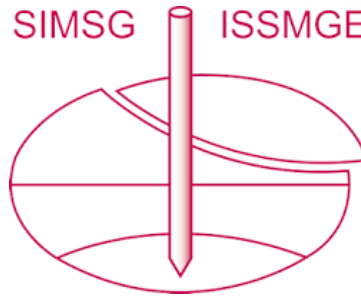


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Risk Assessment for Embankment Dams Assessment of the Probability of Failure by Piping

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Summary The history of embankment dam failures is that about half are caused by piping through the embankment or the foundation. This paper presents methods for estimating the probability of failure by piping taking account of the zoning of the dam, the geology of the foundation, the materials used to construct the dam, and the in-service performance. Two approaches are described, one based on historic performance statistics, the second using event trees.

1. INTRODUCTION

The history of embankment dam failures is that about half are caused by piping through the embankment or the foundation. It is important therefore that when dam safety reviews are carried out, piping failure modes are assessed. Often, the assessment is based on the judgement of the engineers involved, but more recently, some dam authorities in Australia, USA, Canada and Norway, have been using Quantitative Risk Assessment (QRA) methods. These link the probability of failure to the consequences.

To carry out the QRA for existing and new dams, methods are needed for estimating the probability of breaching (leading to rapid release of the reservoir) by internal erosion and piping:

- in the embankment
- from the embankment to the foundation
- in the foundation

for:

- all types of embankment dams
- all types of soil and rock foundations

for:

- initial or preliminary studies, where there are limited resources and funds, eg. for assessing relative risks in a portfolio of dams, and for comparison with other hazards (eg. floods, earthquake)
- detailed studies, which are to determine whether a dam meets acceptable safety criteria, or whether remedial works are needed, and if so, what is needed

Note that in most situations it is the probability of breaching of the dam which is critical. This is quite different to the probability of initiation of internal erosion; incidence of "boils" in the

foundation; or of significant leakage through the dam or/and its foundation. However, there are situations where significant economic losses may result from the loss of the facility, eg. if piping initiates and the dam has to be drawn down or emptied until remedial work can be done.

There are two approaches to assessing the probability of piping failure:

- Historic performance data - eg ICOLD (1974, 1983, 1995) McCann et al 1985, Fell (1995).
- Those based on event trees. Examples are given in Johansen et al (1997), Landon-Jones et al (1995).

These methods are discussed in this paper based on the results of a research project being carried out at the University of New South Wales, and on the first authors experience in dams risk assessment.

2. THE PIPING PROCESS

We, along with others, eg. Von Thun (1996), Johansen et al (1997), have chosen to break down the process of piping into several stages to facilitate analysis, and to allow an understanding of the processes involved. Figure 1 shows schematically the stages of development, for piping in the embankment.

- initiation of internal erosion
- continuation of erosion (as opposed to self healing, eg. on filters)
- progression to develop a pipe in the dam, foundation, or both
- development of a failure mode by the flow of water, either by unravelling, slope instability, slumping of the dam crest by piping, or development of a sufficiently large pipe to drain the reservoir

