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Filter Testing for Dams – No Erosion and Continuing Erosion Boundaries

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Summary The results of a statistical analysis of laboratory filter tests from the literature, including those by Sherard and Dunnigan (1989), and the results of laboratory tests carried out at the University of New South Wales are used to determine criteria for the boundaries of filter test behaviour. These boundaries are compared to the characteristics of dams that have experienced good and poor filter performance to allow the practical application of the criteria to the safety assessment of other dams.

1. INTRODUCTION

One of the primary functions of the filter downstream of the core is to prevent the development of piping through the dam in the event of a concentrated leak through the core. The good performance of dams with filters designed in accordance with modern design criteria have proven that these filters are capable of reliably sealing concentrated leaks (Sherard and Dunnigan, 1989; Peck 1990). However, many existing dams have filters that do not satisfy these criteria, being too coarse by design or having segregated during construction. In the review of the safety of these structures, it is necessary to evaluate the likelihood of damages to the dam in the event of piping developing in the core of the dam, potentially leading to failure (breaching) of the dam. The main issues of concern in these circumstances are:

(i) If a concentrated leak forms through the core of the dam, will the filter prevent continuing erosion of the core material (i.e. will the leak be eventually sealed by the filter)?

(ii) How much erosion of the core material is required for the filter to seal the leak and can this be tolerated?

Since the 1920s there have been numerous experimental and theoretical studies into the development of filter criteria for the design of dams. Despite this, there is little guidance in the literature on the assessment of filters of existing dams, particularly for the situation where filters do not meet current criteria.

Modern design criteria are based on laboratory tests that simulate a crack in the core of a dam exiting into the downstream filter. Among the most widely used criteria are those recommended by Sherard and Dunnigan (1989). These criteria are based on the results of the No Erosion Filter (NEF) test, which allows no visible erosion of a 1 mm diameter hole through the base specimen.

2. FILTER TEST BOUNDARIES

The success/fail criterion of filter test behaviour is usually represented as some measure of erosion loss of the base material. Terms developed to categorise filter test behaviour are as follows:

(i) *No erosion*: – filter seals with practically no erosion of the base material.

(ii) *Some erosion*: – filter seals after "some" erosion of the base material.

(iii) *Continuing erosion*: – the filter is too coarse to allow the eroded base materials to seal the filter allowing unrestricted erosion of the base soil.

The boundaries of the filter test behaviour categories are the no erosion and continuing erosion boundaries as shown in Figure 1.

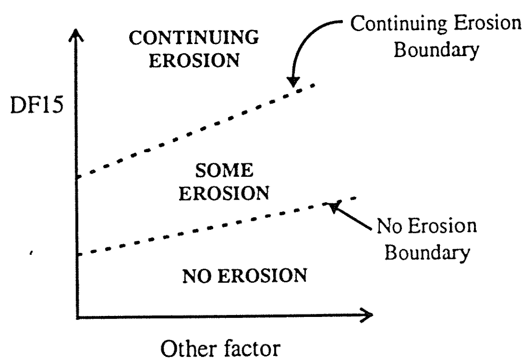

Figure 1. Erosion boundaries of filter test behaviour.

Table 1. Summary results of statistical analysis of the no erosion boundary of filter tests.

Base Soil Group	Fines content *(1)*	Design Criteria of Sherard and Dunnigan (1989)	Range of DF15 for No Erosion Boundary	Proposed Criteria for No Erosion Boundary
1	≥ 85%	DF15 ≤ 9 DB85	6.4–13.5 DB85	DF15 ≤ 9 DB85
2	35–85%	DF15 ≤ 0.7 mm	0.7–1.7 mm	DF15 ≤ 0.7 mm
3	< 15%	DF15 ≤ 4 DB85	6.8–10 DB85	DF15 ≤ 7 DB85
4	15–35%	DF15 ≤ (40–pp%75 μm) x (4DB85–0.7)/25 + 0.7	1.6–2.5 DF15 of Sherard and Dunnigan design criteria	DF15 ≤ 1.6 DF15d, where DF15d = (35–pp%75μm)(4DB85-0.7)/20+0.7

Notes: (1) The subdivision for soil group 2 and 4 was modified from 40% passing 75μm, as recommended by Sherard and Dunnigan (1989), to 35% based on the analysis of the filter test data.

