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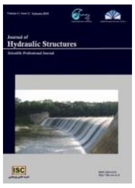

An investigation on the parameters affecting the behavior of broadly graded, dispersive base soil-filter systems in earth dams

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Abstract

Designing appropriate filter materials is as important as ensuring the safety factor of the entire body of earth dams. The performance of the downstream filter zone in earth dams could be significantly influenced by base soil features, particularly in the case of cohesive broadly graded cores. The effects of several variables, such as base soil plasticity, fine content, and clay content, on the properties of effective filter materials were investigated experimentally in the current study. Results obtained through the no erosion filter (NEF) test indicated that the plasticity of base soil materials had no apparent correlation with the corresponding filter materials. However, fine content was found to have significant effects on the boundaries of the no erosion filter, especially for soils classified as Group 1. Although there was a decreasing tendency in D_{15f} size with increasing clay content of the base materials, the effects of clay content on the required filter materials were not as significant as those of fine content. In conclusion, designing filter materials by concurrently considering d_{85} and fine content (F) of base materials appears to be more logical than separately utilizing these effective parameters. In this scenario, the new filter design criterion was derived using regression techniques based on experimental results.

Keywords: cohesive soils; effective filter; soil plasticity; fine content; clay content

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List of notations

$PP \leq$	Percentage finer than 0.002 mm;
$PP \leq$	Percentage finer than 0.005 mm;
F	Fine content (%)
PI	Plasticity index (%)
PSD	Particle size distribution;
D_{15f}	Size of filter material of which 15% of the material passes;

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D_{15bdy}	D_{15f} size of filter material found from no erosion filter test to be the boundary between successful and unsuccessful test;
d_n	Size of base soil materials of which n percentage of the material passes;
n	The percentage passing diameter d_n;
NEF	No - erosion filter;
CL	Low plasticity clay;
CH	High plasticity clay;
ML	Low plasticity silt;
D	Percent dispersion or degree of dispersion;
MDD	Maximum dry density (gr/cm^3);
OMC	Optimum moisture content (%);
K_f	Coefficient of permeability of filter material (cm/sec);
USCS	Unified soil classification system;
Base soi Group 1	A base soil with a fine content of 85% or more;
Base soil Group 2	A base soil with a fine content of less than 85%;
Fine content	Percentage finer than 0.075 mm;
Clay content	Percentage finer than 0.002 mm.

1. Introduction

The phenomenon of soil erosion and sediment transport are among the key hydrodynamic processes recognized as one of the major challenges and an important potential failure mode in the exploitation of surface water resources worldwide [1,2]. Therefore, research has been carried out regarding the design of filters [3]. Generally speaking, the performance of an earth dam is equally dependent on the performance of the core as well as the protective filter. Designing the filter can thus be considered as important as designing the core, and in fact, the two are inseparable as reflected by the way established design criteria have been presented [4,5]. Filter materials must be sufficiently fine to prevent the migration of erodible particles of the base soil, and at the same time, they must be adequately coarse to allow drainage of seepage water without the accumulation of excessive pore water pressure [6]. Hence, filter materials are designed based on two general criteria: retention criterion and permeability criterion. Filter retention criteria are usually expressed in three forms - the geometric grading criterion, the constriction-based criterion, and the hydraulic criterion [7]. The design of filter based on geometric grading criterion basically involves particle size distributions (PSDs) of the base soil and the filter, and is presented in the form of filter-base soil grain size ratios [8-12]. D15f and d85 sizes are often specified as representative sizes for the filter and base soil, respectively, in geometric grading criteria. The phenomenon of internal soil erosion is significantly influenced by relative density, relative particle size distribution of base soils and filters and applied hydraulic gradient [13,14]

On the other hand, the required permeability of filter materials should be specified within the hydraulic criteria. Thus, designing filters based on hydraulic criteria involves considering both the PSD of the base soil and the permeability of the filter. In this approach, the filter's permeability (k_f) and the d_{85} size of the base soil are commonly used as representative parameters. Unlike grading criteria, hydraulic criteria emphasize the relationship between filter permeability and the PSD of the base materials [5].

To address the challenges associated with traditional filter design criteria, the state-of-the-art design criteria known as constriction-based criteria were introduced. This method simultaneously considers the effects of various parameters such as PSD, compaction, grading, surface area, porosity, and uniformity coefficient of filter materials during the design process. The approach involves applying a programming subroutine to convert the filter's PSD curve into constriction size distribution (CSD) curve. After determining the CSD curve of filter materials, two key parameters, namely the controlling constriction size (D_{c35}) and self-filtering constriction size (D_{c95}), are measured. The procedure continues by modifying the PSD curve of the base materials, removing particles larger than D_{c95} size, and measuring the new representative size (d^*_{85}) form the modified PSD curve of the base soil materials. Finally, this criterion emphasizes the relationship between the controlling constriction size of the filter and the modified PSD of the base materials [5].

In the traditional filter design criteria, the actual or modified d_{85} size of base materials is usually used as a representative of the base soil in filter design practices. However, significant questions arise regarding whether the effectiveness of the filter could be influenced by other base soil features such as plasticity, clay content, fine content, etc. It is well known that the process of internal erosion for cohesive base materials is more complex than for non-cohesive ones [15]. This complexity arises because the internal erosion process can be significantly influenced not only by the particle size distribution of core and filter materials but also by the erodibility of base soils [16]. Vakili et al. [17] investigated several base soils, including cohesive, broadly graded and dispersive soils, and found that the erodibility and dispersivity of the base soil significantly impact the formation of internal erosion and, consequently, the required filter materials. They reported the strong and adverse relationship between dispersivity degree of core materials and their corresponding no-erosion filter boundaries [17]. Furthermore, the effects of water quality on the NEF test results, when the base soil materials were broadly graded, cohesive, and dispersive, were examined by Vakili et al. [7] using two different waters including distilled and Malaysian river waters. It has been found that the chemistry of water reservoirs can change the erosion rate of dispersive base materials and, therefore, the required D_{15f} size of filter materials [7].

