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Grain Size Distribution of the Self-Filtration Layer between the Base Soil and the Filter

Yousif A. H. Dallo
College of Civil Engineering, Mosul University/Mosul/ Iraq.
Email: dalloyousif@gmail.com
Yuan Wang
College of Civil and Transportation Engineering, Hohai University, Nanjing, P.R.China

ABSTRACT

Some studies suggested a model to determine the grain size distribution GSD curve of the self-filtration layer that is formed at the base soil-filter interface. From these GSD curves the effectiveness of the filters is assessed assuming that the internal stability of the self-filtration layer reflects the effectiveness of the filter. In this paper a critical discussion to that method is presented. Also some essential modifications for the method are suggested. Finally, in disagreement with that method the applicability of usage of the GSD curve of the self-filtration layer to predict the effectiveness of the filter is found to be unreliable.

Keywords: Base Soil-Filter Interface, Self-Filtration Layer, Filters Assessment; Filtration; Dams, Embankments.

التدرج الحبيبي لطبقة تلامس المرشح مع التربة الاساس

الخلاصة

بعض الدراسات تقترح نموذج لأيجاد التدرج الحبيبي لطبقة تلامس المرشح مع التربة الاساس. من ذلك التدرج الحبيبي يتم تحديد كفاءة المرشح بأفتراض ان ثباتية طبقة التلامس ضد التآكل الداخلي تبين كفاءة المرشح. في هذا البحث نقدم مناقشة نقدية لتلك الطريقة، وعليه نقترح بعض التحويرات المهمة. وأخيرا ،وبتعارض مع نتائج دراسة سابقة، فقد وجد أن تقييم كفاءة المرشح بالاعتماد على التدرج الحبيبي لطبقة تلامس المرشح مع التربة الاساس، لا يمكن الاعتماد عليه.

INTRODUCTION

Filters are important part of earth dams and other hydraulic structures; they provide protection to the base soils (eg. cores or foundations of dams) from being washed out through the voids of the coarser material by seepage forces (Sherard et al. 1984). Generally speaking, effective filters must be fine enough to prevent erosion of the base soil particles, at the same time it must be coarse enough to

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allow the passage of seepage flow. Many dams failures or near failure can be attributed to the absence of proper filters or drains (USSD 2011).

The first specification to design filters was proposed by Terzaghi in the early 1920s (see ICOLD 1994), it is based on laboratory tests of uniform cohesionless soils. Later, many specifications were suggested to design filters, eg. Bertram (1940), Lafleur et al.(1989), Honjo and Veneziano (1989). Recently there are two widely accepted procedures to design filters, namely: The NRCS (1994) design procedure and the ICOLD (1994) design procedure. The NRCS (1994) suggested many criteria to design suitable filters, functioning properly and having no possibility to segregate during construction, also the NRCS criteria prevents using gap-graded filters, yet the internal stability isn't fully considered, where (Dallo et al. 2013) showed that the NRCS design procedure yields internally unstable filters in some special cases.

Raut and Indraratna (2008) suggested a method to assess the effectiveness of the filters from:

$$D_{c35}/d^*_{85} \leq 1 \qquad \ldots (1)$$

Where D_{c35} is the constriction size (a window size among soil particles) corresponding to 35% finer percent. d^*_{85} is the particle diameter corresponding to 85% finer percent of the modified (regarded) base soil grain size distribution (GSD) curve by neglecting the base soil particles with diameters larger than the self-filtering constriction size, D_{c95}, (Raut and Indraratna, 2008). D_{c35} and D_{c95} will be explained later.

Raut and Indraratna (2008) verified their model with large number of experimental data, either conducted by them or obtained from other literatures, including 45 data sets obtained from Lafleur et al.(1989), although that all the data sets presented by Lafleur et al.(1989) are 36. Anyway, the criterion, Eq.(1), successfully assess the effectiveness of the filters compared with the other criteria.

Indraratna and Raut (2006) suggested a method to assess the effectiveness of the filters based on the GSD curve of the self-filtrating layer that is formed at the base soil-filter interface. From that GSD curve they assessed the internal stability against suffusion employing the method of Kenney and Lau (1985, 1986) (will be termed here and after as KL method), and they assumed that if the self-filtration layer is internally stable then the whole filter is effective and vice versa.

