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Filtration of broadly graded soils: the reduced PSD method

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TECHNICAL NOTE

Filtration of broadly graded soils: the reduced PSD method

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INTRODUCTION

Granular filters are used in earth structures, such as embankment dams, to protect fine soils from erosion due to seepage forces. Successful filtration requires that the filter voids are fine enough to capture some of the coarse fraction of the base soil. These retained particles are then able to capture progressively finer base soil particles, and eventually a filter interface forms that is able to prevent any further erosion. This process is called *self-filtration*. Lafleur *et al.* (1989) examined self-filtration in cohesionless, broadly graded base soils. It was found that the extent of mass loss before self-filtration occurs was greater in broadly graded materials: hence a finer filter was required to reduce this mass loss. Filters for cohesive base soils are commonly designed using the Sherard & Dunnigan (1985) design criteria. While these criteria have been developed from extensive laboratory data, they may not be applicable to all fine base soils, particularly broadly graded materials.

In this paper, a series of filtration tests on various base soils are described. Data from the current study, and the published results of laboratory tests from several sources are compared to examine the filtration of broadly graded base soils. Based on this analysis, a new design procedure is proposed for filters to protect fine base soils, which determines the ability of the coarse fraction of the base soil to retain the fine fraction (i.e. a self-filtering base soil).

NO EROSION FILTER (NEF) TESTS

The test for *no erosion filter*—sometimes called the NEF test—was first proposed by Sherard & Dunnigan (1985) to determine the effectiveness of a filter protecting a base soil from erosion. In the test, the base soil sample is compacted against a filter, and a pinhole is driven through the base soil. Water under high pressure is forced through the pinhole, initiating erosion of the pinhole walls. The filter is considered successful if the pinhole shows no visible enlargement after a 20 min test. The coarsest successful filter is called the NEF boundary filter, or critical filter, represented by $D_{15\text{bdy}}$. Sherard & Dunnigan (1985) divided base soils in the NEF test into four groups based on the quantity of fines. The finest two groups are:

(*a*) group 1 base soils, which have >85% of particles <75 μm
(*b*) group 2 soils, which have 40–85% of particles finer than 75 μm.

NEF tests have been performed on 15 samples of core materials from embankment dams within Australia and other sources. Representative base soil particle sizes and the NEF critical filters are presented in Table 1. In this paper, d refers to a base soil particle size, and D refers to a filter particle size. The critical filter sizes, $D_{15\text{bdy}}$, determined from the current experiments are plotted against the d_{85} base soil particle size in Fig. 1. Also shown are the critical filters from published data of 33 NEF tests conducted by:

(*a*) Khor & Woo (1989), who performed NEF tests on broadly graded, sandy soils
(*b*) data for group 2 soils tested by Sherard (1984), as reported by Foster (1999)
(*c*) Delgado (2000), who executed NEF tests on core materials from Spanish dams.

The Sherard & Dunnigan (1985) design criteria are shown as a solid line in Fig. 1. Most of the lab data meet, or are very close to, the design criteria, the notable exception being material AP1, which has a safe critical filter size significantly finer than that required by the design criteria. This material has a ratio $D_{15\text{bdy}}/d_{85} = 1{\cdot}1$. Most of the group 2 materials plot below the line $D_{15\text{F}} = 9d_{85\text{B}}$, where the subscripts 'F' and 'B' stand for the filter and base soil respectively in the original Sherard & Dunnigan (1985) criteria (Fig. 1). The intention here is to investigate why a sharp demarcation occurs between the safe filter boundaries for group 1 and 2 materials, and why material AP1 has such a fine $D_{15\text{bdy}}$.

