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Comparison of the behaviour of various geotextiles used in the filtration of clayey sludge: An experimental study

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Abstract

This paper presents the results of an experimental study of various geotextiles used to filter clayey sludge. The use of geotextiles to filter clayey sludge or suspensions of fine particles in water is more complex than that for filtering suspensions of granular soils. In practice, such applications generally use flocculants to postpone the formation of a low-permeability filter cake. The objective of the present study, which does not use flocculants, is to determine how geotextile characteristics affect the capacity of the geotextile to filter clayey sludge. Three key questions are addressed: (1) What are the main differences between vertical and horizontal filtration? (2) How do geotextile characteristics (nature, opening size, permeability, etc.) affect its capacity to filter clayey sludge? (3) How do clayey sludge characteristics (i.e., grain size distribution and concentration) and the type of flow (i.e., constant head or constant flow) affect the filtering capacity of geotextiles? To evaluate the capacity of a geotextile to filter clayey sludge, we propose three relevant criteria and analyse two filtration phases induced by different cake-formation processes (controlled by the geotextile and controlled by the filter cake). To determine the main differences between vertical and horizontal filtration, the settling of fines in the testing device and its influence on the results are analysed and discussed. This study shows that, for the various clayey sludge tested, the geotextiles (needle-punched nonwoven and thermally bonded nonwoven) with the smallest opening sizes ($O_{90} \leq 60$ μm) give the most promising results for filtering fines without the use of flocculants. Of these geotextiles, the thermally bonded nonwoven structure seems to offer the best filtration performance for the largest range of fines concentration in the sludge.

Keywords:

Geosynthetics, geotextiles, filtration, clayey sludge, fines, suspension.

1. Introduction

In many filtering applications such as in drainage systems, geosynthetics are in contact with the upstream soil, which may include fine particles. In typical applications of this type, the geotextile is confined between the upstream soil and the drainage layer and it helps to create an equilibrium with the upstream particles after limited washout of finer particles by inducing a self-filtration zone (bridging) at the interface between the geotextile and the upstream soil. In this case, the geotextile design is based on three criteria: (i) the geotextile must retain the largest particles and stabilise the skeleton, (ii) it must let the finer particles pass, and (iii) it must maintain a minimum permeability normal to the plane. In addition, some authors such as Giroud (1982), Bouthot et al. (2002) and Aydilek et al. (2005) consider that the number of constrictions of the geotextile influences its filtration behaviour.

Also in some filtration applications, geotextiles may also be placed unconfined with the upstream soil or in contact with soft, fine, saturated soils. In these cases, provided the soil is unconsolidated, the water flow may erode the soil and become charged with fines. With so many small particles in suspension, the geotextile filter cannot create the self-filtration zone described above. In the case of geotextiles with large opening sizes, the geotextile will let many fine particles pass into the drainage system, which in most cases resulting in clogging of the drainage system. The fine particles progressively accumulate at the surface and inside the geotextile, which leads to an increase in the water-head loss at the level of the geotextile by reducing the water flow through the geotextile. This process reduces the water velocity of the corresponding erosion and, consequently, of the number of fine particles in suspension that reach the geotextile. Understanding the process of fine-particle retention by a geotextile and predicting the critical water-head loss in the geotextile is thus of great interest. This phenomenon has been studied by several researchers such as Le Coq (1996), who proposed a model to describe the increase in head loss through a filter due to clogging and Faure et al. (2006), who proposed a method to predict geotextile clogging during filtration of suspended solids. This last study focuses on clay suspensions with very low concentrations (inferior to one gram per litre) and is extended by a very recent study conducted by Sabiri et al. (2017).

The capacity of geotextiles to filter fine particles in suspension is also exploited by environmental applications to dewater sludge. In this case, the sludge is typically introduced inside a geotextile tube or a container, which retains the solid fraction of the sludge and lets most of the liquid effluent pass through (Yee et al., 2012). Flocculants are generally necessary to postpone or avoid the formation of a low-permeability filter cake at the surface of the geotextile and to maintain the proper filling of the container by solid particles (Moo-Young et al. 2002; Muthukumaran and Ilamparuthi, 2006; Lawson, 2006; Delmas, 2007; Satyamurthy and Bhatia, 2009).

More rarely, in the case of draining mining sludge, geotextile filtration of fine particles in suspension without flocculants has also been studied. Recently, studies of filtering fine-grained mineral sludge confirm the feasibility of geotextile filtration for dewatering high-clay-content materials with low hydraulic conductivity (Bourgès-Gastaud et al., 2014). A major difference exists between (1) classical geotextile filtration of compacted soil and (2) geotextile filtration of clayey sludge. In the former case, exogenous water is drained, and the volume is theoretically infinite. In this case, the geotextile must remain permeable during the service life of the earthwork or structure, and clogging, which corresponds to a significant decrease in permeability (Veylon et al. 2016), must be avoided. In the latter case, endogenous water is drained, and the volume is theoretically finite. Filtering such material induces a significant decrease in the permeability of the cake-geotextile system due to the accumulation of fine particles. This phenomenon, which could be considered as clogging, may not be a problem if the entire endogenous volume of water is drained. In this case, it is more appropriate to talk about filter-cake initiation instead of clogging.

All the recent studies concerning clayey-sludge filtration confirm that the physics of filtering particles in suspension with a geotextile differs from the physics of filtering fine, confined soils. These studies show that the geotextile exerts an influence mainly at the early stage before the creation of the filter cake (Kutay and Aydilek, 2004; Weggel and Dortch, 2012). After that stage, the filter cake becomes the major contributor to the permeability of the clayey sludge/filter cake/geotextile system. At the onset of filtration, when the geotextile is clean, sludge filtration is governed by the properties of the geotextile. Over time, as the filtration proceeds, a layer of solids (filter cake) is expected to deposit on the surface of the geotextile. The extent of filter-cake formation and its stability depend on the particle size and particle-size distribution of the solids in the sludge, the concentration of particles, the flow rate, the pressure difference upstream and downstream of the geotextile and the structure of the geotextile (Soo-Khean Teoh et al., 2006; Chi Tien et al., 2011; Weggel and Ward, 2012).

Most studies that use clayey sludge filtration tests to assess geotextile filtration performance use a vertical cell in which the filter geotextile is positioned horizontally (Moo-Young et al., 2002; Aydilek and Edil, 2003; Kutay and Aydilek, 2004; Faure et al., 2006; Muthukumaran and Ilamparuthi, 2006; Weggel and Dortch, 2012; Bourgès-Gastaud et al., 2014; Sabiri et al., 2017). However, to better simulate filtration that occurs on the sides of a geotextile dewatering tube (Yee et al., 2012) or upstream of a vertical drainage trench (Veylon et al., 2016), it is more relevant to position the filtration cell horizontally, which orients the filter geotextile vertically. In this situation, the formation of the filter cake can be affected by sedimentation of particles that can settle before reaching the filter geotextile (where they settle depends on the particle size and particle-size distribution in the solids in the sludge, the particle concentration particles, and the flow rate). Generally, hanging bag tests are used to assess the dewatering performance of the geotextile tube (Kutay and Aydilek, 2004; Koerner and Koerner, 2006; Weggel et al., 2011). However, in such hanging bag tests, clayey sludge is poured into the bags without added pressure, which is not fully representative of the filling of dewatering tubes in the field, in which the sludge is under pressure.

When the filter cake forms, the filtration will generally become controlled after a short period, not by the properties of the geotextile but by the properties of the filter cake. In this case, the filtration process can be evaluated by the theory of filtration in porous media. One main governing parameter will be the increased loss of liquid head through the filter cake as the cake thickness increases during liquid flow. This increase in head loss is partly due to the increased length of the channels through which the water passes.

Another important parameter is the retention, or removal efficiency, of particles from the sludge. In addition, this parameter may, after a relatively short period of time, be determined more by the properties of the filter cake than by the properties of the geotextile. Nevertheless, geotextile characteristics remain important in determining the creation of the cake and its characteristics and stability. Aydilek and Edil (2003) studied the long-term filtration of nonwoven geotextile-sludge systems and emphasised the role of geotextile permittivity (i.e., permeability normal to the plane divided by the geotextile thickness).

To summarise, the global parameters governing filtration performance include but are not limited to the particle type, concentration, size distribution, type of water flow, geotextile characteristics (e.g., opening size, permeability normal to the plane, structure of the geotextile), and orientation of the filter geotextile (i.e. horizontal or vertical).

In general, three overall performance criteria should be considered when using geotextiles to filter suspensions of solids without flocculants:

- The first criterion concerns the retention capacity of the filter: over a relatively short time period, the solid concentration upstream of the geotextile will increase significantly.
- The second criterion is linked to the inevitability of some of the finest particles passing through the geotextile because the geotextile opening size cannot be smaller than the smallest particles. This criterion is reasonably satisfied if the initial loss of solids through the geotextile is limited and stops, or is at least significantly reduced, relatively soon after the onset of filtration.
- The third criterion is linked to characteristics of the filter cake that, once formed, must remain as permeable as possible.

Following the first two criteria, we can deduce that the effluent quality must be acceptable with respect to environmental impact and preferably remain constant with time.

Considering the present knowledge of geotextile filtration of fines in suspension without using additives, it seems important to understand more precisely how the most important geotextile characteristics affect (i) the formation of filter cake from various clayey sludge and (ii) the evolution of the "cake-geotextile" filtration system. Therefore, we use a systematic parametric approach, in which we first evaluate how the filtration system is influenced by several key parameters, including (a) the type of soil (e.g., well graded or uniform), (b) the concentration of fine particles, (c) the type of water flow (e.g., constant flow or constant head) and (d) the type of geotextile. To be representative of the filtration that occurs on the sides of a geotextile dewatering tube or on the side of a vertical drainage trench, and thus separate filtration from sedimentation phenomenon, the filter geotextile is positioned vertically in the filtration cell. We discuss how these experimental conditions affect the experimental results.

After a short description of the main phenomena involved in the geotextile filtration of fine particles in suspension, we describe the performance of various geotextile filters and compare their performance based on an analysis of (i) the retained soils and passed soils before and after the formation of the filter cake, and (ii) the characteristics of the filter cake.

2. PHENOMENA INVOLVED IN THE FILTRATION OF FINE PARTICLES IN SUSPENSION

For geotextile filtration of fine particles in suspension, three main phenomena can be observed: (1) a filtration controlled by the geotextile until the eventual creation of a filter cake, which may be considered as a clog in the system from the point of view of geotextile filtration; (2) a filtration controlled by the formation of the filter cake; and (3) the particles settle inside the sludge, which causes variations in sludge concentration; this last phenomenon indirectly interacts with the filtration processes defined above.

