Defra research into Internal Erosion

A. J. BROWN, Jacobs, Leatherhead, UK
J. D. GOSDEN, Jacobs, Croydon, UK

SYNOPSIS. This paper summarises the background to, and the key findings and conclusions from, two Defra research projects on internal erosion. It then discuses the practical implications for dam owners and panel engineers in terms of monitoring and surveillance. The paper concludes with a discussion on current uncertainties on rates of progression of internal erosion, and what future work would be useful to reduce these.

INTRODUCTION

Internal erosion occurs when the soil particles within an embankment dam or its foundation are carried downstream by seepage flow. Available data on reservoir safety incidents in the United Kingdom in the period 1975-2000 are summarised in Table 1. It can be seen that over half of the incidents where emergency drawdown is considered necessary to avert failure have been a result of actual or anticipated internal erosion. Experience internationally is similar, with ICOLD Bulletin No 99 (ICOLD, 1995) noting that 44% of dam failures internationally are due to internal erosion.

Despite the, on average, two emergency drawdown incidents a year due to internal erosion in UK there have been no failures of dams with loss of life due to internal erosion since the Reservoirs (Safety Provisions) Act was implemented in 1930. It is suggested that a significant contributor to this absence of failures includes the effective surveillance and intervention regime, which has provided time to detect developing problems and lower the reservoir before the problem developed to failure. However, the continued pressure for reduction in costs, and thus reducing frequency of surveillance, together with the increasing average age of UK dams, is likely to lead to increasing risk of dam failure from internal erosion.

Following a serious internal erosion incident in January 2002 (Gardiner et al, 2004) a Defra research contract into early detection of internal erosion was awarded to KBR in 2002. The first phase, a feasibility study, was completed in 2004, with the research report available on the Defra website and reported in Brown and Gosden (2004). Funding difficulties meant that the second stage of the contract, measurement of erodibility of UK soils, was cancelled. The contract was therefore completed (after novation to Jacobs) by production of draft guidance on early detection of internal erosion, and a study into the practicability of real time monitoring. This paper summarises the key points from these projects, as an update on the 2004 paper in Dams and Reservoirs (Brown and Gosden, 2004).

Table 1: Data on internal erosion incidents in the United Kingdom in the period 1975-2000

Level of incident	2: Emergency drawdown	3: Precautionary drawdown
Average number of incidents per year (Brown and Gosden, 2004)	3	10
% of UK incidents due to varying causes (Table 6 of Brown and Tedd, 2003)		
• internal erosion	60%	63%
• slope instability	23%	9%
Inferred annual probability of an incident due to internal erosion, for 2500 UK dams	1 in 500 (0.2%)	1 in 160 (0.6%)
Note: The annual probability of failure at less than 1 in 50,000 is much lower because most incidents do not progress to failure		

FRAMEWORK FOR CONSIDERING INTERNAL EROSION

The framework for assessing the likelihood of each of these types of internal erosion is described in a companion paper on the European Working Group on Internal Erosion (Brown and Bridle, 2008) and is not repeated here. This paper focuses instead on the rate of development of internal erosion, and means to detect and manage this.

RATE OF INTERNAL EROSION - EXPERIENCE

Key elements of historic internal erosion incidents which have been recorded in published papers are summarised in Tables 2 and 3. It can be seen that although incidents during the first few years following construction are generally rapid, incidents at dams more than five years old generally develop much more slowly.

A questionnaire to dam owners on the likely time to failure, if no action was taken, was presented as Figure 3 in the 2004 paper and confirmed the wide variation in time to failure, but also that the rate of development in UK dams is generally modest within the body of the dam but much faster when associated with internal erosion along the contact with a structure.

