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Filter Design Criteria for Base Soils with a Significant Cohesive Content

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Key words

Material, filter mass, filter design, slot test, permeability, pore channel, washout, hydraulic gradient, non-uniform particles.

Abstract: The presence of fines in base soils has a marked influence on the filter behaviour. In the present study the applicability of the filter design procedure for non-cohesive bases, based on design controlling size, (Lone et.al 1996) has been attempted for such bases. Earlier the said criteria have been tried for a limited content of cohesive soils upto 30% in the non-cohesive bases (Dar et.al 2003). In the present study an attempt has been made to ascertain the maximum content of cohesive soil in a base to which the said criteria can be employed. A different methodology has been adopted for carrying out the tests on such bases where the cohesive content exceeds 30%, as in such cases there is virtually no seepage and the failure is caused due to development of cracks and their subsequent enlargement due to erosion. The study has shown that the criteria can be safely adopted upto a 70% of cohesive content in a base soil.

Introduction

Filters have been recognized as a means of controlling the erosion problem due to seepage discharge through embankments, dam foundations and other hydraulic structures and to allow the passage of seepage water through these structures safely i.e. without the migration of base soil. For developing suitable criteria for designing a protective filter which meets the above requirements, there have been several attempts. Most of these attempts are based on or guided by the empirical relations evolved by Terzaghi (1961). Traditionally, the design criteria for soil filters are empirical based and are expressed in terms of certain ratios of the sizes of base soil particles and the filter particles, which vary over wide ranges in different cases (Betram, 1940; Sherman, 1953; USBR, 1987; Sherard, 1984; NRCS, 1994). The general objectives of these criteria were to ensure that the filter material prevent migration of the base soil particles and possesses adequate permeability for free flow of seepage water. Subsequently, several mechanistic models have been developed to predict particle migration and entrapment (Honjo and Veneziano, 1989; Aberg, 1993; Indraratna and Vafai 1997; Locke et al., 2001). In most of the cases, the treatment of the filtration phenomenon qualitatively and quantitatively has often been based on empiricism, not taking into account the real physics of the phenomenon because of difficulty in describing the porous media. The literature reveals that the researchers have a strong feeling about the inherent discrepancies in all the existing criteria. Some of the researchers (Sherard et al. 1984) felt that these criteria need gross modification when the gradation of either the filter or the base is vastly different from those used in the development of these criteria. Indraratna et al. (2007) while elucidating some of the limitations of current professional guidelines that are only based on particle size ratios suggest that it is constriction size rather than the particle size that affects the filtration. Srivastava and Babu (2011) recognized that the design procedures based on particle size distribution are applicable to a particular range of soils tested in the laboratories and do not take into account the sensitivity of the important variables influencing performance of the filter, hence proposed analytical solutions that take into consideration relevant geotechnical properties.

Objective of the Study

The objective of the present study is to extend the design criteria based on design controlling size d* for non-cohesive to the bases containing some percentage of cohesive soil and to find the maximum percentages of cohesive content in bases for which the criteria can be safely adopted.

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Theoretical Background

The present study is based on the design controlling size of a pore channel of a filter mass. This design controlling size which is the minimum pore/window size in a filter mass, has been arrived at by the consideration of packing pattern of non-uniform particles as shown in Figure 1. Spheres have been referred by their diameters. R_1, R_2, R_3 and R_4 are the radii of these four spheres.

