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28th Annual USSD Conference
Portland, Oregon, April 28 - May 2, 2008

Hosted by
Portland General Electric

On the Cover

Portland General Electric's North Fork Dam, on the Clackamas River southeast of Portland, is a thin, variable-radius concrete arch dam with a maximum height of 207 feet and a thickness varying from 32 feet at the base to 8 feet at the crest. The spillway is a 200-foot-long gated ogee-type structure with a 250-foot-long reinforced concrete chute discharging into the tailrace. The spillway is controlled by three, 50-foot-wide by 37.5-foot-high tainter gates. The powerhouse contains two generating units capable of producing 54 MW of power. A fish ladder is located on right side of the dam.

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- Fostering dam technology for socially, environmentally and financially sustainable water resources systems;
- Providing public awareness of the role of dams in the management of the nation's water resources;
- Enhancing practices to meet current and future challenges on dams; and
- Representing the United States as an active member of the International Commission on Large Dams (ICOLD).

Printed in the United States of America
Library of Congress Control Number: 2008924523
ISBN 978-1-884575-42-6

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SEEPAGE AND PIPING TOOLBOX – CONTINUATION, PROGRESSION, INTERVENTION AND BREACH

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ABSTRACT

This paper describes the assessment of the continuation, progression, detection and breach phases of the internal erosion process. After internal erosion has initiated, the next step is continuation which looks at the filter compatibility of the various materials which comprise the dam section or foundation. The latest research on the extent of erosion through porous media is included in methods for evaluation of gradational limits. The potential adverse effects of segregation and internal instability of filters or other zones are also considered in the assessment of continuation. If piping can continue, then the probability of progression is next assessed by looking at the ability of the piping soil to hold a roof and the ability of upstream materials to fill cracks or limit flows through the embankment. The detection and intervention phase considers whether the development of internal erosion is likely to be detected, and if so, the likelihood of intervening actions stopping the process. The assessment considers the ability to observe leakage and to intervene within the time that the failure path develops. Breach can occur by gross enlargement of the pipe, slope instability, unravelling of the embankment or sinkhole development. These remaining branches in the seepage and piping failure event tree provide the numerical estimate of probability of failure.

INTRODUCTION

A unified method to assess piping and seepage failure modes has been developed through a collaborative effort between USACE, Reclamation, and the Australian dam community. The quantification of failure by internal erosion and piping is accomplished by the use of a unified event tree which models initiation, continuation, progression, the potential for intervention and breach. Failure modes considered are internal erosion and piping in the embankment, foundation, and embankment into the foundation.

This paper describes the continuation, progression, detection and breach phases for internal erosion in the embankment. Terminology and an outline of the internal erosion

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and piping process are given in Cyganiewicz et al (2008) in this volume. Fell et al (2008) describe the initiation stage of the internal erosion process.

CONTINUATION OF EROSION

Filters, or transition zones, if they are present, control the “continuation” phase of the process. If the filters are designed and constructed to satisfy modern filter criteria e.g. according to Sherard and Dunnigan (1989); USBR (1987); USDA-SCS (1994), the internal erosion process will almost certainly not continue. If the filter or transition zone particle size distribution is coarser than required for the “no-erosion” filters designed using these criteria, erosion may occur.

The assessment is based upon the concepts of filter erosion criteria for existing dams described in Foster and Fell (2001) and Foster (2007). Depending on the grading of the filters and soil, some, excessive, or continuing erosion may occur. A four way split for filtering behavior is used in the event trees:

(i) **Seals with No Erosion** –if the filtering material stops erosion with no or very little erosion of the material it is protecting. Then the increase in leakage flows is so small that it is unlikely to be detectable.

(ii) **Seals with Some Erosion** – if the filtering materials initially allow erosion from the soil it is protecting, but it eventually seals up and stops erosion. Then leakage flows due to piping based on case histories can be up to 3 cubic feet per second (cfs), but are self healing.

(iii**) Seals with Excessive Erosion** – if the filter material allows erosion from the material it is protecting, and in the process permits large increases in leakage flow (up to 35 cfs), but the flows are self healing. Then the extent of erosion is sufficient to cause sinkholes on the crest and erosion tunnels through the core.

(iv) **Continuing Erosion** – if the filtering material is too coarse to stop erosion of the material it is protecting and continuing erosion is permitted. Then unlimited erosion and leakage flows are likely.

For internal erosion in the dam, there are five possible scenarios for filtering action in the dam and, as shown in Figure 1, this depends on the dam zoning and the failure path under consideration. The approach for estimating the probability of continuation is described for each scenario.