For the case of broadly graded, cohesive, dispersive base materials, the geometric grading criteria of $D_{15f}/d_{85} = 0.6037(d_{85})^{-0.66}$ and $D_{15f}/d_{85} = 10.0\exp(-0.009D)$ were introduced by Vakili et al. [17]. They believe that the former criterion could predict the no-erosion filter boundary better than traditional filter design criteria if only the d_{85} size of base materials is taken into account. However, the latter criterion was considered relatively new because, in addition to particle size distribution, the dispersivity degree of core materials is also considered concurrently in the filter design process.

By and large, there are still uncertainties in designing suitable materials for the case of broadly graded, cohesive, dispersive base materials. To highlight the current problem statement, consider two different base soils, each having the same d_{85} and dispersion degree but differing properties such as different clay and contents. In such cases, materials with similar gradation curves, specifically similar D_{15f} values, might be considered appropriate filters according to universally accepted existing filter design criteria, such as the Sherard and Dunnigan [18] criteria. In other words, the D_{15f}/d_{85} ratios would be identical for both cases, irrespective of other base soil features. Therefore, due to the differing characteristics of base soils, there is a general question: do these base soil-filter combinations exhibit similar behavior in terms of mass retention capability and flow rates? Alternatively, could identical filter materials be effective in both cases? Or do factors like plasticity, fine content, and clay content render the filter system ineffective? Hence, further investigations are necessary to examine the influential parameters of cohesive base soil on the characteristics of required filter materials. In the majority of filter design criteria, only the effects of d_{85} size of base materials are considered. Therefore, the main objective of this study was to assess the effects of base soil features on filter effectiveness, if any.

2. Materials and Methods

The results from the experimental tests program were analyzed to determine:

1- The effect of base soil plasticity on filter effectiveness;
2- The effect of base soil fine content on filter effectiveness;
3- The effect of base soil clay content on filter effectiveness.

To achieve the aforementioned aims, twenty-two base soils with varying characteristics were collected from Batu Gajah, Malaysia. To assess the characteristics of the base materials, all collected samples were tested for particle size distribution in accordance with ASTM D 422 [19], plasticity index following ASTM D 4318 [20], double hydrometer as per ASTM D 4221-99 [21], and standard compaction tests according to ASTM D 698 [22]. Based on the aforementioned tests, the main features of the samples were determined, including fine content, clay content, plasticity index, soil dispersivity, soil class according to the Unified Soil Classification System (USCS), optimum moisture content (OMC), and maximum dry density (MDD), as presented in Table 1.

To assess the performance of various filter-base soil combinations, the NEF tests were carried out. The NEF test, originally developed by Sherard and Dunnigan [18], was followed in this study according to the procedures described by Sherard and Dunnigan [18] and Soroush and Shourijeh [23]. Figure 1 shows a photo of the actual experimental setup of the NEF test equipment.

The NEF test cylinder was transparent, with a diameter of 11 cm and a height of 30 cm. In the test procedures, a drainage layer made of gravel-sized material was placed at the bottom of cylinder, separated from the filter layer by a wire screen. The filter material was 10 cm thick and consisted of 4 compacted sub-layers. The fabricated filter materials were initially saturated and thoroughly mixed. The filter materials placed into the NEF cylinder were compacted using both vibration and tamping techniques. A relative density of 75% was used for the compaction of the filter materials in the NEF test.

Figure 1. A view of the NEF equipment arrangement under test

Instead of using granular-sided materials, a plastic ring was used to intrude into the final filter layer; this plastic ring, which intruded into the final filter layer, also known as water-tight plastic. The overlying base soil was 2.5 cm thick and consisted of 2 sub-layers, each compacted to maximum dry density. Note that the base soil samples were first mixed with distilled water before being compacted in the NEF test cylinder. The amount of water added was equal to the required value to achieve the optimum moisture content determined by the standard Proctor test. The prepared samples were placed in an airtight plastic bag and stored for 24 hours to allow equilibrium between the dissolved salts in the soil pore water. A 1 mm diameter perforation was made through the base soil layer and extended 1 cm into the filter layer. Another wire screen separated the base soil layer from the upper drainage layer, which, like the lower drainage layer, also made up of gravel size material. At the beginning of the test, the inlet valve and air vent were slightly opened while the outlet valve remained closed. After saturating the gravel drain with water and de-aerating it, the air vent was closed and the outlet valve opened. The water pressure of 400 kPa or 4.0 kg/cm^2 was applied during the procedure. In other words, the applied hydraulic gradient was approximately 1600 due to water flow through the perforation.

The performance of filter-base soil system was assessed by collecting the effluent, measuring the flow rate every minute, inspecting the effluent turbidity, and determining the perforation size after each test. A filter material was considered successful in protecting the base soil if no visible erosion occurred- i.e., no enlargement in the initial size of perforation. The duration of each test was typically about 20 minutes. Longer tests were not necessary, as erosion of the base material usually occurs within the first 20 minutes of the test (Delgado Ramos and Locke, 2000).