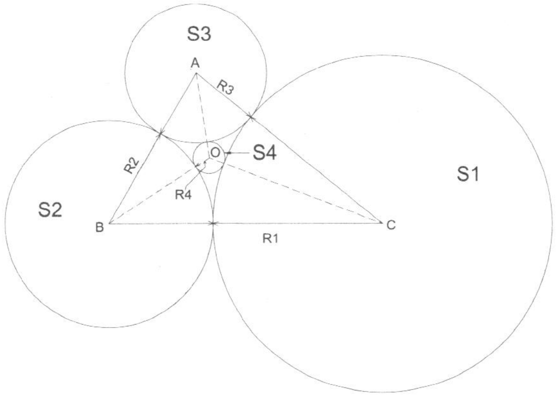

Fig. 1 Assembly of Non-uniform Spheres

The intervening sphere size, which is the function of the sizes of the three surrounding spheres, can be worked out by the use of following equation obtained by equating the area of the triangle ABC with the sum of areas of the triangles AOB, BOC and COA and replacing R_2, R_1 and R_4 by mR_3, n R_3 and β R_3 respectively.

$$\{(1+m+n)mn\}^{1/2} = \{(1+m+\beta)m\beta\}^{1/2} + \{(m+n+\beta)mn\beta\}^{1/2} + \{(1+n+\beta)n\beta\}^{1/2} \qquad (1)$$

The above equation can be used for finding the window size formed between an assembly of three non uniform spheres. This estimation of window size leads then to the minimum constriction pore size of the filter pore channels, and hence the design controlling size.

A design criteria (Lone, 1996) based on this design controlling size of the filter material could make a locally available filter material usable for protecting a given base by suitable minor adjustments of the filter material (about 10 %). As per this criteria the design controlling size d* for a filter to protect a particular non-cohesive base is given by the following relation i.e,

$$d^* = 8 \times d_{85} / (Cu + 4.72) \qquad (2)$$

where, d_{85} = the size that 85% of the base material is finer than this size

C_u = uniformity coefficient of the base material.

The basis of this equation is given in Lone et al. (2005) and the details of the design controlling size are given by Dar et al. (2003).

In this study the above concept has been extended for the design of filters to protecting bases with a significant percentage of cohesive content and to ascertain the extent of presence of percentage of cohesive soil content in base soils upto which the criteria can hold good to fulfill the two basic requirements of protective filters.

Experimental Setup

The experimental setup used for the study is shown in Figure 2. The setup consisted of a cylindrical container of 250 mm diameter and 600 mm length with hopper type base of 80 mm diameter. A grid of rods at 5 cm interval was provided at the end of the cylindrical container for supporting the wire mesh of different sizes to prevent the movement of filter material. A pressure gauge and two air vents were provided at the top of the filter apparatus and a stop cock at the inlet for regulating the supply. Piezometer taps with geotextiles to prevent soil infiltration were provided at intervals along the surface of the cylinder and connected to the manometer/piezometer to measure the intermediate heads. The arrangements were also made to connect the hopper base to 3.75 cm diameter flexible rubber pipe for directing the discharge in a measuring tank.

Materials

For the purpose of study, the granular material obtained from a local river bed and sites adjacent to the said river course was used as filter material. The particle shapes of the river bed material were ranging from spherical to ellipsoidal and the maximum size of filter material used was 63 mm. The shape parameters for a few of these materials are presented in Table 1. For the non-cohesive base material river sand of five different gradations was procured and selected for study. The material used as cohesive content in the tests was obtained from a site adjacent to Srinagar city. The main gradation features of non-cohesive bases designated as BI, BII, BIII, BIV, BV and cohesive base designated as CI are presented in Table 2 and the index properties of cohesive base are given in Table 3.

Table 1 Shape Parameters of Material used as Filter

Size (mm)	b/a	c/a	Flatness ratio $\frac{(a+b)}{2c}$	Shape Factor $\frac{c}{\sqrt{ab}}$	Spherecity {particle volume / ((π/6) a³)}$^{1/3}$
50.0	0.780	0.855	1.417	0.723	0.804
40.0	0.779	0.647	1.394	0.733	0.812
31.5	0.765	0.625	1.440	0.714	0.802
25.0	0.735	0.642	1.371	0.747	0.789
20.0	0.576	0.472	1.715	0.621	0.647
16.0	0.557	0.443	1.845	0.592	0.602
12.5	0.553	0.399	2.046	0.536	0.590
10.0	0.585	0.419	1.977	0.553	0.573
6.3	0.520	0.395	2.063	0.542	0.533

a = Major axis of particle b = Intermediate axis of particle, c = Minor axis of particle