2.1. FILTRATION CONTROLLED BY GEOTEXTILES

In this case, particle retention is determined by the geotextile properties, and clogging is considered from the point of view of geotextile filtration. Clogging corresponds to the end of the passage of fine particles by the geotextile. Once clogging occurs, the filtration is governed by the filter cake that has formed in contact with the geotextile. Before the formation of the filter cake, geotextile filtration may be described by the following analysis.

Considering a given concentration C_s (kg/m^3 or g/L in this study) of solid fines and a given flow F_w (m^3/s or L/min in this study) of sludge, the theoretical flux Q_s (kg/s) (with no filtration) of solid particles passing through the geotextile per second is

$$Q_s = F_w C_s \tag{1}$$

For a given geotextile with a filtration property A, the total mass m_{pA} (kg) of particles passing through geotextile A prior to cake formation is

$$m_{pA} = Q_s\, t_A - m_{rA} \tag{2}$$

where t_A (s) is the time interval between the onset of filtration and cake formation and m_{rA} (g) is the mass of the retained particles.

Similarly, with a more open geotextile, corresponding to filtration property B, we have $t_B > t_A$, and the mass m_{rB} of the retained particles and the corresponding mass m_{pB} of the particles passing through geotextile B can be defined. Repeating this reasoning for a geotextile with a filtration property C, we have $t_C > t_B$, the mass of the retained particles is m_{rC}, and the corresponding mass of the particles passing through geotextile C is m_{pC}. Figure 1 shows the evolution of the filtration phenomena for the three geotextiles with different filtration properties (A, B, C). Figure 1(a) shows the pressure drop versus time until cake formation for the three geotextiles. Cake formation may be characterised by a given overpressure (Δp_{cf}) upstream of the geotextile. Figure 1(b) shows the mass of particles that passes through each individual geotextile versus the theoretical imposed flow of particles.

From this figure, we can deduce the following:

- If the geotextile has small opening size (case A), the filter cake forms rapidly (very few fines pass through the geotextile) and practically no fines pass through the geotextile during the filter-cake phase.
- When the geotextile opening size increases (case B), more fines pass through the geotextile prior to cake formation, and some fines pass through during the filter-cake phase.
- For large geotextile opening size (case C), even more fines pass through the geotextile before cake formation, and a significant mass of fines passes through during the filter-cake phase (i.e., unstable cake).

2.2. FILTRATION CONTROLLED BY THE FORMATION OF A FILTER CAKE

The geotextile filtration process described in section 2.1 may lead to the deposition of a filter cake on the upstream side of the geotextile, resulting in a filtration process determined by the build-up of head-loss drop across the filter cake (Figure 1), which induces a pressure drop in the sludge. To model this pressure drop, we use an equation developed to model the solid-liquid separation process (Kozeny, 1927). By assuming an incompressible filter cake, the pressure drop may be estimated by

$$\frac{\mathrm{d}V}{\mathrm{d}t}=\frac{\Delta p_{\mathrm{f}}A}{\mu\left(\frac{\alpha C_{\mathrm{s}}V}{A}+R_{\mathrm{m}}\right)} \quad (3)$$

where A is the effective filtration area (m²), V is the volume of filtrate (m^3), t is the filtration time (s), Δp_{f} is the pressure drop through the filter cake (Pa), α is the specific filter-cake resistance (m/kg), R_{m} is the filter-medium resistance (m^{-1}), C_{s} is the sludge concentration (kg/m^3) and μ is the viscosity of the liquid phase of the suspension (N s/m^2). Integrating the differential equation leads to

$$\frac{t}{V}=\alpha\left(\frac{\mu C_s}{2A^2\Delta p_f}\right)V+R_m\left(\frac{\mu}{A\Delta p_f}\right) \quad (4)$$

Graphing the experimental data in the form of t/V versus V allows us to determine the specific filter-cake resistance α and the filter medium resistance R_m and to roughly verify the assumption that the filter cake is incompressible. Equation (4) uses t/V, which gives the inverse of the average filtration rate over the period measured and through the surface area of the filter in the test. Knowledge of t/V facilitates the evaluation of the filtration rate over time, which is useful for assessing large-scale applications.

2.3. SETTLING OF PARTICLES INSIDE THE SLUDGE

For a vertical filter geotextile, the settling of particles in the sludge on the upstream side of the geotextile may affect the concentration of solid fines and size distribution that contact the geotextile. This phenomenon depends on the particle diameters, the initial particle concentrations and/or the test conditions (flow rate and length of the filtration cell principally). In addition, the settling properties of the fine solids that pass through the filter geotextile will determine the area affected by the spreading of the particles downstream.

The settling of particles in suspension in a liquid depends on the properties of the particles (shape, size, specific weight, concentration) and of the liquid (density, viscosity, temperature). A settling particle reaches its terminal velocity when the magnitude of the gravitational force equals the magnitude of the drag force. The terminal velocity depends on fluid density, the projected area of the particle on a plane normal to the settling direction and a drag factor. The drag factor depends, among other parameters, on the shape factor, which provides a measure of the deviation from a spherical shape (a unity shape factor corresponds to a perfect sphere). Assuming spherical particles, the terminal velocity for fine particles settling in water may be estimated by using Stokes law, which is valid for a Reynolds number between 10^{-5} and 2:

$$V_t = D_h^{\,2} g \left(\rho_p - \rho_w\right) / 18\mu \qquad (5)$$

In Equation (5), V_t is the terminal velocity of the settling particles (m/s), D_h is the hydraulic diameter of the particles (m), g is the acceleration due to gravity (m/s²), ρ_p is the particle density (kg/m^3), ρ_w is the density of water (kg/m^3) and μ is the viscosity of the liquid (N s/m^2). Equation (5) assumes that particles settle without any interference from other particles (discrete settling). Given high particle concentrations (greater than 0.1% by volume), the settling velocity is reduced compared with the velocity for discrete settling because of the increase in apparent viscosity and fluid density (hindered settling). The hindered-settling velocity may be estimated from the terminal settling velocity by applying a correction factor:

$$V_h = \varepsilon^n V_t \qquad (6)$$

where V_h is the hindered-settling velocity of the particles (m/s), V_t is the terminal settling velocity of the particles (m/s), ε is the ratio of liquid volume to sludge volume and n is a dimensionless exponent (n = 3.65 for ε > 0.6) (Lydersen, 1979).

3. DESCRIPTION OF THE EXPERIMENTAL STUDY

The experiment was designed to facilitate the systematic study of how geotextile characteristics affect the formation of the filter cake. The key parameters governing such filtration systems include but are not limited to the type of water flow, the particle-size distribution, the particle concentration and the geotextile characteristics (e.g., opening size, permeability normal to the plane, and dimensional structure). The various parameters of the testing procedure and the corresponding assumptions are presented below.

3.1. ASSUMPTIONS, TEST PARAMETERS AND TEST CONDITIONS

3.1.1. TYPE OF SOILS USED FOR THE FILTRATION TESTS

The type of the soil in suspension is expected to strongly influence the filtration behaviour. The soil may be described by several parameters such as particle-size distribution, particle type, particle shape and/or particle clay content and plasticity index. As a first step, to reduce the number of tests, we check only how the shape of the granularity curve affects filtration for two soil types: uniform and well-graded. A kaolinite and a silt soil are combined to create the two soils used in these tests.

Figure 2 and Table 1 present the particle-size distributions of the two soils used in these tests. Soil A is a kaolinite with a uniform granularity (CU = 4.5) and soil B, which is the combination of kaolinite and silt (CU = 13), is a fine, well-graded soil.

3.1.2. SLUDGE PROPERTIES, CONCENTRATION OF PARTICLES AND FLOW CONDITIONS

The two soils were tested at different particle concentrations and flow conditions. For the lowest concentrations, a constant sludge flow was used. A flow of 0.5 L/min was maintained until a pressure of 40 kPa was attained on the upstream side of the geotextile filter, following which the test continued with a constant head. For the highest concentrations, a constant head (with a maximum of 10 kPa) was used. The flow rate of 0.5 L/min was chosen to adapt to the cell dimensions and to the range of solid concentrations (70 to 300 g/L) and to well separate filtration and sedimentation behaviour inside the cell. In the two studies that involved filtration tests at constant flow, Faure et al. (2006) applied in their study a flow rate of around 5 L/min for sludge with solid concentration from 0.1 to 1 g/L and Sabiri et al. (2017) applied in their study a flow rate from 0.14 to 0.5 L/min for sludge with solid concentration of 1 g/L. Thus, the flow rate of 0.5 L/min is the same order of magnitude as obtained in previous laboratory studies but is less than the real flow rate used to fill a dewatering tube (Yee et al., 2012).

Table 2 presents the different conditions under which the tests were done.

3.1.3. Testing device and setup of apparatus

Figure 3 and Figure 4 present the test cell used to filter the sludge. A tank upstream with a stirring tool maintained a constant and uniform predefined concentration of fines in the incoming sludge. The monitored pumping system controlled the flow conditions at the entrance of the filtration cell. A pressure sensor was fixed at the top of the cell. The 150-mm-diameter filtration geotextile was held by a metallic grid to avoid deformation of the geotextile during the test. The sludge that passed through the geotextile was regularly weighed during the filtration test and collected for further analysis.

Note that the cell (volume 8.8×10^{-3} m^3) was oriented horizontally and the filtration geotextile vertically. In this configuration, the settling and sedimentation behaviour is separated from the filtration behaviour.

3.2. Geotextiles tested and corresponding test conditions

Table 3 and Table 4 summarise the characteristics of the various geotextiles tested and the corresponding configuration of the tests. To evaluate the influence of different structures with similar characteristic opening sizes, we tested a metallic sieve (W-2; O_{90} = 63 μm; identified by an asterisk in Table 3) to simulate a woven geotextile with a characteristic opening size close to 50–60 μm. This approach was used because of the difficulty of finding a woven geotextile with such a small opening size.

4. Experimental results of the filtration study

A first set of tests of the various geotextiles was done under constant-flow and constant-head conditions and with different concentrations of soils and fines. These tests were stopped when visual inspection indicated that fines had ceased to pass. This approach allowed us to study how the geotextile determines the filtration (section 2.1). To specify the filtration characteristics when determined by the filter cake and for constant-head conditions (section 2.2), some tests were repeated with a longer duration (up to 90 minutes).

4.1. Observations and parameters monitored to characterise geotextile-controlled filtration

The first set of tests allows us to determine and compare the characteristics of filtration when it is controlled by the geotextile. Therefore, detailed observations and specific parameters linked to this specific phase of the filtration system were followed and analysed.

