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Filter Design Criteria for Non-Cohesive Soils with A Limited Cohesive Content

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Introduction

Filters, which are an essential part of most of the hydraulic structures have to fulfil the two principal and contradictory requirements viz.; i) to prevent the migration of the finer soil particles due to the seepage of water and ii) to allow the drainage of seepage water in order to provide a check over the development of seepage forces.

Since 1922 lots of efforts have been made both in theoretical and experimental fields to improve the design criteria for the filters, which should not be conservative, and should be applicable to a variety of base and filter materials. The literature review reveals that as per the efforts made in this direction the condition of internal stability and hydraulic efficiency of the filters have been usually expressed in terms of certain ratio and sizes viz: D_{15}/d_{15} , D_{15}/d_{85} , D_{50}/d_{50} (D and d respectively refer to the grain size of the filter and the base soil, and the subscripts 15, 85, 50 refer to percent finer by weight)etc. which may vary over wide ranges in different cases. However these criteria are more conservative and involve grading constraints of the materials involved. As a result of this wide variation, the field engineers have mostly adopted Terzaghi's (1922) Criteria only for all practical purposes, that proposes the following two equations for satisfying the above referred to two principal requirements of a successful filter:

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$$D_{15}\,(\text{of filter})/d_{85}\,(\text{of base}) \leq 4-5 \tag{1}$$

$$D_{15}\,(\text{of filter})/d_{15}\,(\text{of base}) \geq 4-5 \tag{2}$$

The criterion defined by Eqn.1 is known as piping criterion and that by Eqn.2 is known as permeability criterion. Terzaghi further proposed that both the grain size distribution of the base and the filter should be similar (i.e. approximately parallel) and non-uniformity coefficient $C_u\ (= D_{60}/D_{10}) < 2$. Terzaghi's criteria were probably based on experience and reason.

The experimental work on filter support the general validity of the piping criterion, which has a built in conservatism, providing a safety factor of about 2. The main conclusion that has been put forth is that for filters with D_{15} size larger than about 1.0 mm, the ratio $D_{15}/d_{85} \leq 5$ should be continued as the main criterion for judging filter acceptability. Studies have further shown that the filter criteria that limit the D_{50}/d_{50} and D_{15}/d_{15} ratios are not founded on a sound theoretical or experimental basis and should be abandoned. Terzaghi's filter criteria also do not give a unique gradation for a particular base soil. Sometimes the resultant filter gradation includes too wide a range in particle sizes.

In most of the cases the treatment of the filtration phenomena, qualitatively and quantitatively, has often been based on empiricism, not taking into account the real physics of the phenomenon because of the 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 them like Sherard et al. (1984) felt that these criteria need gross modifications when the gradation of either the filter or the base is vastly different from those used in the development of these criteria.

A recently developed criterion (Lone, 1996) based on the 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.

$$d^* = 8 \times d_{85}/(C_u + 4.72) \tag{3}$$

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

C_u = Co-efficient of uniformity of the base material.

This design controlling size d* is to be achieved as the minimum window size of the primary assembly of the filter mass which is being explained under the heading 'Theoretical Background' in the succeeding pages.

In the present study an attempt has been made to ascertain the application of the above concept to mixed bases (i.e. a base consisting of cohesive and non-cohesive soil contents) and to ascertain the presence of percentage of cohesive soil content in the non-cohesive soils up-to which the criteria can hold good to fulfil the two basic requirements of the filters.

Theoretical Background

In order to understand the concept of design controlling size d* of the filter mass used in the present study, it is necessary to have an idea about the 'Conceptual Model of Particle Packing', used here. This model is discussed below:

For decades researchers have been considering the variety of geometrical packings in order to explain the aggregate properties and engineering behaviour of particulate media. Most of these packings are based on uniform size spheres and inferences drawn therefrom are extended to real particles which are neither spherical nor of uniform size when considered in a mass.

