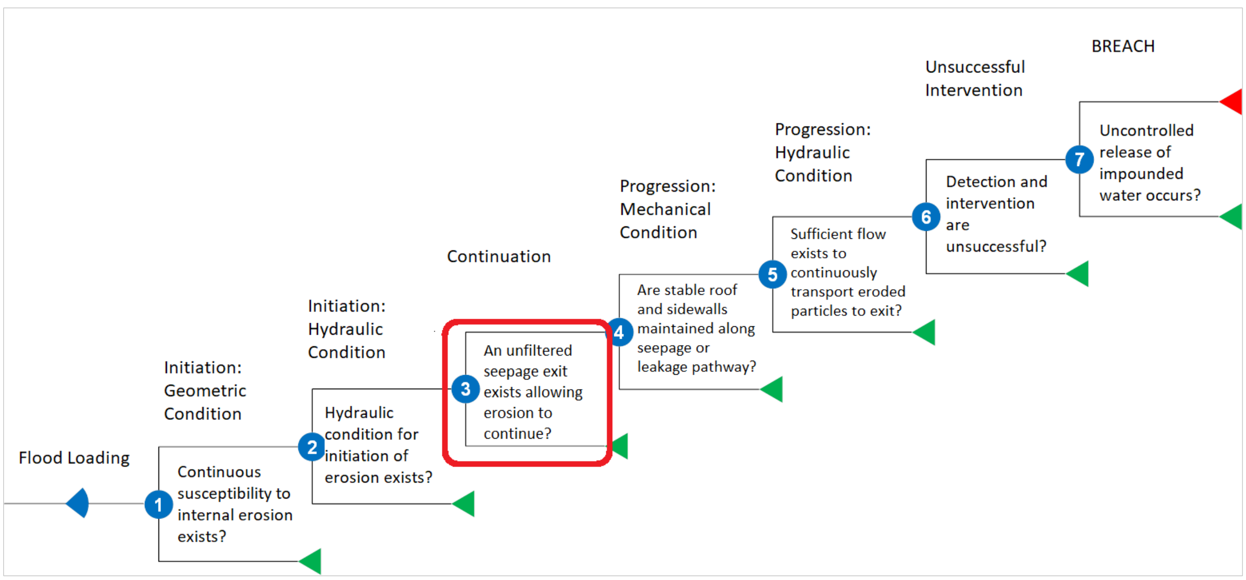

Figure 1. Event tree showing how during a flood as water level rises it imposes hydraulic erosive forces on the walls of a crack across the crest of the embankment, and the seven steps at which the hydraulic shear force may exceed the hydraulic shear strength of soils in the walls of the crack and may cause internal erosion to initiate, continue, progress and cause breach (O'Leary 2019, personal communication)

Expert elicitation is used in carrying out these risk assessments to overcome uncertainties 'because uncertainty is unavoidable in science' (Aspinall, 2010). This article entitled 'a route to more tractable expert advice' reports on eleven experts asked to assess how quickly an internal erosion failure would occur after commencement of a leak into the core of the dam. At that time, without knowledge of internal erosion mechanics, it seems now that the experts would have been speaking of 'unknowns', rather than uncertainties. The best estimates by the eleven experts of time to failure ranged from 40 hours to about 10,000 hours (over 400 days). Conclusions of this kind have left attitudes that suggest there would be plenty of time to avert internal erosion failures after initiation, and that the many steps in the event tree (Figure 1) would occur slowly, allowing time to intervene to prevent breach.

As is now known, the reality is that when substantial erosion commences it will usually be on a rising flood, and the process will progress rapidly, allowing time only to warn people in the floodway downstream to move to higher ground. Uncertainties will remain in estimating water level at which failure occurs, for example, but those uncertainties can be addressed on the basis of uncertain forces, resistance, hydrology, for example, and should - on questions of dam failure - always recognize that internal erosion failures will almost certainly occur on a rising flood and be rapid.

STOPPING EROSION - PREVENTING CONTINUATION - FILTERING

As Figure 1 shows, internal erosion proceeds to failure in four phases: initiation, continuation, progression and breach. If internal erosion initiates, it will continue unless it is stopped by filtering at Step 3, marked in red on Figure 1. If erosion has initiated but is halted by filtering action, the erosion process is arrested and the embankment is safe from internal erosion. The filtering may occur in designed filters, as described later, or in fill zones in the embankment that provide a filter to the core or other upstream fill or foundation stratum.

If the filtering is effective the event tree stops at Step 3, and issues such as speed to failure and precise water level to cause erosion become less important. If the Step 3 filter is a 'continuous' filter, i.e. ineffective and allows large and developing leakage leading to rapid progress to breach, remediation should follow. The steps after Step 3 are helpful in providing re-assurance if the Step 3 filter allows 'some' or 'excessive' erosion before sealing. The case history in Volume 2 applied Fry (2007) to investigate the potential for the glacial till shoulder fill to reduce velocity of flow towards cracks in the clay core and thereby inhibit erosion.