3. STATISTICAL ANALYSIS OF FILTER TESTS

The purpose of the statistical analysis was to determine criteria for the no erosion and continuing erosion boundaries of filter test behaviour. Experimental data used in the statistical analysis of filter tests was collected from the following sources:

(i) **U.S. Soil Conservation Service (USSCS),** reported in Sherard, Dunnigan and Talbot (1984a, 1984b), Sherard and Dunnigan (1989) and unpublished reports by Sherard (1985).

(ii) **US Bureau of Reclamation (USBR)** tests, reported in Karpoff (1955) and USBR (1960).

(iii) **US Corp of Engineers** (1953)

(iv) **Kenney et al** (1985)

(v) **Wyangala and Copeton** Dam filter tests, Water Conservation and Irrigation Commission (1964, 1969).

(vi) **Khor and Woo** (1989) – No Erosion Filter tests.

Only the summary results of the statistical analysis are discussed in this paper; however details of the methodology and results of the analysis are given in Foster and Fell (1998).

3.1 No Erosion Boundary

The analysis of the no erosion boundary was performed on the four soil groups of base soils defined by Sherard and Dunnigan (1989). The experimental range and the proposed criteria are summarised in Table 1 together with the design criteria of Sherard and Dunnigan.

The statistical analysis of the filter test data generally confirmed the interpretation of the NEF tests by Sherard and Dunnigan (1989). For soil group 1 base soils, the proposed criterion for the no erosion boundary corresponds to a probability of erosion of 0.5. The erosion losses suffered in the NEF tests with DF15 slightly coarser than the no erosion boundary were only minor before the filters sealed.

The proposed criteria of the no erosion boundaries for soil group 2 base soils correspond to the lower boundary of the NEF tests of DF15 = 0.7 mm. The lower cutoff for this soil group was changed from 40% fines content (passing 75 μm), as suggested by Sherard and Dunnigan, to 35% to allow for the results of some NEF tests on base soils with fines content in the range 35–40% with no erosion boundaries as low as DF15 = 0.7 mm.

The proposed criteria of the no erosion boundaries for soil group 3 and 4 base soils are coarser than the corresponding Sherard and Dunnigan design criteria because the design criteria have factors of safety included. The filter tests with filters only slightly coarser than the no erosion boundary suffered considerable erosion, and therefore, the proposed boundaries correspond to the lower bound of the experimental data.

3.2 Continuing Erosion Boundary

The slot and slurry tests carried out by the USSCS (Sherard, et al 1984b) used a success/fail criterion which conveniently corresponds to the definition of the continuing erosion boundary. In successful slot and slurry tests, the filter sealed after some erosion of the preformed slot or slurry material. In unsuccessful tests, virtually all of the slurry was washed through the filter and the filter was never sealed (i.e. continuing erosion of the base material).

The soils tested in the slot and slurry tests were generally clays, silts and sandy clays and classified as soil groups 1 and 2. As reported in Sherard et al (1984b), the experimental data for these tests showed a poor relationship of DF15 vs DB85, with DF15/DB85 in the range 9–57. Following the publication of the 1984 ASCE paper, Sherard found the slot and slurry tests defined a continuing erosion boundary given by DF15/9 ≥ DB98 to DB100 for soils with DB85<0.1 mm (Sherard, 1985). DF15/9 approximates the effective opening size of uniformly graded filters (Sherard et al 1984a). This implies the filter only needs to be capable of stopping the very coarsest particles of base material for self-filtering to occur for fine grained soils.

The analysis of the filter test data of soil group 1 base soils found DF15/DB95 gives a better fit to the experimental data than DF15/DB85 and that DF15/9 = DB95 of the experimental data corresponds to the lower limit of the continuing erosion boundary. For tests with DF15/DB95 < 9, all of the filter tests were eventually sealed.

For base soils with DB85 > 0.1 mm, there was insufficient data to determine criteria for the continuing erosion boundary. The majority of the NEF tests were aimed at defining the no erosion boundary and the coarsest filters used were generally only slightly coarser than the no erosion boundary. Also it was often difficult to judge from the descriptions if the filter was eventually sealed for the tests that were judged by the investigators as failures.