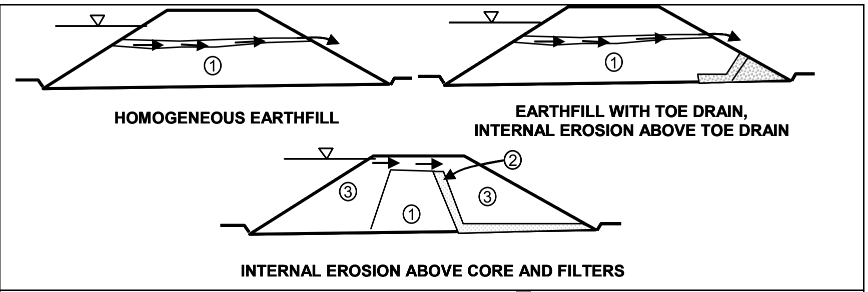
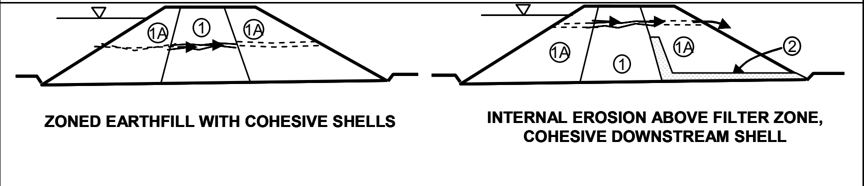
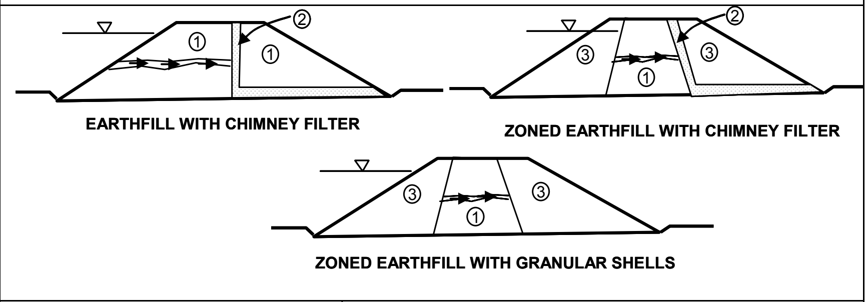
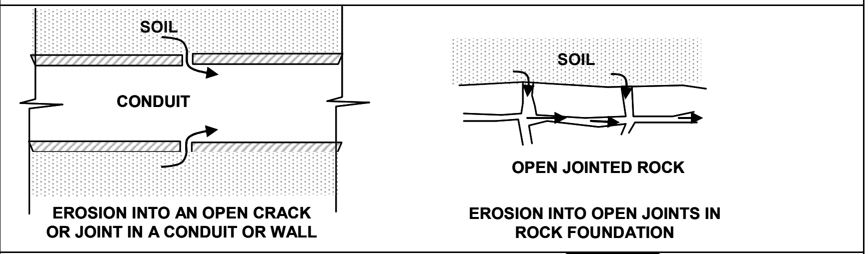
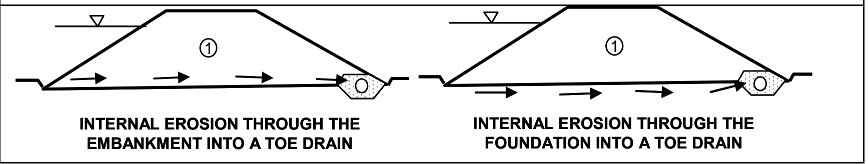
Scenario 1: Homogeneous zoning with no fully intercepting filter	
Scenario 2: Downstream shell of cohesive material which is capable of holding a crack/pipe.	
Scenario3: Filter/ transition zone is present downstream of the core or a downstream zone which is not capable of holding a crack/pipe.	
Scenario 4: Piping into an open defect, joint or crack.	
Scenario 5: Erosion into a toe drain	

Figure 1. Assessment of continuation depending on dam zoning and failure path.

Scenario 1 - Homogeneous zoning with no fully intercepting filter

For this situation there is no potential for filtering action and the probability for continuing erosion is 1.0.

Scenario 2 - Downstream shell of fine grained cohesive material which is capable of holding a crack/pipe

This applies to shell materials containing > 5% plastic fines or >15% non-plastic fines for well compacted materials, and > 15% plastic fines or > 30% non-plastic fines for poorly compacted materials.

The issue for this scenario is whether the crack/high permeability feature that is present through the core is continuous through the downstream shell, or if not, whether it can find an exit. This depends on the mechanism causing the concentrated leak, in particular whether it also causes cracking in the shell, and the material characteristics and width of the downstream shell. Table 1 is used to assess the probability of continuation for this scenario. These probabilities have been assessed by expert judgement.

Table 1. Conditional Probability for Continuation for a downstream shell of fine grained cohesive material which is capable of holding a crack/pipe (Scenario 2)

Predominant Mode of Concentrated Leak	Characteristics of downstream shell zone	Range of Conditional Probabilities for Continuing Erosion
Cracking due to differential settlement. Mechanism causing cracking in the core is also likely to cause cracking of the downstream shell	Well compacted, cohesive materials. Material likely to hold a crack.	1.0
	Poorly compacted, low plasticity materials. Material may collapse on wetting.	0.5 – 0.9
Desiccation cracking near crest, or on construction layer	Similar plasticity to core	0.5 – 1.0
	Lower plasticity than core, less prone to desiccation cracking	0.1 – 0.5
High permeability zone in the core or along the foundation contact, or Cracking due to differential settlement, features causing cracking in the core are not present below the downstream shell.	High permeability feature also likely to be present across the shell zone (e.g. shutdown surface)	0.5 – 1.0
	Leak unlikely to find an exit through the shell (i.e. very wide downstream shell, well compacted, low gradients, different compaction methods and lift thicknesses used in core and downstream shell)	0.01 – 0.1
	Leak likely to find an exit through the shell (e.g.. narrow downstream shell, high gradient across shell, similar compaction methods and lift thicknesses used in core and downstream shell, materials placed in upstream/downstream orientation, feature extends part way through the shell)	0.1 – 0.5
Along outside of conduits passing through the dam	Leak also likely to be common cause through downstream shell (e.g. desiccation cracking on the sides of excavations, poor compaction, arching in trench backfill)	0.5 – 1.0