THE REDUCED PSD METHOD

A new method to determine the self-filtering fraction of a broadly graded base soil, called the *reduced PSD* method, is described in this section, based on an analysis of the AP1 material. The particle size distribution (PSD) of the AP1 material is shown in Fig. 2. The fine critical filter for this material ($D_{15\text{bdy}} = 0{\cdot}19$ mm) and broad grading suggest that the coarse fraction of material AP1 is unable to retain the fine fraction: hence self-filtering does not occur. To determine the self-filtering fine fraction, the PSD is divided at some point n (where n is the percentage passing diameter d_n), and one can then define d_{15} of the coarse fraction and d_{85} of the fine fraction to be

$$d_{15\text{coarse}} = d_{n+0{\cdot}15(100-n)} \tag{1}$$

$$d_{85\text{fine}} = d_{0{\cdot}85n} \tag{2}$$

Bertram (1940) with guidance from Terzaghi conducted detailed laboratory testing to determine if the coarse fraction is able to retain the fine fraction. For an effective filter including self-filtering ability, a conservative expression was found as:

$$\frac{d_{15\text{coarse}}}{d_{85\text{fine}}} \leqslant 5 \tag{3}$$

This method is shown graphically in Fig. 3. Figure 3 is a semi-log plot: the vertical axis is not logarithmic, and the

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Table 1. Base soil properties and results of NEF tests

Sample name	PSD of base soil				NEF, D_{15bdy}: μm	Ratio, D_{15bdy}/d_{85}
	% <75 μm	d_{98}: μm	d_{85}: μm	d_{50}: μm		
Group 1						
BB3	99	40	16	5	125	7·8
BB4	100	35	11	4	100	9·1
KE1	96	120	28	9	350	12·5
CA1	91	500	36	5	325	9·0
HU1	94	400	33	6	370	11·2
CO1	90	400	45	8	800	17·8
RO1	92	250	35	2·2	750	21·4
SF1	98	75	23	8	540	23·5
AS1	100	65	38	20	270	7·1
CW1	94	100	25	7	530	21·2
YY1	98	75	35	7	630	18·0
Group 2						
TH1	55	550	190	70	2000	10·5
AP1	76	550	170	8	190	1·1
BB1	80	650	120	12	780	6·5
AS2	81	250	90	12	1100	12·2

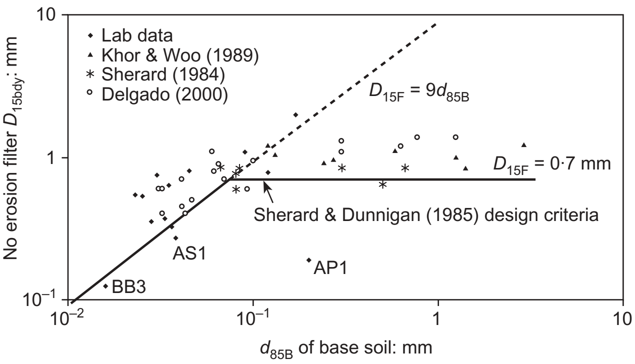

Fig. 1. Results of 48 NEF tests compared with Sherard & Dunnigan (1985) design criteria