It is generally observed that irrespective of the initial packing of spheres, a slight disturbance causes the spheres to rearrange themselves in such a way that three particles would come together in a plane so as to form an inter-particle window. If the third dimension is considered, the gap formed by these three particles in first plan, is occupied by the fourth particle in the second plane and thus forming a tetrahedron, wherein also the windows are formed only amongst the three particles. Hence, this configuration seems to be most logical for studying the engineering behaviour of non-cohesive materials like sand, gravels, boulders etc. In the present study the packing of the particulate media has been considered on the basis of three non-uniform spheres, instead of three uniform spheres that has been in use in most of the cases so far.

The concept of a simple physical model, originally developed by Hussain (1981) to explain in general the shear strength behaviour and in particular, the shear intercept as a result of interlocking, has now been extended to explain the behaviour of protective filters. For this purpose a unit assembly of three spheres of different sizes was considered. These spheres were touching each other and their centres were in a single plane. Such an assembly forms a window whose sides are concave arcs with radii

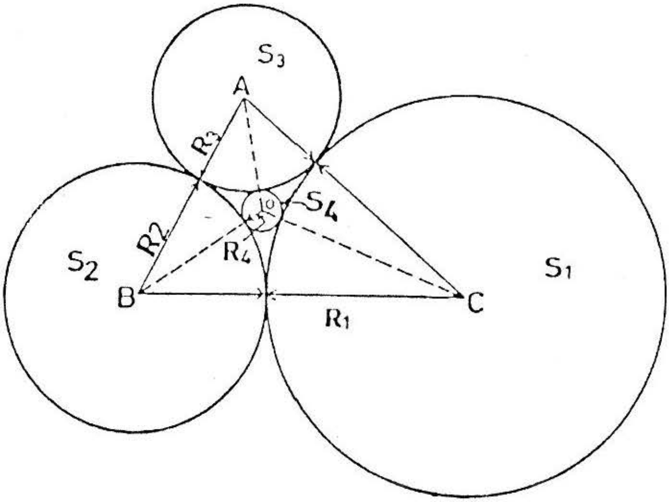

FIGURE 1 : Assembly of Non-uniform Spheres

equal to radii of the assembly spheres. The arrangement is shown in Fig.1. In the figure S_1, S_2 and S_3 are the diameters of primary spheres and S_4 is the diameter of the intervening sphere. Spheres have been referred in the text by their diameters. R_1,R_2,R_3 and R_4 are the radii of the above respective spheres. The below mentioned relations hold good for the assembly shown in Fig.1.

$$R_4 < R_3 < R_2 < R_1 \tag{4}$$

$$\Delta ABC = \Delta AOB + \Delta BOC + \Delta COA \tag{5}$$

From Eqn.4, one gets

$$\begin{aligned}\left[(R_1+R_2+R_3)(R_1R_2R_3)\right]^{1/2} &= \left[(R_1+R_2+R_4)(R_1R_2R_4)\right]^{1/2}\\ &+\left[(R_2+R_3+R_4)(R_2R_3R_4)\right]^{1/2}\\ &+\left[(R_3+R_1+R_4)(R_3R_1R_4)\right]^{1/2}\end{aligned} \tag{6}$$

One can make radii of spheres dimensionless by dividing them with, say R_3

$$R_2/R_3 = m,\ R_1/R_3 = n,\ R_4/R_3 = \beta \tag{7}$$

In terms of these ratios, Eqn.3 reduces to the form

$$\left[(1+m+n)(mn)\right]^{1/2} = \left[(1+m+\beta)m\beta\right]^{1/2} + \left[(m+n+\beta)mn\beta\right]^{1/2} + \left[(1+n+\beta)n\beta\right]^{1/2} \quad (8)$$

The intervening sphere size, which is a function of the size of the three surrounding spheres, can be worked out by the use of Eqn.8 or from the set of curves shown in Fig.2. Other sizes, referred to as filler sizes here, i.e. 5th, 6th and 7th, etc. (Fig.3) for the windows formed between intervening size spheres and primary spheres can also be computed either by using Eqn.8 or Fig.2.

In this way, it will be possible to find the smallest possible pore within a unit assembly of spheres, knowing the radii of surrounding particles.

