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A parametric database study of no-erosion filter tests

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Modern filter design procedures for embankment dams respect criteria stemming from no-erosion filter (NEF) tests. The widespread application of NEF testing has provided experimental evidence of some deviations from the established filter criteria. This paper provides a complementary update to similar database studies of NEF test results. A large database of NEF tests, consisting of 258 group I and group II core soils (i.e. having more than 35% fines content) was analysed and the effects of various core soil characteristics (gradation, fines content, clay content, plasticity index and dispersivity) on experimentally defined no-erosion boundary filters were assessed. The database is unique, as it compiles the largest set of NEF test results. Through rigorous statistical and parametrical analysis, this paper critically compares current filter design criteria with experimental results and provides new insights that may assist and improve current procedures of critical filter design.

Notation

A_r	activity ratio (ratio of PI to the percentage of particles finer than 2 μm)
C_c	clay content, percentage finer than 0.005 mm in adjusted gradation
D_i	filter particle diameter with $i\%$ finer by mass
D_{15b}	no-erosion boundary filter size resulting from NEF test on a base soil
d_i	base soil particle diameter with $i\%$ finer by mass, for the adjusted gradation curve with maximum size of 4.75 mm
F_c	fines content, percentage finer than 0.075 mm in adjusted gradation
M_c	silt content, percentage between 0.005 mm and 0.075 mm in adjusted gradation
m_a	arithmetic mean
N	total number of data points in analysis
n	number of data points per reference
S_c	fine to medium sand content, percentage between 0.075 mm and 1.18 mm in adjusted gradation
s	standard deviation

1. Introduction

Statistical surveys of embankment dam failures reveal that internal erosion, particularly from the embankment, has been

responsible for nearly half of dam failures, with an even higher percentage experiencing non-catastrophic erosion-related incidents/accidents (Foster *et al.*, 1998; Fry, 2016; Fry *et al.*, 2012; ICOLD, 2017; Richards and Reddy, 2007).

To some extent, the initiation of erosion depends on the characteristics of embankment materials (e.g. the core), and filters are designed and constructed as defence barriers to control/suppress internal erosion. When filters fail, that is they fail to stop erosion, internal erosion continuation and progression (to form a pipe or cause sloughing) is the likely scenario that may eventuate in dam breach (Fell *et al.*, 2003, 2015; ICOLD, 2017). The principal role that filters play in dam safety, along with their usually high production and construction costs, make optimal filter design and substantiation a topic that is subject to much scientific debate.

Numerous filter design criteria have been proposed, among which the criteria presented by Sherard and Dunnigan (1985, 1989) are broadly implemented in modern embankment dam engineering. These criteria (see Table 1) stem from extensive no-erosion filter (NEF) tests carried out by Sherard and co-workers at the United States Department of Agriculture Soil Conservation Service in 1980–1985. Since their initial introduction, the criteria proposed by Sherard and Dunnigan

Table 1. Proposed filter criteria based on NEF testing

Reference		Base soil designation			
		Group I	Group II	Group III	Group IV
Sherard and Dunnigan (1985)	F_c : % ^a	≥ 85	40–85	< 15	15–40
	Criterion ^b	$D_{15} \leq 9d_{85}$	$D_{15} \leq 0.7 \text{ mm}$	$D_{15} \leq 4d_{85}^c$	$D_{15} \leq \frac{40 - F_c}{25} (4d_{85} - 0.7) + 0.7 \text{ mm}$
Foster and Fell (1999)	F_c : %	≥ 85	35–85	< 15	15–35
	Criterion	$D_{15} \leq 9d_{85}^d$	$D_{15} \leq 0.7 \text{ mm}^e$	$D_{15} \leq 7d_{85}$	$D_{15} \leq 1.6 \left(\frac{35 - F_c}{20} (4d_{85} - 0.7) + 0.7 \text{ mm} \right)$
Shourijeh and Soroush (2009)	F_c : %	≥ 85	≥ 80	35–80	15–35
	Criterion	$D_{15} \leq 9d_{85}^{f,g}$	$D_{15} \leq \text{minimum of } 0.7 \text{ mm} \text{ and } 6.4d_{85}^g$	$D_{15} \leq 0.7 \text{ mm}^e$	$D_{15} \leq \frac{35 - F_c}{20} (4d_{85} - 0.7) + 0.7 \text{ mm}$
USBR (2011) and FEMA (2011)	F_c : %	≥ 85	40–85	< 15	15–40
	Criterion	$D_{15} \leq 9d_{85}^h$	$D_{15} \leq 0.7 \text{ mm}^e$	$D_{15} \leq 4d_{85}$	$D_{15} \leq \frac{40 - F_c}{25} (4d_{85} - 0.7) + 0.7 \text{ mm}^e$
Fell <i>et al.</i> (2015)	F_c : %	≥ 85	35–85	< 15	15–35
	Criterion	$D_{15} \leq 9d_{85}^i$	$D_{15} \leq 0.7 \text{ mm}^e$	$D_{15} \leq 4d_{85}$	$D_{15} \leq \frac{35 - F_c}{20} (4d_{85} - 0.7) + 0.7 \text{ mm}$
This study	F_c : %	≥ 85	≥ 80	35–80	15–35
	Criterion	$D_{15} \leq 9d_{85}^{f,i}$	$D_{15} \leq \text{minimum of } 0.5 \text{ mm} \text{ and } 5d_{85}^j$	$D_{15} \leq 0.7 \text{ mm}^e$	$D_{15} \leq \frac{35 - F_c}{20} (4d_{85} - 0.7) + 0.7 \text{ mm}$

