Filtration of clayey sludge by the use of geotextiles: experimental study

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ABSTRACT: The filtration of granular soils in suspension in water has been widely studied and is used since many years in different applications. Nevertheless, the geotextile filtration of fine particles in suspension in water, or of clayey sludge, is more complex; in practice when geotextiles are used in such application, additives, like flocculants, are generally considered necessary to postpone (or avoid) the apparition of the "filter cake". The original present study aims to precise more systematically the influence of the geotextile characteristics on the formation of the filter cake, without flocculants. The influence of the key parameters is analysed and discussed in detail. They include the type of soil, the concentration of fines, the type of water flow and the type of geotextile, by a specifically developed testing device with one horizontal cell ended by the tested geotextile placed vertically. The performance of the different systems is compared based on the analysis of the retained and passing soils, the time for clogging, and the global characteristic of the "filter cake". As the permeability of the system will change with the creation of this "cake", the initial permeability of the geotextile is less important than the influence of the geotextile on the creation process of the filter cake. Some criteria to optimize the selection of the geotextile for filtration of fine particles in suspension are proposed. This study allows showing the interest of geotextiles of low opening size and between these different geotextiles with $O_{90} \leq 60$ µm, the thermally bonded nonwoven structure seems to offer the best compromise between the opening size and the support for a filter cake suitable for the long-term permeability of the system.

Keywords: filtration, clayey sludge, fine, suspension, geotextile.

1 INTRODUCTION

The filtration of granular soils in suspension in water has been widely studied and is used since many years in different applications. Nevertheless, the filtration of fine particles in suspension in water, or of clayey sludge, by a geotextile is more complex; in practice when geotextiles are used in such application, additives, like flocculants, are generally considered necessary to postpone (or avoid) the apparition of the "filter cake".

The predicting of geotextile clogging by fine particles in suspension in water without additives has been studied either by empirical models describing the increase of head loss in the geotextile due to clogging or by means of geotextile clogging tests. These works, realised for different geotextiles, as well as for different "low" concentrations of fine particles in water, allow estimating a maximum acceptable quantity of particles injected on the geotextile, until clogging occurs. This quantity is in most cases very low. More recently, studies of filtration of fine-grained mineral sludge confirm the feasibility of this solution for dewatering of high clay content materials with low hydraulic conductivity (Bourgès-Gastaud, S., et al., 2014). Nevertheless, these more recent studies confirm that the influence of the geotextile is mainly observed at the early stage before creation of the “filter cake”. After that stage, the “filter cake” becomes the major contributor to the permeability of the system clayey sludge - filter cake - geotextile. The governing performance parameters include, but are not limited to, the concentration of particles, the particle sizes distribution, the type of water flow and the geotextile characteristics (e.g. opening size, permeability normal to the plane, structure).

The original present study aims at precising more systematically the influence of the geotextile’s characteristics on the formation of the filter cake of fines. The influence of the key parameters is analysed and discussed in detail. They include (a) the type of soil (well graded or uniform) (b) the concentration of fines (6 different concentrations from 70 g/l to 700 g/l), (c) the type of water flow (constant flow or constant head) and (d) the type of geotextile (7 types: thermally bonded nonwoven, needle-punched nonwoven and woven).

A specific testing device has been developed with one horizontal cell ended by the tested geotextile placed vertically. The communication presents the performance of the different systems compared based on the analysis of (1) the retained and passing soils, (2) the time for clogging, (3) the global characteristics of the “filter cake”. As the permeability of the system will change over time with the creation of the “filter cake”, the initial permeability of the geotextile is less important than the influence of the geotextile on the creation process of the filter cake and its characteristics. Criteria retained for optimization of the design of the geotextile for filtration of fine particles in suspension can be summarized as follow: (1) significant increase in solids concentration upstream of the geotextile, occurring over a relatively short period of time, (2) initial loss of fines through the geotextile, but limited over time, (3) effluent quality acceptable with respect to environmental impact.

