Defra

RESEARCH CONTRACT
RESERVOIR SAFETY ADVICE

TASK B : EARLY DETECTION OF INTERNAL EROSION

FEASIBILITY REPORT
Volume 1 of 2: Main Report

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ENGLAND

VOLUME PLAN

Volume

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2 Appendices A to H : Supporting Documentation

A: Terms of Reference
B: Literature Review
C: Results of Questionnaire B
D: Detailed consideration of 6 cases
E: Expert Elicitation
F : Possible techniques for early detection of internal erosion
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1: Bibliography
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DOCUMENT HISTORY RECORD

Rev	Date	Details	By	Chkd	App.
R01	24th April 03	Incomplete draft of Sections 1, 2 issued for discussion at Elicitation workshop	AJB	-	-
R02	1st July 03	Issue Incomplete draft for Internal Review	AJB	-	-
A01	4th July 03	R02 updated and approved for issue as incomplete draft for Steering Group meeting on 11th July; includes only results of questionnaire, first Elicitation session)	AJB	-	-
A02	6th Nov 03	Complete draft issued to client and Steering Group	AJB	JDG	AJB
A05	Oct 2004	Insert Supplement of 12th Nov 03, minor formatting to mount on website	AJB	-	AJB

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EXECUTIVE SUMMARY

This report is produced as part of an ongoing programme of research into reservoir safety in the UK, funded by government. The main objective of this particular project is to:

"provide a cost-effective approach to the early detection of progressive internal erosion in embankment dams"

The project commenced in September 2002 and is due for completion in late 2004. This report is the first of three stages, comprising a feasibility study to propose an outline strategy to achieve the above; this strategy is to be presented for peer review at a meeting of the British Dam Society. The two subsequent stages are development and testing of systems to provide warning of internal erosion, and preparation of technical guidance.

This research project has included a questionnaire to the UK dam industry, use of expert elicitation, literature reviews and informal discussions with practitioners in other countries. In order to keep the length of the main report to manageable proportions, literature reviews and other non-core material has been included as Appendices, the text in the main report being limited to summaries of precedent and other important features.

Section 2 comprises a review of the characteristics of UK dams, Section 3 current practice in managing internal erosion and Section 4 a synthesis of available theory and case history data. It is concluded that

- Internal erosion in the vicinity of appurtenant works appears to be the greatest risk of rapid failure
- The threat from internal erosion to the body of the embankment needs to be considered in the connect of the whole system of core and upstream and downstream shoulders

The proposed outline strategy is given in Table 5.1 and comprises a risk based approach utilising a mixture of the following

a) surveillance
b) investigations to better quantify the risk of failure due to internal erosion; followed where appropriate by upgrading works
c) real time monitoring for Consequence Category A dams

A number of options for Stage 2 of the research, the field trials, have been identified as shown in Table 6.2, with the choice partly dependent on the budget available.

1 INTRODUCTION

1.1 Objectives of Task B

This project is part of a three year contract for reservoir safety advice awarded by Defra to KBR. The contract includes for two specific research contracts, of which this is the second.

Clause 8 of the Specification states that the specific objective is to

provide a cost-effective approach to the early detection of progressive internal erosion in embankment dams;

whilst the introduction to Clause 11 states that it is

to devise an effective solution to the problem of monitoring internal erosion and leakage which undertakers could be expected to adopt without incurring disproportionate expense. The major emphasis should be given to embankment dams which predate modern geotechnical engineering and which, as a consequence, do not incorporate adequately designed filters within the embankment or instrumentation systems. The hazards posed by unprotected pipes and culverts passing through embankment dams require particular attention.……

and describes three stages, as follows

Stage 1 - *The development of a strategy for the early detection of internal erosion in embankment dams.*

- *The starting point will be to assess overall feasibility and the respective roles of surveillance and real time remote monitoring of instrumentation and warning systems.*
- *Techniques for remote monitoring of instrumentation located in or on the dam to detect internal erosion will be identified and evaluated.*
- *The contractor will produce an outline strategy within a year and present it for peer review at a meeting of a professional body (e.g. British Dams Society).*

Stage 2 *– In the light of feedback at the review meeting, the strategy will be refined. Appropriate instrumentation and monitoring systems, which can provide immediate warning of changes to normal leakage levels, will be developed and tested on appropriate dams. Further development of the strategy may then be required.*

Stage 3 *– Technical guidance will be prepared and a meeting of a professional body held to ensure wide dissemination of the strategy and the instrumentation developments.*

Stage 2 is provisional, dependent on the cost and whether part funding can be obtained form other sources e.g. Instrumentation manufacturers.

This report comprises the response to Stage 1 of the Contract.

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1.2 Task overview

1.2.1 Definition of Monitoring

The terms of reference refer to "early detection" and also to "monitoring". It is suggested that monitoring to reduce the probability of internal erosion could be all, or some, of the following

a) Physical monitoring, with trigger values set so that if the readings vary from normal by more than a set amount an alarm is triggered

b) Surveillance, namely audio and visual monitoring by trained staff

c) Physical investigations to improve the understanding of the vulnerability of the particular dam to internal erosion, followed perhaps by physical mitigation measures such as the inclusion of filters

The practicality of Item 'b' will depend on the potential rate of deterioration, and thus how frequently visits would need to be made if any problem was to be identified and action taken in time to avoid a failure. Where a dam was vulnerable to rapid deterioration following initiation of internal erosion the only practicable option may be some form of real time monitoring with an automatic warning system.

1.2.2 Challenges of this task

The challenges are to

a) obtain reliable information on rates of development of internal erosion, and whether all internal erosion is "progressive"; or whether in some circumstances the rate of erosion would stay constant with time

b) identify
  - the key factors controlling the rate of erosion,
  - what may trigger progressive deterioration,
  - the timeline in which deterioration may be noticed and action taken to arrest and control the deterioration
  - the indicators of such deterioration

c) identifying and/ or developing instrumentation which is effective at detecting internal erosion (as differentiated from leakage)

d) defining the criteria to differentiate disproportionate from proportionate expense

e) thus identify practicable and cost effective means of identifying deterioration

1.3 Deliverables for this task

The methodology for responding to the terms of reference were given in the Inception Report and are not reported here. The deliverables for this Task are summarised in Table 1.1.

Table 1.1 : Summary of Deliverables

Item	Implementation programme for Task (in Inception Report)		
	Item number	Date due	Date completed
Inception Report	*5*	*22 Nov. 2002*	*26th Nov 2003*
Questionnaire	*41*	*4 Feb 2003*	*21st March 2003*
Feasibility Report **	**47**	**14 July 2003**	**7th November 2003**
BDS Meeting	50	6 October 2003	London - 27th October 2003 (progress report) Glasgow – December 2003 (completed report)
Tender docs for trial	55	31 October 2003	
Strategy for trial**	53	3 December 2003	
Report on trials**	61	17 August 2004	
Technical Guidelines	**63**	15 September 2004	
BDS Meeting	66	19 October 2004	

** Subject to review by Steering Group as well as Defra

1.4 Structure of Report

The report is structured so that
a) information in common with Task A (“System of incident reporting”) is given in an Annex volume, including the references
b) supporting data is given in appendices, with the key issues discussed in the body of the text.

1.5 Methodology

1.5.1 Introduction

This section summarises the methodology adopted for identifying a cost effective means of early detection of internal erosion.

1.5.2 Literature Review

The results of a literature review is given in Appendix B, with a Bibliography in the Annex volume. The key references are given in Table 1.2.

Table 1.2 : Key papers relevant to early detection of internal erosion (ordered by date)

Authors	Date	Title, Publication
European Working Group	2002	Charles, Gerainger 2001, repeated at BDS 2002 – 70 (previous progress report in 1998 by Charles at European conference)
Fell et al	2001	The time for development and detectability of internal erosion and piping in embankment dams. Univ of New South Wales Report R-399. June. 38pp
ICOLD	2000	Q78, Beijing. “Monitoring of dams and their foundations” (85 papers)
Foster, Fell and Spannagle	2000	A method for assessing the relative likelihood of failure of embankment dams by piping. Pages 1034 onwards includes “factors affecting the warning time and ability to intervene to prevent failure”
Vaughan	2000	a) Internal erosion of dams – assessment of risks b) Filter design for dam cores of clay, a retrospect. Both in Conf Filters and drainage in geotechnical and environmental engineering. Balkema.
Foster and Fell	1999	A framework for estimating the probability of failure of embankment dams by piping using event tree methods. Univ of New South Wales Report DRAFT. April. 38pp
ICOLD	1997	Q 73, Florence. “Special problems with earthfill dams”. (61 papers). General Report by Charles

1.5.3 Questionnaire to dam owners and panel engineers

A questionnaire was developed and issued to recipients listed in Annex 2, covering both their views on internal erosion generally and a request for data on specific instances of internal erosion (52 questions, 93 sub questions). The latter was subdivided into headings as shown in Table 1.3. The results of the questionnaire are discussed in Appendix C, and for some questions also in the main text; the latter as shown in the table.

Table 1.3 : Headings in Questionnaire B

Question number			Number of sub-Q	Section of Main Report
Start	End			
7	18	Background/ Incident details	12	4.4
19	22d	Event detection	7	-
23	28	Rate of deterioration	11	3.2
29	39	Characteristics of dam at location of incident	26	4.6.5
40, 49	44d 49d	Surveillance before/ after	19	3.2
45	48	Prior warnings	7	4.6.5
50	55	Action taken to control	9	3.4, 3.6
56	57	Drawdown capacity	2	-

The results of the Questionnaire are given in Appendix C, with summary plots given in this volume.

For a number of cases the dam owner was visited to obtain more detailed information on the incident, with this given in Appendix D.

1.5.4 Expert elicitation

Elicitation is a process whereby quantitative estimates of the variables of interest (62 questions), with an associated uncertainty band, are made by experts. This is discussed further in Appendix E. Although it was originally intended to have one session with four experts, discussions with the facilitator suggested a larger number of experts would be preferable. Moreover the results of the first session had significant scatter, so it was decided to repeat the elicitation with two additional experts and preceded by a discussion of the factors governing the variables of interest. The expert elicitation therefore comprised two meetings on 14th March and 21st July 2003, with eleven experts as follows:-

Experts	Individuals	Remarks
Steering Group Panel AR	Millmore, Reilly	
Steering group owners' representatives	Dutton, Robertshaw	
KBR Panel AR Engineer	Brown, Gosden, Hewlett, Hughes	
KBR Supervising Engineer	Bruggemann	
Academic	Peter Vaughan, Paul Tedd	Attended second session only

The groups of questions posed are summarised in Table 1.4.

Table 1.4 : Summary of questions adopted for elicitation exercise

Question numbers		Number of questions	Units for response	Results presented in		
				Figure		Table
				Puddle Clay	Homogenous	
1-11	Calibration questions, to calibrate accuracy and informativeness of experts	11				
12-31	% of UK dams with “ongoing” leakage, and internal erosion	6	% of whole population	4.1, 4.3	4.2, 4.4	4.8
	Average leakage, erosion rates	2		4.17, 4.18		
32-46	Quantify • minimum detectable flow rate	17	Whole population	4.18		
	• dam critical flow			4.19		
	• rate of deterioration i.e. ongoing to progressive internal erosion			4.20	4.21	
47 – 57, 72-74	Contributory factors to rate of progression	7	Changes from a notional baseline dam	4.22- 4.24	No questions	4.11
58-71	Chance nodes in event tree	8	For all incidents of progressive internal erosion	4.5, 4.25	4.6	4.8, 4.13
	Total	**40**				

1.5.5 Instrumentation and monitoring systems

Identification of candidate systems has included consultation with manufacturers, as described in Appendices F and G.

1.6 Acknowledgments

The project benefited from a Steering Group to advise Defra, appointed at the suggestion of KBR, which comprised:

Jim Millmore – Chairman	Babtie Group
David Dutton	British Waterways
Andrew Robertshaw	Yorkshire Water
Nick Reilly	Independent

We would like to thank both the Steering group and the following who participated in the Expert Elicitation workshops: Prof. Peter Vaughan, Dr Paul Tedd.

The contribution of Prof Vaughn in provision of a detailed commentary on some of the issues; and Prof Fell of Australia in providing copies of research work on internal erosion are gratefully acknowledged.

2 CHARACTERISTICS OF UK DAMS

2.1 Data in BRE database

There are some 2600 reservoirs which fall within the ambit of the Reservoirs Act 1975, of which about 2100 are embankment dams. There has been a long history of dam construction in the UK with a summary of some of the main events affecting reservoir safety summarised in Table 2.1. It can be seen that modern standards of design and construction have only been available for less than 25% of UK dams.

There is a wide diversity of dams in the UK that comes under the ambit of the Act in terms of age, size, method of construction and ownership. The distribution of British dams in terms of the date of construction and height of dam are illustrated in Tables 2.2 and 2.3; the former including the reservoir capacity. The predominance of small dams should be noted. This is important as it affects the resources which the dam owner is willing to make available to improve dam safety and means that in some cases the owner is a private individual with no 24 hour 'operations room' into which data from a real time monitoring system could be fed. The totals of the various types of embankment dam are summarised in Table 2.4.

Table 2.1 : Chronology of main events relating to dam safety in UK

		Number of dams in UK
1925	Last dam failure causing loss of life	1,500
1930	Reservoirs (Safety Provisions) Act	1,600
1960	Soil Mechanics formalised as science	2,100
1966	Recognition of cracking by hydrofracture	
1974	Flood Studies Report issued - start of modern hydrological techniques	2,300
1985	Reservoirs Act, 1975	2,500

Table 2.2 : Distribution of characteristics of all embankment dams

	Percent of dam population					
	Note 1	10%	25%	Median	75%	90%
Date completed: prior to	67%	1808	1851	1890	1940	1975
Height (m); less than	78%	2.5	4	7	13	21
Reservoir capacity (1000m^3); less than	87%	32	60	160	700	2800

1. % of dams for which this data is available

Table 2.3 : Distribution of embankment dam height and age

	Height				Total
Date of construction	<15m	>=15<30m	>=30m	Not known	
<1840	216	13	0	25	254
>=1840<1960	609	287	37	58	991
>=1960	193	36	27	20	276
Not known	327	24	2	232	585
Subtotal	1345	360	66	335	2106

Table 2.4 : Subdivision of UK embankment dams into types and dam life years

	Dams in existence in 2000		Total dam life years (> 5 years old)	
	Number	% of total	Pre 1975	1975-2000
Concrete core dams	26	1%	779	1,354
Homogeneous Earthfill dams	1,023	49%	88,272	21,308
Other Earthfill dams	264	13%	15,444	5,280
Puddle clay core dams	735	35%	62,857	18,232
Rolled clay core dams	56	3%	214	1,138
Total for all UK embankment dams	2,104		167,566	47,312

2.2 Features relevant to detection of internal erosion

There are a number of features which are common to a significant number of UK dams which have an important influence on the ease of detection of internal erosion. These are summarised in Table 2.5.

Table 2.5 : Features which have an important influence on the ease of detection of internal erosion.

Feature	Problem	Remarks
"Puddle" (homogenous material)	a) "Puddle" is a process which does not necessarily involve imported clay i.e. many "puddle core" dams would actually be homogenous in terms of material b) The puddle was not always in a core i.e. some dams may have had the upstream face puddled following canal practice.	a) Need clarity between "puddle core dam" "puddle face" and "puddle clay core dam" It is likely that much of the data on dam type in the BRE database is ambiguous and is inconsistent in differentiating between these forms of construction b) Example of 'b' is quoted by Vaughan as Aldenham dam near Watford, built to provide compensation water for the Grand Union canal
Dams on permeable foundation	Cannot see changes in seepage	Stronger case for instrumentation e.g. temperature sensing
Small dams	The downstream face and crest have often become woodland; which a) significantly affects the ease of visual detection of internal erosion b) means pore pressures within the embankment are significantly affected by transpiration from the trees	
Culverts through dams	Some old dams have outlet works (and spillways) draining into a culvert, which is within the body of the embankment	This is likely to be a preferential path for internal erosion
Pipes through dams	In small old dams these are sometimes open jointed clay pipes	The joints are likely to be a preferential path for internal erosion

3 CURRENT PRACTICE IN MANAGING INTERNAL EROSION

3.1 Introduction

This section summarises the available data on current practice in monitoring and detecting internal erosion. It is based on the responses to the questionnaire (Appendix C) and informal discussions with a number of dam owners.

The opinions revealed by Questions 2 to 6 of the Questionnaire are summarised in Appendix C, as follows:-

- Table C1 – by category of respondent
- Text Section C.5

3.2 Surveillance

Current practice in relation to Surveillance in UK can be assessed from the questionnaire as follows, being also shown graphically on Figures 3.1 and 3.2.

Q25 – what was the elapsed time between the last surveillance visit and the near miss incident being detected
Although 34 incidents were reported, this question was only answered for 21 of them. For these incidents the last surveillance visit occurred in 43% of cases one day or less; in 52% two days or less and in 76% one week or less.

Views on the required frequency of visits were also indicated as follows:

Q3 – What frequency of visual inspection is required to forestall a Level 2 incident (emergency drawdown) due to Internal erosion?
Overall 35% of respondents suggested to be effective visual inspection is required every 2 days or more frequently, whilst 35% suggested weekly, with scatter around these values. The Panel AR engineers employed by consulting engineers had a greater proportion (45%) who considered every 2 days or more frequently was necessary.

In Australia recommendations in relation to the frequency of surveying are set out in the "Guidelines on dam safety management" (August 2003, 2nd Edition), being based on the consequence class. The key elements of the guidelines are reproduced in Appendix B. For the highest dams the recommended default value is daily, although a note to the table states that the frequency may be increased or reduced taking into account the risk posed by the dam, referring to Pattle et al (1999) as an example of such a process.

3.3 Instrumentation

The opinions revealed by the Questionnaire are summarised in Appendix C,

- Table C1 by category of respondent
- Table C2 by type of dam
- Text Section C.3
- Table 3.1 summarises the responses to the various questions on instrumentation (Q6, 22, 41, 42, 46, 49)

Seepage quantity, turbidity and visual inspection were considered to be of high value, settlement monitoring of medium value and piezometers of low value. For dams where near-miss incidents had occurred instrumentation was installed as follows:-

	Percentage of dams with at least one instrument
Settlement monitoring points	41%
Standpipe piezometer	30%
Other forms of piezometer	3%
V-notch weir	18%

Issues which were not probed in the questionnaire (due to the need to restrict its length) and may be relevant to this project were

a) the usage and value of hand held equipment e.g. crack gauges, thermometer
b) how the number and type of instrumentation, and frequency of reading, varies with dam consequence category, height or age.
c) the reliability of existing instrumentation

3.4 Control of internal erosion

The dam industry reported current practice in closed question 50 and open question 55. The responses to the questions are shown in tabular form in Appendix C together with a summary of the responses to open questions. The most common measure to control internal erosion was to lower the reservoir (73%), with this generally being effective (although 9% reported it as having no effect). Placing a filter downstream was reported by 12%, and dumping material into the reservoir by 6%.

Table 3.1 : Opinion of UK dam industry on different forms of instrumentation

A: Opinion of UK dam industry on value of different types of instrumentation (Q6)

	Standpipe piezometer	Other piezometer	Settlement monitoring	Seepage quantity	Seepage turbidity	Visual inspection	Other (give details in 6h)
High	15%	10%	23%	**78%**	**78%**	**73%**	5%
Medium	20%	25%	**43%**	18%	15%	20%	5%
Low	**48%**	**45%**	30%	3%	5%	5%	5%
None	13%	15%	0%	0%	0%	0%	5%
Blank	5%	5%	5%	3%	3%	3%	80%

B: Indication of internal erosion at time incident was detected (Q22)

	Seepage: Quantity	Seepage: Turbidity or other characteristic	Settlement	Piezometer readings
Strong	**50%**	21%	18%	0%
Medium	15%	6%	0%	6%
Low	24%	21%	12%	0%
No Indication	6%	**44%**	**44%**	21%
No Instruments			21%	**65%**
Blank	6%	9%	6%	9%

C: Instrumentation installed in dam (Q41)

Number	Standpipe piezometers	Other forms of piezometer	Settlement monitoring points	V notch or other quantification of seepage
0 to 0	**59%**	**59%**	**38%**	**56%**
1 to 1	0%	0%	0%	6%
2 to 2	0%	0%	0%	12%
3 to 5	15%	0%	6%	9%
6 to 10	3%	3%	24%	0%
11 to 15	6%	0%	3%	0%
16 to 20	3%	0%	6%	0%
>20	3%	0%	12%	3%
Blank	12%	38%	12%	15%

D: Frequency of reading instruments (Q42)

Frequency (weeks)	Standpipe piezometers	Other forms of piezometer	V notch or other quantification of seepage	Frequency (weeks)	Settlement monitoring points
0 to 0.5	**6%**	**6%**	6%	0 to 4	3%
1.5 to 1	3%	0%	**12%**	5 to 8	0%
2 to 2	3%	3%	0%	9 to 12	0%
3 to 4	3%	0%	6%	13 to 16	3%
5 to 8	0%	0%	0%	17 to 20	3%
9 to 12	0%	0%	0%	21 to 25	6%
13 to 25	3%	0%	0%	26 to 52	**24%**
>25	12%	0%	6%	>52	3%
Blank	71%	91%	71%	Blank	59%

E: Indication of internal erosion prior to incident (Q46)

	Seepage: Quantity	Seepage: Turbidity or other characteristic	Settlement	Piezometer readings
Strong	18%	0%	3%	0%
Medium	3%	3%	9%	6%
Low	24%	18%	3%	0%
No Indication	**44%**	**59%**	**47%**	24%
No Instrument			21%	**50%**
Blank	12%	21%	18%	21%

F : Change in frequency of reading following incident (one year later; Q49)

2= twice as often	Surveillance	Piezometers	Seepage measurement	Settlement
<=1	56%	18%	24%	35%
1.01 to 1.25	0%	0%	0%	0%
1.26 to 1.5	3%	0%	0%	0%
1.51 to 1.75	0%	0%	0%	0%
1.76 to 2	**18%**	6%	6%	3%
2.01 to 2.5	0%	0%	0%	0%
2.51 to 5	0%	6%	6%	3%
>5	0%	**9%**	**15%**	**9%**
Blank	24%	62%	50%	50%

3.5 Investigation of suspected internal erosion

Historically the investigation of suspected internal erosion has been generally to

- monitor leakage flows, including samples of seepage water to measure whether particles are being eroded
- carry out a site investigation to obtain information on the construction of the dam (and appurtenant structures)
- install piezometers to establish the phreatic surface and whether there are any concentrated leaks.

However, in recent years trials of other techniques of non-destructive investigation have been carried out on dams, as summarised in Table 3.2 (list and description of techniques given in Appendix F; some of the techniques may be used for both investigation and/or monitoring)

Table 3.2 : Status of trials of new techniques for investigating suspected internal erosion

Technique	Status	Remarks
Temperature profile within dam	Developed in Germany since 1990 for leakage investigations from canals; used in UK since 2000 with British Waterways now being the sole UK agent (Dutton, 2002). Has been used on several UK dams and many canal embankment locations	In the right conditions can be very effective.
Infrared Thermography	Trial of camera used for assessing the thermal performance of buildings. Tedd & Hart 1998	Although it could detect surface temperature difference of 0.2^{o}C, it was not possible to identify the source of the known wet areas on the downstream face of one dam
Acoustic	Used on concrete faced rockfill dams	To be included in new ICOLD Bulletin on underwater repair techniques
Geophysical		
The EU funded IMPACT programme (Investigation of extreme flood processes and uncertainty; 2001-2004) includes as Theme 6 geophysical investigation of linear flood defence embankments; using Geoelectric, GPR, seismic and gravimetric		The research is in progress, with no results published to date
Resistivity has been trialled by at least two major UK dam owners (in 2000) to investigate the source of a concentred leak		Not published
Other trials are described in Appendix F, including systematic field and laboratory research in Canada		To be published, but probably on commercial basis to recoup research cost

3.6 Physical works arising from internal erosion incidents

Details of techniques currently used as upgrades or remedial works following internal erosion are given in Questions 51 to 57 of the questionnaire (Appendix C).

Question 54 suggests that site investigation was carried out in 40% of cases, the most common number of exploratory holes comprising 11 to 20 holes.

Question 51 and 52 reveal that grouting was the most common works (26%), although in 15% of cases further works were then necessary. Question 57 reveals that in 6% of cases the drawdown capability was increased, to around to between 0.1 and 0.5m/day.

3.7 Promoting and maintaining good practice

In UK management of internal erosion depends on

- The Panel system of individuals with sufficient experience of construction and operation of dams to intercede when things appear to be going wrong. These people are accredited by government (in effect by their peers)
- The system of Engineering Guides, and CPD of both dam owners and panel engineers through professional societies such as the British Dam Society.

Some owners also appoint independent panels to review proposals for physical works (although they are not usually involved in an emergency).

Figure 3.1 : Questionnaire case history data
Frequency of surveillance visits to detect internal erosion (Q3, 25, 40)

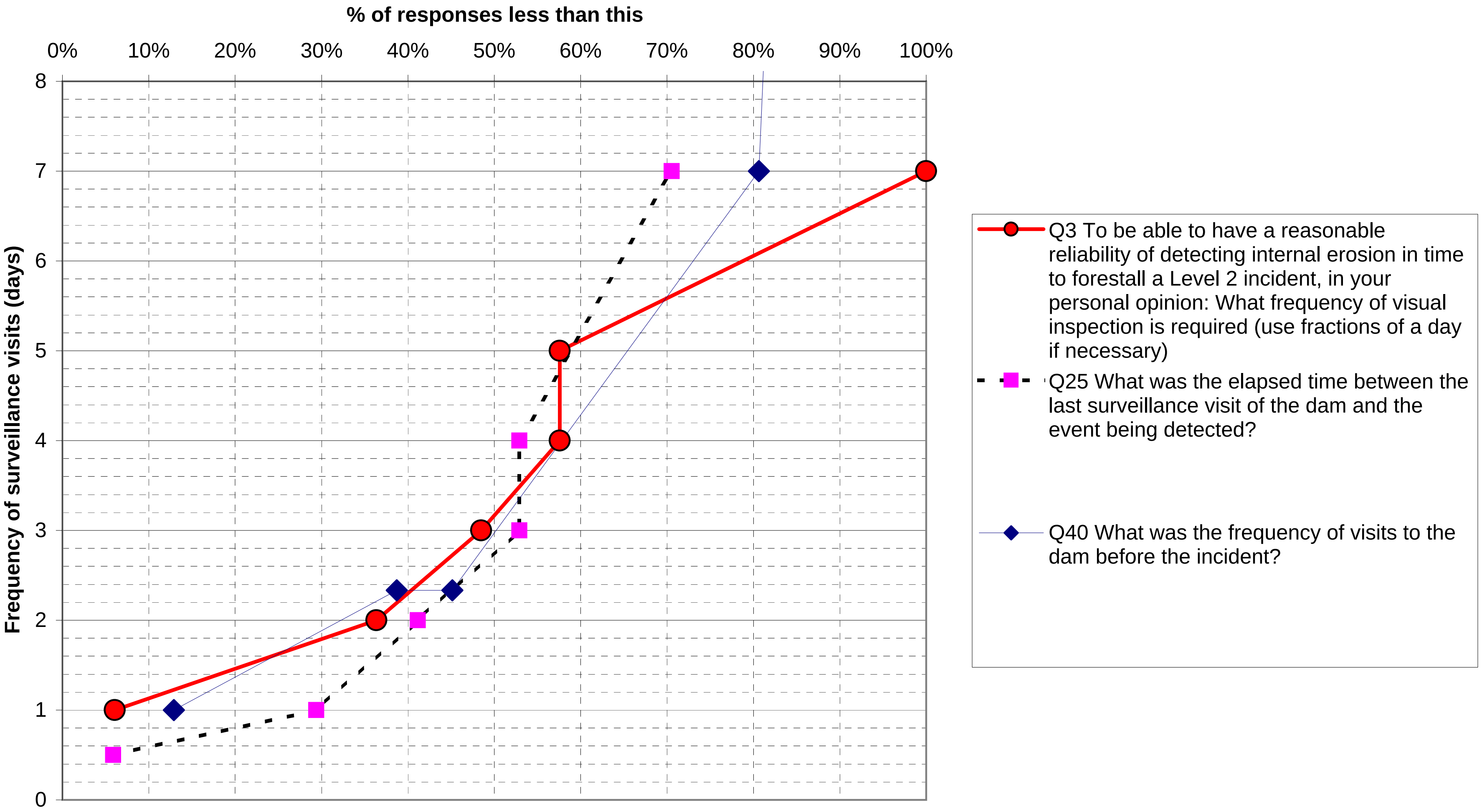
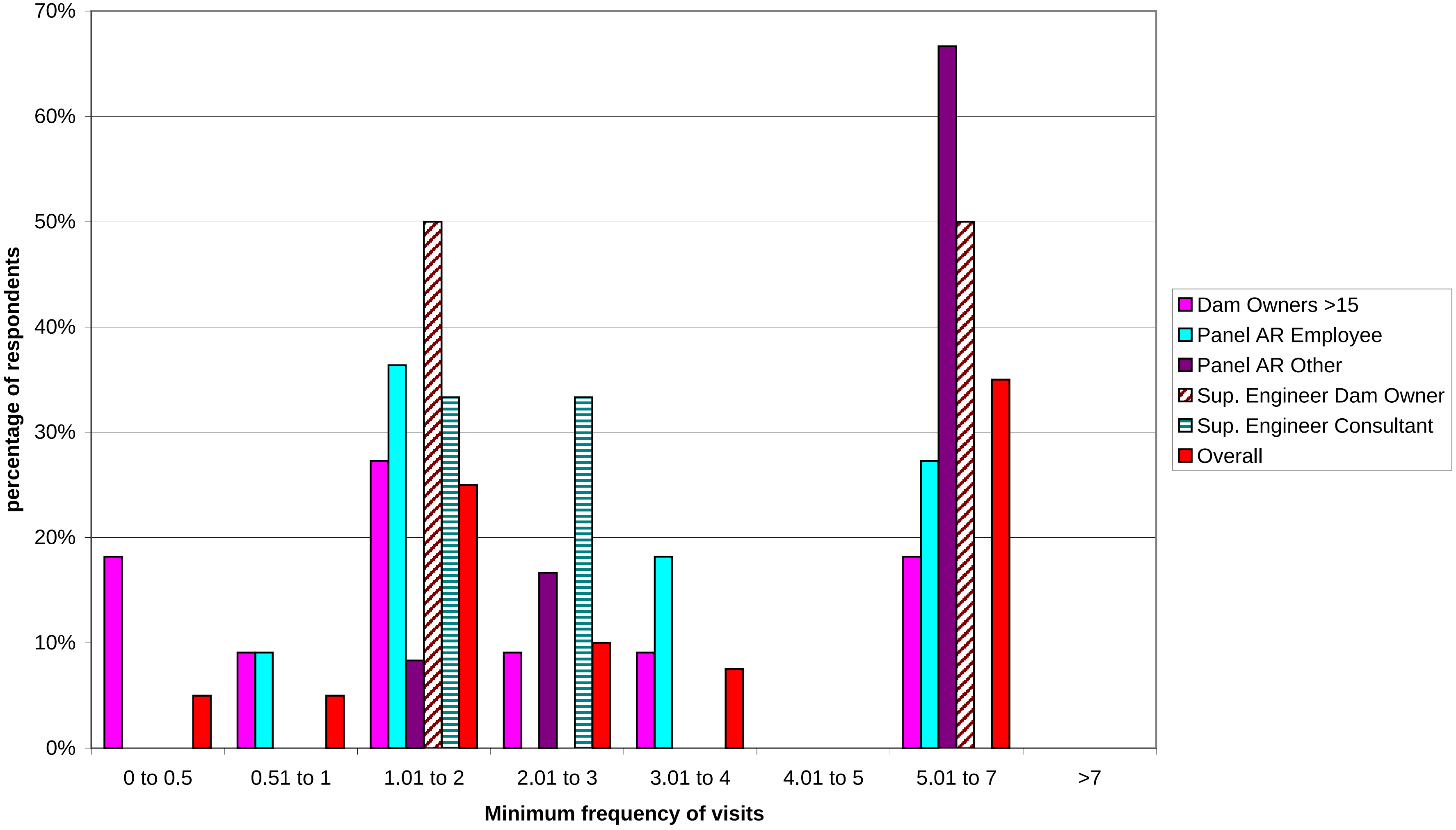


Figure 3.2 - Frequency of surveillance to detect a Level 2 incident by respondent (Q3)



4 SYNTHESIS OF AVAILABLE THEORY AND CASE HISTORY DATA

4.1 Introduction

Before considering ways in which the management of internal erosion can be improved, the objective of this project, it is necessary to first summarise current knowledge of internal erosion. This is carried out both in terms of available theory and in field observations (the empirical approach).