^a% finer than 0.075 mm in gradation adjusted to maximum size of 4.75 mm

^b d_{85} for gradation passing 4.75 mm, in all criteria except for group III base soils which are not broadly graded or gap-graded

^c d_{85} for entire material gradation

^d $D_{15} \leq 6.4d_{85}$ for highly dispersive soils

^e $D_{15} \leq 0.5 \text{ mm}$ for highly dispersive soils

^f $D_{15} \leq 6d_{85}$ for ML and CL-ML soils

^g $D_{15} \leq 7.5d_{85}$ for highly dispersive soils

^h $D_{15} \leq 6.5d_{85}$ for highly dispersive soils

ⁱ $D_{15} \leq 6d_{85}$ for highly dispersive soils

^j $D_{15} \leq 0.3 \text{ mm}$ for highly dispersive soils

(1985, 1989) have been widely recommended by various institutions (e.g. FEMA, 2011; ICOLD, 2017; NRCS, 1994; USACE, 2004; USBR, 2011).

Despite general recognition of the criteria listed in Table 1 and subsequent proven dam performances through application of these rules, filter testing is still the most confident and reliable method for filter selection and design (USBR, 2011). The NEF test is accepted as a proficient filtration test, especially for fine-grained soils. Many researchers have repeated NEF testing to substantiate appropriate filters and assess filter criteria credibility (e.g. Delgado Ramos and Locke, 2000; Delgado Ramos *et al.*, 2012; Foster and Fell, 1999; Khor and Woo, 1989; Shams Molavi *et al.*, 2013; Soroush and Shourijeh, 2004, 2009; Soroush *et al.*, 2006, 2008, 2011e, 2014, 2016; Vakili and Selamat, 2014; Vakili *et al.*, 2015).

However, recently, the abundance of new dam constructions (particularly in developing countries), unfortunate embankment dam internal erosion incidents and rigorous studies involving NEF testing have revealed some anomalies between the accepted 'no-erosion' filter criteria and the observed behaviours of core soils and filters.

The work presented in this paper involved revisiting critical filter design criteria through compilation and analysis of published NEF test results. To this end, a similar investigation presented by Shourijeh and Soroush (2009) was updated with NEF data published in the last decade and subjected to more rigorous statistical and parametric analyses. The paper is organised into four main sections. First, previous database studies of filtration tests are briefly reviewed. The NEF test database under study is then introduced and its particular facets are elaborated. Thereafter, extensive statistical and parametric analyses on core (base) soils and corresponding 'no-erosion' filters is performed. Finally, modifications to the available criteria and guidelines for critical filter design are suggested.

2. Database studies of soil filtration

The NEF criteria in Table 1 are principally inferences drawn from laboratory experiments. Accordingly, Table 1 designates base soils in four groups (groups I to IV) based on their fines content (i.e. passing 75 μm) after the gravel component is sifted out. This is done by graphically regrading the base soil gradation to 4.75 mm maximum size. It should be noted that regrading is not required when the original base soil gradation has less than 15% fines content (passing 75 μm) and is 'neither gap-graded nor broadly graded' (USBR, 2015). Foster and Fell (1999) carefully examined the original NEF testing programme reported by Sherard and Dunnigan (1985, 1989) and detected a total of 162 NEF tests on 65 base soils (28 from group I, 19 from group II, seven from group III and 11 from group IV). The confidence level and reliability of the proposed criteria (Table 1) would be enhanced with the analysis and evaluation of more soils (from reliable filtration tests).

Foster and Fell (1999) outlined an extensive and thorough investigation of approximately 700 filtration tests, considering all feasible filtration test results (i.e. successful, unsuccessful and intermediate). The detailed and sophisticated analysis conducted by Foster and Fell (1999, 2001) demarcated 'no', 'some', 'excessive' and 'continuing' erosion boundaries for soil filtration, which provided a platform for probabilistic studies of internal erosion and piping in embankment dams (Fell *et al.*, 2008, 2015; ICOLD, 2017). Table 1 shows the revised filter criteria proposed by Foster and Fell (1999).

Delgado Ramos *et al.* (2006) compiled a large database of filtration tests on group I and group II base soils. In all, 688 tests were investigated, of which 492 were NEF tests – 105 tests conducted by Sherard and Dunnigan (1985, 1989), 47 tests reported by Foster and Fell (1999) and 340 performed by Delgado Ramos (2000). Similar to the work of Foster and Fell (1999), Delgado Ramos *et al.* (2006) focused on determining transitional boundaries between unsuccessful and successful base soil/filter behaviours. In addition, Delgado Ramos *et al.* (2006, 2016) suggested considering filter permeability in filter design. This, however, was discouraged by Fell *et al.* (2015) because measuring and controlling filter permeability is generally difficult in practical engineering problems.

Shourijeh and Soroush (2009) collated a large filtration database wherein (a) only NEF tests were considered, excluding other testing strategies, and (b) a 'no-erosion' boundary filter and its associated D_{15b} were considered for each base soil. By definition the boundary filter, D_{15b} is the D_{15} of the coarsest filter that prevents erosion in NEF testing (i.e. leads to no erosion for the base soil). By focusing on base (core) soils, a total of 152 group I and group II base soils and the corresponding D_{15b} values determined through NEF testing were studied by Shourijeh and Soroush (2009). This work was founded on the proposition by Sherard and Dunnigan (1989: p. 945) that 'the filter boundary D_{15b} can be considered a property of the base soil in the same sense that results of tests to determine the Atterberg limits and effective shear strength parameters are considered properties of the imperious soil'.