Logical Configuration of Filter Mass

To explain the logical configuration of filter mass on the basis of above packing, a significant number of unit assemblies corresponding to different 'm' and 'n' values were sketched in plane to visualise the real occupancy by the unit assemblies over a given area. It was observed that with different 'm' and 'n' values the area occupied by the regular assemblies (i.e. primary assemblies comprising of S_1, S_2 and S_3 spheres) generally range between 80% and 90% remaining being the pores/windows. Two types of pores/windows exist in this type of packing which approach the random

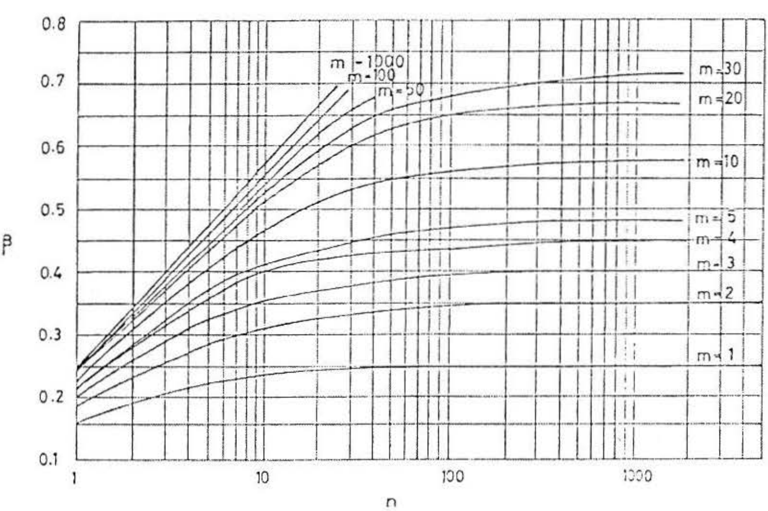

FIGURE 2 : Curves for m, n and β Relationship

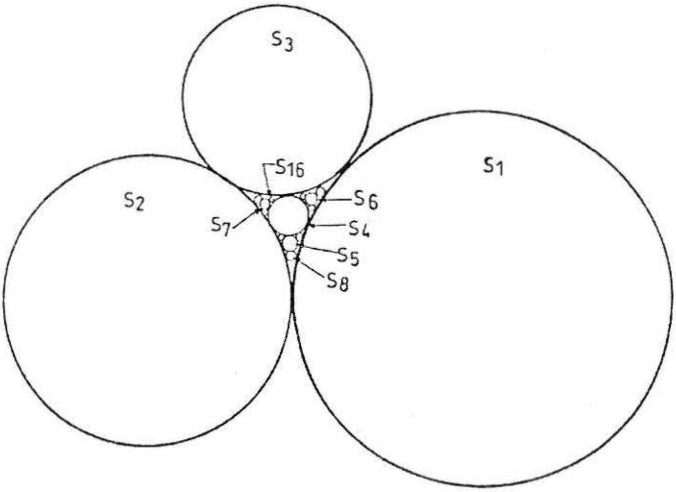

FIGURE 3 : Unit Assembly of Non-uniform Spheres with Intervening Sphere and Fillers

packing (Fig.4). First type of pores/windows consist of pores/windows of regular assemblies and remaining are formed due to lack of fit between the assemblies which do not exist in case of assemblies of uniform size of primary spheres. It is assumed that in a mass, the arrangement will be repeated in subsequent layers such that large size spheres occupy bigger depressions of either the unit assemblies or the spaces due to lack of fit. When a significant thickness of such a random packing is considered, the