4.1.1. Observations of differing filtration behaviours

Depending on the type of geotextile, the concentration and the hydraulic conditions, different filtration behaviours occur:

- When a large quantity of sludge passes through the geotextile, the cell cannot be filled, and stable filtration is not established.
- When a limited quantity of sludge passes through the geotextile, the cell fills, and one of the two following stable systems is established:
    - the geotextile is almost completely clogged after a certain period; no fines but also nearly no water passes through the geotextile by the end of the test;

- a stable filtration system is established; after a certain period, water still passes through the system, and either a relatively small flux of fines passes through or some fines continue to pass through.

For the lowest concentrations of fines and for constant flow, Table 5 presents the ratio of the cumulative mass of the sludge flow through the geotextile to the theoretical cumulative mass of the sludge flow through the geotextile. The abbreviation "cnf" (for "cell not filled") indicates that the cell was not filled after the test, and the abbreviation "cfnst" indicates that the cell was filled but the filter was not stable. In a large majority of the cases, the cell cannot be filled, which means that the geotextile opening sizes are too large to create a filter and/or that the concentration of fines in the sludge is too low.

Similarly, for the highest concentrations of fines and for constant-head conditions, part 1 of Table 6 indicates whether the systems were stable, as determined based on the evolution of the mass of the sludge that passes through the filter and/or the mass of fines that passes through the filter.

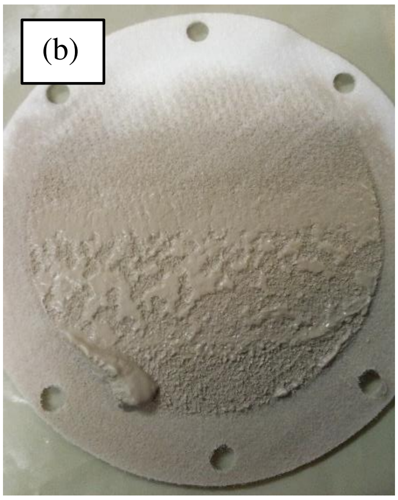


Figure 5 (a) shows a view of typical filtration cell at end of test (NWTB-1, constant flow condition, soil A at 200 g/L) and

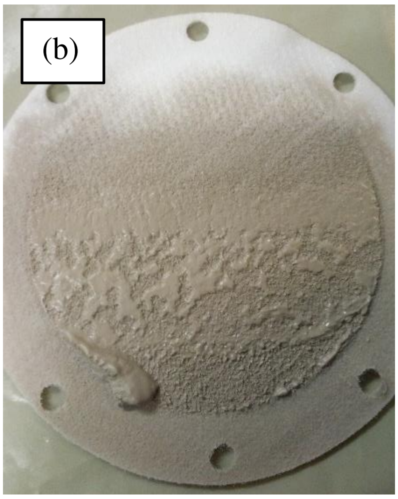


Figure **5** (b) shows a view of a filter geotextile at end of test (NWMB-2, constant flow condition, soil B at 200 g/L). From

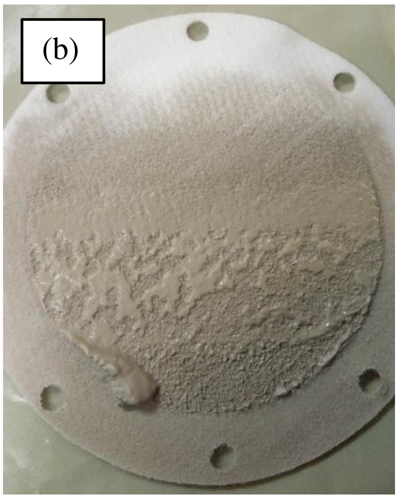


Figure **5** (a) it can be seen that the filter cake is well formed, despite the settling of particles. From

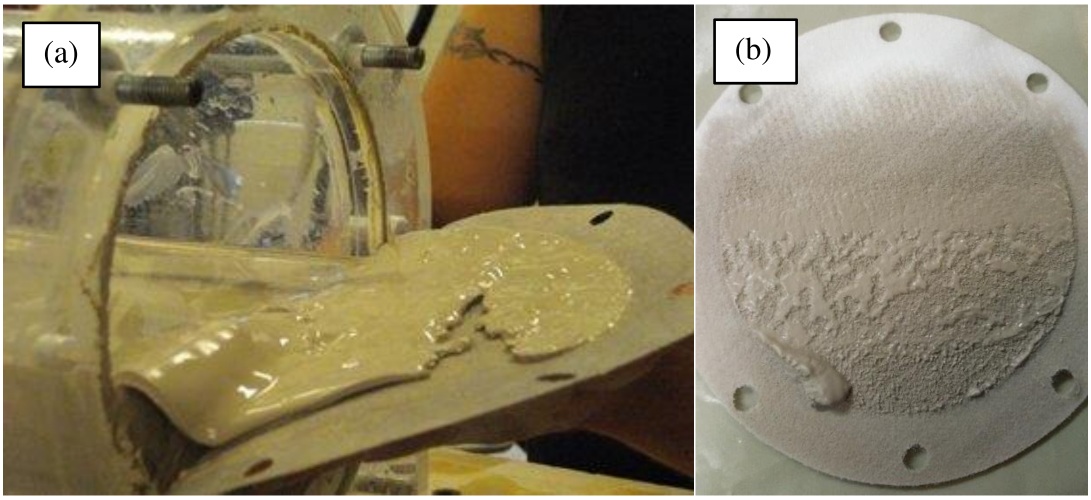


Figure **5** (b) it can be seen that the filter geotextile was not able to create a filter cake, and thus the cell was not filled. With a vertical cell (and horizontal filter geotextile), sedimentation and settling of coarser particles onto filter geotextile would probably have induced filter cake formation.

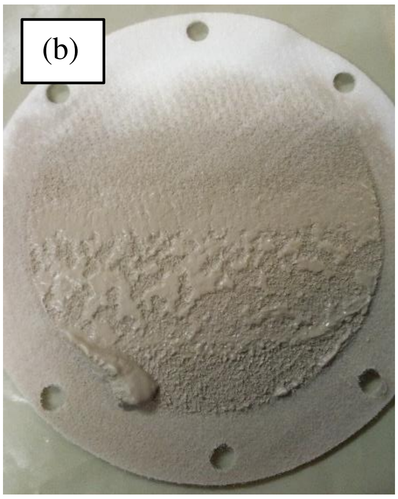


Figure **5** confirms the benefit of the vertical orientation of the geotextile to study the creation of the filter cake by separating filtration from the settling and sedimentation of fines inside the cell.

4.1.2. PARAMETERS MONITORED FOR CHARACTERISING GEOTEXTILE-CONTROLLED FILTRATION

When filtration is established, one can evaluate and compare the behaviour of the various systems based on the three criteria given in the introduction.

4.2. RESULTS OF THE EXPERIMENTS: COMPARISON OF THE VARIOUS GEOTEXTILES

This analysis considers only those tests that allowed the given filtration system to be characterised: for constant-flow conditions, the tests in which the cell was not filled are excluded, because in this case we consider that no stable filtration system was established.

4.2.1. EFFICIENCY OF FILTRATION OF CUMULATIVE MASS THAT PASSES THROUGH THE GEOTEXTILE

4.2.1.1. CONSTANT-FLOW CONDITIONS

For the well-graded soil B, the data given in Table 5 show that, because of the low concentrations in most of the tests, the cell was not filled. The coarser particles settled in the cell before reaching the geotextile filter, and then the finest particles in suspension that reached the filter were too small to be filtered and/or to create a filter cake. Figure 5 shows a view of the cell after the test in constant-flow conditions; the effect of the sedimentation and settling inside the cell is apparent. A large quantity of fines filled the bottom half of the cell. It is interesting to evaluate the theoretical settling of the particles during the test. The constant flow F_w = 0.5 L/min; therefore, considering the 150 mm diameter of the cell and its length of 500 mm, the "transit time" t_t necessary for a fine particle to transit from the cell entrance to the geotextile filter surface is 17 minutes, 40 s. Considering that (1) the entrance of the cell is opposite the filter at the top of the cell (Figure 3) and that (2) the settling speed of the particles can be calculated, assuming that the particles are spherical, the size of the particles capable of reaching the filter may be determined. Clearly, over the duration of the test, the coarser particles fill the cell progressively from the bottom, which reduces the effective volume of the cell and thereby reduces the transit time t_t of the fines, assuming the flow F_w remains constant at 0.5 L/m.

Nevertheless, in a first approach, the very beginning of the test, when the coarser particles have not yet begun to fill the bottom of the cell, is evaluated as follows: Equation (5) assumes that the particles are spherical. The effect of high particle concentration on settling velocity is taken into account according to Equation (6) and allows the theoretical hindered settling $S_{\text{theo h}}(t_t)$ during the transit time to be determined as a function of particle diameter. If $S_{\text{theo h}}(t_t)$ exceeds the diameter of the cell, the corresponding particle will not reach the filter. Table 7 shows that, theoretically, if the particles are considered spherical, the smallest particles (e.g., with a diameter D_{h} = 10 μm or smaller) will reach the filter, but the largest particles (e.g., with a diameter D_{h} = 20 μm or larger) will not reach the filter and will accumulate at the bottom of the cell.

Considering (i) that 20% of the particles with the initial granulometry of the soil B and that pass through the filter have a diameter ≤10 μm and (ii) that only particles with a diameter ≤10 μm reach the filter, the filtration system should theoretically produce a sludge with fine particles (≤10 μm) with a concentration of fines much lower than the nominal concentration: 14 g/L (instead of 70 g/L nominal), 20 g/L (instead of 100 g/L nominal), 40 g/L (instead of 200 g/L nominal) and 60 g/L (instead of 300 g/L nominal).

Nevertheless, with these very specific conditions, Table 5 shows that only the geotextile NWTB-1 allows the retention of fines in suspension and the creation of a filtration system for the two highest nominal concentrations (200 and 300 g/L). This result is probably linked to both the small opening size and the specific structure of this geotextile. Conversely, for uniform soil A, better filtration occurs because of the creation of a filtration system in most of the tests (see Table 5). This result is probably linked to the type and size of particles. In this case, Figure 2 shows that 80% of the particles of soil A are less than 10 μm in diameter. If, as for soil B, the particles may be considered spherical, the evaluation of particle settling inside the cell during the tests is similar. In this case, as presented in Table 7, 80% of the particles in suspension in the cell would reach the geotextile filter, explaining the creation of the filter cake in most of the tests. Thus, the data of Table 5 support the following conclusions, drawn for the tested filter geotextiles, soils and experimental conditions (flow rate, length of the filtration cell, etc.):

- The geotextiles with larger opening sizes (NWMB-1; O_{90} = 91 μm and W-1; O_{90} = 109 μm) cannot block the fines, and the cell cannot be filled.
- For the other geotextiles, filtering occurs, but the mass of the sludge that passes through the filter is less than the theoretical prediction. Ranking the geotextiles from those with a large reduction compared with theory to those with a small reduction gives, assuming equal concentration (100 g/L): NWTB-2, NWTB-1, NWMB-2 and W-2. Similarly, for geotextile NWTB-1, less sludge passes through the filter as the concentration increases. These results are also reflected in Figure 6 by using the efficiency ratio, which is the solid mass retained in the filtration cell divided by the mass of the sludge that passes through the geotextile.