Scenario 3 - Filter/transition zone is present downstream of the core or a downstream shell zone which is not capable of holding a crack/pipe

The probabilities for No Erosion, Some Erosion, Excessive Erosion and Continuing Erosion are estimated using the following steps:

1. **Regrade and select base soil grading.** If the maximum particle size of the core material is >4.75 mm, then regrade the core grading such that the maximum size is 4.75 mm. If the base soil is gap graded, then regrade the base soil grading on the particle size that is missing (i.e. at the point of inflection of the grading curve). Representative gradings are selected to represent the fine, average and coarse grading of the base soil.

2. **Check for a blow out condition.** In cases where there is limited depth of cover over the filter/transition zone, the potential for blow out is evaluated by comparing the seepage head at the downstream face of the core to the weight of soil cover. This is calculated as the ratio of the total stress from the vertical depth of soil (and rockfill) over the crack exit to the potential reservoir head. If the factor of safety is greater than about 0.5 three dimensional effects will be sufficient to make this a non-issue. If the factor of safety is less than about 0.1 it is assumed the filter/transition will not be effective and the probability of continuation is 1.0. Between these limits a probability of continuation between 0.1 and 0.9 is applied.

3. **Check if the filter/transition zone will hold an open crack.** For filter/transition zones that contain an excess of silty or clayey fines (i.e. >15% non-plastic fines for compacted materials, >30% non-plastic fines for uncompacted materials, or >7% plastic fines), then assume the filter/transition zones cracks and estimate the probabilities by considering the ‘cracked’ filter/transition zone as the base soil and the zone downstream of the cracked filter as the filter material.

4. **Check if the filter/transition zone is segregated.** The potential for segregation of the filter/transition/shell materials is assessed by considering the construction practices, the gradation of the materials, and the width of the filter/transition zone. If a continuous segregated layer is likely to be present, then its grading is estimated by assuming that 50% of the finer soil fraction is segregated out leaving the remaining 50% of coarser fraction. Figure 2 represents an approximate graphical method that can be used to estimate the gradation curve of a segregated layer.

5. **Check if the filter/transition zone is internally unstable.** The probability of the filter or transition zone materials being internally unstable is initially assessed using the method described in the companion paper (Fell et al 2008). If the probability of internal instability is ≥ 0.3, then the grading curve is adjusted assuming that 50% of the unstable soil fraction is washed out. The approximate graphical method shown in Figure 2 can also be used to estimate the gradation curve of internally unstable soils after particle washout. If the probability of internal instability is < 0.3, then internal instability is assumed to not occur and the filter grading curves are not adjusted.

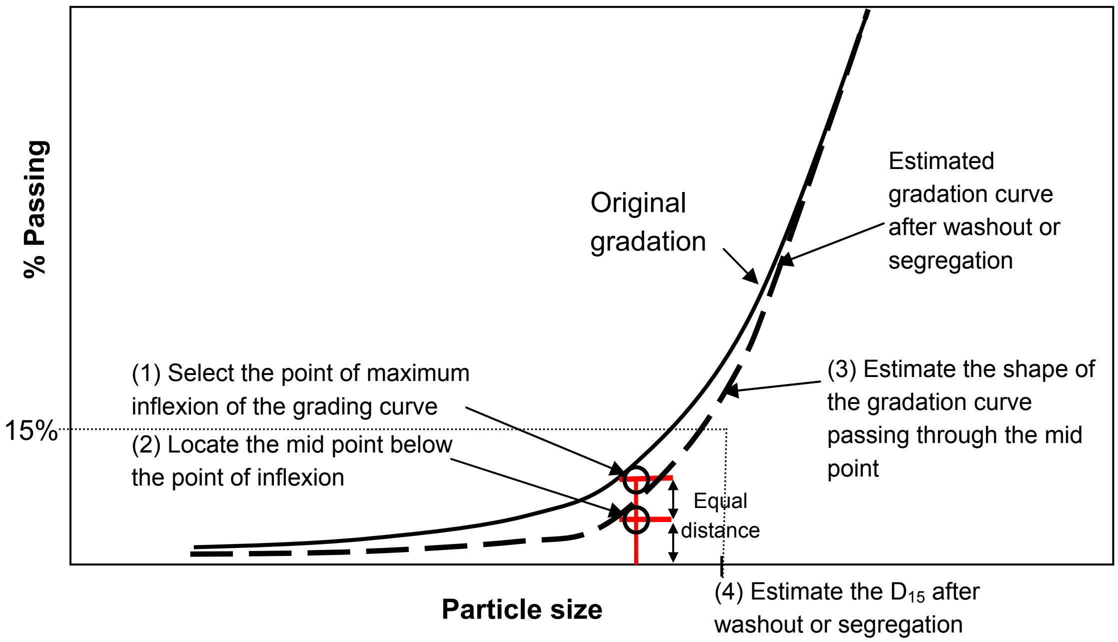


Figure 2. Approximate method for estimating DF15 after washout of the erodible fraction from an internally unstable soil or for a segregated layer.

