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Investigating the Influence of Filter Uniformity Coefficient and Effective Pore Size on Critical Hydraulic Gradient and Maximum Erosion of Dispersive and Non-dispersive Samples

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ABSTRACT

Filter is one of the main components of embankment dams. By a simple but effective performance, filter protects the dam against erosion and soil scouring in impervious core caused by leakage (piping) and makes it safe. Interaction between filter and erodible base soil is a complex phenomenon which is dependent upon several factors, and has challenged researchers for better understanding the filtration system behavior. Therefore, more investigations in this field are needed. Identification of dispersive soil filtration is of great importance because of high erodibility potential of these soils. In this study, in order to evaluate dispersive soil filtration a device is designed and made by the authors for filter testing. This device can measure the hydraulic gradient in flow path by using a controlled flow head. By performing filter tests on dispersive and non-dispersive soil samples, the effect of uniformity coefficient and effective pore size of the filter on critical hydraulic gradient has been studied. The critical hydraulic gradient varies with the change in filter uniformity coefficient, and by increasing the effective pore size of the filter, critical hydraulic gradient is decreased.

Keywords

Dispersive soil, Critical hydraulic gradient, Uniformity coefficient, Effective pore

1. Introduction

Filter is an important component of embankment dams whose main task is to prevent base soil erosion along with providing adequate drainage without an increase in pore pressure and filter blockage. Filtration is a process in which the filter protects the soil against erosion and piping likelihood. Despite using the filters from the early times and numerous researches in this field, piping and internal erosion is still a main cause of dam failure. According to the statistics provided by Foster and Fell up to 1986, 48 percent of large dams' destructions (with heights greater than 15 m) are due to piping and internal erosion (Foster et al. 2000). Geometrical, physical, chemical, hydraulic and even biological factors can affect filtration phenomenon. Therefore the use of experimental and physical models is the most efficient method of investigating filtration, since all effective factors are

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considered in the experiments, simultaneously. Because of the high erosion potential in dispersive soils, investigating these soils filtration and influencing factors is of particular importance. Iranian Committee on Large Dams (IRCOLD), Vol. 8 describes dispersive soils as: “dispersive clay soil refers to soil with the physical-chemical grain condition so that in contact with relatively pure water, single clay particles are dispersed and separated from each other. This clay is highly vulnerable to erosion so that even disposal to very small stresses of water flow with low hydraulic gradient will lead to liquefaction" (IRCOLD 1375). Soil divergence phenomenon of clay soils is a complex physical-chemical mechanism and is discussed considering specific structures of the clay minerals, the osmosis phenolmenon effect, ion exchange, and adsorption quality of clays. Concentrated leakage through joints and cracks in soil mass is the cause of erosion and scouring in dispersive soils. Erosion in this material occurs also in small cracks and flow with low speed. Individual clay particles are usually smaller than the filter pores and therefore dispersive soil erosion continues and the cracks are not blocked. Normal and decentralized water seeping through dispersive soils’ pores does not lead to soil particles being washed (Esmaeeli 1388).

The degree of base soil erosion is associated with the hydraulic gradient within the soil layer. Locke (2001) showed that hydraulic conditions have a significant influence on movement of base soil particles and degree of erosion. Low hydraulic gradient may not be enough for erosion and base soil particles can deposit in filter particles. High hydraulic gradient can dislodge more base soil particles and dilate filter pores so that coarse particles can pass through. Indraratna and Radampula (2002) showed that with every increase in the hydraulic gradient, the erosion rate increases, and after formation of self-filtration layer at the boundary between the filter and the base soil decreases. The hydraulic gradient at which the maximum erosion occurs is called Critical Hydraulic Gradient.

Soil properties such as adhesion, moisture, and etc. are effective on the hydraulic gradient amount required for erosion. Compared to erodibility potential of non-cohesive soils, much greater seepage pressure is needed in cohesive soils to start erosion indicating higher critical hydraulic gradient of cohesive soils. Critical hydraulic gradient for a soil is also dependent upon conditions such as soil soundness or having cracks in soil layer. Among other parameters that affect the critical hydraulic gradient are average size of soil particles mass, base soil compacted density, effective stress between base soil particles, pore pressure between base soil particles, filter particles’ size distribution, filter porosity, diameter of filter pores and uniformity coefficient of filter particles which have a significant effect on the amount of critical hydraulic gradient (Kohler 1993, Mlynarek 2000).