These results are obtained for the flow rate of 0.5 L/min. Higher or lower flow rate would have changed the transit time necessary for a fine particle to transit from the cell entrance to the geotextile filter surface, and thus, regarding sedimentation phenomenon, conditions to create a filter cake.

4.2.1.2. CONSTANT-HEAD CONDITIONS

For the well-graded soil B, part 1 of Table 6 shows that, for a large number of tests (11 out of 20) the filtration system did not stabilise and a large amount of fines continued to pass through the geotextile filter at the end of the test. Nevertheless, the number of tests where stable filtration systems developed provides enough data to compare the behaviour of these filtration systems. As presented in section 2.2, a filtration system can be evaluated by the quantity of sludge that passes through it and, more precisely, by the mass of particles that pass through it (this is the first criterion defined in the introduction). For several geotextiles, Figure 7 compares the mass of the sludge that has passed through the given geotextile by the end of the test as a function of the initial sludge concentration (tests were stopped based on visual observation) and for constant-head conditions. These results allow the different geotextiles to be compared:

- The mass of the sludge, and similarly the mass of fines, that passes through a geotextile decreases with increasing concentration of fines in the sludge; this can be explained by a more rapid formation of the filter cake in contact with the geotextile due to the higher concentration of fines in the sludge.
- The geotextiles with larger opening size (e.g., NWMB-1) let more sludge, and thus more fines, pass through during the test.
- The geotextiles with smaller opening size (e.g., NWTB-1, W-2, NWMB-2) reduce the mass of fines that pass through the filter during the test, whereas the mass of the sludge that passes through is not negligible, which means that water passes through the established filtration system.
- If geotextiles with a thermally bonded structure allow a better stabilisation than the mechanically bonded geotextiles, it appears that, for a given geotextile structure, a small opening size is a key parameter to create a stable filtration system, which is confirmed by the better behaviour of NWTB-1 and NWTB-2 (O_{90} < 50 μm) compared with NWTB-3 and NWTB-4 (O_{90} = 61 and 140 μm) for the thermally bonded structure and NWMB-2 (O_{90} = 54 μm) compared with NWMB-1 (O_{90} = 91 μm).
- By comparing the results from the NWTB and W geotextiles on one side and the NWMB geotextiles on the other, and by considering that the constrictions generally number between 25 and 50 for mechanically bounded nonwoven geotextiles and are equal or close to unity for woven and thermally bonded nonwoven geotextiles, the number of constrictions cannot be considered a relevant parameter for evaluating the filtration of fines in suspensions.

However, because the time required to create a filter cake depends on the type of geotextile, it is of interest to evaluate the average flows that pass through the geotextile (flow of sludge, solid fines, and water) and to study how these parameters evolve (this is the second criterion defined in the introduction). For the second series of tests, which lasted 90 minutes (Table 6, part 2), three parameters became linear with time as soon as the filter system was established and remained so until the end of the test (90 minutes). The tests were finalised after running for 90 minutes. In Table 6, part 2, the asterisk corresponds to a test that started with constant-flow conditions and, when the pressure in the cell reached 10 kPa, continued with constant-head conditions. The time required to establish the filter system may depend on the geotextile; the maximum time observed was 12 minutes.

Table 8 presents the average sludge mass, solid mass and water mass that passes through the geotextile filter after the cell is filled, and the filter system is created. Part (a) of Table 8 compares the concentration of fines in the sludge for different geotextiles (C_s = 500 g/L). The geotextiles with the smallest opening size (NWTB-1 and W-2) block the fines and let water pass through, whereas the geotextile with larger opening size (NWMB-2) continues to let fines pass through at a constant rate until the end of the test. Part (b) of Figure 6 shows the influence of the solid concentration of the sludge for the geotextile NWTB-1. For all initial concentrations tested (C_s = 400, 500 and 700 g/L), no fines pass through the geotextile, and the amount of water that passes through the geotextile decreases as the initial concentration increases. These observations suggest that the characteristics of the filter cake may depend both on the concentration of fines in the sludge and on the type of geotextile. A preliminary characterisation of the filter cakes is presented in section 4.3.

To evaluate the environmental impact of the effluent as defined in the introduction, we look at the filter efficiency, which is defined as the ratio of solid mass in the filtration cell to sludge mass that passed through the geotextile. These quantities were measured at the end of the phase in which filtration was determined by the geotextile and later during the phase in which filtration was determined by the filter cake (the second criterion defined in the introduction). A higher ratio corresponds to a better filter efficiency (Figure 8). A general trend is apparent in which the smaller opening size corresponds to better efficiency, and for similar opening sizes the thermally bonded structure gives the best efficiency. This trend is more deeply analysed along with the characterisation of the filter cakes in section 4.3.

Figure 9 shows the results obtained for uniform soil A. For soil B, the first series of tests allows the different geotextiles to be compared; the results show that both the mass of the sludge and the mass of fines that pass through the geotextile decrease with increasing concentration of fines in the sludge. The geotextiles with larger opening size (e.g., NWMB-1) allow more sludge to pass through during the test, and thus more fines, whereas the geotextiles with smaller opening size (e.g., NWTB-1, W-2, NWMB-2) reduce the mass of fines that pass through. However, the results for filter efficiency for soil A are less systematic than those for soil B.

Table 9 shows the effect of the solid concentration of the sludge for geotextile NWTB-1 evaluated based on the second series of tests (i.e., the 90-minute tests). As was the case for soil B, the results for geotextile NWTB-1 indicate that no fines pass through and that the water flux passing through decreases with increasing initial concentration of fines. Nevertheless, for uniform soil A, the total mass of the sludge that passes through is less than that for the well-graded soil B. These observations confirm the utility of the preliminary characterisation of the filter cakes in section 4.3, which should help to better understand the local behaviour of the filtration process.

4.2.2. PARTICLE-SIZE DISTRIBUTION OF SOILS THAT PASS THROUGH THE FILTER

The results of the tests done when the filter system was stabilised and when the cake was formed indicate that the mass of fines that passed through remained very low; thus, it was not possible to accurately measure the particle-size distribution of the soil that passed through the filter. Therefore, measurements were made for tests in which a reasonable mass of soil passed through the filter. Thus, for some of the tests used for this evaluation, the filtration system was not stabilised, so the geotextile was serving more as a sieve than as a filter. For soil B,

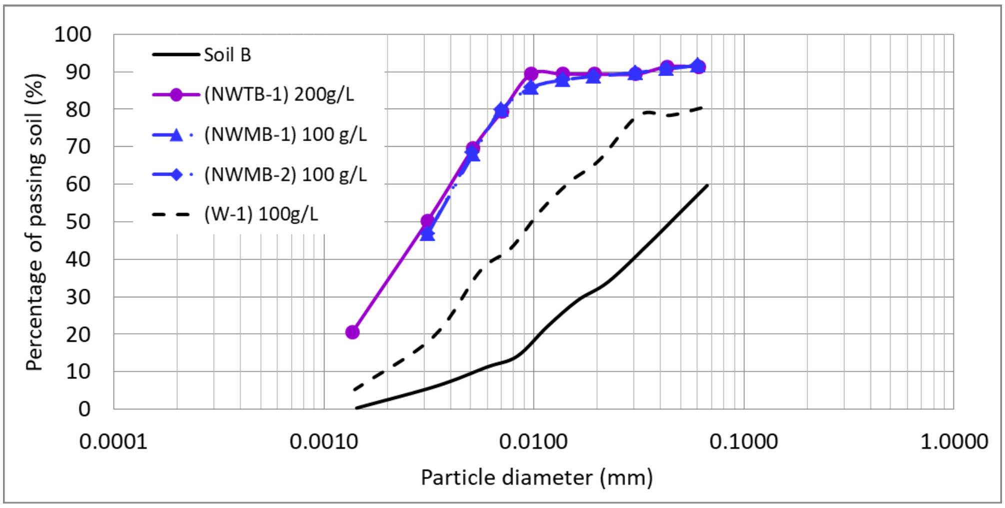
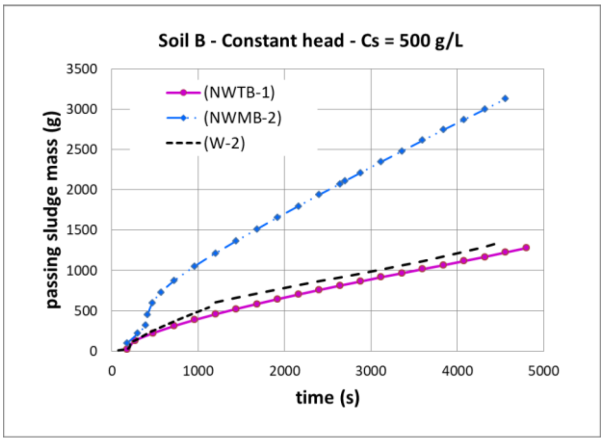


Figure **10** shows the measured particle-size distribution of the soil that passes through the filter under constant-flow conditions. The analysis of the grain-size distributions of this soil shows that, for all nonwoven geotextiles with small opening sizes (<50 to 91 µm), the soil consists of fine particles of diameter less than 10 µm, which are not blocked by the geotextile in the absence of a filter cake. For woven geotextiles with a larger opening size (109 µm), larger particles with diameters up to 30 to 40 µm pass through the geotextile, confirming that, without a filter cake, the geotextile acts as a sieve. In this respect, these results confirm the advantage of geotextiles with small opening size.