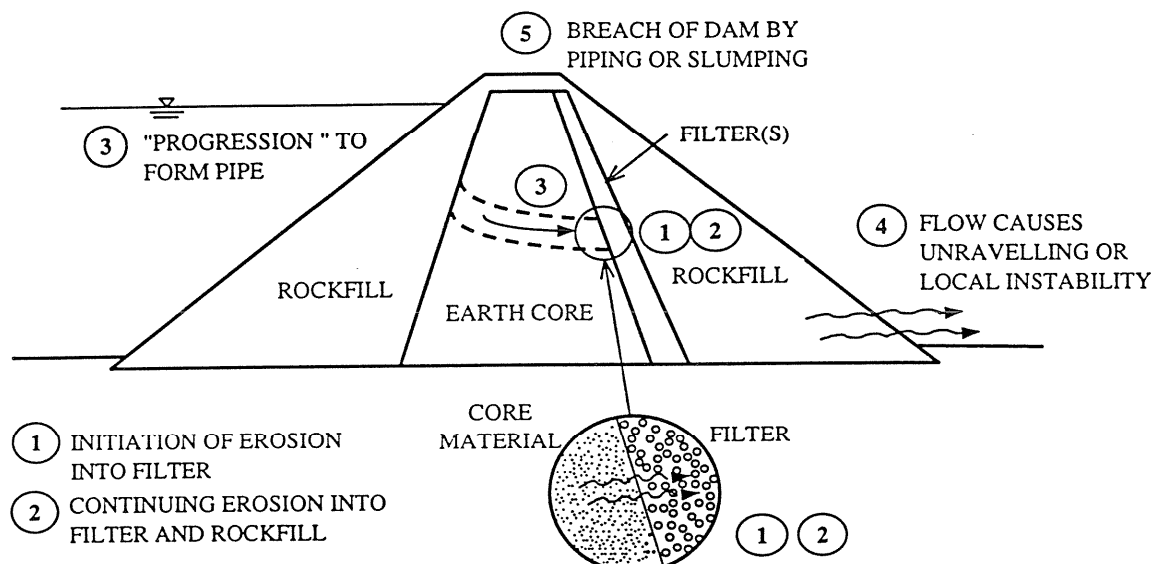


Figure 1. Stages in the development of breaching by piping in the embankment.

- breaching of the dam with sudden release of the reservoir water.

Similar processes are involved in piping in the foundation, and piping from the embankment to the foundation.

3. HISTORIC PERFORMANCE - UNSW METHOD

The Dams Risk Research Project at UNSW has developed an extensive database of dam failures and accidents. This is based on the ICOLD studies, but includes considerably more information on the dams, where it has been possible to obtain it. This includes:

- zoning of the dams
- foundation geology (rock type, soil origin)
- cutoff details
- embankment core soil classification and origin
- compaction of the soil
- details of filters
- observations of performance
- details of the failure or accident timing.

Based on this data, and a detailed assessment of the characteristics of the world population of dams against which the failed dams can be compared, a method for assessing the probability of failure by piping has been developed.

The method is described in detail in Foster et al (1998), and Foster et al (1999). Only the main components are described here.

The method involves the adjustment of the historical average probabilities of failure of the three modes of piping to take account of the characteristics of the dam, such as core properties, compaction and foundation geology, and to take account of the past performance of the dam. These adjustments are made with the use of *weighting factors* which are multiplied to the average probabilities of failure.

To assess the annual probability of failure by piping:

- Determine the average annual probabilities of failure from Table 1 for each of the three modes of piping failure:
 - piping through the embankment, P_e
 - piping through the foundation, P_f , and
 - piping from the embankment into the foundation, P_{ef}
 allowing for the age of the dam ie whether less than or older than 5 years.
- Calculate the weighting factors W_E , W_F and W_{EF} from Tables 2, 3 and 4 to take account of the characteristics of the dam, such as core properties, compaction and foundation geology, the past performance of the dam. The weighting factors are obtained by multiplying the individual weighting factors from the relevant table. So, for example, $W_E = W_{E(filt)} \times W_{E(cgo)} \times W_{E(est)} \times W_{E(cc)} \times W_{E(con)} \times W_{E(ft)} \times W_{E(obs)} \times W_{E(mon)}$.
- Obtain the overall probability of failure by piping (P_p) by summing the weighted probabilities

$$P_p = W_E P_e + W_F P_f + W_{EF} P_{ef}$$

If probabilities are high, allowance must be made for the union of events in this calculation.

Figure 2 shows the dam zoning categories used. Table 5 shows the time of occurrence of piping failures after construction. It can be seen that most failures occur on first filling or in the first 5 years of operation.

If a factor has two or more possible weighting factors that can be selected for a particular dam characteristic, such as different zoning types or different foundation geology types, then the weighting factor with the greatest value should be used. This is consistent with the method of analysis that was used to determine the weighting factors.

Table 1. Average Probability of failure of embankment dams by mode of failure and dam zoning.