2 PRESENTATION OF THE AIM AND THE BASIS OF THE EXPERIMENTAL STUDY

2.1 *General mechanism concerning filtration*

The principles of filtration of particles in suspension have been studied and described by many authors (Moo-Young et al. 2002), (Faure et al., 2006), (Lawson, 2006), (Muthukumaran & Ilamparuthi, 2006), (Delmas, 2007). Although the parameters influencing the behaviour may be the same, it is generally agreed by all the authors that the mechanisms involved in the filtration of particles in suspension, are completely different from the classical filtration in soil drainage applications. In the classical applications, the role of the geotextile filter is to act as a catalyst: it promotes equilibrium of particles after limited washout of finer particles by inducing a self-filtration zone (bridging) at the interface. The design of the geotextile is based on three criteria: retain the largest particles and stabilize the skeleton, let the finer particles pass and keep a minimum permeability normal to the plane. The filtration of particles in suspension constitutes a very different filtration environment compared to conventional filtration in soil and generally geotextile filter criteria therefore have little relevance. Furthermore, the governing performance criteria for filtration of particles in suspension are different to that of conventional soils.
There are three overall performance criteria for the filtration of soil particles in suspension:
- upstream there must be a significant increase in solids concentration, and this must occur over a relatively short period of time;

- downstream there can be an initial loss of solids through the geotextile but the total amount passing through must be limited and this must stop, or be reduced significantly, after a relatively short period of time;
- downstream the effluent quality must be acceptable with respect to environmental impact and preferably remain constant over time.

The filtration and dewatering of the soil is driven by the filtration behaviour of the geotextiles and the properties of the layer/filter cake of solids deposited on the geotextile. Design parameters influencing the filtration include but are not limited to:
- the concentration of particles upstream of the geotextile;
- the particle size distribution;
- the flow (e.g. constant flow or constant head).
- the difference of pressure between the upstream and downstream of the geotextile.

The control parameters of the geotextile are the usual filtration characteristics, opening size and permeability normal to the plane, but also the structure of the geotextile filter. As the permeability will change while increasing "clogging" of the geotextile occurs, the initial permeability of the geotextile is less important than the permeability of the system over time.

When the geotextile is clean, filtration of the slurry will be governed by the properties of the geotextile. As the filtration proceeds, one may expect a layer of solids (filter cake) deposited on the surface of the geotextile. The extent of filter cake formation and its stability will depend on the flow process, on the concentration of particles, on the flow, on the difference of pressure between the upstream and downstream of the geotextile and on the structure of the geotextile (Soo-Khean Teoh, et al., 2006; Chi Tien, Bandaru V. Ramarao, 2011). However, in the case where a filter cake is formed, the filtration will, after a short period, be controlled not by the properties of the geotextile, but by the properties of the filter cake. In such a case the filtration process can be evaluated by the theory of filtration in porous media. One main governing parameter will be the pressure drop through the filter cake that builds as the thickness of the cake increases. This increase in pressure drop is partially due to increased length of the channels that the water passes through and is therefore based on a different mechanism than permeability reduction due to clogging of the geotextile.

Another main parameter will be the retention or removal efficiency for particles in the slurry. Also this may after a relatively short period be more controlled by the properties of the filter cake than the properties of the geotextile, the characteristics of the geotextiles are important to control the creation of the cake and its stability. The particle sizes and particle size distribution of the solids in the slurry are important for the filtration properties of the filter cake. In principle, the compressibility of the filter cake is also of importance.

2.2 *Aim of the study*

The present experimental study aims at precising systematically the influence of the geotextile characteristics on the formation of the filter cake of fines. Some key parameters influencing the system have been analysed in the test program. More specifically, four parameters have been studied:
(a) the granularity of soil (well graded or uniform) ;
(b) the concentration of fines (6 different concentrations from 70 g/l to 700 g/l);
(c) the type of water flow (constant flow or constant head)
(d) the type of geotextile (7 types: thermally bonded nonwoven, needle-punched nonwoven and woven).

As the permeability of the system will change with the creation of the "filter cake", the performance of the different systems is compared on basis of the analysis of the retained and passing soils, the time for clogging and the global characteristic of the "filter cake".

A specific testing device has been developed with one horizontal cell ended with the tested geotextile placed vertically. This design aims at reducing the effect of the sedimentation of the fines during the test on the creation of the cake and the filtration behaviour.

3 EXPERIMENTATION CONCEPT

The design of the experimentation has been developed to allow an easy systematic study of the influence of the geotextile characteristics on the formation of the filter cake. The key parameters governing performance of the filtration system include, but are not limited to, the concentration of particles, the particle sizes distribution, the type of water flow and the geotextile characteristics (e.g. opening size, permeability normal to the plane, dimensional structure). The different parameters of the testing are presented hereunder.

3.1 *Assumptions, test parameters and test conditions*

3.1.1 *Type of soils used for the filtration tests*

The clayey sludge may be characterized by the granularity but also by the type of clay particles. In the present study, it has been chosen to focus only on the influence of the granularity curve shape with two main types of soils, uniform and well graded.