In this study, filter tests are carried out on four soil samples with different dispersal percentages and assuming that the core has been cracked. Critical hydraulic gradient for each sample was calculated by applying controlled water head and recording the changes of outlet water turbidity from the experiment chamber at the same time intervals. Experiments were carried out for both successful and unsuccessful filters and the effect of soil dispersal degree on critical hydraulic gradient has been analyzed.

2. Filter pore size

A description on theoretical concepts of filter pore size distributed (CSD) is fully presented by Indraratna and Locke (2000), Raut and Indraratna (2004) and Locke (2001). Here, the above principles are expanded and a computational approach to determine pore size distribution of filter for particle size distribution (PSD) and known relative density (R_d) is presented.

2.1. Filter Pore size in very dense and very loose particle distributions

In real granular filters, particles are located into groups of three and four, indicating very dense and very loose particle distributions, respectively. Hume (1996) assumed that in filters with the maximum density only very dense arrangements exist and pore size (DcD) is defined as the diameter of the largest circle that can fit within filter three-dimensional particles which is defined by the following Alpha formula:

$$\left(\frac{2}{D_1}\right)^2+\left(\frac{2}{D_2}\right)^2+\left(\frac{2}{D_3}\right)^2+\left(\frac{2}{D_{CD}}\right)^2=$$
$$0.5\left[\left(\frac{2}{D_1}\right)+\left(\frac{2}{D_2}\right)+\left(\frac{2}{D_3}\right)+\left(\frac{2}{D_{CD}}\right)\right]^2 \qquad (1)$$

But real filters are never densed to the maximum value suggesting that the most dense pore model is conservative. In very loose condition, filter particles are located in quadripartite groups as shown in Fig. 2.

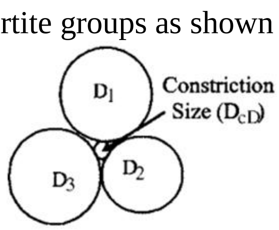

Fig. 1. Filter particle arrangement in very dense condition

For general arrangement of the particles, pore space between the four particles (Sc) is expressed by Silveria (1975) as follows:

$$Sc = 1/8[(D_1+D_2)(D_1+D_4)\sin\alpha + (D_2+D_3)(D_2+D_4)\sin\gamma - (\alpha D_1^2 + \beta D_1^2 + \gamma D_1^2 + \delta D_1^2)] \qquad (2)$$

γ, β and δ can be written in terms of α for the planar geometry. For known α value and maximum Sc, equivalent pore in a very loose arrangement of particles in terms of equivalent diameter, DCL would be as follows:

$$D_{cL}=\sqrt{\frac{4\,S_{c,max}}{\pi}} \qquad (3)$$

Frequency of D_{cL} or D_{cD} occurrence depends on the specific conditions of the constituent particles situations in the arrangement and can be calculated statistically (Silveiya 1975). If filter size distribution curve is divided up to the number of existing particles' sizes described previously, D_{cL} and D_{cD} and their corresponding probabilities could be determined for all unit particle combinations in very loose and very dense conditions that the CSD very loose and very dense models are resulted.

Some researchers use the densest CSD for the simplicity. Particle size distribution (PSD) of filter on the basis of mass or the number of particles can also be applied. However, as described by Locke (2001) although the filter PSD on the basis of mass, which is obtained from sieve test is a good representative of CSD for uniform filters,

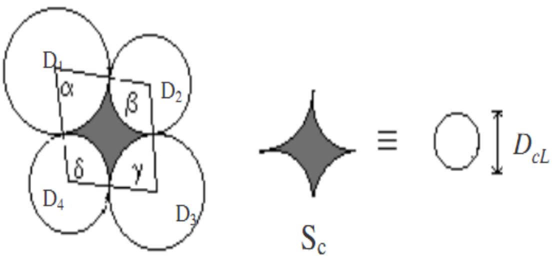

Fig. 2. Filter particle arrangement in very loose condition

but using PSD on the basis of mass instead of CSD in well-graded filters is accompanied with error. This is because large particles with high mass but small number play a significant role in PSD curve. But the chance for the three big particles to be in contact with each other to form a large pore is low. Similarly, using PSD based on the number of particles makes small pores more dominant. Hume (1996) suggested that despite the small number of large particles, due to the larger surface a more contact with other particles exists, and showed that filter PSD based on surface area is a better criterion for the analysis.