6. **Evaluate the DF15 values for the No, Excessive and Continuing Erosion boundaries** using Tables 2 and 3, and Figure 3. The No Erosion criteria are based on the Sherard and Dunnigan (1989) filter design criteria, with some modifications for dispersive soils based on Foster and Fell (2001). The Some, Excessive and Continuing Erosion are based on the Foster and Fell (2001) criteria for evaluating existing dams. Plot the DF15 values for these boundaries against the grading curve limits of the filter/transition material (see Figure 4 for an example).

7. **Estimate the probabilities for No Erosion, Some Erosion, Excessive and Continuing Erosion.** These are estimated based on the proportion of the filter/transition grading that fall into each of the particular erosion categories based on the plot of filter/transition grading curves versus Filter Erosion Boundaries from the preceding step.

Table 2. No Erosion boundary for the assessment of filters of existing dams (after Sherard and Dunnigan 1989 and Foster and Fell 2001).

Base Soil Group	Fines content (1)	Range of DF15 for No Erosion Boundary From Tests	Criteria for No Erosion Boundary
1	≥ 85%	6.4 - 13.5 DB85	DF15 ≤ 9 DB85 (2)
2	40 - 85%	0.7 - 1.7 mm	DF15 ≤ 0.7 mm (2)
3	< 15%	6.8 - 10 DB85	DF15 ≤ 4 DB85
4	15 - 40%	1.6 - 2.5 DF15 of Sherard and Dunnigan design criteria	DF15 ≤ (40-pp% 0.075 mm) x (4DB85-0.7)/25 + 0.7

Notes:

(1) The fines content is the % finer than 0.075 mm after the base soil is adjusted to a maximum particle size of 4.75 mm.

(2) For highly dispersive soils (Pinhole classification D1 or D2 or Emerson Class 1 or 2), it is recommended to use a lower DF15 for the no erosion boundary. For soil group 1 soils, suggest use the lower limit of the experimental boundary, i.e. DF15 ≤ 6.4 DB85. For soil group 2 soils, suggest use DF15 ≤ 0.5 mm. The equation for soil group 4 would be modified accordingly.

Table 3. Excessive and Continuing erosion criteria (Foster and Fell 1999b, 2001).

Base Soil	Criteria for Excessive Erosion Boundary	Criteria for Continuing Erosion Boundary
Soils with DB95<0.3 mm	DF15 > 9 DB95	For all soils: DF15 > 9DB95
Soils with 0.3<DB95<2 mm	DF15 > 9 DB90	
Soils with DB95>2 mm and fines content >35%	DF15 > DF15 which gives an erosion loss of $0.25 g/cm^2$ in the CEF test ($0.25 g/cm^2$ contour line in Figure 3)	
Soils with DB95>2 mm and fines content <15%	DF15 > 9 DB85	
Soils with DB95>2 mm and fines content 15-35%	DF15 > 2.5 DF15 design, where DF15 design is given by: DF15 design=(35-pp%0.075 mm)(4DB85-0.7)/20+0.7	

Notes:

Criteria are directly applicable to soils with DB95 up to 4.75 mm. For soils with coarser particles determine DB85, DB90 and DB95 using grading curves adjusted to give a maximum size of 4.75 mm.