This section of the report therefore

a) sets out a system of definitions to be used for this project, based on both published work by others and the Integrated System research contract by KBR.
b) summarises current design guidelines for new dams
c) describes case histories of internal erosion, with features relevant to defining models of internal erosion (e.g. highlighting some of the complexities, where field observations support available models and where singularities may govern the process)
d) sets out a system of models of internal erosion to be used for this project. This system has been derived as a judgement by the KBR team working on this research project, building on published work by others.
e) summarises the current status of quantification of this model
f) concludes by summarising the basis on which the options for a strategy for early detection of internal erosion may be considered

This Section should be read in conjunction with

- Appendix B - a summary of a literature review.
- Appendix C - the results of the questionnaire to UK dam professionals
- Appendix D - detailed consideration of six case histories
- Appendix E - the results of the expert elicitation exercise

In the text the results of the questionnaire and expert elicitation are prefixed by Q and E, to differentiate the two set of question numbers.

4.2 Definitions

It is important to provide a consistent set of definitions of the factors affecting internal erosion, to provide clarity of thinking in issues such as differentiating causes from effects, and the different mechanisms of deterioration. Definitions used in this report are summarised in Tables 4.1 to 4.4.

Table 4.1 : Key terms relating to Internal erosion

Term	Definition	Source
Seepage	Slow uniform flow of water through a porous medium.	Section 3.4.1 of Johnston et al (1999)
Leakage	Concentrated, uncontrolled flow of water through a crack or defect.	
Internal erosion	The removal of solid material, usually in suspension, from within an embankment or its foundation by the flow of water (thus excludes solution of material)	Charles (1998)

Table 4.2 : Different types of internal erosion (after Charles, 1998)

Piping	a) A process that starts at the exit point of seepage and where a continuous passage or pipe is developed in the soil by backward erosion. When the pipe approaches the source of water there is a sudden breakthrough. b) The hydraulic gradient at the point where the water flows out of the ground is critical, but is difficult to predict as it depends on localised weaknesses in the fill. Cohesionless soils, particularly fine sands and silts are most susceptible. c) Usually commences on the downstream surface of the embankment slope
Suffusion	Mass erosion in soils which are internally unstable. Fines are transported by seepage flow between the larger sizes of the embankment fill or the foundation soils and the process may lead to either an accumulation of fines in some part of the fill, or fines being taken entirely out of the embankment
Concentrated leaks	In cohesive soils which are capable of sustaining an open crack, concentred leaks may occur with erosion of soil particles along the sides of a crack. The crack may be caused by a) Hydraulic fracture, b) Preferential flow paths (inhomogeneous core, interface between layers) c) Hydraulic separation between fill and structure d) Collapse settlement on saturation (possibly leading to wet seams) Erosion may either be along the interface, or into an open crack or joint in the conduit wall

Table 4.3 : Terms relating to the process of internal erosion

(as Table 2.3 of Integrated System Research Report, with some additions specific to internal erosion)

Term used in this report (alphabetical order)	Definition
Contributory factor	Factor which affects the outcome of the application of a mechanism of deterioration (includes Intrinsic condition, operating regime)
Incident	Detectable change in Indicator causing sufficient concern to lead to some action (Levels 1 to 4 as shown in Table C2)
Indicator(s)	Measurable outcome from the application of a mechanism of deterioration e.g. deformation, seepage, instrumentation results.
Intrinsic condition of dam	Current physical property or dimension of the dam which can be measured and which affects the outcome of the application of a mechanism of deterioration. Although initially determined by construction details; this may change with time due to ageing, neglect, maintenance or upgrading.
Failure	Uncontrolled sudden large release of water
Failure mode(s)	Means by which a failure (uncontrolled sudden large release of water) may occur
Mechanism(s) of deterioration	Process by which the integrity of the dam is undermined. The mechanism can have a quantitative threshold above which deterioration is likely to occur e.g. slope protection designed to withstand waves due to 100 year wind
Threat(s)	Random Event (External threat) or Potential Internal Instability (Internal threat) that poses a threat to the integrity of the dam
Stages in mechanism of deterioration	
Initiation	Subdivided into two stages a) pathway for internal erosion initiated b) internal erosion initiates
Continuation	Erosion either controlled/ terminated by a filter, or other protective feature, or continues
Progression	Backward erosion of "piping", or enlargement of concentrated leak
Failure	Breach mechanism forms

Table 4.4 : Definitions of contributory factors to internal erosion

Dispersive soils	Clay soils which disperse or deflocculate in the presence of relatively pure water

4.3 Current practice for design of new dams

4.3.1 Embankments

Current practice for the design of new embankments against internal erosion is summarised in the form of key technical papers in Table 4.5, and in terms of physical measures in Table 4.6. Historically the following have also been adopted at various points in time, but less emphasis is put on them at the present day:-

i) minimum width of clay in relation to head
ii) place the clay wet of optimum such that positive pore pressures develop in the core, greater than the reservoir head, to reduce the risk of hydraulic fracture
iii) incline the core, with the core at the base of the dam upstream of that at the crest, to increase stresses within the core and thus reduce the risk of hydraulic fracture

Table 4.5 : Key references for design of filters for new dams

Author	Date	Title, publication	Remarks
ICOLD	1994	Embankment dams: granular filters and drains. Review and recommendations. Bulletin 95	Includes good literature reviews and set of main references in this area
US Soil Conservation service	1986	Engineering Guide for determining the gradation of sand and gravel filters. Soil Mechanics Note No 1.210-VI	Based on new laboratory tests, also published in papers by Sherard et al, 1985, 1984 (two)
Kenny & Lau	1985	Internal stability of granular filters. Canadian Geotech J.	Alternative approaches to evaluate the safety of broadly graded materials against suffusion are given in Lafleur (1987)
Sherard	1989	Critical filters for impervious soils J Geotech Eng. ASCE. July	Vaughan (1982) has suggested an alternative approach based on permeability of the filter
US Soil Conservation Service	1991	Engineering Guide for the use of geotextiles. Design Note No 24	

Table 4.6 : Features normally included in design of new embankment dams

	Design Feature	Purpose	Remarks
1	Specification of characteristics of material downstream of watertight element (filter)	To block any internal erosion in the event that a pathway has been initiated	The rules for filter design are not universally agreed, with some of the contentious issues described in ICOLD Bulletin 95 (1994)
2	Crack filling fine sand upstream of the impervious element	Wash into any pathway and block flow	
3	Providing adequate drainage capacity	a) To ensure that seepage emerges in a controlled way through graded materials, rather than in an uncontrolled fashion on the downstream face of the embankment b) To prevent saturation of the downstream shoulder	
4	Limiting exit gradients	to avoid piping	modern practice would use zoned fills including filters rather than relying on this, because of the uncertainty over what constitutes tolerable gradients
5	Providing a clean granular soil layer on top of the core which acts as a "capillary break".	To prevent drying out of the core due to evaporation, which is exacerbated where there is a grass cover	This caused serious leakage of the King George Fifth bank of Thames Water in the aftermath of the long partial drawdown adopted as a precaution after the "Dam Busters" raid (Bishop, 1946).

4.3.2 Appurtenant works through embankments

There is no single publication setting out good practice in the design of pipes and culverts through embankment dams. Current design practice to prevent internal erosion associated with appurtenant works to new dams includes the features summarised in Table 4.7.

Table 4.7 : Features normally included in design of new appurtenant works through embankment dams

	Design Feature	Purpose
1	Wherever possible route draw off works through tunnel in abutment	Insitu abutment would normally be non-erodible rock, such that the material surrounding the tunnel would not be susceptible to internal erosion
2	Where a pipe or culvert is unavoidable, locate within a second culvert	So that the reservoir head cannot be in direct contact with the embankment fill
3	Detail the pipe or culvert, where it passes through the core, to have sloping sides with a greater width at the base,	To ease compaction of the interface and thus reduce the risk of low contact pressures
4	Detail a filter and drain around the pipe downstream of the core, as for the embankment.	To block any material being carried along the interface between the appurtenant works and adjacent fill

4.3.3 Areas of uncertainty

There are number of areas where current design practice is not well established, including:-

a) the influence of water chemistry on causing blockage of filters and drains (e.g. precipitation of dissolved minerals due to a reduction in pressure on exiting into atmospheric pressure from within the body of the dam or foundation)
b) the importance and influences of bacteriological growth on the performance of filters and drains

4.4 Case history data: practical observations relevant to progressive internal erosion

4.4.1 Introduction

This section summarises the key case history data on

a) the prevalence of internal erosion
b) features that complicate detection of internal erosion

4.4.2 Prevalence and location of internal erosion

Data is available from the questionnaire (Appendix C) and Elicitation (Appendix D) on the prevalence and location of internal erosion is summarised in Table 4.8.

Table 4.8 : Prevalence and location of leakage and internal erosion

	Questionnaire (Tables C1, C2)	Elicitation[1]
Prevalence of leakage; by location	-	Figures 4.1, 4.2
Along or into a structure	-	10%, 5%
Embankment	-	9,% 11%
Embankment into foundation	-	6%, 3%
Foundation	-	8%, 5%
Prevalence of internal erosion	Q2[2]	Figures 4.3, 4.4
Location	Q13 – 18	
Along or into a structure	39%	18%, 18%
Embankment	38%	11%, 11%
Interface of the embankment with the foundation or abutment	23%	Not separated
Embankment into foundation	Not separated	18%, 8%
Foundation	None	10%, 6%
Mechanism	Q16	Figure 4.5, 4.6
Concentrated leak	41%	58%, 61%
Piping	38%	15%, 14%
Suffusion	9%	4%, 4%
Don’t know/ other	12%	17%, 17% (foundation)

1. For puddle clay, homogenous respectively
2. The number of serious internal erosion incidents a year is given in Table Annex 2.3 and is estimated as three Level 2 (emergency drawdown) incidents a year, and 10 Level 3 (precautionary drawdown) incidents a year. These represent 0.2% and 0.5% of the stock of 1800 UK embankment dams.

In terms of the prevalence of seepage Brown and Gosden (2000) report that over 50% of a portfolio of small dams had longstanding visible seepage, with the most common seepage probably being foundation seepage, where the original design either had no cut-off, or an inadequate cut-off, and seepage is occurring in relatively stable foundation strata. Where changes in seepage have occurred which have required action, this was most often associated either with seepage along, or in the vicinity of, structures, or along the embankment foundation interface, or with tree roots. They consider these percentages are not surprising when viewed in relation to the age, and thus form of construction of these dams, which will not have incorporated internal filters and drains.

The elicitation suggests that the prevalence of leakage is typically about 10 to 20% of UK dams, with internal erosion occurring at 10 to 20% of these.

The issue of which mechanism of internal erosion is prevalent is interesting. It could be argued that piping is only likely to affect new dams, as with old dams any vulnerability to piping would have been exposed in the first few years of their lives. Related issues are how the three types of internal erosion are differentiated in the field, whether the UK dam industry uses the terms as defined in Table 4.2 and thus whether the data available is reliable. All that can be concluded is that concentrated leaks predominate, but that the other two types probably also occur.

4.4.3 Dispersive soils and soil erodibility

The definition of a dispersive soil is given in Table 4.4. This is an important subject area because it affects how rapidly erosion would occur in the event that a leakage path was formed. The erodibility depends on the combination of clay and water chemistry, with dispersive soils eroding much more rapidly than non-dispersive.

Laboratory tests reported in Atkinson, Charles & Mhach (1990, QJEG, 23, pp103-108) showed that of puddle clays from four UK dams tested using a new "Cylinder Dispersion test" one (a puddle clay from South Wales) was dispersive when both the pore water and free water were water from the reservoir. Further information on dispersive clays is given in ICOLD Bulletin No 77 (1990).

Question 38 of the questionnaire asked for details of any dispersion testing that had been carried out. All but one of the responses to the questionnaire reported that no testing had been carried out. The one set of results available wee from an author of this report, where results from a commercial laboratory on Hythe Clay showed it was mildly dispersive.

Vaughan (Pers comm., 2003) notes that as far as he is aware dispersive soil water combinations are very rare in Britain. The only instance he has come across was a laminated pro-glacial soil with layers of fine silt and clay at Osmotherly on the N York moors. It formed the foundation of the dam. This soil would disperse in distilled water without using a dispersant. It was highly erodible.

Research underway in Australia (Wan, Fell, Foster, 2002) involves a modified pin-hole test where a 6mm diameter hole is drilled along the axis of a sample prepared in a standard compaction mould, and the rate of erosion measured. They report that the rate of erosion between different soils can vary by up to 10^6 times (see Section 4.6.4).

The extent to which UK clays would test positive to the standard dispersion tests remains open. On the one hand there is limited evidence to suggest there may be some dispersive clays. On the other hand practical experience over the last few decades suggests it not a common problem.

The issue of testing the erodibilty of soils is discussed further in Section 6.

4.4.4 Effectiveness of downstream shoulder fill as filter

To be effective as a filter the downstream shoulder material must

a) have a suitable grading to trap fines being eroded from the core
b) be non-cohesive, so it cannot sustain an open crack

The filter performance can be examined by drilling and sampling. A more convenient and supplementary method is to measure permeability in-situ (Vaughan, 2000b). If long piezometers with sand pockets are used a complete vertical profile of permeability could be attained from a few holes. However, conclusively establishing whether the material is non-cohesive is less straightforward.

Vaughan (Pers Comm, 2003)

a) suggests that many old transition fills are good filters, (but there is little other published data on this).
b) reports that new filter drains can be installed using slurry trench techniques. The trench is formed in the usual way and filled with the granular filter by a tremmie pipe. A polymer mud is used which self-destructs in a few days, leaving loose sand which is densified by vibration. In New Zealand a connection was drilled from the diversion tunnel to the finished tunnel to ensure drainage (paper in waterpower).

4.4.5 Seepage and interpretation of pore pressure readings

In recent years it has been realised that seepage regimes can be more complex than a simple linear seepage model, due to

a) dependence of permeability on effective stress, pore pressure and insitu structure (e.g. Vaughan in his 1994 Rankine lecture presents observations of non-linear seepage due to this effect, including several different forms of non-linear pore pressure distributions across a dam core)
b) interaction of evaporation, transpiration and rainfall to provide unexpected behaviour in terms of both the position of the top of the saturated zone, and pore pressures in the partially saturated zone (e.g. Vaughan, 1994; Blight, 1997; Vaughn Kovacevic & Ridley, 2002).

‘b’ includes that a dam with a downstream fill of comparable or lower permeability than the average annual rainfall will develop high downstream pore pressures because of rainfall infiltration. Piezometric heads to within 2 to 3m below the slope surface can develop. This has nothing to do with seepage from the reservoir. A variation on this is if there is an impermeable layer within the fill, this may act as an aquaclude. A spring line may then develop on the downstream slope just above the aquaclude. Proving that this has nothing to do with the reservoir can be difficult.

Further difficulties in the interpretation of pore pressures arise from old rubble or pipe drains, which are either not known to be present, or are known to be present but in unknown locations. These may result in local drainage; alternatively collapse and blockage of a pipe drain can force the flow in it to the surface, giving the appearance of a new spring.

These highlight the need for caution in interpreting pore pressure readings

4.4.6 Interpretation of settlement

In principle there are the following potential causes of ongoing settlement after a dam has reached seepage equilibrium:-

a) cyclic loading of dam due to varying reservoir level
b) creep
c) internal erosion

The following text is based largely on contributions from Vaughan (pers comm., 2003).

The first cause occurs in a dam with a reasonably permeable upstream shell in which water pressures go up and down with the reservoir. Effective stresses go up during drawdown and down again during re-impounding. The cyclic soil deformation is not elastic. The dam settles during drawdown but does not recover all the settlement on re-impounding. There is ongoing long-term settlement due to this effect (Tedd, Charles, Holton & Robertshaw, 1997; Kovacevic, Charles, Potts, Tedd & Vaughan, 1997; Vaughan, Chalmers & Mackay, 2000). The settlement is likely to be consistent across the valley, varying with dam height. Settlement is likely to be linear if plotted against the cumulative depth of drawdown (Vaughan, Chalmers & Mackay, 2000). Settlement will be much larger in old uncompacted fills than in newer compacted dam fills.

Long term settlement is often attributed to creep. While creep does sometimes occur, settlement due to cyclic impounding is more probable. With occasional rather inaccurate field measurements the two cannot be differentiated. Detailed observations (Tedd, Charles, Holton & Robertshaw, 1997) show that movement corresponds to reservoir level change. Vertical movement is negligible while the reservoir level is constant

The third cause of settlement is due to loss of material by internal erosion.

Non-cohesive soils cannot sustain an opening under water; they collapse. Settlement is likely to take the form of a sink hole. There may be little sign of a sink hole until it actually breaks the surface. The diameter of the pipe below the sinkhole may be no more than 1m.

In clays (cohesive soils) an erosion path can remain open up to a certain size. Generally stable settlement due to material loss is likely to take the form of a depression (Vaughan, 2000b). The depression is likely to spread over a length approximately given by lines at 60^o to the horizontal from the point of soil loss upwards to the surface. Depressions are likely to be local to points of soil loss and not to affect the dam crest along its whole length.

With central clay core dams with non-cohesive shoulders, typical of UK puddle core dams, the core seems to develop a general depression in response to loss of material at depth. The hole in the core allows loss of upstream fill and a sink hole develops up the upstream boundary of the core, emerging on the crest or upstream face of the dam. The principal risk seems to be overtopping if the sinkhole lowers the crest sufficiently. This mechanism (or something like it) seems to have occurred in several British Dams, as shown in Table B.2 in Appendix B.

The nature of failure if internal erosion of the core occurs is perhaps the greatest uncertainty in evaluating the safety of dams with central clay cores. Clearly the formation of a sink hole over the upstream boundary of the core can cause failure by overtopping, but does not necessarily do so. Further assessment of this risk is desirable.

If a dam is apparently vulnerable to this type of failure, then will accurate settlement measurements give effective early warning?

4.4.7 Change of embankment properties with time

Finite element analyses of cyclic reservoir drawdown indicate that total stresses in a dam core go up when this is simulated; Kovacevic, Charles, Potts, Tedd, & Vaughan,1997; Vaughan, Chalmers & Mackay, 2000). There is intuitive sense in this since continuing strain and stress change is likely to anneal stresses, with low ones rising and high ones reducing. The result from analysis could be controlled by the assumptions assumed, although there is no evidence for this. Field data could be produced to examine this phenomenon.

This and other phenomenon would be expected to change the density and moisture content of the various embankment fills with time. In particular it could be argued that the fills in older embankment dams which were constructed relatively loose, would consolidate with time such that their current density may not be significantly less than more modern equivalents.

4.4.8 Unprotected pipes and culverts

Question 27 of the questionnaire (table C2 in Appendix C) shows that for the case histories provided those with the shortest time to failure were those associated with appurtenant works. This is consistent with the view that if internal erosion occurs in the body of a dam the shoulders may often act to slow, if not prevent failure. This emphasises that priority should be given to consideration of unprotected pipes and culverts, as indicated in the terms of reference for this project.

4.4.9 Mechanisms of failure, including singularities

Back analysis of failures often shows that the initiating cause was often a number of interrelated effects, of which construction and other details not shown on typical sections played an important part. This is discussed further in Section 4.5.2.

4.5 Models of progressive internal erosion

4.5.1 General

It is helpful to have some form of mapping of the process of internal erosion, which covers the overall process from events that initiate internal erosion through to credible mechanisms for failure (breach leading to uncontrolled release of a large quantity of water).

As part of the previous Integrated System research project an "event train" and associated definitions was developed for internal erosion. This has been reviewed and extended as described below.

It has been found that there is no one type of diagram which is ideal for showing the whole process. Some form of **fault tree** would have the benefits of

- a recognised convention for showing relationships and
- quantitative relations between stages

However they cannot deal with cyclic or intermittent behaviour or "rates of deterioration" and do not show the complex relationship(s) between the process itself, contributory factors and indicators.

On the other hand an **event train**, such as that used in the Integrated System has the advantages of flagging the contributory factors and indicators as well as the process (terminology in Table 4.3), but the disadvantage that it is only qualitative.

An important point in building (and testing) any model for the processes of internal erosion is that for internal erosion to occur it is necessary to have all of:-

a) A supply of water
b) A conduit for eroded fines to travel along
c) An exit point where these fines can be discharged downstream of the dam
d) Sufficient velocity (or stress conditions e.g. hydraulic gradient) for fines to be eroded from the sides of the conduit

The process diagram required for this aspect of internal erosion is more complex than those required for estimating the probability of failure, because of the need to include the dimension of time. It is concluded that the process is complex and best shown with a variety of techniques, to capture the complexity of the process, as follows:-

Figure	Title	Remarks
4.7	Event train for internal instability of an embankment dam in service	a) Extended version of that in Integrated System. b) Shows contributory factors and indicators
4.9	Event tree for progression of internal erosion within embankment dam	a) Logic diagram of physical sequence. b) Separate diagrams required for each of the three types of internal erosion listed in Table 4.2.
4.8	Time-based model of progressing internal erosion	Various sequential stages, similar to the four defined by Foster and Fell (2001). However, in practice any internal erosion may be intermittent, reacting to changes in reservoir level etc.

4.5.2 Effect of 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 to form a step to found a culvert
b) construction stage features, such as foundation drains
c) reduced stresses at the interface between the embankment and appurtenant structures (or pipes) through the dam
d) variations in fill materials
e) trial pits, or other localised excavations into the dam

Similarly repairs, or raising of a dam crest may create 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.

4.6 Quantification of Concentrated leakage

4.6.1 General

This section summarises available information on quantification of elements of the internal erosion process model described in the preceding sub-section; including published papers and the results of the questionnaire and expert elicitation carried out as part of this study.

4.6.2 Initiation of Pathway - Hydraulic fracture

4.6.2.1 General

In simple terms hydraulic fracture may be described as occurring when the horizontal reservoir pressure is greater than the sum of the cross valley total stress in the core and any tensile strength of the core. Although historically designers have attempted to reduce the likelihood of hydraulic fracture, it is now recognised that hydraulic fracture may occur even at well built dams and design is instead concentrated on blocking any erosion.

Some of the papers summarising experiences of hydraulic fracture of clay cores and ways in which the likelihood of hydraulic fracture may be predicted include (in order of date of publication)

Author	Date	Title, publication	Remarks
Vaughan et al	1970	Cracking and erosion of the rolled clay core of Balderhead dam and the remedial works adopted for its repair	
Sherard	1986	Hydraulic fracturing in embankment dams. ASCE J Geotech Eng 112(10)	Many dams experience hydraulic fracture, but self heal due to swelling of core

In addition it is now recognised that in certain circumstances hydraulic fracture can occur in watertight elements other than clay e.g.. Brown & Bruggemann, 2002.

4.6.2.2 Features of hydraulic fracture

Reservoir water pressure induces hydro-fracture and contributes to crack and fissure stability. Indicators of hydraulic fracture are

- a sudden development of flow when the crack forms at some depth below water level ;
- probably, a sudden sealing when the reservoir level is dropped a short way. The latter is because a crack shuts as the pressure is reduced. The crack may still be well below the water level. The drawdown level at which leakage stops is not an indicator of the level of the leak.

The interaction of gravitational stress and reservoir seepage pressure is complex. Total stresses within a dam before impounding are often less than the eventual seepage pressure. Thus there is a potential for hydro-fracture. However, as impounding occurs and effective stresses change, the minimum stresses increase to values higher than seepage pressures and cracking does not occur. This may only be true of a thin zone on the upstream side of a core (Vaughan, 1987; Dounias *et al*, 1989 & 1996). The opposite occurs if pore pressures are high at the end of construction and decay by consolidation during and after impounding. Total stresses decrease with the decreasing pore pressure (Prentice, Fletcher &Tedd 1996). The margin against hydrofracture in the body of the embankment is unnervingly small, but it cannot be increased and it seems to be sufficient in the vast majority of dams.

The cause of hydrofracture seems to be local zones of low stress caused by, for instance, arching of a narrow core or steep steps in an abutment, etc. Stress analysis has shown that the narrow puddle filled cut-off trenches used in early dams, which were significantly narrower that the cores themselves, would have been particularly prone to cracking by hydraulic fracture. Note that the trenches were often in fissured rock. While fissured rocks are very poor filters (Vaughan, 2000b), they are generally non-erodible. Thus leakage through a crack in puddle cannot increase and cause a rapid failure. A slow loss of puddle leading to settlement will occur.

Sensitivity to the risk of hydrofracture can be assessed from geometry (the narrowness of the core, the presence of a puddle filled trench, the evenness of the longitudinal profile) backed by stress analysis.

Repairs can be a source of cracking. They can cause stress changes which create a risk of potential hydro-fracture. If a repair offers a seepage path through the dam, some form of filter drainage protection is best added with the repair to ensure self-sealing. Reliance on backfilling and compaction alone is unwise.

The same applies to significant changes to a dam such as raising. Extension upward of an old puddle core will involve a width to height ratio more slender than was adopted in the 19th century after the failures of the Bilberry and Dale Dyke dams and generally found satisfactory.

4.6.2.3 Near surface effects

Points relating to the potential for occurrence of hydraulic fracture just below the maximum retention level (MRL) of the reservoir include

a) the UK dam industry consider that the majority of incidents (82%) had an intake to the erosion path within one metre of MRL (Q17 of questionnaire). It is accepted that this may be based on the evidence that the leak stopped when the reservoir was lowered by this amount; however for some of the dams remedial works would have been limited to the upper part of the dam with the fact that this remedied the leak suggesting that for some of the dams the leak was indeed at this elevation.

b) Fell (personal comm., 2003) considers that in some dams there is evidence, in the form of wet seams just below MRL, that there was saturation settlement of the clay on first filling, leaving a zone of low stress at MRL

c) Dornstadter (1997) presents data showing that at 3m and 5m depth in a dam the seasonal variation in temperature is typically 10 °C and 3°C (for surface variation of 20°C). This is likely to generate horizontal strains which may be sufficient to lead to an increased risk of hydraulic fracture in winter (and or hydraulic separation by structures); the table below showing reported values for the coefficient of thermal expansion (the thermal stress strain behaviour will be complicated, relating to both saturated and unsaturated behaviour)

	Linear coefficient of thermal expansion x 10^{-6}/ °C	Source
Concrete	10-13	Dunnicliffe, 1988; Table 14.1
Mild steel	11.7	
Invar	1.4	
Brick masonry	6	Dunnicliffe, 1988
(unsaturated) Bentonitic clay	300	Page 685 of Thomas & He (1995); quoted as coming from Ohnishi et al, 1987
Water	600	Cooke, 1987

d) In hot weather evaporation and transpiration from the surface of the dam will cause moisture content changes to some depth, which will in the extreme cause shrinkage cracks

Understanding soil behaviour in the upper few metres of the dam is complex. It is understood that insitu measurements by BRE generally commenced at 5m depth, and as the measurements were on reservoirs with significant annual variation in water level this would have masked any seasonal changes in internal stresses.

4.6.2.4 Homogenous dams

Homogenous dams should be less susceptible to hydraulic fracture, due to the flatter slopes giving higher stresses in the body of the embankment. However, if an apparently homogeneous dam has strong layering, this could cause problems. A thin permeable layer along which impounding pore pressures penetrate preferentially can promote hydraulic fracture. A pressure sufficient to cause fracture may be introduced in the crack. If impounding is sufficiently rapid for this to happen without general adjustment of the seepage pressures in the embankment centre to the new water level, increase of total stress in response to this will not occur and the cracking pressure will be lower. The effect of layering is likely to be worst at first impounding, or when impounding is more rapid than previously.

4.6.2.5 Summary

Currently there are a variety of views on the prevalence and mechanism of internal erosion. In particular consideration of seasonal thermal strains in the upper part of the body of the embankment may provide a valuable increase in the understanding of mechanisms and if valid suggests that in terms of season the most vulnerable time for hydraulic fracture in the upper part of an embankment is late winter.

However, the conclusions by Sherard (1986) as reproduced below are still considered valid:
"concentrated leaks occur commonly throughout the impervious sections of embankment dams by hydraulic fracture without being observed…usually these concentrated leaks do not cause erosion, either because the velocity is too low or because the leak discharges into an effective filter. Subsequently the leakage channel is squeezed shut by swelling or softening of the embankment material forming the walls of the crack. In the typical case no measurable leakage emerges downstream, and there is no other indication that a concentrated leak developed and was subsequently sealed. This action probably occurs to some degree in most embankment dams".