The two soils tested are a kaolinite, named soil (A), with a uniform granularity (CU = 4.5) and a well graded soil, named soil (B), formed by the combination of kaolinite and silt (CU = 13). The particle size distributions of soils are presented in figure 1 and in table 1.

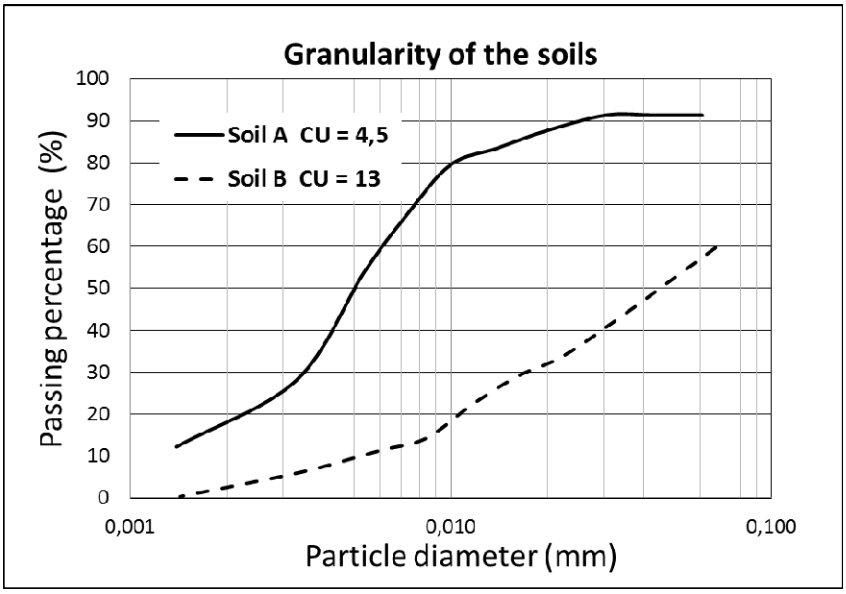


Figure 1. Particle size distribution of the soils used in the filtration tests

Table 1. Particle size distribution of the soils used in the filtration tests

Soil	d10 (mm)	d50 (mm)	d60 (mm)	d85 (mm)	CU
A	0.0014	0.005	0.06	0.016	4.5
B	0.0051	0.045	0.067	0.13	13

3.1.2 *Sludge properties, concentration of particles and flow conditions*

The two soils have been tested at different concentrations of particles for different flow conditions. For the lowest concentrations, a constant flow of the sludge has been used. A flow value of 0.5 L / min is maintained until a pressure of 40 kPa is reached upstream the geotextile filter; after the test is continued with a constant head. For the highest concentrations, a constant head condition (with a maximum of 10 kPa) has been used. The table 2 presents the different conditions of the tests performed.

Table 2. Assumptions of flow and concentrations tested.

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

3.1.3 *Testing device and setup of the apparatus*

Figures 2 and 3 present the test cell used for the filtration of the sludge. Upstream a tank with a stirring tool allows maintaining a constant and uniform predefined concentration of fines in the incoming sludge. The monitored pumping system fixes and controls the flow conditions at the entrance of the filtration cell. A pressure sensor is placed at the top of the cell. The 15 cm diameter filtration geotextile is held by a metallic grid which avoids most of the deformation of the geotextile during the test. The passing sludge is regularly weighted during the filtration test and collected for further analysis.

It can be noted that the cell (volume $8.8*10^{-3}$ m^3) has been placed horizontally and the filtration geotextile vertically. This was done to allow a clear distinction of the settling and sedimentation behaviour with the filtration behaviour.

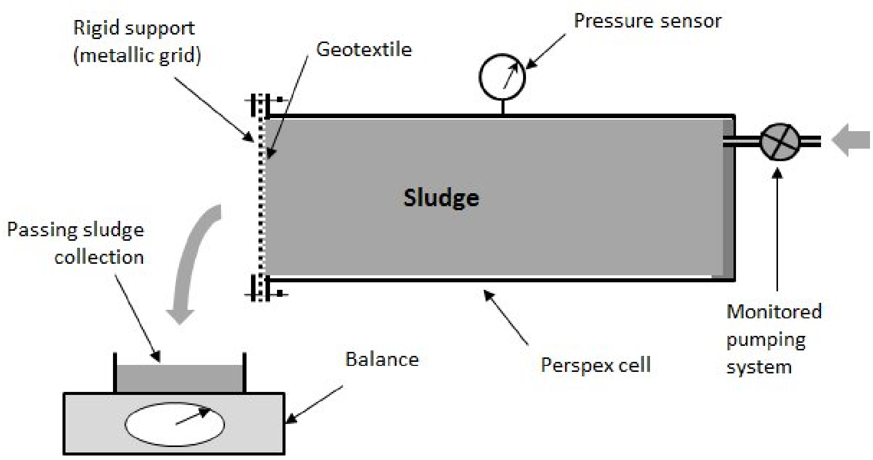


Figure 2. Principle of the test cell used for the filtration of the sludge.

