Defra Reservoir Safety research contract

Engineering Guide to
Early detection of internal erosion

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Executive Summary

The purpose of this Engineering Guide to Early Detection of Internal Erosion is to provide guidance to assist the undertaker and his engineering advisors in the management of the risk of internal erosion at embankment dams. Application of this Guide should therefore lead to a reduction in the number of reservoir emergency drawdown each year, due to serious internal erosion incidents. There is a need for further research into internal erosion. It is anticipated that when this has been completed then this Guide would be updated and merged with the existing Engineering Guide to the Safety of Embankment Dams in the United Kingdom (Johnston et al, 1999) to form the third edition of that guide.

It is suggested that the strategy for managing internal erosion should include both

a) improving understanding of the intrinsic condition of the dam, and thus its vulnerability to internal erosion
b) surveillance and monitoring targeted at early detection of indicators of internal erosion (the dam's current condition)

The Guide provides commentary on the four different types of internal erosion, including likely symptoms. It then discusses how these may be used in a risk analysis of the potential failure modes of the system of the watertight element, its supporting fill and foundation. Recommendations are made that each dam owner should compile a dossier on the hazards, risks and control measures in relation to internal erosion. The level of information required would typically be obtained from desk study. This dossier would be provided to the Inspecting Engineer for review when carrying out an Inspection under Section 10. Where the owner does not have the technical resources to prepare this information he should commission suitable engineering assistance.

In regard to surveillance and monitoring the Guide adopts a risk based approach, giving a suggested starting point for selection of the surveillance frequency, based on Consequence Class and Vulnerability to Internal Erosion. The primary tool for risk management should be surveillance, with monitoring a complementary tool. In a few cases of high consequence dams, real time monitoring may be appropriate.

The Guide includes guidance on how a strategy for risk management of internal erosion may be developed. The tools available for risk management include surveillance, monitoring, emergency planning and structural works. The Guide recommends that the strategy for an individual dam should be based on an "As low as reasonably practicable" (ALARP) assessment. The level of this assessment should reflect the risk, ranging between a simple qualitative assessment for low risk situations and a quantitative assessment including estimates of the cost to save a statistical life for high risk.

1 Introduction

1.1 Internal erosion and its impact

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 period 1975-2000 are summarised in Table 1.1. It can be seen that over half of the incidents which occur each year in the United Kingdom 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.

Table 1.1 Data on internal erosion incidents in the United Kingdom in the period 1975-2000 from BRE database

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 • slope instability	60% 23%	63% 9%
Inferred annual probability of an incident due to internal erosion	1 in 500 (0.2%)	1 in 160 (0.6%)

1.2 The need for early detection of internal erosion

Despite the, on average, two emergency drawdown incidents a year due to internal erosion 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 is the effective surveillance and intervention regime, which has provided time to detect developing problems and lower the reservoir before the problem developed to failure.

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. It is therefore important to take positive steps to ensure early detection of internal erosion, such that there is time for intervention prior to the dam deteriorating to a point where failure is unavoidable.

1.3 Aims and use of Guide

The Engineering Guide to the Safety of Embankment Dams (EGSED) (Johnston et al, 1999) recommends that the safety of embankment dams is managed through the concept of an observational procedure. Traditionally this approach has been applied but with limited given to initial study, such that it is a largely reactive approach to early detection of symptoms of internal erosion, rather than the results of a detailed understanding of the underlying vulnerability of the dam.

This Guide aims to provide engineering guidance on how dam owners and their engineering advisors can develop a strategy for the early detection of internal erosion at their embankment dams, both in relation to underlying vulnerability and the detection of symptoms. The same principles would apply to erodible materials in the foundations of concrete dams, although this guide is not specifically targeted at this type of dam. The Guide is targeted at professionally qualified engineers as of necessity it includes equations and technical information.

Application of this Guide should therefore lead to a reduction in the number of reservoir emergency drawdown each year, due to serious internal erosion incidents.

There is a need for further research into internal erosion. It is anticipated that when this has been completed this Guide would be updated and merged with the existing Engineering Guide to the Safety of Embankment Dams to form the third edition of that Guide.

1.4 Roles and responsibilities

It is suggested that the principle of a permissioning regime should apply to the management of internal erosion. The principles are set out in Box 1-1. There are a number of guidance statements issued by HSE in support of this policy, which are referred to as appropriate later in this Guide.

Thus early detection of internal erosion should form part of the Undertaker's risk control measures at a reservoir, comprising active and ongoing control measures which are documented in company procedures. The role of the Inspecting Engineer, in periodical safety inspections under Section 10 of the Reservoirs Act 1975, is then to review the measures for adequacy, in terms of risk to the public. The role of the Supervising Engineer under the Reservoirs Act 1975 is to watch that the measures, as set out in company procedures and the last Inspection Report, continue to be implemented.

Box 1-1 Principles of "permissioning" regimes (HSE, 2003)

1. Through the political process, the regulator and the regulated are subject to society's views about the tolerability of risk:
    - *"Permissioning" regimes are applied to high hazard industries when there are significant risks of multiple fatalities from a single (or linked series of) event(s); and the proposed regime adds proportionate value in terms of risk control and/or allows specific activities (with clear benefits to society) to proceed.*
2. The legal duty to manage risks lies with the organisations that create the risks - "permissioning" regimes require them to describe how, but a description is not sufficient without the active commitment of the duty holder in practice:
    - *Duty holders must identify the hazards, assess the risks, develop effective control measures and keep a current documentary record of all this;*
    - *The control measures must cover design and hardware, systems and procedures and human factors in a coherent whole;*
    - *Duty holders must implement control measures and keep them up to date;*
    - *Duty holders must make and test arrangements for managing emergencies and mitigating their consequences.*
3. A goal-setting framework is preferable to a prescriptive one because it makes duty-holders think for themselves.
    - *The flexibility of goal-setting is more likely to lead to arrangements for controlling risk which are tailored to the particular circumstances, and which through safety case maintenance and resubmission will remain so;*
    - *Within a goal-setting context, "permissioning " regimes define elements of the management arrangements required.*

1.5 Relationship to other guidance

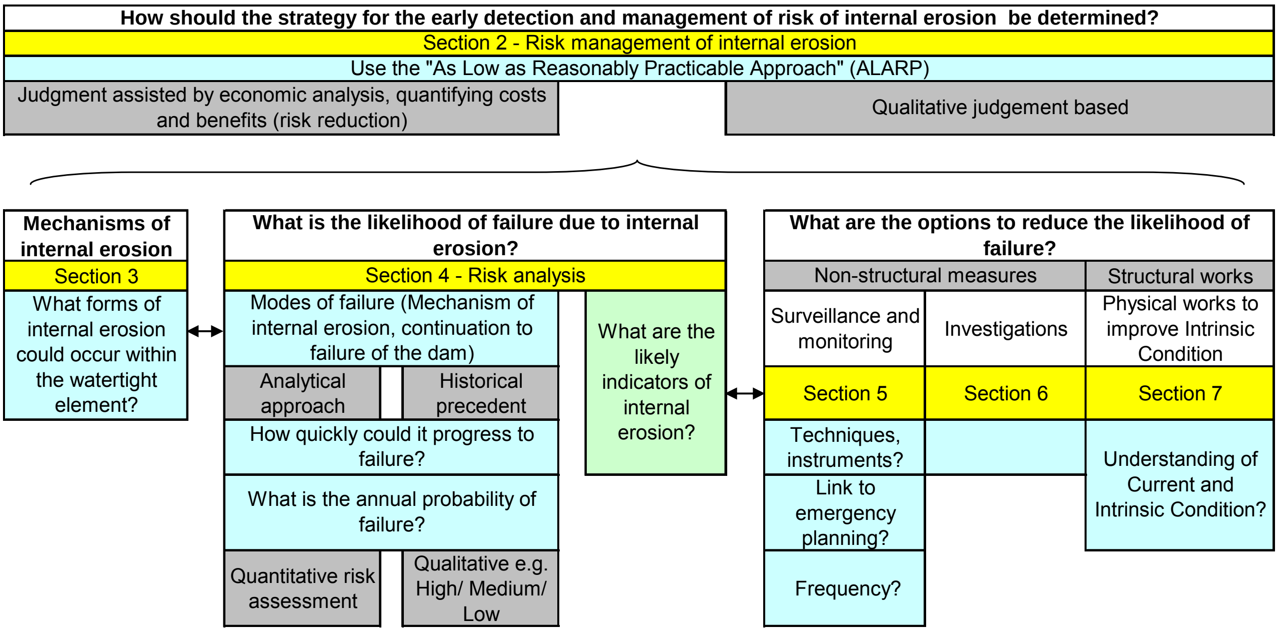
This Guide complements the following existing Engineering Guides,
a) Engineering Guide to the Safety of Embankment Dams in the UK (Johnston et al, 1999) (EGSED)
b) Investigating embankment dams (Charles et al, 1996) (IED)
c) Small embankment reservoirs CIRIA Report 161 (CIRIA, 1996)

It has developed in parallel with research work in Europe into internal erosion, in which one of the authors of this report has participated actively through annual progress workshops. The findings from the European Working Group on Internal Erosion will be published at the European conference in Germany in September 2007. Other useful references are given in the Bibliography at the end of this Guide.

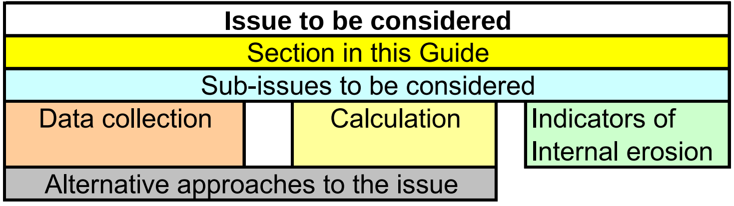
1.6 Structure of Guide

The structure of the Guide is set out in Figure 1.1.

Figure 1.1 : Structure of Guide to Early Detection of Internal Erosion



Key for Figures 1.1, 2.2, 3.1, 4.1 and 5.1



2 Risk management of internal erosion

2.1 Introduction

2.1.1 General

This section sets out the factors that should be considered when defining, and periodically reviewing, a strategy for management of the risk from internal erosion.

The different objectives and content of risk analysis and risk management are summarised in Figure 2.1, as two concentric circles. The first stage (inner circle) of risk analysis is to understand and assess the risk. The second stage (outer circle) manages that risk by appropriate structural or non-structural interventions which incur proportionate cost. Definitions of the key terms are given in Table 2.1. Risk analysis is discussed in Section 4, whilst the principles and tools for risk management are discussed in this section.

The primary control measures to reduce risk from internal erosion are summarised in Table 2.3.

Table 2.1 Key terms in relation to risk management of internal erosion

Term	Definition
Current Condition	Current day performance in terms of seepage, settlement etc. May provide evidence of vulnerability, and indication of time to failure
Intrinsic Condition	Concerned with the physical materials and detailing of the dam (vulnerability to a threat). Vulnerability has to be inferred, where there are no signs of adverse behaviour
Monitoring	Reading and interpretation of instruments, recording some aspect of dam behaviour.
Risk	The product of annual probability of an event and its consequences.
Risk analysis	What is the magnitude of risk?
Risk management	Is the level of existing risk tolerable? What interventions are appropriate and proportionate to manage this risk, either keeping it at its existing level, or to reduce it?
Tolerable	A willingness to live with a risk so as to secure certain benefits and in the confidence that the risk is one that is worth taking and that it is being properly controlled (HSE, 2001, page 3)
Singularities	These are features which are often not shown on “as-built” construction drawings and which may have a significant effect on the mode of, and rate of deterioration due to, internal erosion. These include irregularities in the foundation, construction stage features such as access routes; local drainage; variations in materials; and trial pits/ or other localised excavation and backfilling within the dam.
Surveillance	Visual observation of a dam

2.1.2 Process for determination of strategy for early detection of internal erosion

The thought process for risk management is indicated in Figure 2.2. In broad terms the strategy for early detection of internal erosion could be based on one of the approaches in Table 2.2. In practice it is appropriate on most dams to adopt a mix of the two approaches, with the issue being the weighting given to either of these approaches.

Figure 2.1: Relationship of risk analysis to risk management

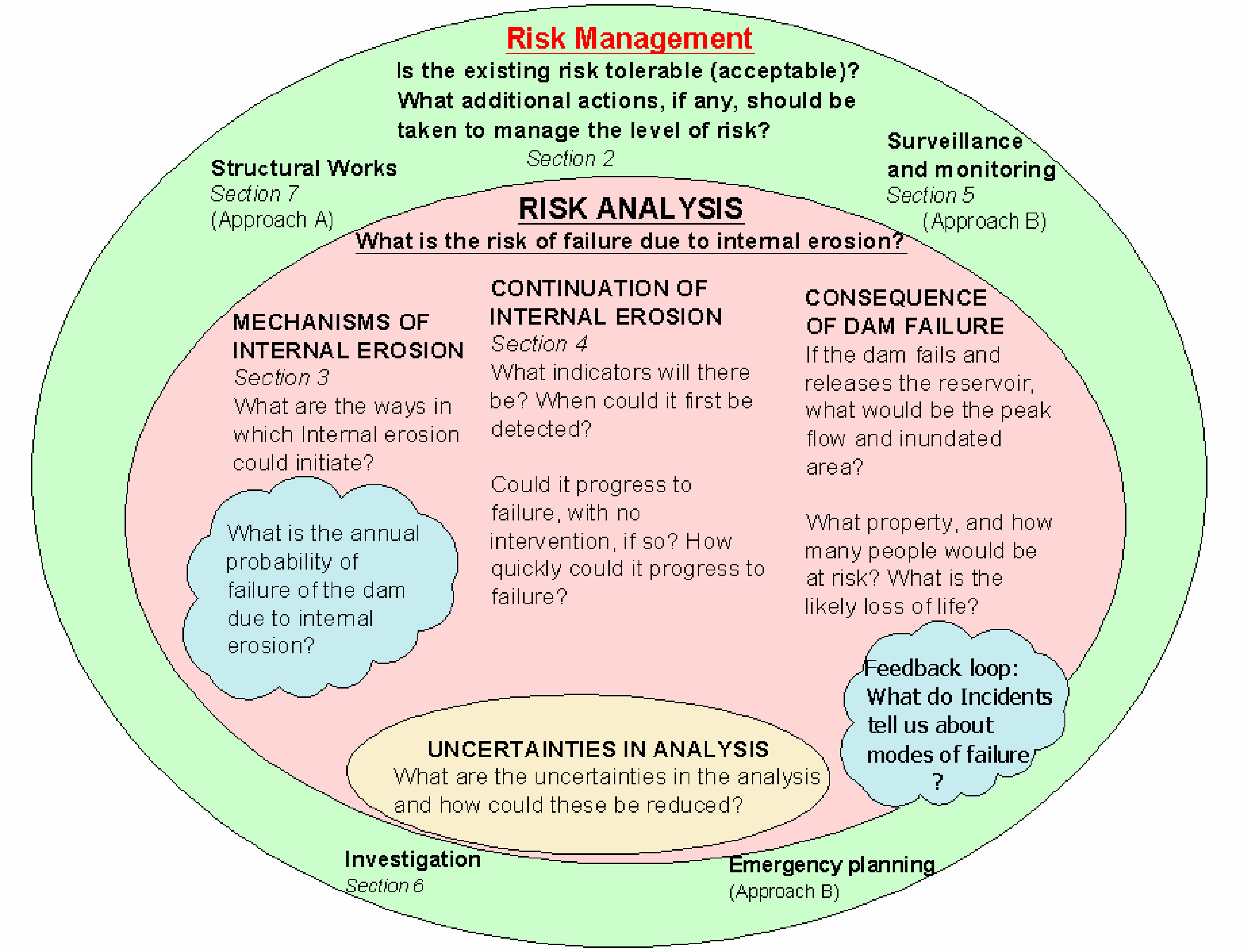
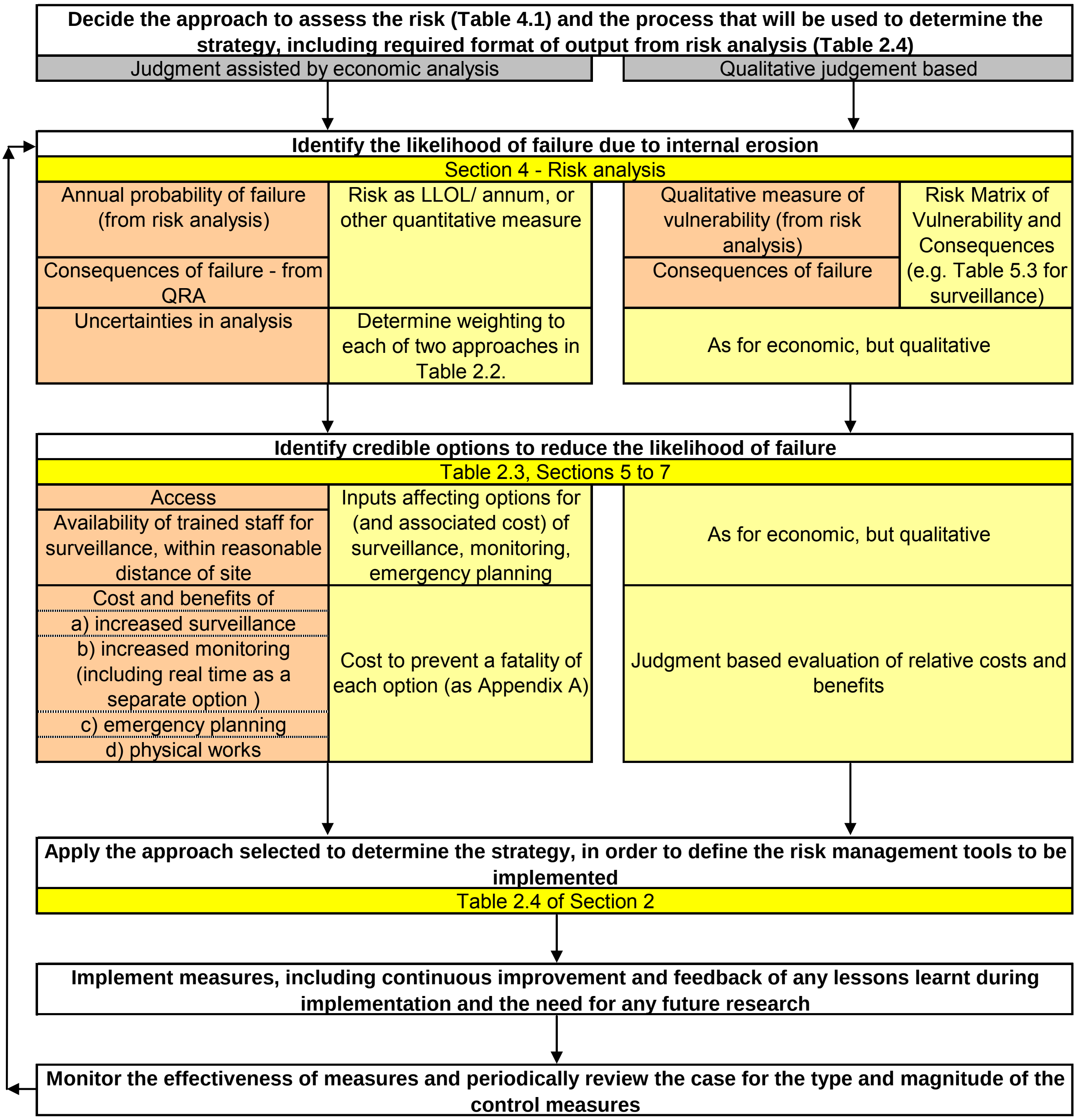