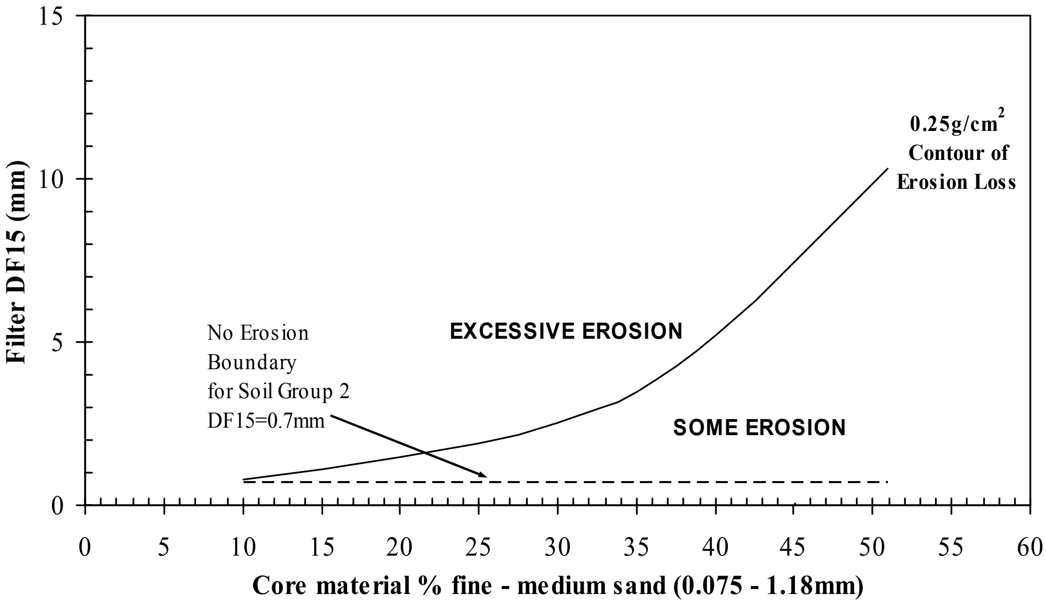
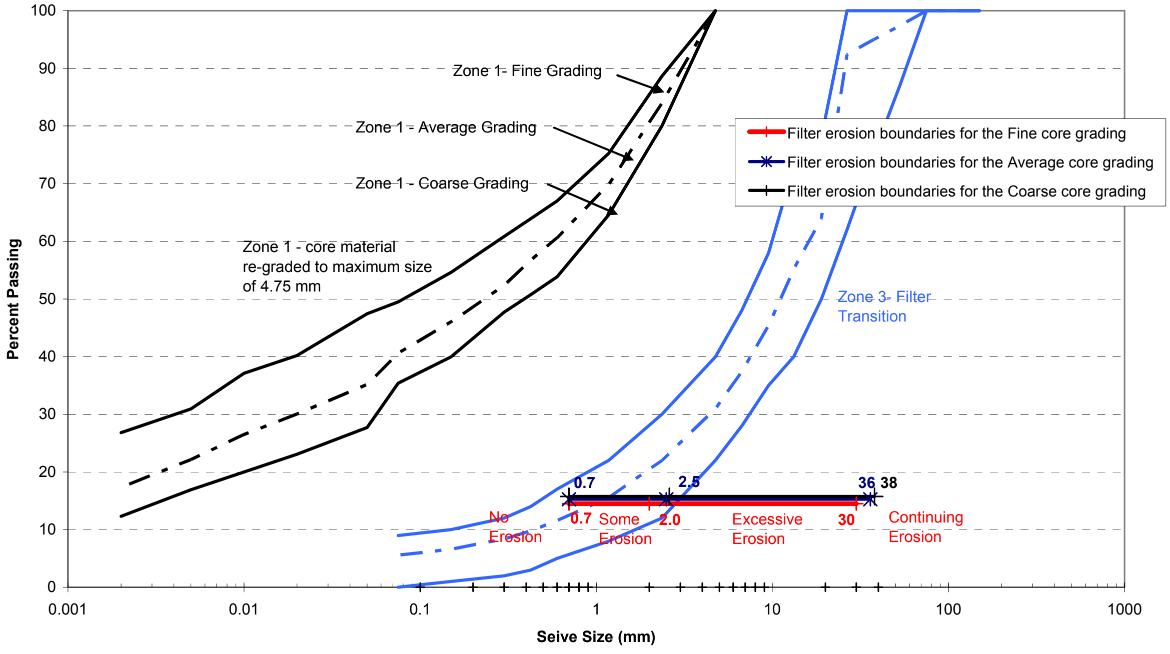


Figure 3. Criteria for Excessive Erosion Boundary.



Assessment of Zone 1 core against no erosion, excessive erosion and continuing erosion criteria

Core Gradation	Base soil sizes (mm)				No Erosion	Excessive Erosion	Continuing Erosion
	DB85 (mm)	DB95 (mm)	% passing 0.075mm	% fine-medium sand (0.075 - 1.18mm)	DF15 (mm)	DF15 (mm)	DF15 (mm)
Fine Grading	1.9	3.3	50	25	0.7	2	30
Average	2.4	4	41	29	0.7	2.5	36
Coarse Grading	2.5	4.2	35	30	0.7	2.6	38

Figure 4. Example of plot showing filter/transition grading compared to Filter Erosion Boundaries.

Scenario 4 - Erosion into a crack or open joint

This would apply where materials may erode into an open joint or crack in a conduit or in an adjoining concrete structure, or for erosion into open defects in a rock foundation. For erosion to continue through an open defect, the defect needs to be sufficiently open to allow the soil surrounding the defect to pass through.

The erosion boundaries are evaluated by comparing the opening size of the defect/joint to the soil gradation using the criteria given in Table 4. The conditional probabilities for No Erosion, Some Erosion, Excessive Erosion and Continuing Erosion are determined by estimating the proportion of soils falling within each erosion category.

Table 4. No, Excessive and Continuing Erosion criteria for erosion into an open defect (Fell et al 2004)

Erosion condition	Comparison of Soil Gradation to Joint/Defect opening size (JOS)	
	Clays, sandy clays, clayey sands	Silt, sand, gravel soils
No erosion	JOS < D_{85} surrounding soil	JOS < 0.5 D_{85} surrounding soil
Excessive erosion	JOS > D_{90} surrounding soil	JOS > D_{85} surrounding soil
Continuing erosion	JOS > D_{95} surrounding soil	JOS > D_{95} surrounding soil

Notes:
JOS = Joint/defect opening size.
D85, D90 and D95 should be based on the average soil grading after regrading.