For filters, 14 different types of clean sandy samples with various PSDs or D_{15f} sizes were artificially prepared. The filter materials placed into the NEF cylinder were compacted using both vibration and tamping techniques. Granular soils, such as filter materials, are typically compacted to achieve a desired relative density. Relative density serves as a compaction index for granular soils [24]. Relative densities of 75% were utilized for compacting the filter materials in the NEF test. It's noteworthy that relative densities of 70% have been observed to suffice in field conditions to mitigate the risk of flow liquefaction during earthquakes [25]. Conversely, Fell et al. [25] argue that there are no discernible benefits in using relative densities exceeding 80% for the filter zone of earth dams. Moreover, employing relative densities greater than 80% can lead to excessive breakdown of filter materials [25]. Therefore, it appears reasonable to apply a relative density of 75% in the test procedure.

Table 1: Characteristics of base materials collected for the current study

Base soil Group	d_{85} (mm)	Fine content (%)	Clay content (%)	D (%)	PI (%)	Soil class based on USCS
1-S_1	0.03	91.0	40	93.0	16	CL
1-S_2	0.065	88.0	35	51.0	17	CL
1-S_3	0.038	92.0	40	61.0	24	CL
1-S_4	0.02	96.0	48	82.0	35	CH
1-S_5	0.015	100.0	41	45.0	31	CH
1-S_6	0.062	86.0	37	32.0	13	CL
1-S_7	0.055	90.0	20	69.0	8	ML
1-S_8	0.050	92.0	35	41.0	12	CL
1-S_9	0.044	88.0	40	82.0	17	CL
1-S_{10}	0.060	88.0	36	75.0	24	CL
1-S_{22}	0.065	87	44	96.0	34	CH
2-S_{11}	0.20	83.0	35	65.0	16	CL
2-S_{12}	0. 10	82.0	33	74.0	20	CL
2-S_{13}	0. 30	76.0	3.5	32.0	15	CL
2-S_{14}	0.15	78.0	7.0	15.0	25	CL
2-S_{15}	0.15	75.0	33	50.0	16	CL
2-S_{16}	0.090	83.0	34	43.0	31	CH
2-S_{17}	0.091	83.0	32	81.0	17	CL
2-S_{18}	0.13	71.0	14	89.0	11	ML
2-S_{19}	0.18	80.0	31	56.0	18	CL
2-S_{20}	0.09	82.0	30	37.0	17	CL
2-S_{21}	0.23	75.0	25	9.0	13	CL

For the preparation of base materials, the base soil samples were thoroughly mixed with water. The quantity of water added was adjusted to achieve their optimum moisture content, as determined by the standard Proctor test (by referring to Table 1). The prepared samples were placed into airtight plastic bags and maintained for 24 hours to achieve equilibrium between dissolved salts in the soil pore water. The base soil was then compacted inside the cylinder using a tamper. The compaction process continued until reaching a final thickness of 25 mm. Note that all base materials were compacted at their maximum dry density (MDD) and optimum moisture content (OMC).

The pressure of water applied in the NEF test procedure was 400 kPa or 4.0 kg/cm^2. In other words, the applied hydraulic gradient was about 1600 due to water flow through the performed hole. Considering the geometry and reservoir heights of large dams, pressures of over 350 kPa must be applied in filter test procedures for a highly accurate simulation of large dams [12]. Note that the duration of each test is normally about 20 minutes and tests for a longer period are not compulsory because erosion of the base materials usually takes place within the first 20 minutes after starting the test [27].

Based on the NEF test results, the boundary between successful and unsuccessful filter materials could be determined for any given core materials with specific properties [18,25]. In this study, the D_{15bdy} values were determined for all base soil specimens.

3. Results and Discussions

3.1. Effects of plasticity of base materials on filter effectiveness

The influence of base soil plasticity on the no-erosion filter boundary is illustrated in Figure 2. The plasticity of the collected base materials was found to have little effect on the no-erosion filter boundary, as already reported by Sherard and Dunnigan [18], Foster and Fell [25], and Zomorodian and Moghadam [28]. However, Delgado et al. [16] found a strong correlation between the plasticity of base materials and the D_{15f} size of required filter materials. Delgado et al. [16] believed that base soil plasticity increases directly with its fine content, thus leading to a decrease in the D_{15f} size of required filter materials. Although there is a general trend of increasing D_{15bdy}/d_{85} ratio with increasing plasticity index, the correlation obtained is not as strong as those obtained by Soroush et al. [29] and Delgado et al. [16].

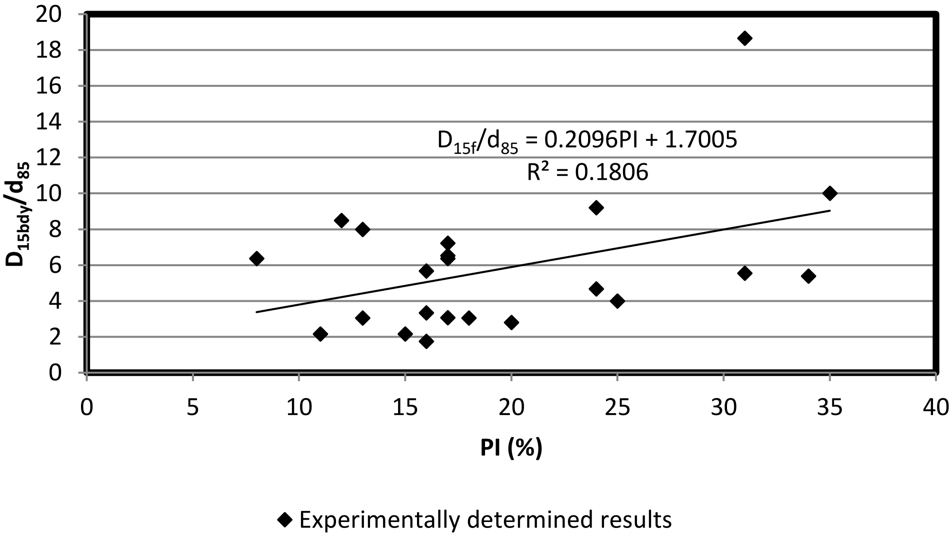

Figure 2. Variation of the plasticity index of the base soils against ratio of D_{15bdy}/ d_{85} for broadly graded, dispersive core materials