4.3.PRELIMINARY CHARACTERISATION OF THE FILTER CAKE

This characterisation is linked to the third criterion described in the introduction (i.e., once formed, the filter cake must be the most permeable possible). For the second series of 90-minute tests,



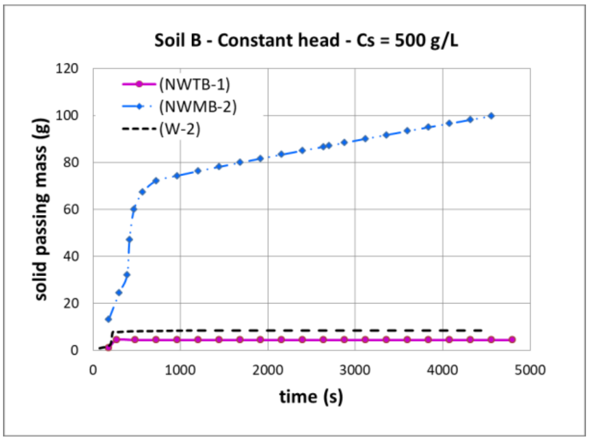


Figure **11** shows the mass of the sludge that passes through the given geotextile as a function of time. For geotextile NWMB-2, the fines continue to pass through the geotextile for the entire duration of the test, whereas geotextiles NWTB-1 and W-2 block the fines after a certain time but still allow water to pass, confirming that the filter-cake behaviour should be evaluated more precisely. As discussed in section 2.2, during the test, when the filter cake appears on the upstream face of the geotextile, the filtration process is controlled by the build-up of head loss, which leads to a pressure drop across the filter cake. This pressure drop may be estimated by Equation (4), and the interpretation of the experimental t/V versus V graph allows the specific filter-cake resistance α to be determined. Figure 12 shows the graphs of t/V versus V for geotextile NWTB-1 (for both soils A and B and for various concentrations) and for various geotextiles for soil B and a concentration of 500 g/L (see Table 6, part 2). In the early stage of filtration, the curves are nonlinear with a decreasing trend that can be interpreted as the filter-cake-stabilisation period. After this period (delimited by a black arrow on the graphs), the filter cake is well established, and the model described by Equation (4) can be applied. In other words, the curves become linear with a positive slope. This use of Equation (4) to model the filtering tests is validated for both soils A and B and for all three geotextile filters (NWTB-1, NWMB-2, W-2). According to Leu (1986), the specific filter-cake resistance α ranges from 1×10^9 m/kg (for easy filtration) to 1×10^{13} m/kg (for difficult filtration). Assuming a viscosity of 1.002×10^{-3} N s/m^2, Table 10 shows the specific filter-cake resistance as determined by the second series of 90-minute tests. The double asterisk corresponds to a test that was started under constant-flow conditions and, when reaching 10 kPa inside the cell, continued under constant-head conditions. The test was finalised after a total duration of 90 minutes. The specific filter-cake resistance for the well-graded soil B falls between 8.8×10^8 and 3.6×10^{10} m/kg for all geotextiles and concentrations tested, whereas for uniform soil A the values calculated are higher: between 4.7×10^{11} and 1.1×10^{12} m/kg. These results are encouraging, at least for the well-graded soil for which the NWTB-1, NWMB-2 and W-2 specific filter-cake resistances α are calculated to lie in the range of easy filtration. Note that the incompressibility assumption linked to the equation from Kozeny (1927) still needs to be verified. The compressibility of the cake is given by the slope of the curve

$$\log(\alpha)=f\left(\ln\left(\Delta p_{\mathrm{f}}\right)\right) \tag{7}$$

where α is the specific filter-cake resistance, and Δp_{f} is the pressure drop through the filter cake. The range of compressibility of the cake varies from zero for incompressible cakes to near unity for highly compressible cakes. For incompressible filter cakes, the rate of filtration is directly proportional to the filtration pressure, the filtering surface, viscosity and the amount of cake. For a compressible cake, the rate of filtration does not increase proportionally with an increase in pressure.

The measurement of the compressibility by tests at different pressures (not yet undertaken in this study), will help to confirm this first approach for the specific filter-cake resistances and to evaluate how pressure increase affects filtration rates. Nevertheless, this first evaluation seems encouraging and confirms that geotextiles showing a good behaviour over long-term tests should continue to be investigated.

5. DISCUSSION AND CONCLUSIONS

The present study gives a better understanding of how the geotextile characteristics affect filtration when subjected to a flow of fines in suspension and without flocculent, geotextile being vertical versus the flow being horizontal. Various parameters have been analysed and discussed in detail: the type of soil (well graded or uniform), the concentration of fines (seven different concentrations ranging from 70 to 700 g/L), the type of water flow (constant flow or constant head) and the type of geotextile (three types, namely, thermally bonded nonwoven, needle-punched nonwoven and woven). Based on an analysis of the soil retained and that passed by the filter geotextile, we compared the different filtration systems. This approach led to a three-stage view of geotextile systems for filtering fine particles in suspension: (1) stabilisation of the filtration process, with a significant and rapid increase in the concentration of solids upstream of the geotextile; (2) an initial loss of fines through the geotextile that is of limited duration, ensuring an effluent with an acceptable environmental impact; and (3) an acceptable long-term water permeability of the filtration system.

The results of the constant-flow experimental study show that the horizontal orientation of the cell and the vertical orientation of the geotextile allow sedimentation/settling to be separated from filtration. Nevertheless, this orientation of the device modifies and reduces the concentration of particles in contact with the geotextile and explains the large number of tests for which the cell could not be filled. Moreover, results interpretation of tests at constant flow conditions were made following the selected flow rate of 0.5 L/min, and, changing the flow rate could change the conditions to create a filter cake.

Two phases of filtration were analysed: (i) filtration controlled by the geotextile, and (ii) filtration controlled by a filter cake. For constant flow, when filtration is controlled by the geotextile, the following conclusions can be drawn:

- The tests using the well-graded soil B show that only geotextile NWTB-1 retains the fines in suspension and allows the creation of a filtration system for the two highest concentrations (200 and 300 g/L); this result is attributed to both the small opening size in this geotextile and its specific structure.
- The tests using the uniform soil A show that
    - the geotextiles with larger opening sizes (NWMB-1; O_{90} = 91 μm and W-1; O_{90} = 109 μm) cannot block the fines and the cell cannot be filled;
    - for geotextiles with opening size $O_{90} \leq 63$ μm, filtration allows less sludge mass to pass through than is predicted by theory, and this difference in mass between experiment and theory is used to rank the geotextiles (from largest difference to smallest), for the same concentration of 100 g/L, as NWTB-2, NWTB-1, NWMB-2, W-2;
    - as the concentration increases, the mass of the sludge that passes through geotextile NWTB-1 decreases.

When filtration is controlled by a filter cake, for constant-head conditions, the tests with the well-graded soil B show that the following results:

- For a concentration C_s = 500 g/L of fines in the sludge, geotextiles NWTB-1 and W-2 block the fines and allow water to pass through, whereas geotextile NWMB-2 continues to allow fines to pass through until the end of the test; the characteristic opening sizes of all three geotextiles are very small ($O_{90} \leq 63$ μm), but the structures differ. The thinner thermally bonded geotextile (and metallic sieve) is less porous than the slightly thicker mechanically bonded geotextile; this difference may explain the different filtration behaviours.

- For geotextile NWTB-1 with initial concentrations C_s = 400, 500 and 700 g/L, no fines pass through and the mass of water that passes through decreases as the initial concentration increases.
- To evaluate effluent quality to determine its environmental impact, we define the filter efficiency as the ratio of solid mass in the filtration cell to sludge mass that passed through the geotextile. It has been shown that smaller geotextile opening size leads to better filter efficiency. In addition, given geotextiles with similar opening size, a thermally bonded structure (thinner and less porous) offers the best filter efficiency.

This work proposes a method to preliminary evaluate the specific filter-cake resistance. The equation derived from liquid-solid-separation theory was shown to provide an appropriate model for the tests of filtering clayey sludge through geotextiles. Note that this study could not verify the assumption of an incompressible filter cake. Nevertheless, if this assumption is accepted, this analysis gives a specific filter-cake resistance $\alpha = 8.8 \times 10^8$ to 3.6×10^{10} m/kg (for well-graded soil), which is promising for the geotextiles evaluated herein.

In conclusion, this experimental study shows that the filtration by geotextiles of fines in suspension and without flocculants remains a delicate topic and calls for a thorough evaluation and a proper design of the geotextile. The results are significantly influenced by the orientation of the geotextile filter (vertical or horizontal) from the settling of the particles during the test and the selected flow rate for tests at constant flow conditions.

For a well-graded soil (such as soil B), when the concentration of fines is low, and the hydraulic conditions correspond to constant flow, only geotextile NWTB-1 allows a filter cake to build progressively and stabilise over time. The other geotextiles tested do not block the fines. When the concentrations increase, and the hydraulic conditions correspond to constant head, the geotextiles with the smallest opening size (NWTB-1 and W-2) produce a stabilised filter system that, after a short time, blocks the fines in suspension while still letting water pass through. The other geotextile (NWMB-2), which also leads to the creation of a filter cake, continues to allow fines to pass through for the entire test and, thus, is inferior with respect to the downstream filtration criteria.

For uniform soil A, the results of the tests show a relatively good performance of the geotextiles performing correctly with the well-graded soil B. Nevertheless, extrapolation to other uniform soils should be handled with care because the results of the tests correspond to the relative positioning of the average diameter of the soil and of the characteristic opening size of the geotextiles, which in the present study can be considered favourable. Other relative values may certainly give very different results.

Considering all the tests done for this study, it appears that, for the soils tested, the thin geotextiles with the smallest opening sizes ($O_{90} \leq 60$ μm) give the most promising results for filtering fines without flocculants. Of these geotextiles, the thermally bonded nonwoven structure provides the best compromise between opening size and geotextile thickness and suitable support for a filter cake to allow long-term permeability. In addition, with a well-graded soil, this structure seems to offer the best filtering characteristics for the largest range of concentration of fines. In terms of practical applications, this study gives worthwhile results for the configuration consisting of a vertical filter filtering a horizontal flux of clayey sludge (e.g., dragging sediment behind a filtering wall, filtering clayey sludge against the side slope of a tailing pond, or filtering clayey sludge injected into a textile tube).