Scenario 5 - Erosion into a toe drain

This scenario is applicable if the failure path under consideration involves a seepage path that exits into a toe drain which could lead to continuing erosion of the embankment or foundation materials. The assessment of erosion into a toe drain considers the observed condition of the toe drain (from video or external inspections) and the design and construction details of the toe drain.

PROGRESSION

The progression stage of internal erosion considers whether the soil will hold a roof over a pipe, whether crack filling action will fail to stop the erosion process, and whether flow in the developing pipe will not be restricted by an upstream zone.

Probability of Forming a Roof

Based on case studies (Foster 1999; Foster and Fell 1999a), the most important factors are:

- The fines content of the soil (% passing 0.075 mm). Soils with ≥ 15% fines are likely to be able to hold a roof regardless of whether the fines were non plastic or plastic.
- Whether the soil is partially saturated or saturated.

Other factors which were considered to be likely to have an influence, were degree of compaction (loose soil would be less likely to support a roof to a pipe than dense), and reservoir operation (cyclic reservoir levels were more likely to cause collapse than steady). Also taken into account were the results of testing by Park (2003), which showed sandy gravel with 5 to 15% non-plastic fines collapsed quickly when saturated. Sandy gravel with 5% cohesive fines collapsed after some time, but very slowly with 15% cohesive fines.

The probability of the soil forming a roof of a pipe is estimated using Table 5.

Table 5. Probability of a soil being able to support a roof to an erosion pipe

Soil Classification	Percentage Fines	Plasticity of the Fines	Moisture Condition	Likelihood of Supporting a Roof
Clays, sandy clays (CL, CH, CL-CH)	> 50%	Plastic	Moist or saturated	1.0
ML or MH	>50%	Plastic or non-plastic	Moist or saturated	1.0
Sandy clays, Gravely clays, (SC, GC)	15% - 50%	Plastic	Moist or Saturated	1.0
Silty sands, Silty gravels, Silty sandy gravel (SM, GM)	> 15%	Non plastic	Moist Saturated	0.7 to 1.0 0.5 to 1.0
Granular soils with some cohesive fines (SC-SP, SC-SW, GC-GP, GC-GW)	5% to 15%	Plastic	Moist Saturated	0.5 to 1.0 0.2 to 0.5
Granular soils with some non plastic fines (SM-SP, SM-SW, GM-GP, GM-GW)	5% to 15%	Non plastic	Moist Saturated	0.05 to 0.1 0.02 to 0.05
Granular soils, (SP, SW, GP, GW)	< 5%	Non plastic Plastic	Moist and saturated Moist and saturated	0.0001 0.001 to 0.01

Notes:
(1) Lower range of probabilities is for poorly compacted materials (i.e. not rolled), and upper bound for well compacted materials.
(2) Cemented materials give higher probabilities than indicated in the table. If soils are cemented, use the category that best describes the particular situation.

Probability of Crack Filling Action

Crack filling from an upstream zone can limit the extent of erosion in the core. This occurs if the materials washed into the crack or pipe is capable of filtering against the downstream filter or transition zone. This will be of greatest benefit in cases where there is poor filter compatibility between the core and downstream filter due to a lack of sand size particles in the core. There is less benefit where the materials that are washed in are of similar sizes to those already in the core, hence the probabilities for crack filling are higher for a well graded core material compared to those for a core which is deficient in sand sizes. Crack filling provides very little benefit where there is no downstream filter/transition zone.

Probability for Upstream Flow Limitation

Upstream flow limitation may occur where there is a relatively fine grained granular material (fine rockfill, or sandy gravel) upstream of the core, or where there is a concrete face slab or concrete core wall. If the flow which can pass through the upstream flow limiting conditions is such that equilibrium between the hydraulic shear stress, and critical (initial) shear stress of the soil is reached, then the pipe will self stabilize.

The other mechanism which may lead to flow limitation in low permeability upstream zones is the condition where the zone fails to support a roof and the developing pipe collapses. For flow limitation by an upstream zone, the assessment considers the characteristics of the upstream zone material, and whether the features which caused the crack or flaw in the core are also present in the upstream zone. Examples; where the foundation profile causing cracking due to differential settlement persist across the core and the upstream zone; where a construction shutdown has resulted in a poorly compacted zone; or cracking due to desiccation.

For flow limitation by a concrete element or other cut-off wall in the dam or foundation, the assessment considers the wall type and integrity of the wall.

DETECTION, INTERVENTION AND REPAIR

General Principles

The likelihood that a particular failure path can be detected, and if so, whether it is possible to intervene (e.g. by lowering the reservoir level), or carry out repairs to prevent the dam breaching is considered as two questions:
1. Will this failure path be detected?
2. Will intervention and repair be possible?

Methods for estimating these probabilities have been developed using expert judgement.

Probability of Not Detecting Internal Erosion

Whether detection is likely depends on:
1. The rate at which the internal erosion and piping, and associated processes, such as instability or unravelling of the downstream face, occurs.
2. The frequency of inspections and observations of monitoring equipment.
3. Whether the concentrated leak is visible to those performing the inspection. This is influenced by the dam zoning, the location of the concentrated leak, and the conditions at the downstream toe.