Table 2: Rate of development of internal erosion incidents at embankment dams

Dam, Date of Incident	Available information on rate of development, and type of internal erosion (Reference)
During wear in period	
Warmwithins, UK June 1970	The dam is a 10m high puddle clay core dam built in the 1860s. It failed over a period of 12 hours, along a new 1.5m diameter tunnel lined with concrete segments installed about 1965. (Wickham, 1992)
Balderhead, 1970	On first impounding the first sinkhole was above the filters on the downstream side of the core, followed six weeks later by large holes on the upstream side of the core. The underdrain water had also become turbid. (Kennard, 1972)
Teton, USA June 1976	The dam failed over a period of 2.5 hours. The dam core was built of wind deposited non-plastic to slightly plastic clayey silts, and founded on moderately to intensely jointed volcanic rocks. The time stated is from the first muddy flow being seen to the first whirlpool being seen in the reservoir. Concentrated leak? (Report into failure of Teton dam)
In service	
Upper Rivington Jan 2002	New concentrated leak into culvert. Emergency drawdown such that the reservoir ceased to overflow 48 hours after being detected, and was 7m below top water level six days after ceasing to overflow. (Gardiner et al, 2004)
Scandinavian dams	35 cases of sinkholes and sudden leakage due to suffosion, generally after many years in service. These usually seal themselves after a short time. Settlements, sinkholes and leakage have often occurred at the junction between an embankment dam and a concrete structure. (Nilsson, 2007)

Table 3: Examples of slow ongoing internal erosion in UK dams

Dam	Inferred erosion rate (Reference)
Brent	1.0 litre/ year measured in V notch chamber (Tedd et al, 1998)
Anonymous	1.0 kg/year measured in V notch chamber (private communication from dam owner, 2007)
Lower Slade	3ft diameter swallow hole exposed when upstream pitching lifted. 60 tons of grout injected into open holes into 70 year old dam, where repairs had been carried out 15 years before. Say 1 ton/ year (Kennard, 1972)
Lluest Wen	A horse fell into a hole near the valve tower at Christmas 1969. Emergency declared with evacuation of old and infirm downstream, 50 ton of clay/ cement grout injected into watertight element, which had been previously treated in 1912. Approx 1 ton/year. (Little, 1977)

RATE OF INTERNAL EROSION – PREDICTION AND RISK ASSESSMENT

It is suggested that the level of detail which is appropriate to apply to the assessment of vulnerability to rapid internal erosion should be on a risk based approach. This considers whether the Undertaker has reduced risk to as low as reasonably practicable (ALARP), namely whether the measures taken have been proportionate to the reduction in risk that could be achieved. The ALARP decision making process is defined in paragraph 124 and Appendix 3 of "Reducing risks, protecting people" (HSE, 2001) with further guidance given at www.hse.gov.uk/risk/theory/alarp.htm. The Interim Guide to Quantitative Risk Assessment (Brown & Gosden, 2004) provides a screening level of risk assessment, which can be a useful first step.

The process to assess the vulnerability of a dam to internal erosion is described in Brown & Bridle (2008), and requires data on the geometric, geological, geotechnical and hydraulic properties of a dam. The vulnerability to rapid failure is an extension of this, but also considers the likely rate of failure. This is likely to vary depending on the erodibility of the soil and type of internal erosion, the latter as indicated in Table 4.

Although in theory analytical predictions of the rate of development of internal erosion at concentrated leaks are now possible, currently this analysis is not common in UK. Nevertheless assessments carried out as part of the research contract comprised a sensitivity study of flow and erosion in a 1m high 3m long crack under 10m head which showed that

a) the rate of erosion varied between 0.1 and 1000kg/ day, depending on the erodibility of the soil (Figure 6 of Brown and Gosden (2004); erodibility as defined by Wan and Fell, 2004)
b) Turbidity of less than about 5FTU is not visible to the human eye; so for this combination of crack width and reservoir head, material eroded from a soil with a value of Erosion Rate Index of between 4 and 6 would not be visually detectable

In terms of risk assessment the rate of development can be categorised in terms of the ability to manage the incident and prevent dam failure, and a suggested categorisation is given in Table 5, together with the implications for bottom outlet capacity.