ZONING CATEGORY	EMBANKMENT			FOUNDATION			EMBANKMENT INTO FOUNDATION		
	AVER- AGE. P_{Te} ($\times 10^{-3}$)	AVERAGE ANNUAL P_e ($\times 10^{-6}$)		AVER- AGE. P_{Tf} ($\times 10^{-3}$)	AVERAGE ANNUAL P_f ($\times 10^{-6}$)		AVER- AGE. P_{Tef} ($\times 10^{-3}$)	AVERAGE ANNUAL P_{ef} ($\times 10^{-6}$)	
		First 5 Years Operation	After 5 Years Operation		First 5 Years Operation	After 5 Years Operation		First 5 Years Operation	After 5 Years Operation
Homogeneous earthfill	16	2080	190	↑	↑	↑	↑	↑	↑
Earthfill with filter	1.5	190	37						
Earthfill with rock toe	8.9	1160	160						
Zoned earthfill	1.2	160	25						
Zoned earth and rockfill	1.2	150	24						
Central core earth and rockfill	(<1.1)	(<140)	(<34)	1.7	255	19	0.18	19	4
Concrete face earthfill	5.3	690	75	↓	↓	↓	↓	↓	↓
Concrete face rockfill	(<1)	(<130)	(<17)						
Puddle core earthfill	9.3	1200	38						
Earthfill with corewall	(<1)	(<130)	(<8)						
Rockfill with corewall	(<1)	(<130)	(<13)						
Hydraulic fill	(<1)	(<130)	(<5)						
ALL DAMS	3.5	450	56	1.7	255	19	0.18	19	4

Notes: (1) P_{Te} , P_{Tf} and P_{Tef} are the average probabilities of failure over the life of the dam.
(2) P_e , P_f and P_{ef} are the average annual probabilities of failure.

Table 5. Time of occurrence of piping failures after construction.

Time of Failure	Piping Mode		
	Embankment	Foundation	Embankment to Foundation
During first filling	49%	25%	24%
During first 5 years operation including first filling	65%	75%	53%
After 5 years operation	35%	25%	47%

The method is intended for preliminary assessments only. It is ideally suited as a risk ranking method for portfolio type risk assessments to identify which dams to prioritise for more detailed studies. Since the method is based on a dam performance database approach, it tends to lump together the factors which influence the initiation and progression of piping and it is not possible to assess what influence each of the factors is having. It is recommended that more rigorous event tree based methods be used for detailed studies, so as to gain a greater understanding of how each of the factors influences either the initiation or progression of piping, or the formation of a breach.

The user of the method is cautioned against varying the weighting factors significantly when applying the method. They have been calibrated to the population of dams so that the net effect on the population is neutral.

The probabilities of failure are based on large dams (>15m height) and so the method may tend to underestimate the probability of failure of piping if applied to smaller dams.

4. EVENT TREE METHODS

A number of organisations have used event trees coupled with expert judgement to assess the probability of piping. Examples are the Coursier Dam study done by BC Hydro (1995) and the study of Prospect Dam (Landon-Jones et al, 1995), and a study of three central core earth and rockfill dams in Norway (Johansen et al, 1997).

In these studies, the event tree is set up to model initiation, progression, possible intervention, and breaching. The probabilities in the event tree are estimated by a panel of "experts" based on their experience, data supplied to them regarding the design and construction of the dam, and selected reading of papers relevant to the topic.

The approach has some advantages compared with the historic performance data approach:

- there is more emphasis on the design, construction and performance of the dam in question
- the problem is broken down into smaller components which usually makes estimation of probability easier
- consideration of design details, such as compliance with filter criteria is possible.