Table 2 Gradation Features of Base Materials

Base	d_{10}	d_{15}	d_{30}	d_{50}	d_{60}	d_{85}	d_{90}	C_u	C_c
BI	0.375	0.450	0.630	1.040	1.160	1.633	1.866	3.093	0.912
BII	0.193	0.225	0.305	0.458	0.536	1.286	1.679	2.777	0.899
BIII	0.244	0.269	0.400	0.514	0.543	0.933	1.000	2.225	1.207
BIV	0.221	0.291	0.350	0.463	0.520	0.850	1.100	2.353	1.066
BV	0.174	0.214	0.275	0.410	0.445	0.564	0.977	2.557	0.977
CI	0.0024	0.0036	0.0065	0.0092	0.0114	0.0240	0.0475	4.75	1.540

Table 3 Index Properties of Cohesive Base Material

Base	Specific Gravity	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Remarks
CI	2.67	31.00	24.3	6.7	CL-ML

CL = Clay of low plasticity

ML = Silt of low plasticity

Test Procedure

The test programme consists of two series of tests.

1. Estimation of permeability of various filter masses.
2. Filter tests i.e. filter base combination tests for stability, particle migration, washout etc.

A permeability test was conducted for each filter material prior to placing the base material with the aim to compare the permeability of filter and base material. The permeability of the filter material was then obtained from Darcy's law. The permeabilities worked out at various temperatures were standardized to viscosity of water at 20 degree centigrade by the relation, (IS: 2720-II)

$$k_{20} = k_t \times \mu_t/\mu_{20} \tag{3}$$

where, k_{20} and k_t are the coefficients of permeability at 20 and t degree centigrade respectively, and μ_{20} and μ_t are the respective viscosities of water at 20 and t degree centigrade. The permeabilities of success filters for different skeleton size and ratio are given in Table 4.

Table 4 Permeabilities of Success Filters

Ratio	Skelton size (mm)	Filler size (mm)	Pore size (mm)	Controlling pore size (mm)	Permeability cm/sec
1:1.5:2	10.0,16.0,20.0	2.360	0.90,0.92,0.98	0.90	2.228
	16.0,25.0,31.5	3.36	1.300,1.32,1.47	1.30	4.30
1:2:3	6.3,12.5,20.0	1.707	0.62,0.66,0.78	0.62	1.488
	10.0,20.0,31.5	2.811	1.002,1.076,1.218	1.002	2.350
1:2:4	16.0,31.5,63.0	4.76	1.67,1.81,2.08	1.670	9.57

Filter tests were carried out with bases of different combinations of cohesive and non-cohesive content. Base soils have been dealt with on the basis of cohesive content in them which has been added in increments of 5% to observe their behavior. During the tests it was observed that there was free flow upto the 30% of cohesive content in the non-cohesive bases, after which it reduced to minor seepage. As such the slot test was carried out i.e. an artificial slot of 1.5 cm diameter was created in the base, Figure 3, resembling the specific conditions for cohesive soil such as presence of cracks, fissures and holes. It is to mention here that most of the authors who have done work for filter design for cohesive materials have chosen the slot size from 0.1 cm to 1.0 cm for different base material. In the present case also the size was chosen arbitrary keeping it closer to already adopted sizes. The slot is adopted only to represent the fissures and cracks which can be from few mm to many cm in the field but in the laboratory when larger sizes were tried there was free flow through the filter i.e., the slot was acting as an outlet for fluid and when the smaller sizes were tried the flow reduced to minor seepage with negligible washout i.e., the slot got blocked. Water under a constant head of 5.5m was made to pass through the main cylinder. The piezometer heads along the filter and base, rate of flow through the specimen and water temperature were measured. The maximum hydraulic gradient upto 30% of cohesive content was about 50, after which the failure of base was due to development of cracks. The washout of non-cohesive part of the base was collected on a mesh of 0.075mm opening andwashout of fine soil which lasted for first few minutes, was estimated by taking samples of muddy water at different intervals and using the equation (Haji et.al 1984)

