Assessing the efficiency of filters protecting base soil subject to erosion

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ABSTRACT: Dams filters are mainly designed using filter criteria based on the grain size distribution (Sherard & Dunnigan, 1985). This paper reports experimental results obtained on the soil-filter system behaviour subject to different hydraulic and geometrical conditions. A silt soil and three sandy gravels were used as the core and different filters (F1, F2 and F3), respectively. The objective of this study was to determine the effectiveness of the filter to protect the silt submitted to erosion under controlled water flow (horizontal and vertical configurations). Particles transport and filtration through each granular filter were analysed as regards to filter retention capacity, particles size selection and grains shape. This study was achieved by conducting a comparison of the behaviour of the three filters against the silt erosion. A comparison of the efficiency of the filters is assessed toward the required usual relationship criterion and the most appropriate for the dam filters.

1 INTRODUCTION

In embankment dams, failures mainly occur due to over-topping or piping and leakage. These failures occur due to inadequacy in construction techniques, quality of material selected, differential settlements, and inadequacies in the design. Dams suffering erosion are usually designed without filters or with non adequate filters. The soil erosion involves the detachment, transport and likely deposition of finer particles though the matrix pores, which are formed by coarser particles. This process affects the stability of the hydraulic structures and leads to permeability reduction of the filter devoted to its protection. Filters are a permeable layer where water flows through it (porous medium). In general, protection of cohesive base soil using granular filters involves a complex process of particles erosion, transport and capture within the filter. Deposited particles within the filter are likely removed by stronger seepage which leads to further increase of permeability and to instabilities at particle scale. Many studies were devoted for evaluating the likelihood of internal instability in the core of dams (base soil) and many criteria were suggested in order to limit soil erosion. There have been a number of experimental and theoretical studies interested in the design of filter criteria for dams. The main filter design criteria are empirical relationships based mainly on the representative size d_{85} (85% finer than 75µm) of the soil to protect and the opening of filter pore D_{15} (sieve size for which 15% of the weighed filter material is finer), suggested for the first time by Terzaghi (1940). The design criteria for critical filters recommended by Sherard & Dunnigan (1985) depends only on the grain size of the impervious soil and are independent of the plasticity and the dispersion potential of the soil fines. Kenny & Lau (1985) suggested a graphical method to asses the susceptibility of a soil to internal erosion based on a method of describing the shape of the grading curve of the soil. The postulated boundary between stable and potentially instable grading curve was defined as $H/F = 1.3$. The empirical criteria describing the importance of the grain size in the design of granular filter was improved by different authors like Vaughan & Soares (1982), Sherard & Dunnigan (1985), Kenney & Lau (1985) and recently Reddi et al. (2002, 2005), Correia et al (2014), Correia et al (2015). A correctly designed filter must retain loose soil particles and thus prevent piping, while it will be able to allow seepage water and avoid the development of high internal pore pressures (Kenney & Lau, 1985; Benamar, 2013). The hydraulic gradient has, on the other hand, an important influence on the erosion of base soil. If the applied hydraulic gradient exceeds a critical value it may break the arching of particles in the cracked zone. Vaughan & Soares (1982) proved that the principle of the perfect filter cannot necessarily be applied if a clay soil is dispersive, since the smallest clay particles might not be filtered by the finest cohesionless filter. Based on the test results Fellow et al (1991), described that for the range of plasticity investigated ($13 < IP < 21$), the weathered clay shale with the lowest plasticity was the most susceptible to piping but plasticity had no apparent influence on the resistance to internal erosion. Delgado et al (2012) conclude that the base soil plasticity has influence in the boundary filter, but it is not as important as the base soil particles size distribution. Multiple lines of defence were considered necessary by Sherard & Dunnigan (1985), one of them, is the use of plastic clay for impervious core, believed to be more resistant to erosion of concentrated leaks. The criteria for the no-erosion boundaries proposed by Foster et al (2001), have shown that other factors such as clay content influence the no-erosion boundary. In an intact condition, Fellow et al (1991), proved that compaction reduces the potential for piping significantly. They shown that the moderately plastic clay core did not pipe until $40 < i < 80$, when the clay was compacted 1% dry of optimum at 95 % standard Proctor energy, and until $160 < i < 240$, when the compaction energy was increased to 100 % of standard Proctor.

2 OBJECTIVE OF THE RESEARCH

In order to design a filter it is recommended to consider the most critical situation, the presence of a concentrated flow through the fine soil (dam core). In this case the particles are eroded when the hydraulic load exceeds the critical value of shear stress of the internal surface cracks. To attempt to explain some of the changes occurring during filtration for a range of hydraulic conditions, the processes of particles detachment and their filtration may be dissociated. This paper describes a laboratory program which separately examines the processes of erosion of cohesive soil at high pressures, resulting in high shear stresses, and filtration operated by a granular filter. Thereafter, laboratory erosion-filtration tests have been conducted applying two flow directions (horizontal and vertical).

This paper is addressed in the following order:
(i) erosion (hole erosion test) results of a representative base soil, (ii) experiments combining base soil erosion with several filters (either horizontal and vertical flow) are used to study the extent to which internal erosion is minimized from the soil protected by a filter, (iii) behaviour of soil filters and the effect of particles shape. In the final section, the results of the experiments are discussed and interpreted to develop the final recommendation for most appropriate filter. Specifically, the complete problem of particles detachment from silt soils and the filtration of eroded particles in the downstream filter are addressed in this paper.

3 EXPERIMENTAL SETUPS

In order to achieve the skills of this study, two appropriate laboratory devices (erosion-filtration cells) are designed to carry out the test program. Experiments were so conducted using two apparatus (Figs. 1, 2) to simulate the interaction between erosion of a base soil and a downstream filter. These test series were conducted at constant hydraulic gradient. The first kind of tests were performed is horizontal flow (Fig. 1) with a small cell; and the second one consisted of No Erosion Filter (NEF) tests proposed by Sherard and Dunnigan (1985), which is the most commonly used test for cohesive material. Figure 2 illustrates the NEF test apparatus (Sherard & Dunnigan, 1985).