Table 2.2 Alternative approaches to a strategy for management of the risk of internal erosion

Approach	Based on	Process for		Likely effectiveness
		Early detection	Risk management	
A	Intrinsic vulnerability	Predicting where internal erosion is likely to occur	Carrying out structural works to prevent, or manage assessed risk of internal erosion	Depends on the quality of data on the dam, the accuracy of modelling of internal erosion processes and the extent to which singularities are present in the dam
B	Current condition	Ongoing observation of current condition	Effective surveillance, monitoring and emergency plans to mitigate effects if internal erosion occurs	Depends on the quality of surveillance and monitoring, and the speed with which monitoring data is assessed

Figure 2.2 : Process to select risk management regime



Note: For key see Figure 1.1

Table 2.3 Alternative ways to reduce the risk of failure due to internal erosion

Option	Purpose	Situations where likely to be appropriate	Further information
Investigations of current or intrinsic condition of dam	Provide an improved understanding of the risk from internal erosion	Where investigation would materially change the assessment of risk	Investigation may be limited to desk study, or could include site investigation and/ or leakage investigations. See Section 6 of this Guide
Surveillance and Monitoring	Early detection of symptoms providing time for intervention	Always appropriate as a means of dealing with residual risk.	Section 5 of this Guide
Emergency planning	a) Planning of measures to be taken in the event that progressive internal erosion is detected, and thus allow more effective use of the time for intervention	Always appropriate as a means of dealing with residual risk.	Covered in Guide to Emergency Planning. The key issue in relation to internal erosion is that the process to be followed when progressive internal erosion is detected should be set out in the emergency plans
	b) Increase the capacity of the bottom outlet	When both the following apply: a) the surveillance frequency would allow early detection of internal erosion, and b) the rate of progression to failure would be such that there is sufficient residual time after detection for the use of the bottom outlet to significantly lower the reservoir	Currently there is no guidance on the desirable bottom outlet capacity. Table 4.3 of this Guide provides some guidance on when the bottom outlet capacity is likely to be relevant
Structural works at dam	Reduce the vulnerability to internal erosion	When both the following apply: a) there is a reliable assessment of the most likely modes, and the risk, of failure, and b) where the proposed works would introduce new risks, then the net effect of the structural works is a significant reduction in overall risk	The Engineering Guide to the Safety of Embankment Dams, supplemented by comments on defensive measures in Section 3 of this Guide.

2.2 Risk management strategy

2.2.1 Principles

Risk management is the process of deciding whether a risk is sufficiently significant to require additional control measures.

The Health and Safety Executive in UK notes that the cost of risk reduction works should be “reasonably practicable”, stating in para 4 of Appendix 3 of HSE (2001):

“Of particular importance … is Edwards v. The National Coal Board (1949). This case established that a computation must be made in which the quantum of risk is placed on one scale and the sacrifice, whether in money, time or trouble, involved in the measures necessary to avert the risk is placed in the other; and that, if it be shown that there is a gross disproportion between them, the risk being insignificant

in relation to the sacrifice, the person upon whom the duty is laid discharges the burden of proving that compliance was not reasonably practicable."

In terms of application of this principle Item 9 of the HSE statement (2001) "Principles and guidelines to assist HSE in its judgments that duty-holders have reduced risk as low as reasonably practicable" (ALARP) states

"This process can involve varying degrees of rigour which will depend on the nature of the hazard, the extent of the risk and the control measures to be adopted. The more systematic the approach, the more rigorous and more transparent it is to the regulator and other interested parties. However, duty-holders (and the regulator) should not be overburdened if such rigour is not warranted. The greater the initial level of risk under consideration, the greater the degree of rigour HSE requires of the arguments purporting to show that those risks have been reduced ALARP"

It is thus implicit that all risk management action should be subject to an ALARP assessment, both in terms of the adequacy of existing arrangements and the case for enhanced measures. This test can either be entirely judgment based, or can use a quantitative analysis, depending on the level of risk. Examples of a quantitative calculation are given in Appendix A.

2.2.2 Strategic approach to development of strategy for risk management

One of the key principles of risk management is that the owner of the hazard is responsible for assessing and managing the risk (see Box 1-1). He can discharge this responsibility in various alternative ways, for example as set out in Table 2.4

It is implicit in all approaches that the owner compiles a documentary record of his assessment of hazards, risks and control measures, including supporting data. This should be provided to the Inspecting Engineer for review when carrying out a periodic Inspection under Section 10 of the Reservoirs Act.

Where the owner does not have technical resources to prepare this information he should commission suitable engineering assistance. This could be by the Inspecting Engineer or by other engineers. However, it must be recognised that compiling this data, carrying out the risk assessment and determining the strategy for management of internal erosion is not part of the Inspection, but is a separate commission.

2.2.3 Evaluation of options

Assessment of candidate options to reduce the risk from internal erosion should take into account factors such as

a) At similar types of dam to the subject dam would
  - candidate structural risk reduction works have prevented recent incidents?
  - the proposed change in surveillance regime have achieved earlier detection?

b) What are the uncertainties in knowledge of the subject dam?

c) What are the limitations of our existing understanding of processes?

The response may be that a phased approach is adopted, utilising non-structural measures such as surveillance whilst further study or research is carried out.

It is implicit that quantitative risk assessment, including ALARP analysis, can be used as an aid to judgement, both to select between the various risk reduction measures available, and also to establish when further risk reduction would be disproportionate. Nevertheless, the ultimate judgment should be made by experienced engineers, based on experience and a risk analysis as described in Section 4.

It is suggested that a precautionary principle is adopted when considering uncertainty, such that where there is uncertainty then conservative assumptions should be made regarding the unknown elements.

Table 2.4 : Alternative approaches to determine the strategy for management of the risk from internal erosion

	Approach to determine strategy for Risk Management	**Description**	**Remarks**	**Format of output from Risk Analysis**
1	Portfolio risk assessment, where the largest reduction in risk across the portfolio for a given investment is selected	a) Owner carries out, or commissions, study of several reservoirs at once, which provides economies in data collection and assessments. This could initially be a pilot study of separate dams from across the whole portfolio. b) This approach can also be used to prioritise works, which provides best value for funds across the whole portfolio.	In UK 'b' may be contradicted by Inspecting Engineers recommending "matters in the interests of safety" on individual dams, in which case the outcome would be closer to Approach 2.	Quantitative Risk Assessment (QRA) (Note 1)
2	Quantitative ALARP analysis on a dam by dam basis	This approach is similar to 3 in that each dam is assessed on a standalone basis, but informed by the QRA and thus providing a more transparent and auditable process. It presupposes a QRA is available, or is carried out as part of the review of the risk management process.		
3	Good practice, based on judgement following this guide and others (qualitative ALARP).	As a minimum compile data relevant to internal erosion, and ask the Panel Engineer to carry out an internal erosion study in parallel with his Inspection. Historically this has often been the approach adopted to spillway capacity, where a flood study has been added to the Inspection commission.	With this approach the owner's action will largely rely on the judgement of his Inspecting Engineer through the Reservoirs Act 1975 Inspection process	Likelihood of failure (and/or speed of failure) as High/ Medium/ Low. This can be entirely judgment based or use one of the tools to assess criticality described in Section 4.3.

Notes.

1. In the medium to long term it would be desirable to quantify this through an analytical approach. However, currently these methods are not sufficiently reliable to use for QRA. The Interim Guide to QRA (Brown & Gosden, 2004) therefore estimates the overall annual probability of failure based on statistical data from historic incidents.

3 Mechanisms of internal erosion

3.1 General

3.1.1 Introduction

This section supplements and extends Section 3.5.2 of the Engineering Guide to the Safety of Embankment Dams (EGSED), reproducing key material such that this Guide is self contained.

Seepage occurs through all dams and structures retaining water, but may not be observable for one or more of the following reasons

- Quantities are so small that they evaporate or otherwise are not noticeable on the downstream face
- The downstream side of the dam includes permeable deposits in the foundations into which seepage can occur without being observed.

Internal erosion occurs when soil particles within an embankment dam or its foundation are carried downstream by seepage flow. This section describes the current knowledge of available criteria to assess the likelihood of internal erosion in the material forming the watertight element of the dam.

3.1.2 Types of internal erosion

Internal erosion can occur in several different ways, the difference being important as it significantly affects both the likely time to failure, and to a lesser extent the indicators of ongoing internal erosion. The international workshop on internal erosion at Aussois in 2005 (Fell and Fry, 2007) defined four different types of internal erosion and the same approach is considered appropriate here. These are defined in Table 3.2. This table also includes

- Comment on the time to failure of each type of internal erosion
- Possible surface expressions of internal erosion

Further detail on each type of internal erosion is included in the subsequent sub-sections. It should be noted that even when the exterior of a dam appears stable there may be undetected voids developing within it. Two examples of UK dams where a slow rate of internal erosion has been observed over several years without any significant surface expression are given in Table 3.1.

Table 3.1 Examples of slow ongoing internal erosion through concentrated leaks in dams

Dam	Inferred erosion rate	Source
Brent	1.0 litre/ year measured in V notch chamber	Tedd et al, 1998
Anonymous	1.0 kg/year measured in V notch chamber	Dam owner
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

Table 3.2 : Definitions and surface indicators of different types of internal erosion

Type of internal erosion	Definition	Time to failure; remarks	Locations	Common surface indicators	
				Dam crest	Downstream face/ toe
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 the upstream and/or downstream 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	Wherever a crack can occur.	Sinkholes or local depressions a) over the core where core material continually collapses. b) where the core material can sustain an open arch then the hole may migrate upstream causing sinkholes or settlement in the non-cohesive material immediately upstream of the core (which cannot sustain an arch). In extreme situations there may be whirlpools	Seepage, suspended fines commencing at critical flow rate. Seepage may be concentrated in homogenous dams, or diffuse in zoned dams where the crack is in the core and the downstream shoulder does not retain fines
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)	Where a pipe can be sustained	Generally no significant settlement, as for the pipe to be sustained the overlying materials forms an arch. Some settlement may occur where the pipe forms partway through the dam, collapses, and reforms	Seepage with fines. In some instances, particularly flood defence embankments, small sand boils have been observed.
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.	Where a fine soil overlies a coarse soil, at the contact e.g. flood embankments where a fine alluvial soil overlies a clean gravel	There may be some settlement, but this is only likely to be detectable when significant erosion has occurred.	Seepage with fines.
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	At the elevation where the seepage velocities are highest in relation to the soil properties at that elevation	In theory there should no settlement, as it is loose fines from within the soil skeleton being eroded, with the soil skeleton remaining unaffected.	Seepage increasing with time until all fines are eroded or the increasing seepage triggers a slope instability or other change in conditions.

3.1.3 Filter Design

Modern dam design would include filters designed to trap any soil particles which had been eroded from the dam. The criteria for filter design can also be used on existing dams to evaluate whether the dam shoulders would trap fines and stop internal erosion. Information on filter design criteria is given in Appendix B.

3.2 Concentrated erosion

3.2.1 General

This is probably the most common form of internal erosion in the UK. This occurs along a crack which may be formed by

a) hydraulic fracture, due to factors such as stress reduction above steps in the foundation along the dam, or above culverts and pipes
b) hydraulic separation between the embankment fill and a structure such as the outlet culvert or spillway
c) desiccation in the top of the core

By definition this mode of failure would be expected to only apply to soils which can maintain a flow of water through an open crack without collapse, namely cohesive soils.

3.2.2 Initiation of erosion and rate of progression

For erosion to occur along the sides of a crack the hydraulic shear stress τ_c (or velocity of flow) must exceed a certain threshold value. This value appears to vary by several orders of magnitude depending on the properties of the core material, from near zero to around 200Pa (Wan and Fell, 2002). The rate of erosion once this threshold is exceeded similarly varies by several orders of magnitude. Test results, as given in Wan et al, are given in Appendix C. These include in Table C.2 proposed rules for assigning preliminary estimates of the representative erosion rate for a soil.

Other data on the erosion rate includes that from the erodibility of clay stream beds and the rate of development of breach of clay embankments. The latter (Wahl, Pers comm.) shows that the erodibility of a particular soil can vary by a factor of 100 depending on the dry density and moisture content. Table 3.3 shows the velocities to cause erosion in stream beds, which confirms the range of limiting velocity of several orders of magnitude.

Table 3.3 Velocities causing erosion of various soil types (after May et al, 2002)

Velocity at which erosion occurs (m/s)	Soil type
Cohesive materials (Table 4.1 in May et al, 2002)	
1.90	Hard clay
1.2 - 1.5	Dense loamy clay
0.4 - 1.0	Loamy sand - heavy medium dense clay
Non cohesive materials (from Box 4.2 Shields method in May et al, 2002)	
0.012	Coarse silt
0.013	Fine sand
0.015	Medium sand
0.030	Coarse sand
0.049	Fine gravel
0.098	Medium gravel

3.2.3 Defence measures

Internal erosion can be prevented, even where a crack occurs, by providing a cohesionless filter on the downstream side of the core which collapses as the crack opens up, thereby sealing it, and has an internal grading which will trap the eroded particles from within the crack (see filter criteria in Appendix B).

3.3 Backward Erosion (Piping)

3.3.1 General

Backward erosion involves the detachment of soil particles when the seepage exits to a free surface at the downstream face of a homogenous dam, or through the foundation to the ground surface downstream of a dam or flood bank. The detached particles are carried away by the seepage flow and the process gradually works its way towards the upstream side of the embankment or its foundation until a continuous pipe is formed. There is some evidence that a pipe can develop for part of the length and then stabilise until the driving head is increased, when the pipe then starts to extend again.

Cohesionless soils, particularly fine sands and silts, are most susceptible. The pipe may

a) form at depth, if cohesionless soils are overlain by a cohesive material or structure which can provide a roof
b) occur close to the phreatic surface, where negative pore pressures in the overlying partially saturated soil provide suction forces which allow the pipe to stay open
c) within the body of the dam, the roof continually collapsing and being carried away by piping water. This collapsing zone is likely to propagate upwards as a zone of increasing looseness. When this zone reaches the phreatic surface, a void may form because the partially saturated fill above the water surface will support the 'crack' forming the arch above the void. This explains why voids are often found at the phreatic surface.