Nevertheless, the given endorsement comes with the following remarks:

1- The plasticity of almost all base soils tested by Soroush et al. [29] was less than 10. However, the plasticity index of base materials collected for the current study ranged from 8% to 35%. Thus, the results obtained in the current study may not be compatible with those of Soroush et al. [29], as the current study covers a wider range of base materials.

2- The compatibility of the NEF test results against the criterion suggested by Delgado et al. [16] is illustrated in Figure 3. The experimentally determined results were found to be incompatible with the criterion suggested by Delgado et al. [16], as the majority of the plots are placed below the line. The criterion becomes questionable, especially for those base materials with a plasticity index less than 20%. In other words, the criterion suggests a D_{15f} size of more than 0.9 mm for base materials with a PI less than 10. However, all base materials tested by Soroush et al.

[29] required filter materials with a D_{15f} size less than 0.4 mm, illustrating the inaccuracy of the criterion. Further evidence from the current study supports this. For instance, sample 1-S7 had an ML classification with a PI of 8%. The criterion suggests a D_{15f} of 1.15 mm as a no-erosion filter boundary. However, the experimentally determined no-erosion filter boundary was 0.35 mm, which is 3.3 times smaller than the criterion. Thus, the base soil features could not be effectively represented by plasticity in filter design purposes.

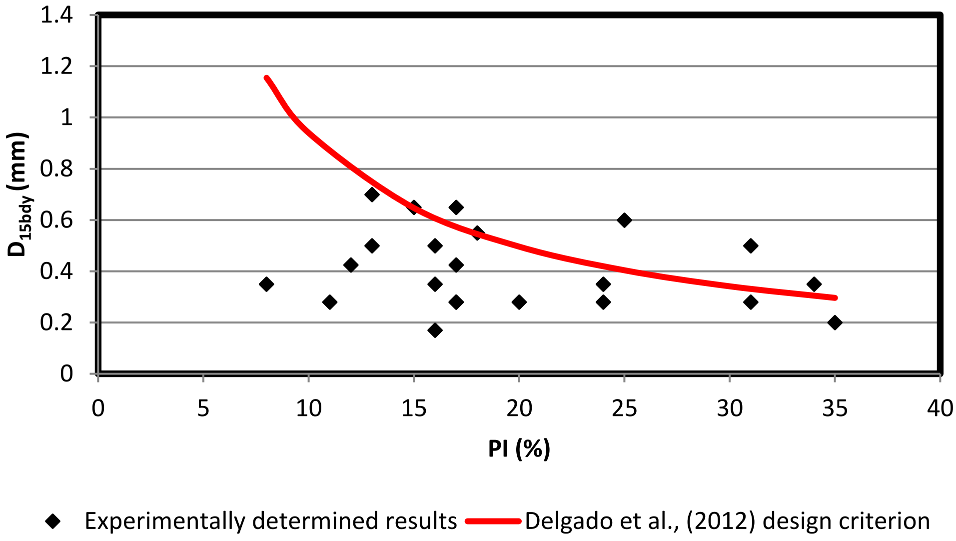

Figure 3. Comparison of the NEF test results with design criterion suggested by Delgado et al., (2012)

3.2. Effects of clay content of base materials on filter effectiveness

The effect of clay content of base soil materials on the no-erosion filter boundary is given in Figures 4 and 5. Generally, the D_{15bdy} size of filter materials tends to decrease, and the D_{15bdy}/d_{85} ratio tends to increase as the clay content of base materials increases. This general tendency could be attributed to the susceptibility of the clay particles to dispersion and de-flocculation. In other words, the extent of eroded particles increases as the degree of segregation of the clay particles increases, thus diminishing the filter effectiveness.

Two definitions exist for clay particles in the literature. Clayey soils are usually defined as soils with particles less than 0.002 mm. However, particles in the range of 0.002 to 0.005 mm are sometimes considered as clay [24]. The better trend could be observed between clay content and required filter materials when particles less than 0.005 mm are considered as clayey soils, as shown in Figures 6 and 7.

The best fit expression obtained by Foster and Fell [25] is compared with the best fit expression derived from the current study for base soils Group 1, as observed in Figure 8. The best fit expression proposed by Foster and Fell [25] could not successfully predict the appropriate filter materials in terms of D_{15f} size, as 10 out of 11 plots are placed below the line, reflecting a no-erosion probability of only 9%.