If the filter material consists of a combination of D_1, D_2, D_3,..., D_n diameters and their mass frequency would be pm_1, pm_2, pm_3,..., P_{mn}, respectively, the relative frequency based on surface area (PSAi) by Hume (1996) is obtained by using the following formula:

$$P_{SAi} = \left(\frac{p_{mi}}{D_i}\right)/\left(\sum_{i=1}^{n}\frac{p_{mi}}{D}\right) \tag{4}$$

Most likely, the actual filters stand between two extremes of very loose and very dense. Regardless of using mass, number or surface area for calculating CSD, the actual pore size (D_c) for each relative density (RD) using Luck (2001) method is calculated according to the following formula:

$$D_c = D_{cD} + P_c(1 - R_d)(D_{cL} - D_{cD}) \tag{5}$$

3. Description of the investigation

3.1. Built filter device and material properties

Along with the purposes of this study, an experimental filter device with the capability of exerting controlled hydraulic gradient was designed and built by the authors. Filter test device is similar to Sherard 1 and Dunnigan 2 devices in architecture (Sherard et al. 1985). The device chamber is made of a Plexiglas cylinder with internal diameter of 140 mm, height of 350 mm and thickness of 5 mm by the capability to withstand up to 600 KPa pressure. To measure the pressure, pressure gauges are installed at the top and bottom of the chamber that make it possible to calculate the hydraulic gradient every moment in the chamber and through the soil. A water pump is used to provide the required head and a pressure reduce device is installed at flow entrance to exert a controlled head to the chamber. It makes it possible to exert different and controlled hydraulic gradients to the chamber and finally, critical hydraulic gradient could be calculated through the calculation of the amount of soil eroded in specific time intervals and known hydraulic gradients. A general schematic of the filter device is shown in Fig. 3.

To investigate the effect of effective pore size of the filter and uniformity coefficient on the maximum erosion and critical hydraulic gradient in dispersive and non-dispersive samples, filter tests by using four different filters were carried out on two highly dispersive and non-dispersive soil samples.

Fig. 3. Schematic view of the built filter device

The main characteristics of the used filters were different uniformity coefficients (cu) and similar D_{15} values (D15 is a diameter of filter particles that 15% of the filter particles are smaller than it). Filter grading curve and base soils used are shown in Fig. 4 on the basis of the particle mass.

Grading curve was also calculated based on the particles' surface area and pore size distribution of the filters using the method described in section 2. Fig. 5 shows the grading curves of the filters based on the particle surface area along with the pore size distribution of the filter.

Base soils characteristics are given in Table 1.

Filter material characteristics are given in Table 2.