The Bulletin deals with existing dams and levees recognizing that new dams will be constructed with filter layers and cutoff walls to protect them from internal erosion. Filters are layers of specifically sized sands and fine gravels built into water-retaining earth dams and levees that allow leaking or seeping water carrying eroded soil particles to pass but filter (trap) the eroded particles.

The now classic references advising on filter sizes are Sherard and Dunnigan (1985, 1989). Details are given in Chapter 7 of Volume 1 of the Bulletin. It should be noted that the filters installed in dams prior to that time should be checked, as their gradings may not provide a fully effective filter.

Fills not designed to be filters may have filtering capability. Their effectiveness, and the effectiveness of filters that may not comply with modern no-erosion standards, can be examined using the 'filter erosion boundary criteria' (Foster and Fell, 2001) information in Chapter 7 of the Bulletin. This assesses if the 'filter' is a no- some- or excessive-erosion filter or if it is ‘continuous’, too coarse to provide any filtering action allowing erosion to progress towards breach. Coarser ‘filters’ allow more eroded particles to pass before enough are filtered (trapped) to ‘seal’ and form an effective filter in-situ. The amount of erosion before sealing results in damage to the embankment, as follows:

- No-erosion filters arrest any erosion immediately without any perceptible change in seepage.
- Some-erosion filters ‘seal’ and arrest erosion after leakage flows containing eroded particles up to about 100 l/s.
- Excessive-erosion filters ‘seal’ after much damage including sinkholes and leakage flows up to 1,000 l/s containing many eroded particles.
- Coarser ‘filters’ do not ‘seal’ or arrest erosion but allow erosion to continue to progress towards failure. In this situation, remediation, filtered berms on the downstream slope or cut-off trenches are the main options.

Figure 2 shows new no-erosion filters installed to protect 200-year old levees as part of remediation works to flood and coastal protection levees in the Rhone Delta, France (Mallett, 2019).

Figure 2. Filters on downstream slope and in drainage trench, flood levees, Rhone Delta Project (courtesy Thibaut Mallet, Symadrem, France).

ADDRESSING THE INTERNAL EROSION THREAT – QUANTIFYING RISK

The threats to dams from extreme natural events had been addressed by ‘deterministic’ approaches. The ‘Probable Maximum Flood’ was applied to address flood overflow issues, and the ‘Maximum Credible Earthquake’ to address stability during earthquakes. However, these extreme events were not associated with any probability of occurrence, consequently the annual risk (probability of occurrence x consequences) could not be quantified. As it is now necessary to make and demonstrate that dams are safe to a consistent and acceptable standard – able to withstand the 1 in 10,000-year earthquake and the 1 in 10,000-year flood, for example - the deterministic approach was dropped in favor of probabilistic approaches.

The internal erosion threat had not been addressed ‘deterministically’. Internal erosion was prevented in new earth dams by filters, described above, capable of arresting erosion if it had initiated. The difficulty with this approach is that many old dams and almost all existing levees do not have filters, and if they do, the filters may not have been designed as ‘no erosion’ filters.

To evaluate probability of occurrence of an internal erosion failure either:

- the probabilities of occurrence of each step in the event tree are found from good practice guides and other knowledge can be totaled to provide an overall probability, or
- the probability of occurrence of the water level that will cause failure estimated from the mechanics in the Bulletin can be found from the flood hydrology for the river or reservoir in question.

In practice, both are used, and application of the knowledge in the Bulletin is increasing as it becomes more familiar.

There are major advantages of deploying actual parameters as this makes clear that the internal erosion results from high hydraulic forces from high water levels during a flood. Using the probabilities approach, particularly going through many steps on the event tree, can indicate very low probabilities. Physically this means that the flood causing the event is of enormous magnitude, with water level far above the crest – in other words, the embankment is not vulnerable to internal erosion.

Also, the magnitude of physical events – floods in this case - with a probability of occurrence lower than about 1 in 10,000-years are at the limits of reasonable estimates and at the limits of safe and economically effective infrastructure.

USACE and USBR have developed and used in-house Quantitative Risk Analysis Risk Assessment methods (e.g. O’Leary, 2016). These are derived from the Fell et al (2008) seepage and piping toolbox. There have been developments making use of new knowledge in the Bulletin (O’Leary, 2019, personal communication).

The quantitative risk assessments carried out by Mallet and Fry (2016) and Mallet et al (2014) are most rigorous in making use of current knowledge of internal erosion mechanics wherever it is available. They also use water level records from past floods to provide probability data. Mallet (2019) gives an easily accessible very full account of the analyses of the 200 km of flood levees at the mouth of the Rhone in France. The event tree is shown in Figure 3.