Table 4: Types of internal erosion (after European Working Group)

Type	Definition	Likely time to failure; remarks
Concentrated erosion	In soils which are capable of sustaining an open crack. Erosion occurs along the sides of the crack where the shear stress (velocity) exceeds the critical value. NB at low flows there may be leakage with no erosion.	The rate of erosion is dependant on the erosion resistance of the clay core, and may be limited by the permeability of both shoulders. Where cracks exist in the dam crest (e.g. desiccation, differential settlement) then the critical failure mode may be concentrated erosion during flood conditions
Backward Erosion (Piping)	Erosion starts at the exit point; a continuous passage is developed by backward erosion when the seepage gradient exceeds the “flotation gradient” of the soil.	Can be fast with little warning. Failure is often associated with first filling, or an increase in seepage gradient (for example under flood conditions)
Contact Erosion	Erosion at the horizontal boundary of a fine soil overlying a coarse soil, where the fine soil is washed into the coarse soil due to horizontal flow	Little information. Likely to be similar to concentrated erosion, but accelerated where along the interface between a structure and the embankment
Suffosion	Mass erosion in soils which are internally unstable. Fines transported by seepage flow between the larger sizes of soil	Normally leads to an increasing quantity of seepage as fines erode, but is unlikely to lead to rapid failure

Table 5: Suggested categorisation of speed of failure due to internal erosion

Speed of failure	Time to failure	Relation to Surveillance frequency	Value of bottom outlet for emergency drawdown
Extremely fast	< 1 day	Unlikely to be spotted	Irrelevant
Fast	1 to 7 days	Where there are frequent visits >50% chance of being spotted while there is still time to avert failure	Dependent on the frequency of surveillance visits, and thus the residual time available for intervention
Medium	8 to 90 days	Good chance of being spotted, provided frequent visits are made	Likely to be of most value
Slow	> 90 days	Almost certain to be spotted provided there are routine surveillance visits.	Magnitude of ongoing inflows likely to be the largest influence on the size of the bottom outlet

SURVEILLANCE AND MONITORING

Once an understanding of the risk from internal erosion has been obtained as described above, the type and frequency of the surveillance and monitoring regime can be determined. It would normally include visual inspection as a minimum, and monitoring on higher consequence dams. Current international practice for the frequency of surveillance visits is generally based on the consequence class of the dam, for example on high hazard dams typically being weekly although ANCOLD guidelines (Table 5.2 of 2003) suggest it should be daily. For low consequence dams a typical frequency is monthly.

It is suggested that it would be more rational if the frequency of surveillance were risk based, in that as well as consequence class it also took account of the probability of (vulnerability to) rapid internal erosion. A suggested risk matrix to determine a surveillance and monitoring regime is given in Table 6, whilst a possible starting point for defining the surveillance frequency of dams in service is given in Table 7. The latter is developed from ANCOLD Guidelines on Dam Safety Management (2003). Both are suggested starting points for application and adjustment on a dam specific basis, following the principle that the cost should be proportionate to the benefits obtained.

Table 6: Indicative risk matrix for the surveillance and monitoring regime at a dam

Vulnerability to internal erosion [1], as output from risk analysis	Consequence Class of dam (as defined in Interim Guide to QRA, 2004)				
	A1	A2	B	C	D
High	α	β	β	γ	δ
Medium	β	β	γ	δ	ε
Low	γ	γ	δ	ε	ε

Notes

1. Ranking on the vertical axis could be on the basis of one of the following
    - The tolerability of risk, comprising the Broadly acceptable, ALARP and Unacceptable zones on the FN chart (Sheet 11.3 of Interim Guide to QRA)
    - Likelihood of failure, as a qualitative assessment
    - Speed of failure, as defined in Table 5, with Fast and extremely fast considered together

Table 7: Indicative surveillance frequency for dams in service

Regime (Table 6)	α	β	γ	δ	ε
Routine visual surveillance					
Exterior; including exterior of culverts/ shafts (and interior where no confined space)	Daily to 48 hours	48 hours to twice weekly	Twice weekly to fortnightly	0.5 to 2 months	Two to six months
Interior of culverts/ shafts, where confined space[2]	Weekly to monthly	Monthly to 3-monthly	3-Monthly to annual	Five yearly	Ten yearly
Number of visits a year by Supervising Engineer[3]	4	3	2	1	1

Notes

1. The timing should be calendar time, and thus occur at weekends and bank holidays where these fall in the routine cycle.
2. The timing can be reduced by say up to two classes, where any progressive internal erosion would be visible by inspection at the downstream end
3. Where the dam owner does not have suitable trained and experienced employees then the frequency of Supervising Engineer visits would normally be increased, and they should include an element of training of the dam owner and his staff

REAL TIME MONITORING

Introduction

One of the Defra research contracts was a review of current practice in real time monitoring, both in relation to dams and other industries, leading to production of a Guidance Note. This section summarizes some of the key findings from this review.