4.6.3 Initiation of internal erosion

For simplicity this is covered with progression, as the conditions for both are similar, and best considered after the review of conditions for Continuation

4.6.4 Continuation

Constraints on whether internal erosion continues once initiated, or whether it ceases, are

a) whether the materials downstream of the impervious element (base soil) will act as a filter to the eroded material.
b) whether material from the upstream shoulder is washed in and blocks the erosion path
c) the reservoir is lowered, such that the erosion path closes under the reduced reservoir load

In this section only the first of these is considered. The main reference on filter design splits the base soil into four different types, as shown in Table 4.9.

Table 4.9 : US SCS Criteria for filters (1986)

Base soil category	Base soil description		Filter criteria D – Filter d – base soil**
		% finer than 0.075mm*	
1	Fine silts and clays	>85%	$D_{15} \leq 9\ d_{85}$ (but 0.2mm min)
2	Sands, silts, clays	40 – 85%	$D_{15} \leq$ 0.7mm
3	Silty and clayey sands and gravels	15 - 39%	$D_{15} \leq$ (40-A)/(40-15) x ($4d_{85}$ -0.7mm) + 0.7mm
4	Sands and gravels	<15%	$D_{15} \leq 4\ d_{85}$

*after adjustment to be 100% passing 4.75mm sieve
**for base soils 1 to 3 adjusted to be 100% passing 4.75mm sieve
Filters are to have a maximum size of 75mm (to avoid segregation) and a maximum of 5% passing the 0.075mm sieve with the plasticity index of the fines equal to zero (to ensure the filter is non-cohesive i.e. will collapse to fill any cracks)

Vaughan (1982) suggests that the boundary of effective filtration is better defined by permeability, with a "perfect" filter being defined such that its permeability $k = 6.1 \times 10^{-6}\ \delta^{1.42}$ in which k is in m/s and δ is in µm; with δ being the diameter of the smallest particle that can arise due to erosion. He argues (2000) that in general adoption of the SCS criteria (the "critical filter") is less conservative than the perfect filter, particularly for sandy clays, but that "in plastic clays the critical filter may be finer than the perfect filter, a paradox since the perfect filter is based on a worst credible design approach".

With broadly graded soils it is not sufficient to consider only the d_{85} of the base soil, but also to consider whether finer fractions could be eroded leaving behind the coarser particles. Quantitative guidance is given in Lafleur (1987) and Kenny and Lau (1985).

It is unknown whether the subdivision of soil into groups relevant to filter design would be directly relevant to initiation and progression of internal erosion, although similar forms of grouping would be expected to apply.

4.6.5 Progression (and initiation) of internal erosion

4.6.5.1 General

There is little published data on the initiating conditions for (and rate of progression of) internal erosion once a pathway has been formed.

4.6.5.2 Wan et al, 2002

The only directly relevant paper is a report on laboratory tests in Australia by Wan et al (2002); the tests being as follow:-

	Erosion test	
	Slot	Hole
Laboratory sample	2.2mm wide x 10mm deep x 1m long slot inside a 0.15m wide x 0.1m deep x 1m long rigid sample box	6mm diameter hole in "standard compaction mould"
Head on inlet, outlet	2500mm, 300mm	Variable 50-800mm; 100mm

Three parameters were defined,

a) the "Coefficient of Soil erosion" C_e, where $\varepsilon_t = C_e\ (\tau_t - \tau_c)$

b) the "Erosion rate index" I, where $I = -\log (C_e)$, and subscripts SET and HET indicates that the value is determined from the Slot and Hole Erosion tests respectively

c) the "Critical Shear Stress", τ_c , taken by the authors as the hydraulic shear stress corresponding to the minimum head at which erosion is first initiated (rather than extrapolating the plot of erosion rate vs. shear stress back to zero shear stress)

where

ε_t is the rate of erosion per unit surface area of slot/ hole at time t (kg/s/m^2)

τ_t is the hydraulic shear stress along the slot at time t (N/m^2)

I varies from less than 2 (extremely rapid erosion) to greater than 6 (extremely slow erosion). A total of 157 tests were carried out on 13 different Australian and American soil types; with predictive equations for coarse and fine grained soils.

It was shown that τ_c tends to increase with Erosion rate index; figure 3 of the paper showing it going from zero at I_{HET} of 2 to about 150kPa at I_{HET} of 6. These are comparable with recommended permissible unit tractive forces for canals given in Figures 7.10 and 7.11 of Chow (1986), which vary from 1.4 to 90kPa.

These equations are given in Table 4.10, together with an application of the test values to some typical UK soils. A sensitivity analysis of how the leakage rate, shear stress on the walls of the crack and rate of erosion varies with I_{HET} and size of hole is presented on Figures 4.10 and 4.11. This confirms that the rate of erosion spans over several orders of magnitude

It is noted that although the list of soils used (table 2 of paper) show two glacial tills (SM) the equations appear inappropriate for UK cohesive glacial tills, as the Balderhead core is shown as extremely resistant to erosion.

Data is also available from the research report (Wan & Fell, 2002), obtainable from the University of NSW in Australia, with some results summarised in Appendix B. This includes that of the 13 soils tested, fine grained soils (clays) generally have an Erosion Rate Index of 3 or greater, whilst the coarse grained soils (clayey sands) have an Erosion Rate Index of 3 or lower.

The sensitivity study considers the variation in the following to the width of a 1m high 3m long crack under 10m average reservoir head:-

Effect of width of crack on	Basis of estimate *(Equation)*	Results plotted on Figure	Comments
Leakage flow	a) Reynolds number < 2000: Laminar flow between parallel plates; $u = gSc^2/12\mu$ *(Eqn 6.21 of Massey, 1989)* b) >2000 as turbulent flow. $u^2 = 2mgS/f$; *(Eqn. 7.2 of Massey, 1989)* with f of 0.02; plus inlet/exit losses of 2.0 $v^2/2g$	4.10	
Average shear stress on sides of crack	$\tau = g\ m\ S$; *Eqn 3.3 of Wan and Fell, 2002b*	4.10	This is average shear stress. Actual shear will vary with position.
Erosion Rate	$\varepsilon = C_e (\tau_t - \tau_c)$ *Equation 1 of Wan et al, 2002a*	4.11a to 4.11c	Each increment of one in Erosion Rate Index, I, corresponds to increase in 10 of erosion rate
Turbidity of leakage flow	Suspended solids i.e. erosion rate/ leakage rate	4.11d	

where

b	crack length
c	crack width
C_e	Coefficient of soil erosion
f	friction factor (coefficient)
g	weight per unit mass of water
I	Erosion Rate Index (=-log(C_e))
m	hydraulic mean depth (area/ wetted perimeter)
S	hydraulic slope (Friction head/ crack length).
u	mean velocity
γ_w	unit weight of water
τ_c	Hydraulic shear stress along crack (subscript c denotes critical shear stress i.e. initiation of erosion)
μ	Absolute viscosity of water (10^{-3} Pa s; table page 4 of Massey, 1989))

Observations on the results of this sensitivity study are:

Figure	Contents	Observations
4.10	Crack width vs. • Leakage flow rate, • shear stress vs.	a) flow is laminar for cracks less than about 0.6mm, and turbulent for wider cracks b) For crack width varying by three orders of magnitude, the leakage flow rate varies by five orders of magnitude (from minimum detectable, to "Dam critical leakage flow"; and shear stress by four orders of magnitude)
4.11a-4.11c	Crack width vs. Erosion rate for six values of Erosion Rate Index I	a) Although the relationships plot broadly as a straight line on linear axes, when six values of I are superimposed and plotted together on log-log paper to allow comparison there is a kink at low erosion (as a consequence of plotting on log-log paper) b) The crack width for the onset of erosion varies from 0.3 to 9 mm (corresponding to leakage flow of 0.1 to 20l/s) c) Rate of erosion for a given, significant, crack width varies by five orders of magnitude depending on Erosion Rate Index. d) If $5m^3$ (10,000kg) taken as critical volume of erosion, then for a 20mm wide crack the time period to reach this cumulative erosion varies from 1 day to 200,000 days (500 years) (or for a clay core, with Erosion Index of 3 to 6 it varies from 1000 days to 500 years)
4.11d	Crack width vs. turbidity	Turbidity for Soil Index 4 to 6 would not be visible by the human eye; that for Soil Erosion Rate Index 6 would be very dirty.

The conclusions are

a) the model postulated by Wan & Fell appears reasonable, although it is questioned whether the erosion rate really has such wide variation (the argument put forward by Fell is that permeability of soils has a similar wide range in value, such that the results are reasonable)

b) the critical shear stress concept implies that there is leakage flow with no erosion, when the shear stress is less than the critical shear stress, which is reasonable for more plastic soils

c) the time period for a critical volume of erosion has enormous range consistent with the results from the questionnaire and elicitation; however, in reality the time to failure will depend on the overall system response (i.e. shoulders as well as core), such that the sensitivity values are an upper bound and may be constrained (reduced) by the effect of the shoulders.

Table 4.10 :Predictive equations from Wan et al (2002) for Erosion rate Index

Parameter			I_{HET} = (Base + S factor x value of parameter at subject dam)		Application to typical UK soils															
Symbol	Units		Coarse grained (SC, SM)	Fine grained (CL, ML, CH)	Coarse grained (SC, SM)								Fine grained (CL, ML, CH)							
					Glacial Till Balderhead; Kennard et al, 1967, Vaughan et al. 1970		Credible of parameter		range of correction		Diff	Remarks	London Clay Atkinson et al, 1990		Glacial Till Balderhead; Kennard et al, 1967, Vaughan et al, 1970		range of correction		Diff	Remarks
					Parameter	Value							Parameter	Value	Parameter	Value				
Base			6.623	-10.201		6.623								-10.20		-10.20				
r_d	Mg/m^3	Dry density of soil	-0.016	9.572	1.99	-0.03	1.7	2	-0.03	-0.03	0.00		1.63	15.61	1.99	19.05	182.33	1745.26	1562.93	
r_d/r_{dmax}	%	Compaction relative to proctor	-0.104	-0.042	102	-10.61	80	110	-8.32	-11.44	-3.12	why more erodible if denser?	95	-3.99	102	-4.28	0.18	-0.01	-0.19	
w	%	Water content	-0.044	0.103	12	-0.53	10	20	-0.44	-0.88	-0.44	small	20	2.06	12	1.24	0.13	0.01	-0.11	
Dw_f	%	(w - OMC)/OMC x 100%	-0.074	0.0097	-20	1.48	-15	15	1.11	-1.11	-2.22		1	0.01	-20	-0.19	0.00	0.00	0.00	Negligible
S	%	Degree of saturation	0.113	Not app.	80	9.04	70	#####	7.91	11.30	3.39		-	-	-		-	-	-	
Clay (US)	%	Mass fraction finer than 0.005mm	0.061	0.042	30	1.83	5	50	0.31	3.05	2.75		42	1.76	30	1.26	0.05	0.00	-0.05	
Fines	%	Fines content (<0.075mm)	Not app	-0.0056	-	-	-	-	-	-	-		85	-0.48	45	-0.25	0.00	0.00	0.00	Small
LL	%	Liquid Limit	Not app	-0.09	-	-	-	-	-	-	-		70	-6.30	25	-2.25	0.20	-0.02	-0.22	
I_p	%	Plasticity Index	Not app	0.111	-	-	-	-	-	-	-		45	5.00	12	1.33	0.15	0.02	-0.13	
Pinhole	Integer	Pinhole test classification expressed as an ordinal number i.e. '1' for Class D1, '2' for D2, '3' for Class PD1,…, '6' for Class ND1	Not app	0.443	-	-	-	-	-	-	-		5	2.22	5	2.22	0.98	0.43	-0.55	
					I_{HET}	7.81								5.69		7.91				

4.6.5.3 Questionnaire and elicitation : rate of deterioration and time to failure

No other references which have been identified which quantify initiating conditions for (and the rate of progression of) internal erosion once a pathway has been formed. The main source of data is therefore the information from the questionnaire and expert elicitation; summarised as follows:-

	Questionnaire		Elicitation
	Figures	Q (see commentary in Appendix=x C)	
timing and magnitude of leakage at different stages in incident case histories	4.12, 4.13	23, 24, 27b	Not app
Effect of soil properties on rate of deterioration	4.14- 4.15	29 to 39	Table 4.11, 4.13 Fig 4.22- 4.24
Rates of erosion	Not app		Fig 4.18
Time to failure, if no intervention	4.20, 4.21		As Questionnaire
Prior warning	None	45 to 48	

Table 4.11 : Outcome from Expert Elicitation of effect of material properties of core on time to failure of puddle clay dams

Q	Base case, and change	Ratio of best estimate of change in time to failure (>1 means dam will fail quicker than base case)	Figure
	Core material : Base case is CH		4.22
49	CL	1.4	
50	ML	2.0	
51	CV	0.96	
52	SC	1.7	
53	GW	2.5	
	Gradient: Base case 1.0		4.23
47	2.5	3.2	
48	5.0	8.6	
	Compaction: Base case 98%		4.23
54	90%	1.5	
55	80%	2.3	

It can be seen that rates of deterioration appear to be very variable. However, it is noted from Q27 of the questionnaire that incidents involving internal erosion into or along appurtenant works appear to have a greater proportion of incidents which were likely to lead to a rapid failure.

4.6.6 Breach mechanisms

Figure 4.9 shows some of the failure mechanisms that are possible, depending on the characteristics of the different zones forming the embankment dam.

Some of these mechanisms are likely to be predominantly rapid “progressive” failures, whilst other mechanisms would be slower, corresponding to “steady erosion”.

Table 4.12 : Failure mechanisms likely to lead to progressive internal erosion

Type of fill forming shoulder	Failure mode			
	Downstream shoulder		Upstream shoulder	
	Progressive	Steady	Progressive	Steady
Cohesive	5	7, 8	1	
Non-cohesive	9, 10	6	4	2, 3

The key issues which are likely to govern which mechanism is most likely to occur at a dam are

a) whether the downstream shoulder fill is non-cohesive, such that it could not sustain a open crack
b) the permeability of the downstream fill

At this stage there is no conclusive data available on which mechanisms are most likely to govern at a particular dam, although the importance of understanding the whole system of core and shoulders should not be underestimated. The magnitude of leakage flow which is considered that could no longer be controlled (dam critical flow) is shown on Figure 4.19, including both the response to Q27b of the questionnaire and the result of the expert elicitation.

Table 4.13 : Outcome from Expert Elicitation of effect of material properties of shoulders on time to failure of puddle clay dams

Q	Base case, and change	Ratio of best estimate of change in time to failure (>1 means dam will fail quicker than base case)
	Upstream shoulder: Base case CL	
56	SC	1.6
57	Rockfill	5.9
	Downstream shoulder: Base case CL	
72	SC	1.7
73	Glacial till	1.4
74	Coarse gravel (London embankments)	2.2

Notes
1. Shown graphically on Figure 4.24

4.7 Quantification of Suffusion and Piping

4.7.1 Suffusion

Although in principle only broadly graded cores should be susceptible to suffusion, it is noted that the following may be vulnerable to suffusion

a) downstream shoulder material of clay core dams, as a secondary effect of concentrated leakage through the core
b) foundation (particularly where there is no positive foundation cut-off)

An important point is that internal erosion by suffusion is less likely to lead to progressive (rapid) failure, than concentred leaks or piping. The expert elicitation estimate of the proportion of internal erosion that is due to suffusion is shown on Figures 4.5 and 4.6.

Skempton & Brogan (1994) describe laboratory tests on internally unstable sandy gravels, which show that a significant proportion of the sand content is washed out by piping at hydraulic gradients far lower than the critical gradient given by classical theory. By contrast piping of the sand from stable sandy gravels occurs at approximately the full theoretical gradient. The tests were considered to broadly confirm Kenny's criterion for the internal stability of granular materials.

Blackwell et al (1995) in a paper on particulate damage to groundwater wells note that for particle migration it is necessary to both have particles fine enough to go through the well filter and a certain minimum velocity of flow (pS157). They quote a paper where the velocity required to mobilise particles with porosity in the range 0.26 to 0.35 and hydraulic conductivity from 1 to 4.5cm/s such that

$$V = 0.098K^{0.356}$$

where V and permeability K are expressed in cm/s. For the range of permeabilities for which the expression was derived the critical velocity is in the range 0.019 to 0.033cm/s

4.7.2 Piping

Careful consideration of allowable and actual seepage gradients to structures on permeable foundations are required. Piping will occur at the downstream toe when the porewater uplift pressures at a point are greater than the total vertical stress at that point. The subject of piping and internal erosion are covered in textbooks such as Cedegren (1989). Papers also include

- Removal of head limitation on Kotri barrage, Pakistan (Elliot, 1994)
- Mathematical analysis for piping in pervious foundations (Yener, 1994)

Preliminary methods of analysis of foundation seepage include Lane's weighted creep theory (USBR, 1973, 2nd edition, but deleted from third edition) and Blighs theory (reproduced in Maccaferri, 1987). These give, respectively, an allowable gradient and weighted creep ratio to control seepage and prevent piping; these values being summarised in Table 4.14. However, no means of estimating the rate of progression of piping, from initiation to failure, have been identified.

Table 4.14 : Published allowable Seepage Gradient to prevent piping

Soil type	Limiting value of coefficient C in Bligh's theory (Maccaferri, 1987)	Limiting value of Lane's weighted creep ratio[1] (USBR, 1973)
Fine sand or silt	18	8.5
Medium sand	12	6.0
Medium gravel	4 to 9	3.5
Boulders with some cobbles and gravel	Not given	2.5
Very hard clay or hardpan	3 to 6	1.6

1. Ratio of head to sum of vertical seepage length plus one third horizontal seepage length

4.8 Unprotected pipes and culverts through embankments

Internal erosion may occur

a) along the outside of the pipe or culvert
b) into the pipe or culvert, through gaps in the wall

The general comments on internal erosion in the previous section are also applicable to 'a'. The only difference is that the size of any aperture due to hydraulic separation may be different (larger in critical situations) from that of apertures in the body of the dam.

In regard to 'b' the key issues are

- whether such gaps may already exist e.g. for the reasons in Table 2.5
- credible mechanisms for new gaps to occur in future (e.g. differential settlement along the pipe or culvert; for example due to erosion of fines from under the culvert due to flow along the outside of the culvert)
- whether any gap would act as a filter to the adjacent fill
- whether the gap could enlarge, or whether it would act as a choke to the volume of leakage and thus the rate of deterioration

In regard to pipes through embankments cast iron has a finite life (Doyle, Seica & Grabinsky, 2003) and soil conditions can encourage corrosion from the outside.

There is little published on 'b' and it is something that requires further consideration, but on a dam specific basis. Where gaps already exist then lining the inside of the pipe or culvert may be an effective way of reducing the risk of internal erosion at this location.

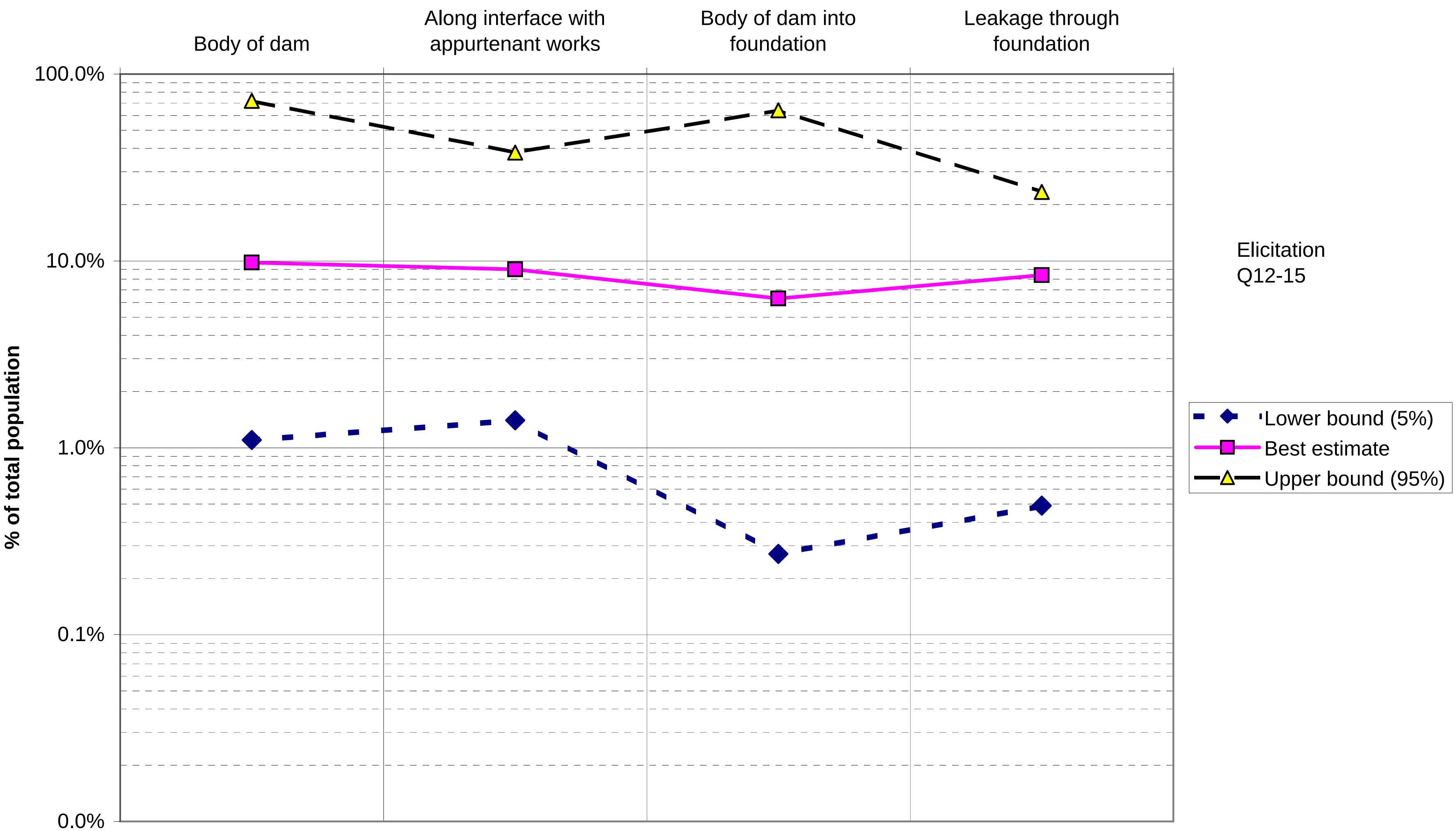
4.9 Conclusions

The understanding of internal erosion processes is still immature; with quantitative methods only available for limited elements of the internal erosion process. Although internal erosion is the subject of one of the working groups of the European Club (Charles, 1998) to date this has largely collected data. The most relevant recent work is that in Australia, both in developing models of internal erosion and laboratory testing of the rate of erosion, with this section drawing significantly on this work.

On the data available at present key conclusions are

a) leakage may occur without internal erosion
b) the rate of deterioration due to internal erosion can be very variable, depending on both the erodibility of the clay, and the properties of the adjacent shoulders
c) In particular some dams may in principle be "intrinsically safe", in that the rate of deterioration of a typical section would be slow ("steady internal erosion"), whilst at other dams once internal erosion commenced the rate of erosion would increase rapidly ("progressive internal erosion")
d) notwithstanding this the importance of "singularities" should not be underestimated, and means that it is unlikely that dams without filters can with complete confidence be considered "intrinsically safe"
e) similarly there are a significant number of additional uncertainties over detailing where a pipe or culvert passes through the embankment, and thus the risk associated with these structures
f) the assessment and management of internal erosion has to be based on experience of performance and observations, in parallel with improving models of progressive internal erosion

Figure 4.1- Percentage of puddle clay dams with ongoing, steady leakage flow



Elicitation
Q12-15

Figure 4.2 - Percentage of homogenous dams with ongoing, steady leakage flow

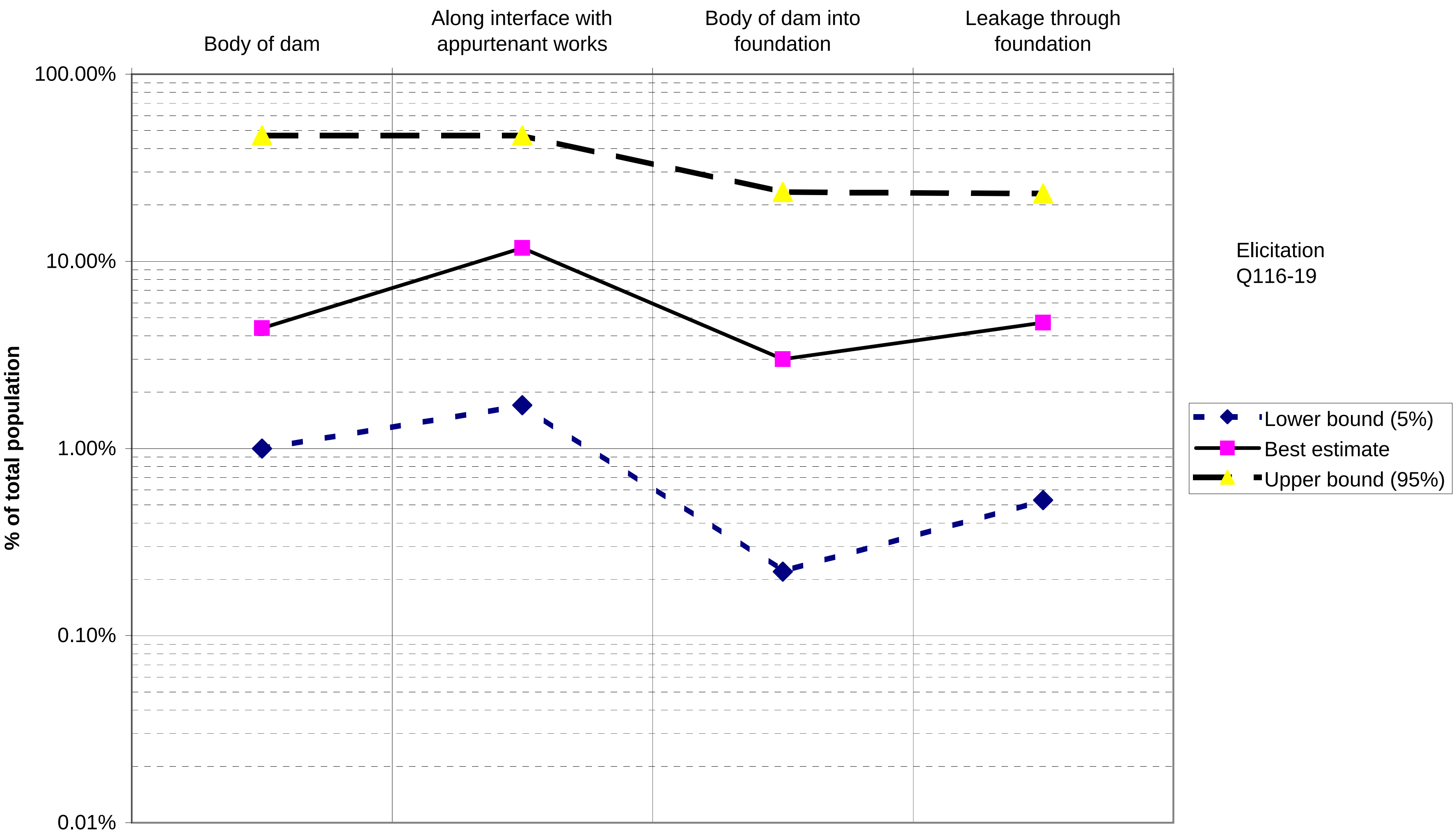


Figure 4.3 - For puddle clay dams with ongoing, steady leakage flow; percentage with ongoing internal erosion

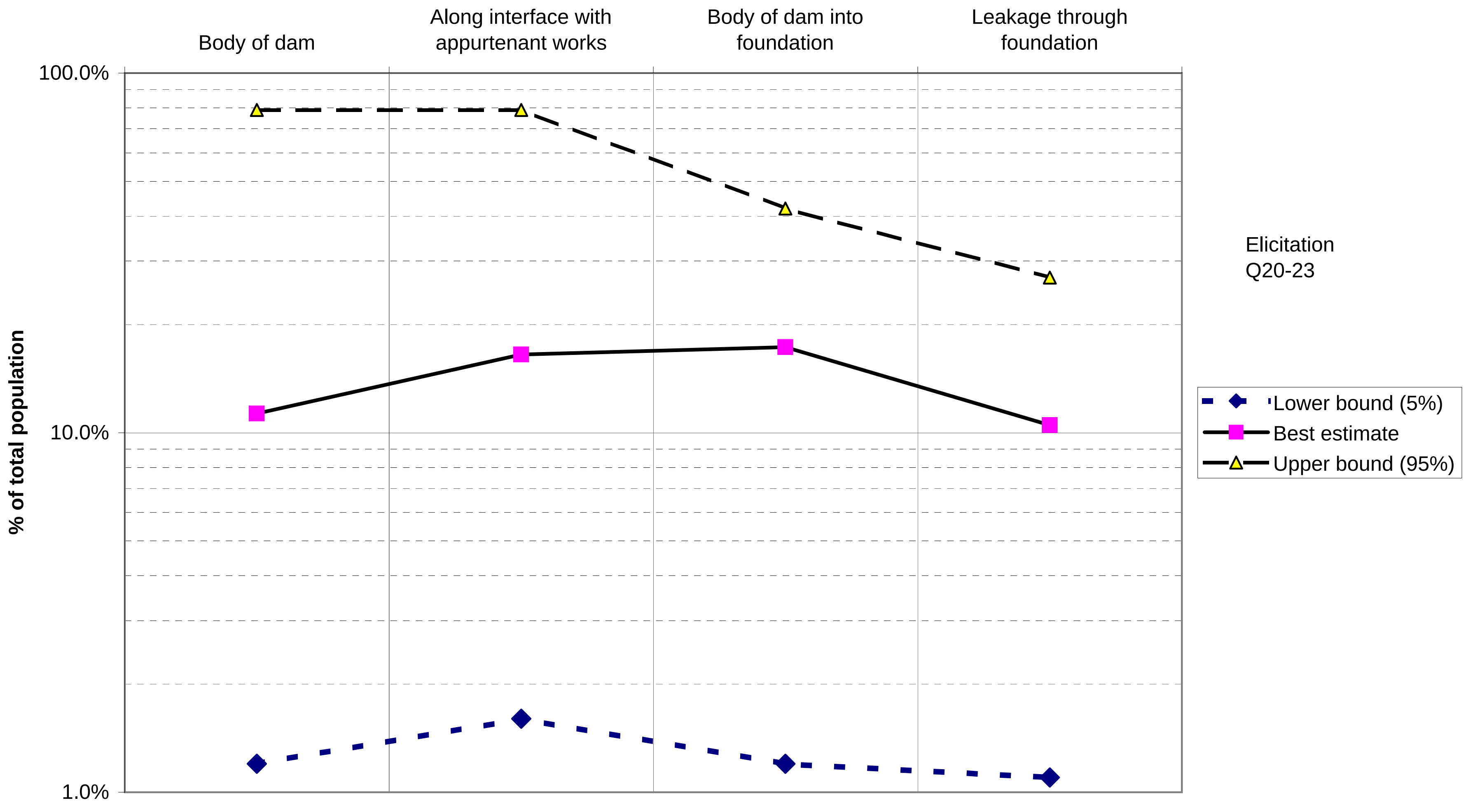


Figure 4.4 - For homogenous dams with ongoing, steady leakage flow; percentage with ongoing internal erosion