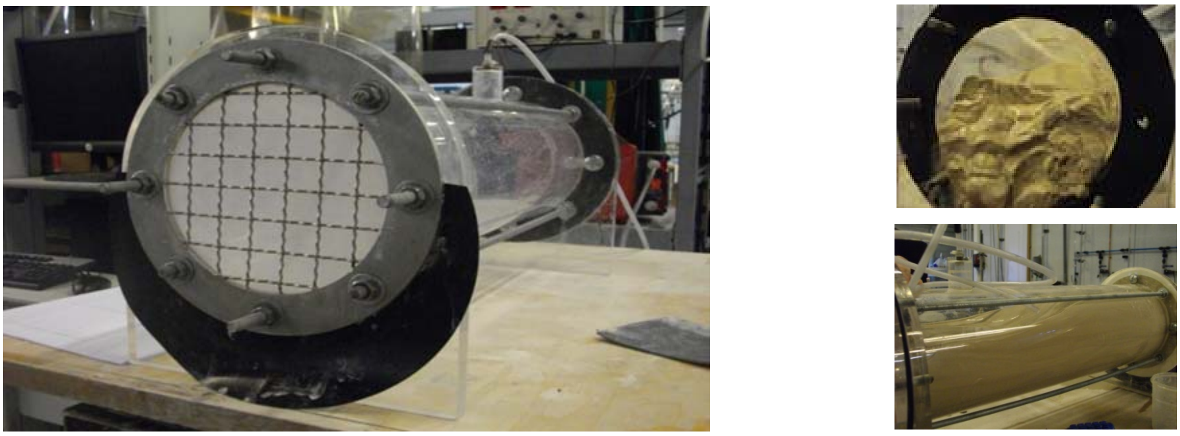


Figure 3. View of test cell before the filling by the sludge (left) and after the test (right); the effect of the sedimentation and the settling inside the cell can be seen on the right photos.

3.1.4 *Geotextiles tested and corresponding test conditions*

Table 3 (3-1 & 3-2) presents the synthesis of the characteristics of the different geotextiles tested with the corresponding configuration of test procedures.

Table 3-1. Measured identification and hydraulic characteristics of the different geotextiles tested. * to simulate a woven with an opening size close to 50 – 60 µm, a metallic sieve has been used (W-2), due to the difficulty to find woven geotextile with such a small opening size.

Geotextile	Structure	O_{90} (µm) (EN ISO 12956)	Water capacity normal to plane (EN ISO 11058)	Mass per unit area (EN ISO 9864)
(NWTB-1)	Thermally bonded Nonwoven	< 50 µm	(-)	(-)
(NWTB-2)		< 50 µm	1 mm/s	(-)
(NWMB-1)	Needle punched Nonwoven	91 µm	105 mm/s	190 g/m²
(NWMB-2)		54 µm	14 mm/s	800 g/m²
(W-1)	Woven	109 µm	13 mm/s	327 g/m²
(W-2)*		63 µm	(-)	(-)

Table 3-2. Soils tested with different geotextiles, hydraulic conditions and concentrations of fines.

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

4 EXPERIMENTAL FILTRATION STUDY RESULTS

4.1 *Observations and parameters followed for the characterisation of the filtration behaviour*

4.1.1 *Observations of the different behaviours*

Depending on the type of geotextile, the concentration and the hydraulic conditions, different behaviors have been observed:

- first case, a large quantity of sludge is passing through the geotextile, the cell cannot be filled, no stable filtration system is established;
- second case, a limited quantity of sludge is passing through the geotextile, the cell is filled and a stabilized system is observed, either;
    - with complete clogging of the geotextile after a certain period of time; no fines but also no water is passing at the end of the test;
    - or with a stabilized filtration system; after a certain period of time no fines are passing, but water is still passing through the system.

Table 4 presents, for the lowest fines concentrations and for constant flow conditions, the system efficiency, evaluated by the ratio (cumulated mass of passing sludge) / (cumulated mass of the theoretical sludge flow). It can be observed that in a large majority of the cases the cell cannot be filled, this means that the geotextile openings are too large to create a filter and/or that the concentration of fines is too low.