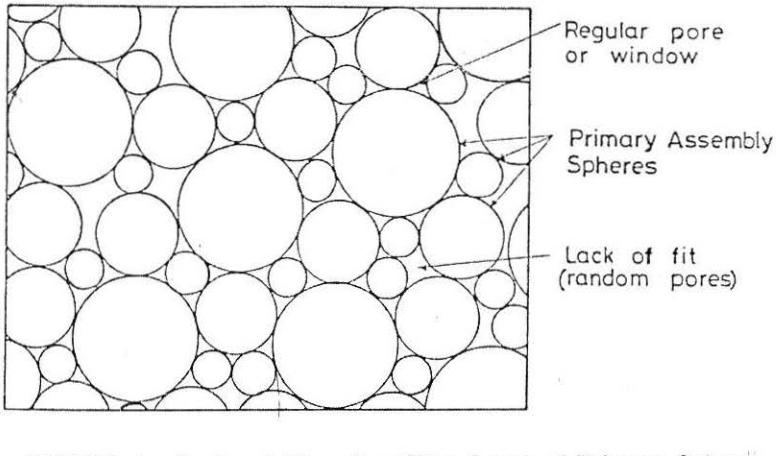

FIGURE 4 : Sectional Plan of a Filter Layer of Primary Sphere Ratio of 1 : 2 : 3

lower voids, formed due to lack of fit, lose their significance because of the subsequent layers. This concept is also in conformity with Witmann (1979) i.e. probability of a pore 'dp' in one sectional plan to meet another pore will be equal or bigger than 'dp' can be expressed by:

$$P^2 = (1-p)^2 \quad (9)$$

where 'p' is the relative probability of one pore to be smaller than a certain pore 'dp' and for m proofs or sectional planes.

$$P^m = (1-p)^m \quad (10)$$

and probability P* of a certain pore after 'm' confrontations to be smaller than 'dp' can be expressed by

$$P* = 1-P^m = 1-(1-p)^m \quad (11)$$

Accordingly the probability of large pores coming one above the other goes on decreasing with increasing thickness of filter i.e. with increasing number of layers. As such the bigger pores whether formed due to lack of fit or resulting from the unit assemblies of primary spheres and intervening sizes lose their significance once the pore channel is confronted by smaller pore in any subsequent layer (Fig.5), so it can be concluded that the

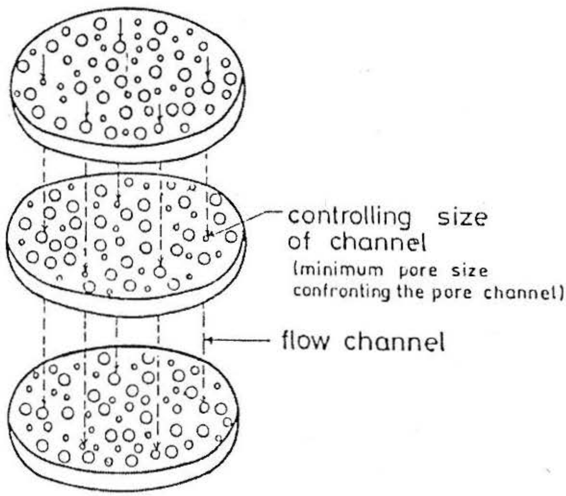

FIGURE 5 : Influence of the Additional Unit Layers on Controlling Size of the Pore Channels

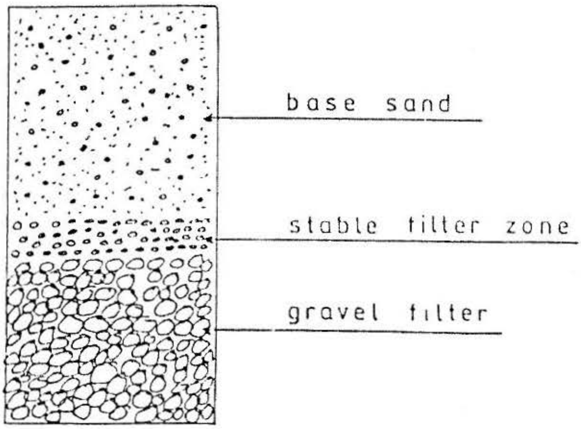

FIGURE 6 : Process of Self-filtration Layer Making

controlling pore (or window) size, hence the design controlling size d*, is the smallest resulting pore/window of the unit assembly (Fig.3) i.e. S_7 in case the unit assembly of filter mass is taken as three primary non-uniform spheres and the intervening sphere S_4; and 16th size i.e. S_{16} in case the unit assembly is represented by three non-uniform spheres S_1, S_2 and S_3 and the intervening sphere of size S_4 and fillers S_5, S_6 and S_7 (Fig.3).