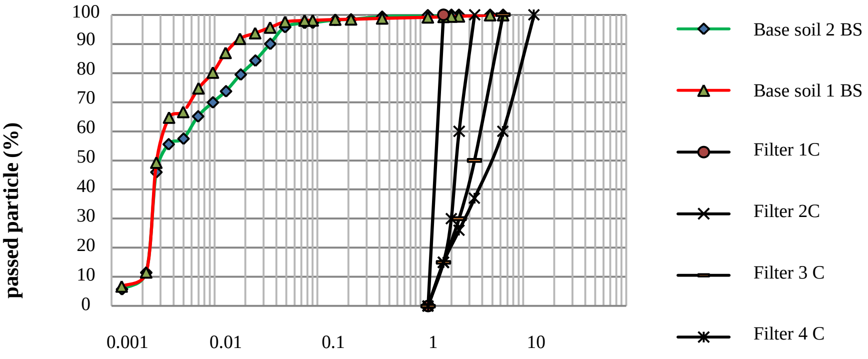

Fig. 4. Grading curve of the used filters and soils

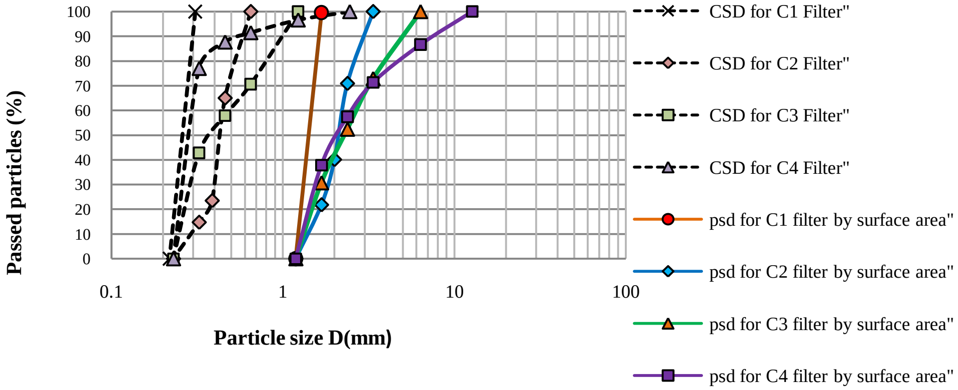

Fig. 5. Filter particles and pore size distribution based on surface area

Table 1. Base soils characteristics

Base soil 2	***Base soil 1***	**characteristic**
50	48	LL (%)
33	34	PL (%)
17	14	PI (%)
2.74	2.75	GS (t/m^3)
CL	CL	USC Classification
D1	ND2	Dispersivity in Pin-Hole test

Table 2. Filter material characteristics

D_{C35}	GS (t/m^3)	Relative density Dr (%)	Uniformity coefficient	filter
	2.67	80	1.33	C1
	2.67	80	1.59	C2
	2.67	80	2.67	C3
	2.67	80	4.33	C4

3.2 Determination of the Critical Hydraulic Gradient

To determine the critical hydraulic gradient in the soil filter system, after arming the device as shown in Fig. 3 and establishment of the flow, input flow head will be gradually increased from 0.5 to 4.8 bars in 1 minute time intervals and both pressures in top and bottom of the chamber are recorded at a constant head to determine pressure changes along the sample. By dividing head changes (m) on the sample length (m), the hydraulic gradient is calculated along the sample. Each head is kept constant for 1 min and the output flow for every constant head is collected in a separate marked container. Water containers are left 24 hours to let the water settle completely. The upper water is removed by a syringe and the containers are transported to the oven to dehydrate completely. The amount of eroded soil per head is weighted by a careful balance and recorded to determine the amount of eroded soil per head. By drawing the hydraulic gradient changes versus erosion rate changes (gr/lit.min), the gradient in which the maxi-mum erosion occurs is introduced as the critical hydraulic gradient.

Hydraulic gradient changes versus erosion rate changes for BS1 non-dispersive and BS2 dispersive samples are shown in Fig. 6 and 7, respectively.

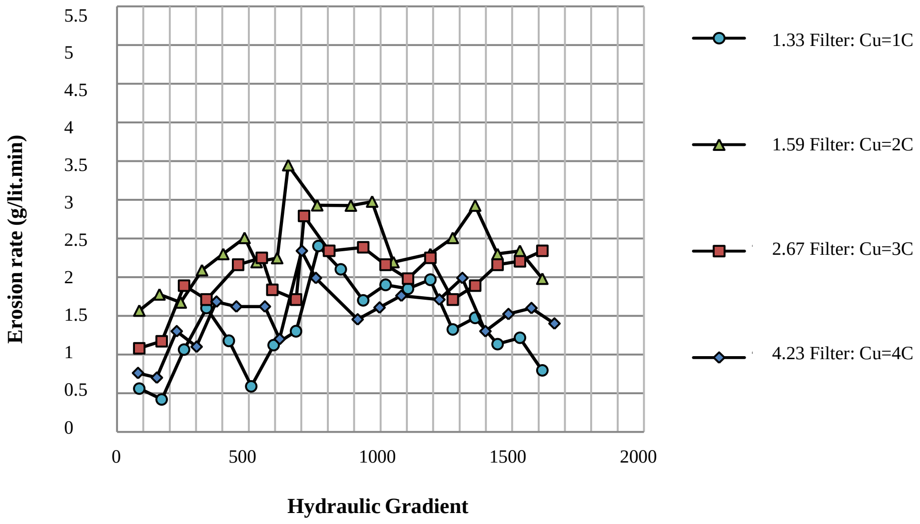

Fig. 6. Changes of erosion rate versus hydraulic gradient of BS1 base soil with different filters