3.1 *Hole erosion-Filtration cell (horizontal flow).*

The apparatus (Fig. 1) consists of a transparent Plexiglas cell with 60 mm inside diameter and 100 mm length. The column is filled in a vertical position by successive layers of materials (base soil and filter). The filter (60mm thin) is made of sand the base soil (15mm thin) is made of silt. After the installation of the filter downward the cell, the base soil is compacted on front of the filter. The upstream remaining volume of the column is filled with glass beads to ensure a homogeneous distribution of the flow in the cell. The sample is then saturated under a low hydraulic load, avoiding the disturbance of the porous medium before the start of test. The experimental device is composed of a water tank, a pump and two piezometric outputs for controlling the hydraulic gradient in the cell. The outlet of the column is directed to a turbiditymeter whose readings were previously correlated with fines concentration. The eroded mass can also be deduced from measured outlet concentration through flow rate data. The sensors are connected to the data acquisition unit controlled by a computer.

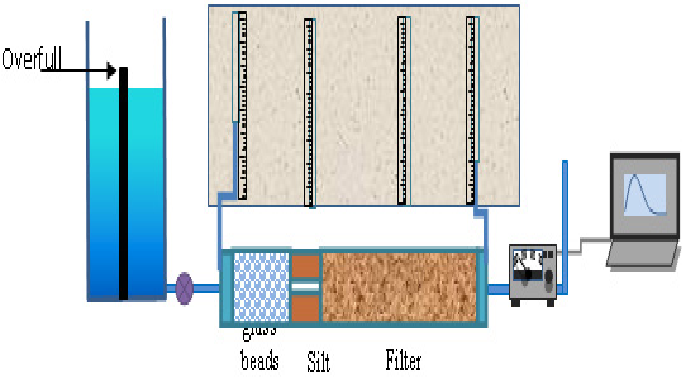


Figure 1: Experimental setup of horizontal flow tests.

3.2 *No Erosion Filter (NEF) apparatus (vertical flow)*

The device used for erosion test in vertical flow conditions is already described by Sherard & Dunnigan (1984) for the No Erosion Test (NET). It is devoted to simulate the filtration of cohesive soils in granular filter with the presence of a crack. The apparatus is shown schematically in figure 2. The so-called NEF test (No Erosion Filter) uses a permeameter (cell made of Plexiglas) which is 140 mm of diameter and 280 mm high. Within the cell a sample of base soil (representing the core) of 25 mm thickness is compacted above the layer of granular filter (150 mm thickness) previously selected. A 10 mm diameter pinhole was drilled through the base soil in order to induce a concentrated flow through the hole towards the filtering layer. The cell was connected to a water supply which provides a selected pressure in a range from 25 kPa to 120 kPa corresponding to the hydraulic gradient range from 9 to 45 m/m, respectively. The cell is equipped with a pressure gauge and the outlet is directed to a turbidity meter and a flowmeter providing continuous record of measured values. A flow induced with a very low pressure is applied trough the soil-filter system and once saturation reached, the water pressure is increased gradually by steps corresponding to selected pressure test values. A particle concentration is derived using a previous correlation between fines concentration and turbidity (NTU). The performance of the soil-filter combination is observed during a processing time close to 10 minutes.

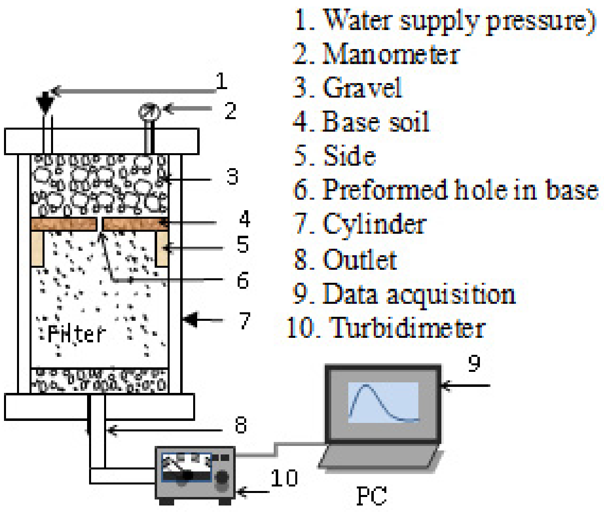


Figure 2: Vertical cell of No Erosion Filter (NEF) test.

4 MATERIALS

The base soil is silt collected from Jossigny (France). The particles size ranges from 0.5 µm to 120µm (Fig. 3). The geotechnical characterization provides a liquidity limit of 37 % and a plastic index Ip = 20, while vane shear test indicates a shear resistance of 4 kPa. According to ASTM standards, this fine soil was classed as a very plastic soil and as lean clay. According to Sherard & Dunnigan (1985) criterion (Tab.1) and used fine soil, three filters are selected for this study: a finer one (F1) and two coarser filters with same grading but with grains of angular shape for filter F2 and rounded shape for filter F3. The particle size distribution of the materials is shown on Figure 3. The used base soil belongs to the group 1 defined in Table 1.

4.1 *Review of existing criterion for design granular filters*

The Sherard & Dunnigan (1985) filter study has been extensively reported in papers and criteria documents of various researches (Fellow et al, 1991; Delgado et al, 2005; Delgado et al, 2012). Foster et al (2001) proposed criteria of No Erosion Boundary Filter Tests for assessing the design of filters of existing Dams. In this criterion the soil group 2 and 4 (Tab. 1) are modified from 40% passing 75µm, as recommended by Sherard & Dunnigan (1985) to 35% based on the analysis of the filter test data of Foster & Fell (2001). Table 1 summarizes the results defining the no-erosion boundary filter.