4. CONTINUING EROSION FILTER TESTS

Additional filter tests were carried out using a modified version of the NEF test, called Continuing Erosion Filter (CEF) tests, to determine the continuing erosion boundary for soils with DB85 > 0.1 mm. The test procedures of the CEF tests were essentially the same as those of the NEF test, as described by Sherard and Dunnigan (1989) but with the following modifications to the procedure:

- water passing through the filter during the tests was collected and the eroded materials dried and weighed to determine the loss of base soil required to seal the filter;
- progressively coarser filters were used until the filter was not sealed;
- thicker base specimens were used to allow for greater erosion losses.

Details of the CEF test setup are shown in Figure 2.

The tests were carried out for such a time until it was evident the filter was sealed or it was judged that the filter was not going to seal no matter how much erosion of the base soil occurred. The filters were judged to have sealed when all of the following conditions were reached:

(a) full mains pressure was maintained in the space above the base specimen as measured on the pressure gauge,

(b) water passing through the filter was clear, and

(c) the flow rate of water passing through the filter had decreased substantially from the initial flow and was relatively constant.

4.1 Results of CEF Tests

Eight base soils were tested using the no erosion and continuing erosion test procedures. The soils were obtained by project sponsors from natural deposits or from the embankment materials of existing dams in Australia and New Zealand. The characteristics of the base soils are presented in Table 2 and the gradation curves are shown in Figure 3.

The differences between the Pinhole Dispersion classification and the Emerson class for soils 4 and 5 in Table 2 are due to them being erodible silty/low plasticity clays, but not having a dispersive clay content.

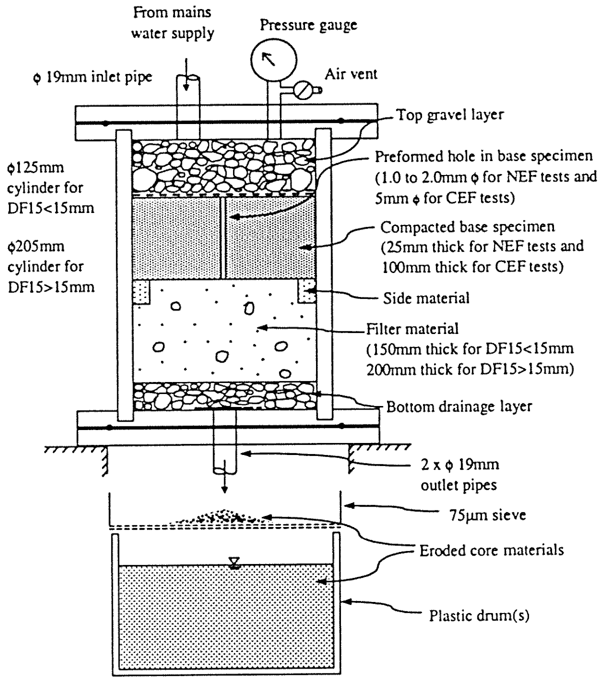

Figure 2. Continuing erosion filter test apparatus.

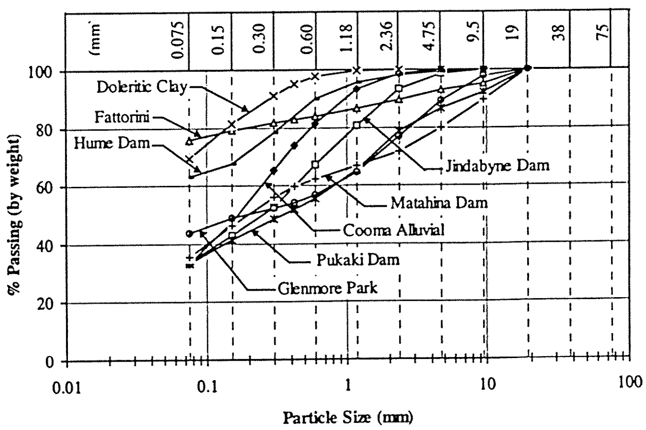

Figure 3. Gradations of base soils.

Table 3 presents a summary of the results of the NEF and CEF tests. The no erosion boundary obtained from the NEF tests and the coarsest filter sealed in

Table 2. Characteristics of the base soils tested.