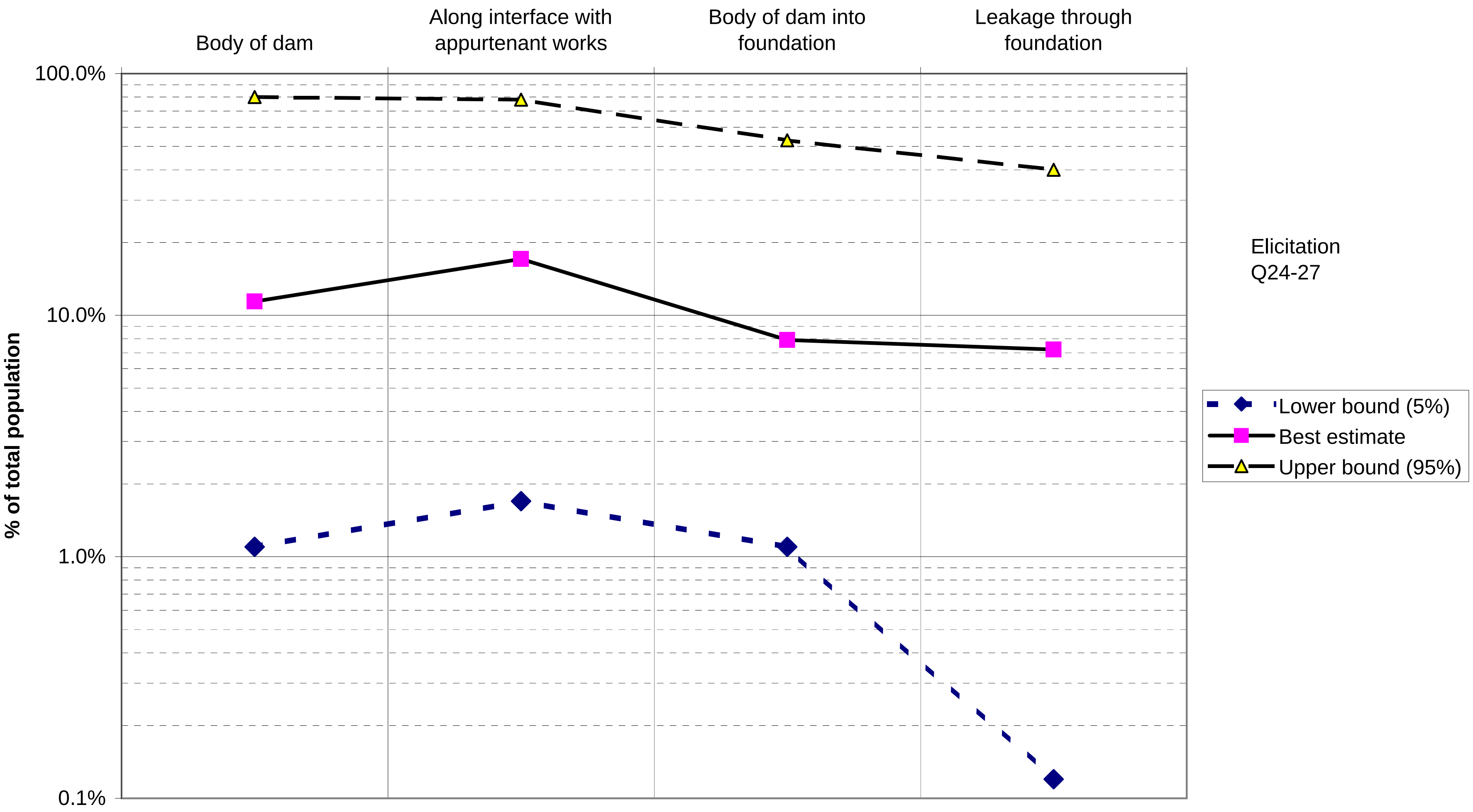
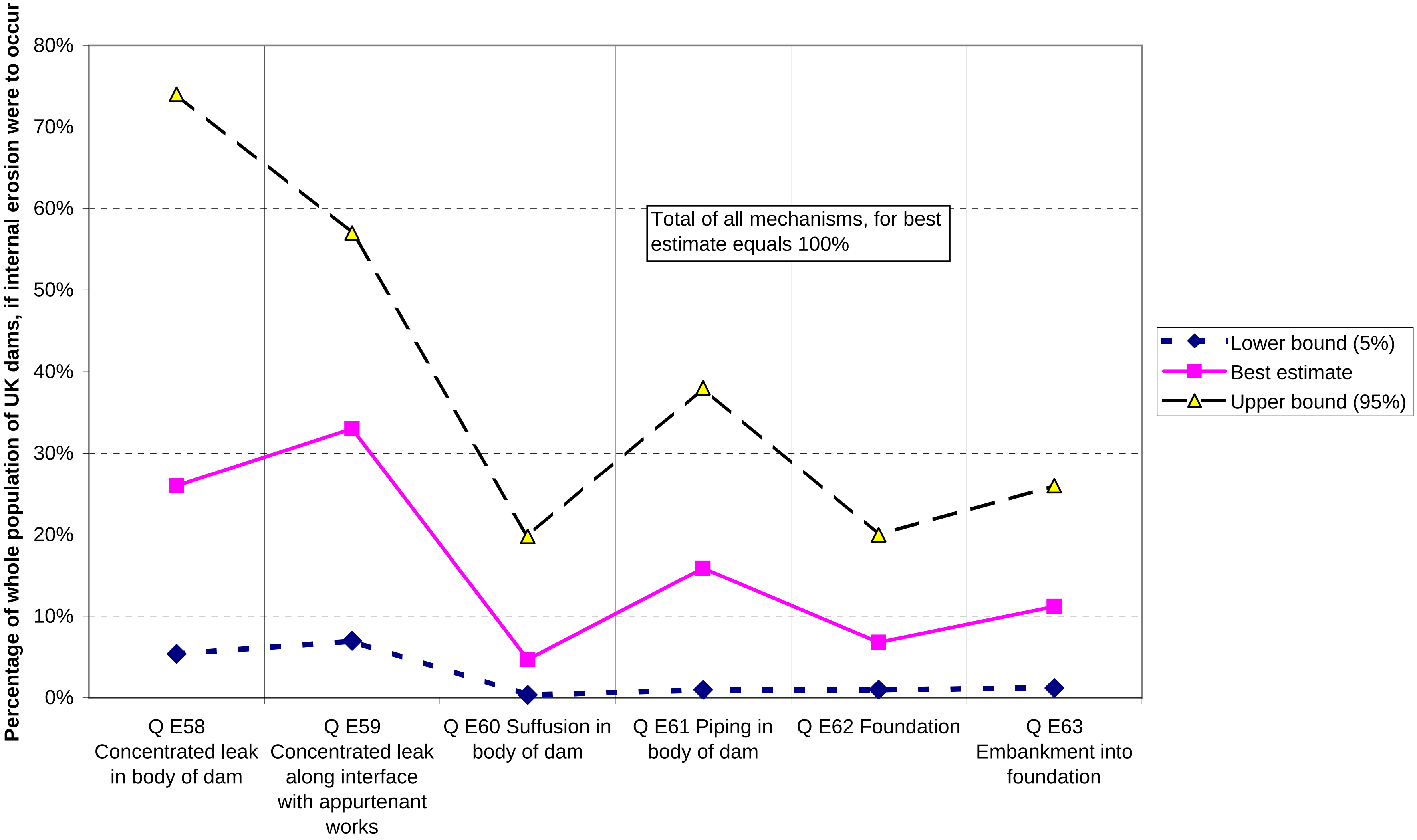


Figure 4.5 - Percentage split into different mechanisms for puddle clay dam



Total of all mechanisms, for best estimate equals 100%

Figure 4.6 - Percentage split into different mechanisms for homogenous dams

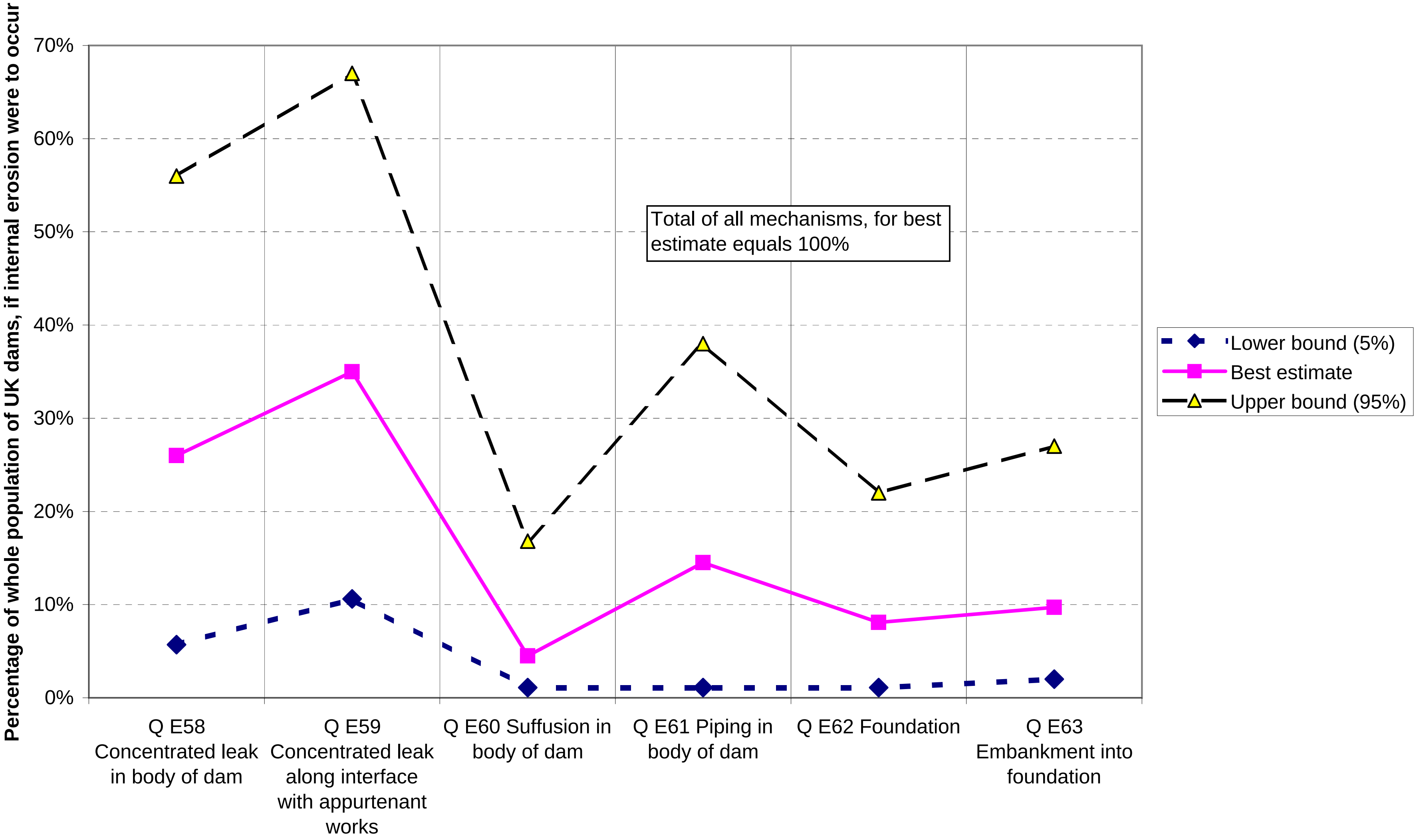

Total of all mechanisms, for best estimate equals 100%

Figure 4.7 Internal erosion : Event train for Internal Instability of an embankment in service

NB: Different event trains would apply for appurtenant works and dams < 5 years old

Stage in Event train

Contributory factors

Intrinsic Condition	***Other***
Narrow core	Reservoir level
Profile of foundation (differential settlement)	Rapid changes
Relative stiffness of shoulder material	Refilling after long drawdown
Permeability/ stiffness of fill	Usually high
Preferential flow paths due to defect in original construction e.g. sand lenses mixed into clay fill	

Mechanism of deterioration (response to threat)

Process for internal erosion

Suffusion - fines	Concentrated leaks - fines	Piping (exit gradient > critical) - mass instability

1. Initiation of pathway

Suffusion - fines	Concentrated leaks - fines	Piping (exit gradient > critical) - mass instability
High gradient	Hydraulic fracture (in body of dam) Hydraulic separation (at appurtenant works, abutments)	High gradient

2. Initiation of Internal erosion (movement of soil particles)

Suffusion - fines	Concentrated leaks - fines	Piping (exit gradient > critical) - mass instability
Loose fines not part of soil matrix	Erosion from sides, crown & invert of pathway	"Blow-out" of impervious layer in foundation
Fines which form part of soil matrix	Erosion at ends, as hole migrates upstream/ downstream	Piping in homogenous soils

Blockers of erosion path

Filters
Upstream shoulder washes in and acts as crack filler
Upstream/ downstream shoulder (or water retaining element) cannot sustain a pipe

3. Decision Point : Continuation (does internal erosion cease?)

Particle migration prevented at downstream constriction (filter, discontinuity width in rock foundation, crack width in structure)
Particle migration ceases at upstream end (concrete cut-off etc)

Hole collapses, stopping flow

No

Rate of erosion: Steady state or accelerating

Dispersive soils	Tortuosity of path
Degree of compaction and compaction moisture content	Reservoir level: - changes; unusually high
Reservoir water chemistry	
Hydraulic gradient across cut-off	

4. Mechanism of deterioration - Progression (see Figure 4.2)

Suffusion - fines	Concentrated leaks - fines	Piping (exit gradient > critical) - mass instability
a) if loose fines not part of the matrix - fines wash out, no settlement but increasing permeability gives increasing flow	Hole enlarges but cannot migrate upstream or downstream, arch forms, migrates to surface	As Concentrated leaks
b) if fines are part of soil matrix, reduction in soil volume, leading to concentrated leak	Hole migrates upstream (to reservoir) or downstream	As Concentrated leaks
	Filter eventually clogs as coarser material carried through	

Failure (breach) mode(s)

Downstream zone (Note 1) Crest width Freeboard	a) Gross enlargement of internal erosion path, including pipe b) Overtopping (due to reduced freeboard caused by sinkhole/ crest settlement) c) Slope instability, due to pore pressure increases on weak layer (and/ or saturation of downstream shoulder)

Suffusion - fines	Concentrated leaks - fines	Piping (exit gradient > critical) - mass instability
c only	all	*a, c*

Indicators (symptoms; see Note 2)

Stage	Leakage downstream	Internal pore pressures	Internal stress	Internal deformation	Surface Settlement
1. Initiation of pathway	Minor	Wet seam in core	Very local		
2. Initiation of Internal erosion	Minor Turbidity	very localised	Minor	Minor	Negligible
4. Mechanism of deterioration - Progression	Increasing discharge, turbidity	Void commences	Minor	Very local to void	Sometimes medium (but delayed)
Failure (breach) mode(s)	Major discharge, turbidity	Medium range of influence	Minor	Medium	

Notes

1. Can it support a roof? How erodible? Flow capacity vs. through flow due to internal erosion
2. Other mechanisms of deterioration of dam that may affect indicators
    - Settlement e.g. Collapse on saturation
    - Long term changes in pore pressure distribution due to changes in reservoir levels (reservoir operation)
    - Mining under dam
    - Leaching/ precipitation by reservoir water
    - Deterioration of water tight element (where formed by materials other than soil)
    - Tree roots
    - Animal activity (moles, rabbits)

Figure 4.8 Time based model of Progressing Internal Erosion

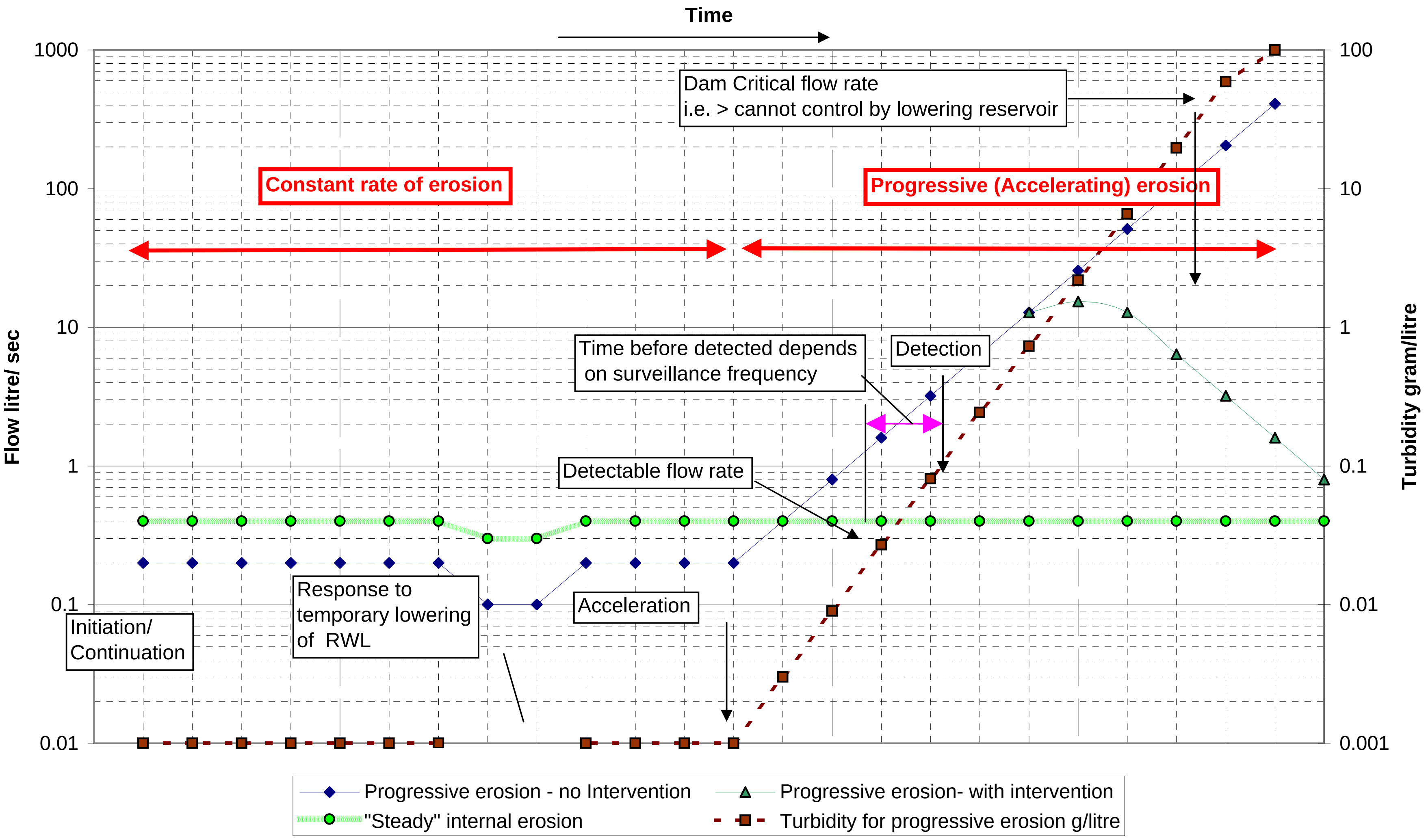
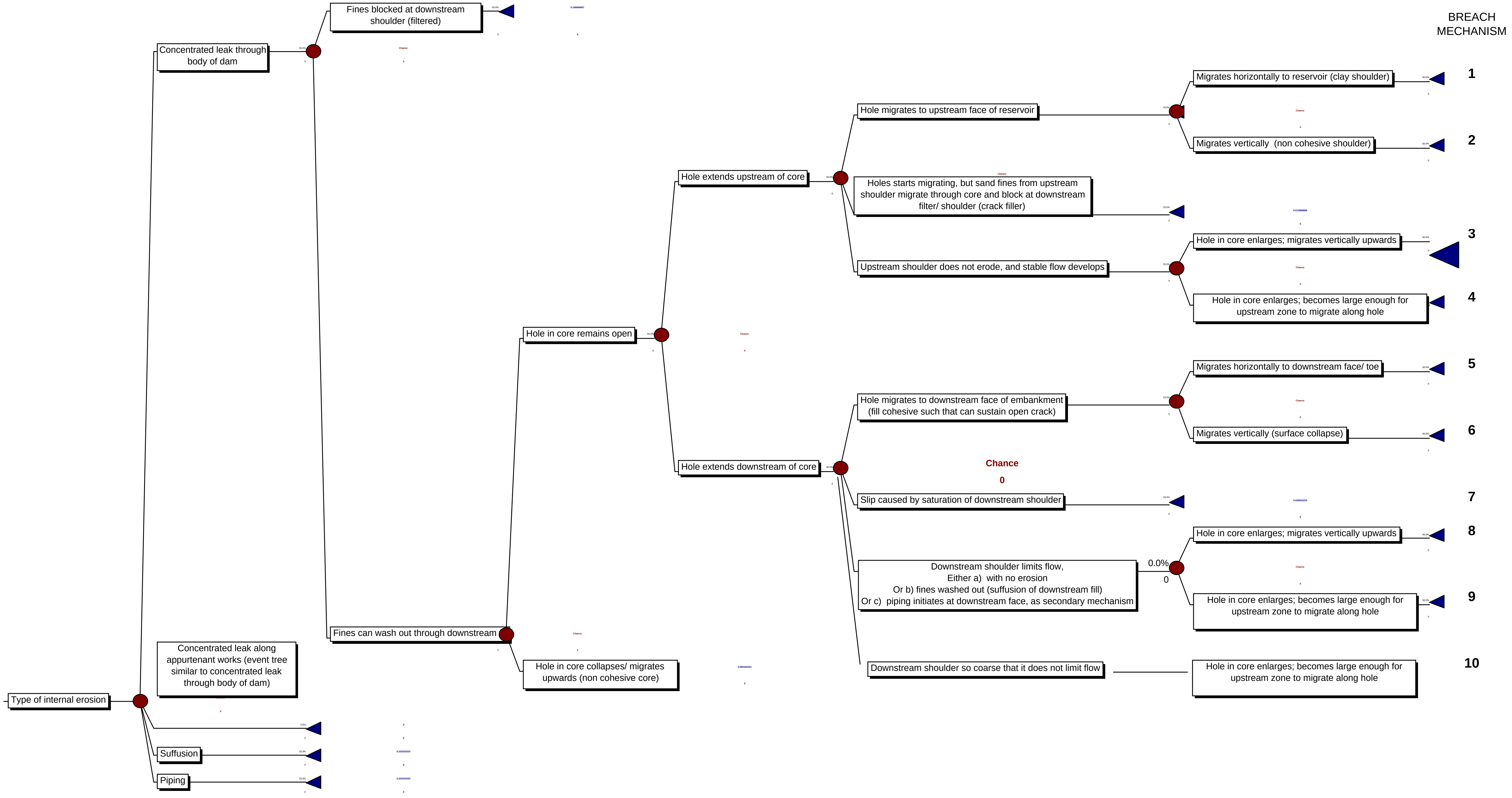


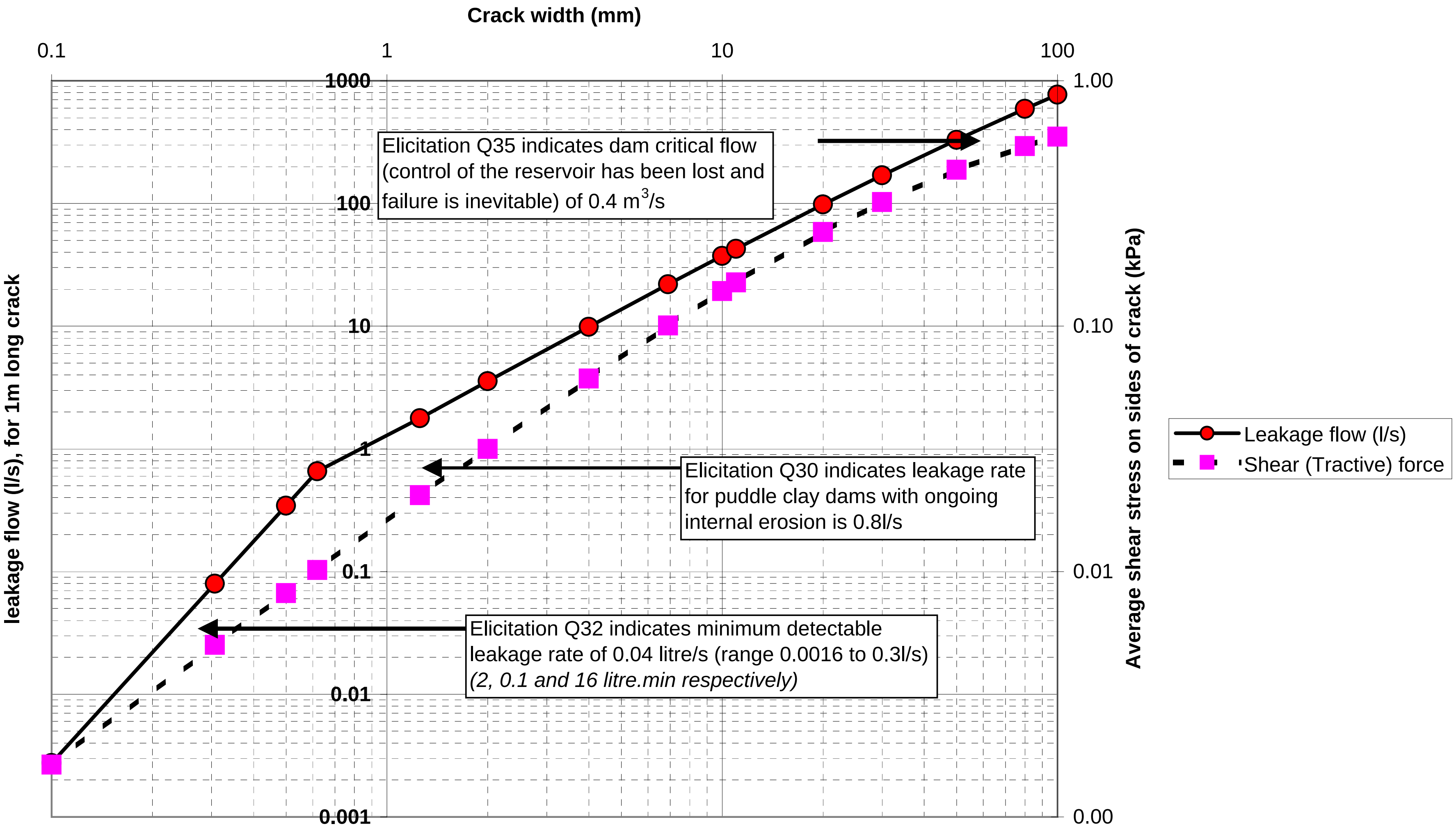
Diagram #1

Figure 4.9 Event tree for progression of Internal erosion within an embankment dam



Notes
1 Progression may depend on rate e.g. short term vs. long term strength (drained vs. undrained strength)
2 separate trees for foundation; embankment into foundation
3 Likelihood of each path at some of chance nodes will depend on type of embankment dam and/ or appurtenant works

Figure 4.10 : Effect of crack width on Leakage flow and average shear stress on sides of crack



Elicitation Q35 indicates dam critical flow (control of the reservoir has been lost and failure is inevitable) of 0.4 m^3/s

Elicitation Q30 indicates leakage rate for puddle clay dams with ongoing internal erosion is 0.8l/s

Elicitation Q32 indicates minimum detectable leakage rate of 0.04 litre/s (range 0.0016 to 0.3l/s) *(2, 0.1 and 16 litre.min respectively)*

Figure 4.11a Effect of crack width on erosion rate for an Erosion Rate Index of 4

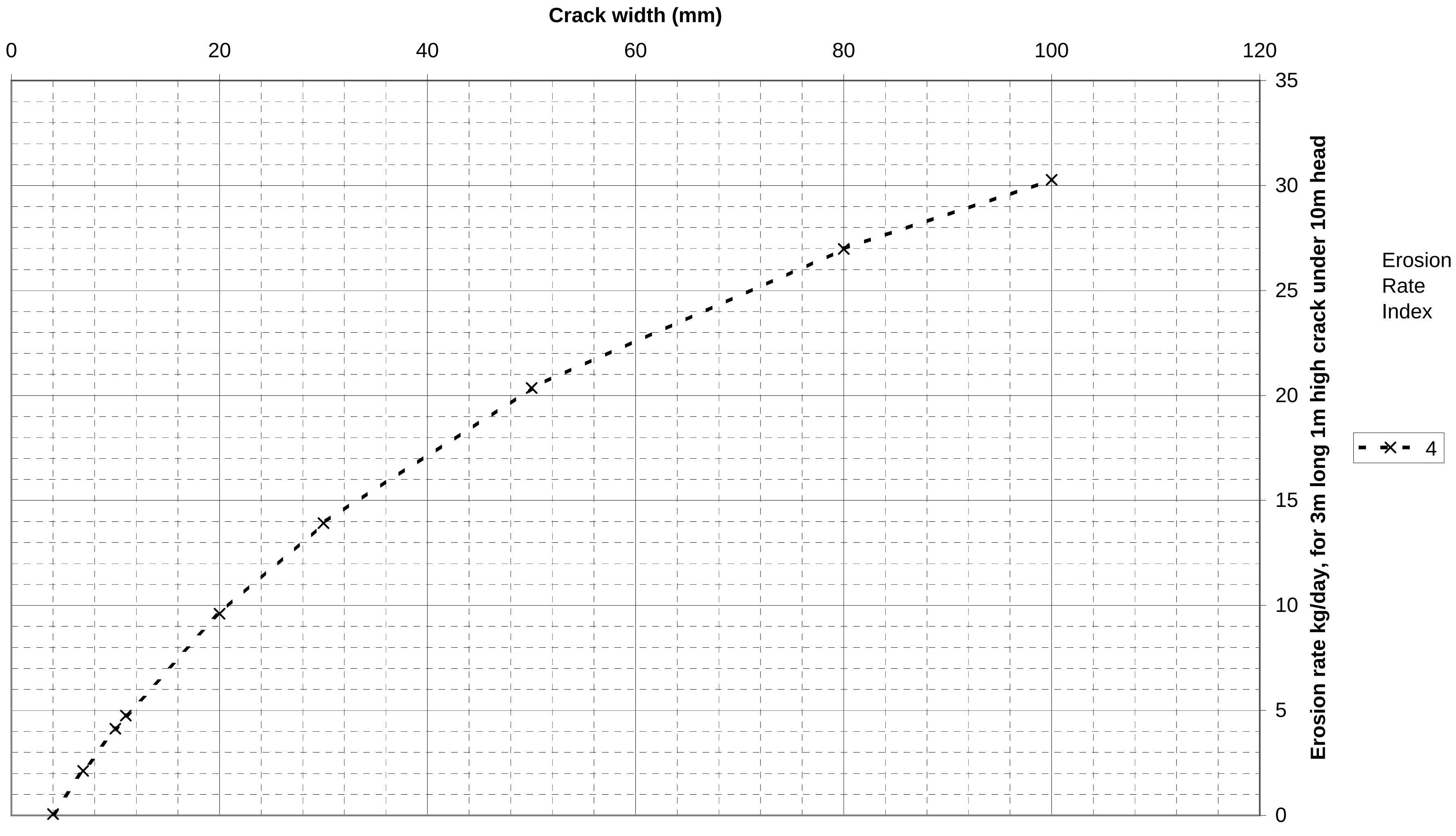


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Figure 4.11b Effect of crack width on eroion rate, for Erosion Rate Index of 1