In later sections of this paper, the study of Shourijeh and Soroush (2009) is expanded to include more data and the results are studied statistically and discussed in more detail.

3. Database specifications

The database under study consisted of 258 group I and group II core (base) soils and their corresponding 'no-erosion' filters determined from NEF testing. The portfolio of contributing references, alongside a concise description of their main NEF testing procedural specifications, is presented in Table 2, which is updated from the previous study of Shourijeh and Soroush (2009).

Table 2. Inventory of NEF testing research incorporated in the database

Investigator	NEF test information					Number of base soils per group	
	ϕ_A : mm	L_B : mm	L_F : mm	ϕ_h : mm	P_w : kPa	Group I	Group II
Sherard and Dunnigan (1985, 1989)	100	25	80–100	1	410	23	15
	280	100	NA	5–10			
Khor and Woo (1989)	170	25	130	1.5	400	—	9
Rowhani (1996)	139	25	100	1	300–450	—	10
Khavas (1998)	167	90	110	5 and 10	400–500	—	4
Foster and Fell (1999)	125	25	150	1 and 2	240–300	—	6
	205	100	200	5			
Nasr (1999)	167	90	110	5 and 10	400–500	—	4
Kamali (1999)	139	25	100	1	300–450	20	4
Delgado Ramos (2000)	80	25	100	1	400	10	7
Hossieni (2000)	167	90	110	5 and 10	400–500	—	3
Locke (2001)	100–200	NA	NA	1	200–600	11	4
Mirata and Gürlér (2004)	100	25	40	1.5	250	1	2
USBR (2004) ^a	267	25	152	2	275	2	3
Farzaneh (2005)	139	25	100	1	300–450	4	—
Soroush and Shourijeh (2005)	110	30	120–140	1	400	11	—
Farzaneh (2007)	139	25	100	1	300–450	4	—
Soroush <i>et al.</i> (2010a) ^a	110	30	120–140	1	400	6	—
Soroush <i>et al.</i> (2010b) ^a	110	30	120–140	1	400	5	—
Eskandary (2011) ^a	140	30	100	1	400	4	—
Soroush <i>et al.</i> (2011a) ^a	110	30	120–140	1	400	6	4
Soroush <i>et al.</i> (2011b) ^a	110	30	120–140	1	400	7	3
Soroush <i>et al.</i> (2011c) ^a	110	30	120–140	1	400	6	—
Soroush <i>et al.</i> (2011d) ^a	110	30	120–140	1	400	1	—
Soroush <i>et al.</i> (2012a) ^a	110	30	120–140	1	400	6	—
Soroush <i>et al.</i> (2012b) ^a	110	30	120–140	1	400	—	1
Shams Molavi (2013) ^a	110	30	120–140	1	400	2	—
Soroush <i>et al.</i> (2015) ^a	110	30	120–140	1	400	8	—
Vakili <i>et al.</i> (2015) ^a	110	25	100	1	400	10	11
Farzaneh (2015) ^a	139	25	100	1	300–450	3	—
Ramezani Fouladi (2016) ^a	110	30	120–140	1	400	16	2
Total number of base soils in each group						166	92

Notes: L_B , base specimen thickness; L_F , filter thickness; NA, not available; P_w , water pressure; ϕ_A , apparatus diameter; ϕ_h , hole diameter

^aEntries to NEF database since the work carried out by Shourijeh and Soroush (2009)

For each base soil, the principal properties considered are as follows.

- Particle size distribution (i.e. gradation) information, namely d_{85} , fines content F_c (= percentage passing 75 μm), clay content C_c (= percentage finer than 5 μm), silt content M_c (= percentage particles between 5 μm and 75 μm) and fine to medium sand content S_c (= percentage of particles between 75 μm and 1.18 mm). As in filter design guidelines (Fell *et al.*, 2015; ICOLD, 2017; NRCS, 1994; USBR, 2011), this information represents base soils adjusted (i.e. scalped) to a maximum size of 4.75 mm.
- Atterberg limits and related information, specifically the plasticity index (PI), activity ratio ($A_r = \text{PI}/\% < 2 \mu\text{m}$) and soil denomination as per the unified soil classification system (USCS).
- Dispersivity information, including double hydrometer and pinhole test results.

It is worth noting that all this information may not be available for some base soils; in such cases, no attempts were made by the authors to foresee/predict missing data.

Concerning filter properties, only D_{15b} is considered as the sole influential filter parameter in the database. It should be mentioned that, for filter materials, the complete gradation (Foster and Fell, 1999), fines (if any) content (Soroush *et al.*, 2012c), relative compaction (Soroush and Shourijeh, 2009) and permeability (Delgado Ramos *et al.*, 2016) may influence the filtration of base (core) soils. On the whole, such information was not reported in pertinent literature and hence was not sought/considered by the current authors.

Consequently, for each core (base) soil, the database relates a no-erosion boundary filter, that is D_{15b} (D_{15} of the coarsest filter that prevents erosion), determined from NEF testing to an array of base soil properties.

4. Database analysis

4.1 Base soil group I: fine silts and clays

Group I soils with $F_c \geq 85\%$ are the finest core soils considered for filter design (Table 1). From the results of NEF testing, Sherard and Dunnigan (1985, 1989) stated that, for this base soil group, D_{15b}/d_{85} generally ranges from 7 to 12, and $D_{15} \leq 9d_{85}$ is considered as the design criterion. While no correlation between D_{15b} and base soil properties (i.e. relative erosion resistance, Atterberg limits and dispersive erosion tendency) could be established, an experimentally defined D_{15b}/d_{85} ratio of 5.7 to 6.2 was observed for low-plasticity clays (i.e. CL-ML soils).