			Index Properties		Gradation		Dispersivity	
Soil No.	Name	Geological Origin	LL	PI	% fines <75 µm	DB85 (mm)	Pinhole Dispersion	Emerson Class
1	Fattorini Creek	Colluvial	42	19	76	0.8	D1	1
2	Doleritic clay	Residual (dolerite)	62	22	70	0.2	ND1	5
3	Hume Dam	Tertiary alluvial	33	15	63	0.4	D1	1
4	Pukaki Dam	Glacial till	NP	NP	36	6.8	D1	5
5	Jindabyne Dam	Residual (granite)	38	11	34	1.5	D1	5
6	Matahina Dam	Residual (greywacke)	26	8	33	4.1	D1–D2	2
7	Cooma Alluvial	Alluvial	31	10	33	0.7	PD1	2
8	Glenmore Park	Residual (shale)	42	21	44	3.7	PD1–PD2	2

Table 3. Summary of no erosion and continuing erosion filter tests

Soil Name	No Erosion Boundary DF15 (mm)	Coarsest Filter Sealed in CEF Tests DF15 (mm)	Filter Not Sealed in CEF Tests DF15 (mm)
Fattorini Creek	0.2 - 0.3	1.0	2.0
Doleritic clay	0.5 - 0.7	3.35	4.75
Hume Dam	0.3 - 0.5	9.5	12.7
Pukaki Dam	2.0 - 3.35	38	-
Jindabyne Dam	4.75 - 6.7	25	-
Matahina Dam	1.0 - 2.0	9.5	12.7
Cooma Alluvial	6.7 - 9.5	12.7	19
Glenmore Park	0.7 - 1.0	12.7	19

the CEF tests are shown for each of the base soils tested.

The results show that coarse filters with DF15 several times larger than the DF15 for no erosion were capable of being sealed in the CEF tests. Generally, the DF15 of the coarsest filter that was sealed was in the range of 4 to 17 times the DF15 obtained for the no erosion boundary (except for Cooma Alluvial which was only 1.6 times higher).

The no erosion boundaries obtained for the two dispersive base soils, Fattorini and Hume Dam, are lower than the Sherard and Dunnigan design criterion for soil group 2 soils ($DF15 \leq 0.7$ mm). Sherard and Dunnigan claimed the no erosion boundary is independent on the dispersivity of the soil (Sherard 1985; Sherard and Dunnigan 1989). However, in the USSCS study, only 2 of the 28 group 1 soils and none of the group 2 soils were dispersive and the results of the NEF tests on the two dispersive soils in this study show the no erosion boundary can be lower than the design criteria. Whilst the NEF tests on the Fattorini Dam and Hume Dam soils with $DF15 = 0.7$ mm failed to meet the criteria of the NEF test, the initial concentrated leaks were successfully sealed without significant erosion (hole enlarged to 2–4 mm diameter).

4.2 Factors Influencing Erosion Losses to Seal Concentrated Leaks

The results of the CEF tests were subdivided into two groups based on the observed behaviour – soils with $DB95 > 2$ mm and soils with $DB95 < 2$ mm. For base soils with $DB95 < 2$ mm, the filter was sealed for tests with filters corresponding to filter opening sizes (DF15/9) equal up to about DB95. For tests with $DF15/9 > DB95$ the filter was not sealed and large erosion losses occurred. This is the same as the criterion for group 1 soils, and it is concluded that the continuing erosion boundary for all base soils with $DB95 < 2$ mm is given by $DF15/DB95 < 9$.

For base soils with $DB95 > 2$ mm, relatively large erosion losses were measured for filters with DF15/9 much less than DB95. It was not possible to define a continuing erosion boundary for these soils due to difficulties in the interpretation imposed by the limited flow capacity of the test apparatus and due to the restriction of the maximum sized DF15 of the filter (38 mm) that could be tested in the test cylinder.

The erosion losses measured in the CEF tests are related to the proportion of fine to medium sand sizes in the base soils. Figure 4 shows the erosion losses plotted against the DF15 of the filter and the percentage of base particles with sizes in the range 75 µm – 1.18 mm (after the grading of the soil is regraded to a maximum particle size of 4.75 mm) for the base soils with $DB95 > 2$ mm. The erosion losses are expressed as the mass of loss per area of filter face sealed.