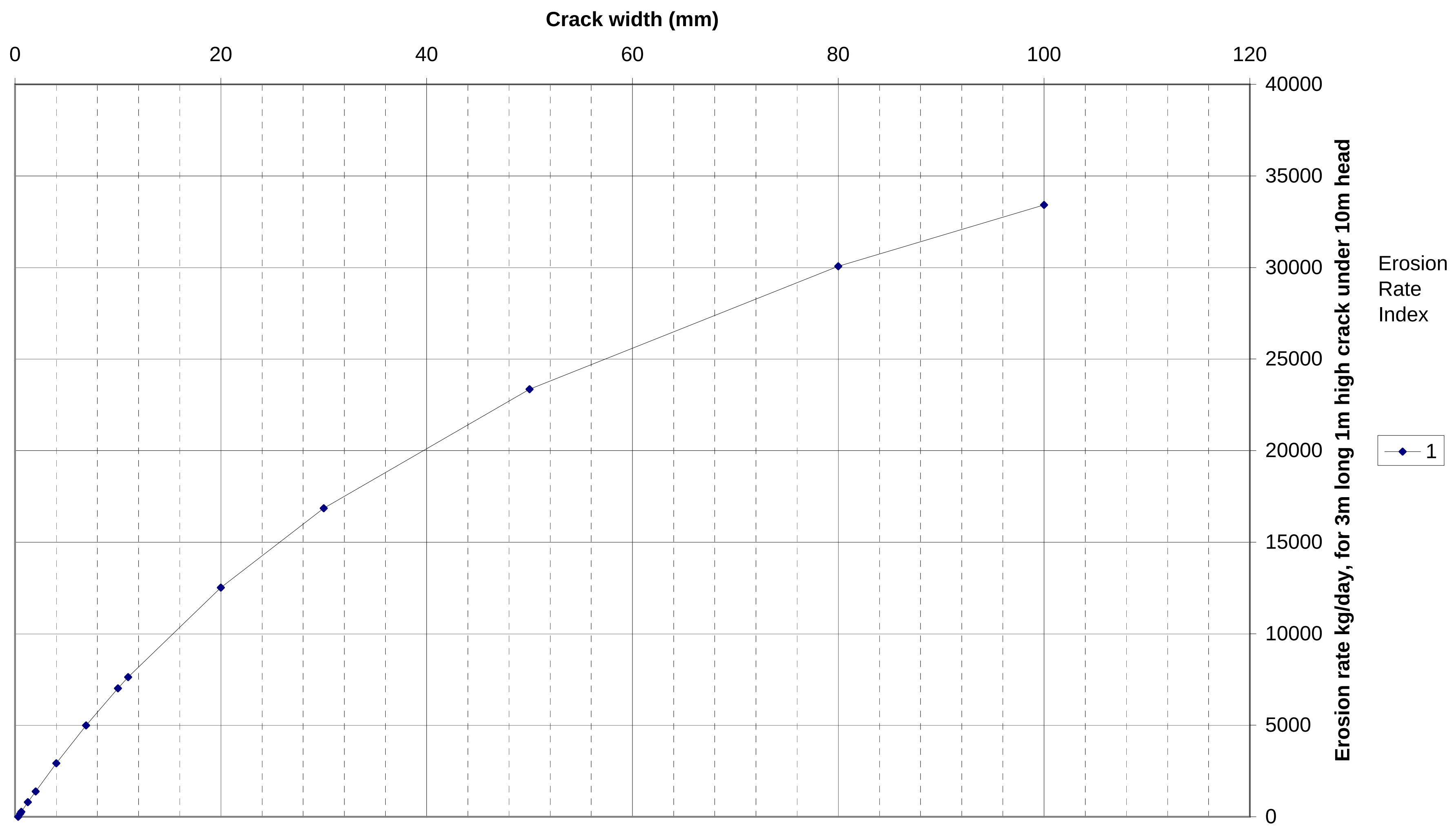
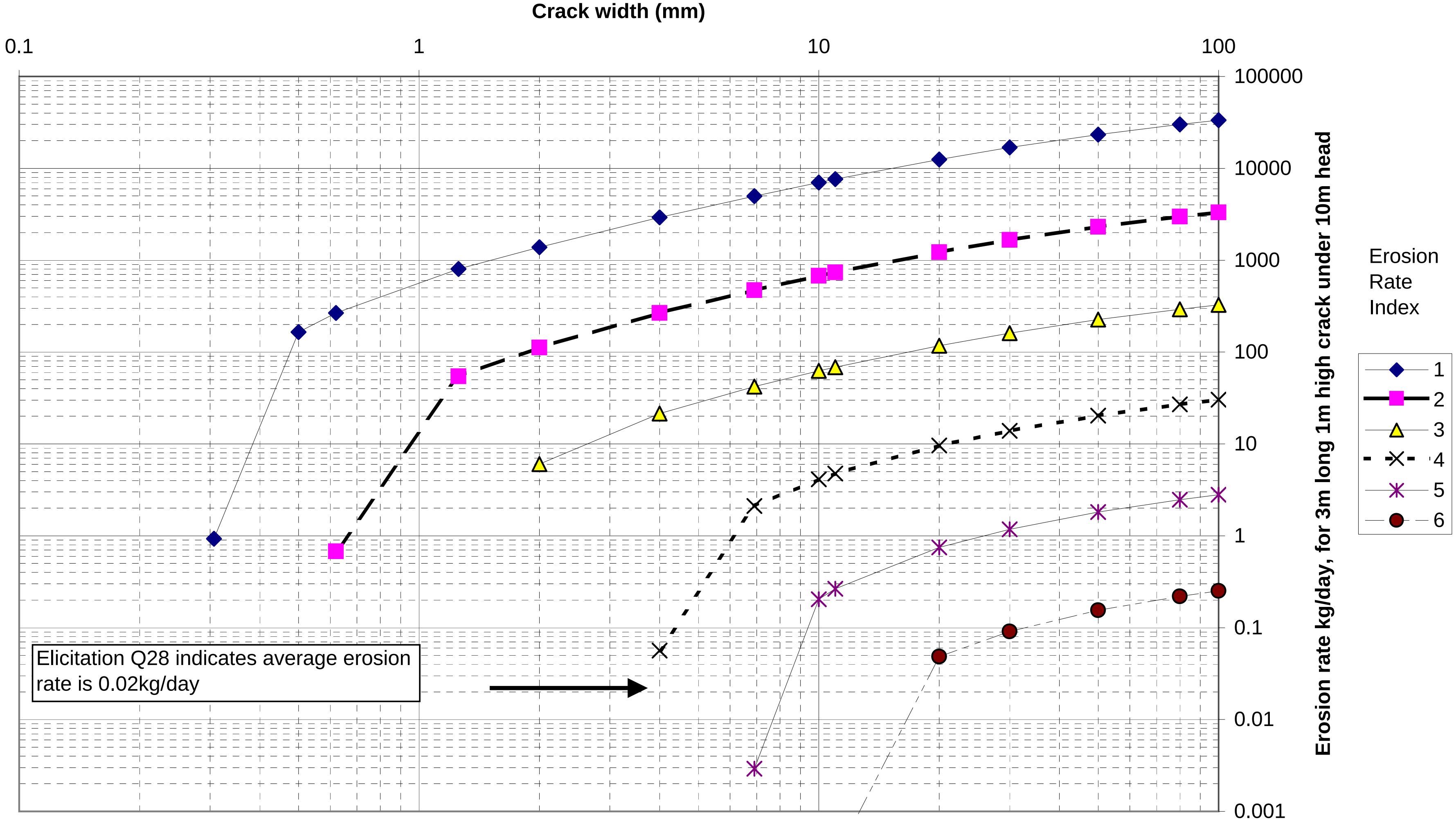


Figure 4.11c Effect of crack width on erosion rate, for Erosion Rate Index of 1 to 6



Elicitation Q28 indicates average erosion rate is 0.02kg/day

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Figure 4.11d Variation of turbidity with crack width and Erosion Rate Index

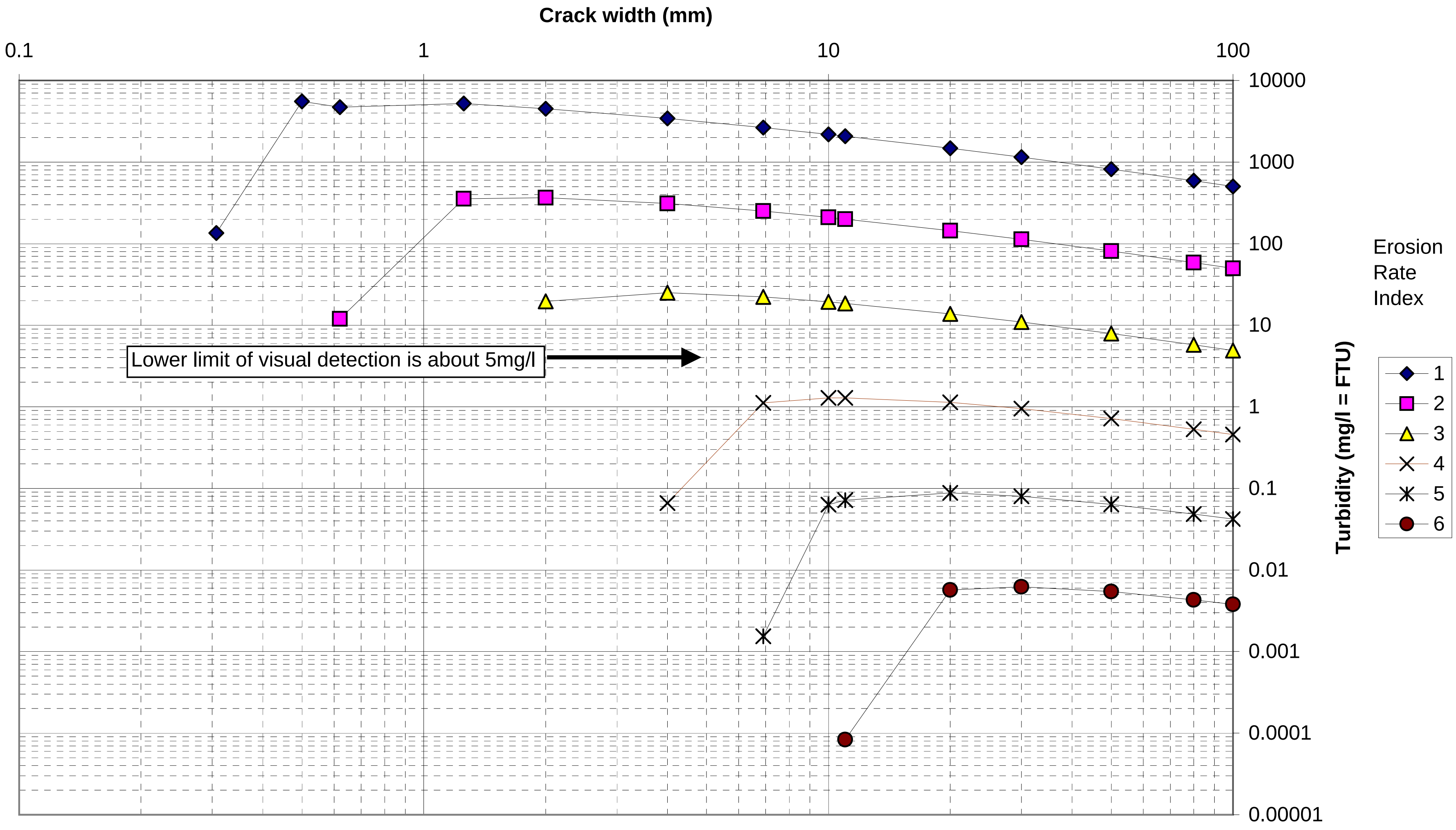


Figure 4.12 - Questionnaire case history data
Timing of actions following detection of serious internal erosion (Q23)

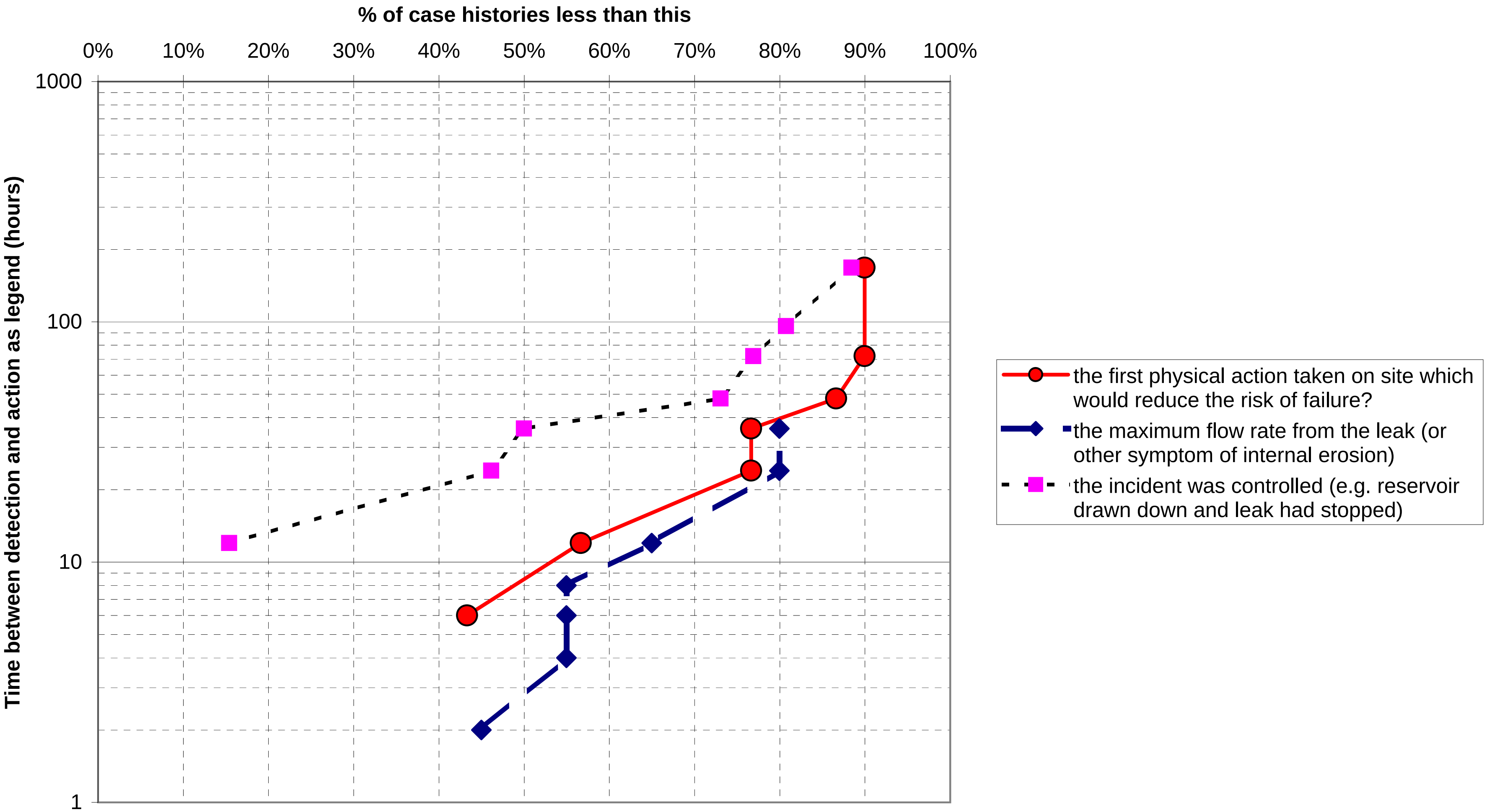


Figure 4.13 - Questionnaire case history data
Magnitude of internal erosion leakage flow at various stages in incident (Q24, 27b)

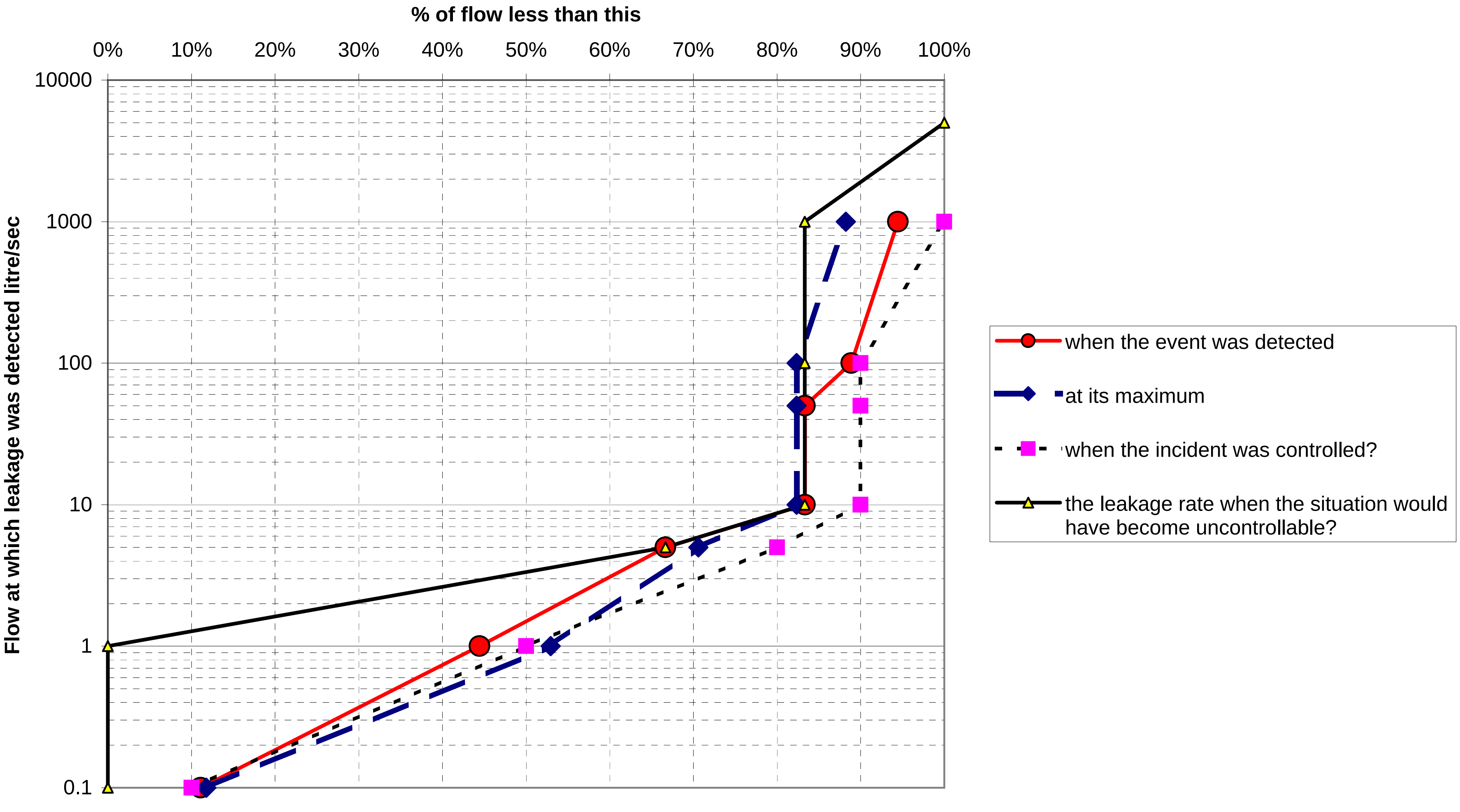


Figure 4.14 - Questionnaire case history data
Relationship of estimated time to failure (Q27a) to Gradient across impervious element at original ground level (Q34)

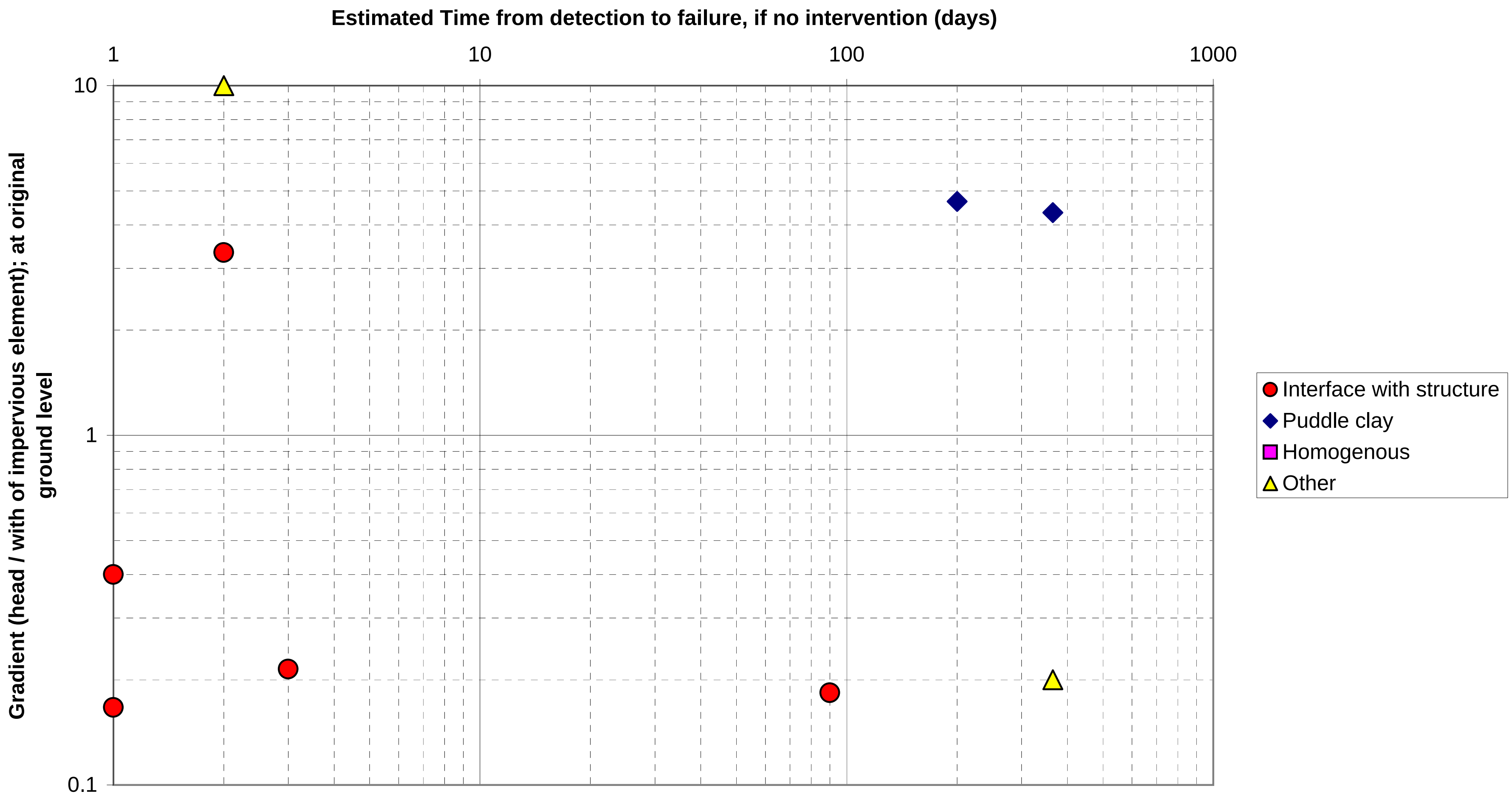


Figure 4.15 - Questionnaire case history data
Relationship of estimated time to failure (Q27a) to dam height (Q11)

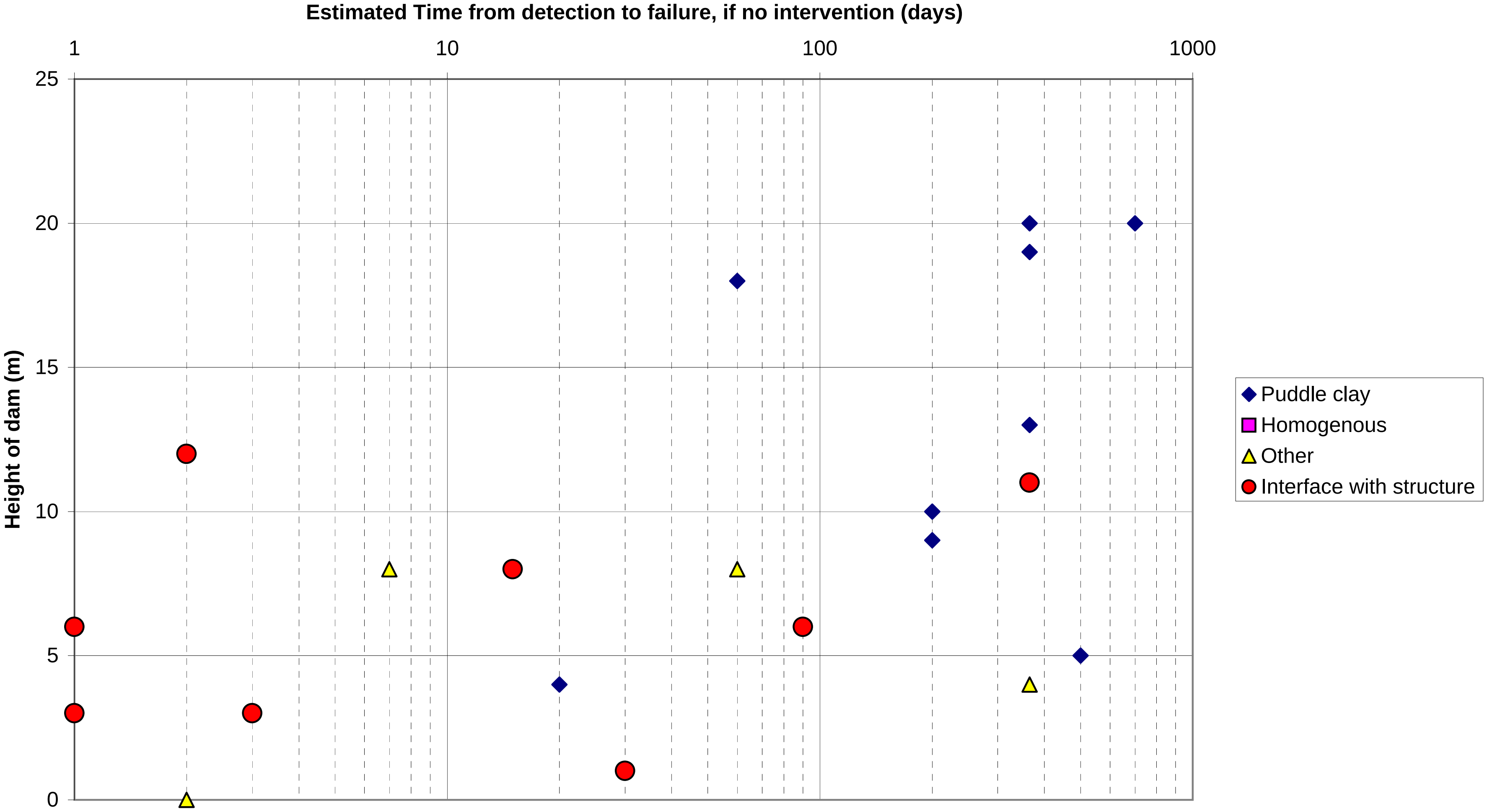


Figure 4.16 - Questionnaire case history data
Relationship of estimated time to failure (Q27a) to Plasticity Index of the watertight element (Q31c)