Foster and Fell (1999) suggested that D_{15b}/d_{85} for group I base soils is between 6.4 and 13.5. Similarly, Shourijeh and Soroush (2009) reported that D_{15b}/d_{85} is generally in the range from 7 to 13.5, although it may be as high as 27.

4.1.1 Variation of D_{15b} with d_{85}

For 166 group I soils, the frequency distribution of d_{85} is illustrated in Figure 1(a). For base soils in this group, $F_c \geq 85\%$, thus $d_{85} \leq 0.075$ mm. The average d_{85} of the data was found to be 0.039 mm, which corresponds to the mean dimension of silt-sized particles (i.e. 5–75 μm). While 64% of the data (107 soils) have d_{85} in the range 0.02–0.05 mm, only one base soil has a d_{85} less than 0.01 mm. Overall, concerning d_{85} , the data are normally distributed, covering the entire spectrum of group I base soils.

The distribution of D_{15b} , shown in Figure 1(b), implies that 92% of the data (152 soils) have $D_{15b} < 0.6$ mm. The single D_{15b} higher than 0.9 mm may be regarded as an outlier, and will be cautiously dealt with (or removed) in further considerations. It is worth noting that only five of the base soils (i.e. 3% of the data) have $D_{15b} < 0.2$ mm, thus complying well with design guide assertions that prohibit critical filters with a D_{15b} lower than 0.2 mm (Fell *et al.*, 2015; ICOLD, 2017; USBR, 2011). Interestingly, the average D_{15b} for the reported data is 0.41 mm, which is quite close to 0.425 mm, determined as the upper size limit of fine sands.

The frequency of D_{15b}/d_{85} observations for group I core soils ($N = 166$) is illustrated in Figure 1(c). D_{15b}/d_{85} is lower than 15 for 80% (i.e. 131) of the base soils, while $D_{15b}/d_{85} < 10$ for 48% of the data (79 soils). More precisely, 33% of the data show $D_{15b}/d_{85} \leq 9$, suggesting that $D_{15b}/d_{85} = 9$ may be unsafe in providing no erosion for some base (core) soils. In addition, 3% of the data (five base soils) show inordinately low D_{15b}/d_{85} values of < 5 . For four base soils (around 2% of the data), D_{15b}/d_{85} is in excess of 30, and these data were omitted from further analysis.

The plot of D_{15b} against d_{85} for group I base soils is illustrated in Figure 2. Accordingly, 97% of the data (160 base soils) have

D_{15b}/d_{85} values between 4 and 30. Evaluation of the data reveals that, for $d_{85} \geq 0.04$ mm, D_{15b}/d_{85} is lower than 13.5 (except for one base soil). In addition, it is implicitly discernible that an arbitrary D_{15b} is associated with a variety of d_{85} sizes. These observations imply that (a) D_{15b}/d_{85} is predominantly influenced by d_{85} (i.e. the denominator), thus an increase in D_{15b}/d_{85} is not essentially related to higher D_{15b} , but rather controlled by a lower d_{85} and (b) base soil characteristics other than d_{85} prominently influence filtration processes.

4.1.2 Clay content and silt content

The fines content (F_c) of base soils comprises clay (C_c = percentage passing 5 μm) and silt (M_c = percentage between 5 μm and 75 μm) fractions; that is, $F_c = C_c + M_c$. As shown in Figure 1(d), C_c shows a fairly normal distribution for group I base soils, with average of 41.8%. In addition, 69% of the data (114 soils) have $30\% \leq C_c < 60\%$ and hence few of the base soils in the data base are rich in clay or full of silt. Figure 3 illustrates the variation of D_{15b}/d_{85} with C_c . Accordingly, 83% of soils with $C_c \geq 40\%$ have $D_{15b}/d_{85} > 9$ whereas, for $C_c < 40\%$, 52% of the data plot below $D_{15b}/d_{85} = 9$. Previous studies imply that clay content significantly influences the filtration behaviour of fine silts and clays (Delgado Ramos *et al.*, 2006; Foster and Fell, 1999; Shourijeh and Soroush, 2009) and contemporary investigations on soil erosion characteristics have revealed that an increase in clay content reduces soil erodibility (Hanson *et al.*, 2010; Wan and Fell, 2004). It should be noted that an increase in C_c is associated with a finer gradation, possessing a smaller d_{85} and, intuitively, a higher D_{15b}/d_{85} . In other words, soils with higher C_c do not essentially reflect a coarser D_{15b} , yet their cohesive bonds and relative erosion resistance leads to a median D_{15b} , which, in combination with their tiny d_{85} , leads to a high value of D_{15b}/d_{85} .

Figure 4 shows the variation of D_{15b}/d_{85} with silt content, M_c (= percentage between 5 μm and 75 μm). Although not clearly distinct, there is an overall trend of decreasing D_{15b}/d_{85} with an increase in M_c . This observation would be predictable by the trend of D_{15b}/d_{85} plotted against C_c (Figure 3). According to Figure 4, 47% of base soils with $M_c \geq 50\%$ have $D_{15b}/d_{85} < 9$ whereas, for soils with $M_c < 50\%$, 79% plot above $D_{15b}/d_{85} = 9$.