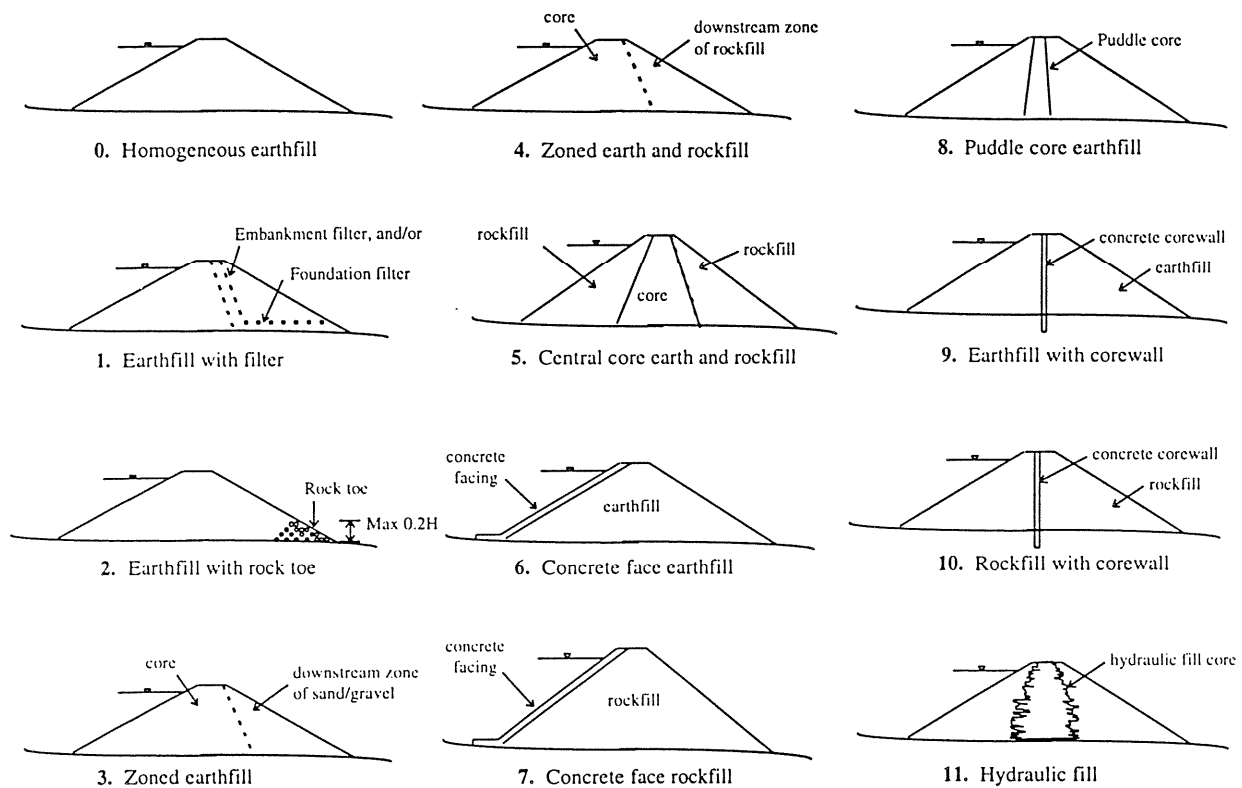


Figure 2. Dam Zoning Categories

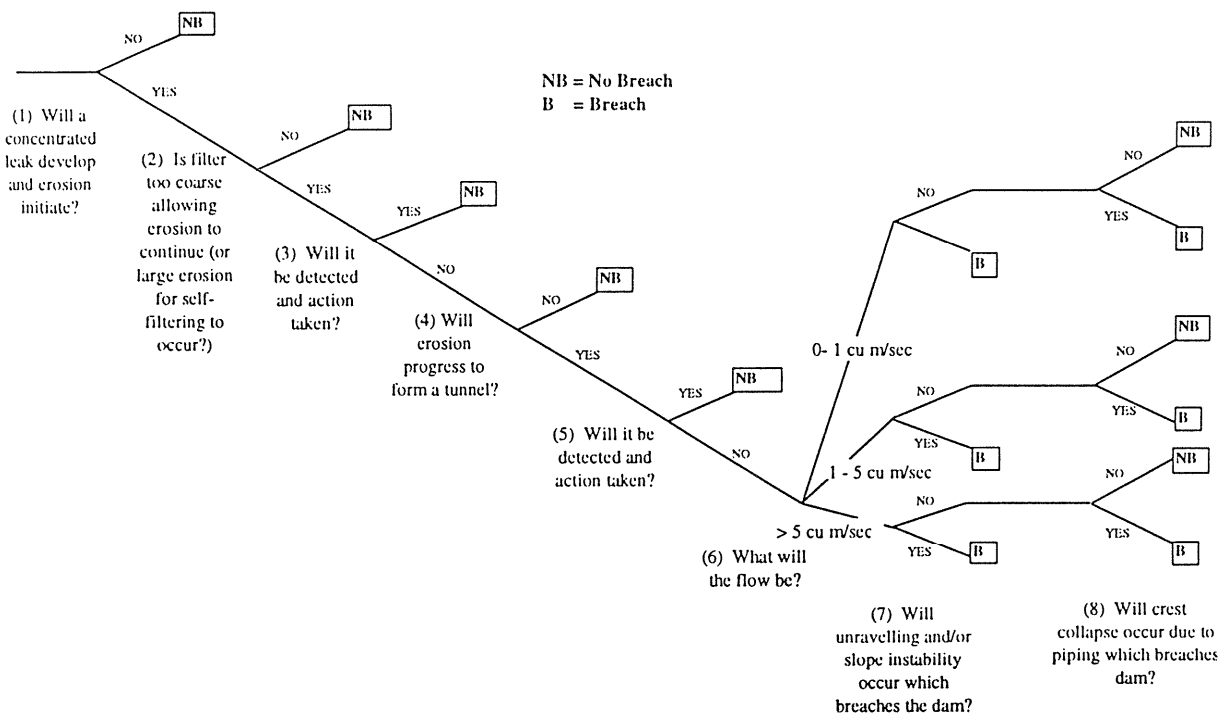


Figure 3. Detailed event tree - piping in the embankment

Table 2. Summary of the weighting factors for piping through the embankment mode of failure.

FACTOR	GENERAL FACTORS INFLUENCING LIKELIHOOD OF FAILURE				
	MUCH MORE LIKELY	MORE LIKELY	NEUTRAL	LESS LIKELY	MUCH LESS LIKELY
ZONING	Refer to Table 1 for the average annual probabilities of failure by piping through the embankment depending on zoning type				
EMBANKMENT FILTERS $W_{F(filt)}$		No embankment filter (for dams which usually have filters (refer to text)) [2]	Other dam types [1]	Embankment filter present - poor quality [0.2]	Embankment filter present - well designed and constructed [0.02]
CORE GEOLOGICAL ORIGIN $W_{F(ego)}$	Alluvial [1.5]	Aeolian, Colluvial [1.25]	Residual, Lacustrine, Marine, Volcanic [1.0]		Glacial [0.5]
CORE SOIL TYPE $W_{F(cst)}$	Dispersive clays [5]	Clayey and silty sands (SC, SM) [1.2]	Well graded and poorly graded gravels (GW, GP) [1.0]	Clayey and silty gravels (GC, GM) [0.8]	High plasticity clays (CH) [0.3]
	Low plasticity silts (ML) [2.5] Poorly and well graded sands (SP, SW) [2]			Low plasticity clays (CL) [0.8]	