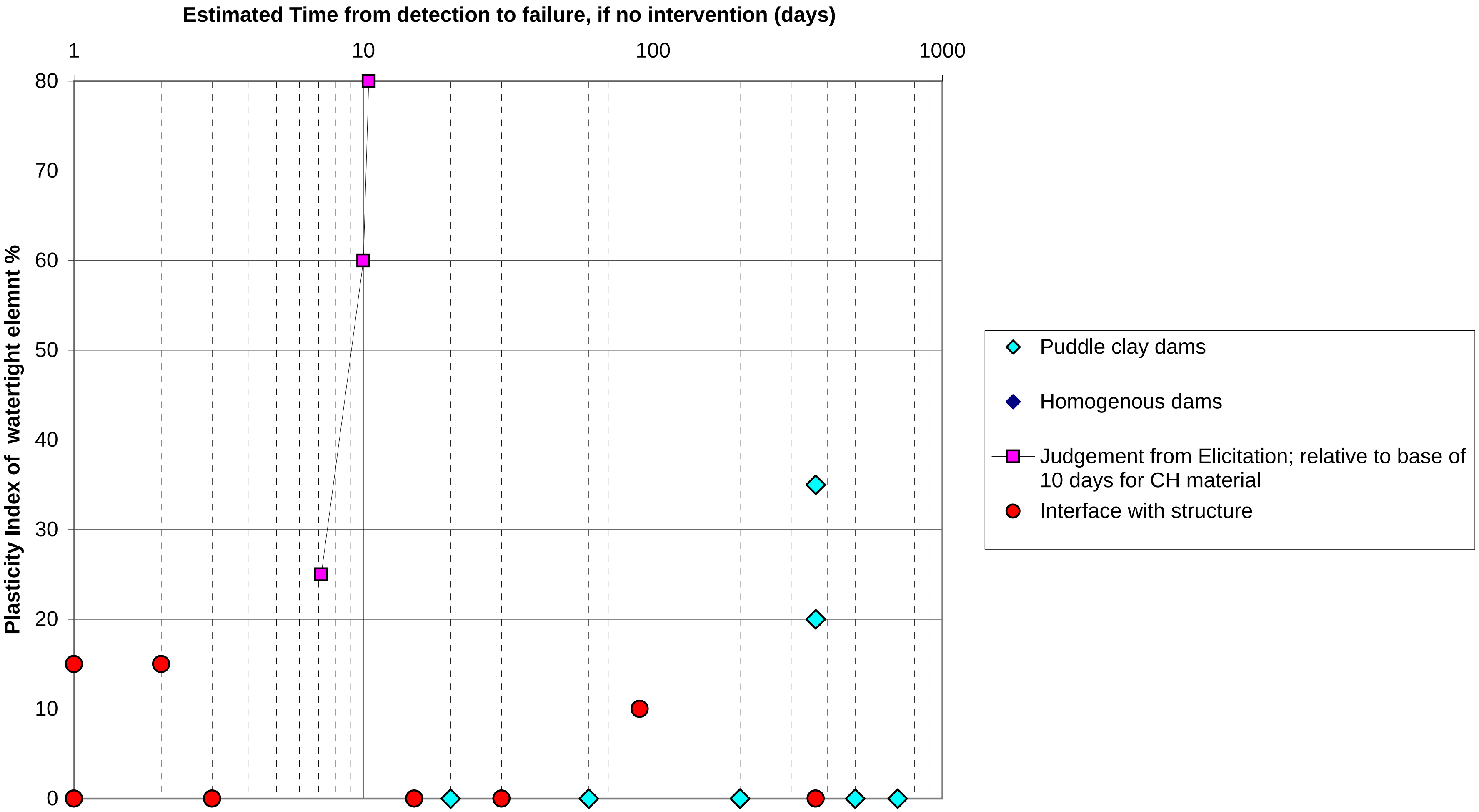


Figure 4.17 - Leakage rates: average ongoing and minium detectable

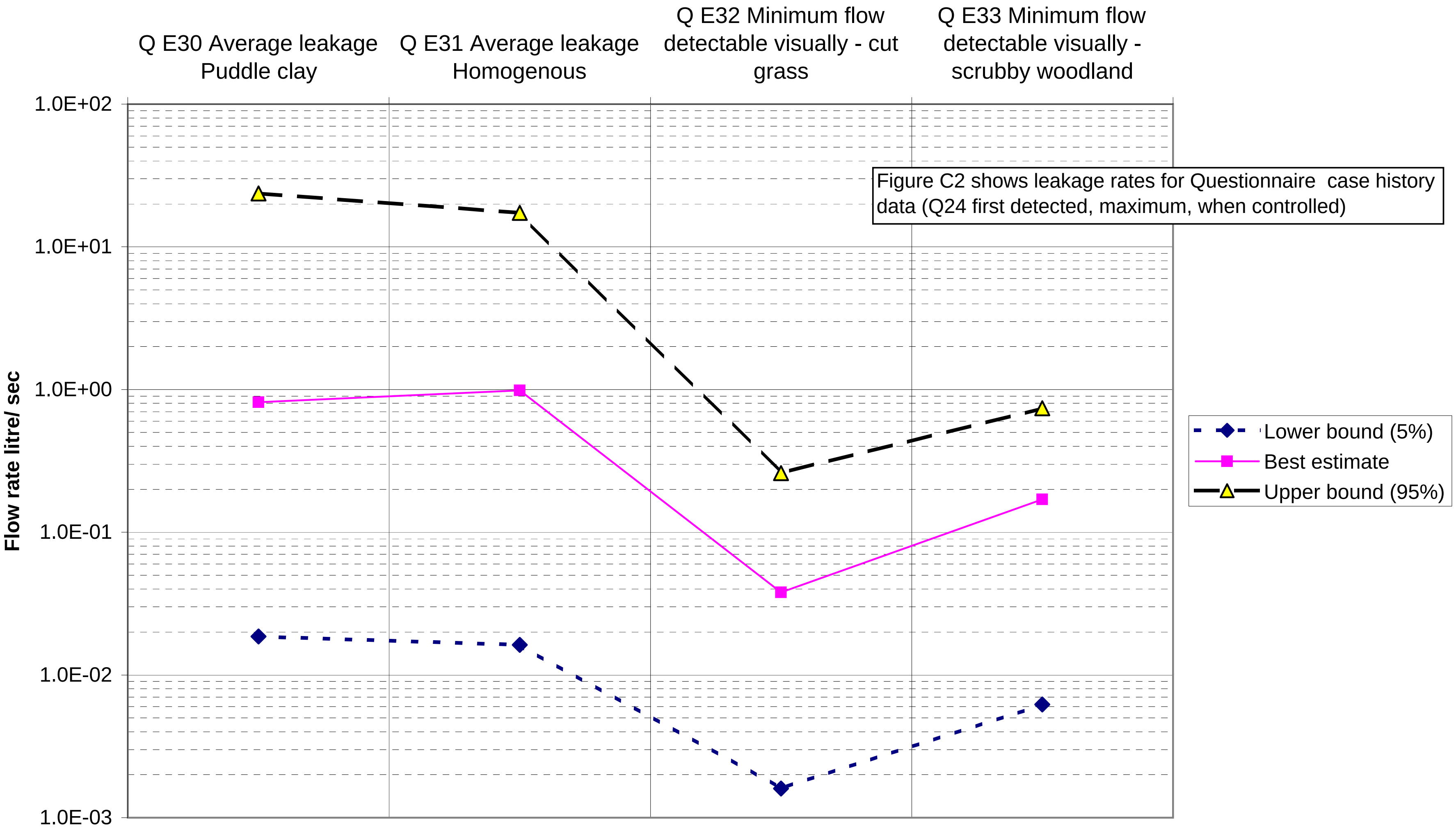


Figure C2 shows leakage rates for Questionnaire case history data (Q24 first detected, maximum, when controlled)

Figure 4.18 - Average erosion rate, for dams with ongoing internal erosion

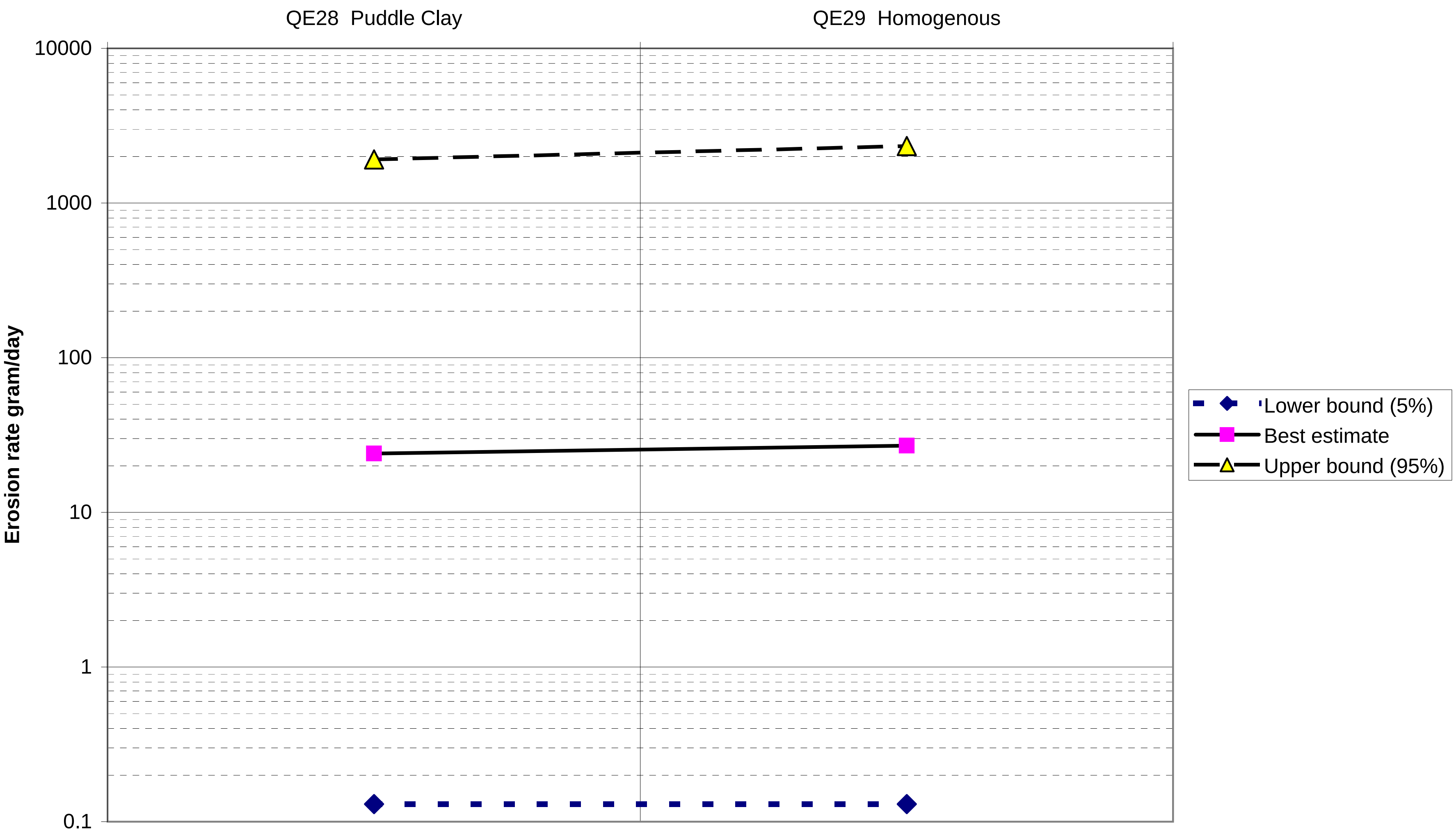


Figure 4.19 - Distribution of Dam Critical flow for population of all UK embankment dams

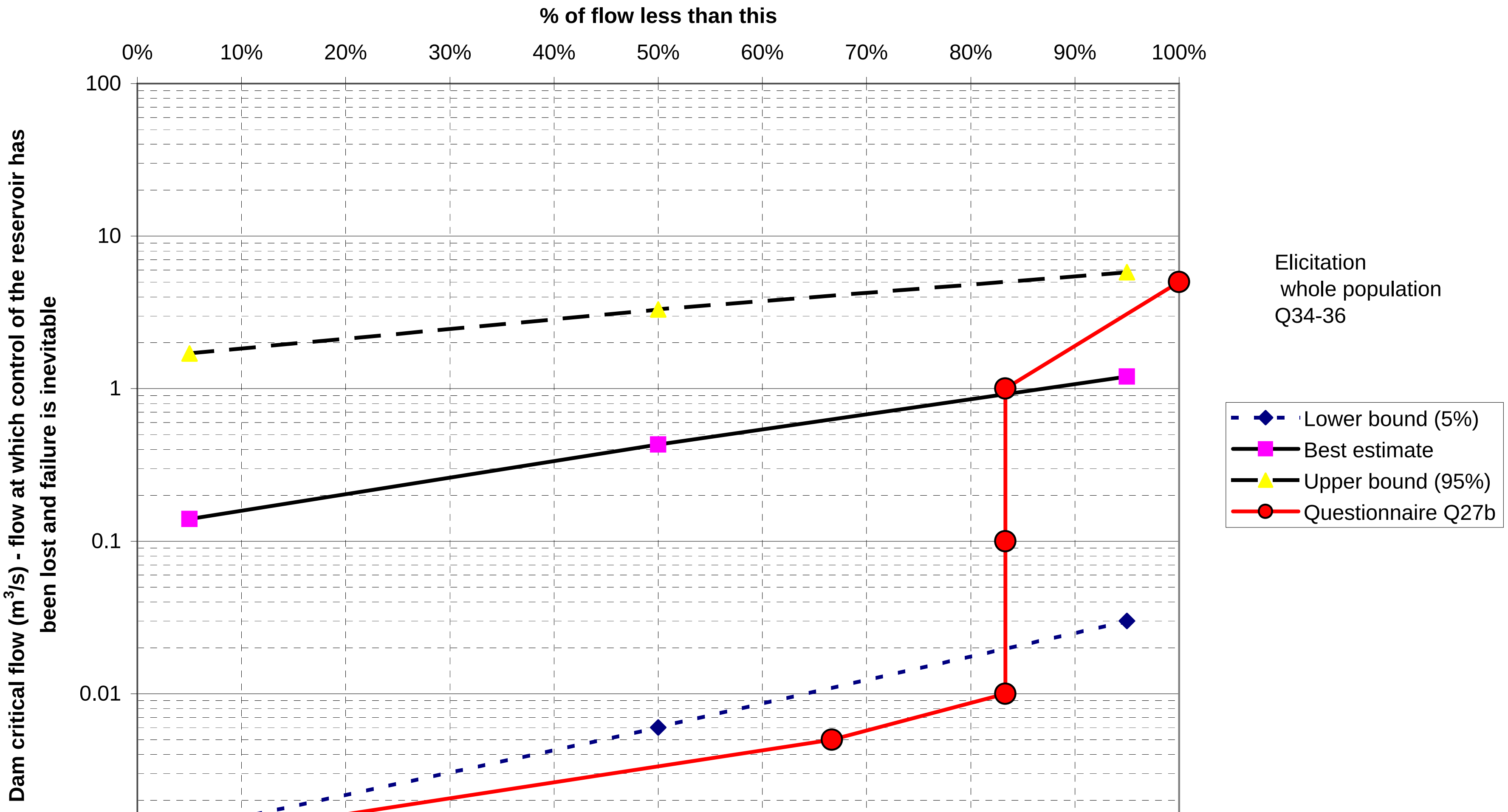
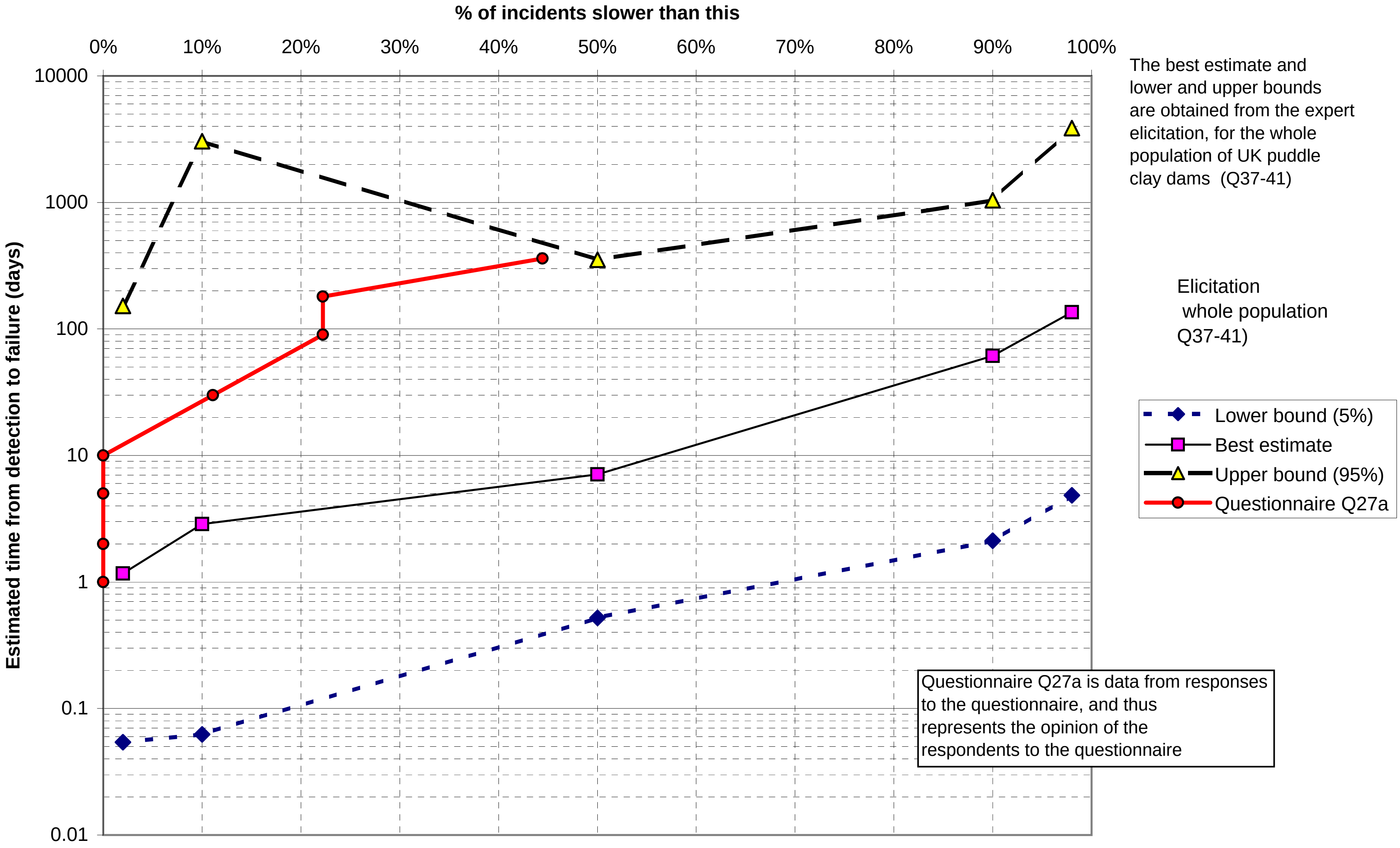


Figure 4.20 - Estimated time from detection to failure of puddle core dams, if no intervention



The best estimate and
lower and upper bounds
are obtained from the expert
elicitation, for the whole
population of UK puddle
clay dams (Q37-41)

Elicitation
whole population
Q37-41)

Questionnaire Q27a is data from responses to the questionnaire, and thus represents the opinion of the respondents to the questionnaire

Figure 4.21 - Time from detection to failure of homogenous dams, if no intervention

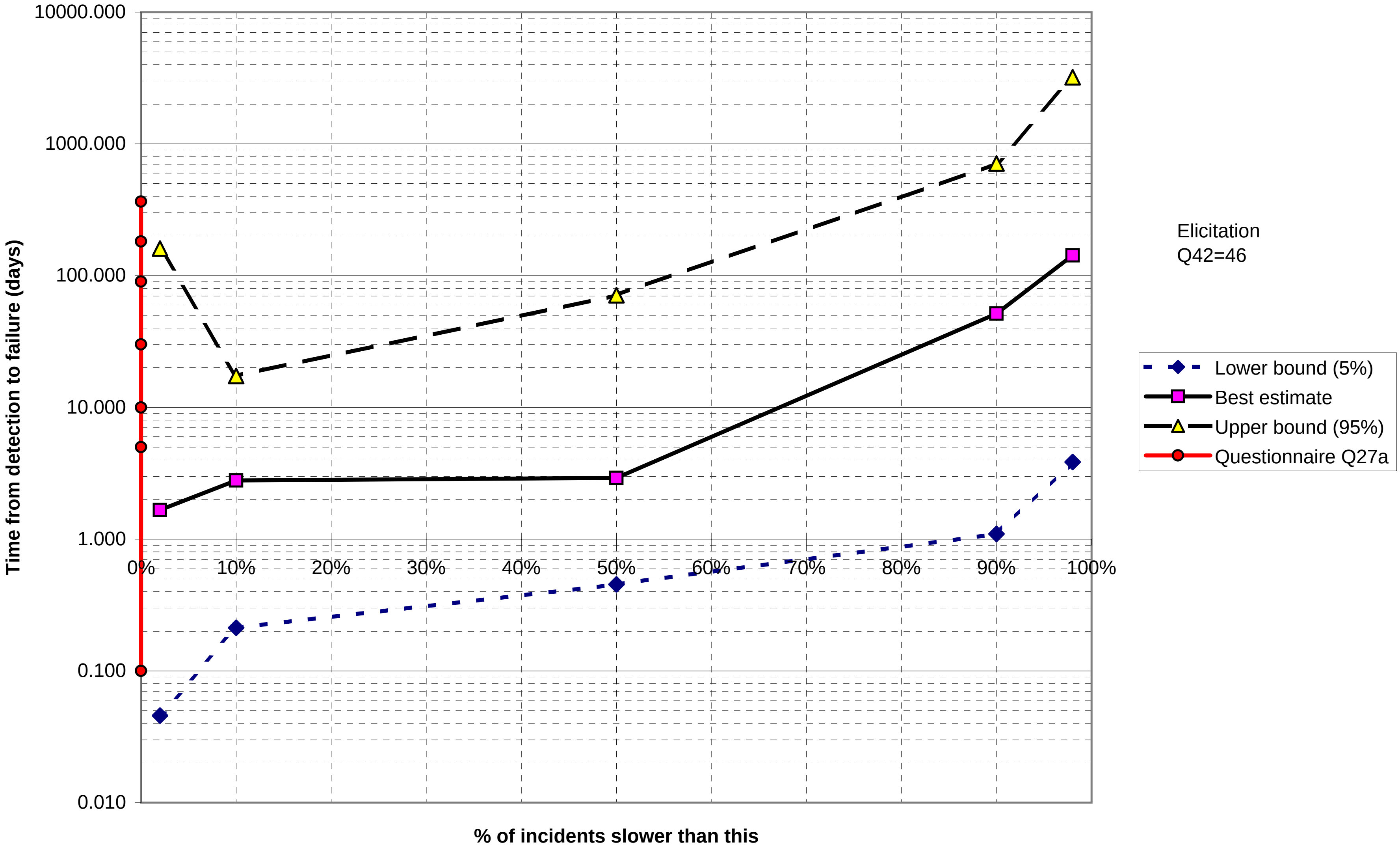


Figure 4.22 - Effect of characteristics of core material on time to failure (puddle clay dam)

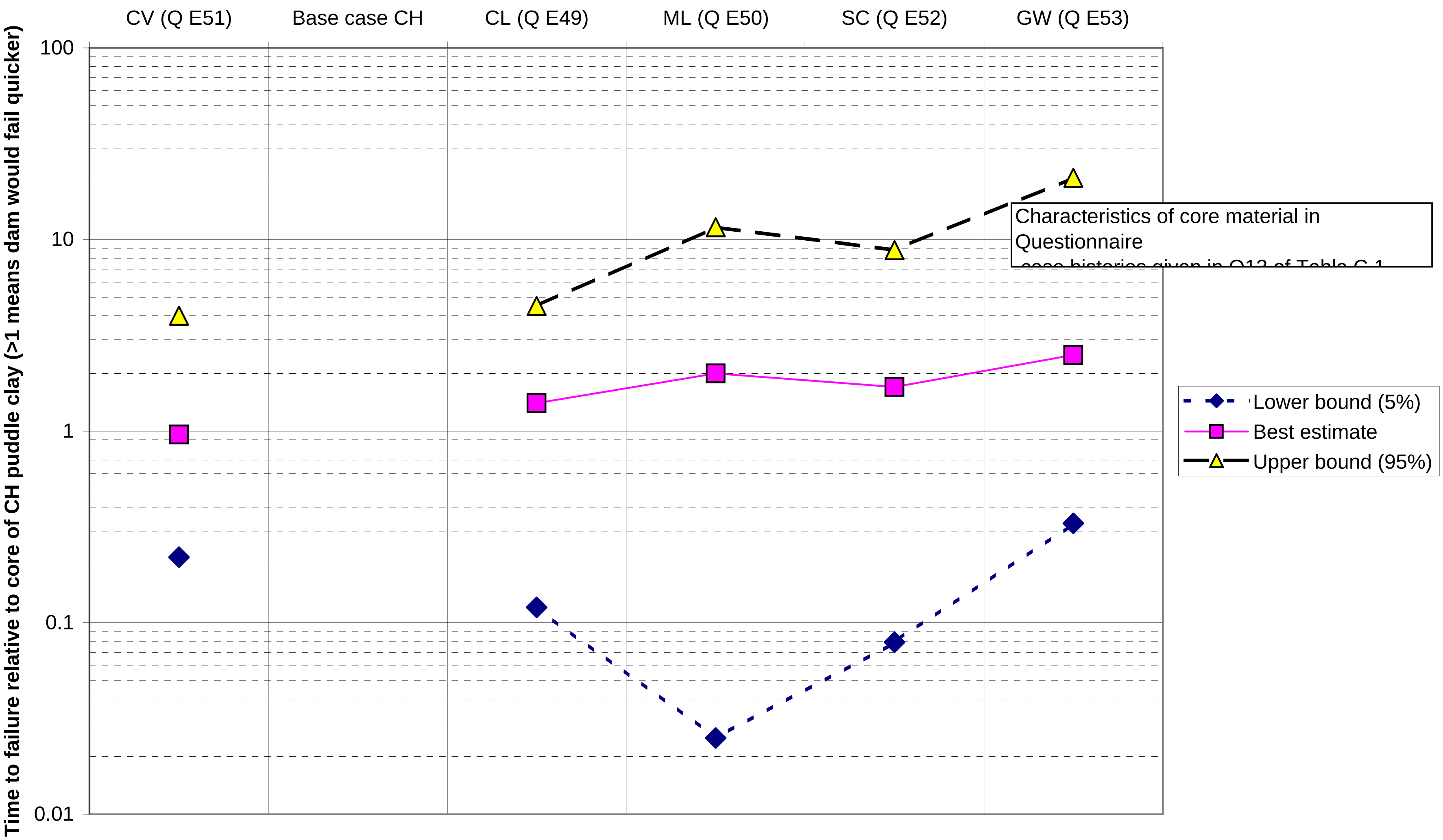


Figure 4.23 - Effect of compaction and hydraulic gradient on time to failure (for puddle clay dam)

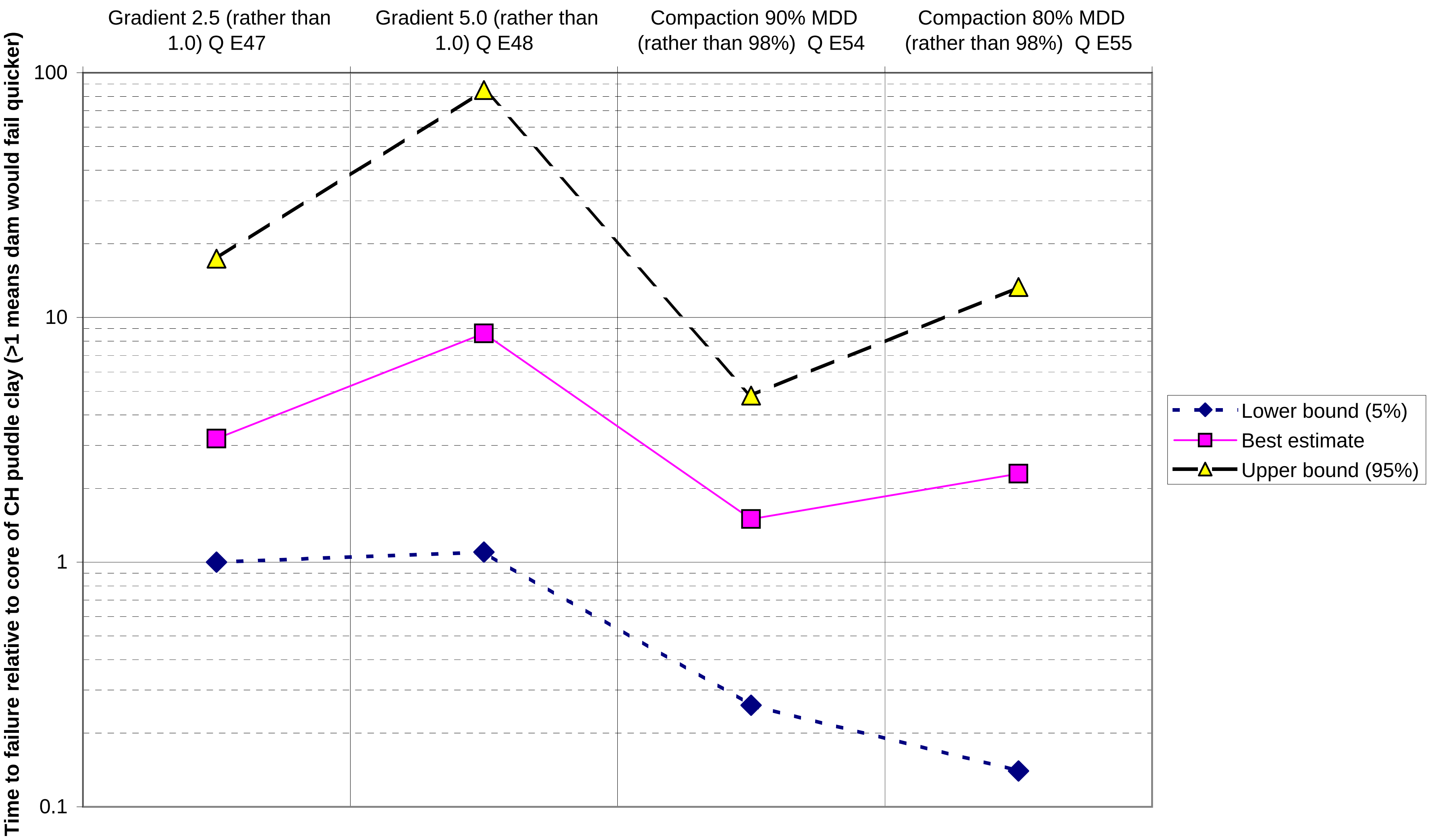


Figure 4.24 - Effect of characteristics of dam shoulders on time to failure (for puddle clay dam)