Sherard *et al.* (1984) stipulate that retaining silt-sized particles is prerequisite to the successful filtration of fine silts and clays (i.e. group I base soils). However, recent developments in soil erodibility measurements indicate that silty soils are normally more erodible than clayey soils (Fell *et al.*, 2013; Regazzoni *et al.*, 2008). It may be envisaged that the erosion product of clayey soils is coarser than individual silts due to the cohesive bonds holding clay particles together (Locke, 2001). Delgado Ramos *et al.* (2012) reported NEF tests on clayey soils with aluminium sulfate as a 'coagulating' additive: 'as expected the aluminium sulfate increased floc size and thereby increased filter size' (ICOLD, 2017: p. 169).

Figure 1. Frequency variations (histograms) of (a) d_{85} , (b) D_{15b} , (c) D_{15b}/d_{85} , (d) C_c and (e) PI and (f) bar chart of soil classification (USCS) for group I base soils (m_a , arithmetic mean; N , number of data points; s , standard deviation)

4.1.3 PI

The variation in PI for 134 group I base soils is illustrated in Figure 1(e). This plot shows that 74% of the data (99 base soils) have $PI < 20\%$, reflecting the average PI routinely

encountered in clay/silt mixtures originating mainly from sedimentary environments. Such soils are abundantly available in many areas worldwide for use as core materials in embankment dams. Core soils at both ends of the PI variation (i.e.

Figure 2. Variation of D_{15b} with respect to d_{85} for group I base soils; N (number of data points) = 165; n , number of data points per reference

Figure 3. Variation of D_{15b}/d_{85} with clay content, C_c , for group I base soils ($N=161$)

possessing very high or very low PI) are infrequent: only two soils have $PI > 50\%$ and about 7% (nine soils) have $PI < 5\%$. Pursuing this a step further, the variations in base soil category defined according to the USCS are shown in Figure 1(f). For the group I base soils with available USCS information ($N=148$), 12% are CH, 70% are CL, 11% are CL-ML and 8% are ML. The MH type is extremely uncommon, with only one representative. The populations of soil categories represent the actual domain of soil classes encountered in embankment dams. On this subject, comprehensive statistical studies by Foster *et al.* (1998) revealed that (a) CL soils represented the

majority of various soils types in embankment dam cores and (b) 34% of cores experiencing erosion damages/failures consisted of CL soils and 18% were ML soils.

The variation of D_{15b}/d_{85} with respect to PI is plotted in Figure 5. The data are highly scattered, with no clear trend emerging. Nonetheless, the concentration of data with D_{15b}/d_{85} between 6 and 9, or even with $D_{15b}/d_{85} < 6$, is much higher where $PI < 10\%$. A decrease in PI generally leads to higher soil erodibility (Hanson *et al.*, 2010; Wan and Fell, 2004), conceivably demanding finer filters.

Figure 4. Variation of D_{15b}/d_{85} with silt content, M_c , for group I base soils ($N=161$)

Figure 5. Variation of D_{15b}/d_{85} with PI for group I base soils ($N=129$)

Delgado Ramos *et al.* (2012) asserted that D_{15b} decreases as PI increases, and attributed this conclusion to the fact that soils with higher PI are generally finer, hence having a smaller d_{85} which requires a finer filter. Such performance was not observed and deduced for the data studied in the current work. In brief, Delgado Ramos *et al.* (2012: p. 875) state that ‘the base soil plasticity has influence in the boundary filter, but it is not as important as the base soil particle size distribution’.

4.1.4 Activity ratio (A_r)

According to Fell *et al.* (2013: p. 358) ‘The main physical parameters influencing the erosion of cohesive fine-grained soil

are the particle size distribution (grain size), the clay fraction and the clay mineralogy’. Unfortunately, information concerning mineralogical compositions of the base soils is mostly unavailable in the database.

The activity ratio (A_r) may be considered as an indirect indicator of mineralogy for clay particles (Mitchell and Soga, 2005). The A_r is the ratio of PI (%) to the percentage of particles finer than $2 \mu m$. As shown in Figure 6, no perceptible relationship between D_{15b}/d_{85} and A_r – as a mineralogical descriptor – exists. Delgado Ramos *et al.* (2012) also inspected correlations between D_{15b} and clay mineralogy and found no significant relationship.

Figure 6. Variation of D_{15b}/d_{85} with activity ratio, A_r , for group I base soils ($N=126$)

4.1.5 Dispersivity potential

Dispersive erosion is an associated issue in the filtration of fine silts and clays (i.e. group I soils). This is of particular interest as various laboratory test procedures for determining dispersive soils, namely pinhole tests (ASTM D 4647 (ASTM, 2006a)), crumb tests (ASTM D 6572 (ASTM, 2006b)), double hydrometer testing (ASTM D 4221 (ASTM, 2011)) and chemical analysis (Sherard *et al.*, 1976), give different results regarding the dispersivity of fine clays/silts (Fan and Kong, 2013).

Sherard and Dunnigan (1989) stated that D_{15b} is not related to a tendency for dispersive erosion. Contrary to this, filtration studies – specifically those containing NEF results – state that dispersive group I base soils require finer no-erosion filters, that is D_{15b} (Table 1). The criteria of $D_{15} \leq 6.4d_{85}$ and $D_{15} \leq 6.5d_{85}$ have been recommended by Foster and Fell (1999) and USBR (2011), respectively, whereas Shourijeh and Soroush (2009) suggested $D_{15} \leq 7.5d_{85}$. More recently, Fell *et al.* (2015) proposed even finer filters for dispersive group I soils complying with $D_{15} \leq 6d_{85}$ and, through elaborate NEF tests, Vakili *et al.* (2015) advised $D_{15} \leq 5.5d_{85}$.