4. Results Analysis

Unlike the expected amount of erosion to increase with the hydraulic gradient and the maximum erosion rate occurring in highest hydraulic gradient, it can be seen from Fig. 6 and 7 that by increasing the hydraulic gradient, erosion rate changes does not follow a regular trend. But in all the experiments by increasing the hydraulic gradient, a jump increase of erosion rate occurs in a certain amount so that the erosion occurred in higher gradients is less than this value. In other words, the maximum erosion occurs in a specific hydraulic gradient which is called the critical hydraulic gradient. Erosion rate in critical hydraulic gradient increases suddenly which implies yielding the soil particles' strength against erosion.

In both dispersive and non-dispersive samples by changing the uniformity coefficient of the filter, erosion rate and critical hydraulic gradient changes for all gradients. For BS2 dispersive sample, the filter with uniformity coefficient of 1.33, the least erosion occurs during the test. By increasing the uniformity coefficient to 1.6, maximum erosion is observed and then by increasing uniformity coefficient up to 2.67 and 4.23, erosion is decreased. According to Fig. 8 that shows the critical hydraulic gradient by increasing uniformity coefficient of the filter for BS2 dispersive sample schematically, maximum critical hydraulic gradient occurs in uniformity coefficient of 1.33 and minimum critical hydraulic gradient occurs in uniformity coefficient of 1.6. Then by increasing uniformity coefficient to 2.67 and 4.23, critical hydraulic gradient increases.

The process is the same for the maximum erosion that is shown in Fig. 9. It can be stated that for a determined uniformity coefficient the filter shows the best performance that should be determined by filtration test.

Non-dispersive BS1 sample shows a similar behavior to BS2 dispersive sample that is schematically shown in Fig. 10 and 11.

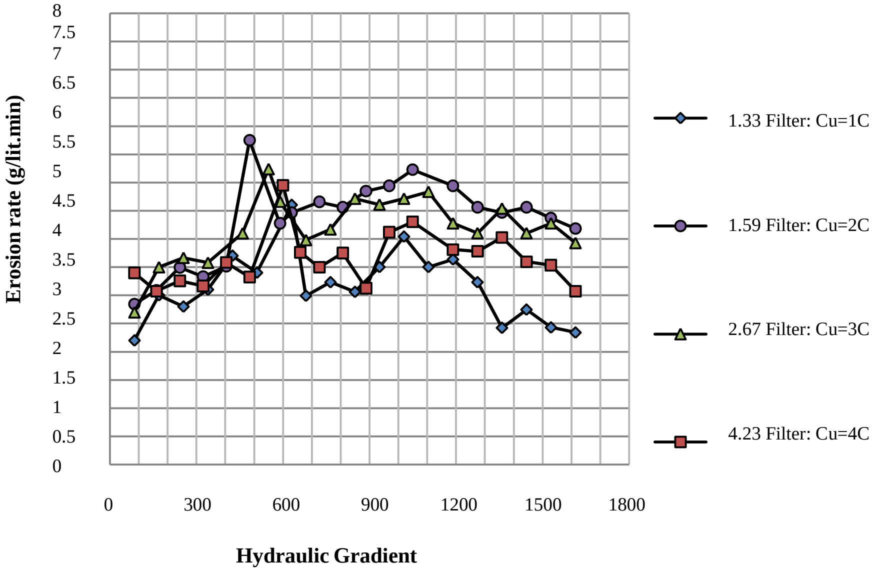

Fig. 7. Changes of erosion rate versus the hydraulic gradient of BS2 base soil with different filters

Despite the better performance of the filter by increasing the uniformity coefficient from 1.59 to 4.23, the filter performance in all these cases is weaker than cu=1.33 case. Generally, no regular relationship between uniformity coefficient of the filter and filter performance was observed in this study. The only difference between dispersive and non-dispersive samples is that the overall erosion in dispersive samples is more.