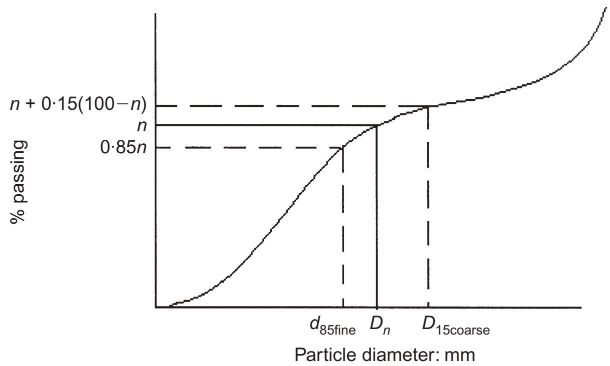

Fig. 3. Method to assess self-filtration of a soil

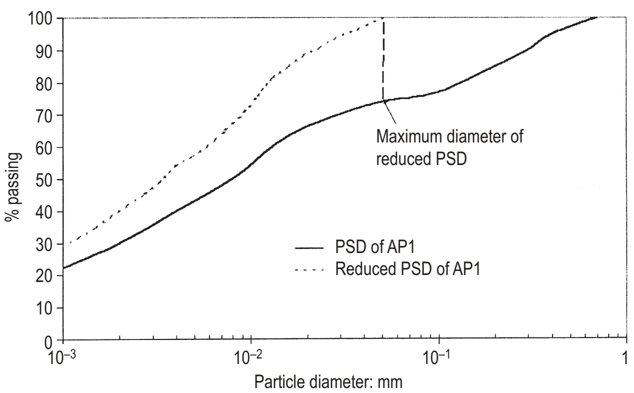

Fig. 2. PSD and reduced PSD of material AP1

multipliers of n (e.g. $0{\cdot}85n$) will not be affected by the log scale.

The PSD should be divided at some point n, and equation (3) is then checked to determine whether this part of the PSD is stable. As an example, data from Fig. 2 for the AP1 material imply that when $n = 50\%$, $d_{15coarse} = 0{\cdot}011$ mm and $d_{85fine} =$ 0·007 mm. This gives a ratio $d_{15coarse}/d_{85fine} = 1{\cdot}6$. Considering increasing values of n, the largest diameter $d_{15coarse}$ complying with equation (3) is the coarsest particle of the stable PSD. All larger particles may be captured by the filter, but will not form voids small enough to retain the finer particles of the base soil. Continuing the example for material AP1, the maximum diameter of the stable PSD was found to be $d_{15coarse} = 0{\cdot}055$ mm, when $n = 68\%$ and $d_{85fine} = 0{\cdot}011$ mm. The reduced PSD, considering only the particles finer than the $d_{15coarse}$ diameter, defines the stable self-filtering fraction of the soil, shown in Fig. 2 for the AP1 material. The proposed technique suggests that a successful filter must be able to retain the self-filtering reduced PSD.

DESIGN OF FILTERS FOR BROADLY GRADED BASE SOILS

The reduced PSD has been determined for each of the base soils tested, and for the data taken from the earlier work of Sherard (1984), Khor & Woo (1989) and Delgado (2000). Comparison with the critical filter diameter is shown for group 1 materials only in Fig. 4, along with the Sherard & Dunnigan (1985) design criterion $D_{15F}/d_{85} = 9$. This criterion, when applied to the reduced PSD, seems overly conservative for most data. The line $D_{15F}/d_{85reduced} = 12$ forms a lower bound for the majority of the measured NEF boundaries. Sample AS1 plots below this design line; this material is a clay with a very uniform coarse fraction ($d_{98B}/d_{85B} < 2$). Sherard & Dunnigan (1985) also noted that

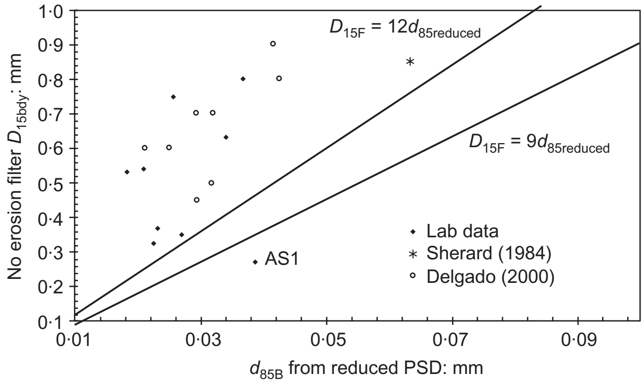

Fig. 4. NEF boundary against d_{85} of the reduced PSD for soil group 1 materials only

uniform materials have a slightly lower D_{15bdy} value, so this result is not unexpected. This analysis suggests that the reduced PSD method can be used to determine a safe filter for group 1 soils. All the materials tested were clays with PI $>$ 10. Based on these observations, a new design criterion for group 1 soils, with PI $>$ 10 and $d_{98}/d_{85} > 2$, is proposed as