As such taking the minimum pore/window size of the unit assembly, as the controlling size of the flow channels (Kenney et al., 1985), one can estimate the size of the base material that can be retained by the filter before the formation of the self-filtration layer at base-filter interface, Fig.6. The self-filtration layer is the layer formed at the base-filter interface by the contribution of the base material sizes coarser than d* in order to retain the finer base fraction thereafter. Before the formation of this layer, there can be some loss of fines, which is usually experienced in the initial stage of the filter tests.

Thus knowing from Eqn.3, the required design controlling size d* for retaining a particular base, a filter is selected for which the controlling pore size is equal or slightly less than this d*. The primary assembly sizes for filter are selected on the basis of available material or that can be made conveniently available. The required intervening and filler sizes, which actually controls the filter behaviour and constitute about 10%, can be arranged conveniently, if not available at site.

From the geometry and mathematical calculations for various assemblies with varying 'm' and 'n' value, it has been observed that about 90% of the

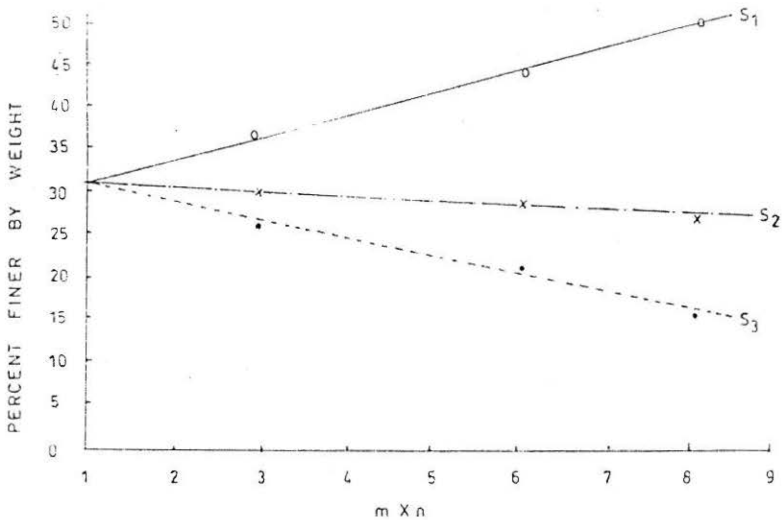

FIGURE 7 : Variation Pattern of individual Primary Assembly Sizes

structure consists of primary sizes, 7 to 8% constitutes the intervening size and 3 to 4% the filler sizes, which control the filter behaviour with respect to permeability and washout.

It has been observed that the percentage mass of individual primary assembly spheres (S_1, S_2 and S_3) varies with the variation in 'm' and 'n' values of unit assemblies. The variation pattern of individual primary assembly sizes for different 'm' and 'n' values is shown in Fig.7. The figure shows percentage of S_1, S_2 and S_3 with respect to the product of their 'm' and 'n' values. The product of 'm' and 'n' is relevant to percentage weight of different primary assembly sizes, because the weight is the function of the particle size. With the help of curves shown in Fig.7 one can find the required individual percentages of primary assembly sizes, and accordingly the percentages of intervening and filler sizes can be estimated.

The filter design based on above conceptual model has been successfully adopted for protecting the base materials of cohesionless nature in the laboratory studies.

In the present study the experiments were conducted for ascertaining the extent of cohesive base content in the non-cohesive bases up-to which the filter design procedure on the basis of above model can be employed successfully.

Experimentation

General

As described earlier, the physical behaviour of filter is dependent on the pore configuration of filter mass and on the gradations of the filter and base materials. The present investigation has been carried out to have an idea about the filter behaviour for the bases with a certain content of cohesive material. The experimental set-up, materials used and procedure adopted are described in the following sections.

Experimental Set-up

The detailed arrangement for carrying out the tests is shown in Fig.8. The salient features of set up are as follows:

- main cylinder made of steel having 250 mm diameter and 600 mm length excluding hopper base.