3.3.2 Initiation criteria and rate of progression

Various published criteria for the overall average gradient for piping to occur are summarised in **Table 3.4**. Schmertmann (2000) uses the average hydraulic gradient, but includes a further correction for the uniformity coefficient. Weijers and Sellmeijer (1993) noted that backward erosion may initiate at 40% of the gradients needed for complete piping at the exit point. Perzimajer et al (2007) combined these two observations to provide a criterion for the critical exit gradient as shown in Figure 3.1. Justin et al (1950) quote the following equation from Harza (1935) for the critical gradient i_p in the vicinity of the exit point

$$i_p = h/L = (1-P)(S-1)$$

where h is the difference in head, P the porosity or per cent voids expressed as a decimal and S is the specific gravity of the soil.

Calculation of the average hydraulic gradient and comparison with the criteria in **Table 3.4** is in principle straightforward and provides an initial screening. However it is the gradient local to the free surface exit point which is likely to be important. This is difficult to calculate reliably, because of the variability of soil properties and density. The conclusion in EGSED that "The hydraulic gradient at the point where the water flows out of the ground is critical but is difficult to predict as it can depend amongst other things on localised weaknesses in the fill or foundation" is endorsed.

Table 3.4 Published criteria for critical average gradients to initiate backward erosion and form a pipe

Soil type	Limiting value of		Critical average gradient (reproduced in Perzimajer et al, 2007)		
	Coefficient 'c' in Bligh's theory[1] (1912, reproduced in Maccaferri, 1987)	Lane's weighted creep ratio[2] (1935, reproduced in USBR, 1973)	Muller-Kirchenbauer	Weijers and Sellmeijer, 1993[3]	
				Cu =1.5	Cu =3
Fine sand or silt	18	8.5	-	0.09	0.14
Medium sand	12	6.0	0.06-0.08	0.16	0.24
Coarse sand	-	-	0.08-0.10	0.18	0.26
Medium gravel	4 to 9	3.5	0.12-0.17	0.28	0.34
Boulders with some cobbles and gravel	Not given	2.5	-	-	-
Very hard clay or hardpan	3 to 6	1.6	-	-	-

Notes
1. Bligh - Overall seepage path length L must be greater than the product of 'c' and the net head difference across the structure to avoid piping
2. Lane – The weighted creep ratio should be less than the quoted values for safety against piping, where "the weighted creep distance" of a cross section of dam is the sum of vertical distances along the dam/ soil interfaces (steeper than 45°) plus on-third of the horizontal distances along the interface (less than 45°). The weighted creep ratio is the weighted creep distance divided by the effective head. Reverse filter drains, weep holes and pipe drains are aids to security from underseepage and recommended safe weighted –creep head ratios may be reduced up to 10% if they are used"
3. Cu is the coefficient of uniformity i.e. D_{60}/ D_{10} of the soil

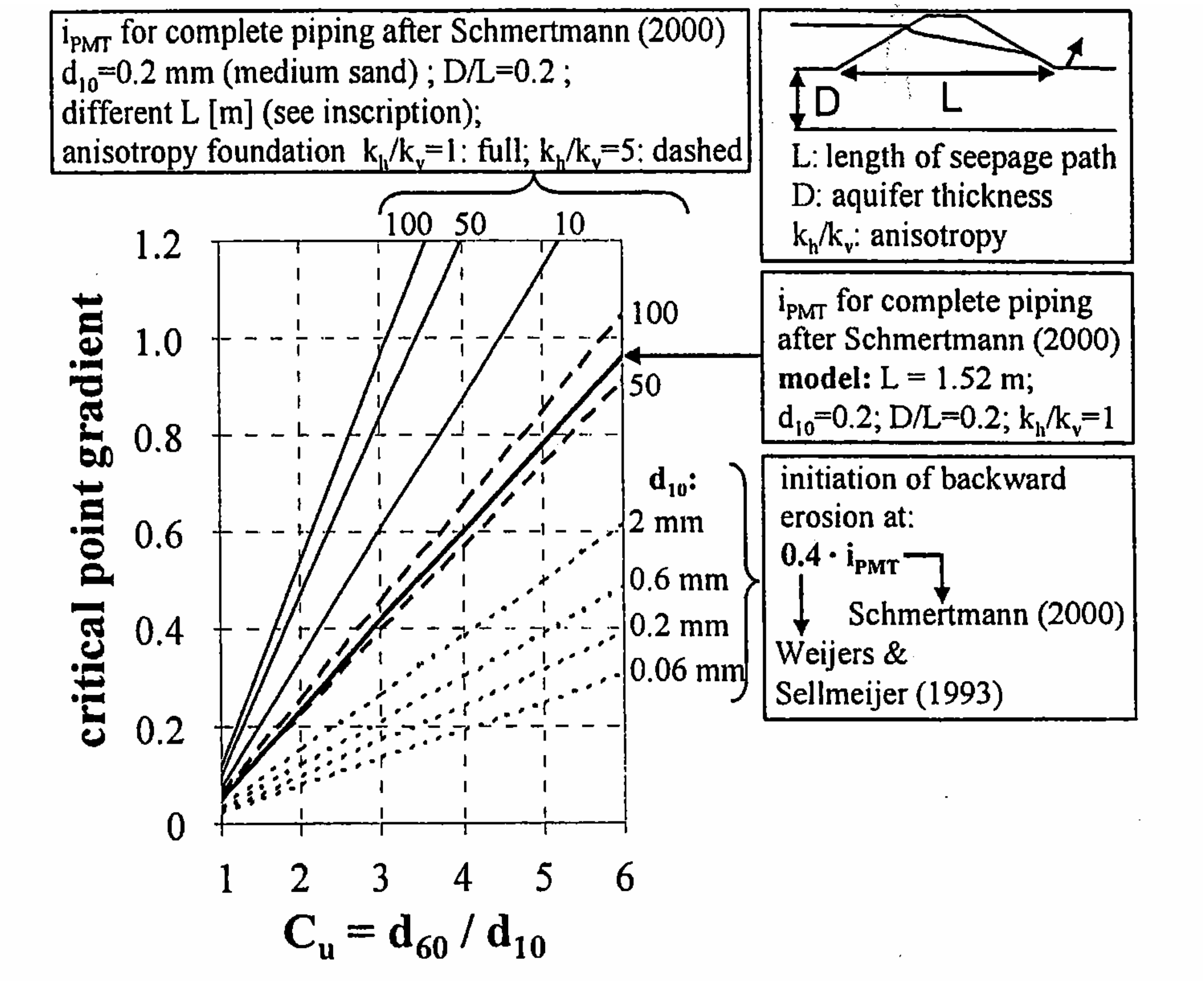
3.3.3 Defence measures

The simplest defence is to provide a reverse filter on the downstream face, comprising successively coarser granular soils which allow drainage whilst preventing transport of fines. The filter rules in Appendix B may be used to determine suitable properties for the blanketing material.

The following is taken from Justin et al (1950); "Where sand boils appear at the toe, due to the vertical seepage gradient being such as to cause the vertical effective stress to reduce to zero, to prevent imminent failure it is necessary to quickly ring the boils with sand bags, or other means, so that some back pressure is exerted on the boils. If this is done sufficiently quickly it is usually possible to establish a condition of stability, so that although water continues to flow out of the boils it will not carry material with it. Where horizontal piping has started the only remedy is to dump rock grading from fine to coarse right into the downstream face where the horizontal piping is occurring, so that improvised drain and filter will be formed and the piping stopped. Both horizontal and vertical piping are serious and may lead to complete failure of the dam if not promptly corrected".

Sellmeijer & Koelewijn (2007) describe similar sand boils downstream of flood embankments in the Netherlands, and the ongoing research programme into internal erosion. Early work culminated in the TAW (1999) design rules. More recent work includes finite element modelling and the field experiment program "Ijdijk" to be conducted 2007-2009.

Figure 3.1 Critical point gradient to initiate backward erosion (from Perzimajer et al, 2007)



3.4 Contact Erosion

Contact erosion has not been reported as an issue in UK dams. The US Bureau of Reclamation call this “scour” when considering the risk of erosion at the contact between the base of a core and (open jointed) rock foundation. Some European countries report that it occurs in the foundation below flood embankments. It appears to be more commonly an issue on flood embankments where clay embankments or soils overly gravel alluvium, with no positive cut-off such that there is a significant flow velocity within the gravel layer which leads to erosion of particles from the base of the clay layer. This is not normally an issue for UK dams and is therefore not considered further.

3.5 Suffosion

3.5.1 General

This occurs in broadly graded soils, whereby fines are removed from the matrix of coarser particles by the seepage water, leaving the intact soil skeleton formed by the coarser particles. Soils which are susceptible to suffosion are internally unstable, and comprise coarsely graded and gap graded soils. Documented case histories include suffosion in WAC Bennet Dam in Canada and dams in Sweden. Although this mode of failure is predominantly relevant to cohesionless soils, laboratory tests have shown that it can also occur in soils with some clay content.

3.5.2 Initiation criteria and rate of progression

There are no commonly agreed criteria for initiation of suffosion, with Perzimaier (2007) noting various equations but also the significant differences between them.

3.5.3 Defence measures

As for concentrated erosion, suffosion can be controlled by provision of an appropriate filter on the downstream side of the vulnerable soil, which traps the eroded fine particles. Filter rules for these soils are given in Appendix B.

3.6 Pipes and culverts

3.6.1 Vulnerability

Pipes and culverts are especially vulnerable to concentrated leaks for a number of reasons, including that

a) where located in the valley bottom they are vulnerable to settlement due to the underlying alluvium, which may lead to cracks into which internal erosion can occur

b) where located on the valley side a step may have been cut into the hillside to form a platform for construction. This results in a near vertical edge to the foundation, which is likely to lead to reduced vertical stresses in the soil adjacent to the step, and thus increased risk of hydraulic fracture

c) In other situations the drawoff may have been constructed in a trench along the valley side, where it passes under the core, in order to maintain the correct invert level, with similar vulnerabilities on the trench sides as for a step in the valley side

d) the backfill around the pipe
    - is often less well compacted than the majority of the embankment fill
    - is more vulnerable to seasonal moisture content changes than the body of the embankment, due to its proximity to the atmosphere

Pipes and culverts should only be more vulnerable to suffosion and backward erosion than the adjacent embankment where the seepage velocities are higher than the embankment, due to the detailing of the structure.

Historically anti-seepage collars were used around pipes to increase the seepage path length. However this is no longer considered good practice because the increased difficulties of achieving good compaction around the collars.

Similarly historically structures were detailed with vertical sides. Modern practice is to detail the edges to have slight side slopes, which significantly improves the ease of compaction, and thus contact stresses between the soil and structure.

3.6.2 Defensive measures

Internal erosion can be prevented in the same way as for concentrated erosion, by provision of a cohesionless filter around the whole perimeter of the pipe. Ideally this filter should be immediately downstream of where the pipe passes through the watertight element, being contiguous with the filter in the adjacent embankment. However, where fitted retrospectively it can be located at the downstream end of the pipe. This has been a standard upgrade in the USA for many years (Talbot and Ralston, 1985).

3.7 Other contributory factors to the occurrence of internal erosion

3.7.1 Variability in fill properties

All fill materials are naturally variable, being obtained from geological deposits. There may have also been changes in sources of fill during construction. Assessment of the likelihood of internal erosion should take this into account, preferably using statistical analysis of a range of test results.

3.7.2 Singularities

Singularities are defined as those features of a dam which do not occur on the typical section drawing, but may have an important influence on the occurrence of internal erosion. These include

a) irregularities in the foundation e.g. local steepening where a step was constructed to found a culvert, or change in geological stratum
b) inhomogeneities associated with backfill around a culvert
c) construction stage features, such as local drains, haul roads across the core, frozen ground during winter breaks in fill placing
d) trial pits, or other localised excavations into the dam
e) repairs, or raising of a dam crest may have created conditions which increase the risk of internal erosion, particularly at the interface of the new and old works.

Thus although analysis, including sensitivity analysis, of “typical sections” is a key tool, consideration should also be given to what singularities may be present at a dam and the influences they may have on the occurrence of internal erosion.

3.7.3 Local groundwater

There are several dams where the regional groundwater is high, with springs encountered during construction in the base of the dam, being piped to the downstream toe. In these situations continuing flow from the spring may eventually lead to internal erosion.

3.7.4 Water chemistry

In some circumstances the reservoir water may cause chemical changes in the clay forming the watertight element, which lead to time dependent changes in permeability and/or resistance to erosion of the watertight element.

3.7.5 Mineralogical changes in fill properties with time

Mineralogical changes in the fill itself can change the properties of the fill, and thus its resistance to internal erosion. Research into this subject includes a Babtie report in 1986 (DETR contract PECD 7/7/193).

3.7.6 Seasonal changes in temperature

Although not generally a problem in UK, freezing and thawing of the upper part of the core has led to serious leakage in Scandinavia, such that it is now common practice to place insulation above the top of the core.

Nevertheless seasonal variation in temperature in UK can have an important effect on the likelihood of internal erosion, both because of

a) the risk of desiccation of the upper part of the core (if not covered with a capillary break), which leads to cracks along which concentrated erosion can occur. It has been postulated that ongoing high level leakage in some dams and canal embankments is due to sand being washed into desiccation cracks at the top of the core, forming permanent zones of higher permeability
b) because of the significant variation of viscosity with temperature, which leads to higher flow rates, which may be sufficient to initiate erosion (see Box 3-1)

Although seasonal variation in seepage quantities due to seasonal variations in groundwater levels adjacent to a dam is common, there is also more limited evidence that there is a seasonal variation in incidents of new or increased leakage, with peaks in July and December (Slides of BDS meeting on Feb. 2004, on BDS website).

With the risk of increasing seasonal variation in temperature as a result of climate change, the introduction of a capillary break to reduce evaporation from the top of dam cores is suggested as good practice. This could include clean gravels, or some form of impermeable membrane (a double layer of Visquin (1000 gauge) has been used on some dams).

Box 3-1 Variation of permeability with temperature

The permeability of a soil at temperature T, k_t, can be reduced to that at 20^0C, k_{20}, by using $K_{20} = K_T \mu_T / \mu_{20}$.

The variation of viscosity with temperature can be seen below, and it can be seen for temperatures ranging from a peak in the summer of say 250C to winter of 0oC the variation in viscosity, and thus permeability is a factor of around 2

Temperature - t - (oC)	Dynamic Viscosity - μ - (N s/m2) x 10-3
0	1.787
5	1.519
10	1.307
20	1.002
30	0.798
40	0.653

3.8 Summary of key issues

Any strategy for the early detection of internal erosion should be based on a good understanding of the mechanisms of internal erosion, and what geotechnical parameters are required to evaluate the likelihood of internal erosion. Table 3.2 summarises the different types of internal erosion, and likely surface indicators. Figure 3.2 provides a matrix of the different types of internal erosion, and data required to evaluate the likelihood of each occurring. Both of these can be used to provide a prediction of the most vulnerable locations and indicators if internal erosion were to occur. These are then used both in the risk analysis in Section 4, and identification of indicators on which surveillance and monitoring should focus in Section 5.

Figure 3.2 Summary of key data necessary to evaluate the risk of internal erosion

	Concentrated erosion	Backward erosion	Contact erosion	Suffosion
Geometry of core and dam, and hydraulic gradients	Average (and local) hydraulic gradient along potential erosion path			
Properties of shoulders - will they act as flow limiters?	Flow velocity (shear stress) on sides of crack			
Sensitivity to possible crack widths?				
Geotechnical data on core	Shear stress (velocity) for onset of erosion	Critical gradient	Shear stress (velocity) for onset of erosion	Internally unstable?
Foundation cut-off?		Will it effectively interrupt internal erosion pathway?		
	Use the outcome from above to define what are the likely indicators and location of internal erosion (e.g. seepage, turbidity, stress and strain changes in the body of the dam)?			

Note: For key see Figure 1.1

4 Risk analysis

4.1 Introduction and principles

4.1.1 General

This section sets out the thought processes that may be used to assess the risk of internal erosion in an embankment dam and its foundation located within the United Kingdom. It is structured as follows

a) principles
b) available information on precedent for behaviour
c) assessment of potential modes of failure

The risk of failure in the context of this section is deemed to comprise the probability that internal erosion will occur and the consequence for the safety of the dam if it does. Thus the consequences of dam failure are not considered in this section, although they should be included in any assessment of the overall risk of dam failure.