In the database under study, information concerning the dispersive tendency of base soils is limited. Having said that, Figure 7 illustrates the variation of D_{15b}/d_{85} with dispersion percentage (measured by double hydrometer tests) for group I base soils. From the highly scattered data, a general trend of decreasing D_{15b}/d_{85} with an increase in dispersion percentage is weakly discernible. Both moderately dispersive (dispersion = 30–50%) and highly dispersive (dispersion > 50%) soils (Bell and Maud, 1994) may require filters significantly finer than $D_{15b} = 9d_{85}$. As shown in Figure 7, the criteria of $D_{15b} \leq 6d_{85}$

and $D_{15b} \leq 5.5d_{85}$ are very close and respectively correspond to no erosion for 94% and 96% of the data. The variation of D_{15b} with d_{85} for highly dispersive soils (pinhole classification D1 or D2) is shown in Figure 8. The limited data suggest that while $D_{15b}/d_{85} \leq 9$ is fairly safe in most cases, $D_{15b}/d_{85} \leq 6$ assures no erosion for all results.

4.2 Base soil group II: sandy silts and clays

Core soils with $35\% \leq F_c < 85\%$ are designated as group II (Table 1). In the original categorisation of Sherard and Dunnigan (1985, 1989), base soils with $40\% \leq F_c < 85\%$, were considered in group II, for which the experimentally defined D_{15b} generally ranged from 0.7 to 1.5 mm and no relation between D_{15b} and the base soils' gradations characteristics (i.e. d_{85}) was found. Additionally, Sherard and Dunnigan (1989) claimed that base soils with 35–40% fines content have filtration behaviours similar to group II base soils, in so far as 'the filter boundary D_{15b} is of the order of 0.8–1.5 mm, independent of the d_{85} size' (Sherard and Dunnigan, 1989: p. 943). Subsequent research by Foster and Fell (1999) revealed that base soils with $F_c = 35\text{--}40\%$ are better considered in group II, and this notion has since been implemented in some filter criteria (Fell *et al.*, 2015; Shourijeh and Soroush, 2009). Furthermore, Foster and Fell (1999) reported $D_{15b} = 0.7\text{--}1.7$ mm for group II, irrespective of d_{85} .

4.2.1 Variation of D_{15b} with d_{85}

As illustrated in Figure 9(a), the frequency variation of d_{85} for group II base soils is highly biased to finer/smaller d_{85} sizes (note that the standard deviation (s) is higher than arithmetic mean (m_a)). This means that, that in dealing with group II base soils, designers/specialists were commonly inclined towards selecting finer base soil gradations close to group I.

Figure 7. Variation of D_{15b}/d_{85} with dispersion percentage for group I base soils ($N=50$)

Figure 8. Variation of D_{15b} with d_{85} for highly dispersive (pinhole classification D1 or D2) group I base soils ($N=15$)

Concerning this idea, USBR (2011: p. 72) asserts that ‘if the base soils fall within more than one category for new or existing dams, then generally use the finer side of the range of gradations’.

According to Figure 9(b), D_{15b} for group II base soils is generally (96% of the data) lower than 1.6 mm. Moreover, 48% of the data (44 base soils) have $D_{15b} < 0.8$ mm. There is only one instance with D_{15b} higher than 2.2 mm, and this outlier is not included in further analyses.

The variation of D_{15b} with d_{85} for 91 group II base soils is shown in Figure 10. No clear trend between D_{15b} and d_{85} can be discerned but, in general, finer base soils (i.e. lower d_{85}) require a smaller D_{15b} . Inspection of Figure 10 implies that

66% of the data have $D_{15b} \geq 0.7$ mm and, where $d_{85} \geq 0.3$ mm, the criterion of $D_{15b} = 0.7$ mm may be considered safe overall in ensuring no erosion. Of note, some data points presented in Figure 10, particularly those with $D_{15b} < 0.7$ mm, are drawn from soils with a dispersive tendency. The filtration properties of such group II base soils are studied separately in forthcoming sections.

4.2.2 Fines content

Figure 9(c) illustrates that F_c observations for group II base soils are inclined to higher values: 57% of the data (52 soils) have $F_c < 75\%$, while 29% (27 soils) have $F_c \geq 80\%$. This is not surprising recalling the d_{85} variation (Figure 9(a)) and noting that, logically, soils on the finer edges of core material ranges are chosen for NEF testing and filter substantiation (USBR, 2011).

Figure 11 illustrates the variation of D_{15b} with F_c (i.e. percentage $< 75 \mu\text{m}$) for group II base soils. An overall trend of decreasing D_{15b} with increasing F_c is shown, and this trend is more pronounced for $F_c > 75\%$. It is intuitively inferable that finer base soils would most likely require finer filters. As noted by Shourijeh and Soroush (2009), group II base soils with a high fines content impart behaviours similar to group I bases; hence, D_{15b}/d_{85} might better represent their no-erosion boundary. Subsequently, Shourijeh and Soroush proposed that, for group II base soils with $F_c \geq 80\%$, D_{15b} should be selected as 0.7 mm or $6.4d_{85}$, whichever is the smaller.

A scatterplot of D_{15b}/d_{85} against F_c for group II base soils is shown in Figure 12. When $F_c < 80\%$, almost all the data have $D_{15b}/d_{85} < 6.4$. However, for $F_c \geq 80\%$, D_{15b}/d_{85} shows a drastically different range, from 1 to 13.