Early detection in the internal erosion process is usually difficult, particularly for erosion initiating along a crack or by backwards erosion, because the amount of leakage is very small at the initiation of the failure process. Fell et al (2001, 2003) record that most piping incidents are first identified as a concentrated leak in the progression phase. Suffusion is more likely to be detected by piezometers because the process is slower to develop. The presence of conditions potentially leading to heave and backward erosion in the foundation may also be detected by piezometers provided they are correctly positioned and read as reservoir levels rise.

The probability of not detecting internal erosion is evaluated as follows:

- Assess the probability that the concentrated leak is not able to be observed. This considers factors which could prevent seepage being observed (e.g. an embankment toe which is drowned by tail water or where founded on preamble foundation soils), the dam zoning, and the effectiveness of seepage monitoring systems.
- Consider the probability that given the leak is observable, it is not detected. This considers the time for the development of a concentrated leak to initiate a breach, the frequency of inspections, and/or reading of monitoring instruments. Guidance is given in the toolbox for estimating the approximate time for development of internal erosion, and this estimate is based on the method described in Fell et al (2001, 2003).

Probability of Not Intervening

The assessment of probability considers the time for the development of internal erosion and the practicality to intervene successfully within this time. If the time for development of internal erosion is relatively short, i.e. less than 12 hours, than the probability for not intervening will be high (0.9-0.99) as generally it will be impractical to intervene successfully in this time. If the development of internal erosion is very slow (i.e. develops over weeks or months), intervention has a fair chance of being successful where: (1) there is a straight forward method of intervention, and there are personnel, equipment, materials, and large resources are available; (2) it is a small or medium storage with large gate discharge capacity allowing the reservoir to be drawn down to stop the failure process.

BREACH

For internal erosion, breach may occur by one of the following four mechanisms:

- (i) Gross enlargement of a pipe in the embankment followed by settlement or collapse of the embankment into the pipe resulting in the crest dropping to below reservoir level and being overtopped.
- (ii) Instability of the downstream slope of the embankment, or embankment and foundation, resulting in settlement and overtopping of the crest.
- (iii) Unravelling or sloughing of the downstream slope of the embankment resulting in settlement and overtopping of the crest.
- (iv) Progressive development of a vertical sinkhole into a pipe in the core, resulting in settlement and overtopping of the crest.

Methods for estimating these probabilities have been developed by expert judgement.

Breach by Gross Enlargement

For breach to occur by gross enlargement of a pipe, the pipe must stay open until it is so large that the settlement of the crest or collapse of the embankment into the pipe lowers the crest to below the reservoir level. Breach by this mechanism is considered to be negligible in cases where the downstream shell is unable to support a roof of a pipe (e.g. free draining rockfill or coarse sandy gravel).

If there is no intervention, the process can only stop if one or more of the following occurs:

a) The hydraulic shear stresses in the pipe reach an equilibrium condition with the erosion resistance of the soil. This will not happen unless the reservoir level drops giving a lower gradient, as the hydraulic shear stress increases with hole diameter for a constant gradient.

b) The reservoir empties or falls below the entrance of the pipe before a breach mechanism is able to develop. This depends on the rate of erosion of the embankment materials and the time for the reservoir to recede below the invert of the pipe. An analysis of the rate of enlargement of a pipe was carried out as part of the study to aid in this assessment.

Generally the probability will be high for this breach mechanism unless the downstream shell is unable to support a roof of a pipe or internal erosion develops in the upper part of the dam under a short duration flood loading conditions

Breach by Slope Instability

For breach to occur by instability of the downstream slope, the internal erosion in the foundation must increase pore pressures in the embankment and/or foundation, so the factor of safety falls below 1.0, and the resulting sliding deformations must be such as to result in loss of freeboard so the reservoir overtops the dam crest.

The probability of breach by slope instability is assessed as follows;

a) Estimate the probability of slope instability occurring due to increased seepage flows resulting from internal erosion. The assessment considers the effectiveness of the internal drainage measures in the dam in preventing pore pressures rising in the dam, the slope of the downstream face and the downstream shell materials. Different probabilities are assigned to each branch of the event tree depending on the filter erosion condition since these influence the amount of leakage that could develop through the embankment.
b) Estimate the probability of loss of freeboard due to instability. The factors considered, in order of importance, are the freeboard at the time of the incident, the presence of strain weakening materials in the dam and foundation, and the crest width.
c) The probability of breach by slope instability is equal to the product of these two probabilities.

Breach by Sloughing or Unravelling

For sloughing to occur, the downstream face would have to be relatively steep, and the shell material a cohesionless soil, probably sandy gravel, or gravely sand, possibly with some silty fines. The process would have to be allowed to continue until it gradually eroded away the crest and allowed the reservoir to overtop the embankment.

Unravelling usually relates to the progressive removal of individual rocks by fairly large seepage flows flowing through a downstream rockfill shell.

The assessment considers the material in the downstream zone, the downstream slope of the embankment, and the freeboard at the time of the incident. Different probabilities are assigned to each branch of the event tree depending on the filter erosion condition since these influence the amount of leakage that could develop through the embankment.