The KL method is used to assess the internal stability of cohesion less soils, based on the shape of the GSD curve, as shown in Figure (1). Where the finer percent (*F*) corresponding to an arbitrary particle diameter (*D*) is determined, then finer percent corresponding to the particle diameter (4*D*) is determined, from which the value of (*H*) can be easily calculated, *H*=finer fraction difference between *D* and 4*D*. The internal stability is determined by calculating the H/F ratios in the range of $F \leq 0.2$ for widely-graded soils, and in the range of $F \leq 0.3$ for narrowly-graded soils. The soil is considered as unstable if the ratio (H/F) leis below the stability boundary (H/F=1.0).

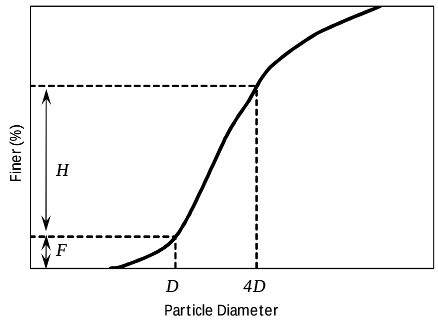

Figure (1) Determination of F and H for Kenney and Lau(1985, 1986) method

Formation of the self-filtrating layer depends on many factors; including the relative density of the filter, and the GSD of both the base soil and the filter.

The self-filtration layer is formed by filtration of the base soil particles inside the filter. To illustrate the filtration process, let us examine a base soil particle with diameter (d_1) under seepage flow forces, this particle will enter a pore of the filter if its diameter is less than the constriction size “the window that connecting two pores”. Now, again if its diameter is less than the new constriction then it will pass to next pore, and so on until it encounters a constriction with a diameter less than its own diameter, accordingly, it will be captured and becomes a part of the filter.

Indraratna and Raut (2006) method is also based on determination of the constriction size distribution curve (CSD) as suggested by Silveira (1965), Silveira et al. (1975) and Locke et al.(2001). The CSD curve represents the sizes of all constrictions “windows” among the filter particles and their corresponding percentages. Some important values can be obtained from the CSD curve, namely: D_{c35} and D_{c95}, which represent the constriction size corresponding to 35 and 95 finer percent respectively.

The authors believe that, the method suggested by Indraratna and Raut (2006) needs essential modifications for many reasons related to the diameter of the base soil Particles that formed the self-filtration layer and the reasonableness of using the KL method to assess the internal stability of the self-filtration layer.

CRITICAL REVIEW OF THE INDRARATNA AND RAUT (2006) MODEL

Indraratna and Raut (2006) suggested, in their model, to determine the GSD curve of the self-filtration layer based on the following assumptions:

1- The erodible base soil particles that captured by the filter are accumulated in a loose state inside the pores. These particles have a porosity of about (n_b=0.4).

2- The percent of the filter particles (P_F) to the percent of the erodible base soil particles (P_B) in the self-filtration layer, can be computed from:

$$P_F/P_B = (1/n_f - 1)/(1 - n_b) \quad \text{…. (2)}$$

Where: n_f and n_b are the porosities of the filter and erodible soils particles respectively.

3- All the base soil particles with diameters less than D_{c95} of the filter will be accumulated inside the pores of the filter.

The GSD curve of the self-filtration layer can be obtained by mixing the GSD curve of the filter and the GSD curve of the base soil particles with diameter less than D_{c95} (i.e. the modified bas soil GSD curve). The percent of mixing the two GSD curves depends on Equation (2) as can be seen in Figure (2).

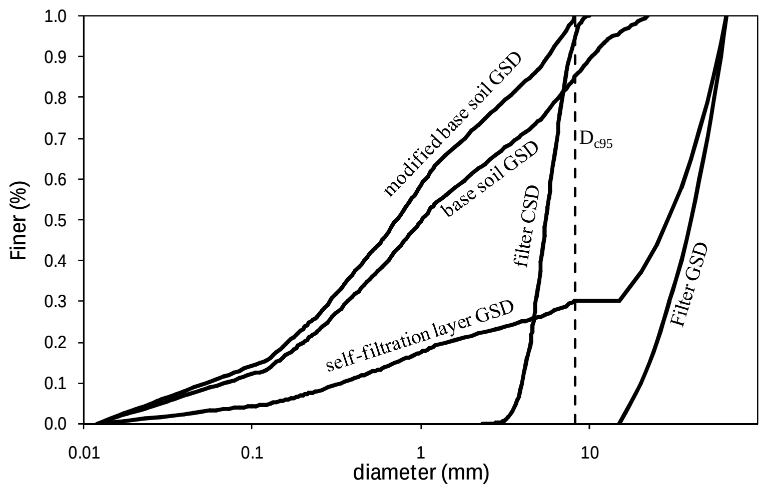

Figure (2) Illustration of the method Indraratna and Raut (2006).