Table 4. For constant flow conditions, system efficiency, evaluated by the ratio (cumulated mass of passing sludge) / (cumulated mass of the theoretical sludge flow).

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

*cnf : cell not filled

Similarly, the table 5 presents, for the highest fines concentrations and for constant head conditions, the level of stabilization of the systems, evaluated by the passing sludge mass and/or passing fines mass evolution.

The figure 4 presents typical behaviors of filtration cell. After emptying the cell at the end of the test, the photo (a) shows the cake formed at the contact with the geotextile and at the bottom of the cell the accumulation of fines linked to the settling and sedimentation phenomenon. The photo (b) confirms the interest of the vertical placement of the geotextile showing that the creation of the cake is not influenced by this settling and sedimentation of the fines inside the cell and that the observations made correspond largely to the filtration system behaviour. The photo (c) shows the cake created in the case of the (NWTB-1) geotextile.

Table 5. For constant head conditions, the level of stabilization of the systems, evaluated by the passing sludge mass and/or passing fines mass evolution: (S) stabilized system (no fines passing after a certain time), (U-S) unstabilized passing system (fines continue passing during time).

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

(a) (b) (c)

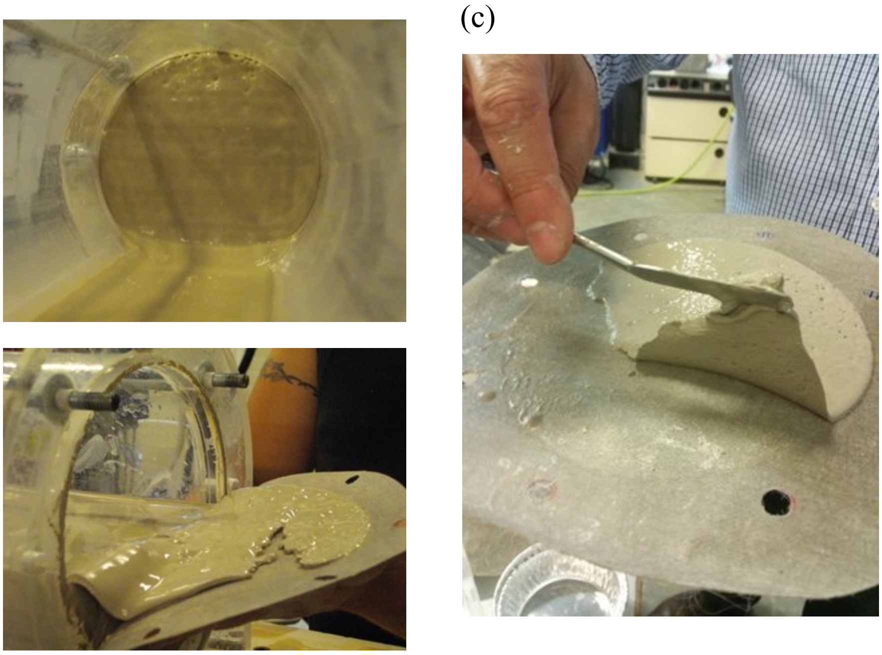


Figure 4. View of typical observations of filtration cell at the end of the test.

4.1.2 *Parameters followed for the characterisation of the filtration behaviour*

When the filtration is established, one can evaluate and compare the behaviours of the different systems based on the following criteria:
- (1) the effluent quality acceptable with respect to environmental impact; this means that both the total mass of sludge and more precisely the total mass of fine particles shall be controlled and minimized;
- (2) when fine particles are passing through the geotextile during the test, this shall be limited during short period of time and the phenomenon shall stabilize; in this respect, it can be considered that clean water continuing to go through the system is a positive point;
- (3) a significant increase in solids concentration upstream of the geotextile, occurring over a relatively short period of time, may also be considered as a positive behaviour as this is clearly a consequence of fulfilling the criteria (2).

The following analysis of the tests results is based on these three main criteria.

4.2 *Results of the experimental study: comparison of the different geotextiles*

For this analysis, only the tests where a filtration system behaviour has been observed are analysed; this means that for constant flow conditions the tests where the cell could not be filled are excluded, are considered as a failure to establish a stabilized filtration.