When could this be appropriate for UK dams?

Real time monitoring may be appropriate at high consequence dams where it is considered there is a possibility of rapid development of internal erosion, if it initiated. It is emphasised that this should not be a substitute for visual inspection, as visual inspection covers the whole of the dam structure, whereas monitoring only covers the element or part of the structure where the sensors are installed.

Current practice

ICOLD Bulletin 118 (2000) provides case histories and guidance on automated monitoring at dams internationally. In UK real time monitoring of sensors is now standard practice in the water industry as part of the de-manning to reduce operational costs. It is also sometimes necessary to demonstrate compliance with discharge consents or other statutory requirements.

ENSURING RESERVOIR SAFETY

In the UK, British Waterways undertakes real time monitoring of key assets for operational purposes, including some dams, using a system developed in-house. Parameters monitored relate mainly to operational issues of water levels, weir operation, flows at gauging weirs, sluice operations and gate positions. Alarms are incorporated where appropriate, with relevant personnel being notified directly by mobile telephone or pager if a trigger level is reached. A ‘reach out’ facility, in which remote operation can be undertaken, for example of drawoff sluices, is also available at a limited number of sites. At a few sites the sluice operation is automatic based on reservoir water levels, with various fail-safes included in the system.

The real time monitoring system is internet based and has been in operation since 2004. All software has been developed in-house. In general, remote readings are recorded at 30 second intervals, being averaged to provide a reading over 5-minute intervals. Where mains power is not available, the power source is commonly solar cells and batteries. In order to conserve batteries, stored information is only transmitted to the central server every 24 hours, although the stations can be polled at any time in-between if required. 90% of the information is relayed by mobile telephone technology, with the remaining 10% being transmitted by land line. Data from the last ten years, including information obtained both manually and remotely, can be retrieved upon request. There are no limits to the number of persons who can access the database at any one time. Problems associated with the system include the susceptibility to vandal damage and the rapid rate at which current technology becomes obsolete.

In relation to reservoir safety water levels are recorded automatically at some reservoirs, although water levels noted manually at the remaining reservoirs are also entered into the database. Manually read v-notch, piezometer and flows measured using jugs will soon be entered into the same database. The information can readily be extracted from the database live through the internet, and presented in graphical format which is considered better than Excel format. In summer 2009 SCADA monitored V-notches will be monitored at a remote reservoir with a history of seepage above a small town; the V-notches will have trigger flows set, which will raise an alarm.

A number of UK water companies have each installed real time monitoring of seepage at V notch weirs at one or two dams, generally because of specific issues at those dams. In Canada it is now routine practice by BC Hydro to have real time monitoring of flows and turbidity at the seepage weirs at all of their dams.

Parameters

The parameters which are most useful to provide early warning of internal erosion are seepage flows and turbidity. It is noted that suspended fines in seepage water cannot be seen visually where Formazine Turbidity Unit (FTU) is less than 5, and thus would only be detected by quantitative monitoring. For clay fines an approximate conversion is 2.5mg/l per FTU, such that seepage of 5 litres/ min with a FTU of 5 could correspond to solids of 90g/day

Procurement and maintenance

The practicality, cost and reliability of real time monitoring is significantly dependent on resources available within the Undertaker's organisation to install and maintain any system. Table 8 contrasts current practice at a water treatment works and at British Waterways. As a budget figure the cost of real time monitoring of a simple V notch chamber is likely to be of the order of installation cost of £20k for the civils works and monitoring equipment; an annual maintenance cost of £1k/ year; and £5k every ten years for replacement of sensors and other monitoring equipment. This cost is thus likely to only be proportionate at high consequence dams, where it provides a significant reduction in the probability of failure.