Figure 9. Frequency variations (histograms) of (a) d_{85} , (b) D_{15b} , (c) F_c , (d) S_c and (e) PI and (f) bar chart of soil classification (USCS) for group II base soils

Figure 13 shows the variation of D_{15b} against d_{85} for group II base soils with $F_c \geq 80\%$. According to the figure, $D_{15b} = 0.7$ mm is certainly unsafe and most base soils require finer no-erosion filters. Moreover, taking the minimum of 0.7 mm and $6.4d_{85}$

(Table 1) is also inadequate for nearly half of the data. By disregarding allocated dispersive base soils (Figure 13), the newly suggested criterion of selecting D_{15b} as the minimum of 0.5 mm and $5d_{85}$ is safe for 90% of base soils. At first glance,

Figure 10. Variation of D_{15b} with d_{85} for group II base soils ($N=91$)

Figure 11. Variation of D_{15b} with fines content, F_c , for group II base soils ($N=91$)

$5d_{85}$ may seem unduly conservative, yet group II base soils always have $d_{85} \geq 0.075$ mm; hence, the proposed criterion is in fact delineating a D_{15b} bounded between 0.375 mm and 0.5 mm.

4.2.3 Fine to medium sand content

The variation of fine to medium sand content (i.e. percentage of particles between 75 μ m and 1.18 mm), S_c , for group II base soils is shown in Figure 9(d). The figure shows that S_c is normally distributed (particularly when compared with F_c) in the range of 5% to 60%, with 41% of the data (38 base soils) having $S_c < 20\%$.

The variation of D_{15b} with S_c is presented in Figure 14: D_{15b} increases with an increase in S_c in so much as, for $S_c \geq 30\%$,

the criterion of $D_{15b} = 0.7$ mm ensures no erosion for 92% of the data. For base soils with $S_c \geq 30\%$, F_c is delimited between 36% and 68%, suggesting that in the filtration of group II base soils, fine to medium sand particles play a more significant role as the fines content decreases. Continuing-erosion filter tests carried out by Foster and Fell (1999) demonstrated that fine to medium sand particles in the base soil influence filtration and contribute to forming a self-filtration layer.

This analysis validates the proposition by Shourijeh and Soroush (2009) that group II base soils have diverse filtration behaviours depending on their fines content (F_c). The entire domain of group II core soils have $35\% \leq F_c < 85\%$. When

Figure 12. Variation of D_{15b}/d_{85} with fines content, F_c , for group II base soils ($N=92$)

Figure 13. Variation of D_{15b} with d_{85} for group II base soils with $F_c \geq 80\%$ ($N=27$)

$F_c \geq 80\%$, base soils are close to group I and reflect similar filtration properties. For $65\% \leq F_c < 80\%$, fines are preponderant in the soil fabric and hence dominate filtration. In the case of coarser base soils with $35\% \leq F_c < 65\%$, fine to medium sand particles are ample and significantly influence filtration behaviour.

4.2.4 PI

From the PI frequency variation illustrated in Figure 9(e) it is apparent that group II base soils have lower PIs than group I soils due to their lower F_c and, in turn, higher S_c . Moreover,

83% of the data (note that $N=70$) have $PI < 20\%$, corresponding to lean clays/silts with sand.

Group II base soils with available USCS information ($N=65$) are categorised in Figure 9(f). As anticipated from the possible base soils in this group (i.e. $F_c = 35-85\%$), a variety of soil classifications are encountered, from high-plasticity clays (CH) to cohesionless silty-sand soils (SM). Among the group II base soils, the most frequent classes are CL (57%), CL-ML (12%) and ML (8%). The SC, SC-SM and SM groups combined represent 15% of the data. This further corroborates the notion

Figure 14. Variation of D_{15b} with fine to medium sand content, S_c , for group II base soils ($N=91$)

that NEF tests by researchers on group II base soils have been concentrated on finer soils close to group I.

Figure 15 shows the variation of D_{15b} with PI for group II base soils. Wherever the base soil was non-plastic, the PI was assumed to be 1% in order to avoid zero values. A clear relation between D_{15b} and PI cannot be recognised, but it is apparent that, with a decrease in PI, the number of data points with $D_{15b} > 0.7$ mm increases. An increase in PI is associated with a finer gradation curve, possessing a higher F_c , which requires a finer filter (D_{15b}). Note that, for sandy soils, an increase in PI is generally less influential in depleting

erodibility in comparison with fine silts and clays (Fell *et al.*, 2013).

4.2.5 Dispersivity potential

The filter design criteria shown in Table 1 all commonly state that for dispersive group II base soils it is safe to consider $D_{15b} \leq 0.5$ mm. In Figure 13, dispersive group II base soils with $F_c \geq 80\%$ are indicated by encircled symbols. Obviously, $D_{15b} = 0.5$ mm is not suitable for such soils, implying that $D_{15b} \leq 0.3$ mm would better ensure no erosion. Similarly, Vakili *et al.* (2015) suggested $D_{15b} \leq 0.28$ mm for highly dispersive group II base soils.

Figure 15. Variation of D_{15b} with PI for group II base soils ($N=69$)

Figure 16. Variation of D_{15b} with d_{85} for highly dispersive group II base soils ($N = 14$)

Figure 16 illustrates the variation of D_{15b} with d_{85} for all highly dispersive group II base soils. The data are very limited, especially when noting that (a) half the base soils (seven out of 14) were analysed in Figure 13, devoted to $F_c \geq 80\%$, and (b) a unified approach for determining highly dispersive soils was not involved (i.e. defined by either pinhole or double hydrometer tests). Despite these setbacks, for highly dispersive group II base soils with $F_c < 80\%$, the $D_{15b} \leq 0.5$ mm criterion may be considered adequate for 71% (five out of seven base soils) of the data.