The parametric study from suggested criteria and used base soil (with d_{85} = 45.5 µm) involves filter samples which lead to the ratio (D_{15F} / d_{85}) of 5 in the case of filter F1 and 11 for both filters F2 and F3. The second filter F2 was selected after testing filter F1 which is find to be prone to suffusion and for improving its efficiency finer fraction (lower than 400µm) was removed and so filter F2 was designed. The third filter has the same grain size distribution than filter F2 (whose grain shape is angular) but rounded grain shape. The filter F1 has been used just with horizontal flow. During the test we observed that even the fine particles of the filter F1 are eroded under a high hydraulic load. Two filters (F1 and F2) are used in horizontal flow tests, while the filters F2 and F3 are tested in vertical flow conditions.

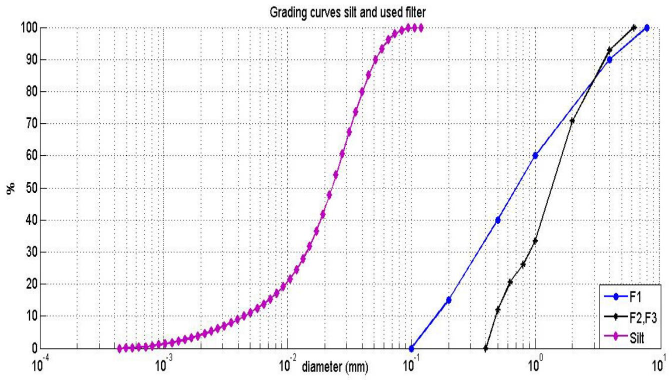


Figure 3: grain size distribution for different filters and silt.

Table 1: Summary results of filter criterion proposed by Sherard & Dunnigan (1985) and Foster & Fell (2001).

Base soil group	Fines content (passing 75 µm) (%)	Design criteria of Sherard & Dunnigan (1985)	Experimental range of DF15 for no-erosion boundary (Foster et Fell 2001)	Criteria for no erosion boundary filter (Foster & Fell 2001)
1	≥85	D15≤9d85	6.4d85-13.5d85	D15≤9d85b
2A	35-85	D15≤0.7 mm	0.7-1.7mm	D15≤0.7mm b
3	<15	D15≤4d85	6.8d85-10d85	D15≤7d85
4A	15-35	D15≤(40-pp%75µm) ×(4d85-0.7)/25+0.7	1.6D15-2.5D15 of Sherard & Dunnigan design criteria	D15≤1.6D15d, where D15d=(35-pp%75*µm) (4d85-0.7)/20+0.7

5 RESULTS AND DISCUSSION

Engineers often use the Unified Soil Classification system which is based on particle size grading, plasticity and organic matter content for estimation of the shear strength of the soil. These attributes are important for road and dam construction. In the first time we investigate the ease of initiating erosion in the base soil. For this purpose the relationship relating erosion rate to shear stress of base soil was assessed as recommended by Wan & Fell (2004). In the second time, the effectiveness of selected filters submitted to a concentrated leak was studied using a combination of erosion-filtration test within two different flow configurations.

5.1 *Erosion sensitivity of the base soil (silt)*

In order to investigate the erosion rate of the tested base soil, the apparatus showed on Figure 1 was used without filter in order to perform a Hole Erosion Test for studying the erosion of selected silt (Fig. 4). The investigation of the base soil erosion was performed according to Wan & Fell (2004) methods. The erodibility of a soil can be described in terms of behaviour with two aspects (Huang, 2014): The rate of erosion when a given hydraulic shear stress is applied to the soil, and the ease of initiating erosion in the soil. The linear model was extensively used (Bendahmane, 2006) by assessing a linear relationship between the rate of erosion and the applied hydraulic shear stress:

$$\varepsilon = C_e(\tau_t - \tau_c) \tag{1}$$

Where ε is the rate of erosion per unit surface area of the hole at a given time t (kg / s / m^2), C_e is the proportionality constant named the coefficient of soil erosion (s / m), τ_t is the hydraulic shear stress along the hole (N / m^2), and τ_c is the critical shear stress (N / m^2).

The critical shear stress τ_c (hydraulic shear stress corresponding to erosion initiation) can be obtained by extrapolating the regression line of the plot of ε versus τ to null value of ε. Figure 4 shows the variation of erosion rate with hydraulic load for Jossigny silt, leading to τ_c value close to 11 Pa and C_e value equal to 1.92×10^{-5} s/m. Wan & Fell (2004) suggested the use the Erosion Rate Index (I), defined as:

$$I = -\log(C_e) \tag{2}$$

The index I values range from 0 to 6 for the soils tested by the authors. A small value of I implies a more rapidly erodible soil. For the base soil used in this study the Erosion Rate Index value is close to 4.71. According to Wan & Fell (2004) guidelines, the silt tested provides an HET index value within the range 4 to 5 and so classified in soils group 4 with moderately slow erosion.

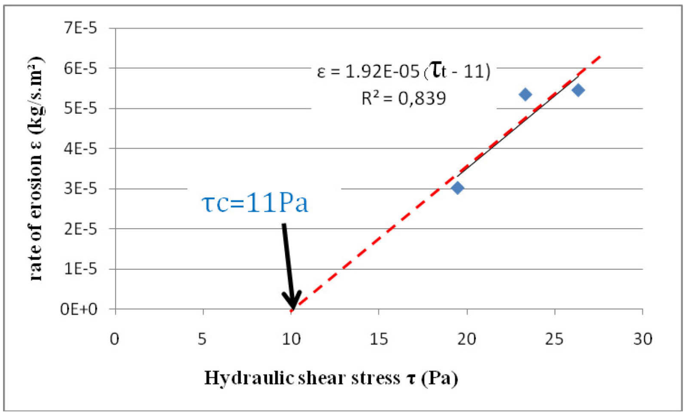


Figure 4: Evolution of erosion rate (ε) with hydraulic shear stress (τ).