4.1.2 Evaluation of the risk of failure due to internal erosion

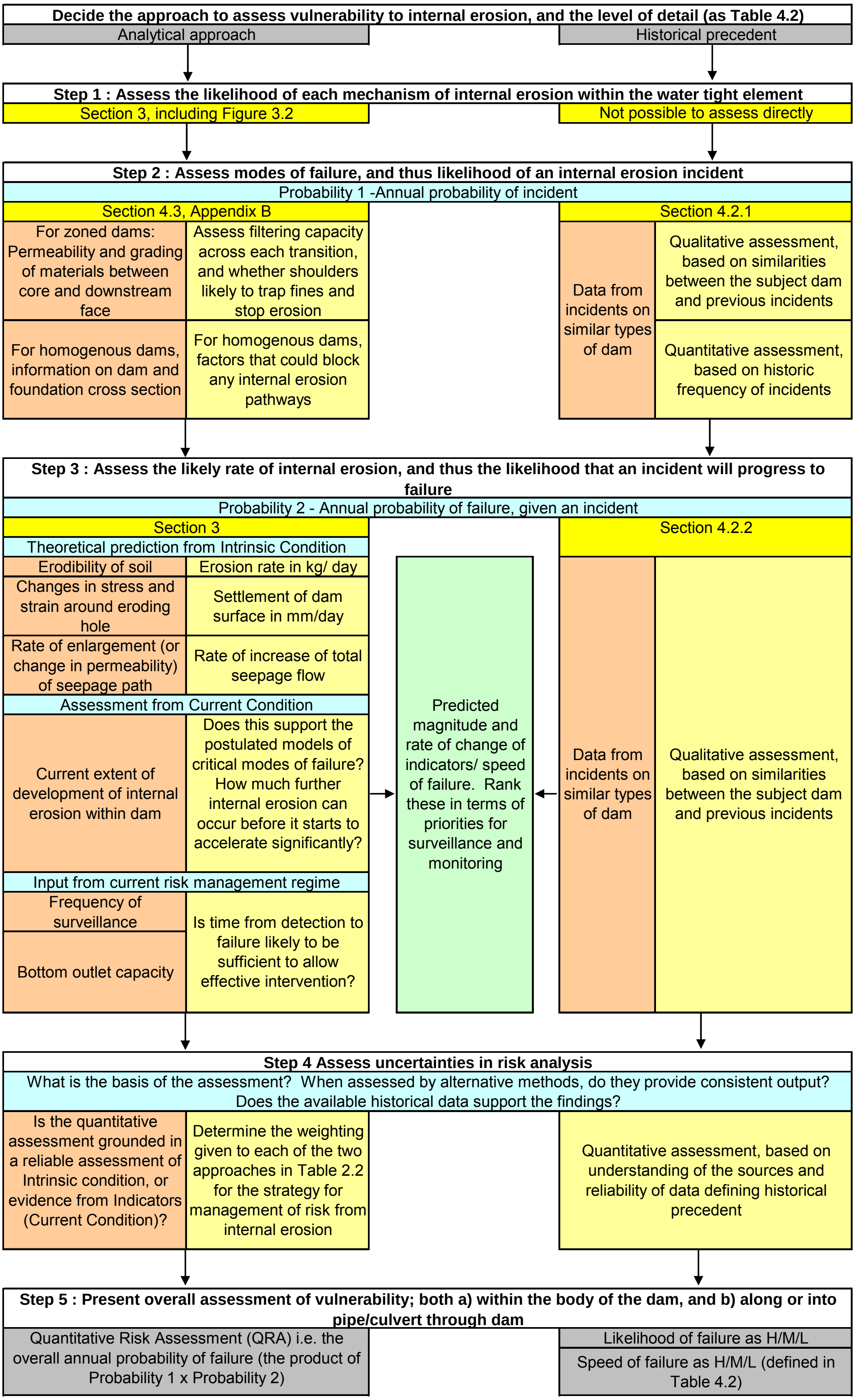
Modes of failure due to internal erosion should be considered in terms of the impact of internal erosion of the watertight element (or its foundation) and on the behaviour of the system comprising the dam shoulders, foundation and reservoir operation.

The assessment of the vulnerability to internal erosion may be carried out using either or both of the methods shown in Table 4.1, and following the thought process in Figure 4.1. The output should include both the likely indicators (surface and internal) of internal erosion (from Step 3) and an overall assessment of risk (Step 5), expressed using one of the formats shown in Table 2.4..

Table 4.1 Alternate approaches to assess the risk of failure from internal erosion

Method	Description	Remarks
Historical precedent	Collection of data on incidents on dams of similar materials and construction type	There may be undetected differences from previous incidents, which lead to very different behaviour
Analytical assessment of risk	Assessment of likely steps in modes of failure, including mathematical analysis of factors governing each step	Currently the full science for this analysis does not exist. However, the thought process is indicated in Figure 4.1. It may be beneficial to consider separately a) the likelihood of an incident occurring, and once an incident has initiated the likelihood that the incident will progress to failure b) the rate at which the mode of failure could progress, as this is key to determining the effectiveness of surveillance and emergency planning as practicable risk management tools.

Figure 4.1 : Thought process for steps in risk analysis



Decide the approach to assess vulnerability to internal erosion, and the level of detail (as Table 4.2)

Analytical approach

Historical precedent

Step 1 : Assess the likelihood of each mechanism of internal erosion within the water tight element

Section 3, including Figure 3.2

Not possible to assess directly

Step 2 : Assess modes of failure, and thus likelihood of an internal erosion incident

Probability 1 -Annual probability of incident

Section 4.3, Appendix B

For zoned dams: Permeability and grading of materials between core and downstream face

Assess filtering capacity across each transition, and whether shoulders likely to trap fines and stop erosion

For homogenous dams, information on dam and foundation cross section

For homogenous dams, factors that could block any internal erosion pathways

Section 4.2.1

Data from incidents on similar types of dam

Qualitative assessment, based on similarities between the subject dam and previous incidents

Quantitative assessment, based on historic frequency of incidents

Step 3 : Assess the likely rate of internal erosion, and thus the likelihood that an incident will progress to failure

Probability 2 - Annual probability of failure, given an incident

Section 3

Theoretical prediction from Intrinsic Condition

Erodibility of soil

Erosion rate in kg/ day

Changes in stress and strain around eroding hole

Settlement of dam surface in mm/day

Rate of enlargement (or change in permeability) of seepage path

Rate of increase of total seepage flow

Assessment from Current Condition

Current extent of development of internal erosion within dam

Does this support the postulated models of critical modes of failure? How much further internal erosion can occur before it starts to accelerate significantly?

Input from current risk management regime

Frequency of surveillance

Bottom outlet capacity

Is time from detection to failure likely to be sufficient to allow effective intervention?

Predicted magnitude and rate of change of indicators/ speed of failure. Rank these in terms of priorities for surveillance and monitoring

Section 4.2.2

Data from incidents on similar types of dam

Qualitative assessment, based on similarities between the subject dam and previous incidents

Step 4 Assess uncertainties in risk analysis

What is the basis of the assessment? When assessed by alternative methods, do they provide consistent output? Does the available historical data support the findings?

Is the quantitative assessment grounded in a reliable assessment of Intrinsic condition, or evidence from Indicators (Current Condition)?

Determine the weighting given to each of the two approaches in Table 2.2 for the strategy for management of risk from internal erosion

Quantitative assessment, based on understanding of the sources and reliability of data defining historical precedent

Step 5 : Present overall assessment of vulnerability; both a) within the body of the dam, and b) along or into pipe/culvert through dam

Quantitative Risk Assessment (QRA) i.e. the overall annual probability of failure (the product of Probability 1 x Probability 2)

Likelihood of failure as H/M/L

Speed of failure as H/M/L (defined in Table 4.2)

Note: For key see Figure 1.1

Table 4.2 Preliminary guidance on definitions of speed of failure due to internal erosion

Speed of failure	Time to failure from initiation	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, even with low frequency surveillance visits on low consequence dams	Magnitude of ongoing inflows likely to be the largest influence on the size of the bottom outlet

4.2 Historical precedent

4.2.1 Probability of an incident

Data on the probability of incidents, both in UK and internationally, is given in the KBR research report (KBR, 2002) which preceded the Interim Guide to QRA (2004), and summarised in Brown and Tedd (2003). These are summarised in Table 1.1. Charles and Boden (1985) includes in Appendix 1 a schedule of 88 individual incidents up to 1984, including the nature of the incident and fences where further details can be found.

4.2.2 Time to failure

A key issue in terms of management of the risk of failure due to internal erosion is the speed of failure. Available data on individual failure and incidents is summarised in Table 4.3 and Table 4.4 respectively, whilst data on the potential spread of time to failure across the portfolio of UK dams is summarised in Figure 4.2. The data in the figure is obtained from two sources

a) questionnaire to 117 respondents in 2003, requesting specific case history data. This produced a total of 34 incidents from 19 respondents. One of the questions asked was how long it would have taken for the incident to develop to failure, if there had been no intervention. Some of these incidents were at dams, and others at appurtenant works

b) expert elicitation with a panel of eleven experts, as described in Brown and Aspinall (2004). The panel were asked to provide the spread of time to failure of puddle and homogenous dam, again if no action were taken once an incident had initiated. The significant uncertainty in these estimates should be noted with the 5% and 95% confidence limits being broadly one order of magnitude in time to failure

It can be seen that the expert elicitation and experiences of incidents at appurtenant works suggested a median time to failure of 3 to 10 days, albeit with a wide spread between one day and in excess of six months. The experiences of incidents at puddle clay core dams suggested that incidents developed more slowly here, with a median time of around one year.

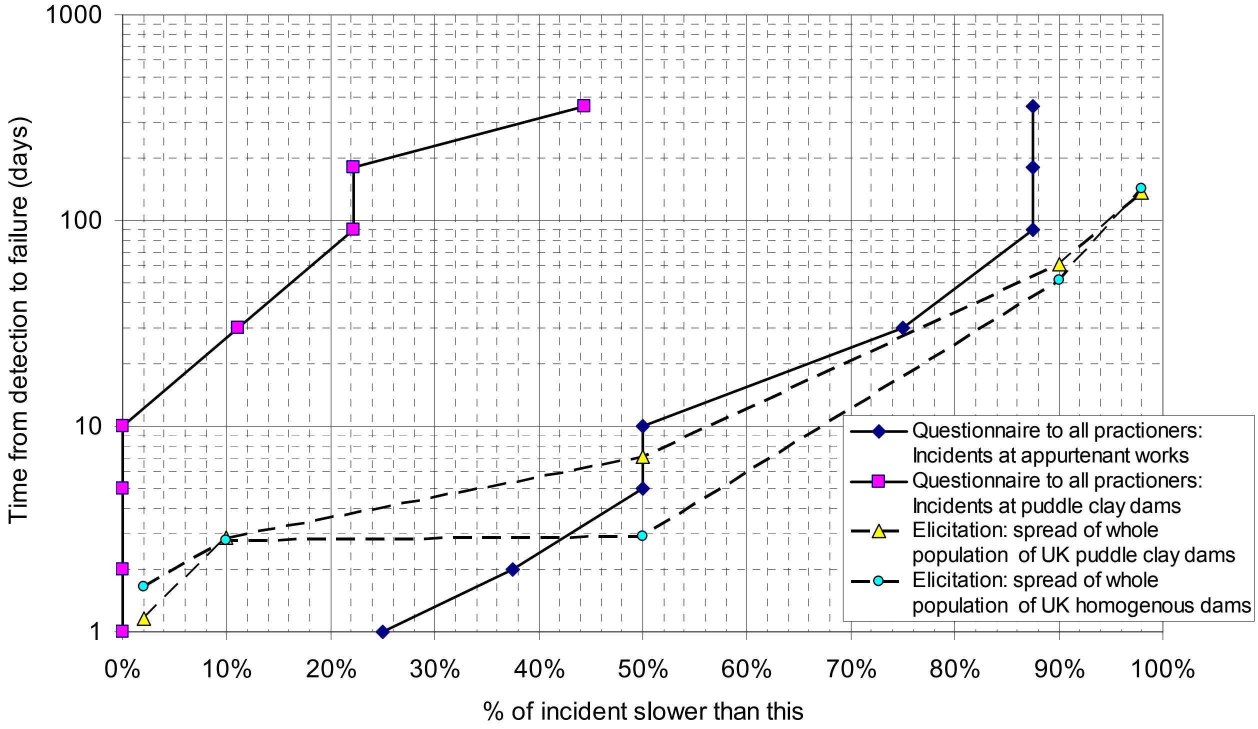
Table 4.3 Available data on time to failure, for dam failures and serious incidents

Dam	**Date of failure**	**Time to failure**	**Reference**	**Remarks**
Warmwithins, UK	November 1970	12 hours	Wickham, 1992	The dam is a 10m high puddle clay core dam built in the 1860s. The failure occurred along a new 1.5m diameter tunnel lined with concrete segments installed about 1965
Teton, USA	June 1976	2.5 hours	Report into failure of Teton dam	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.

Table 4.4 Available data on rate of development of serious internal erosion incidents

Dam, Date of Incident	**Available information on rate of development of internal erosion**	**Reference**
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
Upper Rivington Jan 2002	New 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, 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.	Bartsch & Nilsson, 2007

Figure 4.2 Indicative distribution of likely time to failure in UK dams, if no intervention once incident detected



4.3 Modes of failure

4.3.1 General

An analytical assessment of whether internal erosion could lead to failure of the dam, and if so how and at what rate may determined through criticality analysis. This is described in Section 3 of BS5760-5:1991, with criticality being “a combination of the severity of an effect and the probability or expected frequency of its occurrence”. It is therefore a measure of risk, albeit having a less rigorous (and hence less costly) approach to its evaluation. It is a method of reliability analysis intended to identify failures which have consequences affecting the functioning of the system. Although more commonly applied to complex systems, beginning at the item or subassembly level for which the basic failure criteria (primary failure modes) are available, the principles are relevant to evaluation of the likelihood of internal erosion.

As shown in Section 3, for internal erosion there are a number of mechanisms of deterioration by which the dam retaining the reservoir could potentially fail. There are various techniques by which the criticality of potential failure mechanisms could be estimated, which include
a) FMECA analysis as given in BS 5760-5:1991 (an example of its application to flood gates on hydroelectric reservoirs is given in Sandilands and Noble, 1998)
b) Fault tree analysis as given in BS 5760-7:1991
c) Event trains for internal stability as included in the Interim Guide to Quantitative Risk Assessment for UK Reservoirs, 2004 (see Section 2.7.1)
d) The element of LCI diagrams as given in CIRIA, 2000 covering internal erosion

Figure 4.1 shows the following steps within this process:

1 Likelihood of internal erosion
2 Likelihood of an internal erosion incident
3 Where internal erosion is likely to continue, the rate of internal erosion
4 Assessment of uncertainties
5 Present output from risk analysis

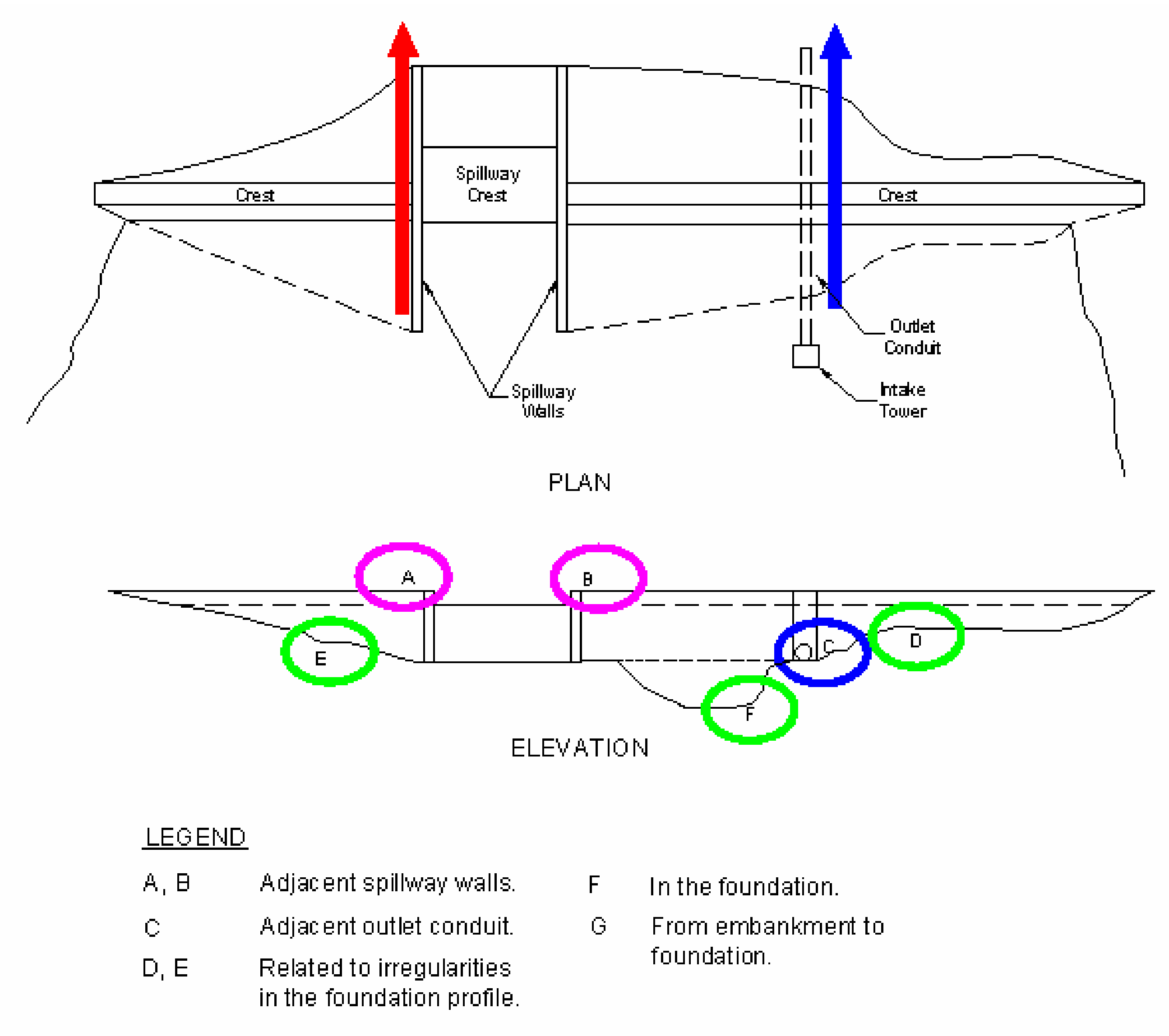
Steps 2 and 3 are equivalent to the “Continuation” and “progression” phases in Fell.