6. ACKNOWLEDGEMENTS

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7. NOTATION

A	effective area of filtration (m^2)
α	specific filter cake resistance (m/kg)
C_s	concentration of solid fines in the sludge (kg / m^3)
D_h	hydraulic diameter of a particle (m)
ε	ratio of the volume of liquid over the volume of sludge
F_w	flow of sludge (m^3/s)
g	acceleration of gravity (m/s²)
Q_s	theoretical flux (with no filtration) of solid particles passing through the geotextile per second (kg/s)
m_{pA}	mass of particles passing through the geotextile A (kg)
m_{rA}	retained mass of particles by the geotextile A (kg)
μ	viscosity of the liquid phase of the suspension (N s/m^2)
n	exponent
Δp_{cf}	characteristic pressure drop for the cake formation (Pa)
Δp_f	pressure drop through the filter cake (Pa)
R_m	filter medium resistance (m^{-1})
ρ_p	density of the particle (kg/m^3)
ρ_w	density of water (kg/m^3)
$S_{theo\ h}(t_t)$	theoretical hindered settling of the particle during the transit time t_t (m)
t	filtration time (s)
t_A	time for clogging for the geotextile A (s)
t_t	"transit time" necessary for a fine particle to transit from the entrance in the cell to the surface of the filter geotextile
V	volume of filtrate (m^3)

V_h hindered settling velocity (m/s)

V_t terminal settling velocity of the particle (m/s)

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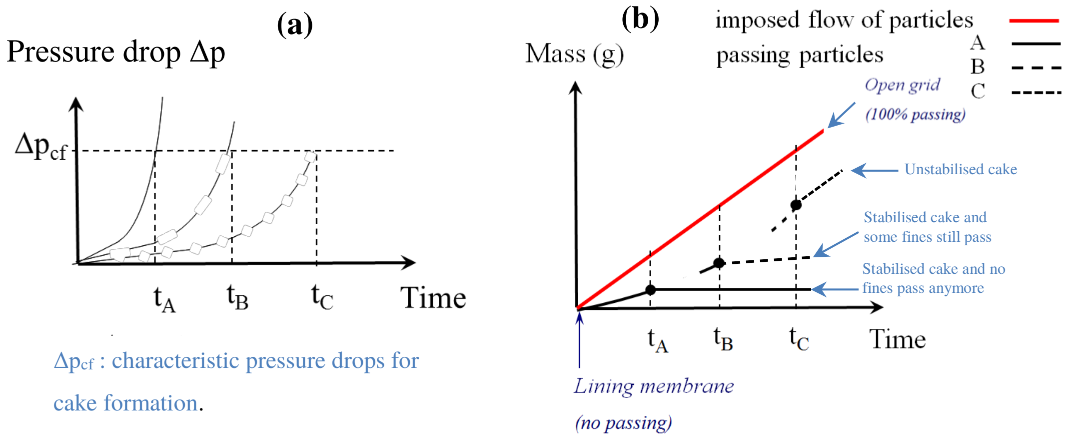


Figure 1. (a) Pressure drop as a function of time and (b) mass that passes through geotextile filter as a function of time. t_A, t_B and t_C are the time intervals between the onset of filtration and filter-cake formation for geotextiles A, B and C when exposed to a flow of water charged by particles (*no scale*).

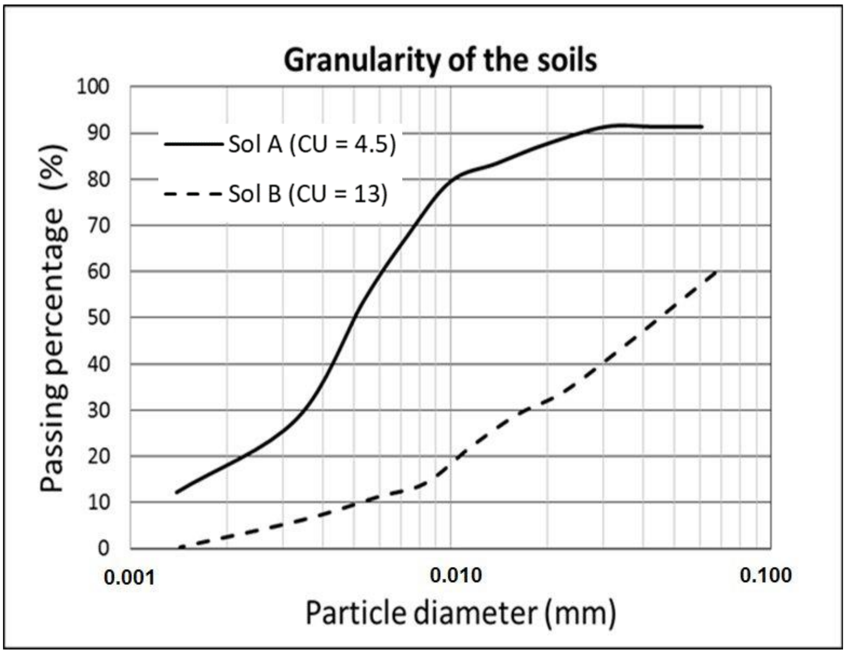


Figure 2. Particle-size distribution showing the fraction of particles that pass through the geotextile filter as a function of particle diameter for the two soils used in the filtration tests.

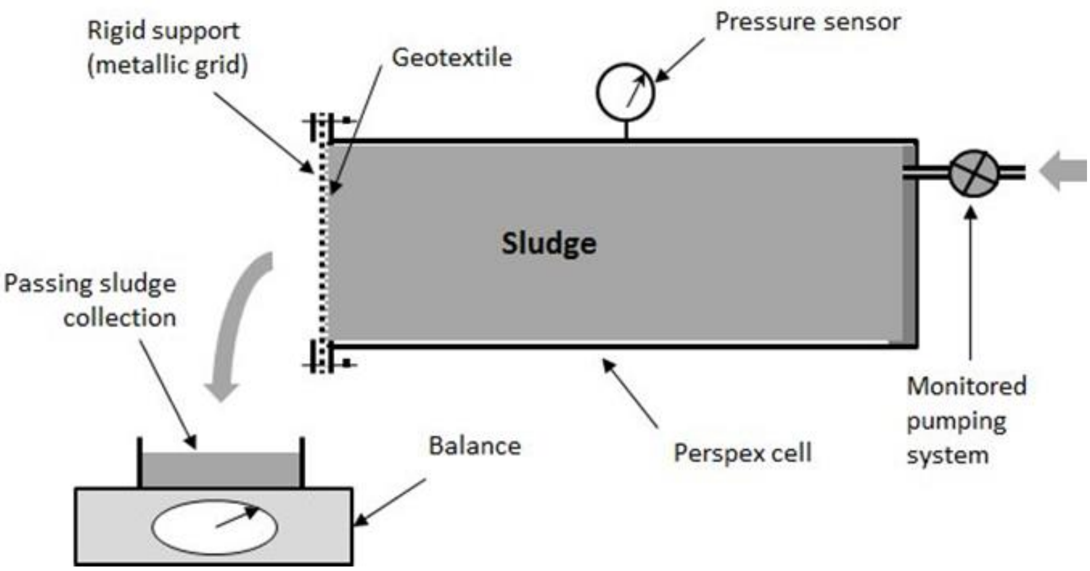


Figure 3. Principle of test cell used for filtering sludge (no scale).

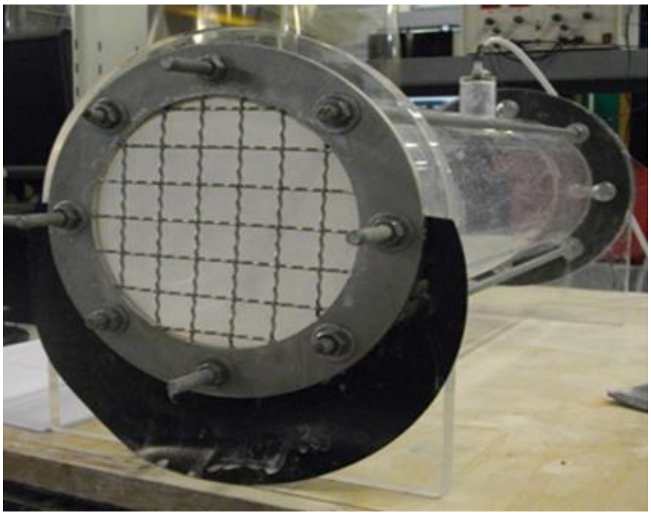


Figure 4. View of test cell before filling by sludge.

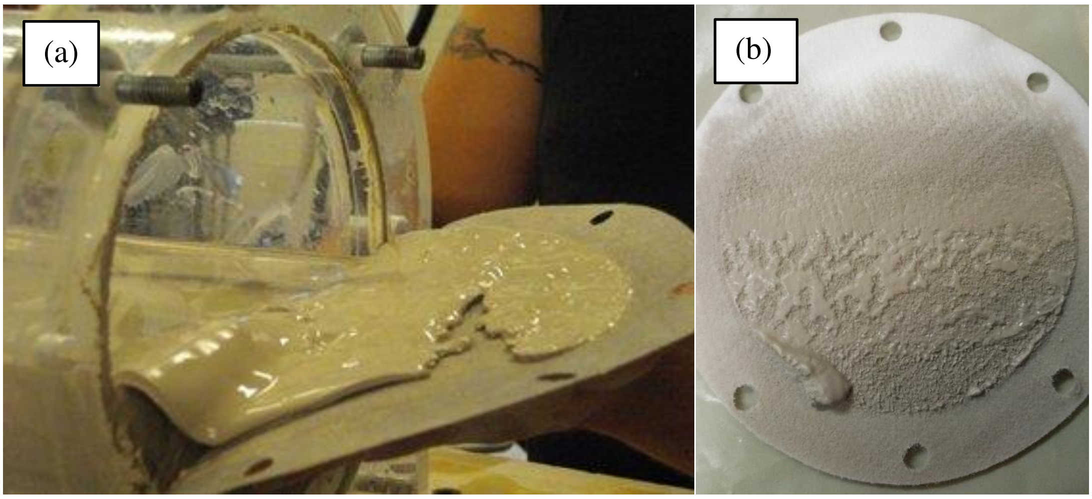


Figure 5. (a) View of typical filtration cell at end of test (NWTB-1, constant flow condition, soil A at 200 g/L). (b) View of a filter geotextile at end of test (NWMB-2, constant flow condition, soil B at 200 g/L).