It can be seen from Figure 4 that for a constant DF15 size, the erosion losses tend to be lower for base soils with higher proportions of fine to medium sand sizes. Contours of equal erosion loss, determined by interpolation between the data points, are shown plotted on Figure 4. The contours cover the range of DF15 of about 2 to 13 mm which correspond to filter opening sizes (given by DF15/9) in the range of 0.2

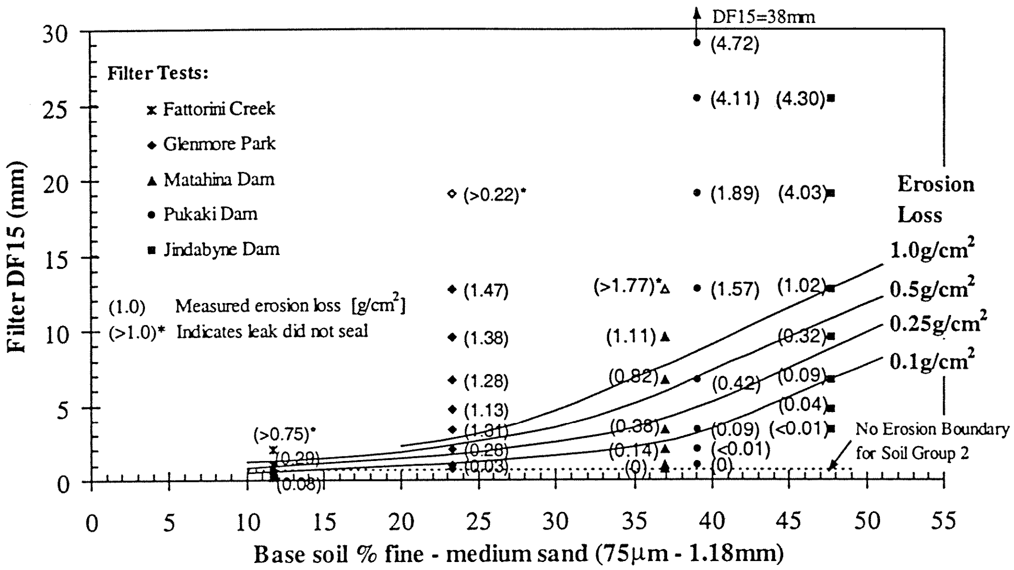

Figure 4. Erosion losses of base soil measured in the CEF tests.

to 1.4 mm, i.e. about the same as fine to medium sand sizes.

Therefore base soils with a low proportion of fine to medium sand sizes would be expected to require larger erosion losses to yield the same quantity of particle sizes necessary for self-filtering of the base soil to occur for this range of filter sizes.

5. FILTER PERFORMANCE OF DAMS

There are numerous cases of incidents described in the literature involving piping of core materials into downstream filters in central core earth and rockfill dams (Ripley 1984). While these incidents have resulted in damages to the dam in the form of sinkholes and large leakages, none have actually resulted in failure (i.e. breaching) of the dam (Foster, Fell and Spannagle, 1998).

Figure 5 presents the gradations of the filters of some of the dams with poor filter performance. The case histories generally involved piping of core materials into coarse or segregated downstream filters in zoned earthfill or central core earth and rockfill dams. The dams were generally constructed in the 1960's to 1970's which coincides to a period when there was a trend away from the use of uniformly graded multiple filters and towards the use of a single filter of substantial width and broad gradation (Response by Ripley in ICOLD, 1994). The filter gradings shown in Figure 5 have wide gradings and low proportions of sand sizes which would tend to make them susceptible to segregation during construction and also potentially make them internally unstable.

There are also several reported cases of concentrated leaks that have developed through the cores of dams but which have evidently sealed due to the downstream filter as evidenced by observations of near hydrostatic piezometer levels in the downstream section of the core and 'wet seams' in the core (Sherard 1985). Peck (1990) also describes several examples from the literature of dams which have shown evidence that some form of filtering action has taken place at the core–filter interface.