5.2 *Effect of filter opening size on particles retention*

Two filters (a fine one and a coarse one) were tested downstream of eroded (hole erosion) silt. In order to investigate the beginning of internal erosion and to detect the initiation point and to carry out time-dependent measurements of the concentration of eroded matter a turbiditymeter was placed immediately at the outlet of the column, allowing continuous records. The first test was carried out with filter F1, and owing to its instability it was rapidly suffering suffusion since the applied hydraulic gradient exceeds the value 3 m/m. Then fine particles (< 180 µm) are released from matrix and transported to the outlet, reducing filter performance. A second filter F2 was so designed by removing fines (< 400 µm) susceptible to suffusion.

Figures 5 and 7 shows the variation of the records time for the outlet concentration in filters F1 and F2, respectively. The results describe a curve increasing rapidly to a maximum value which depends on the hydraulic gradient and a slow decreasing part before reaching a residual value of concentration. Figure 5 indicates that internal erosion depends strongly on the applied hydraulic load. For the same texture, when increasing the hydraulic load, the amplitude of the maximum concentration increases and the time associated with reaching the peak decreases. Thus, the curve obtained for the highest gradient (i = 9) has a steeper shape, while that obtained for the lowest gradient (i = 3.15) has a spread form.

The mass loss (cumulated eroded dry mass) was deduced using equation 3 (where Q(t) is the solid flow rate). The cumulative eroded mass is obtained from the time integration of the product of concentration and flow rate. The evolution of cumulated mass loss with time testing is shown on figures 6 and 8.

$$M_g = \int_{t=0}^{t} Q(t)dt \tag{3}$$

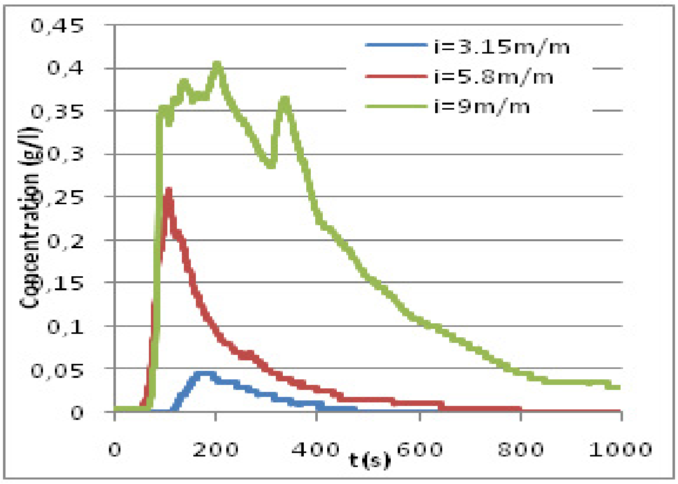


Figure 5: Concentration in of eroded particles filter F1.

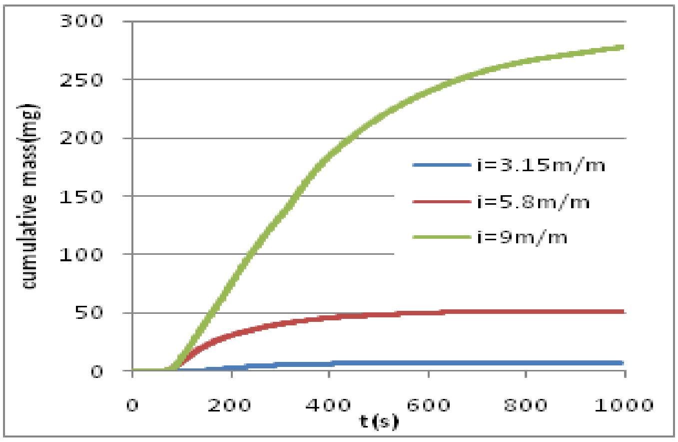


Figure 6: Cumulative mass of eroded particles with filter F1.

Figure 6 shows that the cumulative eroded mass increases with the applied hydraulic gradient. During the test, the diameter of the hole increases and as a result the lateral area submitted to erosion increases. The outlet concentration rises with gradient increase (Fig. 5). The increasing of gradient from 5 m/m to gradient 9 m/m produces a dramatically increase of the concentration which involves a high cumulated eroded mass (about 300 mg after 17 min testing) (Fig. 6).

The matrix of the second filter F2 (Fig. 3) corresponds to a sandy gravel with a grain size distribution ranging from 400 µm to 6300 µm, and designed to be stable. Although we started the test with a high gradient (i = 10.2 m / m), the maximal unfiltered concentration (Fig. 7) shows moderate values (from 0.5 g / l to 2.5 g / l) for tested gradients. The resulting cumulative mass increases from 100 mg to 450 mg (Fig. 8), in the same order as that occurring with filter F1 instead of the larger opening of filter F2. All the results underline a large difference of magnitude of erosion rate through cumulated mass loss, which vary from 300 mg in the filter F1 under a gradient of 9 m/m to 100 mg for a gradient of 10 in the filter F2 (Figs. 6, 8). So, filter F2 seems to be more effective and will be used in the vertical filtration.