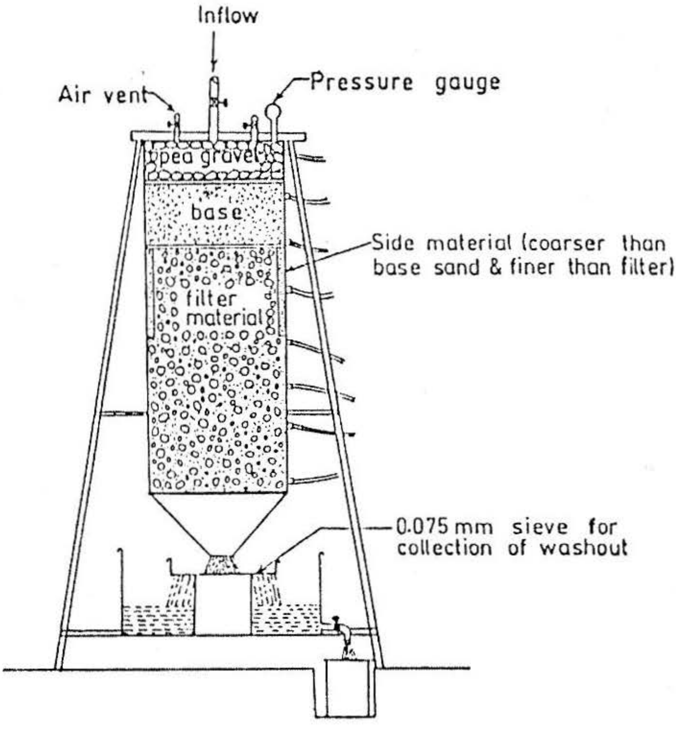

FIGURE 8 : Main Body of Filter Apparatus

- arrangements for connecting the hopper base to 37.5 mm diameter flexible rubber pipe.

- top flange made of steel with arrangements for connecting it to the inlet pipe of 37.5 mm.

- maximum head of water available through the constant head tank as 5.5 m.

- In order to ensure the constant water supply to the tank from the overhead tank, a pump of 60 metric h.p. was used to fill the overhead tank, which has a capacity of 1.75 lakh litres. The water from the filter apparatus was going to the cement concrete sump wherefrom it was again supplied to the overhead tank with the help of above-mentioned pump.

- quantity of flow was measured in a graduated tank at the location of outlet.

- brass pinch-cocks were used as piezometer connectors for facilitating the instantaneous closure and resumption of supply to the piezometers.

- the filter apparatus was fixed on a rigid steel stand.

TABLE 1 : Shape Parameters of Material used as Filter

Size (mm)	b/a	c/a	Flatness ratio $(a+b)/2c$	Shape factor $c/\sqrt{ab}$	Sphereeity $\frac{(\text{particle vol.})^{1/3}}{\{(\pi/6)\cdot a^3\}^{1/3}}$
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	0.553

a = Major axis of particles
b = Intermediate axis of particles
c = Minor axis of particles

Materials

The granular material obtained from the beds of river (Sindh Nallah) at Ganderbal Srinagar and sites adjacent to the river course was used as filter material. The particle shapes of the riverbed material ranged from spherical to ellipsoidal. The shape parameters of these materials are presented in Table 1.

For the base material river sands of three different gradations were selected for various filter tests. The material used as cohesive content in the tests was obtained from the R.E.C. Srinagar Campus. The specific gravity of this soil was 2.67.

The main gradation features of the three sands and cohesive soil are presented in Table 2.

Filter Test with Bases

Three types of bases designated as BI, BII, and BIII, [illegible]ng proportions of cohesive and non-cohesive soils were tested against the filters designed on the basis of the design controlling size concept, Lone (1995).

The samples were designated as under:

Base BI without cohesive content as BI-00

Base BI with 5% cohesive content as BI-05

Base BI with 10% cohesive content as BI-10 and so on.

Similarly second base was designated as BII-00, BII-05 and so on and the third base as BIII-00, BIII-05, etc. as per the presence of cohesive content.