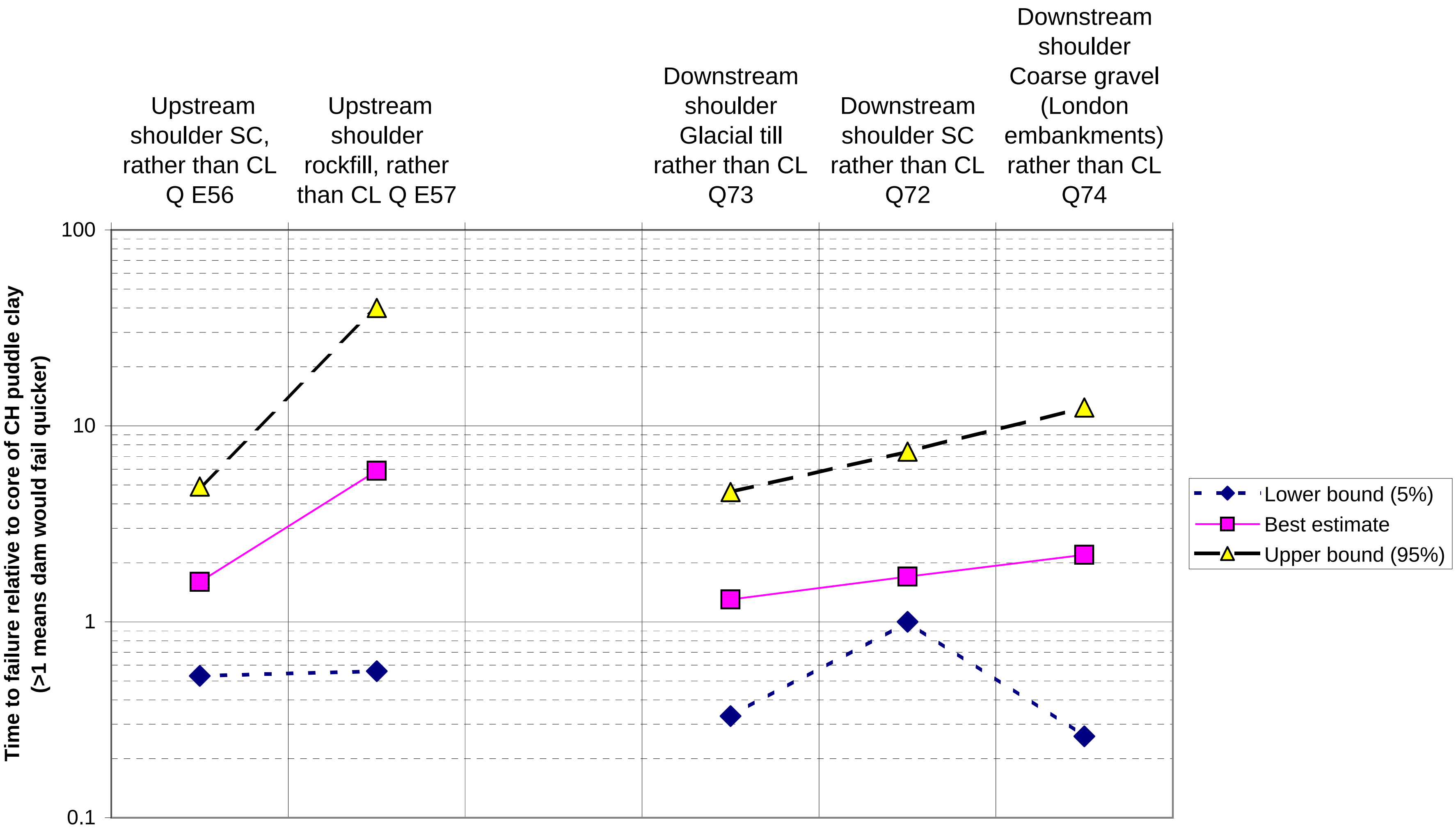
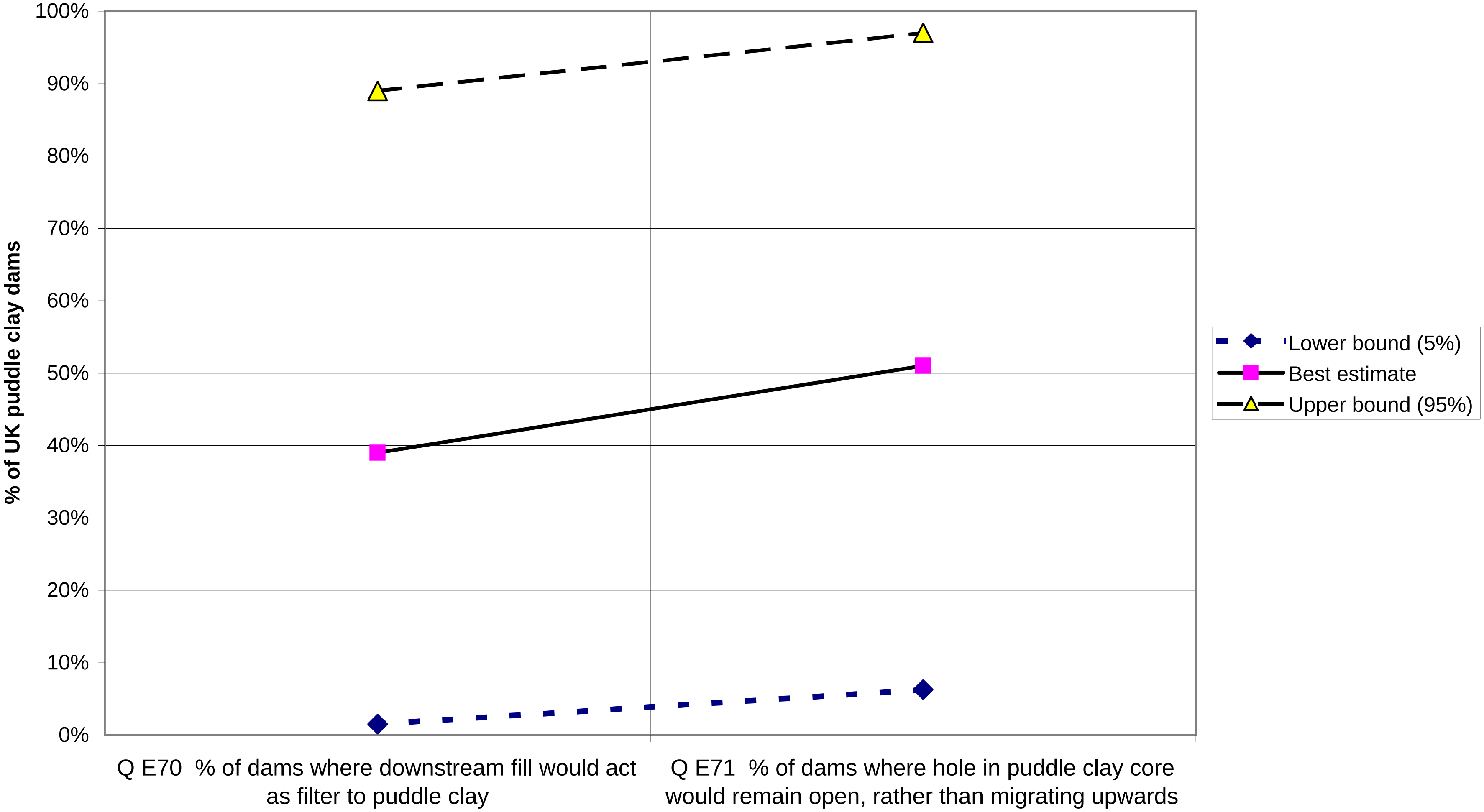


Figure 4.25 - For concentred leaks at puddle clay dams, percentage of dams that would behave in particular way



5 STRATEGY FOR EARLY DETECTION OF INTERNAL EROSION

5.1 Introduction

This section of the report addresses the requirement of the terms of reference
Stage 1 - *The development of a strategy for the early detection of internal erosion in embankment dams.*

- *The starting point will be to assess overall feasibility and the respective roles of surveillance and real time remote monitoring of instrumentation and warning systems.*
- *Techniques for remote monitoring of instrumentation located in or on the dam to detect internal erosion will be identified and evaluated.*

In terms of early detection of internal erosion practical difficulties include

- differentiating leakage from internal erosion
- differentiating "steady" internal erosion from "progressive" internal erosion
- is there a threshold level of leakage (and internal erosion) below which there is very low risk.

As discussed in Section 1.2.1 it is considered that monitoring should be considered as having a wider remit, such that it includes physical investigations to quantify the vulnerability of a particular dam to internal erosion, which in turn may lead to physical works. Thus parameters which may provide means of early detection of internal erosion are broadly in two groups:-

Indicators	Outcome from the process of internal erosion (i.e. internal erosion must already be occurring)
Intrinsic condition	This provides a measure of vulnerability to internal erosion, but does not actually provide information on whether internal erosion is occurring

This section deals with

a) defining the strategy for early detection of progressive internal erosion
b) the use of "indicators" for "early detection of progressive internal erosion"; in particular how to prioritise parameters and instrumentation to provide early detection
c) the role for surveillance and continuous monitoring of instrumentation (whether downloaded periodically, or transferred in real time to a central control room)
d) the role of intrinsic condition

It is noted that this project is limited to indicators relating to internal threats, and does not cover threats remote from the dam.

5.2 Strategy

5.2.1 Long term objective

The overall purpose of a strategy for early detection of internal erosion is to obtain time

- in which mitigation actions can be taken to avert failure (which could include physical upgrading works)
- if failure cannot be prevented, to warn and evacuate people from the dam break inundation zone

An important point is that no detection system can be 100% reliable, so an important part of defining any monitoring system is to consider how reliable it is likely to be, and what measures could be taken to improve the reliability.

It is therefore implicit that the importance of early warning is greater where the risk of loss of life and/ or damage resulting from a failure is high; namely that the amount of advance warning time and reliability of the detection should be greatest where the risk is greatest.

Other important points are that

a) early detection is of no value unless action can then be taken promptly to terminate, or at least manage, the internal erosion
b) for very high hazard dams the probability of progressive internal erosion may be unreasonably high, and physical measures to make the dam less vulnerable to internal erosion may be justified

This suggests that the strategy for early detection of internal erosion should be risk based. This is illustrated in Figure 5.1, where both what constitutes the inherent vulnerability of the dam and the frequency of monitoring depend on the risk posed by the dam. The long term objective should be to be able to quantify the various elements of the figure, in order to allow ALARP analysis of the degree to which the three risk control measures to manage risk are justified.

5.2.2 Interim strategy

In considering how the concept in Figure 5.1 may be applied now, the significant uncertainties in estimating the annual probability of failure due to progressive (rapid) internal erosion should be noted. It is therefore considered that it is more appropriate at present to link the risk control measures to the consequences of failure, rather than risk, albeit with provision for adjustment on the basis of an assessment of the vulnerability of a dam to failure. The suggested consequence class diagram is that to be included in the Interim Engineering Guide to Quantitative risk assessment, as shown on Figure 5.2.

The proposed current strategy for early detection of internal erosion is given in Table 5.1, the basis of this strategy being discussed in the remainder of this section.

Table 5.1 : Proposed Outline Strategy for early detection of internal erosion

1	The strategy for early detection of internal erosion should consider detection as one of the suite of three risk control measures to reduce risk from progressive internal erosion, namely • monitoring (detection) • planning of measures to be taken in the event internal erosion is detected • reduction of vulnerability
2	A risk based approach should be used to define the extent to which these risk control measures should be applied. Separate consideration should be given to the risks posed by the dam embankment, and associated with any appurtenant works through the embankment.
3	In the medium term, pending increasing quantitative understanding of the probability of failure due to progressive internal erosion, a) dam consequence class may be used in lieu of quantitative estimates of risk to define the frequency and type of monitoring b) this may be modified by carrying out a screening level assessment of vulnerability and failure modes. This will result in assigning a preliminary vulnerability classification *(based on core erodibility, properties of the dam shoulders and form of construction of appurtenant works)*
4	Although surveillance remains the primary mechanism for detection of internal erosion, for high consequence dams and those vulnerable to rapid deterioration it is likely to be appropriate to install real time monitoring systems, with these identified on the basis of the most likely failure modes
5	Preferred methods of detection are shown in Tables 5.3 and 5.4
6	Frequency of monitoring are shown in Tables 5.7 and 5.8
7	Upgrades are shown in Table 5.6

5.3 Prioritisation of Indicators

The choice of which indicators best provide for early detection is based on the results of the questionnaire (e.g. Table 3.1) and a ranking by KBR of the value of the candidate indicators in terms of value to "early detection of progressive internal erosion".

The criteria, and basis of scoring, for determining whether the indicators are viable for use in early detection are shown in Table 5.2; whilst candidate indicators together with their score are summarised in Tables 5.3 and 5.4. This shows that indicators are preferred in the following ranking

Rank from		Indicator	Instrument
Body of dam (Table 5.3)	Appurtenant works (Table 5.4)		
1=	1=	Turbidity	Turbidity meter
1=	1=	Flow rate	Visual
3	3	Flow rate	V notch
4	4	Extent of wet area	Visual
5	5	Crest settlement	Levels, or settlement gauges
Not app.	6	Voids on outside of culvert	Ground probing radar
6	7	Temperature	GTC probes
7	8	Acoustic	
8	9=	3D deformation	
Not app.	9=	Cracks in culvert	
9=	11	Self potential	
9=	Not app.	Electrical resistivity	

Table 5.2 : Criteria for determining the priority of Indicators for use in early detection of internal erosion

Issue (may need to be assessed separately for each of different types of internal erosion – Table 4.2)		Remarks	Basis of scoring
1	How the parameter relates to potential failure modes e.g. • does indicator relate to leakage, or internal erosion • is the parameter symptomatic of “progressive”, or “steady” internal erosion?	Statler (2003) describes the US BOR performance parameter process in which the monitoring programme is devised on the basis of monitoring indicators which are related to the most likely failure modes. Similar approach described by Pattel & Knoop, 1999	3 is the maximum if the parameter only measures leakage
2	Radius of influence of the zone in which a change in the parameter occurs, and whether the instrument reads only a point value, or is a zonal technique e.g. • how likely is a “normal” number of instruments likely to identify internal erosion		
3	Ease of sampling e.g. • location : where is internal erosion occurring (upper part of dam, lower part, along interface with structure) • method; is sample required for parameter to be quantified, and if so is pump required to take sample?		5 is the maximum score for a surface expression which is likely to be indicative of internal changes 3 is the maximum score where the instrument has to be installed inside the dam, but the reading is simple
4	The magnitude of the change in parameter that would occur representative of a Level 2 incident, relative to a) The accuracy to which the parameter can be measured, b) The magnitude of the change in the parameter that occurs naturally due to • changes in reservoir level • rainfall • other seasonal change c) Thus the uncertainty in setting trigger levels for alarms	Preferably it would also be possible to a) Differentiate leakage from internal erosion b) Identify how far internal erosion had progressed from initiation to the dam critical flow rate	
5	Timing of measurable change in the parameter: a) Sufficiently in advance of failure to allow preventative action to be taken? b) Detectable by instrumentation before any change could be detected by surveillance (visual inspection); either because the change is within the ground or because the initial change is too small to be seen by the naked eye?	a) In clays the response time of piezometers may also be significant, such that a response in the instrument would occur a significant time after the initiation of a erosion pathway b) ‘b’ would justify installing instruments which were read (or downloaded) only as part of a surveillance visit, even if readings were not sent remotely to some control room	
6	Long term reliability of equipment, if a permanent installation, including • ease of installation (and replacement)? • who will maintain (owner, or specialist under subcontract)? • suitable for long term use in partially saturated soil?	a) Cost is covered separately in Section 5.7 b) e.g. can it be recalibrated insitu?	3 is the maximum score for Instruments installed in dam; 5 is the maximum score for instruments exterior to dam

Table 5.3 : Candidate Parameters (Indicators) for early detection of internal erosion in body of dam

	Indicator of internal erosion	Location (sampling point)	Ref	Measurable parameter Description	Instruments	Indicative estimate of			Scoring against criteria in Table 5.2						Total Score	Ranking	Remarks
						Value indiative of dam failure Note 1	Minimum detectable value	Units	1	2	3	4	5	6			
CF	Concentrated flow	Exit point on downstream side of dam	1	Flow rate	V notch weir	400		l/s	3	3	5	5	4	4	81	3	
			2	Flow rate and turbidity	Visual (surveillance)	400	0.04	l/s	3	3	5	5	4	5	84	1	Q32, 35 of elicitation
			3	Turbidity	Turbidity meter				5	2	4	5	5	3	84	1	
			4	Water chemistry					1	2	2	3	3	2	43		
			5	Extent of wet area on ds face	Visual (surveillance, or TV camera)	na	0.1	m^2	2	3	5	5	4	5	79	4	
		Internal (dam/ foundation)	6	Temperature		10	0.1	^{o}C	2	4	3	3	2	2	56	6	
			7	Electrical resistance	Geophysical (Resistivity)				2	3	3	3	2	2	52	9	
			8	Voltage generated by flow	self potential				2	3	3	2	3	2	52	9	
			9	Noise	Acoustic			dB	2	3	3	3	3	2	55	7	
PP	Change in pore pressure	Internal (dam/ foundation)	10	Piezometer readings				kPa	1	1	4	2	3	3	45		
IS	Change in Internal Stresses	Internal (dam/ foundation)	11	Total stress				kPa	1	1	3	2	3	2	39		
V	Void within dam	Internal (dam/ foundation)	12	Gamma ray					1	2	3	2	3	2	43		Near surface is dwarfed by cosmic rays?
			13	Electrical resistance	Geophysical (Resistivity)				1	2	3	2	3	2	43		
SD	Surface Deformation (settlement, or horizontal movement)	Crest	14	Level		1000	1	mm	2	4	5	3	2	5	71	5	
		Upstream/ downstream faces	15	3D deformation		1000	2	mm	1	3	4	2	2	4	53	8	
ID	Internal deformation	Internal (dam/ foundation)	16	3D deformation		100	1	mm	2	1	3	2	2	2	41		
								maximum possible	*5*	*5*	*5*	*5*	*5*	*5*	*105*		
								Weighting	5	4	3	3	3	3			

Notes

1 At Dam critical flow; defined as the concentrated flow when control of the reservoir has been lost and failure is inevitable

2 Scoring is for any form of Internal erosion; i.e. concentrated leak, suffusion, piping; but not leakage alone

3 Score is 5 for high value, 0 for low value

Table 5.4 : Candidate Parameters (Indicators) for early detection of internal erosion asociated with appurtenant works

	Indicator of internal erosion	Location (sampling point)	Ref	Measurable parameter Description	Instruments	Indicative estimate of			Scoring against criteria in Table 5.2						Total Score	Ranking	Remarks
						Value indiative of dam failure Note 1	Minimum detectable value	Units	1	2	3	4	5	6			
CF	Concentrated flow	Exit point inside, or on downstream side of appurtenant works	1	Flow rate	V notch weir	400		l/s	3	3	5	5	4	4	81	3	
			2	Flow rate and turbidity	Visual (surveillance)	400	0.04	l/s	3	3	5	5	4	5	84	1	Q32, 35 of elicitation
			3	Turbidity	Turbidity meter				5	2	4	5	5	3	84	1	
			4	Water chemistry					1	2	2	3	3	2	43		
			5	Extent of wet area on ds face	Visual (surveillance, or TV camera)	na	0.1	m^2	2	3	5	5	4	5	79	4	
		Along interafce between appurtenant works and body of embanekmnt	6	Temperature		10	0.1	^oC	2	4	3	3	2	2	56	7	
			7	Not used											0		
			8	Voltage generated by flow	self potential				2	3	3	2	3	2	52	11	
			9	Noise	Acoustic			dB	2	3	3	3	3	2	55	8	
PP	Change in pore pressure	In vciinty of appurtenant works	10	Piezometer readings				kPa	1	1	4	2	3	3	45		
IS	Change in Internal Stresses	In vciinty of appurtenant works	11	Total stress				kPa	1	1	3	2	3	2	39		
V	Void on outside of appurtenat works	Along culvert	12	Ground probing radar					2	5	4	3	2	2	63	6	
			13	Not used											0		
SD	Surface Deformation (settlement, or horizontal movement)	Crest	14	Level		1000	1	mm	2	4	5	3	2	5	71	5	
		Upstream/ downstream faces	15	3D deformation		1000	2	mm	1	3	4	2	2	4	53	9	
ID	Internal deformation	Inside culvert	16	Crack widths		100	0.1	mm	2	1	4	2	3	4	53	9	
			17	Level		100	1	mm	1	2	4	2	2	5	52		
								maximum possible	*5*	*5*	*5*	*5*	*5*	*5*	*105*		
								Weighting	5	4	3	3	3	3			

Notes

1 At Dam critical flow; defined as the concentrated flow when control of the reservoir has been lost and failure is inevitable

2 Scoring is for any form of Internal erosion; i.e. concentrated leak, suffusion, piping; but not leakage alone

3 Score is 5 for high value, 0 for low value

5.4 Role for Surveillance and for real time monitoring

5.4.1 Comparison of features

Table 5.5 summarises and contrasts some of the main features of surveillance and real time monitoring of indicators.

An intermediate solution, which is a compromise between the two extremes is that instruments are read continually by a data logger on site, but that readings are downloaded manually at the time of the surveillance visits. This has the advantage that more precise readings are being taken (criterion 4), which may detect changes not discernible to the human eye, but that the additional costs of data transmission to a remote station are avoided.

Table 5.5 : Comparison of features of surveillance and real time monitoring

	Criterion[1]	Surveillance	Real time monitoring
1	Relation to failure mode	Only downstream area can be inspected	Depending on location of instrumentation may be possible to monitor development of erosion in core
2	Zone of influence	Whole of visible dam surface can be inspected	Depends on type; although only the points at which monitoring is installed are monitored Adoption of a zonal technique (e.g. temperature, resistivity) could provide scanning of significant sections of the dam (although depth and edge limitations exist)
3	Ease of sampling	Hand held equipment (e.g. crack gauges, thermometer) can be used to sample/ measure whole of visible external surface	Sampling locations limited to positions where instruments are installed
4	Magnitude of change in parameter	Only changes sufficient to be detectable by the human eye	**Precision of instrument (which is likely to be much higher than the human eye)**
5	Timing of measurable change	Only detected at visits, so there would be a delay up to the time interval between visits	Should be instantaneous; only limits being precision of instrument and any lag in change of parameter being measured relative to onset of internal erosion
6	Reliability	a) Limited by potential for human error; although can be improved by careful selection of personnel and training **b) Whole of visible dam surface can be inspected, so should provide early detection when internal erosion is occurring at an unexpected location**	Limited by equipment reliability
7	Management of alarm	Would need to raise by telephone	**Automatically triggered in control room (although would need to check that this is not a false alarm)**

Notes. 1. Criterion as Table 5.2; except that additional criterion (No 7) added

5.4.2 Response to detection of internal erosion

Important issues in deciding the respective roles of these two methods of detection are

a) whether the dam owner has any form of 24 hour control, or incident, room to which the real time monitoring could be transmitted, and where action would immediately be taken in the event of an alarm being raised. Where the owner does not have such a facility the value of real time monitoring would be significantly reduced. In theory it is possible that commercial companies could provide a control room as a commercial service to owners of a small number of dams, but this seems unlikely to be cost effective at the present time.
b) The extent to which the base station computer in the control room can
   - obtain values for variables such as reservoir level, rainfall and temperature
   - adjust the trigger levels for these variables,

   before screening the "internal erosion parameter" against the adjusted trigger level (if this is not done then either the trigger levels will be set too low, resulting in an unreasonable number of false alarms, or set too high such that any alarm is not given in good time)
c) If there is a 24 hour control room, how far from the dam site is it, and how long would it take the dam owner to get personnel on site to implement the emergency on-site plan?
d) How fast the reservoir could be lowered, in the event that progressive internal erosion was detected? If it could not be lowered or other remedial action taken, the value of early detection is in providing increased time for warning and evacuating the downstream population)

Where the dam is owned by an individual then real time monitoring is likely to be disproportional costly.

5.4.3 Conclusion

In principle the three groups of monitoring each have significant advantages compared to each other;

a) for surveillance that the whole visible surface of the dam can be monitored,
b) for instrumentation that in general it would be more precise than visual observation,
c) for real time monitoring that any change in conditions could be automatically relayed to a control room.

The advantages of 'c' is unlikely to be realised unless the dam owner has a control room which is manned 24 hours a day. Although in principle dam owners without this facility could obtain the service through some form of service provider, this is likely to be disproportionately costly.

It is considered that the advantages of the three groups of monitoring are such that any monitoring programme should consider some form of combination of the three, the choice depending on the failure modes of the dam, consequences of failure, the availability of staff for surveillance and cost.

5.5 Intrinsic condition

At some dams which are extremely high risk, or which are particularly vulnerable to internal erosion it may be appropriate to carry out some form of investigations and/or physical works to reduce the probability of internal erosion occurring. This approach was adopted in Northern Ireland (Cooper, 1987; Posskit, 1974).

Table 5.6 lists aspects of intrinsic condition which are likely to affect the vulnerability to progressive internal erosion. At this stage it is not possible to prioritise these.

5.6 Special issues at unprotected pipes and culverts

The comments above in relation to the body of the dam are also applicable here. The main differences are

a) detection is in principle simpler, as any flows into the culvert can be collected at the end and measured
b) upgrading works are significantly more complex, as it is almost impossible to treat the contact of the pipe and watertight barrier (core), other than by grouting. The option of adding filters at the downstream face is less effective, because of concerns that any internal erosion along the contact with the core may not then continue to the downstream end of the pipe, but instead be diverted into the downstream shoulder and/ or foundation

5.7 Assessment of proportionate approach

The terms of reference call for a “cost-effective” approach, and for the need to avoid “disproportionate cost”. The issue of what constitutes proportionate cost may be evaluated by the “as low as reasonably practicable” (ALARP) approach.

Table 5.7 shows the annual expenditure that would be justified, based on a cost to save a statistical life of £10M. This suggests that an annual cost of about £22k/annum would be justified for a typical Category A1 dam, but reducing to £330/annum for a Category B dam.

Table 5.8 gives indicative costs of possible alternative options for increased monitoring in relation to early detection of internal erosion. It can be seen that for a Category A1 dam both increased surveillance and some real time monitoring would be justified, but that for a Category B dam an increase in visit frequency of say one a month would only just be justified.

It is emphasised that these estimates are only indicative, and the results would change significantly depending on the assumptions made.

Table 5.6 : Candidate Parameters relating to Intrinsic Condition (vulnerability or change resulting from internal erosion)

	Aspect of Intrinsic Condition affecting vulnerability to internal erosion	Measurable parameter	Units	Technique for measuring		Remarks
					BS test number	
1	**Internal geometry**	Gradient across watertight element		Field		
2	**Materials forming embankment**					
	a) watertight element	Plasticity Index		Laboratory		
	b) upstream shoulder	Gradation				
	c) filter	Durability				
	d) downstream shoulder	Soil chemistry e.g. Dispersive				
	e) foundation					
3	**Condition of materials forming embankment**					
	a) watertight element	Density (Compaction)				
	b) upstream shoulder	Moisture content				
	c) filter	Permeability				
	d) downstream shoulder	Resistivity				
	e) foundation	Total stress (3 dimensions)				
		Pore pressure				
4	**Materials forming appurtenant works through embankment**					
	a) structural element through dam	Porosity				
	b) joints in structural element	Strength				
	c) location of "water retaining surface"	Elasticity				
	d) original excavations for construction of appurtenant works	"Backfill, Filter" as embankment				
	e) (special) backfill local to appurtenant works	Corrosiveness to cast iron etc (resistivity, pH, redox potential, sulphides)				
	f) filter					
5	**Condition of materials forming appurtenant works through embankment**					
	a) structural element through dam	Cracks/ deformation				
	b) joints in structural element	Erosion/ removal				
	c) location of "water retaining surface"	"Backfill, Filter" as embankment				
	d) original excavations for construction of appurtenant works	Voids behind structural element				
	e) (special) backfill local to appurtenant works					
	f) filter					
6	**Reservoir**					
	Chemistry of reservoir water (relative to embankment materials)					
	Operation of reservoir level					
7	**Other**					

Table 5.7 : Indicative ALARP calculation of proportionate cost for early detection of progressive internal erosion

1 Dam Consequence Category	2 Median likely loss of life No warning	3 Median physical damage in dam failure £M	4 Annual probability of failure	5	6	7	8 Annual risk (current) £/annum	9 Proportionate cost for early detection £/annum	10 Cost for preventing a fatality £M	Remarks
				Current	Reduction by early detection	With early detection in place				
							3 x 5			
A1	200	200	UK median	2.0E-05	2	1.0E-05	4,000	22,000	10,000,000	
A2	30	30	UK median	2.0E-05	2	1.0E-05	600	3,300	10,000,000	
B	3	3	UK median	2.0E-05	2	1.0E-05	60	330	10,000,000	
C	0.05	0.5	10 x median	2.0E-04	2	1.0E-04	100	100	10,000,000	
D	0.005	0.1	20 x median	4.0E-04	2	2.0E-04	40	30	10,000,000	

Table 5.8 Indicative incremental annual costs of options for increased monitoring in relation to "early detection of internal erosion"

Surveillance

Extra visits/ week	1	No	
Visit duration; incl travelling	2	hours	
Labour	£15	hour	£1,560
Mileage	10	miles	
Travel	0.45	p/mile	£234
			£1,794

Instrumentation (flow, turbidity, water level)

Capital cost	£3,500
Installation	£1,000
Data logger	£5,000
Capital	***£9,500***
Annualised	£633
Hardware + software operating costs	100
Data collection monthly (3 hrs/ month)	621
Data interpretation (2 days@ £60/hr)	900
	£2,254

Extra over for real time monitoring

Data transmission - GPRS	£1,000
Computer + software in control room (split over say 10 dams)	£1,000
Capital	***£2,000***
Annualised	£133
	£200
	-£311
	£23

5.8 Frequency of monitoring

As suggested in Section 5.2 monitoring should be risk based, depending on both the probability of failure of the dam and consequences if the dam failed. The proposed approach is shown as follows

Table 5.9 – suggested base frequency of monitoring (including when real time monitoring would be appropriate)
Table 5.10 – adjustment to this, for dam specific vulnerability

Table 5.9 is based on the ANCOLD Guidelines for dam safety management, with some adjustment for the ALARP analysis above. Table 5.9 is derived by KBR. Other possible factors considered but not included in Table 5.9 are the rate of refilling a dam (higher rates would make it more vulnerable to hydraulic fracture)

Table 5.10 Preliminary adjustment to base frequency for dam specific vulnerability

Element of dam	Less vulnerable	Median	More vulnerable
Downstream shoulder	Satisfies filter rules against core	Will inhibit leakage, although not satisfying filter rules against core	Clean rockfill
Core	Low erosion potential	Medium erosion potential	High erosion potential
Upstream shoulder	Sand fines which would act as a crack filler	Non-cohesive	Cohesive material which could sustain a crack and allow a pipe to migrate to the reservoir
Appurtenant works	No pipe or culvert through embankment	Pipe or culvert through embankment	Pipe or culvert has open joints or cracks within the watertight element

Note

1. Vulnerability score is obtained by adding -1 for a less vulnerable feature, and +1 for a more vulnerable feature. Where the score is ≥ 1 then the monitoring frequency should be increased by one consequence class; where the score is ≤ -2 then the monitoring frequency may be reduced by one consequence class.
2. It is preferable that a dam specific risk assessment should be carried out for the subject dam to assess its vulnerability and probability of failure, but this table may be used as a preliminary adjustment to the values in Table 5.9.