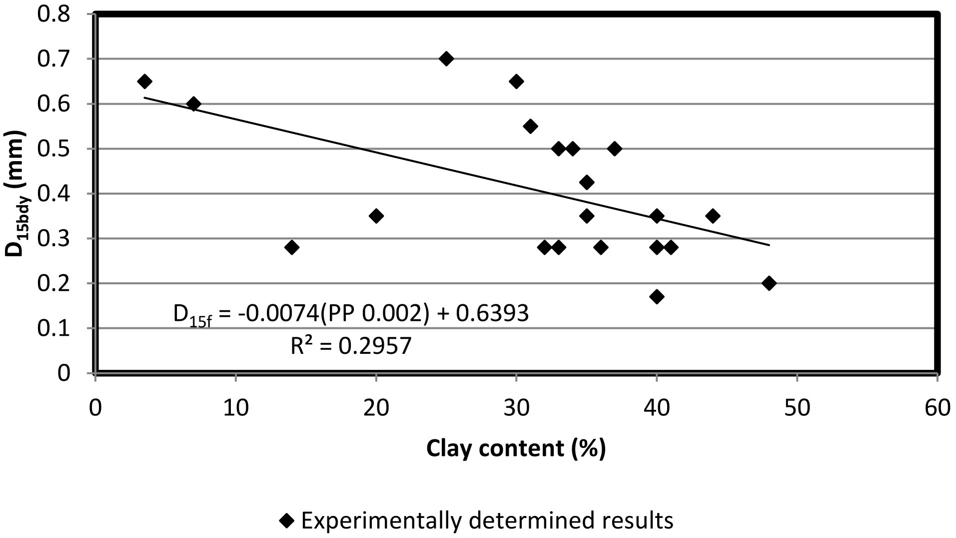

Figure 4. Variation of the clay content (PP ≤ 0.002) of the base soils against experimentally determined filter boundary (D_{15bdy}) for broadly graded, dispersive core materials

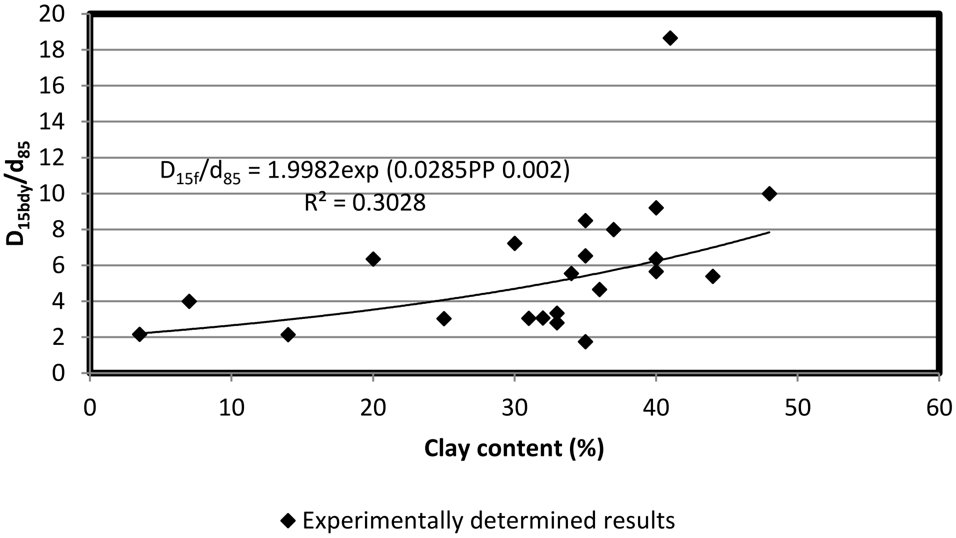

Figure 5. Variation of the clay content (PP ≤ 0.002) of the base soils against ratio of D_{15bdy}/d_{85} for broadly graded, dispersive core materials

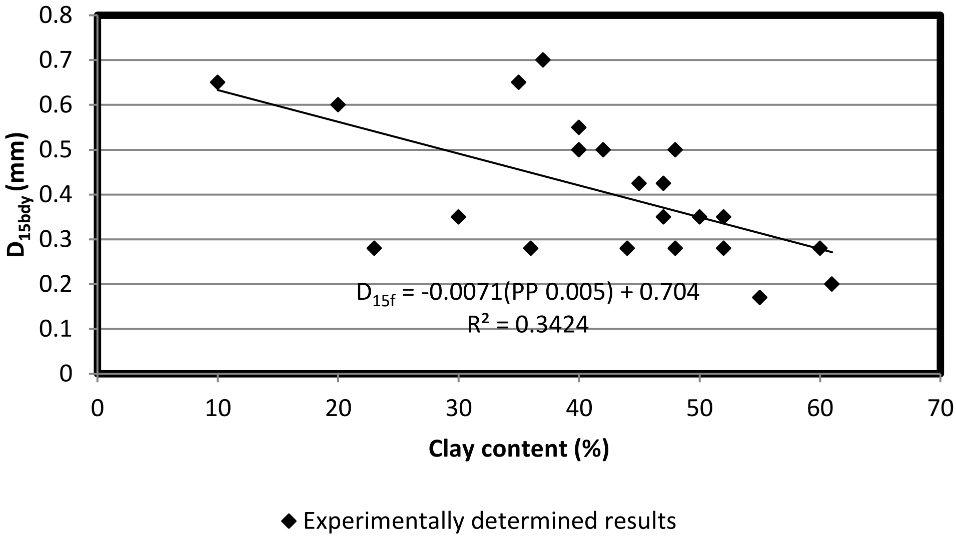

Figure 6. Variation of the clay content (PP ≤ 0.005) of the base soils against experimentally determined filter boundary (D_{15bdy}) for broadly graded, dispersive core materials