4.3.2 Locations of internal erosion pathways

The locations of more likely internal erosion pathways are indicated in Figure 4.3.

Appurtenant works are vulnerable to internal erosion along the contact with the embankment, or into the structure, as these often provide preferential leakage paths along which internal erosion can develop rapidly . Although information on the construction of appurtenant works at other dams by the same engineer as the subject can be useful, caution should be exercised as in some cases the engineer’s design changed with time.

Figure 4.3 Typical preferential pathways for internal erosion



4.3.3 Data requirements – Intrinsic condition

Evaluation of the most likely modes of failure relating to internal erosion requires a good understanding of

a) the physical processes involved in the mechanisms of internal erosion (described in Section 3)
b) the materials used in the construction of the dam, and their vulnerability to internal erosion
c) the inter-relationship of different materials making up the dam
d) reservoir operation, and its effect on pore pressures and lateral loads within the body of the dam

It is suggested that this can best be obtained by

a) desk study of drawings
b) study of other archive information (including other dams designed by the same engineer)
c) study of the performance and construction of similar type and age dams

d) knowledge of the local geology and thus properties of the various fill materials likely to have been used in construction of the dam.

One of the key groups of input data into a risk analysis is the internal construction and materials used to build the dam, the strata in the dam foundation and the associated geotechnical properties. Appendix D presents some published information on

- typical forms of construction of UK embankment dams
- the range of clays used in construction of the watertight element
- sources of data on the various geological clay strata in the UK, which is likely to have been used to construct dams situated on these strata

This data is then used as part of Steps 2 and 3 in Figure 4.1. Attention is drawn to the wide range of soils types used to form the watertight element of UK dams, ranging from intermediate plasticity silts, to extremely high plasticity clays; this being illustrated on Figure D.1. Available data also suggests some soils used in water tight element are dispersive i.e. likely to deflocculate and erode if subjected to concentred erosion.

Consideration should also be given as to what is unknown, and also uncertainties in what is known, as these may have a significant effect on the risk of internal erosion. These can include singularities, how site and regional conditions may change in future, and how these may influence the risk of failure (e.g. increased risk of desiccation from climate change). The limitations of the current understanding of behaviour should also be noted, and the range of possible behaviour considered.

4.3.4 Use of Current Condition to test models of failure modes

Part of the process of postulating a mode of failure should be to test the hypotheses against the observed behaviour of the dam, historically and at the current time. Where piezometers or other instrumentation are available this should include comparison of observed readings with predicted. This often leads to changes in the assumptions about behaviour. Attention is drawn to the fact that permeability is stress dependent, and that the position of the phreatic surface can be markedly influenced by surface infiltration (Vaughan, 1994).

5 Surveillance and monitoring

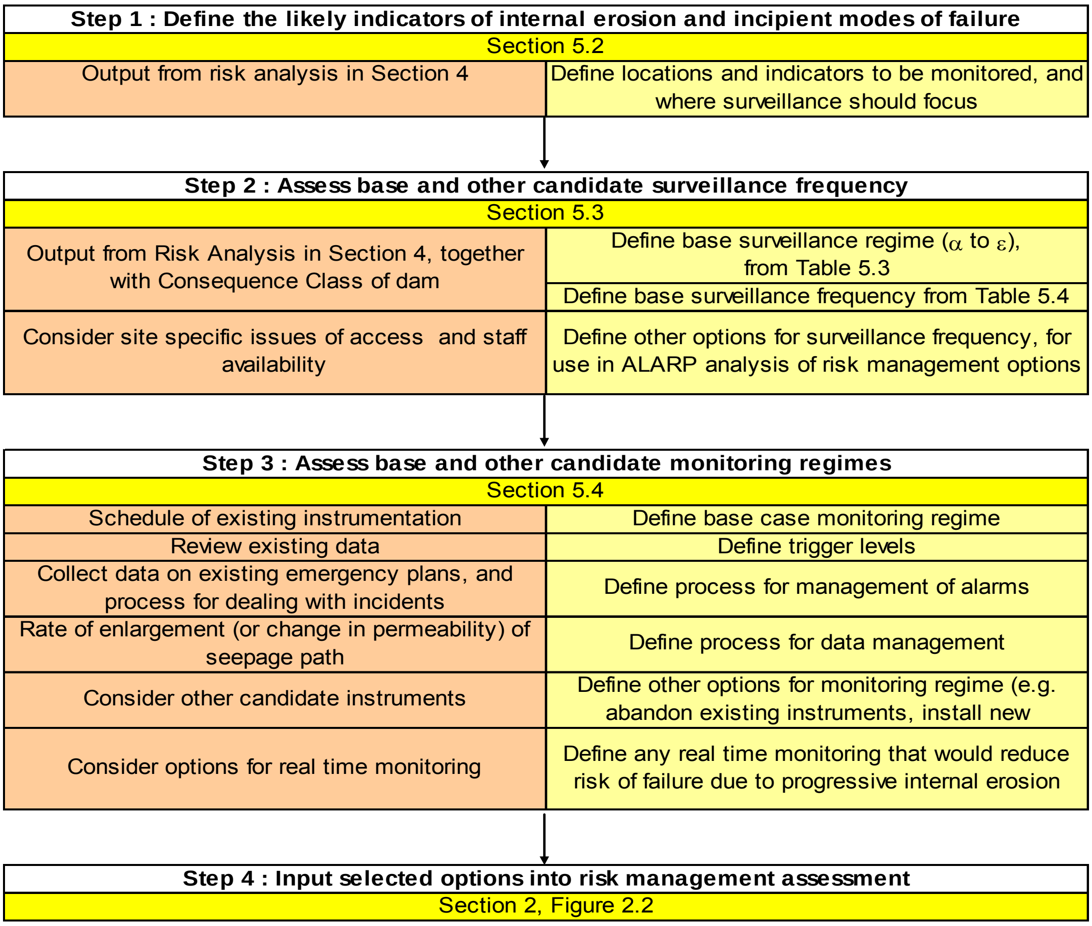
5.1 General

This section sets out the thought processes that should be used to assess options for surveillance and monitoring regimes to manage the risk of internal erosion in an embankment dam and its foundation. It complements Chapters 5 and 7 of EGSED, and is structured as follows

a) Potential indicators of internal erosion
b) Considerations in defining the surveillance regime
c) Considerations in defining the monitoring regime

Figure 5.1 shows the suggested thought process.

Figure 5.1 Suggested thought process to define options for surveillance and monitoring regimes



Step 1 : Define the likely indicators of internal erosion and incipient modes of failure	
Section 5.2	
Output from risk analysis in Section 4	Define locations and indicators to be monitored, and where surveillance should focus

Step 2 : Assess base and other candidate surveillance frequency	
Section 5.3	
Output from Risk Analysis in Section 4, together with Consequence Class of dam	Define base surveillance regime (α to ε), from Table 5.3 Define base surveillance frequency from Table 5.4
Consider site specific issues of access and staff availability	Define other options for surveillance frequency, for use in ALARP analysis of risk management options

Step 3 : Assess base and other candidate monitoring regimes	
Section 5.4	
Schedule of existing instrumentation	Define base case monitoring regime
Review existing data	Define trigger levels
Collect data on existing emergency plans, and process for dealing with incidents	Define process for management of alarms
Rate of enlargement (or change in permeability) of seepage path	Define process for data management
Consider other candidate instruments	Define other options for monitoring regime (e.g. abandon existing instruments, install new
Consider options for real time monitoring	Define any real time monitoring that would reduce risk of failure due to progressive internal erosion

Step 4 : Input selected options into risk management assessment
Section 2, Figure 2.2

Note: For key see Figure 1.1

5.2 Location and types of Indicators of internal erosion

5.2.1 General

Use of surveillance and monitoring as a means to manage the risk from internal erosion should be based on the likely types of indicator, as well as their potential magnitude and location. These will vary between dams and should have been defined in the risk analysis, building on the different types of internal erosion as shown in Table 3.2.

In particular it is noted that identification and measurement of seepage does not in itself provide any information on whether internal erosion is occurring. Nevertheless, changes in seepage quantity are likely to be related to internal erosion, such that seepage water emerging on the downstream side of the dam is generally a priority for monitoring.

5.2.2 Seepage water emerging on downstream face of dam

(a) General

Where surface flows are evident this is simplest to measure. However, in some circumstances it may not occur as surface flow, for example because

a) the downstream toe of the dam is submerged by the reservoir of a dam just downstream
b) the surface soils comprise permeable deposits through which seepage from the dam can occur without any surface expression.

Where there are no surface flows a toe ditch could be installed along the downstream toe of the dam to collect seepages (or an impermeable cut-off trench to divert seepages to the ground surface). A toe drain should normally include a filter around the pipe system, which would trap migration of any fines which may be present in seepage emerging from the downstream face.

It is noted that seepage flows emerging at the toe of the dam may reflect local infiltration from rainfall or more remote groundwater as well as being seepage from the reservoir. In the former situation examination of base readings, neglecting peak flows due to local infiltration, may provide a more reliable indication of long term changes in performance.

(b) Suspended solids

The various techniques for measurement of suspended solids are shown in Table 5.1. Attention is drawn to the fact that suspended solids are not visible to the naked eye when turbidity drops below 5FTU. It is also noted that the flow velocity in any V-notch chamber is unlikely to fall to the terminal velocity of fine silt and clay of 0.01mm/s and 0.001mm/s respectively, such that any sediment collected in outfall chambers is likely to only be coarse silt (1mm/s fall velocity). Thus the only reliable way of detecting total suspended solids is turbidity measurement.

Where there is a deposit of ochre, due to precipitation of high ion concentrations in groundwater, or biological action leading to build up of deposits, then this is likely to mean an increased frequency of cleaning of any turbidity meter, and make isolation of suspended silt impractical.

Table 5.1 Techniques for measurement of suspended solids in water

Technique	Test method	Principle of measure	Remarks
Suspended solid	Determination on water sample	Evaporate sample and weigh residue	Require water sample
Turbidity	BS6068-2.13:2000	a) Scatter of light by suspended or colloidal matter in the sample; light being measured at 90° to the incident light and compared to light scattered by standard formazine solution b) Test results expressed in formazine turbidity units (FTU) (approx equal to mg/litre for low turbidity)	a) Routine water quality test for water and sewage treatment works. b) Glass becomes obscured with time; requires cleaning between daily and weekly c) Limit of visual detection is 5 FTU, technique can measure down to 0.1FTU. Normal river water say 100FTU; rivers overseas in Africa 1000 to 10,000ppm
Particle counting	Various e.g. ISO/TR 16386:1999; BS 3406	Various light based e.g. photon correlation (BS3406-8:1997); optical fibre (Zhang et al, 2000)	a) Historical use in evaluating contamination of hydraulic fluids e.g. BS5540-5: 1987 b) Need to decide which size particles are being counted c) An alternative method to turbidity, but less widely used

5.2.3 Seepage associated with pipes or culverts

Seepage associated with pipes or culverts can be measured in the same way as for seepage emerging from the embankment. The main difference is that seepages carrying fines can also emerge into the pipe, at construction joints or defects in the pipe or culvert and not just at the downstream face as in the case of the embankment.

5.2.4 Concentrated seepage within body of dam

It is not possible to observe behaviour internally, so detection has to rely on monitoring. Moreover it is not normally possible to directly measure suspended solids in internal leakages. Thus normally detection relies on detection of concentrated seepage flow. Appendix E summarises the various techniques that may be used to detect seepage within the body of a dam.

Zonal techniques which measure temperature or other change related to the concentrated seepage across the full depth of the dam are more likely to be successful in detecting seepage than point measurements such as piezometers. However, these involve both significant amounts of data and interpretation of the data to pinpoint the leak and are therefore more suited to investigations than ongoing surveillance and thus early detection.

Interpretation of readings from zonal methods also have to take into account:

a) seasonal variations due to variation in both temperature and total dissolved solids (TDS) of the reservoir water, which then affects the temperature, resistivity and induced current (self potential) of seepage zones within the embankment
b) Where internal erosion is occurring with washing out of fines, this commonly leads to changes in porosity, which changes resistivity and induced current

5.2.5 Deformation and strains associated with internal erosion

Deformation is generally only useful in providing warning time where the rate of internal erosion is slow, and includes cycles of collapsing of soil into the internal erosion pathway, which then migrate to the dam surface. Where this applies both surveillance and monitoring may be used to detect the movements.

The type of settlement will depend on the type of internal erosion and the soils forming the dam. Where the migration is in the form of a sinkhole then crest levelling pins are unlikely to be directly over the sinkhole and thus may not give any warning. Where a concentrated sinkhole cannot be sustained and deformation is dispersed over a wider area then crest pins may give advance warring of localised settlement. It is good practice to have three lines of settlement points, with lines say 2m upstream and 2m downstream of the respective edges of the core, as well as along the centreline of the core.

5.2.6 Geochemistry of groundwater and reservoir water

Analysis of the constituent elements of reservoir water, local groundwater and seepage can prove invaluable in determining the source of seepages emerging at the toe of a dam. Analysis should include the main anions and cations (Table 5.2), such that results can be presented and analysed on Trilinear and Durov diagrams (Lloyd & Heathcote, 1985, Brandon, 1986). In addition minor ions that are important to the hydro-geochemistry of the local water should be determined. The publication “Physical Properties of Major Aquifers” (Environment Agency, 1997) gives indications of ions which are likely to be present in the main aquifers, and there are various publications on individual aquifers (e.g. Morgan-Jones, 1985). Information can be obtained from the Environment Agency groundwater groups and the local water authority for the area.

Table 5.2 : Major constituents of groundwater

	Major ions	
Cations	Ca^{2+}, Mg^{2+}, Na^+, K^+,	
Anions	SO_4^-, $Cl^{-,}$ HCO_3^-, NO_3^-	See Lloyd p96 onwards for how to calculate bicarbonate etc from alkalinity and hardness

5.2.7 Summary –Strategy for surveillance and monitoring

The primary lesson from experience of internal erosion incidents is that many were first identified by surveillance, and would not have been identified solely by monitoring. Thus the primary tool for identification of internal erosion will always be surveillance. Nevertheless there are limitations to surveillance, and Table 5.3 summarises the suggested roles for surveillance and monitoring.

It is suggested that a risk based approach is adopted to defining the surveillance and monitoring regimes. Thus the frequency and extent of surveillance and monitoring is based on a risk matrix with the horizontal axis comprising the consequences of failure and the vertical the output from the risk analysis. The suggested approach is shown in Table 5.4. Following the precautionary principle, where the vulnerability of a dam to internal erosion is unknown then it should be classified as high.

Table 5.3 Suggested roles for surveillance and monitoring

Tool	Purpose	Remarks
Surveillance	Identify location of new indicator, or gross change in existing indicator	Some indicators are not visible to the naked eye until they have developed significantly. Thus monitoring is a important supplement to surveillance.
Discrete point monitoring	Provides means of quantifying and identifying gradual changes over time of broadly distributed effects of internal erosion indicators	Unlikely to be at location of new indicator (e.g. sinkhole) May be of value to be frequent (real time) where there is an existing indicator which has been identified through risk analysis as a key indicator of progressive internal erosion.
Distributed (zonal) monitoring	Occasional use to identify internal changes in the dam, before there are indicators at the dam surface	Too data intensive to be a tool for frequent monitoring

Table 5.4 Suggested risk matrix to select the surveillance and monitoring regime at a dam

Vulnerability to internal erosion [2], as output from risk analysis	Consequence Class of dam[3]				
	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. This is the suggested starting point, for application and adjustment on a dam specific basis, following the principle that the cost should be proportionate to the benefits obtained.
2. Ranking on the vertical axis could be on the basis of one of the following
    - the annual probability of failure, when the suggested boundaries between the three categories of risk to the public are overall risk from dam failure of loss of life of 1 in 100 (10^{-2}) per year and 1 in 10,000 (10^{-4}) per year (i.e. the sloping lines on the FN chart on Sheet 11.3 of the Interim Guide to QRA
    - Likelihood of failure, as a qualitative assessment
    - Speed of failure, as defined in Table 4.2 (with Extremely fast and fast defined as "High"
3. The dam owner may select a higher consequence class if failure of the dam would include significant business or other losses, for example it was the only source of water to a major town
4. Although this matrix applies to "early detection of internal erosion", the same principles can be applied in relation to other failure modes, for example failure of pipework.

