Progress in assessing Internal Erosion

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SYNOPSIS The European Working Group on Internal Erosion presented its Interim Report at the 7th European Conference on dams in Freising in Germany in September 2007, this being the culmination of interactions which had commenced in 2004. This paper summarizes the main technical outcomes from the working group. It then comments on practical implications of progress in understanding internal erosion for dam engineering in the United Kingdom.

INTRODUCTION

The European Working Group on Internal Erosion (EWGIE) was set up in 1993 under the chairmanship of Andrew Charles, with a report of progress to the 2001 European Conference and 2002 BDS Conference (Charles, 2001, 2002). 47 case histories were collected and preliminary conclusions drawn as to the features that increase the vulnerability of dams to internal erosion.

Following a number of serious incidents and failures in Europe due to internal erosion, research funding became available, with chairmanship of the EWGIE passing to Jean Jacques Fry of EDF (Brown and Carter, 2004). An inaugural workshop on definitions and research needs was held at Aussois in April 2005 (Fell and Fry, 2007), with subsequent and ongoing annual workshops. The Interim Report of the European Working group of ICOLD was published at the European Conference on dams in Freising in 2007. It is planned to publish the final report in 2010, at the next European conference.

The focus of the EWGIE is production of technical analytical methods which can be used by engineers to both assess the risk of internal erosion in existing earth structures, and for design of new structures. The presentations and attendees at the workshops are a mix of PhD output and work by practising engineers, most being the engineers for owners of major portfolios of dams.

Ensuring reservoir safety into the future. Thomas Telford, London, 2008

It is suggested that the level of detail which is appropriate to apply to the assessment of vulnerability to internal erosion should be on a risk based approach. This considered whether the Undertaker has reduced risk 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.

FRAMEWORK FOR CONSIDERING INTERNAL EROSION

The process of internal erosion is best considered as a series of steps, which can lead from initiation through to progression, as summarized in Table 1, each being applied to the four types of internal erosion shown in Table 2. Further detail on definitions is given in the overview paper in Fell and Fry (2007), being based on the Fell (New South Wales Univ) model of the stages of internal erosion, which itself was based on US Bureau of Reclamation work.

Table 1: Stages of internal erosion

	Phase	Key issues
1	Load conditions	Reservoir level changes. Seismic, Seasonal effects such as sun shrinkage, frost and thawing; External loads such as animal holes, tree roots and human effects such as terrorism or accidents
2	Location	Embankment, appurtenant works, foundation
3	Initiation	Will particles start to move? Four types of internal erosion are differentiated, as shown in Table 3
4	Continuation (Filtration)	Will filters / shoulders stop erosion?
5	Progression	Will the pipe stay open, or collapse? What are the hydraulic conditions, in terms of critical shear stress and rate of erosion? Are there upstream or downstream conditions that would limit progression?
6	Detection	How can the internal erosion be detected, and how far will it have progressed by then?
7	Intervention	What options are there for ways to stop internal erosion, and how effective will they be? E.g. Diaphragm wall? Toe filter?
8	Breach	What is the mechanism(s) which leads to a breach? Four modes are identified a) gross enlargement of pipe b) loss of freeboard (crest settlement) c) slope instability d) unraveling

Table 2: Types of internal erosion

Type	Definition
Concentrated erosion	In soils which are capable of sustaining an open crack, or in the interconnecting voids in a continuous permeable zone. Erosion occurs along the sides of the crack (or voids) where the shear stress (velocity) exceeds the critical value. NB at low flows there may be leakage with no erosion.
Suffosion	Mass erosion in soils which are internally unstable. Fines transported by seepage flow between the larger soil particles.
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.
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

The Interim Report highlights that for a safety evaluation of internal erosion it is necessary to have data, and a corresponding analytical model, in four the following broad areas:-

a) geometry of the dam,
b) geology of the foundation,
c) geotechnical parameters of the soils comprising the dam and its foundation,
d) hydraulic parameters of permeability and erodibility of soils, and boundary conditions for seepage and flow analysis.

MODES OF FAILURE

In applying the framework for considering internal erosion and thus the vulnerability to internal erosion at a particular dam it has been found helpful to apply the event tree process developed by the US Bureau of Reclamation (Cyganiewicz et al, 2005), as a means of thinking through the processes which determine the vulnerability of a dam to failure by internal erosion. An example of this is given in Table 3, applied in a workshop process of six dam engineers to a cast iron pipe with downstream control in an old dam. This is similar to the event train process in the Interim Guide to QRA (2004). The probability of an answer "Yes" to each step (i.e. the process moving towards failure) can be estimated in a workshop process, and when multiplied together provide an estimate of the overall probability of failure.