COMPACTION $W_{F(cc)}$	No formal compaction [5]	Rolled, modest control [1.2]	Puddle, Hydraulic fill [1.0]		Rolled, good control [0.5]
CONDUITS $W_{F(con)}$	Conduit through the embankment - many poor details [5]	Conduit through the embankment - some poor details [2]	Conduit through embankment - typical USBR practice [1.0]	Conduit through embankment - including downstream filters [0.8]	No conduit through the embankment [0.5]
FOUNDATION TREATMENT $W_{F(ft)}$	Untreated vertical faces or overhangs in core foundation [2]	Irregularities in foundation or abutment, Steep abutments [1.2]		Careful slope modification by cutting, filling with concrete [0.9]	
OBSERVATIONS OF SEEPAGE $W_{F(obs)}$	Muddy leakage Sudden increases in leakage [up to 10]	Leakage gradually increasing, clear, Sinkholes, Seepage emerging on downstream slope [2]	Leakage steady, clear or not observed [1.0]	Minor leakage [0.7]	Leakage measured none or very small [0.5]
MONITORING AND SURVEILLANCE $W_{F(mon)}$	Inspections annually [2]	Inspections monthly [1.2]	Irregular seepage observations, inspections weekly [1.0]	Weekly - monthly seepage monitoring, weekly inspections [0.8]	Daily monitoring of seepage, daily inspections [0.5]

Table 3. Summary of weighting factors for piping through the foundation mode of failure.