Table 8 Range in variation in strategy for real time equipment

<table>
<tr><th>Issue</th><th>Water Company – Real time monitoring installed at water treatment works</th><th>British Waterways</th></tr>
<tr><td>Equipment installation</td><td>In-house staff</td><td>External contractor</td></tr>
<tr><td>Maintenance cleaning: frequency and by whom</td><td>Twice a week by plant engineers who visit each WTW regularly</td><td rowspan="3">All carried out by external contractor six monthly, and under call-out where problem identified</td></tr>
<tr><td>ICA check i.e. check that it still works correctly</td><td>By instrument technician (the company employs 50 specialist ICA staff)</td></tr>
<tr><td>Recalibration</td><td>Periodically; often in the laboratory at the WTW</td></tr>
<tr><td>Instrument replacement</td><td>On failure, or when technology superseded</td><td>Ten years</td></tr>
<tr><td>Replacement of batteries in power pack</td><td>Not relevant</td><td>Routinely as part of six monthly check</td></tr>
<tr><td>Alarm sent to</td><td rowspan="2">24 hour control centre, manned by in-house staff</td><td>Mobile phone of Duty Engineer</td></tr>
<tr><td>24 hour control centre for receipt of alarms from public</td><td>Contracted out to First Response (West Midlands Ambulance Service)</td></tr>
</table>

Use of data

A key element of assessing the practicality and value of real time monitoring is the use and archiving of the data collected. This will depend on the software used and management of alarms. For water companies and other major owners with control rooms which are manned on a 24/7 basis real time monitoring should be a viable option, although some development work would be required to integrate it with other existing real time systems. For owners who do not have this resource then the system could be developed to provide a SMS text or other form of automatic alarms, but this is likely to be less reliable.

FUTURE RESEARCH

The research projects identified that there is still much work to be done to bring our understanding of internal erosion to the same level as our understanding of other threats to dam safety, such as hydrological assessment. Issues identified for future research are summarised in Table 9.

Table 9: Priorities for future research relating to internal erosion

Description
Laboratory testing of threshold, and rate of internal erosion, of sides of pathway through core, similar to that in Australia. This would be an extension of the pinhole test (BS1377:part 5: 1990 Section 6.2); including changes such that a 6mm hole is used instead of a 1mm hole, and the rate of erosion is measured
Collection and analysis of data on incidents, specifically a) Lessons learnt reports from incidents b) Data collected as part of the database, to allow statistical analysis, on the range of geotechnical properties of UK dams relevant to internal erosion c) Data on the annual probabilities of an incident, and dam failure respectively, both inferred from incidents and estimates in published papers
Materials present in UK dams a) Desk study of existing site investigation reports on SI carried out in the past, and (relevant) published data on geological strata b) Field investigation with associated laboratory testing of core and shoulder to better understand the range of properties for typical UK dams; followed by identification and analysis of the credible failure mechanisms for the system of dam core and supporting shoulders c) Field investigation of construction details of pipes and culverts through dams, where the dams have been discontinued

CONCLUSIONS

The overall objective for the research project was to "provide a cost-effective approach to the early detection of progressive internal erosion in embankment dams". Although there is no simple single tool which can achieve this objective, the research project and other ongoing parallel research in Europe and elsewhere have led to an increased understanding of the vulnerability to, and potential rate of development of, internal erosion. This has highlighted

- The large variability in erodibility of materials used to form the watertight element of dams
- That internal erosion can occur at a slow rate for many years with no apparent surface effect, and with suspended particles in concentrations too low to be detected visually
- The rate of development is likely to vary significantly depending on the type of internal erosion
- The increased likelihood of internal erosion along the contact with structures, relative to internal erosion in the body of the dam

Site specific engineering assessment to inform an assessment of the vulnerability to internal erosion should include

a) The consequences of the failure of the dam, in terms of impact on people and property downstream, and thus what measures would be proportionate to reduce the likelihood of failure to as low as reasonably practicable
b) Determination of the erodibility of the material(s) used to form the watertight barrier
c) An understanding of the system response, as to how the dam shoulders or other elements may affect internal erosion of the watertight element

Suggestions have been made of normal surveillance type and frequency, following a risk based approach. Real time monitoring has been reviewed in relation to current practice, potential costs and issues relating to data and alarm management.

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