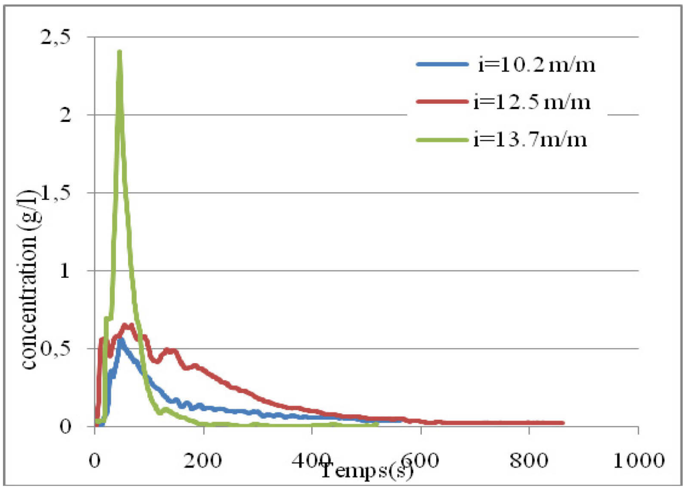


Figure 7: Concentration in of eroded particles filter F2.

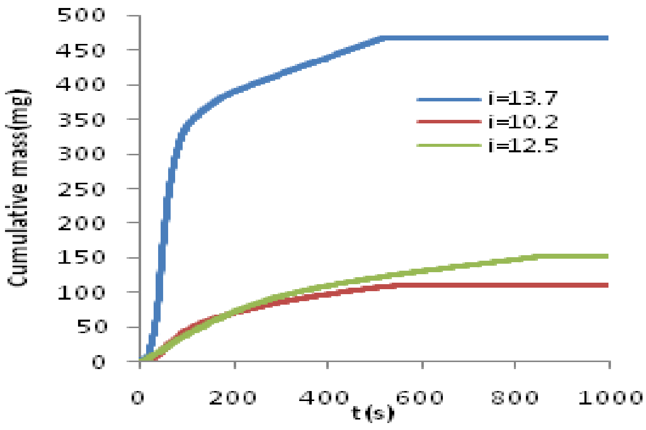
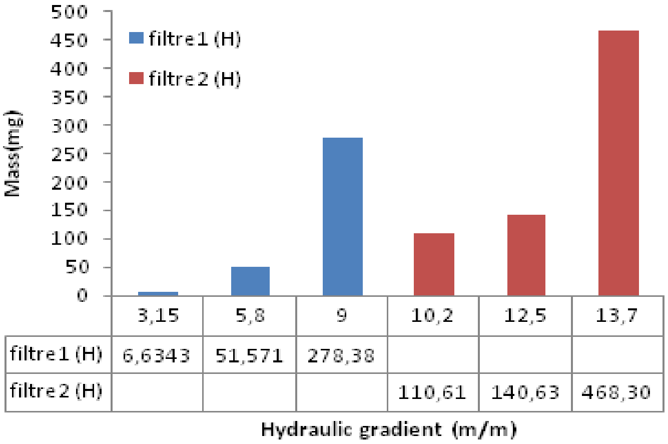


Figure 8: Cumulative mass of eroded particles with filter F2.

The diagram of Figure 9 illustrates the comparison of mass loss from both filters; Filter F2 retains more particles than F1 which allows large erosion. So, the remove of particles finer than 400 µm from the filter F1 provides a more effective filter F2 even if it is coarser.



	3,15	5,8	9	10,2	12,5	13,7
filtre1 (H)	6,6343	51,571	278,38			
filtre2 (H)				110,61	140,63	468,30

Figure: 9 comparison of eroded mass in filters F1 and F2 (horizontal flow).

The filter medium operates like a sieve with opening size that controls filtration against the base soil. Filter with larger opening size cannot prevent erosion of base soil. But the smaller opening creates a self filtering layer within soil particles, making a system stable (Nguyen, 2012). If we try to compare both filters used in the horizontal flow, we can conclude that the filter F1 has the smallest opening size but is the instable one. The smallest particles of filter F1 have a size of 100 µm, which is smaller than the largest particle (120 µm) of base soil.

5.3 *Non Erosion Filter results*

5.3.1 *Effect of hydraulic load on erosion progress*

In order to investigate the scale effect of erosion-filtration process, vertical filtration tests using downward flow were performed. A sufficient high-pressured flow through filter is rapidly applied from the top of the sample to examine whether the base soil is eroded. The sample was suggested to hydraulic gradient ranging from 9 to 45 m / m, with an increment of 9 m / m. The results are expressed as time-concentration evolution and cumulative eroded masse. In this case, the cumulative eroded mass decreases rapidly with increasing hydraulic gradient (Fig. 10) from 400 mg (for i= 9 m / m) to 50 mg (for i=45 m / m). The first load applied induces a detachment of a significant amount of particles, which decreases gradually with the increasing of hydraulic load. These results can be explained by the full saturation of the immediate ring close of the hole that makes the particles easily detachable, while following inner surface being not fully saturated is less prone to erosion. For which the inlet side is usually more eroded than the outlet side. One can note that enlargement of the hole is not uniform and is more important upstream of the channel.

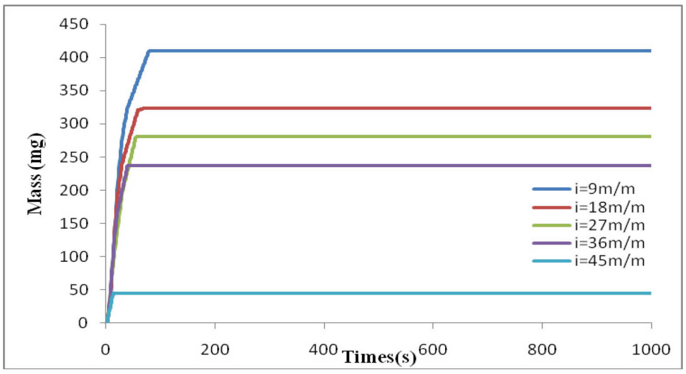


Figure 10: Cumulative eroded Mass in vertical flow (filter F2).