5.3 Surveillance

5.3.1 Suggested regime

The suggested starting point for frequency of surveillance visits is given in Table 5.5. The frequency adopted at a particular dam should be based on a dam specific assessment, as defined in Note 1 to the table, and including an allowance for the reliability of the assessment of vulnerability and consequence class.

It is suggested that the routine surveillance visits should

a) be carried out by operators who are trained to understand the potential failure modes, and symptoms of dam failure, with this training updated at regular intervals

b) be documented on a form where the operator has to enter Yes or No as to whether there are signs of seepage or settlement.

c) have a defined extent, to include the full extent of the downstream toe, the abutment mitres and the upstream waterline, as well as the dam crest.

5.3.2 Commentary on basis of recommended surveillance frequency

Three separate sources of information relevant to surveillance frequency have been considered in preparing Table 5.4 and Table 5.5

a) The estimated time to failure for UK dams from detection of a serious leak, as set out in Figure 4.2 of the Guide, which if split into three equal classes would justify visits daily, 3 to 4 days and every 10 days

b) current practice in the United Kingdom; a recent survey of seven major dam owners revealed that one visits at 48 hour intervals (including weekends); increasing to daily when an incident occurs, two visit twice a week and the other four visit weekly

c) available information on current practice internationally, as summarised in Table 5.6

Table 5.5 Suggested starting points for defining the surveillance frequency for dams in service

	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	Fortnightly to every two months	Two to 6 months
Interior of culverts/ shafts, where confined space[3]	Weekly to monthly	Monthly to 3-monthly	3-Monthly to annual	Five yearly	Ten yearly
Number of visits a year by Supervising Engineer[4]	4	3	2	1	1

Notes

1. This is an indicative combination of types of surveillance in normal circumstances. The dam owner may vary from this on the basis of special circumstances, following the principle that the cost should be proportionate to the benefits obtained.
2. The timing should be calendar time, and thus occur at weekends and bank holidays where these fall in the routine cycle.
3. 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
4. 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

Table 5.6 : Current International practice as to surveillance frequency

Country/ Authority	Frequency for dam hazard category		Reference
	High	Low	
ANCOLD, Australia	Daily	Monthly	ANCOLD Guidelines on Dam Safety Management, 2003, Table 5.2
British Columbia	Weekly	Monthly	Water Act British Columbia Dam Safety Regulation, 2000
Auckland Regional Council, New Zealand	Monthly	Monthly	Daily during first impounding
New Zealand Dam Safety Guidelines	Weekly to monthly	Monthly to 4 monthly	The New Zealand Society on Large Dams, 2000
World Bank	Weekly	Monthly	Regulatory frameworks for dam safety A Comparative Review, 2002

Note: The Guidance Notes provided by the following organisations do not provide any guidance on frequency of surveillance visits

- Federal Guidelines for Dam Safety (FEMA 93); Prepared by the Interagency Committee on Dam Safety, June 1979, Reprinted April 2004
- Association of State Dam Safety Officials, USA: Owner-Responsible Periodic Inspection Guidance Dec 2005
- FERC, USA Chapter 14 Dam safety performance monitoring program (although there is reference in Section 4.1 to “Daily/weekly operator’s inspections and reports”

5.4 Monitoring

5.4.1 General

Details of the main indicators and the instruments which can be used to monitor them are described in Chapter 7 of EGSED. The advantage of monitoring is that it provides both quantitative values of the measured parameters and also data on parameters measured internally with the dam.

Instrument type and location should be selected on the basis of the output from the internal erosion risk analysis, defining the most likely locations and types of indicators. Selection of instruments should also consider, where practicable, how calibration of the instrument will be periodically rechecked, and adjusted if necessary.

Similarly the frequency of monitoring should be determined from an understanding of the vulnerability of the dam to rapid failure due to internal erosion, as well as the typical timescale of changes in reservoir level and other factors to which the dam responds. In some situations real time monitoring of key indicators such as seepage flow and turbidity may be proportionate as a risk reduction measure. This is discussed further below.

5.4.2 Management of alarms and anomalies

It is important that, where monitoring is carried out, the readings are checked for anomalies (and significant changes in behaviour) as soon as practicable. Ideally this would be at the same time as the reading is taken. This can be done by entering the readings into a spreadsheet or similar, which includes automatic checks against previous measurements and predefined trigger levels. These trigger levels can then be linked into predefined actions in an emergency plan as shown in Table 5.7.

Problems have been experienced where a new operator has taken over the reading of instruments. It is therefore preferable that the procedures for readings, and readings, are documented, and periodically reviewed by the Supervising Engineer, or other responsible person, to eliminate this problem.

Table 5.7 Suggested link of instrumentation readings to emergency plan

Alarm level	Trigger	Possible actions by Undertaker
Watch	a) Instrumentation exceeds “orange” trigger level. b) Unusually heavy rainfall which could lead to a major flood is predicted. c) An earthquake or major flood has occurred	• Instrumentation checked and readings repeated to see if instrument error. • Immediate visit by Supervising Engineer to the dam
Alert	a) Instrumentation reading exceeds predefined “red” trigger level b) Some other aspect of behaviour is significantly outside the normal range	Increasing escalation of actions, including • repeating and increasing the frequency of readings • Inform Duty Manager • Inspecting Engineer to visit site

5.4.3 Definition of trigger levels

In an ideal world trigger levels for internal erosion would be developed from appropriately calibrated models. The initial trigger level would then be simple; any deviation from the theoretical steady state would represent grounds for increased observation. In reality it may be appropriate to look at several different measurements at the same time. Ongoing research internationally includes the concept of an intelligent data management system which looks at data and combinations of data in any number of ways – multiple parameter regression, neural networks etc.

However, for practical purposes for dams in UK trigger levels are generally set using analysis of behaviour to date (such that for any new instrumentation trigger levels have to be provisional, and reviewed after experience in operation).

Setting trigger levels is not straightforward where behaviour is significantly influenced by reservoir level and rainfall. For some existing instruments it may not be possible to set trigger levels which would provide a reliable warning. In these circumstances it may be possible to modify the physical location of the instrumentation in some way to make it less susceptible to rainfall, for example. Where this is possible this should be one of the options considered as a risk reduction measure.

5.4.4 Data interpretation and management

It is important that there is a systematic process for collecting, reviewing, reporting and archiving monitoring data.

The process of review should normally include
a) immediate review, for any sudden step change in behaviour

b) periodic review to identify longer term trends, including recording and reporting that review. In this context it has been found helpful to plot readings
   - against reservoir level as well as against time
   - over 5 to 10 years, as well as shorter time periods

Historic monitoring data can be invaluable in understanding changes in behaviour, especially where available during first impounding or following significant structural works. Monitoring data should always be preserved indefinitely.

5.4.5 Situations where real time monitoring may be appropriate

There is evidence that although in some situations internal erosion may continue at a slow rate for years, in other situations the rate of deterioration can be rapid (or accelerate after a long stable period) and lead to rapid failure. Appurtenant works appear to be particularly vulnerable to this rapid deterioration.

Thus although surveillance (visual inspection) should always be the primary tool for assessing the condition of a dam, in some circumstances real time monitoring of key indicators may be a proportionate part of the dam safety management process. This applies where the nature of the soils and/or detailing of interfaces between the embankment and structures is such that internal erosion could progress rapidly to failure (“progressive internal erosion”) and the consequences of failure include significant risk to people downstream.

It may also be appropriate in some circumstances to provide quantitative readings at frequent intervals due to fast changes in local environmental conditions, such as
a) reservoir levels in pumped storage schemes
b) where the structure is very sensitive to temperature variations, which occur over a daily cycle
c) where there is concern over leakage at high reservoir levels, as floods pass through the reservoir. This may be monitored as part of an investigation, as it is likely that structural works would be carried out if this was considered to be an issue.

A third scenario where real time monitoring may be useful is in order to understand how seepage, or other indicators react to rainfall or other changes, and thus to better understand the behaviour of a dam. In this case it would be similar to real time monitoring to provide early detection of progressive internal erosion, but without an alarm.

Reference should be made to a separate Guidance Note on Real Time Monitoring, which provides commentary on the issues to be considered when deciding whether to include real time monitoring as part of a balanced strategy for risk management of internal erosion.

6 Investigations

6.1 General

6.1.1 Introduction

This section covers the issues of investigating embankment dams to determine
- the vulnerability to internal erosion, and
- whether seepage and internal erosion are occurring

This section provides a supplement to the BRE Report "Investigating embankment dams" (IED) (Charles et al, 1996). Additional information on zonal techniques to detect leakage within the body of a dam are given in Appendix E.

6.1.2 Risk based approach

The extent to which investigation may be justified depends on factors such as
a) the extent to which investigation may reduce the estimate of annual probability of failure; for example by changing from
   - a conservative assumption due to uncertainty (for example it is unknown whether a dam has a clay core or is homogenous), to
   - a less conservative assumption due to increased knowledge

b) the consequences if a problem developed; for example if the reservoir was small and the dam had a large capacity outlet such that it could be lowered quickly in the event of a structural problem
c) whether on ongoing internal erosion is suspected, and confirmation would significantly change the risk control measures applied

It is unlikely to be justified to carry out site investigation to determine the vulnerability to internal erosion if the dam is Consequence Class C or lower. The high cost of boreholes on the shoulders of dams is noted, due to the costs of ensuring safe access on steep slopes. Conversely desk study can be very cost effective, particularly if carried out in batches of dams founded on similar geological strata.

6.2 Desk study information

The process of desk study is described in Annex A of BS5930:1999. For dams there are three main groups of data source
a) drawings and other documents relating to the specific dam
b) information relating to dams designed by the same engineer
c) information on local and regional geology, relying on the fact that most dams are built almost entirely of soil excavated locally (particularly for dams built prior to the invention of the internal combustion engine, when imported material would have been brought to site with horse and cart).

The latter should provide valuable information in the majority of cases, with the main uncertainties for clay core dams being where both alluvial clay and clay from solid deposits could have provided practicable sources of clay.

7 Structural works

7.1 Introduction

This subject of carrying out structural works to embankment dams to strengthen the watertight element is well covered in Chapter 8 of EGSED. The item described below is covered here as a means of reducing the vulnerability to internal erosion.

7.2 Addition of downstream filter

Addition of a toe filter berm is a straightforward way of adding a filter to control internal erosion and has been adopted on many dams. However, it accepts that fines may be eroded from the core through the downstream shoulder and only trapped at the upstream edge of the new filter berm. In Sweden the design criteria (Bartsch et al, 2007) include that the berm can safely pass a flow of 0.5m^3/s/m, in recognition of the high flows that may occur.

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Kennard MF	1972	Examples of the internal condition of some old earth dams. Journal of the Institution of Water Engineers, v 26, n 3, May, 1972, p 135-154
Kleiner DE	2005	A review of filter criteria for embankment dams. US society dam Conf.
Kofoed V, Montgomery J, Gardiner K	2006	Identifying leakage paths in earthen embankments. Proc BDS Conference at Durham. Pp119-128 Pub Thomas Telford
Lane, E.W	1935	Security from under-seepage masonry dams on earth foundations, Proc. American society of civil engineers [republished with discussions in 1935 in Transactions American society of civil engineers, paper no. 1919, Volume 100, pp. 1236-1351].
Little AL	1977	Investigating old dams. Q Jl Eng. Geol. Vol 10. p271-280
Lloyd & Heathcote	1985	Natural inorganic chemistry in relation to groundwater. Clarendon press, Oxford. 296pp
Maccaferri	1981	Flexible gabion structures in river and stream training works. Section one – Weirs for river training and water supply.86pp
May R W P, Ackers J C and Kirby A M	2002	Manual on scour at bridges and other hydraulic structures. Report C551 CIRIA, London ISBN 0 86017 551 0
Morgan-Jones	1985	The hydro geochemistry of the Lower Greensand aquifers south of London, England. Quarterly Jour. Eng. Geology 18, pp 443-458
Perzimaier S, Muckenthaler P, Koelewijn AR	2007	Hydraulic criteria for internal erosion in cohesionless soil. Paper to European Working Group at Aix les Bains
Sandilands NM and Noble M	1998	A programme of risk assessments for flood gates on hydro electric reservoirs. BDS Conf. Pp27-38. Pub Thomas Telford.
Schmertmann, J.H	2000	The no-filter factor of safety against piping through sands, Judgment and innovation – the heritage and future of the geotechnical engineering profession, ASCE, Reston, pp. 65-132.
Sellmeijer & Koelewijn	2007	Engineering tools for piping – neural networks created using FEM. Proc European working group on Internal erosion
Talbot JR and Ralston DC	1985	Earth dams seepage control. SCS experience. Symposium on seepage and leakage from dams and impoundments. ASCE Geotechnical Division. Denver, Colorado. Pp44-65
TAW	1999	Technische Adviescommissie voor de Waterkeringen 1999: *Technisch Rapport Zandmeevoerende Wellen* (in Dutch)
Tedd P, Dutton DPM, Horton IR	1998	Investigating internal erosion at Brent Dam. Proc BDS Conf. pp71-78
USBR	1973	Design of small dams. 2nd Edition.
Vaughan PR	1994	Assumption, prediction and reality in geotechnical engineering. Geotechnique 44(4) 573-609.
Wan CF and Fell R	2002	Investigation of internal erosion and piping of soils in embankment dams by the slot erosion test and the hole erosion tests. UNICIV Report R-412. July. ISBN 85841 379 5

Wan CF and Fell R	2004	Investigation of rate of erosion of soils in embankment dams ASCE Geotech April 373-380
Walters R C S	1971	British geology. 2nd Edition. Pubs Butterworks. ISBN 0-408-70191-9
Weijers JBA and Sellmeijer JB	1993	A new model to deal with the piping mechanism. In Brauns, Heibaum and Schuler (Edt) Filters in Geotechnical and Hydraulic Engineering, Rotterdam, Balkema, 345-355
Wickham	1992	Collapse of an earth embankment dam. Dams and reservoirs. October 2(3) 18-19
Zhang FH, Lewis E, Sculley PJ	2000	An optical fibre sensor for particle concentration measurement in water systems based on inter-fibre light coupling between polymer optical fibres. Tran of the Inst of measurement and control 22.5 pp413-430. from internet

Appendix A - ALARP calculation

The ALARP (As Low As Reasonably Practicable) approach compares the reduction in risk that would be achieved from possible works against the cost of the works, to assess whether the cost of the works is proportionate to the reduction in risk achieved. This may be quantified by calculating the cost to prevent a fatality (CPF) as follows (where PV is present value)

$$\text{CPF} = \frac{\text{PV (Cost of risk reduction measures)} - \text{PV } (\Delta \text{ Pf x Damage})}{\text{PV } (\Delta \text{ Pf x Likely Loss of Life (LLOL))}}$$

where Δ Pf is the change in annual probability of failure due to the proposed risk reduction works. At its simplest where the CPF is less than the “value of preventing a fatality” (VPF) then the candidate works would be proportionate risk reduction measures; whilst where CPF exceeds VPF then the cost is disproportionate.

The value that should be assigned to VPF is a difficult decision and includes consideration of

- Direct costs (measurable) such as earning potential of the victims, injury and long term health impairment of other victims not included in the LLOL value, and emergency services costs
- Indirect (business losses)
- Intangibles (psychological impact on people, environmental damage) – it could be argued that a value should be assigned to the Intrinsic Value of a Human Life (irrespective of age, health, education etc)

However, HSE (2002, para 25) notes that “gross” disproportion is required before ALARP is satisfied and defines a

$$\text{Proportion Factor (PF)} = \frac{\text{Cost to Prevent a Fatality (CPF)}}{\text{Value to Prevent a Fatality (VPF)}}$$

The purpose of a PF “grossly” greater than unity is to allow for the imprecision of estimates of costs and benefits and also to ensure that the duty holder robustly satisfies the ALARP principle. HSE guidance (HSE, 2002, para 26 onwards) notes the proportion factor should always be gross, that the value is likely to vary with the level of risk and should be argued in the light of particular circumstances. Guidance issued by individual directorates in UK quote proportion factors of 1 to in excess of 10, using VPF of £1M.