FACTOR	GENERAL FACTORS INFLUENCING LIKELIHOOD OF FAILURE				
	MUCH MORE LIKELY	MORE LIKELY	NEUTRAL	LESS LIKELY	MUCH LESS LIKELY
ZONING	Refer to Table 1 for the average annual probability of failure by piping through the foundation				
FILTERS $W_{F(filt)}$		No foundation filter present when required [1.2]	No foundation filter [1.0]	Foundation filter(s) present [0.8]	
FOUNDATION TYPE (below cutoff) $W_{F(fnd)}$	Soil foundation [5]		Rock - clay infilled or open fractures and/or erodible rock substance [1.0]	Better rock quality →	Rock - closed fractures and non-erodible substance [0.05]
CUTOFF TYPE (Soil foundation) $W_{F(cts)}$ OR CUTOFF TYPE (Rock foundation) $W_{F(ctr)}$	Sheetpile wall Poorly constructed diaphragm wall [3]	Shallow or no cutoff trench [1.2] Well constructed diaphragm wall [1.5]	Partially penetrating sheetpile wall or poorly constructed slurry trench wall [1.0] Average cutoff trench [1.0]	Upstream blanket, Partially penetrating well constructed slurry trench wall [0.8] Well constructed cutoff trench [0.9]	Partially penetrating deep cutoff trench [0.7]
SOIL GEOLOGY TYPES (below cutoff) $W_{F(rg)}$, OR ROCK GEOLOGY TYPES (below cutoff) $W_{F(rg)}$	Dispersive soils [5] Volcanic ash [5] Limestone [5] Dolomite [3] Saline (gypsum) [5] Basalt [3]	Residual [1.2] Tuff [1.5] Rhyolite [2] Marble [2] Quartzite [2]	Aeolian, Colluvial, Lacustrine, Marine [1.0]	Alluvial [0.9] Sandstone, Shale, Siltstone, Claystone, Mudstone, Hornfels [0.7] Agglomerate, Volc. Breccia [0.8]	Glacial [0.5] Conglomerate [0.5] Andesite, Gabbro [0.5] Granite, Gneiss [0.2] Schist, Phyllite, Slate [0.5]
OBSERVATIONS OF SEEPAGE $W_{F(obs)}$ OR OBSERVATIONS OF PORE PRESSURES $W_{F(nbp)}$	Muddy leakage Sudden increases in leakage [up to 10] Sudden increases in pressures [up to 10]	Leakage gradually increasing, clear, Sinkholes, Sandboils [2] Gradually increasing pressures in foundation [2]	Leakage steady, clear or not observed [1.0] High pressures measured in foundation [1.0]	Minor leakage [0.7]	Leakage measured none or very small [0.5] Low pore pressures in foundation [0.8]
MONITORING AND SURVEILLANCE $W_{F(mon)}$	Inspections annually [2]	Inspections monthly [1.2]	Irregular seepage observations, inspections weekly [1.0]	Weekly - monthly seepage monitoring, weekly inspections [0.8]	Daily monitoring of seepage, daily inspections [0.5]

Table 4. Summary of weighting factors for piping from the embankment into the foundation - accidents and failures.