5.3.2 *Evolution of hydraulic conductivity*

After saturation of the filter in the cell, the measurement of the initial hydraulic conductivity is performed using a flow-meter placed at the outlet of the column. The hydraulic conductivity k is so deduced from flow rate measurement using Darcy's law:

$$Q = -k\frac{A\Delta h}{L} \tag{4}$$

$$\Delta h = Z + \frac{\Delta P}{\rho g^2} \tag{5}$$

Where z is a reference level, Q is the flow rate, ρ is the fluid density, A is the apparent area of the material and ΔP is the pressure drop. The hydraulic conductivity variation of filter F2 calculated in vertical flow (figure 11) indicates a decrease with increasing hydraulic gradient. The detachment of a large amount of particles from the hole inside surface and their partial filtration provides a significant pressure drop leading to drastic reduction of hydraulic conductivity when applying successive hydraulic gradients of 9 and 18. The hydraulic conductivity falls down after the second hydraulic load (i=18 m / m) before decreasing moderately at each following load. From the hydraulic gradient of 27 m / m, the hydraulic conductivity decrease remains of the same magnitude, leading to a stable residual value of hydraulic conductivity.

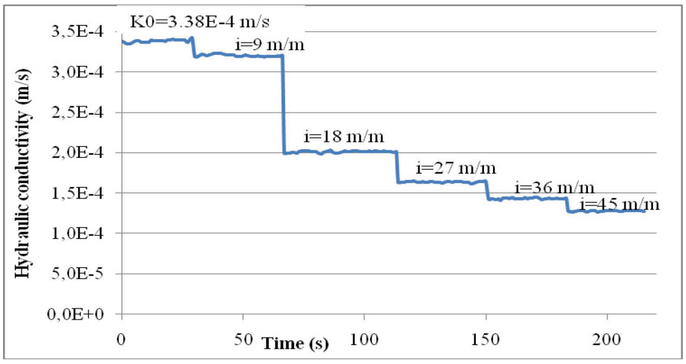


Figure 11: Hydraulic conductivity variation of filter F2.

5.3.3 *Particle size distribution of recovered particles from filter F2*

During filtration trapped and recovered particles depend on the relative size of flowing particles and filter opening (constrictions distribution and pore size). In order to investigate the qualitative performance of the filter F2, the particle size distribution (PSD) of filtered particles (in both upper and lower sides of the filter) and recovered ones at each hydraulic gradient at the outlet of the filter is carried out (Fig. 12). For filtered particles (dashed lines) it is shown that particles retained by the filter upstream are coarser than that retained downstream, as reported in several filtration studies (Reddi, 2002; Bradford, 2005; Benamar, 2009, 2013). As regards to the recovered particles (solid lines) PSD of recovered particles seems to have a similar shape and d_{90} size is the same in the different cases of water pressure. However, PSD of particles recovered under a gradient of 18 (second loading step) stands out from other curves, indicating the recovery of finer particles. The recovered samples are finer than the initial base soil. The effect of applied pressure is evident on the size distribution of recovered particles, since increasing pressure leads to recover coarser particles, at least during the two first hydraulic gradients. The size d_{50} of recovered particles is finer than that of collected ones from the filter (trapped particles). The analysis of the size distribution of retained particles within the filter at the end of the test shows that large size particles (coarse fraction) are retained by the filter. The grain size distribution of the filter material advocates the blocking of large silt particles in the voids formed by the matrix.

Based on the results of filter tests on uniform base soils, Sherard & Dunnigan (1985) conclude that uniform filters act similar to laboratory sieves, with an opening sieve size approximately equal to D_{15F} / 9. In Figure 13 PSD of recovered particles passing through the filter showed that more than 85 % of passing particles (30 µm < d_{85} < 50 µm) are finer than D_{15F} / 9 (56 µm). If considering the filtered particles, 30 % of them are larger than the opening size (56 µm) of the filter proposed by Sherard & Dunnigan (1985).

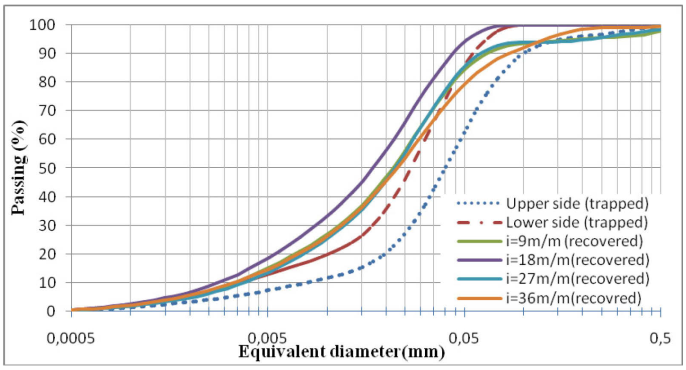


Figure 12: Particle size distribution of trapped particles (dashed lines) and recovered particles (solid line) in filter F2.

5.3.4 *Assessing filter criteria*

In order to assess the boundary between the stable and instable gradation of a filter used in this experimental investigation the criteria proposed by previous authors are evaluated by matching their predictions with these experimental results. The criterion of Foster & Fell (2001) for the No Erosion boundary filter suggested that for soil group 1 (fines content ranging between 85 % and 100 %), the experimental range of D_{15F} must be between 6.4 × d_{85} to 13.5 ×d_{85}. The used filter F2 was designed with $D_{15F} = 11 \times d_{85}$, which do not meet Sherard & Dunnigan (1985) criterion, but satisfy the No Erosion boundary filter criterion proposed by Foster & Fell (2001) (Tab. 1). Lafleur et al (1989) suggested a filter criterion with a coefficient of uniformity Cu less than 20 (Cu = 4 for the filter F2), that for a convenient permeability the relation $D_{15F} \geq 4 \times d_{15}$ must be achieved. The used base soil involves d_{15} size close to 7.3µm while the filter D_{15F} is close to 500 µm. These values show that they meet the above criterion.