$$\text{Percentage of solids} = [\{(\gamma_s-\gamma_w) / (1-\gamma_s/ G\gamma_w)\gamma_w\}] \times 100 \qquad (4)$$

where, γ_s= unit weight of suspension, γ_w= unit weight of clear water ,G = specific gravity of soil. Borderline success cases were indicated where very small quantity of base material passed through the filter (i.e. the washout was less than 1% to 1.5%) and the base deformation was insignificant. Further, for the bases with slot the borderline success filters were considered with no visible increase in slot diameter and very slight erosion of base soil. The unsuccessful filters were considered where the slot got eroded progressively larger with more and more loss of fines or sometimes the filter face got sealed rapidly in the initial stage of the test due to the eroded base material from slot sides. The tests were run till the rate of flow became relatively constant with time.

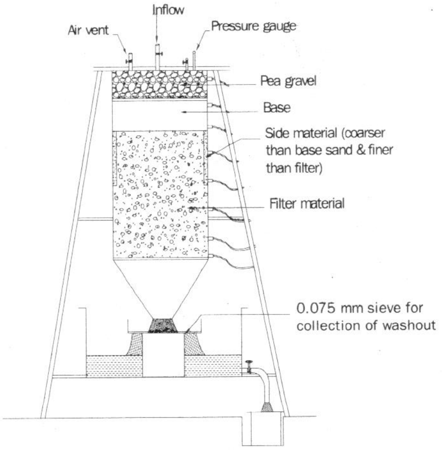

Fig. 2 Main Body of Filter Apparatus

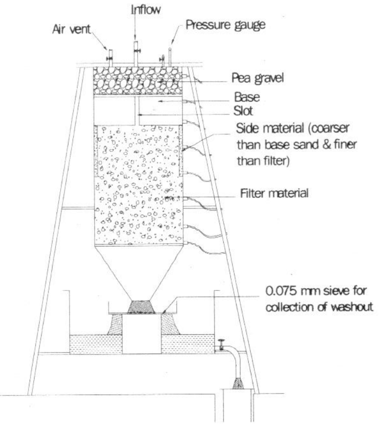

Fig. 3 Position of Experimental Setup for Filter Tests with Slot

Filter test with Base BI

Filter for base BI was designed for design controlling size d* of 1.672 mm obtained from Eq. (2). Subsequently a filter of primary assembly size 16.0 mm, 31.5 mm, 63.0mm and filler size 4.76 mm was adopted for which the controlling pore size worked as 1.67 mm. The base was then subjected to filter test against the filter mass. The same base was tested with varying percentages (5% increments) of cohesive soil CI, against the same filter. It was observed that upto 30% of cohesive soil content the model worked successfully i.e. the washout was within 1 to 1.5% of the base soil, most of which got collected in the initial stages of the test and completely vanished within four hours in most of the cases, thus indicating the attainment of both structural and hydraulic stability. This condition remained steady and did not change even after the test was run for a longer period. After 30% of cohesive content addition in the base, though there was no washout, yet the free flow reduced to minor seepage. As such the above procedure of test worked only upto the 30% of cohesive content in base BI. After 30% of cohesive content, the slot test was adopted i.e. an artificial slot was created in the base and the test was run as described above. The slot test resembles the field conditions for cohesive soils like fissures, cracks and holes formed by different settlements, shrinkage during dry spells, decay of organic matter, vibration during earthquakes, rodrants etc. It was observed that the above filter worked successfully up to 70% of cohesive soil content in the base i.e. no significant increase in the slot diameter was seen, discharge was reasonable and the washout remained reasonably within the limits. However, beyond 70% of cohesive soil content, it was seen that the filter designed on the above basis did not remain successful any more. The results of tests for BI with different cohesive contents are given in Table 5.