FACTOR	GENERAL FACTORS INFLUENCING LIKELIHOOD OF INITIATION OF PIPING - ACCIDENTS AND FAILURES				
	MUCH MORE LIKELY	MORE LIKELY	NEUTRAL	LESS LIKELY	MUCH LESS LIKELY
ZONING	Refer to Table 1 for the average annual probability of failure by piping from embankment into foundation				
FILTERS $W_{EF(filt)}$	Appears to be independent of presence/absence of embankment or foundation filters [1.0]				
FOUNDATION CUTOFF TRENCH $W_{EF(cot)}$	Deep and narrow cutoff trench [1.5]		Average cutoff trench width and depth [1.0]	Shallow or no cutoff trench [0.8]	
FOUNDATION TYPE $W_{EF(fnd)}$		Founding on or partly on rock foundations [1.5]			Founding on or partly on soil foundations [0.5]
EROSION CONTROL MEASURES OF CORE FOUNDATION $W_{EF(ecm)}$	No erosion control measures, open jointed bedrock or open work gravels [up to 5]	No erosion control measures, average foundation conditions [1.2]	No erosion control measures, good foundation conditions [1.0]	Erosion control measures present, poor foundations [0.5]	Good to very good erosion control measures present and good foundation [0.3 – 0.1]
GROUTING OF FOUNDATIONS $W_{EF(gr)}$		No grouting on rock foundations [1.3]	Soil foundation only - not applicable [1.0]	Rock foundations grouted [0.8]	
SOIL GEOLOGY TYPES $W_{EF(sg)}$, OR ROCK GEOLOGY TYPES $W_{EF(rg)}$	Colluvial [5] Sandstone interbedded with shale or limestone [3] Limestone, gypsum [2.5]	Glacial [2] Dolomite, Tuff, Quartzite [1.5] Rhyolite, Basalt, Marble [1.2]	 Agglomerate, Volcanic breccia Granite, Andesite, Gabbro, Gneiss [1.0]	Residual [0.8] Sandstone, Conglomerate [0.8] Schist, Phyllite, Slate, Hornfels [0.6]	Alluvial, Aeolian, Lacustrine, Marine, Volcanic [0.5] Shale, Siltstone, Mudstone, Claystone, [0.2]
CORE GEOLOGICAL ORIGIN $W_{EF(cgo)}$	Alluvial [1.5]	Aeolian, Colluvial [1.25]	Residual, Lacustrine, Marine, Volcanic [1.0]		Glacial [0.5]
CORE SOIL TYPE $W_{EF(cst)}$	Dispersive clays [5] Low plasticity silts (ML) [2.5] Poorly and well graded sands (SP, SW) [2]	Clayey and silty sands (SC, SM) [1.2]	Well graded and poorly graded gravels (GW, GP) [1.0] High plasticity silts (MH) [1.0]	Clayey and silty gravels (GC, GM) [0.8] Low plasticity clays (CL) [0.8]	High plasticity clays (CH) [0.3]
CORE COMPACTION $W_{EF(cc)}$	Appears to be independent of compaction - all compaction types [1.0]				
FOUNDATION TREATMENT $W_{EF(ft)}$	Untreated vertical faces or overhangs in core foundation [1.5]	Irregularities in foundation or abutment, Steep abutments [1.1]		Careful slope modification by cutting, filling with concrete [0.9]	
OBSERVATIONS OF SEEPAGE $W_{EF(obs)}$	Muddy leakage, Sudden increases in leakage [up to 10]	Leakage gradually increasing, clear, Sinkholes [2]	Leakage steady, clear or not monitored [1.0]	Minor leakage [0.7]	Leakage measured none or very small [0.5]
MONITORING AND SURVEILLANCE $W_{EF(mon)}$	Inspections annually [2]	Inspections monthly [1.2]	Irregular seepage observations, inspections weekly [1.0]	Weekly - monthly seepage monitoring, weekly inspections [0.8]	Daily monitoring of seepage, daily inspections [0.5]

However, there are some problems including:

- there is little or no basis upon which the expert panel can estimate probabilities for progression and breaching, and it is only marginally better for initiation of piping. Hence, the outcome is very dependent on the panel members and hard to document other than as “expert judgement”
- the data provided for the expert panel is likely to be biased towards failures, and as a result, probabilities of piping are likely to be overestimated.

The Dams Risk Research Project at UNSW is developing databases and other information to aid expert panels in their assessment of probabilities for:

- will a concentrated leak develop?

- initiation of internal erosion
- continuation of internal erosion
- progression to develop piping
- development of a failure mode and breaching of the dam.

The concept is that this information will be available to improve the accuracy, and facilitate justification of the probabilities at each branch in the event trees. The event trees would be similar to that shown in Figure 3, which is for piping through the embankment. Similar event trees are to be developed for piping from the embankment into the foundation, and piping in the foundation.

Considering each of the stages in development of piping failure in turn:

(a) Will a concentrated leak develop?
Whether piping can develop in a dam depends on whether a concentrated leak can form.

In this context a concentrated leak is:

- a transverse crack through the core of the dam
- a continuous high permeability zone in the core due to poor compaction of a layer
- high permeability zone (due to poor compaction) or a crack adjacent a conduit through the core, or adjacent to a wall, eg. spillway.