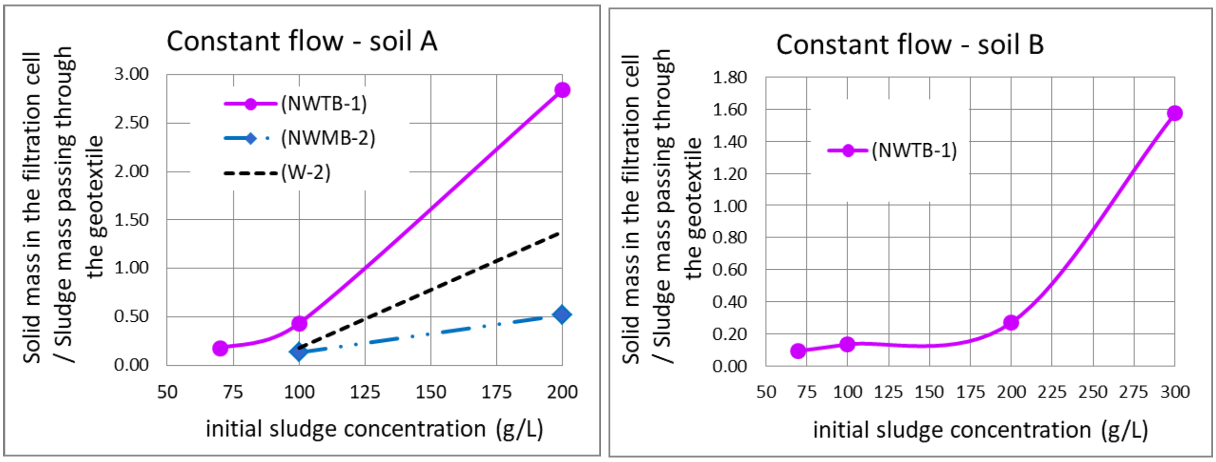
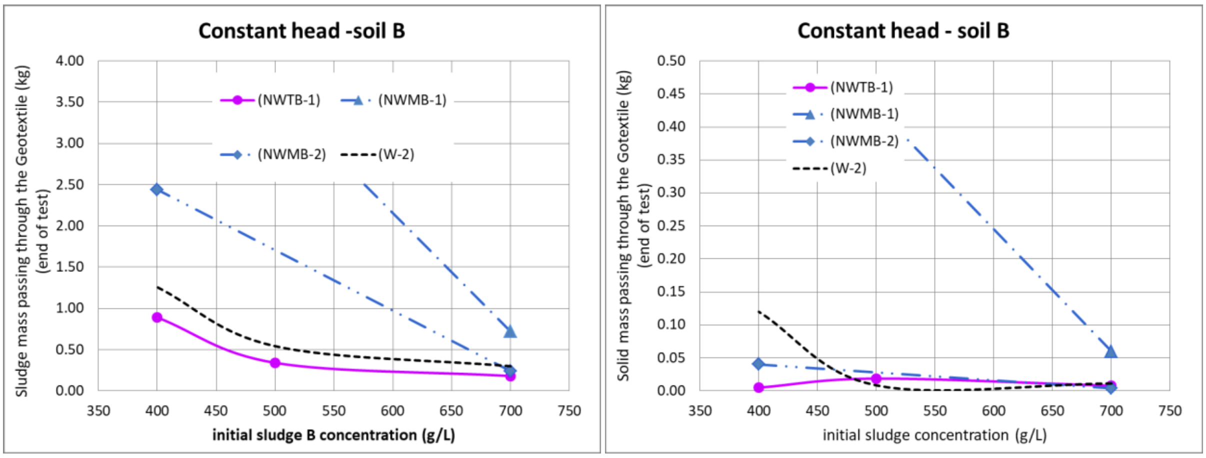


Figure 6. (a) Under constant-flow conditions and for soil A, ratio of solid mass retained in filtration cell to sludge mass that passes through geotextile as a function of initial sludge concentration and for several geotextile filters. (b) Same as panel (a) but for soil B and for the single geotextile filter. Both panels refer to phase where the filtration is controlled by the geotextile.



(left) Sludge mass passing through the geotextile measured at the end of the test

(right) Solid (fines) mass passing through the geotextile measured at the end of the test

Figure 7. (a) Sludge mass that has passed through the filter by end of test as a function of initial sludge concentration for four geotextile filters. Soil B was used for these tests, which were done under constant-head conditions. (b) Same as panel (a) but for solid mass instead of sludge mass. Both panels refer to phase where the filtration is controlled by the geotextile.

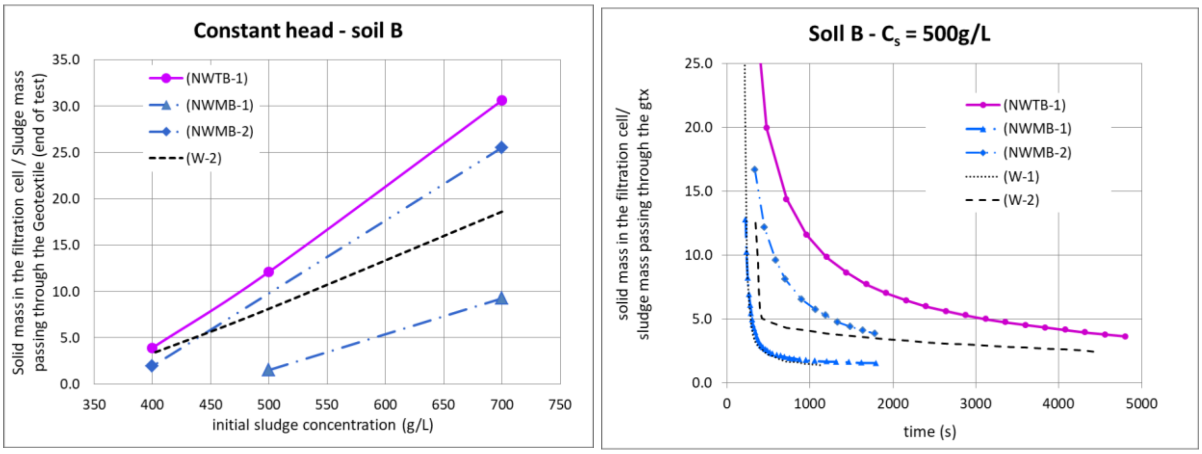


Figure 8. (a) Ratio of solid mass in filtration cell to sludge mass that passes through geotextile filter during test as a function of initial sludge concentration and for four geotextile filters. Tests were done under constant-head conditions, used soil B and filtration was controlled by the geotextile. (b) Same ratio as in panel (a) shown as a function of time from onset of filtration. Concentration of fines was C_s = 500 g/L and filtration was controlled by filter cake.

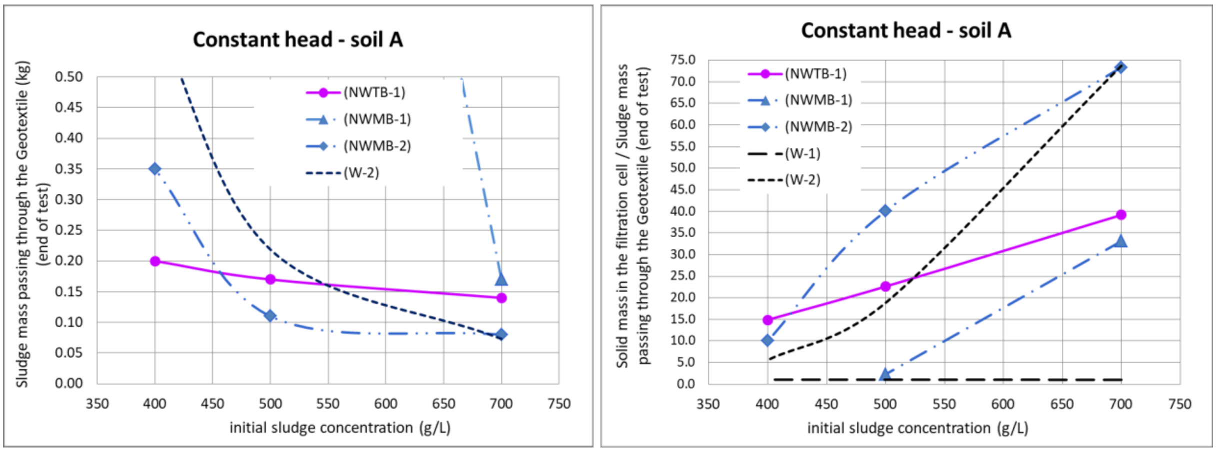


Figure 9. (a) Solid mass that passes through geotextile filter during test as a function of initial sludge concentration and for four geotextiles. (b) Ratio of solid mass in the filtration cell to sludge mass that passes through the geotextile filter during test as a function of initial sludge concentration and for five geotextiles. For both panels (a) and (b), tests were done under constant-head conditions, used soil A and filtration was controlled by the geotextile.

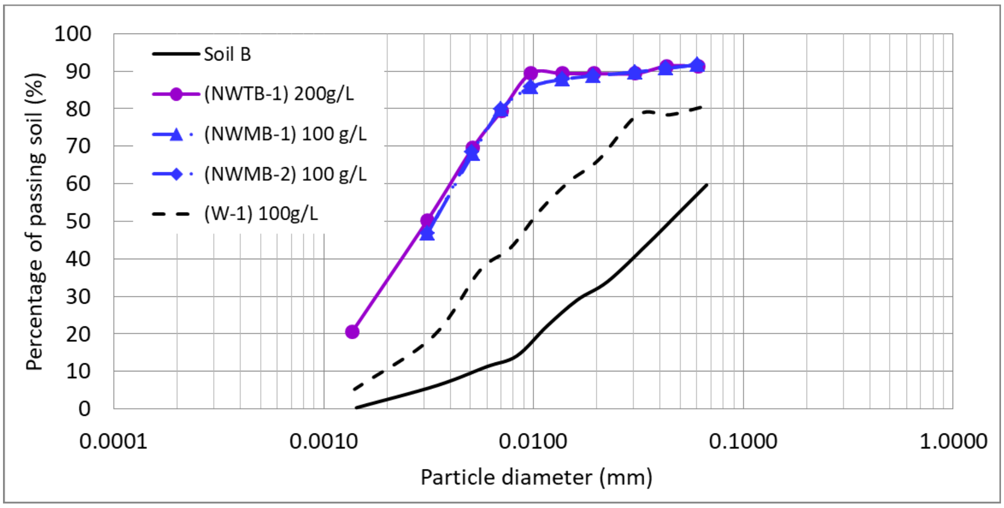


Figure 10. Particle-size distribution shown as fraction of particles that pass through filter as a function of particle diameter under constant-flow conditions and for soil B. Filtration was controlled by the geotextile.

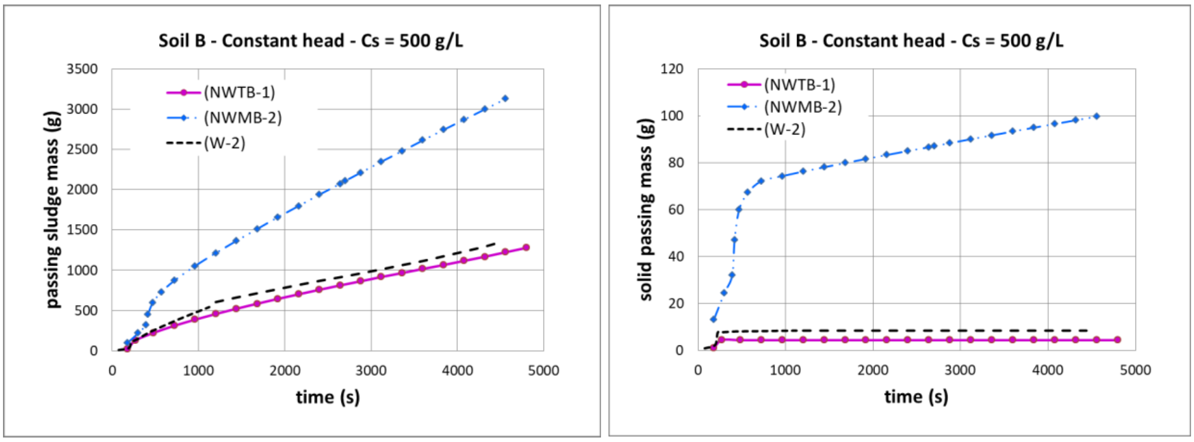


Figure 11. (a) Sludge mass that passes through the geotextile filter as a function of time from onset of filtration and for three geotextiles. Tests were done under constant-head conditions, with a fines concentration of 500 g/L, soil B and filtration controlled by the filter cake. (b) Same as panel (a) but for solid mass instead of sludge mass.