Filter Tests with Base BII to BV

The same procedure as described above was adopted for filter testing of bases BII to BV with different percentages of cohesive soil. The results show that these bases also followed the above behaviour i.e., the bases were successfully retained by the filter procedure described earlier upto 70-75%, with slot test after 30%. The results are tabulated in Tables 6-10.

Table 5 **Results of Tests for Base BI with Different CI Content**

Design controlling size: 1.672mm
Filler size: 4.76mm
Primary assembly size: 63.0:31.5:16.0mm
Controlling pore size: 1.670mm

Base	Washout (g)	Hydraulic Gradient	Discharge (cm^3/sec)	Permeability (10^{-3} × cm/s)
BI-00	40.00	31.59	774.40	46.94
BI-05	49.00	32.49	678.12	43.87
BI-10	62.50	32.00	647.16	41.20
BI-15	75.65	35.50	594.20	34.10
BI-20	70.63	47.46	114.39	4.910
BI-25	21.00	48.33	68.70	2.900
BI-30	2.00	48.99	6.85	0.285
BI-35	27.80		86.58	
BI-40	29.25		86.15	
BI-45	36.10		88.24	
BI-50	47.10		89.10	
BI-55	47.50		96.15	
BI-60	57.20		97.95	
BI-65	66.50		98.24	
BI-70	72.50		108.23	
BI-75	268		110.50	

Table 6 Results of Tests for Base BII with Different Cl Content

Design controlling size: 1.372mm
Primary assembly size: 31.5:25:16.mm
Filler size: 3.36mm
Controlling pore size: 1.300mm

Base	Washout (g)	Hydraulic Gradient	Discharge (cm³/sec)	Permeability (10⁻³ × cm/s)
BII-00	34.50	40.66	518.52	25.90
BII-05	36.00	41.46	451.61	22.20
BII-10	66.23	42.67	437.50	20.90
BII-15	73.43	45.50	386.39	17.30
BII-20	69.02	48.66	95.06	3.98
BII-25	24.35	49.81	59.17	2.42
BII-30	2.00	48.74	6.69	0.28
BII-35	26.50		83.30	
BII-40	24.40		68.96	
BII-45	25.80		75.45	
BII-50	42.80		81.28	
BII-55	55.60		85.55	
BII-60	54.25		86.95	
BII-65	57.35		95.24	
BII-70	66.50		100.26	
BII-75	249		109.26	

Table 7 Results of Tests for Base BIII with Different Cl Content

Design controlling size: 1.075mm
Primary assembly Size: 31.5:20:10.0mm
Filler size: 2.811mm
Controlling pore size: 1.002mm

Base	Washout (g)	Hydraulic Gradient	Discharge (cm³/sec)	Permeability (10⁻³ × cm/s)
BIII-00	37.00	40.40	414.47	20.90
BIII-05	42.90	41.01	442.87	22.00
BIII-10	63.70	42.00	424.71	20.60
BIII-15	52.16	46.40	366.70	16.10
BIII-20	56.66	47.28	90.51	3.90
BIII-25	38.30	49.83	54.06	2.21
BIII-30	Nil	49.81	6.36	0.26
BIII-35	26.85		70.31	
BIII-40	24.85		71.25	
BIII-45	28.50		79.21	
BIII-50	42.75		80.81	
BIII-55	52.60		85.56	
BIII-60	69.52		86.60	
BIII-65	68.15		94.23	
BIII-70	77.91		98.26	
BIII-75	258.60		104.36	