Factors which would influence the probabilities include:

(i) Transverse cracking

- compaction density ratio, water content
- soil classification
- irregularities in the foundation profile
- geometry of cutoff trench
- differential settlement due to soil in the foundation
- width of the core (compared to the height of the dam)
- location of the core, eg. central or sloping upstream
- presence of tree roots and rodent's holes.

(ii) High permeability zone

- foundation preparation and clean up
- compaction density ratio and water content
- cleanup after wet, dry, rainy, frozen periods during construction
- general quality of construction control.

(iii) High permeability zone adjacent a conduit or wall

- detailing of the conduit, eg.
 - presence of concrete surround
 - buried in a trench or not
 - width of trench, slope of excavation
 - presence of cutoff collars
 - finish on the concrete surround
 - slope of sides of concrete surround
- type of soil surrounding the conduit or wall
- compaction density ratio and water content
- detailing of the wall, eg.
 - slope relative to vertical
 - angle relative to axis of dam
 - finish on the wall
 - presence of cutoff collar.

The ideal situation is that these factors are assessed by relationships to a database of performance — including dams which have failed, experienced accidents, and performed without incident. We will do what we can in this regard in the analysis of case studies detailed, but it is clear that reliance will have to be made on the literature on the subject and on expert judgement. This is of concern, because, being at the front of the event trees, the probabilities assigned have a major influence on the overall outcome.

(b) Initiation and continuation of internal erosion. This is discussed in Foster and Fell (1999) in this conference proceedings. In qualitative terms the results will be used as shown in Table 6.

Table 6. Application of no erosion and continuing erosion boundaries.

Erosion Zone	Probability of Initiation	Probability of Continuing
No erosion	Low	Very low
Some erosion	Medium to high	Low to medium
Continuing erosion	High to very high	Medium to high

Quantification will be more difficult to achieve.

(c) Progression to develop piping

The assessment of the probability of internal erosion progressing to form a pipe is a difficult one and, to our knowledge, has not been studied in any quantified way. Von Thun (1996) presents some valuable concepts. Factors which will influence whether progression occurs include:

- the soil classification and origin
- compaction density ratio and water content (in the dam) and relative density (of sandy soils) and strength (of clayey) soils in the foundation
- seepage gradients and distances (eg. core width, cutoff trench width). In particular, the presence of critical gradients leading to blowout (of foundations)
- layering of the soil (interbedded cohesive and non cohesive soils) may be more likely to support a roof for a pipe
- continuity of cracks, high permeability zones
- presence of conduits and walls, which provide a continuity, and one side of the "pipe"
- detailed geometry of the dam zoning, and the foundation.

We plan to assess these factors through the analysis of detailed case studies and from the literature, but doubt if any rigorous quantification will be possible. We therefore expect to develop methods which are aids to expert judgement.

We have also just started some laboratory testing using a 1 metre long sample with a preformed slot, through which water is passed.

This has shown some interesting results on a dispersive, medium plasticity sandy clay:

- Erosion rates are similar for soils compacted at 95% and 98% density ratio (standard compaction), but much higher at 90%
- Erosion rates are significantly lower for soils compacted at 95 - 98% density ratio, optimum water content (OWC) plus 2% water content than for samples compacted at OWC -1%. Samples compacted at OWC -3% erode much more rapidly
- All soils compacted at 90% density ratio erode rapidly

- When the flow is stopped for 5 minutes, the erosion on restarting is rapid, much quicker than prior to shut-down. This may be replicated in dams during filling and emptying cycles.

(d) Development of a failure mode and formation of breach

The formation of a breach can occur in several ways, all of which need to be assessed and probabilities assigned:

- unravelling of the downstream slope
- instability of the downstream slope
- collapse of the crest into the pipe hole
- gross enlargement of the pipe hole, with continuing erosion leading to breach of the dam.

At this stage we have not developed these but intend to use the information developed for flow-through rockfill dams to assess unravelling, and assessments from case studies to assist in the other modes.

It is important to note that experience in central core earth and rockfill dams, is that of the rockfill has large discharge capacity, a breach will not develop. This is apparent from the database, and is discussed in Johansen et al (1997).

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