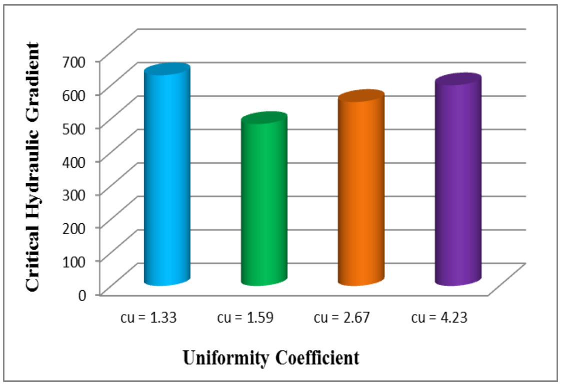

Fig. 8. Changes of Critical hydraulic gradient by increasing uniformity coefficient of the filter for BS2 dispersive sample

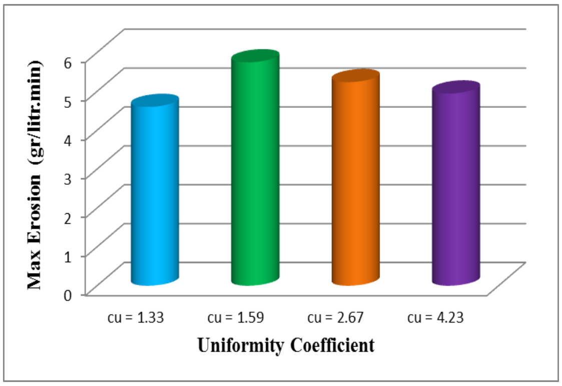

Fig. 9. Changes of the maximum erosion by increasing the uniformity coefficient of the filter for BS2 dispersive sample

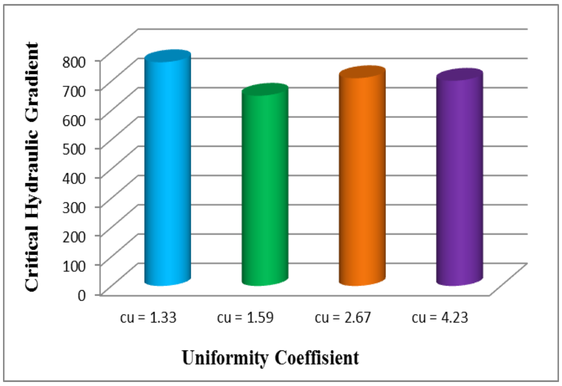

Fig. 10. Changes of critical hydraulic gradient by increasing the uniformity coefficient of the filter for BS1 non-dispersive sample

Effect of the pore size distribution of the filter

Uniformity coefficient effect on the performance of C series was described. To justify the performance of these filters, pore size value of C series filters was calculated by the method described in section 2. Pore size distribution curve of these filters are drawn as Fig. 5 to investigate the effect of filter pore size on their performance.

Considering Dc_{35} (a hole diameter that 35% of the filter pores are smaller than it) as the effective filter pore, it is observed that according to Fig. 5, c1, c4, c3 and c2 filters have the minimum D_{c35} value, respectively. Variations of the critical hydraulic gradient into D_{c35} changes for C series filters and Ba3 dispersive sample are plotted in Fig. 12. It can be seen that by increasing Dc_{35}, the critical hydraulic gradient decreases. The reason is that by increasing Dc_{35}, filter resistance against erosion decreases so the maximum erosion of the base soil occurs at the lower hydraulic gradient.

Also, maximum changes of erosion by increasing the amount of D_{c35} are shown in Fig. 13. This figure shows that by increasing D_{c35}, maximum erosion that occurs in critical hydraulic gradient increases because filter resistance against erosion decreases due to increasing the effective pore diameter.