Indraratna and Raut (2006) employed the KL method to assess the internal stability of self-filtration layer. They assumed that if the self-filtration layer is internally stable then the entire filter is effective and vice versa.

The above assumptions sound good, yet we have some observations. The first observation is related to the assumption that all the particles of the base soil with a diameter less than the D_{c95} will be accumulated inside the self-filtration layer; but, as indicated by Indraratna et al. (2007), the probability of forward movement of the base soil particles with diameter less than D_{c35} is high, hence, these particles cannot be part of the self-filtration layer as assumed by Indraratna and Raut (2006). So, we believed that, only the particles with a diameter larger than D_{c35} and less than the D_{c95} will be accumulated inside the pores of the self-filtration layer for ineffective filters. The particles with diameter less than D_{c35} cannot be captured by the filter especially within the self-filtration layer which has a relatively thin thickness of few centimeters as found by field and laboratory tests (USSD (2011).

The second observation is related to the use of the KL method to assess the internal stability of the self-filtration layer. The KL method checks whether the fine particles can be washed out (suffused) or not from the main soil skeleton. Formation of the self-filtration layer inherently means that the all fine particles are already "*captured*" by the main soil skeleton of the filter and become a part of the filter, so it is not reasonable to check whether these particles will be eroded or not.

Another observation is regarding to the porosity of the erodible base soil particles that captured by the self-filtration layer (n_b). We believe that assuming $n_b = 0.4$ for all soil types is not accurate; of course the porosity depends on many factors including the particles' shape and the grain size distribution. Indraratna and Raut (2006) adopted this value from Kenney and Lau (1985), actually the value mentioned by Kenney and Lau (1985) represents the value of porosity for the soil tested by them, so it is not accurate to generalize it. To overcome this problem, we will employ the method of Aberg (1992), which is a semi-empirical method, based on the GSD and the relative density of the soil to determine the void ratio (e) of cohesionless soils from:

$$e = 2c\frac{\int_0^1 (y/x_{(y)})dy}{\int_0^1 dy/x_{(y)}} + 2d \qquad \text{…(3)}$$

where y is the finer percentage corresponding to the particle diameter $x_{(y)}$; c is a coefficient depends on the shape of the soil particles c = 0.75 for sand and gravel while c =0.6 for spheres; and d is a constant depends on the relative density "Rd" of the soil, d = 0.18 for minimum relative Rd =0, d = 0 for maximum relative Rd =1.0, for any other relative density $d = 0.18 \times (1 - Rd)$.

THE SUGGESTED MODEL

Based on the previously mentioned observations we suggest the following assumptions to determine the GSD curve of the self-filtration layer, and to assess the effectiveness of the filter:

1-The CSD of the filter at the specified relative density is determined according to method suggested by Silveira (1965), Silveira et al. (1975), and Locke (2001). From the latter curves the values of D_{c35} and D_{c95} will be obtained.

2-Only the base soil particles with diameter larger than D_{c35} and less than the D_{c95} will be accumulated inside the pores of the self-filtration layer.

3-The GSD curve of the base soil particles that accumulated in the pores of the filter, is drawn in the range D_{c35} and D_{c95}. And their porosity, n_b, can be calculated employing the method of Aberg (1992). Knowing that these particles are in a loose state (i.e. $d \approx 0.18$ for Equation (3))

4-Equation (2) will be adopted to determine the combination ration of the filter particles to the erodible base soil particles. Accordingly the GSD curve of the self-filtration layer is obtained.

5-The KL method can't be applied to assess the internal stability of the self-filtration layer. A reasonable method to assess the effectiveness of the filter is suggested by Raut and Indraratna (2008) [Equation (1)] and will be adopted here.

6-The CSD curve of the self-filtration layer is obtained and the D_{c35} of the self-filtration layer is compared with d^*_{85} of the base soil. If $D_{c35}/d^*_{85} \leq 1$ then the filter is effective (Raut and Indraratna 2008).