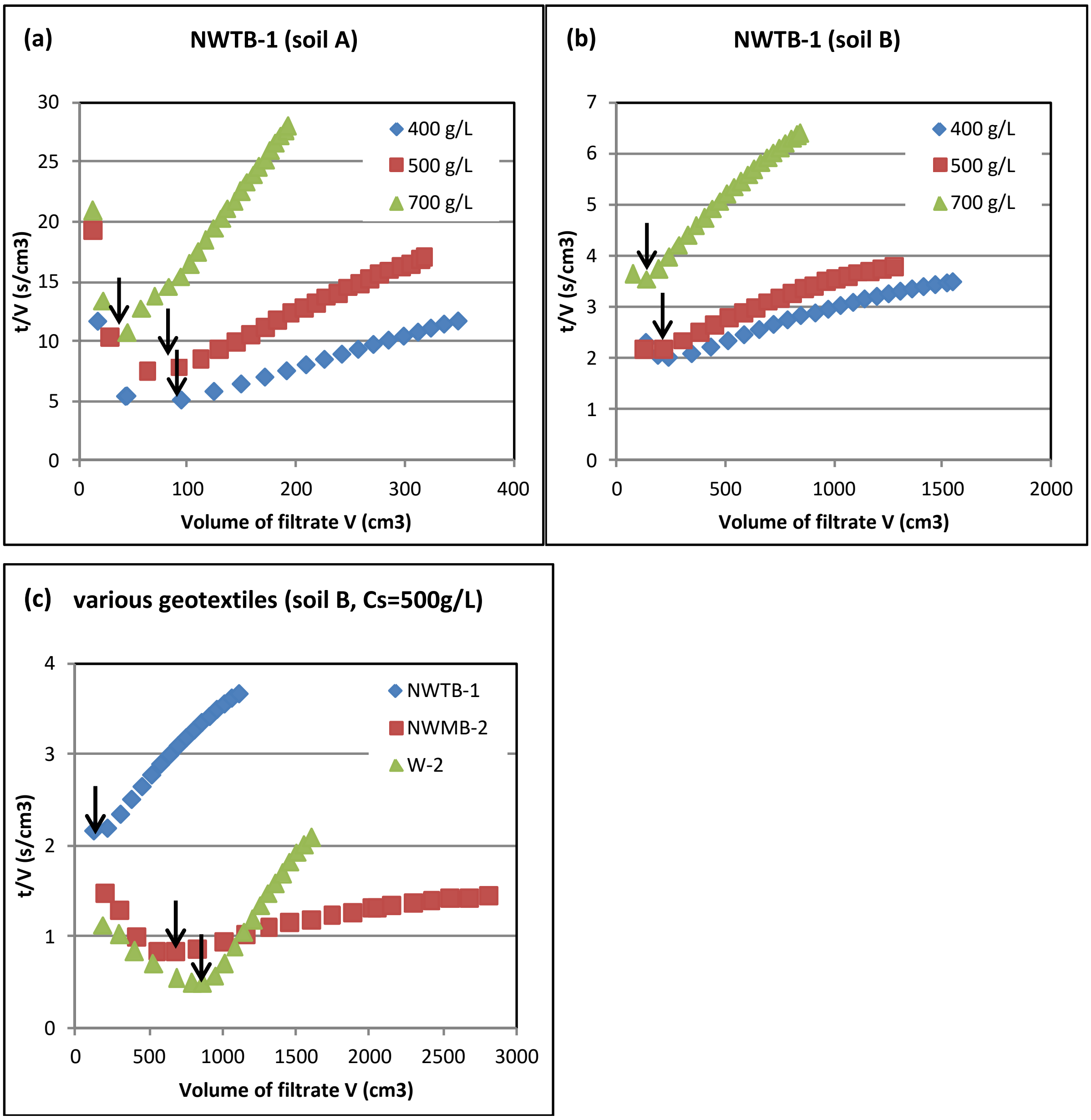


Figure 12. Inverse of time-averaged filtration rate as a function of the volume of filtrate for geotextile filter NWTB-1 and several concentrations of fines for (a) soil A and (b) soil B. (c) Same as panel (b) but for a concentration of fines of C_s = 500 g/L and for various geotextile filters.

Table 1. Particle-size distribution for soils used in filtration tests.

Soil	d_{10} (mm)	d_{50} (mm)	d_{60} (mm)	d_{85} (mm)	CU
A	0.0014	0.005	0.06	0.016	4.5
B	0.0051	0.045	0.067	0.13	13

Table 2. Assumptions of flow and concentrations of solid fines used in tests.

Sludge flow condition	Concentration of solid fines (g/L)			
Constant head (10 kPa)	400	500	700	
Constant flow (0.5 L/min.)	70	100	200	300

Table 3. Main physical and hydraulic characteristics of the various geotextiles tested.

Geotextile	Structure	O_{90} (µm) (EN ISO 12956)	Water capacity normal to plane (mm/s) (EN ISO 11058)	Mass per unit area (g/m^2) (EN ISO 9864)
NWTB-1	Thermally bonded nonwoven	<50	8	160
NWTB-2		<50	1	220
NWTB-3		61	20	125
NWTB-4		140	50	125
NWMB-1	Needle punched nonwoven	91	105	190
NWMB-2		54	14	800
W-1	Woven	109	13	327
W-2*		63	127	

Table 4. Soils tested with various geotextiles, hydraulic conditions and concentrations of fines.

Hydraulic conditions	Constant flow (0.5 L/min)				Constant head (10 kPa)		
Concentration of fines (g/L)	70	100	200	300	400	500	700
Geotextile	Soil tested						
(NWTB-1)	A, B	A, B	A, B	B	A, B	A, B	A, B
(NWTB-2)	A, B	A, B				A, B	A, B
(NWTB-3)	B	B				B	B
(NWTB-4)	B	B				B	B
(NWMB-1)		A, B	A, B		A, B	A, B	A, B
(NWMB-2)		A, B	A, B	B	A, B	A, B	A, B
(W-1)		A, B	A, B		A, B	A, B	A, B
(W-2)	B	A, B	A, B	B	A, B	A, B	A, B

Table 5. For constant-flow conditions, system efficiency is given in terms of percent of cumulated mass sludge that passes through the filter per theoretical cumulated mass of same. “cnf” and “cfnst” indicates respectively “cell not filled” and “cell filled but filter not stabilised”.

Soil	Soil A			Soil B			
Concentration of fines (g/L)	70	100	200	70	100	200	300
NWTB-1	12%	11%	3%	cnf	cnf	40%	13%
NWTB-2	16%	7%		cnf	cnf		
NWTB-3				cnf	cnf		
NWTB-4				cnf	cnf		
NWMB-1		cnf	cnf		cnf	cnf	
NWMB-2		22%	21%		cnf	cnf	cnf
W-1		cnf	cnf		cnf	cnf	
W-2		35%	8%		cnf	cnf	cfnst

Table 6. For constant-head conditions, level of stabilization of the system observed in the first set of tests as determined by the evolution in time of the mass of sludge that passes through the filter and/or the mass of fines that passes through the filter. “S” indicates a stabilised system (i.e., fines are blocked by filter after a certain time), and “U-S” indicates an unstabilised system (i.e., fines continue to pass through filter over time).

Part 1: Tests were stopped based upon visual observation that fines were blocked by filter.

Soil	Soil A			Soil B		
Concentration of fines (g/L)	400	500	700	400	500	700
NWTB-1	S	S	S	S	S	S
NWTB-2		S	S		S	
NWTB-3					cnf	U-S
NWTB-4					U-S	U-S
NWMB-1	U-S	S	S	U-S	U-S	S
NWMB-2	S	S	S	U-S	U-S	S
W-1	S	S	S	U-S	U-S	U-S
W-2	S	S	S	S	S	S

Part 2: Same tests as in part 1 above, but tests ran for 90 minutes.

Soil	Soil tested			
Concentration of fines (g/L)	300	400	500	700
NWTB-1	B*	A, B	A, B	A, B
NWMB-2			B	
W-2			B	

Table 7. Dependence of theoretical hindered settling S_h during the "transit time" on the theoretical particle diameter D_h and on the sludge concentration C_s, for soils A and B.

S_h (mm)	C_s = 70 g/L	C_s = 100 g/L	C_s = 200 g/L	C_s = 300 g/L
D_h (10 μm)	86	82	71	61
D_h (20 μm)	>300	>300	>250	>200

Table 8. Under constant-head conditions and for soil B, table gives average sludge mass and average solid mass that passes through the geotextile filter after cell is filled. (a) Comparison of different geotextiles for a given solid concentration of fines in the sludge (C_s = 500 g/L) and (b) comparison of solid concentration of fines in the sludge for geotextile NWTB-1.

(a) Soil B (C_s = 500 g/L)	Average sludge mass passing through geotextile (g/min)	Average solid mass passing through geotextile (g/min)	Average mass of water passing through geotextile (g/min)
NWTB-1	14.2	0.0	14.2
NWTB-2	20.0	not measured	not measured
NWTB-3	17.7	not measured	not measured
NWTB-4	87.0	not measured	not measured
NWMB-2	35.1	0.4	34.7
W-2	13.8	0.0	13.8

(b) Soil B, NWTB-1	Average sludge mass that passes through geotextile (g/min)	Average solid mass that passes through geotextile (g/min)	Average mass of water that passes through geotextile (g/min)
C_s = 400 g/L	15.4	0.0	15.4
C_s = 500 g/L	14.2	0.0	14.2
C_s = 700 g/L	8.4	0.0	8.4

Table 9. Same as Table 8(b) but for soil A and geotextile NWTB -1.

Soil A, NWTB-1	Average sludge mass that passes through geotextile (g/min)	Average solid mass that passes through geotextile (g/min)	Average mass of water that passes through geotextile (g/min)
C_s = 400 g/L	3.9	0.0	3.9
C_s = 500 g/L	2.9	0.0	2.9
C_s = 700 g/L	1.7	0.0	1.7

Table 10. Specific cake resistance α measured in second series of tests, which ran for 90 minutes.

Specific cake resistance α (m/kg)			
Concentration of fines (g/L)	400	500	700
Soil A			
NWTB-1	4.7×10^{11}	5.6×10^{11}	1.1×10^{12}
Soil B			
NWTB-1	1.6×10^{10}	1.7×10^{10}	3.6×10^{10}
NWMB-2		$8.8 \times 10^{8**}$	
W-2		2.8×10^{10}	