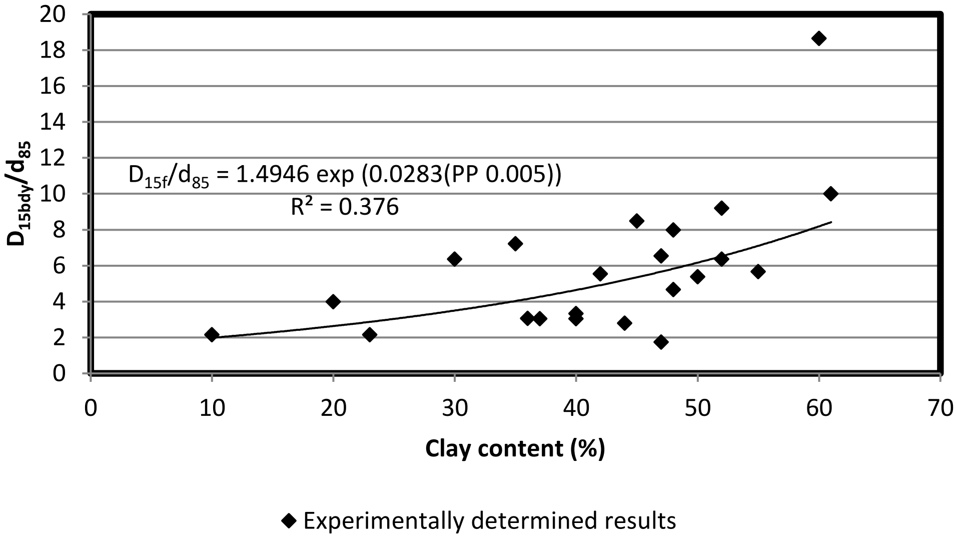

Figure 7. Variation of the clay content (PP ≤ 0.005) of the base soils against ratio of D_{15bdy}/ d_{85} for broadly graded, dispersive core materials

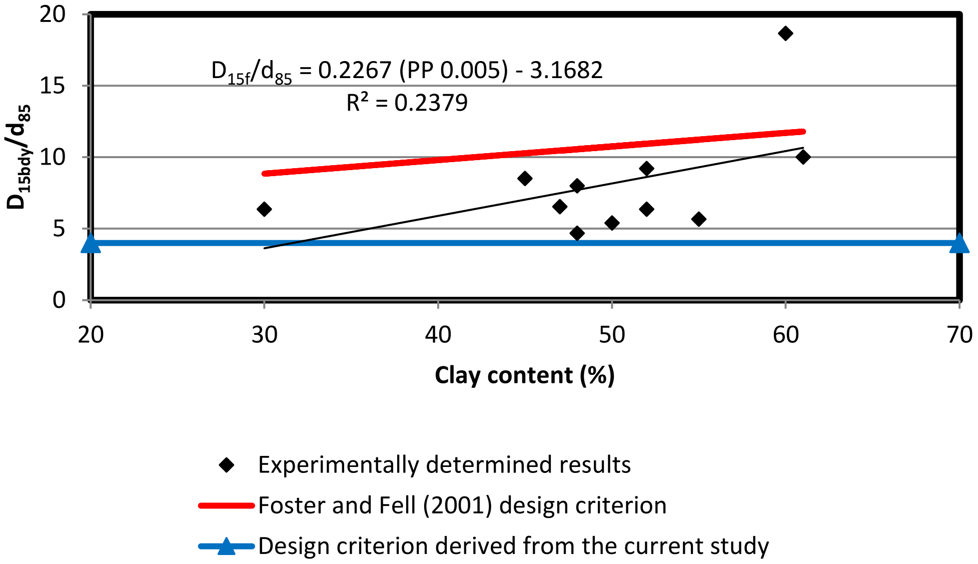

Figure 8. Comparison of the NEF test results with Foster and Fell [25] design criterion for base soil of Group 1

Consequently, as experimentally determined by the current study, selecting the criterion of $D_{15f}/d_{85} = 4.0$ as the no-erosion lower bound could be logical for various broadly graded, cohesive, dispersive base materials of Group 1 with different clay content.

3.3. Effects of fine content of base materials on filter effectiveness

The influence of fine content of base soil materials collected on the required filters is diagrammatically illustrated in Figure 9.

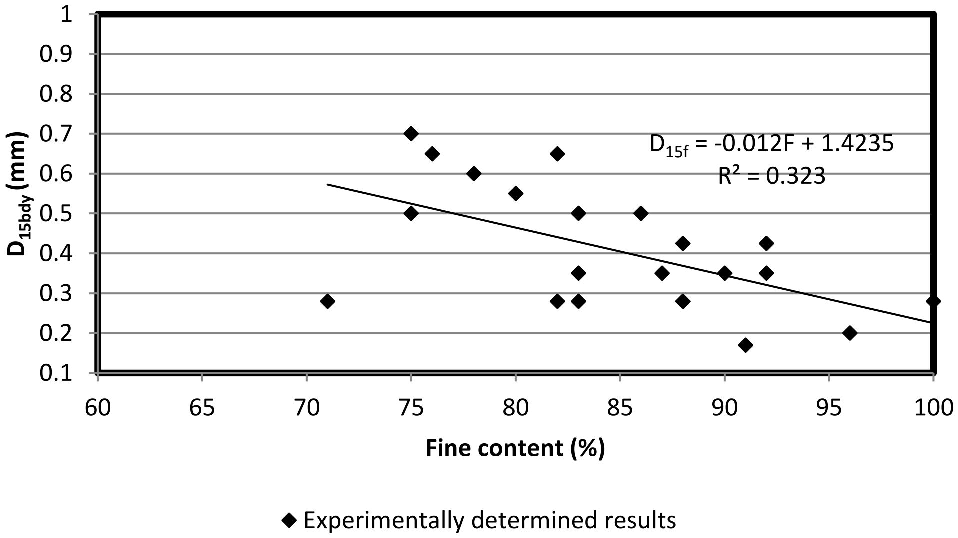

Figure 9. Variation of the fine content of the base soils against experimentally determined filter boundary (D_{15bdy}) for broadly graded, dispersive core materials