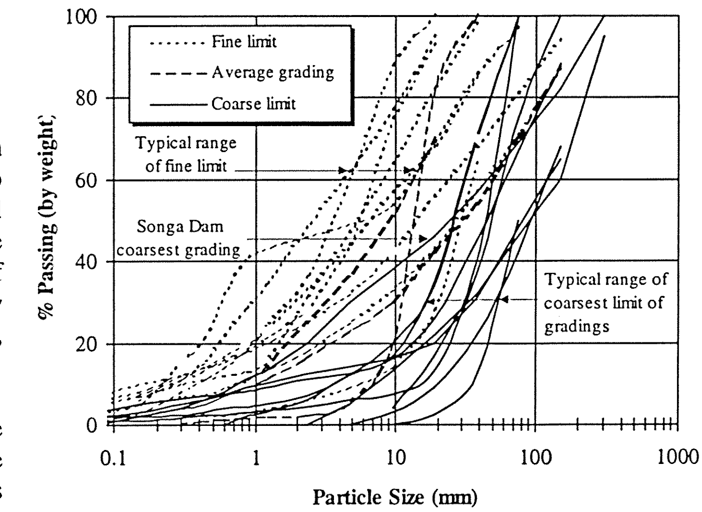

Figure 5. Gradings of filters which have experienced poor filter performance.

Only two dams, Rowallan Dam and Whitemans Dam, were found in the literature which have experienced poor filter performance involving piping of fine grained core materials with DB95 < 2 mm. In both cases, the finest core material and coarsest filter combination fall into the continuing erosion category as defined by the laboratory tests, i.e., DF15/9 > DB95. At Rowallan Dam, the filter with the coarsest grading has a filter opening size (DF15/9) of 11/9 = 1.2 mm, and this is larger than the DB95 of the finest grading of contact clay soil of 0.9 mm. At Whitemans Dam, core materials were eroded into the downstream gravel zone; the filter opening size of this coarsest gravel zone material

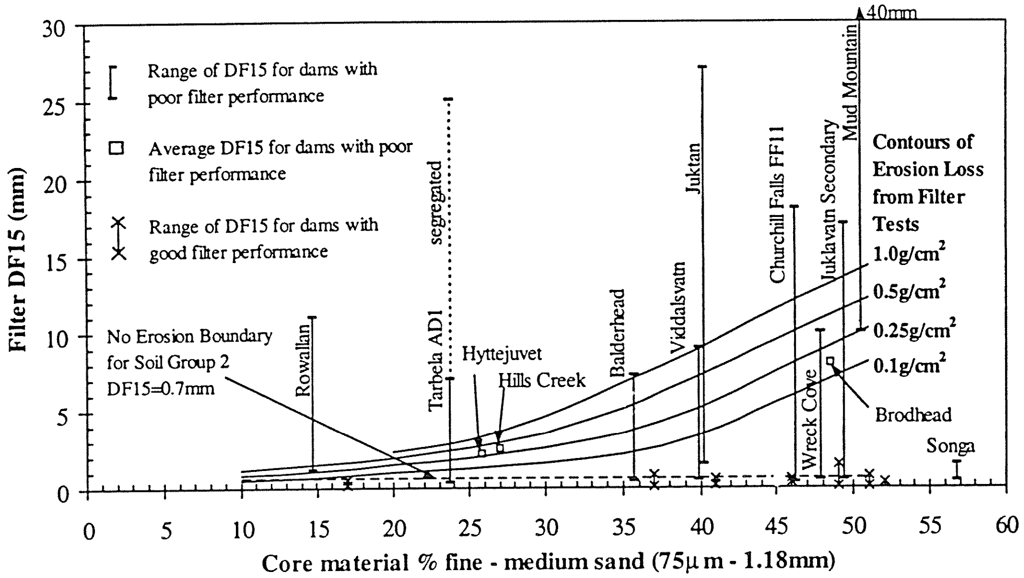

Figure 6. Comparison of erosion losses measured in filter tests to dams with poor and good filter performance.

was 1.0/9 = 0.11 mm and the DB95 of the finest core grading is 0.075 mm.