TABLE 2 : Gradation Features of Base Materials

Material	Sizes (mm)						
	d_{10}	d_{15}	d_{50}	d_{60}	d_{85}	d_{95}	C_u
BI	0.1920	0.2630	0.3180	0.3730	0.8530	1.6290	1.943
BII	0.2220	0.2620	0.4780	0.5330	1.3150	2.6290	2.400
BIII	0.2200	0.2510	1.3700	1.5600	2.5100	4.0100	7.090
Cohesive Soil	0.0024	0.0065	0.0092	0.0114	0.0240	0.5500	4.750

Filter for base BI was designed for a design controlling size d* of 1.02 mm obtained from Eqn.1. Subsequently a filter of primary assembly size 10 : 20 : 31.5 mm was adopted for which the controlling pore size worked as 1.01 mm. The base was then subjected to the filter test against this filter mass under a hydraulic gradient that varied from 0.1 to a maximum of 38.19 and discharges varying up-to a maximum of 215.05 cm^3/s. The permeability was measured as 11.47×10^{-3} cm/sec.

The same base was tested with varying percentages (5% increments) of cohesive soil content (as detailed in Table 6) against the same filter in the same way as discussed above. It was observed that upto 30% of cohesive 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 4 hours in most of the cases, thus indicating the attainment of both structural and hydraulic stability. After this the conditions remained steady state and this condition did not change even after the test was run for several hours.

Higher gradients were used to observe the filter behaviour against the worst conditions, and also to account for the field condition where lower gradients are operational over longer durations.

After 30% cohesive content addition in the non-cohesive base, though there was no washout yet the free flow reduced to minor seepage. As such the above procedure worked only upto the 30% of cohesive content in the base BI.

The results for base with different cohesive soil contents and at maximum hydraulic gradient i.e. at the worst condition are presented in Table 3. Similarly the tests were conducted for BII and BIII with the varying

TABLE 3 : Results of Tests for Bases BI-00 to BI-30

Base	Washout (g)	Hydraulic gradient	Discharge (cm^3/sec)	Permeability (10^{-3}cm/sec)
BI-00	14	38.19	215.05	11.47
BI-05	30	39.05	200.56	10.46
BI-10	53	38.19	175.95	9.39
BI-15	55.5	39.52	153.61	7.92
BI-20	14	39.62	69.21	3.56
BI-25	5	39.71	37.03	1.90
BI-30	nil	39.81	6.50	0.33

TABLE 4 : Results of Tests for Bases BII-00 to BII-30

Base	Washout (g)	Hydraulic gradient	Discharge (cm^3/sec)	Permeability (10^{-3}cm/sec)
BII-00	17	36.76	345.625	19.15
BII-05	58	37.05	276.500	15.23
BII-10	103	39.71	199.540	10.24
BII-15	114	39.80	172.810	8.85
BII-20	20	41.04	62.500	3.10
BII-25	6	41.14	41.670	2.06
BII-30	nil	41.23	7.400	0.36

TABLE 5 : Results of Tests for Bases BIII-00 to BIII-30

Base	Washout (g)	Hydraulic gradient	Discharge (cm^3/sec)	Permeability (10^{-3}cm/sec)
BIII-00	21	39.81	219.94	11.20
BIII-05	57	40.57	165.42	08.31
BIII-10	69	41.14	145.53	07.14
BIII-15	71	41.22	091.29	04.51
BIII-20	23	41.52	029.41	01.44
BIII-25	07	41.57	016.13	00.79
BIII-30	nil	41.61	007.19	00.35

cohesive contents for which also the said procedure worked upto 30% of cohesive content. The results for these tests are presented in Tables 4 and 5.

Discussion and Conclusion

The test results of the three bases with different cohesive contents show that up-to 30% of cohesive content in non-cohesive bases, the filter design procedure for non-cohesive bases hold good. With the increasing percentage of cohesive content, the washout and permeability go on decreasing. It has been noticed that at about 30% cohesive soil content in the mixture, the permeability becomes very low, free flow is reduced to minor seepage and washout is practically non-existent. As such the above design procedure is not recommended for the bases having cohesive content more than 30%.

The perusal of test results indicates that the presence of fines in non-cohesive soils such as sands has a marked influence on the filter behaviour, when such soils are used as bases. It affects overall gradation and effective pore channel, thus influencing the permeability and quantity of washout. It is further noticed that up to a particular limit of cohesive content in base the base-filter behaviour can be studied as in case of non-cohesive bases but beyond that limit the mixed base behaves like an impervious material and washout becomes insignificant. Under this situation the function of the filter becomes irrelevant if it is designed on the same lines as for non-cohesive bases.