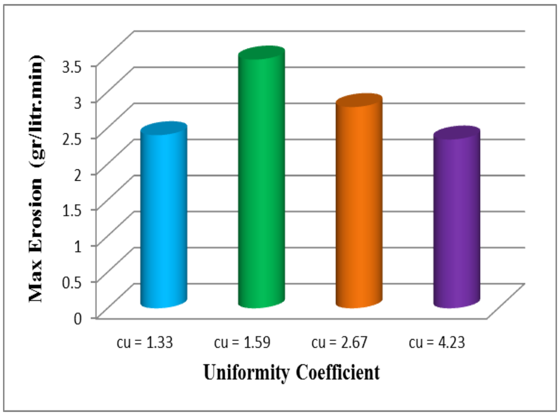

Fig. 11. Maximum erosion by increasing the uniformity coefficient of the filter for BS1 non-dispersive sample

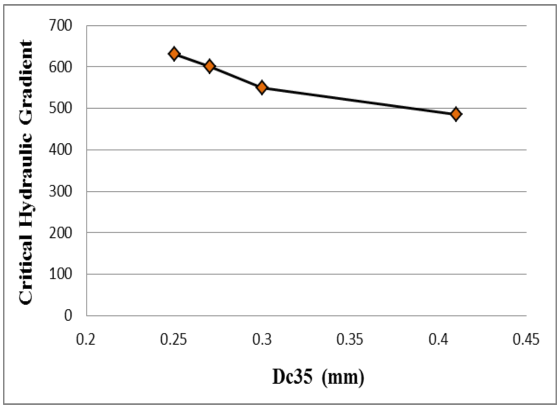

Fig. 12. Changes of critical hydraulic gradient by increasing D_{c35} of the filter for BS2 dispersive sample

As can be seen from Fig. 14 and 15, the process is the same for Bs1 non-dispersive sample and increasing effective pore size of the filter in two dispersive and non-dispersive samples has a similar effect on filter performance, except that the erosion is much greater in dispersed soils.

So, the contradictory behavior of filters with different uniformity coefficients could be justified as their behavior is dependent upon D_{c35} value prior to their uniformity coefficient. In fact, the base soil around the filter with lower D_{c35} yields against erosion in higher hydraulic gradients and the maximum

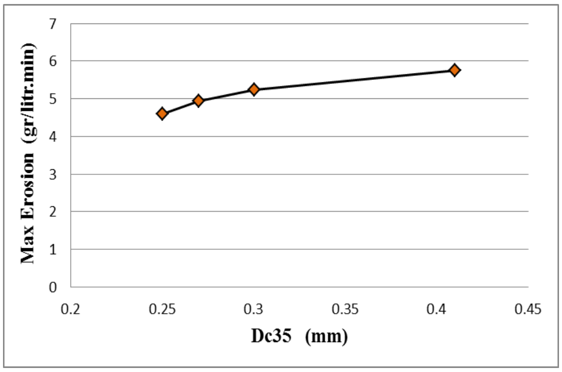

Fig. 13. Changes of the maximum erosion by increasing the D_{c35} of the filter in BS2 dispersive sample

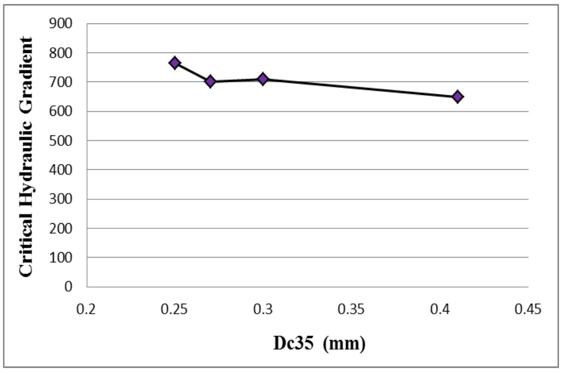

Fig. 14. Changes of the critical hydraulic gradient by increasing D_{c35} of the filter in BS1 non-dispersive sample