The other dams with poor filter performance generally have broadly graded core materials which fall into soil groups 2 and 4 (fines content 15–85%) and have DB95 > 2 mm, which places them in the soil types where a continuing erosion boundary could not be identified by the CEF tests. Figure 6 shows the range of DF15 of the filter plotted against the average percentage of fine-medium sand sizes (% 75 μm – 1.18 mm) of the core material for the dams which have had poor and good filter performance. The contours of equal erosion losses from the CEF tests and the no erosion boundary for soil group 2 soils (DF15 = 0.7 mm) are shown on the plot. The percentage fine-medium sand has been taken off the grading curves of the core materials after adjustment to a maximum particle size of 4.75 mm.

Dams with good filter performance generally have filters with an average DF15 ≤ 0.5 mm, which is finer than the Sherard and Dunnigan design criterion for soil group 2 base soils (DF15 ≤ 0.7 mm). The coarsest gradings are only slightly coarser than this (DF15 up to 1.5 mm).

Dams with poor filter performance have filters with an average DF15 > 1.0 mm and generally with DF15 greater than or equal to about the 0.25 g/cm^2 contour of erosion loss. Where a range of filter gradations is given, the coarsest grading is significantly coarser than the design criteria. Balderhead Dam has the finest coarse limit grading of the filter (DF15 = 7 mm) and this is 10 times coarser than the recommended design criteria. The DF15 for the coarsest gradings is typically greater than or equal to about the 1.0 g/cm^2 contour.

One notable exception is Songa Dam, which has a range of DF15 of 0.4–1.5 mm; this is considerably lower than the other dams with poor filter performance. However, the gradings of the filter for Songa Dam (Figure 5) have a wide grading and low proportion of sand sizes which, as discussed further on, would have made the filters particularly susceptible to segregation during placement. Therefore it is likely that the actual gradings of the filter in this dam are probably locally much coarser than that shown.

6. PROPOSED CONTINUING EROSION BOUNDARY FOR SOILS WITH DB95 > 2 mm

The continuing erosion boundary proposed for soils with DB95 > 2 mm defines the filter DF15 that has the potential to result in increases in leakages and in the formation of sinkholes and tunnels through the core in the event of a concentrated leak developing through the core. The criteria are based on the comparison of the CEF test results to the characteristics of the dams with good and poor filter performance, as shown in Figure 6. The proposed criteria are as follows:

(i) average DF15 greater than the DF15 which yields an erosion loss of 0.25 g/cm^2 in the CEF test, as represented by the 0.25 g/cm^2 contour line in Figure 6, and/or

(ii) an upper limit DF15 greater than the DF15 which yields an erosion loss of 1.0 g/cm^2 in the CEF test, as represented by the 1.0 g/cm^2 contour line.

The continuing erosion boundary for soils with DB95 > 2 mm is based on CEF tests on base soils with fines content greater than about 30%. As shown by the no erosion boundaries for soil groups 3 and 4, the self-filtering capabilities of soils with fines content less than 30% are more likely to be influenced by grain sizes coarser than fine to medium sand sizes and so the contours of erosion losses shown in Figure 6 are probably not applicable to these soils. In the absence of any other basis on which to develop criteria, the proposed criteria for the continuing erosion boundary are based on excessive erosion in the laboratory tests. For soil group 3 soils, < 15% fines content, significant erosion losses (defined as > 100 g base material loss) occurred for DF15/DB85 > 9. For soil group 4 soils, with fines content of 15–35%, the descriptions of the unsuccessful NEF tests suggest the erosion losses are significant for filters with DF15 slightly coarser than the no erosion boundary. Therefore, the proposed criterion is based on the upper limit of the no erosion boundary given by:

$$DF15 > 2.5DF15_{design}$$

where $DF15_{design}$ is given by:

$$DF15_{design} = (35-pp\%75\mu m)(4DB85-0.7)/20 + 0.7$$

7. CONCLUSIONS – APPLICATION OF FILTER TEST EROSION BOUNDARIES

7.1 Design of Filters for New Dams

Whilst it has been demonstrated that filters coarser than the filters recommended by the Sherard and Dunnigan (1989) criteria are capable of sealing concentrated leaks, the authors do not advocate the relaxation of the filter criteria for the design of critical filters for new dams. Dams with filters designed and constructed in accordance with these criteria have proven in practice that they are capable of reliably sealing concentrated leaks. The criteria have become widely accepted in practice and they are not considered to be unduly conservative. However some additional issues, raised by the findings of this study, should be considered when designing filters in accordance with the criteria recommended by Sherard and Dunnigan (1989). These are described in the following points.