The process can also be used to explore potential structural works to reduce the probability of failure, and this is also included in Table 3. This shows that the addition of a upstream valve would have no impact on the annual probability of an incident occurring, but would reduce the probability of the incident progressing to failure (estimated in the workshop as by a factor of 100). Conversely a structural relining of the pipe would reduce both the probability of internal erosion commencing, and the probability of failure (estimated in the workshop as by factors of 40 and 100 respectively).

Table 3: Example of Event tree analysis applied to a bottom outlet pipe laid within the embankment fill

	Stage	Features affecting probability of internal erosion progressing at the subject dam	Potential risk reduction measures
1	Outlet pipe cracks		
2	Initiation	Internal erosion initiates along the outside of the pipe	Reline pipe
3	Continuation – is there an unfiltered exit?	Various exists, some unfiltered	
4	Progression - does a roof form	Assume void can develop along the top, sides or bottom of the pipe	
5	Progression - is the flow unlimited	Flow is limited by the diameter of the bottom outlet pipe i.e. maximum flow through the 280mm pipe is 1000l/s.	Add upstream valve
6	Is early intervention unsuccessful	High level and imported pumps would be used	
7	Will the dam breach process initiate?	The likelihood of breach is reduced by the presence of a rockfill toe	
8	Will heroic intervention be unsuccessful	The rockfill toe should slow the rate of breach development i.e. maximum flow is say 200l/s/m if spread out over 5m width	

TOOLS TO QUANTIFY VULNERABILITY TO INTERNAL EROSION

General

Tools to quantify the vulnerability to internal erosion are still being refined, but basic tools are now available, and are described in papers in the Interim Report of the EWG with highlights given below.

Concentrated erosion

Tools to predict the vulnerability of the watertight element of a dam to the various causes of cracking (hydraulic fracture, differential settlement etc) are reasonably well understood, with Sherard (1986) noting that cracking of the core probably occurs in most embankment dams. In cohesive soils the onset of internal erosion occurs when the shear stress imposed by water flow exceeds the critical shear stress of the soil, determined from the Hole Erosion test or similar. It appears to vary by several orders of magnitude depending on the properties of the core material, from near zero to around

150Pa (Wan and Fell, 2002, 2004). The quoted rate of erosion once this threshold is exceeded similarly varies by several orders of magnitude.

The imposed shear stress τ and flow velocity in the crack can be calculated from standard hydraulic methods and will vary depending on whether flow is laminar or turbulent. Thus the drag force τ on the sides of the crack (or voids) is :

$$\tau = \gamma_w . R_H . i$$

where :

γ_w : is the water specific weight (9.8 kN/m^3)

R_H : hydraulic radius

i : hydraulic gradient

In interconnecting voids R_H is equal to the pore diameter Dp/4, where Dp(m) is issued from the maximal permeability with k (m/s): Dp $=\sqrt{(1E^{-5}*K)}$; whilst in a extended crack of height much greater than width R_H may be taken as half crack width.

Suffosion

Internal erosion of fines within the matrix will occur when the flow velocity in the pores is sufficient to move particles within the pores of the soil.

The mean pore velocity V_{pav} due to seepage flow can be estimated from the Darcy velocity estimated from seepage analysis as follows:

$$V_{pav} = \frac{V}{n\ T}$$

where n is the porosity and T is the Tortuosity (taken as $2/\pi = 0.64$). The relationship between particle size D (mm) and velocity to cause movement may be taken from Equation 20 or Figure 4 of Perzimaier et al (2007), but for pore velocity less than 10^{-2}m/s (particle < 100μm) is approximately $D = 11.5\ V_{pav}^{1.285}$.

The size of particles within the soil which are vulnerable to movement, due to the soil being internally unstable, may be estimated using Kenney and Lau (1985, 1986).

Backward Erosion (Piping)

For detailed analysis the safety factor against piping would be calculated from pore pressures at the toe of the dam taken either from piezometers, or detailed seepage analysis. However, for preliminary analysis average gradients along the whole length of the potential failure path may be used. Critical average gradients for piping were given by Bligh (1910), Lane (1935) and recently by Weijmers and Sellmejier (1993). The latter quote

0.34, 0.28, 0.24 and 0.14 for gravel, coarse, medium and fine sand respectively, all for a uniformity coefficient of 3.