VERIFICATION OF THE MODEL

Lafleur et al. (1989) performed a detailed filtration study. In their study they tested 5 types of filters against 9 different base soils (see Figure (3) and Figure (4)), in total there were 36 data sets. 34 of them are possible to be analyzed here, as shown in Table (1) these data were used to verify the current model and to check the applicability of the self-filtration layer to determine the effectiveness of the filter for a certain base soil. Also these data were used to check the applicability of Indraratna and Raut (2006) model itself. The results of the analysis show that the Indraratna and Raut (2006) model extremely underestimates the effective filters, where all the effective filters shown in Table (1) were predicted to be ineffective. Figures (5) show some of these results. Which makes a conclusion that the Indraratna and Raut (2006) method is not accurate regardless our observations.

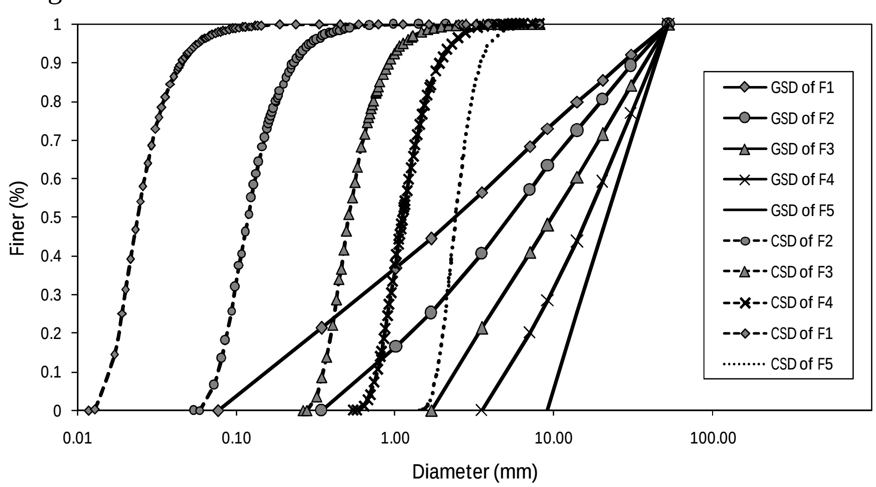

Figure (3) Grain size distribution of the filters (F1 to F5) with the Corresponding CSD curves (for Rd=1).

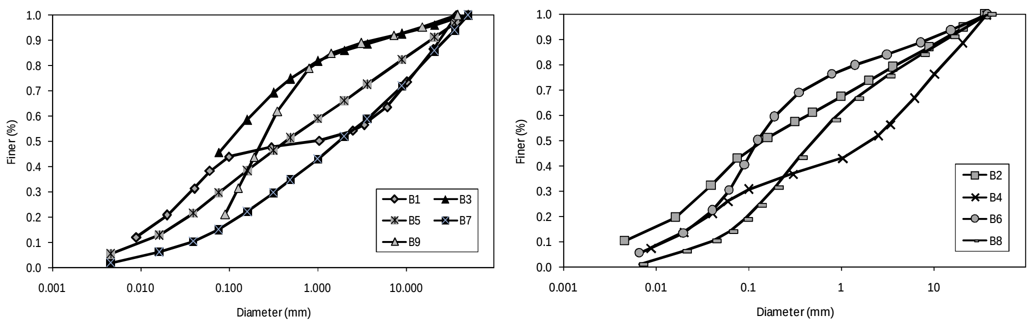

Figure (4) Grain size distribution of the base soils (B1 to F9)