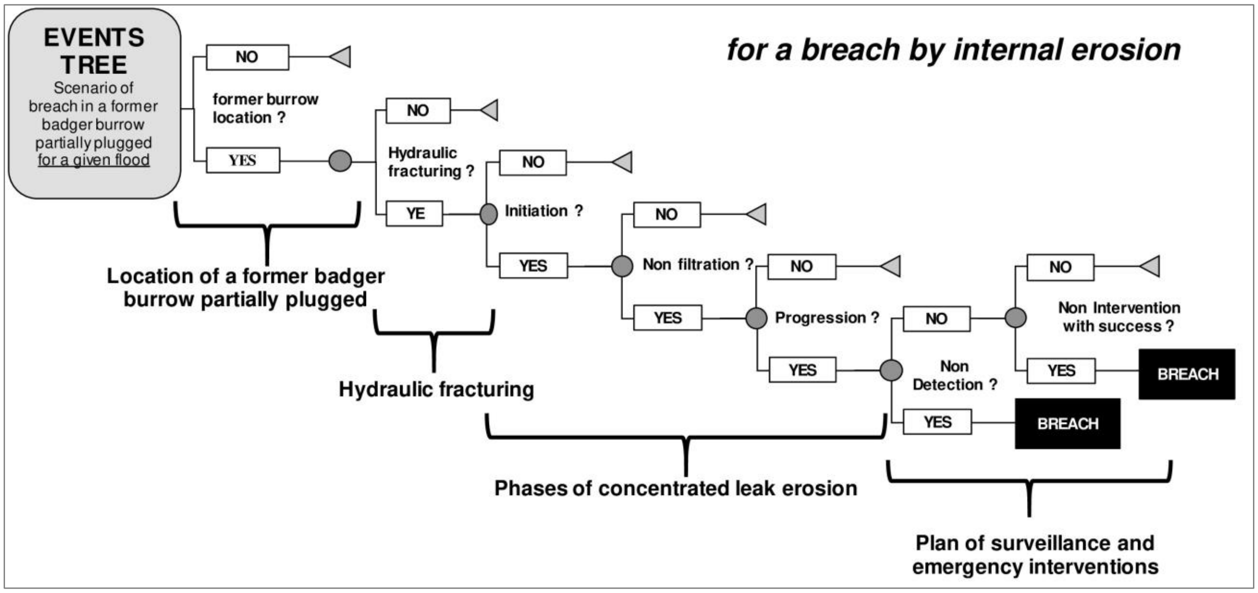

Figure 3. Event tree for quantitative risk analysis of damaged flood levees, subsequently used to design and implement remediation for 200 km of flood levees (from Mallet, 2019, courtesy of Thibaut Mallet, Symadrem)

Bridle (2018a) notes that the risk to dams from failure and release of water in earthquakes, during floods and by internal erosion should be the same. The consequences of deaths and damage in the flood plain will be similar, and the flood hydrology provides water level estimates and probability needed for the estimation of both flood risk (causing failure by erosion of external surfaces by overflowing water) and internal erosion risk.

SUMMARY, RECOMMENDATIONS AND CONCLUSIONS

ICOLD Bulletin 164 on internal erosion presents the mechanics of internal erosion making it possible to understand how erosion occurs in the soils and earth fill in water-retaining embankment dams and levees and their foundations. Erosion occurs when the erosive force of water flowing through the embankments overcomes the resistance of the soils in them. The erosive force is highest when water level is highest, when floods pass through the reservoir or waterway. Erosion will initiate and accelerate, possibly to failure, as a flood rises. Consequently, there will be time only to warn people to move to higher ground out of the dambreak floodway. It is therefore advisable to investigate and analyze the vulnerability of embankments before any large floods occur.

Filters, designed as filters, or as fills with filtering capability, stop erosion from continuing. If effective filters are present, erosion will be halted, and the embankment will be safe from internal erosion. If erosion cannot be halted, remediation will be needed. Event trees need not proceed beyond the ‘filtration’ step in many cases.

Quantitative risk assessment necessarily addresses uncertainty at some steps in event trees, but advancing knowledge is gradually providing engineering approaches to reduce uncertainty. Proceeding through many steps can sometimes result in extremely low probabilities of failure by internal erosion. Knowledge of the mechanics can be used to assess whether a very low probability, meaning that a very high water level (possibly above the crest) would be necessary to cause failure, is realistic. If so, the embankment would not be vulnerable to internal erosion. If not, further investigations would be needed to better understand the particular vulnerabilities of the dam or levee in question.

ICOLD Bulletin 164 (2017, 2016) on internal erosion, and the enlarging community of researchers and practitioners in internal erosion, the internal erosion conferences and working groups, and the imperatives of dam and levee safety and risk assessment, particularly quantitative risk assessment, have developed greater understanding of internal erosion, now being increasingly deployed to guard against internal erosion failures in water-retaining earth embankment dams and levees.

ICOLD, aided by the ICOLD Internal Erosion Working Group (see EWGIE27-UBC, 2019), plans to update the Bulletin from time to time (Bridle, 2018b). Currently work is in hand, leading ultimately to the issue of another bulletin, to address the uncertainties of the matter of transverse cracking across the crests of embankments. Currently much remediation is carried out to address the possibility of concentrated leak erosion through such cracks. The new bulletin will advise on methods to determine whether the crack dimensions would or would not be sufficient to allow erosion of the walls of the cracks as flood water rises and flows through the crack.

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