5. Summary and conclusions

In spite of all advances in understanding internal erosion and piping for embankment dams, protective filters are commonly designed and substantiated implementing simple experimentally derived criteria. The critical filter design criteria listed in Table 1 were first introduced by Sherard and Dunnigan (1985) and still hold today, three decades after their initial presentation.

In this study, critical filter design criteria (Table 1) were revisited by investigating an extensive database of 258 group I and group II (i.e. $F_c \geq 35\%$) core (base) soils and their associated no-erosion filters. The main updates of the current investigation in comparison with the study reported by Shourijeh and Soroush (2009) are that the number of data incorporated was increased (258 instead of 152 previously analysed), specifically those concerning dispersive core (base) soils, and a more rigorous statistical/parametric analysis was applied to the database.

The database's salient feature is that it is collated entirely from NEF test results. The parametric study assessed the influences of various core soil parameters (d_{85} , clay content (C_c), silt content (M_c), fines content (F_c), fine to medium sand content (S_c), PI, dispersivity) on experimentally determined values of

D_{15b} (the no-erosion boundary filter). The aforementioned parameters have complicated reciprocal interactions; that is, an increase in one results in the other's decline or increase. Translating their influences on NEF test results in a quantitative manner into simple/straightforward criteria and design rules would thus require utmost caution and precision. Therefore NEF test results should have the final say in filter design.

For group I cores ($F_c \geq 85\%$), the main conclusions inferred from the parametric study are as follows.

- Soil particle size represented by d_{85} is the most significant factor in filtration.
- Clay content (C_c) and PI positively affect filtration, while the activity ratio (A_r) seems ineffective.
- Soils with $d_{85} < 0.04$ mm or $C_c > 40\%$ may reflect a high D_{15b}/d_{85} in NEF testing, yet this does not essentially mean a coarser filter (i.e. a higher D_{15b}). In fact, D_{15b} for such soils falls in the general D_{15b} ranges observed for group I soils and hence the $D_{15}/d_{85} \leq 9$ criterion should not be relaxed.
- Base soils with a PI less than 10%, or classified as ML/CL-ML, have comparatively low erosion resistance, thus accentuating the conservative $D_{15}/d_{85} \leq 6$ criterion.
- In the authors' opinion, soils having both PI < 10% and $d_{85} < 0.04$ mm are highly erodible and problematic in regard to filtration and require very careful filter design.
- When the soil is dispersive, the criterion of $D_{15}/d_{85} \leq 6$ is safe.

Regarding group II core soils ($35\% \leq F_c < 85\%$), the following findings are presented.

- Filtration is dominantly controlled by the fines content, F_c .
- When $F_c \geq 80\%$, the soil behaves essentially similar to group I base (core) soils and requires a comparatively fine no-erosion filter. Such soils have $D_{15b} \geq 0.35$ mm, for which $D_{15} \leq \min(5d_{85} \text{ and } 0.5 \text{ mm})$ seems a safe and logical criterion.
- Wherever $d_{85} \geq 0.3$ mm or $S_c \geq 30\%$ or $F_c < 65\%$, the D_{15b} value from NEF testing is almost always higher than 0.7 mm; thus, the $D_{15} \leq 0.7$ mm criterion is expected to be reliable. This also applies safely to soils with F_c between 65% and 80%.
- Dispersibility would require $D_{15} \leq 0.3$ mm for soils with $F_c \geq 80\%$ and $D_{15} \leq 0.5$ mm otherwise.
- The PI has little influence on filtration.

The foregoing conclusions are reflected in the amended criteria summarised in Table 1. The flowchart provided in Figure 17 should also provide useful advice to designers of filters to resist internal erosion in new dams.

Figure 17. Flowchart for critical filter design of group I and group II core soils

It is important to note that, of the 258 core soils (groups I and II) studied herein, 75% have $F_c \geq 80\%$. Furthermore, from 213 core soils with available USCS information, 66% are CL soils. As already discussed, this unavoidable bias is a result of designers/specialists dealing with NEF tests reported in the literature selecting finer representatives for core soil ranges, which necessitate finer filters.

For embankment dam design, proficient filtration testing supersedes established formulae, on the condition that designed filters are not coarser than the criteria in Table 1. 'If the designer has any doubts concerning the filter's performance, filter tests should be conducted. For example, dispersive soils, very fine grained cohesionless soils, highly plastic soils, and soils prone to desiccation may require extra precautions' (USB, 2011: p. 53). NEF tests have been repeatedly performed worldwide and much experience concerning precise, practical NEF testing is available that may pave the way for designers/specialists. Even with overall agreement to the filter criteria provided in Table 1, the authors strongly advocate filter testing, and particularly NEF tests, for filter substantiation in embankment dams.

Future studies could focus on comparing filter criteria and NEF test results with soil erosion characteristics such as those deduced from hole erosion tests (Wan and Fell, 2004). In addition, it would be effective to associate boundary filters (i.e. D_{15b}) satisfying NEF tests with filter permeability. Systematic NEF and continuing-erosion filter tests (involving measurements of eroded soil mass) may help bracket a 'some erosion' boundary in terms of filter D_{15} and base soils properties (d_{85} , F_c etc.).

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