Although there is a general tendency for decreasing D_{15bdy} size of filter materials with increasing fine content of base materials, the effects of fine content may be observed more appropriately in Figure 10, where the scattering of D_{15bdy}/d_{85} versus fine content has been plotted. In other words, Figure 10 illustrates the concurrent effects of particle size distribution (PSD) and fine content of base materials on the no-erosion filter boundary. The correlation between these variables is governed by an exponential function and can be expressed as follows:

$$D_{15f} = d_{85} \times (0.0164 \times \exp(0.0672\,F) \tag{1}$$

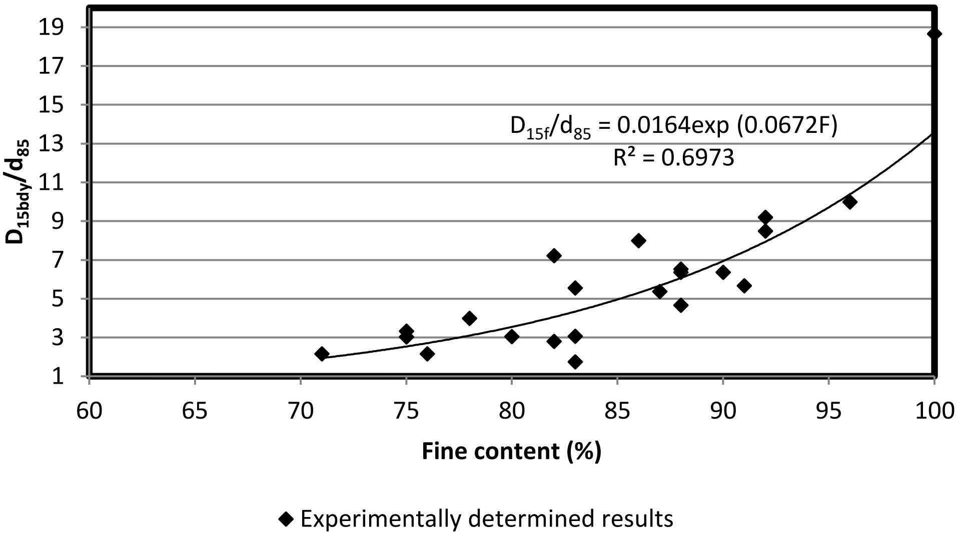

Figure 10. Variation of the fine content of the base soils against ratio of D_{15bdy}/d_{85} for broadly graded, dispersive core materials

Decreasing D_{15bdy} size of required filter materials with increasing fine content of base soil materials was as expected. In other words, the base soil becomes finer or smaller as its fine content increases, and thus, finer filter materials are needed for retaining the erodible particles of base soil materials.

Variations in fine content were found to have significant effects on the no-erosion filter boundaries of base soils of Group 1, as observed in Figures 11.

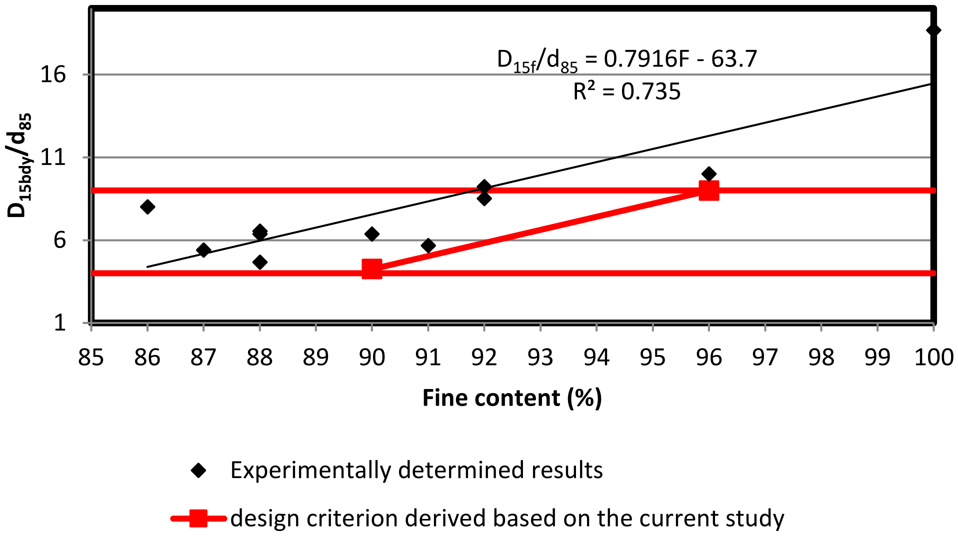

Figure 11. Suggestion a new design criterion for base soils of Group 1

Based on results plotted in Figure 11, safe filter materials could be designed by considering fine content and d_{85} size of base materials simultaneously as follows:

1- As long as the fine content of base materials is more than 85% but less than 90%, the criterion of $D_{15f}/d_{85} = 4.0$ could be applied.

2- For base soil material with fine content in the range of 90% to 96%, the criterion of $D_{15f}/d_{85} = 0.7916F - 67.0$ could be applied.

3- For base material with fine content more than 96%, the criterion of $D_{15f}/d_{85} = 9.0$ could be applied.

It is interesting to note that, although fine content was found to significantly determine the characteristics of required filter materials for base soils of Group 1, as observed in Figure 12, its effect on the no-erosion filter boundary of soil Group 2 is negligible.