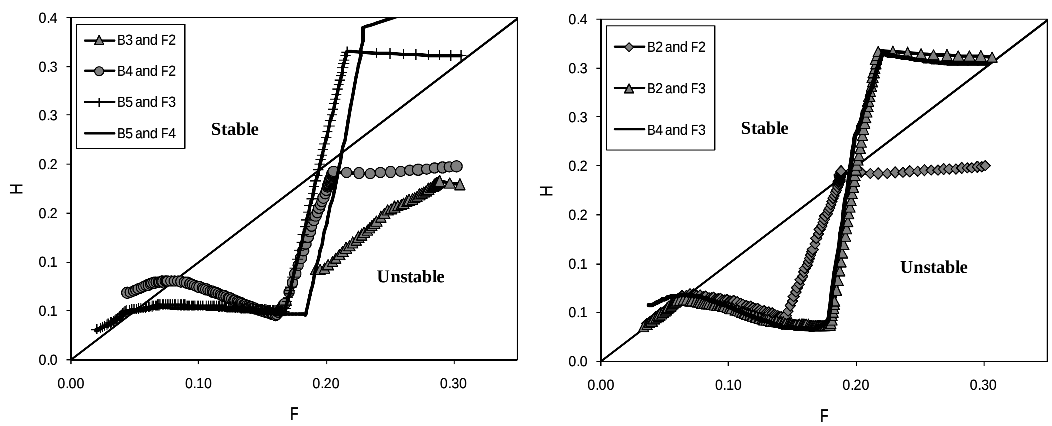

Figure (5) Internal stability assessment of some self-filtration layers according to KL method.

Table (1) Base soils and filters properties, and the Assessment of the current model.

Base	Filter	Rd	porosity (n_f)	porosity (n_b)	self-filtration layer D_{c35}	self-filtration layer D_{c95}	d_{85}^*	D_{c35}/d_{85}^*	assessment	Laboratory assessment
B1	F1	0.04	0.255	0.490	0.018	0.074	0.048	0.380	E	E*
	F2	1.00	0.213	--	**No S.F.L.****	--	--	--	--	I*
	F3	0.84	0.296	--	**No S.F.L.**	--	--	--	--	I
	F4	0.70	0.333	0.492	0.481	1.752	0.130	3.702	I	I
	F5	0.98	0.337	0.509	0.636	2.136	0.162	3.922	I	I
B2	F2	0.24	0.306	0.480	0.136	0.352	0.140	0.972	E	E
	F3	0.65	0.316	0.492	0.228	0.845	0.275	0.831	E	E
	F4	0.80	0.324	0.496	0.391	1.373	0.416	0.941	E	I
	F5	0.92	0.342	0.507	0.657	1.894	0.552	1.190	I	I
B3	F2	0.23	0.307	0.483	0.072	0.262	0.141	0.511	E	E
	F3	0.24	0.355	0.490	0.277	0.918	0.310	0.893	E	I
	F4	0.57	0.345	0.494	0.432	1.375	0.371	1.164	I	I
B4	F2	0.00	0.331	0.478	0.098	0.418	0.144	0.681	E	E
	F3	0.52	0.329	0.375	0.276	0.981	0.271	1.019	I	E
	F4	0.54	0.348	0.491	0.570	2.148	0.995	0.572	E	I
	F5	0.79	0.352	0.505	0.811	2.873	1.388	0.584	E	I
B5	F3	0.66	0.315	0.492	0.215	0.802	0.369	0.583	E	E
	F4	0.73	0.331	0.494	0.437	1.616	0.652	0.671	E	E
	F5	0.73	0.357	0.504	0.877	3.092	1.140	0.769	E	I
B6	F2	0.32	0.297	0.485	0.075	0.343	0.181	0.417	E	E
	F3	0.63	0.318	0.494	0.214	0.815	0.274	0.784	E	E
	F4	0.48	0.353	0.492	0.567	2.387	0.407	1.393	I	I
	F5	1.00	0.335	0.509	0.578	1.688	0.347	1.664	I	I
B7	F2	0.00	0.331	0.479	0.100	0.435	0.283	0.352	E	E
	F3	0.34	0.346	0.489	0.327	1.308	0.740	0.442	E	E
	F4	0.65	0.338	0.493	0.473	1.785	0.992	0.477	E	I
B8	F2	0.01	0.330	0.479	0.097	0.436	0.299	0.325	E	E
	F3	0.67	0.314	0.494	0.208	0.767	0.478	0.435	E	E

	F4	0.51	0.350	0.491	0.547	2.195	0.951	0.575	E	E
	F5	0.53	0.373	0.501	1.115	4.029	1.380	0.808	E	I
B9	F2	0.16	0.314	0.483	0.074	0.349	0.256	0.325	E	E
	F3	0.08	0.369	0.491	0.370	1.468	0.577	0.640	E	I
	F4	0.54	0.348	0.493	0.506	2.036	0.618	0.819	E	I
	F5	0.46	0.378	0.500	1.252	4.408	0.710	1.765	I	I