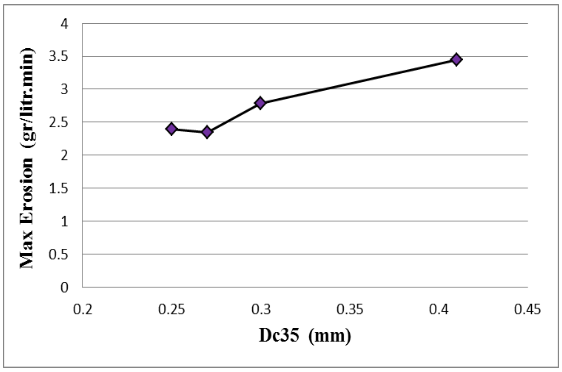

Fig. 15. Changes of the maximum erosion by increasing D_{c35} of the filter in BS1 non-dispersive sample

amount of erosion is also less. So the reason for the lower erosion rate of c1 filter with uniformity coefficient of 1.33, and higher erosion rate in c2 filter with uniformity coefficient of 1.6 comparing to c3 filter with uniformity coefficient of 2.67 and c4 filter with uniformity coefficient of 4.23 is related to the difference in D_{c35} size of these filters. This is true for both dispersive and non-dispersive samples. Although a higher erosion rate occurs in the dispersed samples, but has a similar behavior to non-dispersive sample against D_{c35} changes.

5. Conclusion

By changing the uniformity coefficient of the filter in CEF test, critical hydraulic gradient and maximum erosion rate changes. It can be said that for a specific uniformity coefficient, the filter has the best performance and it should be determined by the filter test. In fact, no regular relationship between the uniformity coefficient of the filter and its performance was observed. In filters with different uniformity coefficients for all dispersive and non-dispersive samples, by increasing the effective pore diameter of the filter, D_{C35} the critical hydraulic gradient decreases and the maximum erosion increases. In fact, performance of the filters with different uniformity coefficients is better justified on the basis of the effective pore diameter of the filter (DC_{35}) and the filter with smaller effective pore diameter has a better performance.

References

Esmaeeli, D. Evaluation of the diagnostic criteria of the clay soils' dispersal using chemical tests, M.Sc. thesis, Azad university of Zanjan, Zanjan, 1388.

Iranian National Committee on Large Dams, Committee of materials for embankment dams, identification and application of dispersive soils in 8 embankment dams, 1375 issue.

Foster M., & Fell R., Attachment 5: White paper No.2-The Internal Erosion and Piping Process, ASDSO – FEMA WORKSHOP, 2000.

Humes, C. 1996. A new approach to compute the void-size distribution curves of protective filters Proc., GeoFilters ’96, J. Lafleur and A. L. Rollin, eds., Bitech Pub., Montreal, 57– 66.

Indraratna, B., and Locke, M. 2000, Analytical modeling and experimental verification of granular Filter behavior. Keynote paper, Filters and drainage in geotechnical and geo-environmental engineering, W. Wolski and J. Mlynarek eds., Balkema, Rotterdam, The Netherlands, 3–26.

Kohler , H. J.(1993) The influence of hydraulic head and hydraulic gradient on filtration process, Filter in Geotechnical and hydraulic engineering, Germany, pp.225-240.40

Locke, M., Indraratna, B., and Adikari, G (2001). Time-dependent particle transport through granular filters. J. Geotech. Geoenviron. Eng., 127 (6), 521–529.

MlynarekJ. (2000) Geo drains and geo filters-retrospective and future needs, in filters and Drainage in Geotechnical and Environmental Engineering in the 3rd International conference: geofilters 2000, pp27-47

Raut, A. K., and Indraratna, B. 2004, Constriction size distribution of a non-uniform granular filter. Proc., 15th South East Asian Geo-technical Conf., Bangkok, Thailand, 409– 414.

Sherard, J. L.,Dunnigan, L. P. (1985) Filters and leakage control in embankment dams, Proceedings of a Symposium on Seepage and Leakage from Dams and Impoundments. (Volpe, R.L. and Kelly, W.E. (eds)), ASCE, 1985, pp. 1-30.

Silveira, A., de Lorena Peixoto, T., Nogueira, and J. 1975. On void size distribution of granular materials. Proc., 5th Pan-American Conf. of Soil Mechanics and Foundations Engineering, 161–176.