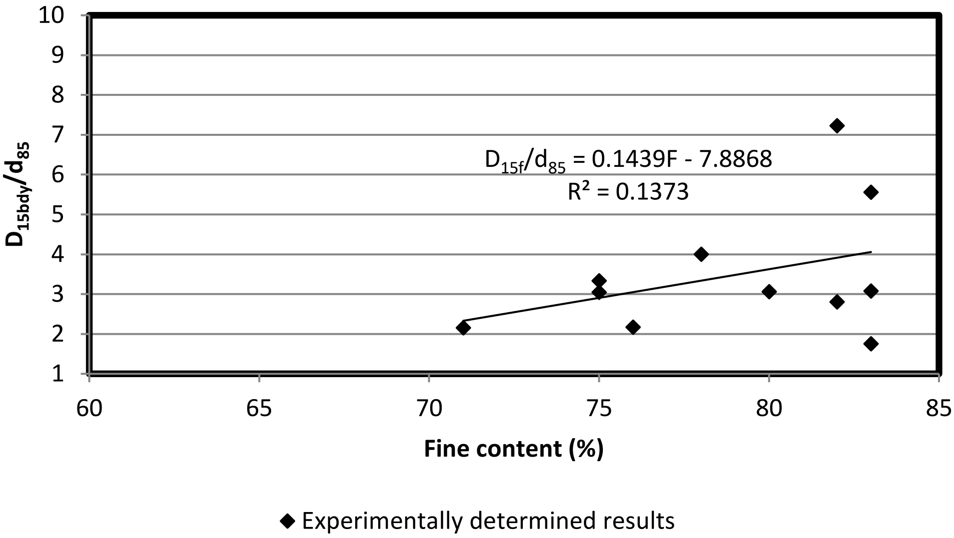

Figure 12. Variation of the fine content against ratio of D_{15f}/ d_{85} for Group 2

The hydraulic filter design criterion by Delgado et al. [30] for soils of Groups 1 and 2 is given together with experimentally determined filter requirements in Figure 13. Since only 2 out of 22 plots are placed below the line, following the criterion would mean having an erosion probability of only 9.0%, demonstrating the accuracy of the criterion suggested by Delgado et al. [30]. Although the criterion suggested by Delgado et al. [30] had a considerable factor of safety in relation to the base materials tested in this study, its application could become questionable for base soils Group 2 as the criterion has suggested filters with high permeability values.

Finally, designing filter materials by concurrently considering d_{85} and fine content of base materials seems to be more logical than separately using these effective parameters. Otherwise, it is recommended to design the required permeability of filter materials by considering the fine content of base materials and following a hydraulic criterion like Delgado et al. (2006).

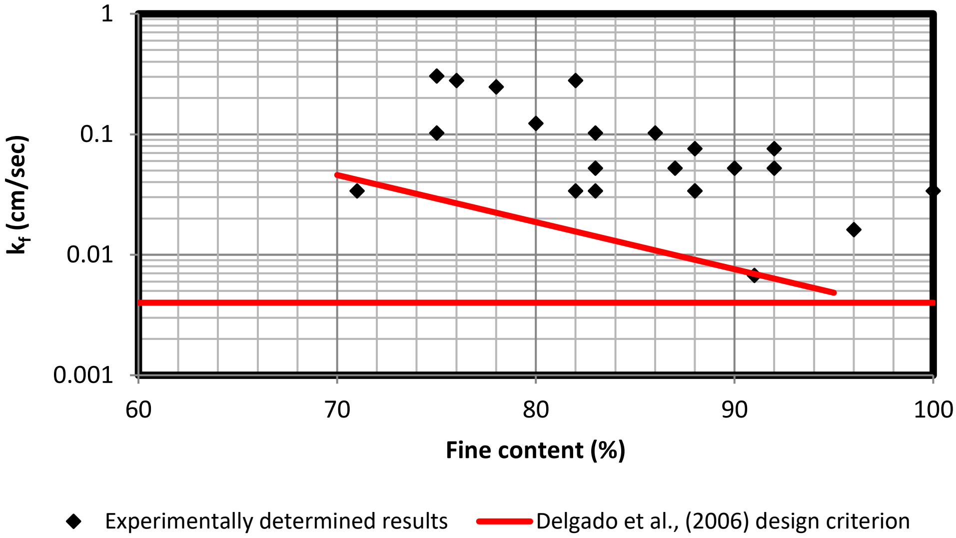

Figure 13. Comparison of the NEF test results with design criterion suggested by Delgado et al., [30]

4. Conclusions

As demonstrated in this research study, base soil plasticity was found to have negligible effects on no-erosion filter boundaries. In other words, results from the current study demonstrate that fine content could determine no-erosion filter boundary more substantially than clay content. Consequently, as experimentally determined by the current study, selecting the criterion of $D_{15f}/d_{85} = 4.0$ as the no-erosion lower bound could be logical for various broadly graded, cohesive, dispersive base materials of Group 1 with different clay content. Finally, only considering d_{85} as a base soil representative may result in inappropriate filter design. Therefore, in addition to the particle size distribution (PSD) of base materials, the effects of other base soil features such as fine content could be taken into consideration by using the formula $D_{15f} = d_{85} \times (0.0164 \times \exp(0.0672F))$. The study suggests categorizing base soils of Group 1 into several groups and designing filter materials as follows:

1- $D_{15f}/d_{85} = 4.0$ for $85\% \leq F < 90\%$;
2- $D_{15f}/d_{85} = 0.7916\,F - 67.0$ for $90\% \leq F < 96\%$;
3- $D_{15f}/d_{85} = 9.0$ for $F \geq 96\%$.

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