4.2.1 *Cumulated mass passing through the geotextile and filtration efficiency evaluation*

Constant flow conditions

For the well graded soil (B), it can be seen (Table 4) that, due to the low concentrations in most of the tests, the cell could not be filled. It has been observed that the coarser particles are settling in the cell before reaching the geotextile filter and then the finest particles in suspension reaching the filter are too small to be filtered, and/or to create a cake. The granularity curves of the corresponding passing soil shows that 80 % of the particles are smaller than 30 µm for all geotextiles. Considering that all geotextiles tested have an opening size (O_{90}) larger, or equal, to 50 µm and that 40 % of passing particles of the initial granulometry of the soil B have a diameter (≤ 30 µm), the observation shows that the system behaves as a sludge with fine particles having a diameter (≤ 30 µm) with much lower concentrations of fines than the nominal ones: 38 g/L (instead of 70 g/L nominal), 40 g/L (instead of 100 g/L nominal) and 80 g/L (instead of 200 g/L nominal). Further tests with higher concentrations should confirm this phenomenon.

On the contrary for the uniform soil (A), a better behaviour is observed. This is probably linked to the fact that, due to the nature of the particles, in that case no important settling or sedimentation is observed in the cell before the sludge reaches the geotextile filter. From the Table 4, it can be seen that:

- the geotextiles of larger opening size (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, a filter behaviour is observed with a reduction of the mass of passing sludge compared to the theoretical flow; from the higher reduction to the lower, the geotextiles are classified as follows, for the same concentration (100 g/L): (NWTB-2), (NWTB-1), (NWMB-2), (W-2). Similarly for a same geotextile (NWTB-1) a higher reduction of the mass of passing sludge is observed when the concentration increases. These results can also be shown with the ratio of the (solid mass retained in the filtration cell) divided by the (sludge mass passing through the geotextile) (Figure 5).

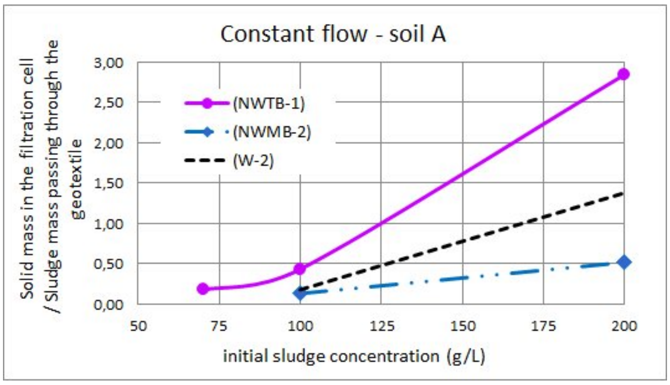
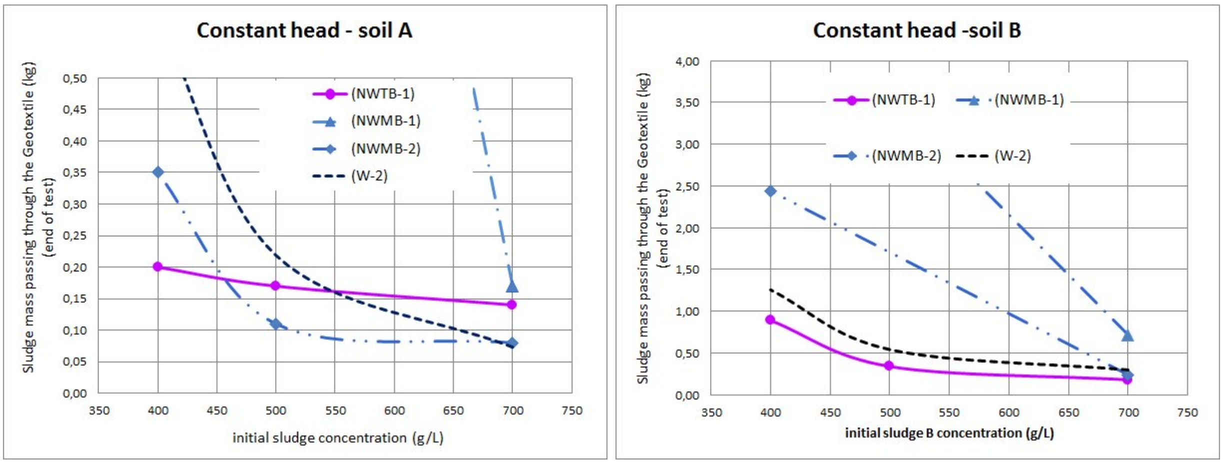