The consideration of Sherard criterion (D_{15F} / d_{85} < 9) in the design of the two investigated filters shows that the filter F1 (D_{15F} / d_{85} = 5) which meets the above criterion shows some instability against internal erosion. In opposite, filter F2 (D_{15F} / d_{85} = 11) which do not meet the above criterion provides more filtration efficiency even if it is coarser. These results suggest the careful use of filtration criteria assessed for particular soils.

5.4 *Retention capacity*

Filters are provided in a dam to entrap base soil particles that erode and at the same time prevent the development of any high hydraulic gradients at the base soil-filter interface due to clogging. In order to study filter efficiency and to examine the way that the base soil is eroded, high hydraulic gradient was rapidly applied at the top of the sample. In order to assess a correlation between the both laboratory models (horizontal and vertical), non-dimensional parameters are needed. The retention capacity is defined as the ratio of retained mass by the filter and eroded one from the hole of the base soil. The second parameter used is the ratio between the retained particles volume and void volume of the filter. Although the tests are not performed under the same hydraulic gradients, the retention capacity results of retained particles to eroded one are detailed in table 2 for the case of vertical flow and table 3 for the horizontal one. The report was 0.93 (more than 90 %) in vertical flow for different gradient, while it does not exceed 0.75 (75 %) in the horizontal flow. The filter F2 was more efficiency in vertical flow conditions and obtained value of retention capacity are quite similar.

Previous tests reveal that particles under low flow velocity settle down very quickly resulting in severe and shallow damage to the filter (Reddi, 2002; Sharbaree, 2005; Benamar, 2006, 2013; Alem, 2015). Higher flow velocity can carry the particles further, thus the damage is averaged along the volume of the core leading to depth filtration. The mass multiplied by the shape factor indicate that vertical flow (338 for i = 9 m / m) caused more retained mass then those observed in horizontal flow (5.53 for i = 10.2 m / m).

Table 2: Retention capacity (vertical flow).

Vertical Flow				
i(m / m)	Retained mass (mg)	Eroded mass (mg)	Retention capacity	R_M*(1/15)
9	5827	409	0.93	338
18	8557	733	0.92	530
27	14938	1014	0.94	965

R_M is retained mass in the filter.

Table 3: retention capacity (Horizontal flow).

i(m / m)	Retained mass (mg)	Eroded mass (mg)	Retention capacity	R_M*(1/6)
10.2	331	110	0.75	5.53
12.5	845	251	0.86	14.09
13.7	1142	719	0.71	19.04

5.5 *Influence of the grain shape of the filter*

The detachment of fines particles and their transport throughout the filter is conditioned by the granular distribution, but also depend on the grain shape of the filter which appears as a key parameter of seepage flow in porous medium. The results reported by Benamar et al (2004, 2009) and Marot et al (2012) demonstrate that suffusion and deposition processes depend on the grain angularity which contributes to increase the suffusion resistance and high filtration. The results reported show that recovered mass is greater in the medium with rounded shape than in that of angular shape. They conclude that rounded shape eases the particles transport toward the outlet of filter and likely detachment of previous retained particles. It is evident that filter efficiency depends on the mutual relationship of a combination of many factors. The grain shape of the soil grains represents a great importance in the process of internal erosion and its control. In this way, in order to attempt to explain the effect of grain shape in the filtration mechanism, a third filter (F3) collected from Seine River (France) providing the same grain-size distribution that the filter (F2) but with rounded grains shape was selected (Fig.3).

5.5.1 *Effect on Hydraulic conductivity*

In order to match the variation of hydraulic conductivity with retained mass within the filter, the time-variation of the relative hydraulic conductivity (k/k_0) ratio is plotted against cumulative retained mass (Fig. 13). The results illustrate that once retained particles accumulate within the filter its hydraulic conductivity downfalls. The erosion of base soil clogs several pores and leads to a drastic reduction of hydraulic conductivity. Figure 13 shows that hydraulic conductivity reduction reaches 35 % and 40 % under a gradient of 18 m / m for the filter F3 and the filter F2, respectively. The effect of particles filtration on hydraulic conductivity reduction is due to successive deposition of particles within the filter and which are not detached by the occurring higher pressure. The decrease of hydraulic conductivity is related to the increase of retained mass within the filter. We can note that even if retained mass increases linearly with increasing hydraulic gradient the hydraulic conductivity seems to reach an asymptotic value after the hydraulic gradient of 27 m / m.

Comparing the filter F2 and F3, we can see (Fig. 13) that the filter F2 trapped more particles and his permeability reaches lower value compared to the filter F3.

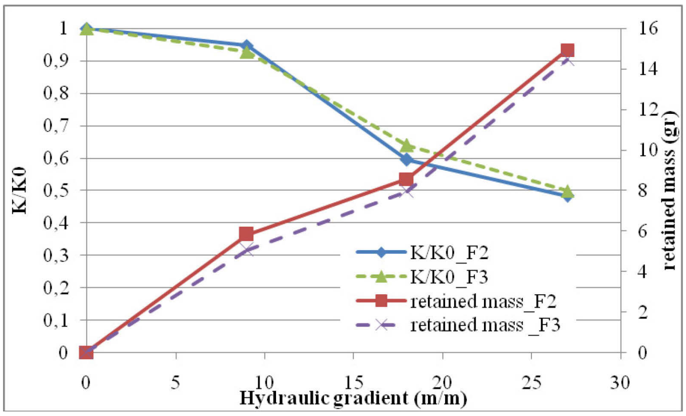


Figure 13: Relative hydraulic conductivity and mass loss versus hydraulic gradient during filter F2 testing in vertical flow.