It is concluded that beyond 30% of cohesive soil content in the base, the filters are to be designed on the basis of procedure laid down for cohesive materials. The concept of filter design on the basis of pore channel requirement for the controlling size of non-cohesive base content is not of much relevance after this percentage and filter is to be designed considering the specific conditions for cohesive soils such as presence of cracks, fissures and holes. In clayey materials the washout is conceded as an erosion phenomenon from such fissures and cracks which start enlarging under high hydraulic gradients and endangers the structures.

Gradation curves drawn for the bases with different cohesive contents indicate increase in the values of respective coefficients of uniformity with increase in cohesive soil content. At the indicated failures of the tested bases, it was observed that the 'C_u' value at the failure is about 22 to 26 times as that for the non-cohesive base material (Tables 6 to 8).

So it can be inferred that the filter design on the basis of pore channel concept for non-cohesive content of bases can hold good upto a maximum of 30% content of cohesive material in the non-cohesive bases. Secondly the

TABLE 6 : Variation of C_u for Bases BI-00 To BI-30

Base	d_{60} (mm)	d_{10} (mm)	C_u
BI-00	0.373	0.192	01.943
BI-05	0.375	0.164	02.290
BI-10	0.375	0.085	04.410
BI-15	0.350	0.013	26.920
BI-20	0.337	0.010	33.700
BI-25	0.312	0.008	39.000
BI-30	0.300	0.007	42.850

TABLE 7: Variation of C_u for Bases BII-00 To BII-30

Base	d_{60} (mm)	d_{10} (mm)	C_u
BII-00	0.533	0.222	02.40
BII-05	0.533	0.182	02.93
BII-10	0.533	0.085	06.27
BII-15	0.516	0.014	37.94
BII-20	0.490	0.0095	51.58
BII-25	0.483	0.008	60.37
BII-30	0.450	0.007	64.28

TABLE 8: Variation of C_u for Bases BIII-00 to BIII-30

Base	d_{60} (mm)	d_{10} (mm)	C_u
BIII-00	1.560	0.220	007.09
BIII-05	1.500	0.170	008.82
BIII-10	1.455	0.085	017.12
BIII-15	1.410	0.015	094.00
BIII-20	1.360	0.011	123.64
BIII-25	1.280	0.008	160.00
BIII-30	1.170	0.007	167.14

'C_u' concept can also guide for the presence of cohesive soil content in the non-cohesive soils.

Moreover the above bases and corresponding filters when checked for well known Terzaghi's piping criterion i.e. $D_{15}/d_{85} \leq 5$, it was seen that the values of this criterion were in the range of 8 to 9 and $D_{15}/d_{15} = 30$ to 35. As per Terzaghi's Criterion, these filters should have been rejected, but instead worked satisfactorily when put to the test as per the model discussed in the paper. Though theses filters did not find conformity with Terzaghi's Criteria, yet they fully satisfied Sherard (1984a) experimental findings, according to which D_{15}/d_{85} approaches a value of 9. According to Sherard (1984a), a ratio upto 9 is quite satisfactory.

For the bases with cohesive content upto 30%, the design procedure is briefed as under:

1. From the gradation curve of the base find the values of d_{85} and coefficient of uniformity C_u.

2. Using the relation (Eqn.3), find the design controlling size d*.

3. Choose suitable Primary Assembly Particle sizes (S_1, S_2 and S_3) as per the requirement and availability of the material. Find the 'm' and 'n' values.

4. With the help of Fig.7, find the respective weight percentages of the materials corresponding to S_1, S_2 and S_3.

5. With the help of curves presented in Fig.2 find the intervening and filler sizes, that constitute about 7 to 8% and 3 to 4% of filter mass respectively.

The above sizes of the filter be placed carefully in order to avoid any segregation and to ensure the even distribution of the filler and intervening sizes in the filter mass.

The present studies are of preliminary nature and immense research efforts are required before definite criteria for bases containing cohesive content are arrived at.

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