Application of the ALARP approach is illustrated as follows

- Box A.1 provides an estimate of the average annual probability of failure of UK dams which come under the Reservoirs Act 1975
- Box A.2 provides an example of the calculation of proportionate cost of risk reduction works
- Figure A.1 extends the calculation in Box A.2 to a range of initial annual probabilities and likely loss of life (LLOL)

It can be seen that proportionate cost varies significantly (by orders of magnitude) depending on the level of risk i.e. annual probability of failure and consequences in terms of likely loss of life.

Box A.1 Annual probability of failure of UK dams in service (1975-2000)

The annual probability of failure of dams in service (more than 5 years old) which come under the Reservoirs Act 1975 is estimated as follows:

Total number of dam life years for dams in service 1975-200 = 47,312
(from BRE database, as reproduced in Table 4 of Brown and Tedd, 2003)

Annual probability of failure = Number of failures/ Number of dam life years = 0/47,312 =< 2x 10^{-5}

Box A.2 Example of calculation of proportionate cost

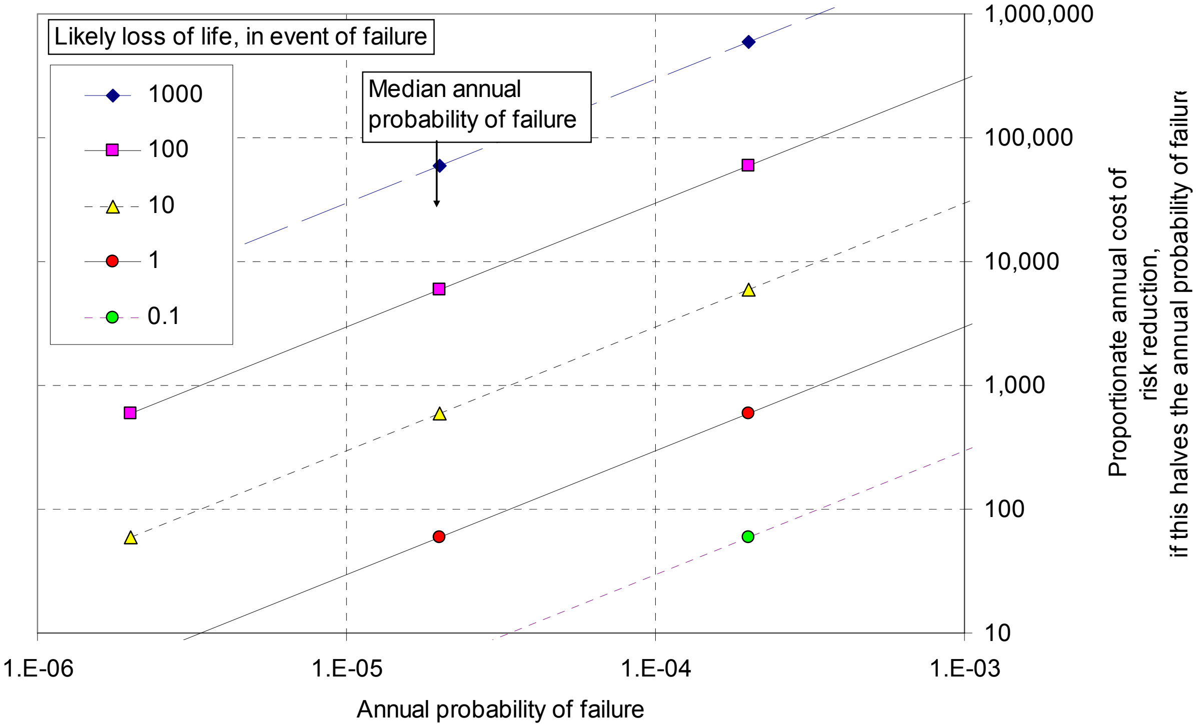
Calculation of what would represent proportionate risk reduction measures, using the ALARP approach, is set out below, for the following assumptions

- Median UK dam, with an initial probability of failure of 2×10^{-5}, and consequences in the event of dam failure of likely loss of life of 100 lives and property damage of £1M/life i.e. £100M
- The candidate works would halve the annual probability of failure
- A proportion factor of 5 and VPF of £1M/life
- Present value of future costs and benefits obtained using Treasury recommended discount rates, which currently equate to a factor of 29.8 (say 30) on the annual risk (available at www.hm-treasury.gov.uk/economic_data_and_tools/greenbook/data_greenbook_index.cfm)

Cost of proportionate risk reduction measures
= PF x CPF x PV (Δ Pf x Likely Loss of Life (LLOL)) + PV (Δ Pf x Damage)
= 5 x £1,000,000 x 30 x (2 x10^{-5} x 0.5 x 100) + 30 x (2 x10^{-5} x 0.5 x £100,000,000)
= £150,000 + £30,000 = £180,000

Equivalent ongoing annual cost = £180,000 / PV factor = £180,000 / 30 = £6,000/ year.

Figure A.1: Illustration of how proportionate cost of risk reduction works varies with annual probability of failure and consequences



Appendix B - Filter design

There is an extensive literature on filter rules, including ICOLD Bulletin No 95 (1994) and a review in 2005 of the need to update the Bulletin (Kleiner, 2005). This review contrasted the “perfect filter” approach (Vaughan and Bridle, 2004) and the “critical filter approach” of other authors and concluded that there was no need to update the ICOLD Bulletin. Some of the key methods for assessing the filtering capacity of soils are summarised in Table B.1.

Table B.1 Methods available for assessing filtering capability of a soil

Reference	Area of application	Comments
Particle size distribution		
Sherard & Dunnigan (1989)	Clay-silt-sand and fine gravel soils	Based on extensive no erosion (sample with a pre-formed hole), slot and slurry tests by the USDA-SCS. Widely adopted. Dams constructed with filters designed using these criteria and earlier similar criteria (e.g. USBR, 1977, 1987) have performed well in practice
Kenney & Lau (1985) and Kenney et al (1985)	Sand-gravel soils	Recommends use of controlling constriction size
Foster & Fell (1999, 2001)	Clay-silt-sand-fine gravel soils	Used Sherard & Dunnigan (1989) test results and further no erosion tests. Recommended modification of Sherard and Dunnigan (1989) design criteria, particularly for dispersive soils. Introduced the concept of excessive and continuing erosion
Opening size and particle size distribution		
Lafleur et al (1989, 1993)	Clay-silt-sand-gravel soils	Particularly applicable to broadly-graded soils; has designed rules for linearly graded, gap graded and concave upward grading distributions, and separate rules for dispersive soils
Braun & Witt (1987), Schuler & Brauns (1993, 1997) and Witt (1993)	Clay-silt-sand gravel soils	Propose the use of probabilistic analysis
Particle size - permeability (refer Bridle, 2005)		
Vaughan & Soares (1982)	Clay-silt-sand-gravel soils	Based on filter tests with flocs of the clay size soil in a dilute suspension; the floc size is determined from hydrometer tests in the reservoir water, with no dispersant added (this test provides the so called ‘perfect filter’) The method potentially gives very fine filters

Appendix C - Test results from Wan et al, 2002

Wan and Fell (2002) carried out a series of tests on 13 soil samples which showed that C_e, defined below, is in the order of 10^{-1} to 10^{-6} kg/s/m^2/Pa.

$$I = -\log(C_e)$$

$$\dot{\varepsilon}_t = C_e(\tau - \tau_c)$$

where

I	is the Erosion Rate Index (subscript HET shows that I was determined from the hole erosion test)
$\dot{\varepsilon}_t$	is the rate of erosion rate per unit surface area of the slot/ hole (kg/s/m2)
C_e	Is a proportionality coefficient termed the Coefficient of Soil Erosion (s/m; simplified from kg/s/m2 per N/m2)
τ	Is the hydraulic sheer stress along the slot/ hole (N/m2)
τ_c	is the Critical Shear Stress for initiation of erosion (N/m2)

When an Erosion Rate Index I_{HET} is quoted for a soil, the percentage compaction and the water content of the test specimen of the soil should also be stated, as I_{HET} is strongly influenced by the degree of compaction and the water content. The Erosion Rate Index corresponding to 95% compaction and optimum water content is called the Representative Erosion Rate Index ($\tilde{I}_{HET}$) of the soil. Soils can be classified into 6 groups according to their Representative Erosion Rate Index, $\tilde{I}_{HET}$. The 6 groups are shown in Table C.1.

Table C.1 Groups of Erosion rate Index (after Wan and Fell, 2002)

Group No.	$\tilde{I}_{HET}$	Description	Individual results of soils tested by Wan and Fell			
			Geological origin	**USCS classification**	**Initial shear stress N/m^2**	**C_e (from HET)**
1	<2	Extremely rapid	Glacial till, Residual (granite)	SM	5, 5	0.10 0.02
2	2 – 3	Very rapid	Glacial till, Residual (granite)	CL(Teton), SM, SC	10, 12, 20	4E-3 2E-3 1E-3
3	3 – 4	Moderately rapid	Alluvium, Residual (dolerite, basalt)	CH, CL	10, 55, 60, 115	6E-4, 2E-4, 1E-4 2E-4
4	4 – 5	Moderately slow	Alluvium, Colluvium	CL(Hume)	80	2E-5
5	5 – 6	Very slow	Residual (sandstone of andesitic, basaltic origin)	CL, CH	100, 155	2E-6 2E-6
6	>6	Extremely slow	Alluvium	CL	155	<1E-6

There is no reliable simple method of prediction of τ_c or erosion rate index I from soil index properties. Wan and Fell provide the following equation for fine grained soils (8.3 in their report), but note the significant scatter:

$$\hat{I}_{HET} = -10.201 + 9.572\rho_d - 0.042\ \rho_d / \rho_{d_{\max}} + 0.103\omega\ + 0.0097\Delta\omega_r$$
$$-0.0056 Fines + 0.042 Clay(US) - 0.090 LL + 0.111 I_P\ + 0.443 Pinhole$$

where

ρ_d	is the dry density of the soil in Mg/m^3,
$\rho_d / \rho_{d_{\max}}$	is the percentage compaction in %,
ω	is the water content in %,
$\Delta\omega_r$	is the water content ratio in %,
Fines	is the fines content (< 0.075mm) of the soil in %,
Clay(US)	is the mass fraction finer than 0.005mm in %.
LL	is the Liquid Limit in %,
I_P	is the Plasticity Index in %,
Pinhole	is the Pinhole Test Classification expressed as an ordinal number, i.e. ‘1’ for Class D1; ‘2’ for Class D2, ‘3’ for Class PD1, …, ’6’ for Class ND1).

The equation was obtained from multiple linear regression models obtained from statistical analysis of the test data of the HET. They also provided guidance on preliminary estimation of erosion rate, reproduced here as Table C.2.

Table C.2 Proposed Rules for Preliminary Estimation of the Representative Erosion Rate Index of a Soil (as Table 8.2 of Wan and Fell, 2002).

<table>
<tr><th rowspan="3">Parameters</th><th rowspan="3">Values</th><th colspan="6">Erosion Rate Index (See Note 1)</th></tr>
<tr><th>Extremely rapid</th><th>Very rapid</th><th>Moderately rapid</th><th>Moderately slow</th><th>Very slow</th><th>Extremely slow</th></tr>
<tr><th><2</th><th>2 - 3</th><th>3 - 4</th><th>4 - 5</th><th>5 - 6</th><th>>6</th></tr>
<tr><td colspan="8">Predictions for coarse-grained soils (See Note 3):</td></tr>
<tr><td rowspan="2">USCS Classification
(See Note 2)</td><td>SM</td><td>Very likely</td><td>Likely</td><td>Likely - Neutral</td><td>Unlikely</td><td colspan="2">Very unlikely</td></tr>
<tr><td>SC</td><td>Neutral - Likely</td><td colspan="2">Very likley</td><td>Likely - Neutral</td><td>Unlikely</td><td>Very unlikely</td></tr>
<tr><td rowspan="3">Degree of Saturation</td><td><70%</td><td>Very likely</td><td>Likely</td><td>Neutral - Unlikely</td><td>Unlikely</td><td colspan="2">Very unlikely</td></tr>
<tr><td>70 - 80%</td><td>Likely</td><td colspan="2">Very Likely</td><td>Likely</td><td>Unlikely</td><td>Very unlikely</td></tr>
<tr><td>>80%</td><td>Neutral</td><td>Likely</td><td>Very likely</td><td>Likely - Neutral</td><td>Unlikely</td><td>Very unlikely</td></tr>
<tr><td rowspan="3">Fines Content (<0.075mm)</td><td><30%</td><td>Very likely</td><td>Likely - Neutral</td><td>Unlikely</td><td colspan="3">Very unlikely</td></tr>
<tr><td>30 - 40%</td><td>Neutral - Likely</td><td colspan="2">Very Likely</td><td>Likely - Neutral</td><td>Unlikely</td><td>Very unlikely</td></tr>
<tr><td>40 - 50%</td><td>Unlikely - Neutral</td><td>Likely</td><td>Very likely</td><td>Likely</td><td>Neutral - Unlikely</td><td>Unlikely</td></tr>
<tr><td rowspan="3">Clay Content (<0.002mm)</td><td><10%</td><td>Very likely</td><td>Likely - Neutral</td><td>Unlikely</td><td colspan="3">Very unlikely</td></tr>
<tr><td>10 - 20%</td><td colspan="3">Very likely</td><td>Likely - Neutral</td><td>Unlikely</td><td>Very unlikely</td></tr>
<tr><td>>20%</td><td>Unlikely</td><td>Likely - Neutral</td><td>Very likely</td><td>Likely - Neutral</td><td colspan="2">Unlikely</td></tr>
<tr><td colspan="8">Predictions for fine-grained soils (See Note 3):</td></tr>
<tr><td rowspan="5">USCS Classification</td><td>CH</td><td>Very unlikely</td><td>Unlikely - Neutral</td><td colspan="2">Likely</td><td colspan="2">Very likely</td></tr>
<tr><td>MH</td><td>Unlikely</td><td>Likely</td><td colspan="2">Very likely</td><td colspan="2">Likely</td></tr>
<tr><td>CL</td><td>Unlikely - Neutral</td><td>Likely</td><td>Very likely</td><td colspan="3">Likely</td></tr>
<tr><td>CL - ML</td><td>Neutral - Likely</td><td colspan="2">Very likely</td><td>Neutral - Likely</td><td colspan="2">Unlikely</td></tr>
<tr><td>ML</td><td>Likely</td><td>Very likely</td><td>Likely - Neutral</td><td>Unlikely</td><td colspan="2">Very unlikely</td></tr>
<tr><td rowspan="3">Degree of Saturation</td><td><70%</td><td>Likely - Neutral</td><td colspan="2">Very likely</td><td>Likely - Neutral</td><td>Unlikely</td><td>Very unlikely</td></tr>
<tr><td>70 - 80%</td><td>Unlikely</td><td>Neutral - Likely</td><td colspan="2">Very likely</td><td colspan="2">Likely</td></tr>
<tr><td>>80%</td><td>Unlikely</td><td>Unlikely - Neutral</td><td colspan="2">Likely</td><td colspan="2">Very likely</td></tr>
<tr><td rowspan="3">Soil mineralogy</td><td>Kaolinites or illites or chlorites only</td><td colspan="3">Unlikely</td><td>Neutral - Likely</td><td>Very likely</td><td>Likely</td></tr>
<tr><td>Some smectites or vermiculites</td><td>Unlikely</td><td>Likely</td><td colspan="2">Very likely</td><td>Likely</td><td>Unlikely</td></tr>
<tr><td>With cementing materials (e.g. iron oxides, aluminium oxides, gypsum, etc.)</td><td colspan="3">Unlikely</td><td>Neutral - Likely</td><td colspan="2">Very likely</td></tr>
</table>

Notes :

1 Erosion Rate Index is taken as the negative LOG of the Coefficient of Soil Erosion, which is defined as the slope of the rising portion of the curve obtained by plotting the rate of mass removal per unit area against shear stress.

2 Soils used for construction of dam cores usually contains a considerable fraction of fines. Coarse-grained soils used for construction of a dam core are usually SC or SM. It is less common to find dam core materials belonging to GW,GP, GM, GC, SW, or SP.

3 Fine-grained soils means soils containing more than 50% by mass of fines (namely silts and clays). Fines means soil particles finer than 0.075mm. Coarse-grained soils means soils containing less than 50% by mass of fines (namely gravels and sands).

Appendix D - Properties of materials present in UK dams

D.1 Introduction

This appendix presents some published information on

- typical forms of construction of UK embankment dams
- the range of clays used in construction of the watertight element
- sources of data on the various geological clay strata in the UK, which is likely to have been used to construct dams situated on these strata

This data can be used to inform the risk analysis, described in Section 4.

D.2 Zoning of embankment dams

Most dams have some form of coarser fill shoulder supporting the core, such that the interaction between the shoulders and the core is crucial to whether internal erosion can develop to failure. Where the shoulders immediately adjacent to the core satisfy modern filter rules in relation to the core material, then internal erosion cannot progress.