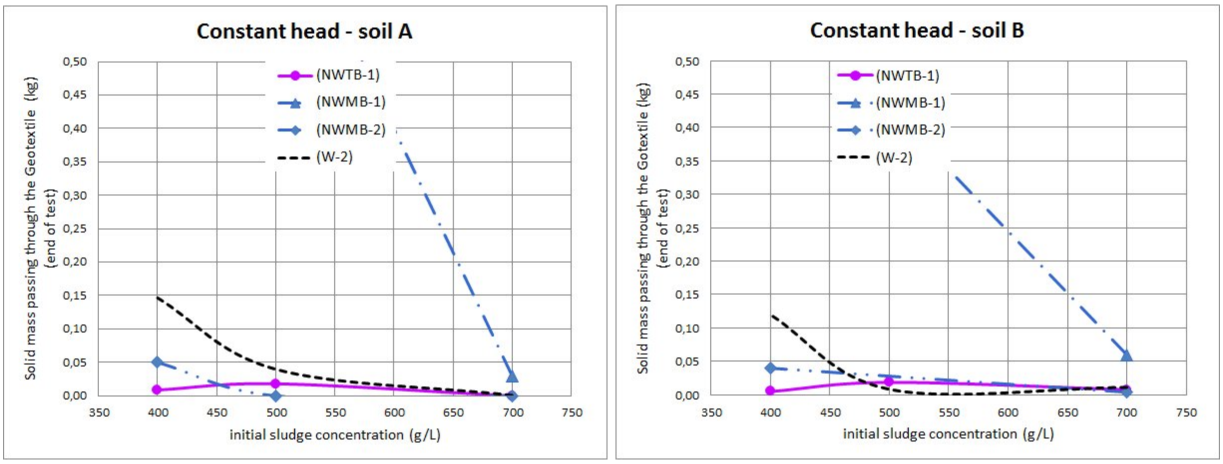
Figure 5. Compared ratio of the (solid mass retained in the filtration cell) divided by the (sludge mass passing through the geotextile) depending on the geotextile and the initial sludge concentration.

Constant head conditions

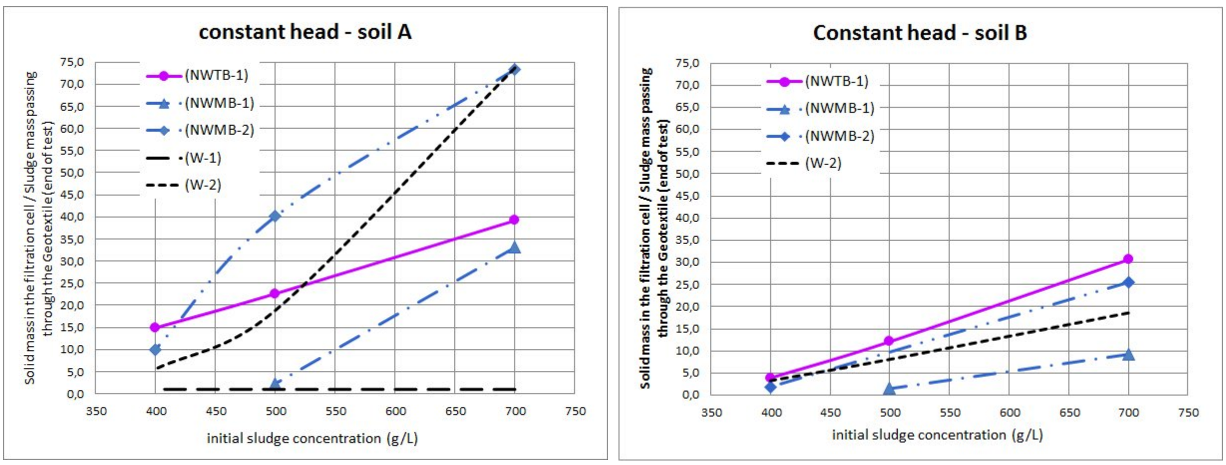
Figure 6 presents the compared behaviors depending on the geotextile and the initial sludge concentration in constant head conditions.



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



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



(c) Solid mass in the filtration cell / Sludge mass passing through the geotextile measured at the end of the test

Figure 6. Compared filtration behaviors depending on the geotextile and the initial sludge concentration in constant head conditions

For this first series of tests, if the filtration behaviour has been stabilized (no fines passing observed) the test has been stopped. To evaluate the effluent quality with respect to environmental impact as defined in the first point of the paragraph 4.1.2, the two (a) graphs presenting the sludge mass passing through the geotextile measured at the end of the test, and the two (b) graphs presenting the solid (fines) mass passing through the geotextile measured at the end of the test, allow to compare the different products:

- it can be observed that the mass of sludge, and similarly the mass of fines, passing through the geotextile decreases when the fines concentration in the sludge increases, both for soil (A) and for soil (B); this can be explained by a quicker creation of the cake in contact of the geotextile in case of an higher concentration of fine;
- the geotextiles of higher opening size (e.g. NWMB-1) let pass more sludge, and thus more fines, during the test;
- for both soils, uniform and well graded, the geotextiles with smaller opening size (e.g. NWTB-1, W-2, NWMB-2) reduce the quantity of fines passing through; and in the meantime the mass of sludge passing through is not negligible; which means that water is passing through the established filtration system.