(i) Design of filters for dispersive soils

Sherard and Dunnigan recommended the same DF15 irrespective of the dispersivity of the core material, however it appears this was based on only a limited number tests on dispersive soils. The NEF tests carried out on two dispersive soils in this study required filters finer than that recommended by the design criteria. Therefore, for the design of critical filters for dispersive core materials, it is recommended that NEF tests be carried out to confirm the DF15 for no erosion.

(ii) Soil Groups 2 and 4 subdivision

It is recommended that the subdivision of soil groups 2 and 4 should be changed to a fines content of 35% instead of 40% as defined by Sherard and Dunnigan (1989). Some NEF tests on soils with 35–40% fines content indicated the no erosion boundary to be as low as DF15 = 0.7 mm, which is the design criterion for soil group 2.

7.2 Assessment of Filters of Existing Dams

An assessment of filters of existing dams should consider how the filter might perform in the event of a concentrated leak developing through the core. Filter performance is classified into three categories as described in the following points.

(i) *Seal with no erosion* – rapid sealing of the concentrated leak with no potential for damage and no or only minor increases in leakage.

(ii) *Seal with some erosion* – sealing of the concentrated leak but with the potential for some damage and minor to moderate increases in leakage.

(iii) *Partial or no seal with large erosion* – slow sealing or no sealing of the concentrated leak with the potential for large erosion losses and large increases in seepage, potential for the development of sinkholes on the crest and erosion tunnels through the core.

Table 4. Likelihood of the filter performance in the event of a concentrated leak.

Comparison of DF15 in the dam to the filter test erosion boundaries		**Likelihood of filter performance in the event of a concentrated leak**		
Average DF15 in the dam	**Coarsest DF15 in the dam**	**Seals with No Erosion**	**Seals with Some Erosion**	**Partial or No Seal with Large Erosion**
< NE	< NE	Highly Likely	Unlikely	Highly Unlikely
< NE	>NE and < CE	Equally Likely		Unlikely
> NE	< CE	Unlikely	Equally Likely	
> NE and < CE	> CE	Unlikely	Unlikely	Likely
> CE	> CE	Highly Unlikely	Unlikely	Highly Likely

Notes: NE = No Erosion Boundary, CE = Continuing Erosion Boundary

Table 4 shows the likely filter performance based on the filter characteristics relative to the filter test erosion boundaries. The assignment of the qualitative likelihood terms shown are based on the comparisons of the case histories with good and poor filter performance to the filter test erosion boundaries on the assumption that the filter materials are not susceptible to segregation or internal instability. If poor construction practices are used and/or if the filter gradings have characteristics that are susceptible to segregation or internal instability, then the likelihood terms should be adjusted towards poor filter performance being more likely.

Characteristics of sand–gravel filters that would tend to make them susceptible to segregation are:

(i) broad grading, with maximum particle sizes > 75 mm,

(ii) a low percentage of sand sizes (< 40% finer than 4.75 mm), and

(iii) poor construction practices, e.g. end dumping from trucks, high lift heights and poor control of stockpile and handling operations.

Even though a particular dam may have filters which are coarser than the continuing erosion boundary, this does not necessarily suggest that the dam will fail in the event of a concentrated leak. An assessment of the likelihood of a piping event leading to failure of the dam needs to take into consideration the likelihood of the progression of piping leading to some breaching mechanism such as toe unravelling or crest settlement leading to overtopping. In an event tree approach, this is considered by the branches leading on from the assessment of filter performance. An overview of the factors affecting the progression of piping are given in Fell and Foster (1999).

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- Gutteridge Haskins and Davey
- Hydro-Electric Corporation, Tasmania
- Melbourne Water
- NSW Department of Public Works and Services
- NSW Dam Safety Committee
- Pacific Power
- Department of Natural Resources, Queensland
- Snowy Mountains Engineering Corporation
- Snowy Mountains Hydro-Electricity Authority
- SA Water
- Sydney Water Corporation
- Western Australia Water Corporation

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