5.5.2 *Grain size distribution of trapped and recovered particles from the filters*

Grain size distribution analysis was performed on samples of effluent collected at the end of each applied hydraulic gradient. Figures 14 shows that the comparison of grading of trapped particles within the upper side of the filters indicates that larger particles are better filtered in the granular matrix of filter F2 than in filter F3. This result is related to the narrow pores which can be formed by the angular grains of the filter F2. Figure 15 represents the grain size distribution of trapped particles within the lower side of the filters and the grain size distribution of recovered particles from each filter. The curves demonstrate that the modal diameter of the particles in the effluents (recovered particles) remains always smaller than that observed for the particles trapped in the lower side of the filter (dashed lines), indicating the filtration efficiency of used materials. The comparison of the size of eroded particles under a gradient of 9 m / m advocate the blocking of large silt particles in the voids formed by the grains.

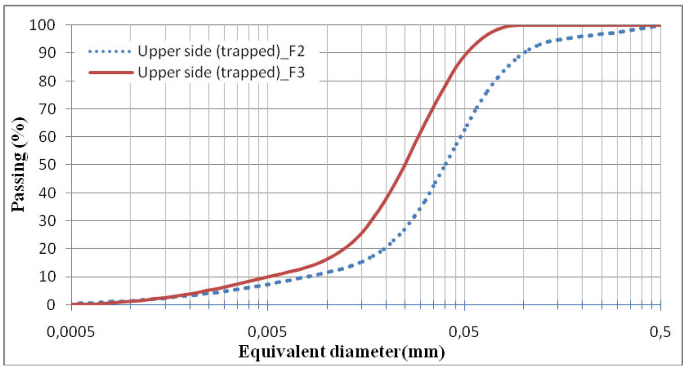


Figure 14: Particle size distribution comparison of trapped in the upper side of filter F2 and F3.

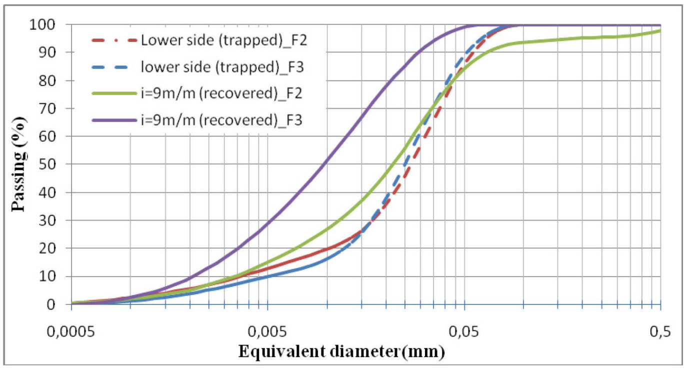


Figure 15: Particle size distribution of trapped in the lower side of filter F2 and F3and of recovered ones at a gradient of 9 m/m.

The table 4 presents the d_{85} from PSDs in the both filters (F2 and F3) of recovered and trapped particles and the ratio D_{15}/d_{85}. It is observed that the criterion $D_{15} / d_{85} \leq 11$applied in the design of both filters has been met with the filter F2 but not with the filter F3 which provides a ratio greater than 11 in the different cases. This result indicates that grain angularity contributes to increase filtration and so provides a high suffusion resistance.

Table 4: Comparison of the ratio D_{15}/d_{85} in filters F2 and F3 for trapped and recovered particles.

	Silt	Filter (F2)	Silt	Filter (F 3)
i (m / m)	d_{85}(µm)	D_{15}/d_{85}	d_{85}(µm)	D_{15}/d_{85}
9 (recovered)	51.37	10	24.70	20
18 (recovered)	40.24	12	33.57	15
27 (recovered)	51.37	10	33.57	15
36 (recovered)	65.58	8	35.62	14
Upper Side (trapped)	83.71	6	58.04	9
Lower side (trapped)	48.42	10	45.47	11

5.5.3 *Retention Capacity*

Particle movement in porous medium is a very complex process due to the complexity of porous medium network and forces governing particles movement. Retention capacity is defined as the ratio of retained mass by the filter and eroded one from the hole of the base soil. Table 5 summarized the retention capacity obtained for both filters F2 and F3. It is obvious that filter F2 has a high retention capacity (93 %) than filter F3 (81 %) for applied hydraulic gradient of 9 m /m. This result demonstrates that suffusion process within the filter depends on the grain angularity. With a same grain size distribution, angular shape of the grains contributes to the increase of the retention capacity of the filter.

Table 5: Effect of the gains shape on the retention capacity.

	Capacity of retention	
i (m / m)	FILTER F2	FILTER F3
9	0.93	0.81
18	0.92	0.86
27	0.94	0.91

6 CONCLUSION:

This study, devoted to investigate and attempt explaining many changes occurring during filtration for a wide range of hydraulic load. In order to get decoupled erosion and filtration in the first step, the processes of particles detachment from base soil and their filtration were dissociated. Two experimental devices (horizontal and vertical flow) have been used to study the coupling between the internal erosion process along a hole and the role of downstream filter. The predominant role of many parameters in the erosion process has been demonstrated in particular the hydraulic gradient whose effect is evident on the size distribution of recovered particles, since increasing gradient leads to recover coarser particles. The interaction at the soil-filter interfaces according to the characteristics of erodibility of the upstream soil was involved. It was found that filter efficiency depends on the relationship of a combination of many factors such as:

- The consideration of Sherard et al (1985) criterion ($D_{15F} / d_{85} < 9$) in the design of the two investigated filters shows that the filter F1 ($D_{15F} / d_{85} = 5$) which meets the above criterion shows some instability against internal erosion. In opposite, filter F2 ($D_{15F} / d_{85} = 11$) which do not meet the above criterion provides more filtration efficiency even if it is coarser. These results suggest the careful use of filtration criteria assessed for given types of soils.
- The grains shape of the filter material affects suffusion process in the way that this latter depends on the grain angularity of filter material. With a same grain size distribution, filter F2 with angular grains show more retention capacity than filter F3.

From obtained results, the main recommendation when designing filters is to be careful in the use of existing geometrical criteria which do not include hydraulics. So, filter performance defined in this study may be a key for evaluating the filter effectiveness using the laboratory erosion-filtration tests.

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