For this reason, it is interesting to look at the filter efficiency as defined in the paragraph 4.1.2 point (3). It may be evaluated, for instance, by the ratio (Solid mass in the filtration cell) divided by (Sludge mass passing through the geotextile) measured at the end of the test (Figure 6 –(c)); the highest ratio corresponds to a better efficiency. It can be seen as a general trend that the lowest is the opening size, the better is the efficiency. Nevertheless, at this stage of the study, it would be interesting to evaluate in more details the long term behaviour of the filtration system (geotextile + cake) and to compare the different geotextiles for a longer period of time. The fact that in this first study the tests have been stopped based on visual observation of the passing fines doesn't allow to characterize the cake formed and to evaluate its long-term behaviour. Nevertheless, the present results confirm a clear difference between the different types of geotextiles. This justifies the next step of this study on the characterisation of the different cake resistances with regards to the geotextile used. The first results of this second study, seems to confirm that the structure of the product have a significant influence on the filtration behaviour. These results will be presented in another publication.

Particle sizes distribution of the passing soils

The particle size distribution of the passing soil has been measured and is presented, for instance for soil B in the constant flow conditions, in the figure 7.

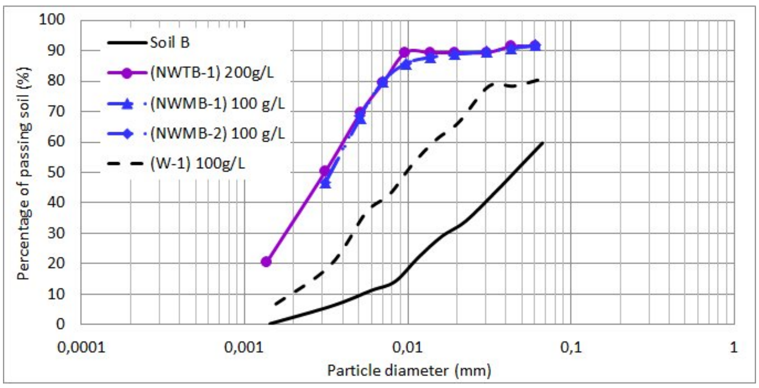


Figure 7. Compared particle size distribution of the passing soil for constant flow conditions (soil B)

The analysis of the grain size distributions obtained on the passing soils shows that for all nonwoven products with a small opening size (< 50 µm to 91 µm), the passing soil is made of fine particles with a diameter ≤ 10 µm, which are not blocked by the geotextile when in suspension when the cake is not formed. For the woven product with a larger opening size (109 µm), larger particles with a diameter up to 30 to 40 µm are not blocked by the geotextile. This confirms the interest of geotextiles with small opening sizes.

5 DISCUSSION AND CONCLUSION

The present study allowed to precise the influence of the geotextile characteristics on the filtration behaviour when submitted to a flow of fines in suspension. Different parameters have been analysed and discussed in detail: the type of soil (well graded or uniform), the concentration of fines (6 different concentrations from 70 g/l to 700 g/l), the type of water flow (constant flow or constant head) and the type of geotextile (7 types: thermally bonded nonwoven, needle-punched nonwoven and woven).The specific testing device with one horizontal cell ended by the tested geotextile placed vertically allowed separating the filtration behaviour from the settling and sedimentation phenomenon. The performance of the different systems has been compared on basis of the analysis of the retained and passing soils. It allows to propose a step by step analysis for optimization of the design of the geotextile for filtration of fine particles in suspension: (1) stabilization of the filtration process, (2) significant increase in solids concentration upstream the geotextile, occurring over a relatively short period of time, (3) initial loss of fines through the geotextile limited during time ensuring an acceptable effluent quality with respect to environmental impact, (4) long term acceptable permeability of the filtration system to water flow.

This study allows showing the interest of geotextiles of low opening size and between these different geotextiles with O_{90} ≤ 60 µm, the thermally bonded nonwoven structure seams to offer the best compromise between the opening size and the support for a filter cake suitable for the long-term permeability of the system. This first step needs to be confirmed by the ongoing specific study on the characterisation of the filter cake performance and its long term behaviour.

6 ACKNOWLEDGEMENTS

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