The most likely location for piping is in the foundation, where overlying cohesive soils mean a roof will remain stable. Piping in the embankment is likely to initiate as backsapping and local slope instability at the toe of the dam because any embryonic pipe within the embankment would tend to collapse. A possible exception is in the vicinity of the phreatic surface, where a roof may be sustained over a pipe due to suction forces in the overlying partially saturated soil

Contact erosion

The methodology for estimating the onset of contact erosion is similar to that for concentrated erosion, but with suitable adjustment for pore size and/ or crack width.

SYSTEM RESPONSE

Even where internal erosion initiates it may not continue, and if its does continue it may not lead to failure. For example where the shoulders of a dam are of fine cohesionless materials migration of fines from the shoulders may block any concentrated erosion within the core. Secondly as the flow through a crack in the core increases the head loss in the shoulders will increase, which will reduce the head across the core, potentially to a shear stress (or velocity) below which erosion stops. In assessing internal erosion it is therefore important that all stages of internal erosion are considered, as shown in Table 1, and that the interaction between the various elements of the system are understood.

FILTER DESIGN

It must be appreciated that some migration of particles within the body of a dam under hydraulic loading is likely to occur in all dams, and is part of the bedding in process for new dams. What can be prevented is loss of those particles from the dam, and this is one of the roles of filters; to trap particles on the face subjected to water load. Where the number of particles trapped is large, this leads to clogging on the upstream face. A second role is to provide drainage of water seeping through the dam, such that the phreatic surface is drawn down towards the base of the dam thereby improving the stability of the downstream face and its foundation. Clogging is not an issue for fine filters on the downstream side of the core as it increases impermeability of the water retaining system. However, it could be a problem where it occurred in a filter blanketing the foundation, as it could lead to increased uplift pressures.

The issue of filter design is well covered in the ICOLD Bulletin (1994), with an example of application of this and more recent rules given in Bridle (2008) and not repeated here.

DEBATABLE ISSUES

How variable are UK "puddled clays"?

It is clear that the term puddle relates to the form of construction, and not the properties of the clay. Figure 1 is reproduced from Moffat (2002) and shows clearly the wide variation of plasticity of clays used in UK dams, and that in fact some dams have cores constructed of silt. Non-cohesive silts will be vulnerable to rapid erosion in the event of a concentrated leak.

Are UK soils dispersive?

Recent laboratory testing as part of feasibility studies for dam rehabilitation works, and new flood detention reservoirs is summarized in Table 4 and has showed that some UK clays are dispersive, that is the clay flocs are either naturally dispersed into single clay particles or small clay flocs, or vulnerable to dispersion when the water chemistry changes. This is similar to the findings from Atkinson et al (1990) where tests on four UK puddle clays showed one is dispersive. Dispersive clays are more vulnerable to extremely rapid erosion in the event of concentrated leakage. It is considered that further research is required into this aspect of UK soils.

Figure 1 The range of fine grained soils used in UK "puddle clay core" dams (as Table 3 of Moffat, 2002)