$$D_{15F} \leqslant 12d_{85reduced} \tag{4}$$

The NEF boundary filter diameter and d_{85} of the reduced PSD are plotted for the group 2 materials in Fig. 5. Comparison of Figs 1 and 5 indicates that the Sherard & Dunnigan (1985) filter criterion for group 2 materials, requiring $D_{15F} = 0{\cdot}7$ mm, is a lower bound for filter tests on all group 2 soils regardless of their ability to self-filter, and that significantly coarser filters are suitable for self-filtering base soils. The line $D_{15F}/d_{85reduced} = 9$ represents a conservative filter for the majority of the data. Notable exceptions are the materials S5, 81W895, BJV-C1 and BJV-C3. These four materials are sandy silts, having a low plasticity index, PI $<$ 6, while the remaining group 2 materials are sandy clays and clayey sands with PI $>$ 10. This suggests that the clay fraction causes particle aggregation, and produces larger particles that are stable during filtration. This aggregation of particles does not occur in low-plasticity materials such as sandy silts. These silty materials behave more like a non-cohesive base soil, and a filter retention ratio of $D_{15F}/d_{85B} < 4$ is probably more appropriate. Based on this analysis, a new design criterion is developed for group 2 materials.

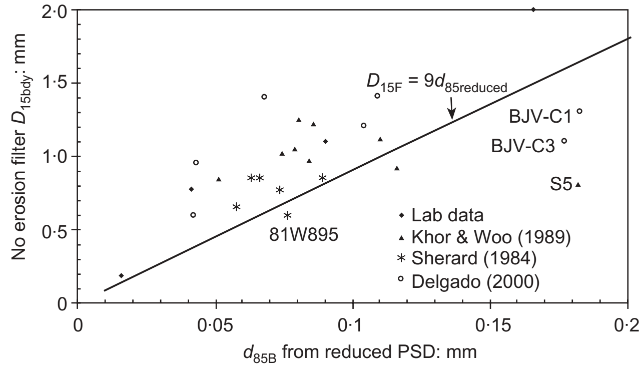

Fig. 5. NEF boundary against d_{85} of the reduced PSD for soil group 2 materials only

(*a*) For PI $>$ 10:

$$D_{15F} \leqslant 9d_{85reduced} \tag{5}$$

(*b*) For PI $<$ 10:

$$D_{15F} \leqslant 4d_{m85reduced} \tag{6}$$

CONCLUSIONS

Broadly graded base soils may be unable to self-filter, because the coarse fraction of the material is often too coarse to act as a filter for the fine fraction. This means that filters designed by traditional filter design criteria (e.g. Sherard & Dunnigan, 1985) to retain the coarse fraction of the base soil may allow continued erosion of the fine fraction because self-filtration does not occur. A series of 15 no erosion filter tests, and published results of another 33 tests, were compared to examine filtration of broadly graded materials. One material was shown to have a critical filter diameter of $D_{15F} = 0{\cdot}19$ mm, while the Sherard & Dunnigan (1985) design criterion allowed $D_{15F} = 0{\cdot}7$ mm.

A new technique, called the reduced PSD method, has been introduced to determine the self-filtering stable fraction of a broadly graded base soil. Examination of the laboratory data based on the reduced PSD showed that the following design criteria may be adopted.

(*a*) For group 1 materials (with >85% of particles finer than 75 μm), having PI $>$ 10 and $d_{98}/d_{85} > 2$:

$$D_{15bdy}/d_{85reduced} \leqslant 12$$

(*b*) For group 2 materials (having 40–85% of particles finer than 75 μm) the design relations are:

for PI $>$ 10, $D_{15bdy}/d_{85reduced} \leqslant 9$ (clayey soils)

for PI $<$ 10, $D_{15bdy}/d_{85reduced} \leqslant 4$ (silty soils)

In comparison with the commonly used Sherard & Dunnigan (1985) criteria, these new design criteria often allow coarser filters for self-filtering base soils, while significantly finer filters may be necessary to protect some broadly graded materials.

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