* E= Effective; I=Ineffective
** No S.F.L.= no self filtration layer is formed

A typical example of the analysis is base soil B8 with filter F5 as shown in the Figure (6). D_{c35} and D_{c95} of filter F5 are 2.875 and 6.384 mm respectively. The latter two values also represent respectively the minimum (d_{min}) and maximum (d_{max}) diameter of the base soil particles that are accumulated in the self-filtration layer. Applying the method of Aberg (1992) to the latter soil particles gives the void ratio, hence the porosity can be calculated, n_b=0.501. The porosity of filter can be calculated as n_f=0.373 from the data presented by Lafleur et al. (1989) assuming the specific gravity of the soil Gs=2.65. Accordingly we found P_F/P_B=3.32 which means the percent of filter particles in the self-filtration layer is P_F=77% and the percent of erodible soil particles P_B=23%. Knowing all these values enables us to determine the GSD of the self-filtration layer, as shown in Figure (6). D_{c35} and $D_{c95}$of the self-filtration layer are 1.115 and 4.029 mm respectively, which is obtained from the CSD of the self-filtration layers. The ratio ($D_{c35}/d^*_{85} = 0.808$) so the soil is predicted to be stable. The results of all the filters and base soils are shown in Table (1), it can be seen that there are 10 cases where wrongly predicted, 9 of which are ineffective filters but predicted as effective filters. For this reason we think it is unsafe to design a filter based on the GSD curve of the self-filtration layer, where a lot of ineffective filters will be assessed as effective. For these ineffective filters, the calculated D_{c35} of the self-filtration layer is less than d^*_{85} of the base soil which means that the filter must be effective, although that these filters were found in the lab to be ineffective filters. Which may mean that formation of the self-filtration layer in these soils is very slow which allows washing out of large amount of the base soil before formation the self-filtration layer.

For the analyzed soils in this paper, the porosity n_b is found to be about 0.5 as shown in Table (1), so the assumption of nb=0.4 is not accurate. It is worth to mention that for base soil B1 with filters F2 and F3, no self-filtration layers are expected to be formed, because that the values of D_{c35} and D_{c95} lies within the gap of these two soils.

We believed that the filters' efficiency will be improved with time, where the interaction layer will be able to capture smaller particles. But this needs more detailed experimental study.

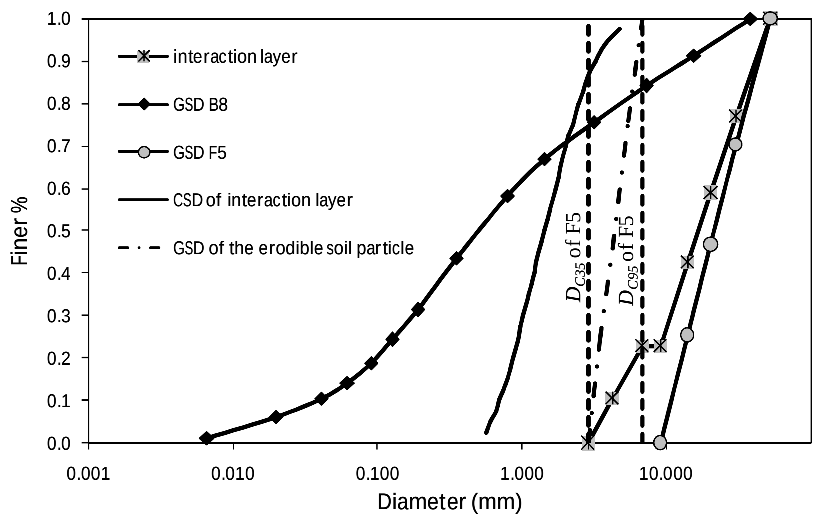

Figure (6) a typical example of the analysis (Base soil B8 with filter F5).

CONCLUSIONS

The following conclusions can be obtained.

1. For gap-graded base soils, if the value of (D_{c35} and D_{c95}) of the filter lies within the gap of the base soil then no self-filtration layer will be formed at all.
2. Some filters have $D_{c35}/d^{*}_{85} < 1$which means that they must be effective, although that, these filters were found in the lab as ineffective filters. Which may mean that formation of the self-filtration layer in these soils is very slow which allows washing out of large amount of the base soil before formation the self-filtration layer.
3. The value of the porosity of base soil particles that washed inside the self-filtration layer is about (n_b =0.5) for the data analyzed here.
4. The method of Indraratna and Raut (2006) underestimates the effectiveness of the filters.
5. Prediction the effectiveness of the filter based on the self-filtration layer is unreliable.

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