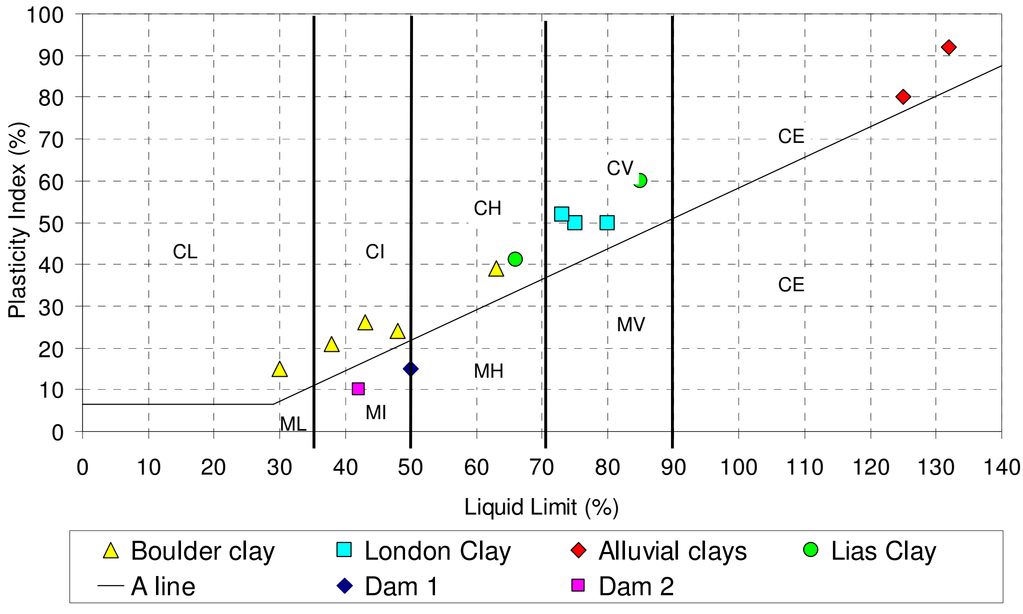

Table 4: Results of dispersion related testing on soils used in UK dams

Dam	LL	PI	%< 75µm	Double Hydrometer	Crumb	Pinhole
A	31	12	62, 69	47%, 42%	Both dispersive (1 x G3, 1 x G4)	Not tested
B	27 to 54	8 to 28	39 to 99	9 tests, 5 >50%, 1x 30-50%	10 tests 1xG4, 2xG2, 7xG1	9 tests, 1xD1, 3xND3 4xND2, 1xND1
C	35	19	76%	29%, 30%	Both Dispersive (G3)	ND2 (non-dispersive)

Notes. Test methods and classification of results described in Head (1982) and BS 1377-5, Section 6. For hydrometer tests 100% is that addition of chemical dispersant does not increase % passing 0.002mm; Sherard et al (1976) suggests that > 50% is classified as dispersive and 30 to 50% as slightly dispersive. The range of potential results for Crumb and Pinhole test are G4 (dispersive) to G1 and D1, D2, ND4 to ND1; ranging from Dispersive o Non-dispersive.

<u>Does the likelihood of internal erosion vary with the time of year?</u>

It sis suggested that the vulnerability of dams to internal erosion will vary seasonally. This is partly because the permeability of a soil varies due to variation of viscosity of water with temperature, water at 20^{o}C having 56% of the viscosity at 0^{o}C. Secondly in summer there is the risk of desiccation of cores which are not protected by a capillary break, which can lead to surface cracks along which concentrated leakage can occur. Figure 7 of Brown (2007) examines the seasonality of a limited number of internal erosion incidents, this data suggesting the frequency of incidents in the summer is up to three times higher than other seasons.

STATUTORY OBLIGATIONS

Currently most Inspection Reports under Section 10 of the Reservoirs Act 1975 do not consider the adequacy of the embankment, in the same way that the adequacy of the spillway to pass the design flood is considered. This is partly because Statutory Instrument 1986 No 468 which sets out the minimum contents of a Section 10 Report does not explicitly require comment on the adequacy of embankment, whereas it does require comment on the following

> *v – adequacy of the waste weir or overflow*
> *vii – adequacy of the margin between dam level and overflow level*
> *viii – efficiency of the scour pipe or discharge culvert or other means of lowering the ……reservoir*

It is of relevant to note that Form E of the 1930 Act required "*…particular reference to (b) leakages, settlement or movement of reservoir banks or walls, movement of surrounding land which might affect stability of* *reservoir"* This is downgraded in the 1975 Act into "*recommendations involving …the installation of instruments or gauges for measuring leakages, deflections, settlement, uplift, pore pressures or similar matters"*

CONCLUSIONS

The understanding of internal erosion has progressed significantly in recent years following research work in Australia and Europe, with key developments published in Fell and Fry (2007) and the Interim Report of the European Working Group in Freising (2007). This paper has highlighted some of the key issues.

These developments have significant implications for UK dam engineers, in that it is practicable to carry out a basic assessment of vulnerability to, and risk of, internal erosion, It is therefore recommended that the contents of Section 10 reports should include an explicit statement of the adequacy of the dam embankment or other structure retaining the water, similar to that on adequacy of the spillway and outlet. It is recommended that

a) Legislation is changed to add to SI 1986 No 468 Schedule 2 "(ix) a statement as to the adequacy of the dam and its foundation, in terms of ability to retain the reservoir"
b) Guidance on Section 21(5) of the Reservoirs Act should include that the Undertaker should provide "information on the material properties of the dam and its foundation (e.g. geotechnical for earth embankments, concrete and rock for concrete dams), where available"

The level of detail should vary with the consequences of failure, following a risk based approach, and could start with a screening level quantitative assessment of risk. Where more detailed assessment is warranted this would require increased data, but as a minimum owners could carry out a portfolio wide desk study of the information that is available on all of their dams, including construction drawings (although these may be unreliable), site investigation and published geotechnical data on geological deposits in the area which are likely to have been used in dam construction. For some very high consequence dams it may then be appropriate to carry out further site investigation to establish, or confirm, dam construction details, including the filtering ability of the downstream shoulder and erodibility of the core.

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