Breach by Sinkhole Development

For breach to occur by sinkhole development into an erosion pipe in the embankment, the sinkhole or crest settlement would need to be sufficiently large to settle the crest to below reservoir level. For internal erosion in the foundation, loss of freeboard can also occur by excessive settlement of the embankment induced by the loss of foundation materials.

The approach is as follows:
a) The probability of a sinkhole or crest settlement developing as a result of the internal erosion is 0.6 for internal erosion in the embankment and 0.3 for internal erosion in the foundation. This estimate was based on the observed incidence of sinkholes and crest settlement in case history data (Foster and Fell 1999a, 2000)
b) Estimate the probability that the sinkhole causes loss of freeboard. The factors considered in the assessment are the freeboard at the time of the incident, the width of the crest, and the core material.
c) The probability of breach by sinkhole development = probability of a sinkhole multiplied by the probability of loss of freeboard due to the sinkhole.

ACKNOWLEDGEMENTS

The contribution of the researchers at UNSW, and many colleagues in Reclamation, USACE, URS and Australian Dams Organisations in developing and trialling these methods are acknowledged with thanks.

Permission to publish granted by Director, Geotechnical and Structures Laboratory, USACE

REFERENCES

Cyganiewicz, J., Sills, G., Fell, R., Davidson, R., Foster, M., Vroman, N., (2008). S*eepage and piping toolbox-overview*, USSD Conference, Portland, OR. 28th April-2nd May 2008.

Fell, R., Foster, M., Davidson, R., Sills, G., (2008). *Seepage And Piping Toolbox-Initiation Of Internal Erosion*, USSD Conference, Portland, OR, 28th April-2nd May 2008.

Fell, R., Wan, C.F. and Foster, M. (2004). *Methods for estimating the probability of failure of embankment dams by internal erosion and piping – piping through the embankment*. UNICIV Report No. R-428, The University of New South Wales, Sydney, Australia. ISBN 85841 395 7.

Fell, R., Wan, C.F., Cyganiewicz, J. and Foster, M. (2001). *The time for development and detectability of internal erosion and piping on embankment dams and their foundations.* UNICIV Report No. R-399, ISBN: 84841 366 3. School of Civil and Environmental Engineering, The University of New South Wales.

Fell, R., Wan, C.F., Cyganiewicz, J. and Foster, M. (2003). *Time for development of internal erosion and piping in embankment dams*. ASCE Journal of Geotechnical and GeoEnvironmental Engineering, Vol. 129, No.4, 307-314.

Fell, R. and Wan, C.F. (2005) Methods for estimating the probability of failure of embankment dams by internal erosion and piping in the foundation and from embankment to foundation. *UNICIV Report No R-436, The University of New South Wales,* Sydney, Australia 2052.ISBN: 85841 403 1.

Foster, M.A. (1999). *The probability of failure of embankment dams by internal erosion and piping.* PhD thesis, School of Civil and Environmental Engineering, The University of New South Wales.

Foster, M.A. (2007) *Application of no, excessive and continuing erosion criteria to existing dams.* In Internal Erosion of Dams and their Foundations, Editors R Fell and JJ Fry, Taylor Francis, 103-114.

Foster, M.A. and Fell, R. (1999a). *A Framework for Estimating the Probability of Failure of Embankment Dams by Piping Using Event Tree Methods.* UNICIV Report No. R-377. School of Civil and Environmental Engineering, The University of New South Wales. ISBN: 85841 343 4.

Foster, M.A. and Fell, R. (1999b). *Assessing Embankment Dam Filters Which Do Not Satisfy Design Criteria.* UNICIV Report No. R-376, School of Civil and Environmental Engineering, University of New South Wales. ISBN: 85841 343 4, ISSN 0077-880X.

Foster, M. and Fell, R. (2000). *Use of Event Trees to Estimate the Probability of Failure of Embankment Dams by Internal Erosion and Piping.* 20th Congress on Large Dams, Beijing. Vol. 1, 237-260. ICOLD, Paris.

Foster, M. and Fell, R. (2001). *Assessing embankment dams, filters which do not satisfy design criteria*, J. Geotechnical and Geoenvironmental Engineering, ASCE, Vol.127, No.4, May 2001, 398-407.

Park, Y. (2003) *Investigation of the ability of filters to stop erosion through cracks in dams*. PhD dissertation, Virginia Polytechnic Institute, Blacksburg, Virginia, USA

Sherard, J.L. and Dunnigan, L.P. (1989). *Critical filters for impervious soils.* J. Geotech. Eng. ASCE, Vol.115, No.7, 927-947.

USBR (1987). *Design standards No.13, Embankment dams. Chapter 8, seepage analysis and control*. US Bureau of Reclamation, Denver.

USACE (1994). EM1110-2-2300 *Earth and rock-fill dams – General design and construction considerations*, US Army Corps of Engineers.

USDA-SCS (1994). *Gradation Design of Sand and Gravel Filters.* United States Department of Agriculture, Soil Conservation Service, Part 633, Chapter 26, National Engineering handbook.