Table 5.9 Suggested Guide for "in service " dam monitoring

Parameter	Consequence category				
	A1	A2	B	C	D
Visual surveillance					
Exterior	Daily	Daily to Tri-Weekly	Twice Weekly to Weekly	Monthly	Monthly[4]
Exterior of culverts/ shafts (and interior where no confined space)	Daily	Daily to Tri-Weekly	Twice Weekly to Weekly	Monthly	Monthly[4]
Interior of culverts/ shafts, where confined space	Weekly to monthly	Monthly to 3 monthly	3-Monthly to 6-Monthly		
Instrumentation					
Seepage incl turbidity	Daily (TR)[2]	Daily to Tri-Weekly (TR)[2]	Twice Weekly to Weekly (TC)[2]	Monthly	Monthly[4]
Surface Movement	Yearly	2-Yearly	Consider	Consider	
Zonal technique (e.g. resistivity, thermal)	5-Yearly	5-Yearly to 10 Yearly			
Parameters required to adjust trigger level					
Rainfall	Daily (TR)[2]	Daily to Tri-Weekly (TR)[2]	Twice Weekly to Weekly (TC)[2]	Monthly	Monthly[4]
Reservoir level	Daily (TR)[2]	Daily to Tri-Weekly (TR)[2]	Twice Weekly to Weekly (TC)[2]	Monthly	Monthly[4]

Note

1 These frequencies may need to be varied according to the conditions at, and the type, and size of the dam, and applies to instrumentation already installed at the dam.

2 The frequencies quoted assume manual reading of the instrumentation. Where automated readings are available more frequent reading would be appropriate.

TR - telemetry recommended

TC - telemetry considered

3 The frequency of reading and location of the monitoring instruments to be at the discretion of the dams engineer.

4 The frequencies listed for very low Hazard Category dams are suggestions, the dam owner and his Supervising and Inspecting Engineers should determine appropriate monitoring.

Figure 5.1 Process diagram illustrating strategy for early detection of internal erosion

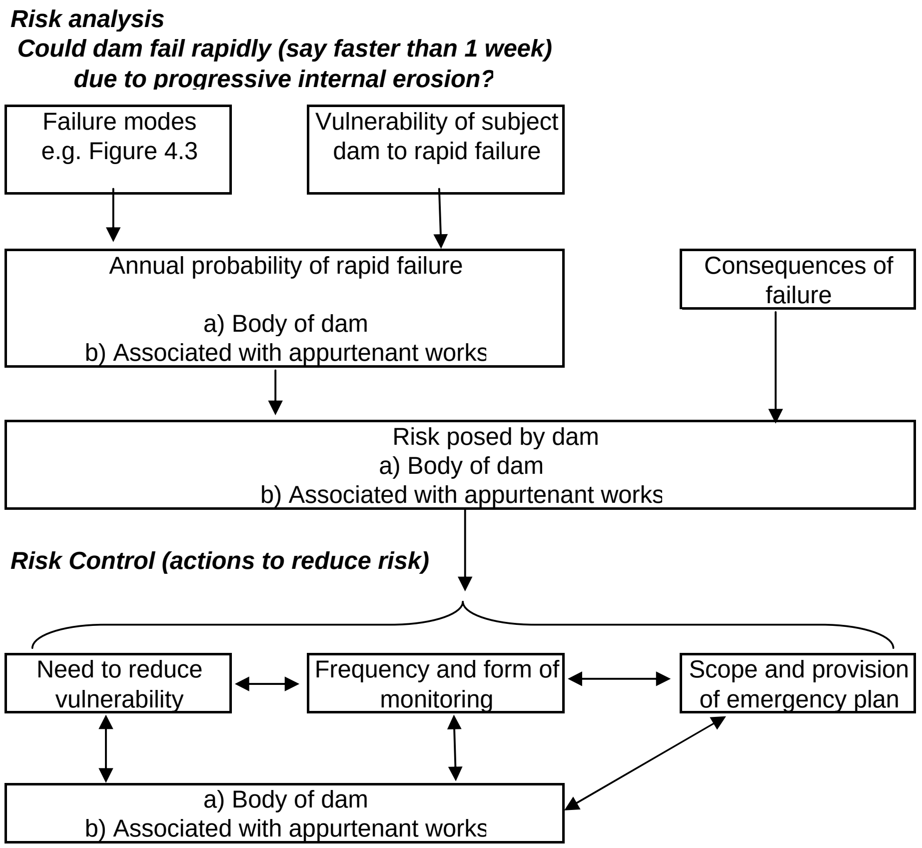
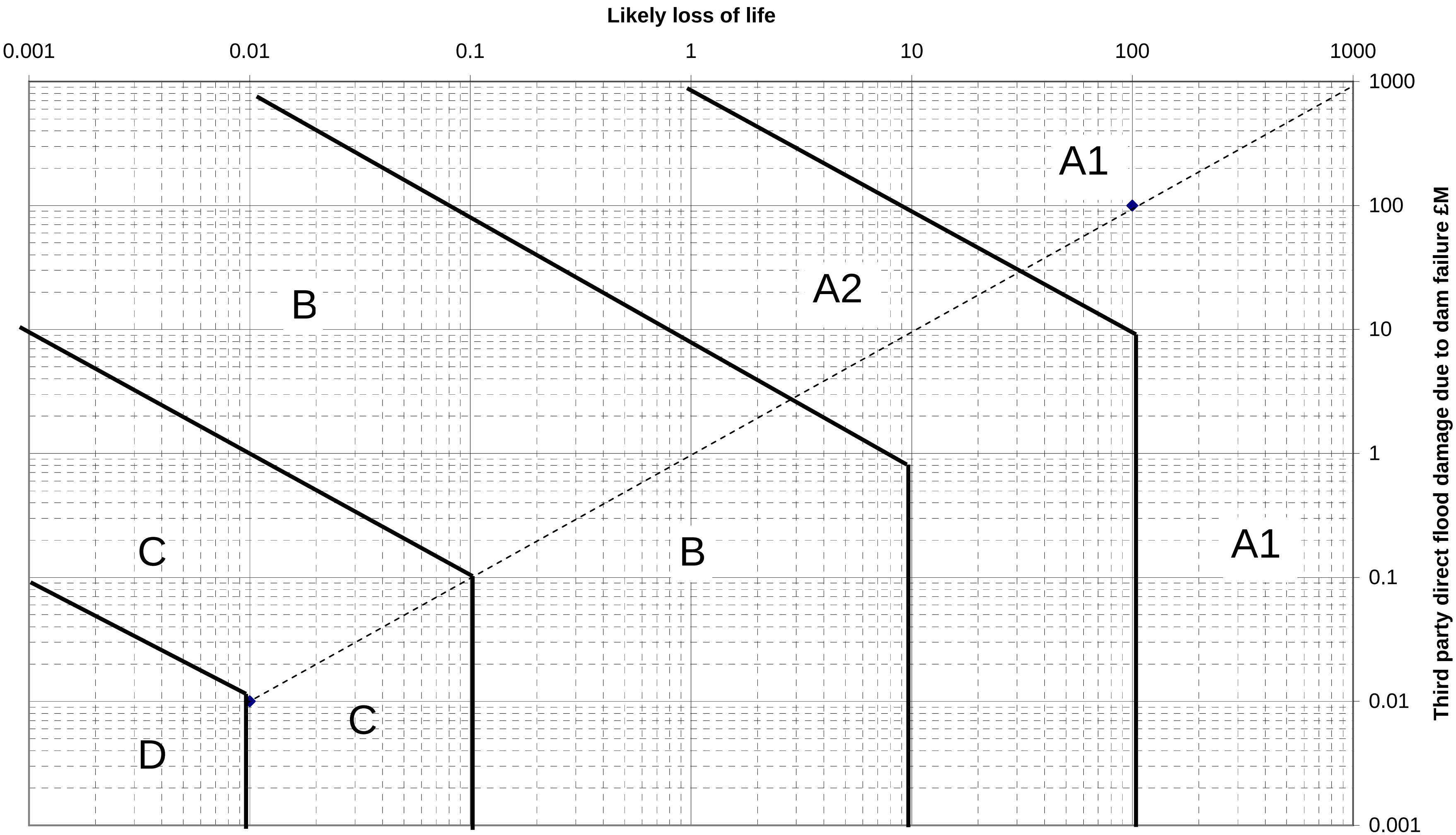


Figure 5.2 Consequence diagram for UK dams



6 ACTIONS TO PROGRESS AN EFFECTIVE SOLUTION TO MONITORING INTERNAL EROSION

6.1 Future research

It is clear that there are a number of significant uncertainties in relation to the current understanding of internal erosion which can only be resolved by a long term (10 year) programme. Issues which would be on such a shortlist are shown on Table 6.1

Table 6.1 : Issues for future research

1	The expert elicitation which has been carried out to date could be probed and extended by a further workshop 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)
2	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 is used instead of a 1mm hole, and the rate of erosion is measured)
3	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
4	Ditto for construction details of pipes and culverts through dams
5	Risk assessment, using Monte Carlo analysis to look at the probability of internal erosion, for credible ranges of core and shoulder parameters
6	Field techniques to investigate suspected internal erosion should be improved, through development and trials of alternative systems including a) Temperature measurement b) Acoustic c) Self potential d) Resistivity
7	Investigation of the viability of the use of gamma ray activity as a measure of the erosion of fines

6.2 Field trials

The terms of reference (TOR) call for

Stage 2 *– In the light of feedback at the review meeting, the strategy will be refined. Appropriate instrumentation and monitoring systems, which can provide immediate warning of changes to normal leakage levels, will be developed and tested on appropriate dams. Further development of the strategy may then be required.*

The KBR Inception report suggested that a sum of £200k be allowed for "a contract for development, supply, installation and demonstration of any instrumentation". Defra have indicated that the sum being requested for the financial year 2004-2005 is only £50k.

There are a number of important points regarding the terms of reference

a) the TOR refer to "normal leakage levels"; it could be argued that "and/ or onset of internal erosion" should be added after this text.
b) the TOR refer to "instrumentation" to "provide immediate warning"; it could be argued that a more effective means of reducing the probability of failure due to internal erosion is to identify the most vulnerable dams and carry out upgrading works

On this basis we have therefore identified four options for field trials, as shown in Table 6.2 (two with sub-options). Ideally all of Options A to C would be adopted (budget cost £75-150k). However, if the funds are limited then the priority would appear to be appurtenant works, when Options A1, B and C1 could be adopted (budget cost £40-70k).

Table 6.2 : Options for field trials

Option		Indicative cost	Objective		Argument for	Argument against
		(£k)	Remarks			
A1	Trial of package of "off the shelf" equipment for real time monitoring, comprising measurement of all or some of flow, turbidity, temperature, rainfall and reservoir level; with readings transmitted to remote station	15-30	Cost will depend to the extent to which the dam owner would contribute in terms of costs of installation and monitoring	Better understanding of issues and difficulties in real time monitoring	This is closest to what the TOR envisaged	c) really "pilot" with off the shelf equipment (it is debatable whether an instrumentation manufacturer could justify development of special equipment, if market was only say 200 units) d) "development" rather than research i.e. better value may be obtained in choosing other options first
A2	As A1, plus include development of software package to test data against trigger levels and sound alarm when exceeded (this would include development of methodology for defining trigger levels)	E/O 15-40	Would need to identify a company interested in developing the software defining trigger levels	As A1, plus issues in determining trigger levels and software to determine if readings exceed these levels		
B	Extend Expert Elicitation workshop, but limited to the top six experts and appointing protagonist to review questions, and argue for/ against the 5% and 95% values of say 20 of the 60 questions	10	Either 2 days at KBR offices, or more intense session of one evening and following day at hotel	Better understanding of issues affecting vulnerability	Cheap, improve information from elicitation at little cost	Money better spent on other issues
C1	Laboratory testing of erosion rate on samples taken from existing dams, following technique in Fell; for say minimum 10 different clay core types	15-30	Cost will depend on whether commercial laboratory, or whether laboratory testing could be a PhD at an appropriate university	Identify which dam cores most vulnerable to erosion, and potential rate of erosion	This would inform which dams required more frequent monitoring, and possibly upgrades	Change from terms of reference
C2	As C1, but also carry out field investigation at say 2 of these dams to establish range of properties of shoulders, followed by assessment of credible failure modes by internal erosion	E/O 20-40		Improve understanding of issues affecting vulnerability		
D	Field trial of temperature sensing and resistivity, with a variety of test positions etc	50- 100		Improve reliability of these techniques, as means of identification of leakage (and possibly internal erosion)	Provide additional tools for detection of internal erosion	This would duplicate work by BC Hydro and under the IMPACT programme (see Appendix F6.2and Table 3.1 of this report respectively). Collaboratively funded research with the EU, or other organisations may achieve better value for money in this subject area

1. Costs are only indicative for identifying preferred option(s). Once the preferred option(s) are identified then budget prices for funding purposes will be provided after consultation with potential suppliers

7 GLOSSARY

7.1 Acronyms

ALARP	As Low as is Reasonably Practicable
ANCOLD	Australian National Committee on large Dams www.ancold.org.au
ASDSO	USA : Association of State Dam Safety Officials. Set up in 1983, has annual conference e.g. see Kalkani, 1998. www.damsafety.org
BDS	British Dam Society www.britishdams.org
BHS	British Hydrological Society. Chronology of British Hydrological events on www.dundee.ac.uk/geography/cbhe
BOR	United States Bureau of Reclamation. www.usbr.gov. Dam safety office Website borworld.usbr.gov/dsi. Responsible for dams in 17 western states of USA
CBA	Cost Benefit Analysis
CDA	Canadian Dam association. *website www.cda.ca/cda/main*
CEH	Centre for Ecology and hydrology *http://www.nerc-wallingford.ac.uk/ih/*
COSHH	Control of Substances Hazardous to Health Regulations
COMAH	Control of Major Accident Hazards Regulations (SI 1999/743) – implementing Council Directive 96/82/EC (the COMAH Directive)
DCF	Dam Critical Flood
DEFRA	Department for Environment, Food and Rural Affairs. *Website defra.gov.uk/environment*
EA	Environment Agency (England). Flood warnings now available 24 hours/ day at www.environment-agency.gov.uk/floodwarning
EC	European Commission
FEMA	Federal Emergency Management Agency, USA www.fema.gov/mit/damsafe
FMEA	Failure Modes and effect analysis (defined in terminology)
FMECA	Failure Modes, effect and criticality analysis
FEH	Flood Estimation handbook (IH, 1999) 5 volumes http://www.nwl.ac.uk/feh/index.html
FERC	Federal Energy Regulatory Commission, USA
FRS	Floods and Reservoir safety. (ICE, 3rd Edition, 1996)
FSR	Flood Studies Report (NERC, 1975), and associated Supplementary reports (1978-1988); also Guide (IH, 1978)
HSC	Health and Safety Commission
HSE	Health and Safety Executive *Website www.hse.gov.uk/hse.board*
HSW	Health and Safety at Work
ICE	Institution of Civil Engineers *Website* www.ice.org.uk
ICODS	US Inter-agency committee on dam safety (described on FEMA website; ad-hoc committee set up in 1977; by 1998 had become “Federal Guidelines Development Subcommittee”)
ICOLD	International Commission on Large Dams. website *www.icold-cigb.org*
IFF	Imminent failure flood
LCI	Location, cause, indicator diagram, as described in RMUKR (CIRIA, 2000, Section 5.4.1)
LLOL	Likely loss of life, following dam failure
PAR	Population at risk, in event of dam failure

PMF/ PMP	Probable maximum flood/ probable maximum precipitation
QRA	Quantitative Risk Assessment
R2P2	Reducing Risk, protecting people (HSE, 2001)
USACE	United States Army Corps of Engineers. *Website* *www.usace.army.mil/inet/usace-docs*. Responsible for dams in eastern USA
USSD	United States Society on Dams (previously USCOLD). *Website* www2.privatei.com/~uscold/

7.2 Definitions and Terminology

ALARP (As low as reasonably practicable)	A societal risk criterion in the F/N chart. Tolerable only if risk reduction is impracticable or if its cost is grossly disproportionate to the improvement gained.
Assessing Engineer	The engineer carrying out the safety assessment using the Integrated System. Although this would often be the Inspecting Engineer carrying out a periodical inspection, this is not a pre-requisite for application of the system.
Cause Consequence diagram	This is constructed by defining a critical event and then developing the causes and consequences of this event. The forward development is similar to an event tree and the backward development is similar to a fault tree (Lees 1996, section 9/34)
Consequence	The outcome or result of a risk being realised e.g. the impact on the downstream areas resulting from a dam failure as well as the impact on the dam itself.
Criticality	Likelihood that the particular mechanism of deterioration could occur x Consequence for dam safety if it did occur
Dam critical external threat e.g. Critical Flood, Critical earthquake	The magnitude of the external threat that represents the integration of the conditional probability of failure (system response) over the range of potential load. (At this stage taken as equal to the Imminent failure event)
Dam-break analysis	An analysis which provides an estimation of downstream flooding effects resulting from dam failure. The analysis includes a dam breach analysis and the routing of the dambreak hydrograph through the downstream channel.
Dam break affected zone	That zone of flooding where the changes in depth and velocity of flooding due to dam break are such that there is a potential for incremental loss of life. The dambreak affected zone is sometimes limited to those areas where dambreak causes a rise in level of floodwaters greater than 300mm (this definition as ANCOLD, 2001; note that in 1998 FEMA in the US suggested greater than 600mm (Graham, 2000, page 955).

Deterministic approach	Leading to reasonably clear cut solutions based on prescriptive rules without considering the uncertainties in the analytical process. A typical result of a deterministic safety approach is the factor of safety (Kreuzer, 2000)
Event tree analysis	A technique which describes the possible range and sequence of outcomes which may arise from an initiating event
Emergency plans	The procedures to be followed in the event of predicted likely failure of a dam, including the actions to be taken by the dam owner/operator and the emergency services.
Engineering judgement	The professional opinion of an appropriately qualified engineer (different from Expert Judgement)
Event Train	The sequence of events starting with an initiating event and ending with its consequences. How could xxxx have happened? The number of intermediate events is dependent on the failure mechanism being considered, e.g. leakage of a dam, an escalation of the leakage, leading to failure of the dam, a release of water, with the consequence of potential fatalities. It varies from logic diagrams which quantify the probability of events, as event train are purely qualitative.
Event Tree	An event tree is used to develop the <u>consequences</u> of an event, i.e. what happens if xxxx happens?. The event tree is both a qualitative and a quantitative technique. Qualitatively it is used to identify the individual outcomes of the initial event, while quantitatively it is used to estimate the frequency or probability of each outcome. An event tree is constructed by defining an initial event e.g. overtopping and the possible consequences which flow from this. The main elements of the tree are event definitions and branch points or logic vertices; these points being precisely defined as TRUE / FALSE (see Section 9.6 of Lees, 1996)
Expert Judgement	Opinion of quantitative likelihood of an event elicited by a trained elicitor under controlled conditions, and which satisfies axioms of probability theory (see Skipp & Woo, 1993)
External threats	External loads such as floods and earthquake are random natural events which can be measured and extrapolations made to estimate the magnitude of extreme events that could cause failure of the dam. They are different from the specific mechanisms that can cause degradation of the dam, which are termed mechanism(s) of deterioration.
Failure (of a dam)	A uncontrolled sudden large release of retained water (large is in relation to the downstream channel and is taken to be greater than the lesser of the mean annual flood or bank full flow)

Failure mode(s)	Means by which a failure (uncontrolled sudden large release of water) may occur. Four failure modes are differentiated in this contract, namely external erosion (including overtopping), internal erosion (through body of dam, or at contact with a structure), sliding and appurtenant works.
Fault tree	A logic diagram is used to develop the causes of an event. It starts with the event of interest, the top event, such as a dam failure, and is developed from the top down. The fault tree is both a qualitative and a quantitative technique. Qualitatively it is used to identify individual paths which led to the top event, while quantitatively it is used to estimate the frequency or overall probability of that event, e.g. failure of complete system through the use of AND/OR TESTS at each branch point (see Section 9.5 of Lees, 1996)
F-N curve	A graph showing the relationship between the frequency of an event (F) causing N or more fatalities plotted on a log-log plot and the number of fatalities (N). They may be plotted on a 'non-cumulative' basis and are referred to as fN curves, or on a 'cumulative ' basis and referred to as FN curves (where F is the likelihood of N *or more* fatalities). Examples of these and other forms of presentation are given in Annex 1 of Ball & Floyd (1998).
FMEA	Tabular approach using columns to define function e.g. separate columns for • how function fails, • the failure mode that causes functional failure • assessing the effects of that failure both locally and globally. Description given in BS 5760-5:1991 and ANCOLD (2001).
FMECA	As FMEA but also assesses both the likelihood of the event occurring and the consequences (the last two columns of FMEA). Description given in BS 5760-5:1991.
Frequency	A measure of likelihood expressed as the number of occurrences of an event in a given time or in a given number of trials. See also Likelihood and Probability.
Hazard	A situation with a potential for human injury, property damage or other undesirable outcome.
Imminent failure load	External load of a magnitude such that the dam would just fail e.g. Imminent failure flood
Incident	Detectable change in Indicator causing sufficient concern to lead to some action (three levels are used in NDD; Levels 2 to 4 as shown in Table C.2)
Indicator	Measurable outcome from the application of a mechanism of deterioration e.g. deformation, seepage, instrumentation results (see Table 2.3).

Inspecting Engineer	A qualified civil engineer employed by the undertakers to inspect a reservoir in accordance with Section 10 of the Reservoirs Act 1975.
Integrated system	A system for carrying out a Risk assessment on a single dam, that quantifies the overall probability of failure from all the various threats to the safety of a dam, evaluates the consequences of failure and thus the risk posed by the dam and provides some measure of whether this risk is tolerable.
Internal threat	Internal threats relate to mechanisms of deterioration that occur within the body of the dam. These are • not necessarily random natural events (and thus amenable to statistical analysis), • often difficult to measure (and thus not amenable to analysis of trend or other time or dose related analysis of measured parameters) • much less well understood in terms of mechanism of behaviour
Intrinsic condition	Current physical property or dimension of the dam which can be measured and which affects the outcome of the application of a mechanism of deterioration. Although initially determined by design and construction details; this may change with time due to ageing, neglect, maintenance or upgrading.
Joint probability	The probability that two or more variables will assume certain values simultaneously or within particular time intervals.
Large dam	That listed on the *World Register of Large Dams* published by ICOLD. To qualify for the ICOLD register of large dams the dam must be 15m above the lowest foundation level. However, dams between 10 and 15m in height may be included if they also exceed one of the following criteria: length of crest 500m, reservoir capacity 1 Mm^3, maximum flood discharge of $2000m^3/s$ or if the dam had difficult foundation problems or is of unusual design.
Large raised reservoir	As defined in the Reservoirs Act 1975, namely designed to hold, or capable of holding more than $25,000m^3$ above the lowest natural ground level adjoining the reservoir
Likelihood	Used as a qualitative description of probability and frequency.
Logic diagrams	Diagrams such as event tree, fault tree and cause consequence diagrams which quantify the probability of events through logic gates at the intersection points (i.e. have GO/NO-GO or AND/OR gates) and probabilities on each branch.
Mechanism(s) of deterioration	Process by which the integrity of the dam is undermined. The mechanism can have a quantitative threshold above which deterioration is likely to occur e.g. slope protection designed to withstand waves due to 100 year wind

Monte Carlo Simulation	Determination of the probabilities or annual probabilities of events for complex systems, where the system configuration and the failure and repair characteristics of the dam's components (input data) are known or can be estimated. The time period is divided into small increments and simulation of operation of the system repeated until the output probability distribution stabilises.
Overtopping	Water flowing over the top of the dam, other than over spillweirs or other overflow devices.
Panel engineer	A civil engineer appointed to panels by the Secretary of State under the Reservoirs Act 1975, who can be appointed by an undertaker to inspect, design or supervise a reservoir.
Portfolio risk analysis	Assessment of risk for a group of dams within a defined responsibility
Probability (type)	It may appear intuitively obvious what is meant by probability, but the word in fact has several meanings. Moreover, the distinctions are of some practical importance. They are relevant, for example, to the question of the relative weight which should be attached to field data and to other information available to individuals. The following is reproduced from Lees (1996, Section 7.4) "a) *Equal likelihood* - One definition of probability derives from the principle of equal likelihood. If a situation has *n* equally likely and mutually exclusive outcomes, and if n_A of these out-comes are event A, then the probability P(A) of event A is: $P(A)= \frac{n_A}{n}$ This probability can be calculated a *priori* and without doing experiments. The example usually given is the throw of an unbiased die, which has six equally likely outcomes: the probability of throwing a one is 1/6. This definition of probability is often of limited usefulness in engineering because of the difficulty of defining situations with equally likely and mutually exclusive outcomes. b) *Relative Frequency* - The second definition of probability is based on the concept of relative frequency. If an experiment is performed *n* times and if the event A occurs on n_A of these occasions, then the probability P(A) of event A is: $P(A)= \lim_{n \to \infty} \frac{n_A}{n}$ This probability can only be determined by experiment. This definition of reliability is the one which is most widely used in engineering. In particular, it is this definition which is implied in the estimation of probability from field failure data.

c) *Personal Probability (Expert judgement)* - A third definition of probability is degree of belief. It is the numerical measure of the belief which a person has that the event will occur. Often this corresponds to the relative frequency of the event. But this is not always so, for several reasons. One is that the relative frequency data available to the individual may be limited or non-existent. Another is that even if he has such data, he may have other information which causes him to think that the data are not the whole truth. There are many possible reasons for this. The individual may doubt the applicability of the data to the case under consideration, or he may have information which suggests that the situation has changed since these data were collected.

It is entirely legitimate to take into account such personal probabilities. There are several branches of probability theory which attempt to accommodate personal probability. These include ranking techniques (e.g. Siegel, 1956), which give the numerical encoding of judgements on the probability of ranking of items, and Bayesian methods (e.g. Breipohl, 1970), which allow probabilities to be modified in the light of additional information. Further discussions of personal probability are given by Savage (1962) and by Tribus (1969)."

It should be noted that ANCOLD also distinguish three different types of probability, where 'a' and 'b' above are included in one type (statistical) with a separate type as follows:

Mathematical - a probability based on axioms (self evident truth). A probability curve being a mathematical abstraction where the mathematician is interested in the formal properties of such curves independent of their interpretation.

Probability (terms)

Care should also be taken in differentiating whole life probability from annual rate (termed annual probability in this report); as there are important constraints on the way they may be combined.

Although annual probability are strictly rates the distinction becomes negligible when they are small. If events are occurring at rate λ, then the probability of one of more of these events occurring in unit time is $1-e^{-\lambda}$. And when λ is small, this is almost exactly the same as λ. So a rate of λ per annum equates almost exactly to an annual probability of λ, provided λ is small. How small does it need to be? Well, 10^{-3} is certainly small enough, and even 10^{-1} is not bad. It is emphasised that since they are small within the context of this project we can also think of them as mean rates per annum.

	It is also important to understand the difference between annual probability (AP) and annual exceedance probability (AEP). The latter tends to be used when defining design loading, where all events in excess of the design threshold are of interest.
	Both annual probabilities and annual exceedance probabilities technically refer to the probability of one *or more* events occurring in a year. This is unimportant as when the probabilities are small, the chance of two or more occurring in a year is extremely small, so (to the same order of approximation as approximating annual probabilities by rates) the probability of one or more event in a year is almost exactly equal to the probability of just one.
Probability density function	A function describing the relative likelihood that a random variable will assume a particular value in contrast to taking on other values.
Qualitative risk assessment	A risk assessment process conducted purely on a qualitative basis with no numerical data.
Quantitative risk assessment	A risk assessment process involving the use of numerical data. This is normally undertaken when a facility or operation has a major hazard potential for either the workforce, fixed assets or the public.
Reliability	Likelihood of successful performance of a given project element. It may be measured on an annualised basis or for some specified time period of interest. Mathematically, Reliability = 1 – Probability of failure.
Return period	The average expected time (in terms of probability) between floods equal to or greater than a stated magnitude.
Risk	The probability or frequency of an event occurring with a measurement of the event's consequences (Lees 1996, Section 9/97). (NB: There are a number of alternate definitions for risk as described in Section A1 of RMUKR. From a recommendation of Prof. T. O'Hagan and the E&P Forum 1996 (from the oil and gas industry) the above definition is the preferred definition for this study.)
Risk Analysis	The quantitative evaluation of the likelihood of undesired events and the likelihood of harm or damage being caused. It involves identification of the hazard, assessment of the probability of its occurrence and the magnitude of its consequences.
Risk assessment	Combines risk analysis with evaluation of the acceptable risk (as Figure E.1 and 6.1 of the report on Intergation of Floods and refervoid safty, derived from Figure 1 of Kreuzer, 2000)

Risk aversion	A phrase that indicates the inherent aversion to "high risk", or more correctly high consequence, events. It is accepted that events resulting in multiple fatalities should occur at a lower frequency than events that cause a single fatality, usually at a rate proportional to the number of fatalities (i.e. an event causing ten fatalities should occur at a frequency at least ten times lower than events causing single fatalities).
Risk control	Actions to avert risk by alternative solutions and to reduce risk by surveillance.
Risk evaluation	Evaluation of what constitutes tolerable risk (risk acceptance criteria)
Risk management	Combination of risk assessment and risk control to manage risk to a tolerable level along with normal commercial risks.
Section 105 survey	A survey undertaken by the Environment Agency to identify areas at risk of flooding, undertaken in accordance with Section 105 of the Water Resources Act, 1991.
Societal concern	Societal concerns arise when the realisation of a risk impacts on society as a whole i.e. a large number of people may be killed at one time, where potential victims are particularly vulnerable (such as children) or where the nature of the risk inspire dread (such as long term or irreversible effects) (taken from par. 31 to 32 of HSE Guidelines (Dec 2001) on whether dutyholders have reduced risk to ALARP level)
Supervising engineer	A qualified civil engineer employed by the undertakers to supervise a reservoir in accordance with Section 12 of the Reservoirs Act 1975.
Threat	Random Event (External threat) or Potential Internal Instability (Internal threat) that poses a threat to the integrity of the dam. The latter is subdivided as shown on Table 2.2.
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, 2000, page 3)
Uncertainty	Previously used to refer to situations where the likelihood of potential outcomes could not be described by objectively known probability density functions. Now used to describe any situations without sureness, whether or not described by a probability distribution. In the context of dam safety, uncertainty can be attributed to (i) inherent variability in natural properties and events, and (ii) incomplete knowledge of parameters and the relationships between input and output values.
Vulnerability	The extent that people, property etc could be impacted by a dam failure
Wear-in	Failures in the first five years of the life of a dam