Table 8 Results of Tests for Base BIV with Different CI Content

Design controlling size: 0.961mm — Primary assembly Size: 20.0:12.5:6.3mm

Filler size: 2.36mm — Controlling pore size = 0.900mm

Base	Washout (g)	Hydraulic Gradient	Discharge (cm^3/sec)	Permeability (10^{-3} × cm/s)
BIV-00	31.00	40.40	280.61	14.15
BIV-05	37.00	42.20	251.06	12.12
BIV-10	45.62	43.25	234.88	11.00
BIV-15	45.00	45.55	232.54	10.40
BIV-20	52.68	47.50	86.27	3.70
BIV-25	18.40	48.00	49.48	2.10
BIV-30	nil	49.61	06.08	0.25
BIV-35	26.54		57.14	
BIV-40	26.70		60.60	
BIV-45	29.23		62.60	
BIV-50	32.00		70.43	
BIV-55	43.50		76.60	
BIV-60	40.75		78.05	
BIV-65	47.00		79.05	
BIV-70	47.50		88.96	
BIV-75	50.55		99.92	
BIV-80	330		123.96	

Table 9 Results of Tests for Base BV with Different CI Content

Design controlling size = 0.621mm — Primary assembly size: 20.0:12.5:6.3mm

Filler size: 1.707mm — Controlling pore size: 0.620mm

Base	Washout (g)	Hydraulic Gradient	Discharge (cm^3/sec)	Permeability (10^{-3} × cm/s)
BV-00	32.00	45.80	146.13	6.5
BV-05	40.25	45.72	109.96	4.9
BV-10	47.48	46.58	40.01	1.75
BV-15	35.50	48.47	39.26	1.65
BV-20	41.00	48.74	38.76	1.62
BV-25	15..50	49.83	26.91	1.10
BV-30	nil	49.83	4.16	0.17
BV-35	26.54		55.70	
BV-40	36.36		58.60	
BV-45	39.50		68.70	
BV-50	55.55		70.70	
BV-55	56.24		76.92	
BV-60	60.15		78.82	
BV-65	69.76		79.63	
BV-70	72.50		85.5	
BV-75	75.60		90.92	
BV-80	320		118.40	

Table 10 Results of Filter Tests for Bases with Different Cohesive Content CI.

Base	Design controlling size (d*) mm	Controlling Pore size (mm)	Success up to (%age of fines)	Failure at (%age of fines)
BI	1.672	1.670	70	75
BII	1.372	1.300	70	75
BIII	1.075	1.002	70	75
BIV	0.961	0.961	75	80
BV	0.620	0.620	75	80

Results and Discussions

The results indicate that upto a cohesive content percentage of 70 to 75, the model proposed by Lone et.al (1996) works satisfactorily. Moreover the flow behaviour is highly influenced by the percentage of fines. It has been noticed that at about 30% and above cohesive content in the bases, the permeability becomes very low, free flow is reduced to minor seepage and washout is practically non-existent. This indicates that upto 30% of cohesive content in the bases, the flow is free through the media and beyond 30% of cohesive content in the bases, the base behaves like an impervious material and washout becomes insignificant. The failure in such cases is conceded either as an erosion phenomenon from fissures and cracks which start enlarging under high hydraulic gradients or clogging at the filter base interface resulting in development of very high hydraulic gradients. Further it could be inferred that beyond 70% of cohesive content in the bases the filter designed on the above concept did not remain successful any more.

Conclusion

The perusal of test results indicate that the filter design procedure for non-cohesive bases, based on design controlling size of filter mass hold good upto a maximum of 70% cohesive content in the bases. However, the methodology of carrying out the test for ascertaining the validity of criteria beyond 30% content of cohesive soil varies. This is because of the reason that beyond 30% cohesive content in the non-cohesive base the base behaves like an impervious material and washout becomes insignificant and the base shows the clogging behaviour. The failure of such bases is conceded either as an erosion phenomenon from fissures and cracks which start enlarging under high hydraulic gradients or clogging at the filter-base interface resulting in development of very high hydraulic gradients. This effect in the bases, in the present study was achieved by making the slot in the bases and the results showed the above filter design procedure can be used successfully upto a maximum of 70% cohesive content in the filter base, beyond which the design procedure did not hold good. Such investigations are also in conformity with the recommendations by erstwhile investigators that the filters designed for non-cohesive bases can be conservatively applied to cohesive bases.

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