A description of the variation of characteristics of typical embankment dams in UK is given in Table D.1. Further information on standard design and construction practice is given in Kennard (1994), Skempton (1989) and Binnie (1981). The latter includes a chapter on each of the main engineers active from around 1820 to 1900, with a list of dams mentioned in the text in an Appendix. Kennard and Skempton refer to broadly post and pre 1960 practice in UK dam design and construction.

D.3 Watertight element (core)

Moffat (2002) includes geotechnical index data on “puddle clays” relevant to internal erosion, and his data on Atterberg limits is reproduced in Figure D.2.

Table 2 of Moffat’s paper shows that for two of the 32 dams for which data are provided the "clays" are in fact silts, whilst Table 12 shows that some "puddle clays" are dispersive i.e. will deflocculate and erode if subject to concentrated leakage. There is other evidence that some British clays may be dispersive, particularly where they form part of a sedimentary sequence of interbedded sand and clays, or weathered from such a deposit. Thus although dispersive clays are not widespread, caution should be exercised as the clays used in some dams may be dispersive.

There is also evidence that at some dams the same material was used in both the shoulders and core, the only difference being that the core was placed using a “puddling” process. With time the higher initial moisture content of the core is likely to reduce, such that the dams become broadly homogenous.

Published papers on geological materials which may have been used as “puddle clay” are summarised in Table D.2.

Table D.1 Typical features of UK zoned dams (after Moffat 2002)

Phase	Period	Max core ht (m)	Core H/b	Impervious element	Cut-off provisions	Shoulders	Key dates (page numbers in brackets refer to page in Binnie, 1981)
Early	1800-1840	25	3 to 4	Central puddle, or thick upstream (1.0-1.5m) blanket	Puddle in key trench	Random fill	1730 first use of punned clay barrier 1766 first foundation cut-off trench c1795 puddle clay barrier first employed 1820 Roman cement introduced 1824 Portland cement introduced
Pennine Phase 1	1840–1865	30	3.5 to 6	Puddled in situ i.e. water added to clay in place in dam and puddled by boots and puddling tools/clay spades	Puddle clay in trench, as necessary	Random fill: lifts up to 1.2m; no compaction	1852 Bilberry failure 1864 Dale Dyke failure
Pennine Phase 2	1865-1880	35	3 to 5			Select fill against core (Moody zoning) lifts to 1.2m; toe drainage, compaction incidental	1870 Slip joint in culvert (p149) 1870 Stop using peat as support to puddle 1877 First use of cementation process to seal fissures in rock – Thomas Hawksley (p119, 153)
Pennine Phase 3	1880-1945	35	3 to 4	Puddle Clay prepared (“Pugged”) away from the embankments		As above but may be limited compaction	
Pennine Phase 4	1945-1960	45	3 to 5.5		Concrete in deeper trenches and grout curtain	As above but controlled compaction	
Modern	Post 1960	90	2.5 to 3	Broad rolled clay core	Rolled clay key trench and/or grouted cut-off	Engineered, with zoned compacted earthfill and/or rockfill. Drainage/filters etc	

Notes

1. H = maximum core height above base; b= maximum core width at base

D.4 Shoulder materials

There is no comparable published survey of the properties of shoulder materials. These will normally have been obtained by excavation in the reservoir area, and may also include spoil from tunnel and spillway excavations. The excavation methods in place at the time the dam was built should be considered and will normally dictate the maximum particle size present (e.g. historic rockfills will be finer than modern rockfills excavated with large mechanical plant).

D.5 Foundation

One of the key sources of information on materials present under the shoulders of the dam is (where it exists) the longitudinal section along the cut-off excavation. In all cases careful study should also be made of published geological information, such as geological maps and sheet memoirs. Other useful references include Walters (1971), which includes 75 pages of a detailed account of the geology of British dams.

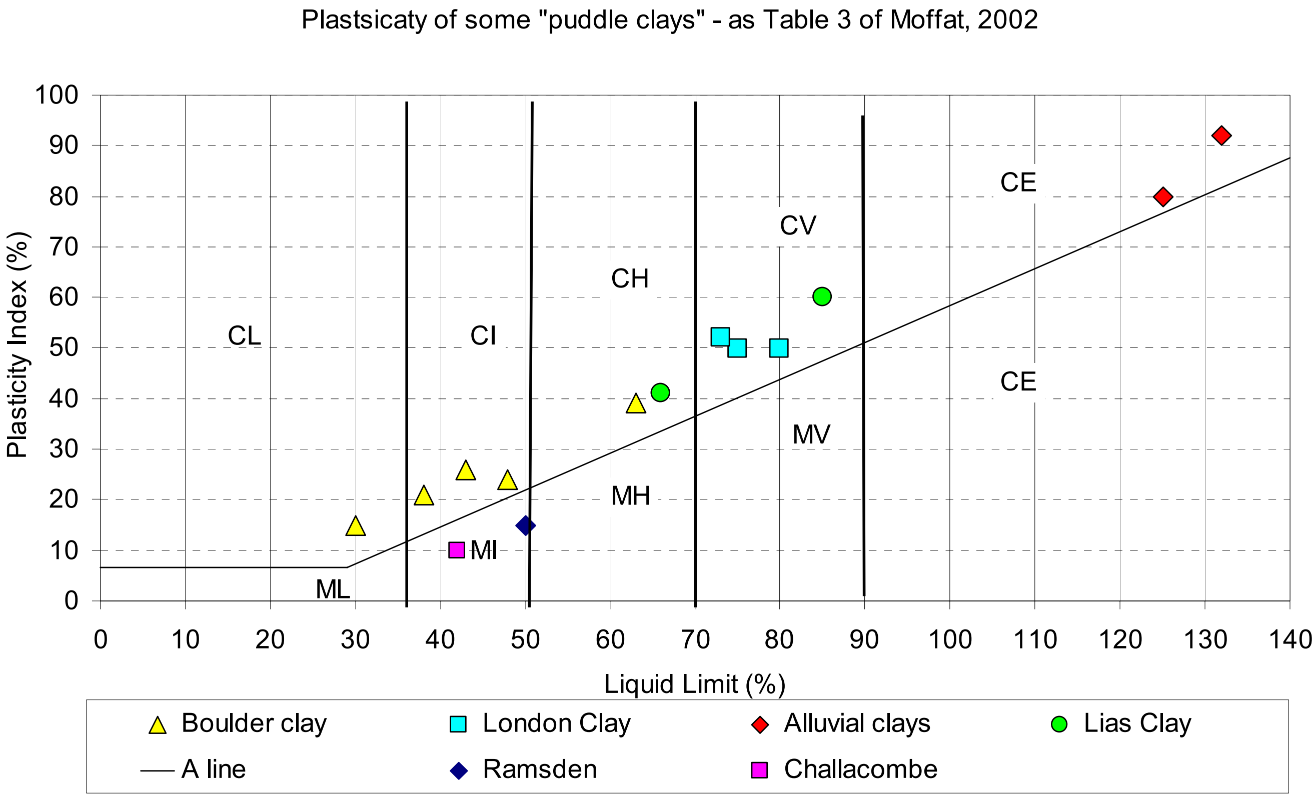
Table D.2 Published generic information on geological materials which may have been used as "puddle clay"

Geological origin of material	**Reference**		
	Author	**Year**	**Journal**
Claygate Beds and Bagshot Beds	Bell & Culshaw	1999	Some geotechnical properties of the Claygate Beds and Bagshot Beds of South Essex QJEG Vol 32
Coal Measures	Taylor RK	1988	Coal measures mudrocks: composition, classification and weathering processes. QJEG. 21. pp85-99
Glacial till (Boulder Clay)	N A Trentor	1999	Engineering in glacial tills. CIRIA Report C504
	Hughes DB et al	1998	The glacial succession in lowland Northern England. QJEG 31, 211-234
	Kittle JA	1988	Some geological and engineering characteristics of lodgement tills from the Vale of St Albans, Hertfordshire. QJEG 21, pp183-199
Keuper Marl	Chandler RJ	1969	The effect of weathering on the shear strength properties of Keuper marl. Geotechnique, 19, 321-334
London Clay	Burnett JB	192	A regional engineering geological study of the London Clay in the London and Hampshire Basins. QJEG, 7, 257-295
	Chandler RJ and Apted JP	1988	The effect of weathering on the strength of London clay. QJEG 21, pp59-68
Lias Clay	Chandler	1972	Lias Clay: weathering processes and their effect on shear strength. Geotechnique, 22, 403-431
Peat	Hobbs	1986	Mire morphology and the properties and behaviour of some British and foreign peats. QJEG 19, 7-80
General	Wroth CP	1978	The correlation of index properties with some basic engineering properties of soils. Canadian geo. J 15(2) 137-45

Notes:

1. The above is not exhaustive, being limited to geological strata for which an overview of the strata properties has been identified.
2. Although not normally used as puddle clay, peat was sometimes used on either side of a core to "protect it" during construction

Figure D.1 The range of fine grained soils used in "puddle clay" dams (after Moffat, 2002)



Appendix E - Distributed (zonal) techniques of leakage detection

Chapters 7 and 8 of IED provides a good source of guidance, with candidate techniques in Table E.1. Attention is drawn to a number of publications which postdate IED as shown in Table E.2. Further information on use of zonal techniques is given in Brown (2006).

Table E.1 Candidate parameters for detection of concentrated seepage within dam

Indicator	**Instrument**	**Typical change due to seepage**	**Remarks**
Change in temperature, when reservoir temperature varies from that in body of dam	Vertical probes Fibre optics	Medium	a) With appropriate interpretation temperature measurements can be used to infer the quantity of seepage. b) Fibre optics are ideally located below the phreatic surface, and 10m below the dam surface (to minimise external influences such as changes in air temperature, rainwater infiltration). Thus although extremely useful in new dams, and under new toe berms they are of less use for monitoring existing dams c) Further information in Table E.3
Change in pore pressure	Piezometer	Small, and local to seepage	Change small, so hydraulic, pneumatic or vibrating wire preferable to standpipe because a) change small b) response time faster
Resistivity	Electrodes spaced along dam crest	Small	Resistivity also varies with a) material type (clay vs. granular fill); b) temperature (factor of 2), c) total dissolved solids, d) porosity (e.g. if fines are washing out due to internal erosion) and e) water content (lower in saturated upstream shoulder; also varies with varying reservoir level, and where significant infiltration occurs due to rainfall).
Geophysical	One electrode in reservoir, and one downstream of dam	Small	a) specialist interpretation required, including stages of additional data acquisition following initial interpretation of results b) An example is described in Kofoed et al, 2006
Self potential		Small	

Table E.2 Some outputs from Dam Safety Interest Group (DSIG) project entitled "Investigation of geophysical methods"

Report No**	Title	Authors
205A	A parameter study for internal erosion monitoring	HydroResearch, Lund University, Sweden
205B/1	Self potential field data acquisition manual	Robert Corwin, US
205B/2	Laboratory testing of the streaming potential phenomenon in soils for application to embankment dam seepage investigations	Megan Schiffer (Univ British Columbia)
205C	Long term resistivity and self potential monitoring of embankment dams. Experiences from Hallby and Sada Dams, Sweden.	HydroResearch, Lund University, Sweden
205D	Engineering seismic surveys at a test embankment near Seven Sisters, Manitoba (Dam crest seismic investigations)	Various Canada, US
205E	A study of through-dam seismic testing at WAC Bennett dam.	Peter Gaffran, Michael Jefferies
	Guide to resistivity testing	Due 2007
	Guide to temperature sensing	Due 2007

Notes

d) These can be ordered from www.ceatech.ca.

e) Elforsk, the Swedish company set up by a group of hydropower owners to facilitate research into dam safety also publish research reports into this subject area; these can be downloaded free from their Swedish language website www.elforsk.se/rapport/rapplista_vat.shtml and include some equally useful reports. There are also relevant papers at www.hydroresearch.se/publications.html.

Table E.3 : Principles of the use of temperature anomalies in seepage flow.

Principle of detection	The technique measures temperature of the ground which has changed due to the flow of water at a different temperature (advection). In winter the reservoir temperature is constant with depth (typically 4^{o}C i.e. maximum density; although the surface may drop to zero when the lake freezes over. In summer there is stratification, with an upper warmed zone (max in UK say 24^{o}C), and a lower zone still at the winter temperature i.e. not as good for temperature sensing 19mm internal diameter probes are driven into the ground, and cables with sensors at 1m centres are then lowered into the ground. As the act of installing the probes generates heat, and the sensors are at different temperature to the ground it is necessary to leave the sensors to stabilise with the adjacent ground after dropping cable into hole (typically 45 minutes, for probes to cool down, plus10 minute for sensors to stabilise) On completion the probes are withdrawn, allowing the hole to squeeze shut on its own
Ground temp	This varies seasonally with depth; down to about zero change at 6 to 10m (variations go deeper in gravel) There is also an increasing time lag with increasing depth, relative to both the embankment and reservoir surfaces (about 3 months for the latter)
Interpretation	It is understood this is currently done manually i.e. it requires expert interpretation rather than being automated through a computer program. It is based on comparing the temperature of an "unpercolated" section with other sections, both in horizontal and vertical sections. in theory could relate magnitude of temperature anomaly (and/or radius of anomaly) to quantity of seepage, but in practice this is not done i.e. only used to identify location of leak
Limitations	• only tells you about seepage, not internal erosion • less effective where reservoir is not full • probes generally limited to 10m depth • small flow and particularly small concentrated flows may be impossible to detect (i.e. measurements are normally made at 10m centres) • "sterile" times of year when reservoir water is same temperature as dam (although may be counterbalanced by time history of leak area remembering being at different temperature from adjacent ground). This "sterile" time varies with depth e.g. at 1m depth is weeks 16-24, at 6m depth is later (plus shorter duration) • There is little information on potential long term drift of temperature sensors; it may not be important if assessment is to compare the temperature at one probe to other sensors, but could be important if looking at long term phase and amplitude
Variations to overcome "sterile" periods	Heat pulse – not done in UK; uses rate of cooling to assess seepage velocity. Have to get whole probe to same temperature. Need a lot of energy (over 12 hours heating to get stable). In principle could do the same with "Frost pulse". Tried in UK – used liquid CO2. Difficulties in getting to constant cold temperature
Changes in leakage	Change in amplification and lag will allow an estimation of change in leakage (although monthly readings are required i.e. a permanent monitoring system). Leakage is increasing where increasing amplitude and reduction phase shift. It is understood that there is German PhD which covers the relevant theory This is useful where on permeable foundation, and seepage does not emerge at the surface
Permanent installation	One permanent installation has been installed in UK yet. (Indicative cost £40k for 220m long x 13m deep, 20m spacing) Differentiate those where probes permanently installed, but still manual reading, and those where sensors connected to remote readout (this would be a lot of sensors!! E.g. 10 probes at 10m deep = 100 sensors) Would need to develop software to do automatic interpretation e.g. "base" is average of all readings at a given depth?

Appendix F - Future Research

The mechanisms of internal erosion are still poorly understood and significant further research is justified to reduce this uncertainty. This sub-sections updates the suggested future research set out in Table 6.1 of the Feasibility report for this project (KBR, 2004), as shown in Table F.1.

Table F.1 : Issues for future research

	Description	**Priority**	**Remarks**
	Mechanisms of internal erosion		
1	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, covered under BS1377:part 5: 1990 Section 6.2; including changes such as that a 6mm hole is used instead of a 1mm hole, and the rate of erosion is measured)	H	
	Modes of failure		
2	The expert elicitation which has been carried out to date to provide quantitative values for issues relating to modes of failure (and the associated uncertainty could be probed and extended by further session where the arguments for and against the range of values estimated are explored by appointing protagonists to argue the case for each of the extreme values (one for the 5% limit, and another for the 95% limit)	L	
3	Risk assessment, using Monte Carlo analysis to look at the probability of internal erosion, for credible ranges of core and shoulder parameters	L	
4	Collection and analysis of data on incidents, specifically • lessons learnt reports from incidents • data collected as part of the database, to allow statistical analysis, on the range of geotechnical properties of UK dams relevant to internal erosion • data on the annual probabilities of an incident, and dam failure respectively	H	
	Materials present in UK dams		
5	Desk study of existing site investigation reports on SI carried out in the past, and (relevant) published data on geological strata	H	The variable quality of site investigation is noted, and may limit the value of this exercise
6	Field investigation (with associated laboratory testing including erosion tests with core and shoulder) to better understand the range of properties of shoulder materials for typical UK dams; followed by identification and analysis of the credible failure mechanisms for the system of dam core and supporting shoulders	M	Best value for money would be obtained by carrying out high quality ground investigation at say three dams which have recently been, or about to be discontinued, to obtain data on both the core and shoulders.

7	Field investigation for construction details of pipes and culverts through dams, where the dams have been discontinued	H	
	Investigations and monitoring		
8	Field techniques to investigate suspected internal erosion should be improved, through development and trials of alternative systems including • Temperature measurement • Acoustic • Self potential • Resistivity	M	
9	Investigation of the viability of the use of gamma ray activity as a measure of the erosion of fines	I	