Technical Paper by W. Haegeman and W.F. Van Impe

FILTRATION PERFORMANCE TESTING OF GEOTEXTILES FOR VACUUM CONSOLIDATION DRAINS

ABSTRACT: The effectiveness of a drainage system used for vacuum consolidation of dredged sludge is very important since it affects consolidation of the sludge and the removal of drained water. The performance of soil-geotextile systems in a filtration test under unidirectional flow is reported for five drains. A new apparatus was developed for filtration tests under a simulated vacuum pressure and tests were conducted with sludge and different nonwoven geotextiles in order to evaluate the clogging potential and retention capacity of these materials under rather severe combinations of geotextile and soil characteristics. Testing under hydraulic gradients of 40 to 60, and for a duration of 200 hours, yielded a steady state permeability value for four sludge-geotextile systems. Progressive increase of the permeability was observed for one geotextile. Results from the filtration tests are compared and discussed.

KEYWORDS: Filtration, Sludge, Geotextile, Permeability, Soil retention, Piping.

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1 INTRODUCTION

A vacuum consolidation technique was used to increase the storage capacity of a 5 m thick submerged dredged sludge basin (Figure 1). Two rows of 80 mm diameter horizontal drains at a 1 m centre-to-centre spacing were installed at the bottom of the basin at depths of 23 and 24 m. The nonwoven geotextiles enveloping the drains are essential for separation, drainage, and filtration purposes. The geotextiles act as a filter through which drainage is allowed, while sludge particles are retained from migrating and blocking the vacuum system.

The pore size distribution of geotextiles is dependent on the applied stresses because geotextiles are compressible. As a consequence, an applied vacuum pressure has a significant influence on the permeability and the filtration capacity of geotextiles. To evaluate this influence, and the performance of the drains, the filtration process was modelled in an apparatus containing the geotextile and the dredged slurry under a high pressure with a correspondingly high hydraulic gradient. Five brands of nonwoven geotextiles and one sludge sample, which has a particle size distribution with 80% by weight passing the 63 μm sieve, were used in the testing program.

The purpose of the current paper is two-fold: to present the specimen preparation, installation, and testing procedure for a sludge-geotextile system in a consolidation-type, long-term flow test; and to examine the issues of sludge consolidation and filtration, as well as clogging of the sludge-geotextile system under high hydraulic head conditions.

2 TEST APPARATUS, MATERIALS, AND METHODOLOGY

2.1 Apparatus

A permeameter was designed and constructed at Ghent University in Belgium to assess the long-term flow rate behaviour of nonwoven geotextile filters. For each test, a site specific soil layer is placed above a candidate geotextile specimen and a liquid permeant is passed through the system under a high hydraulic head. A cross section of the test apparatus is shown in Figure 2.

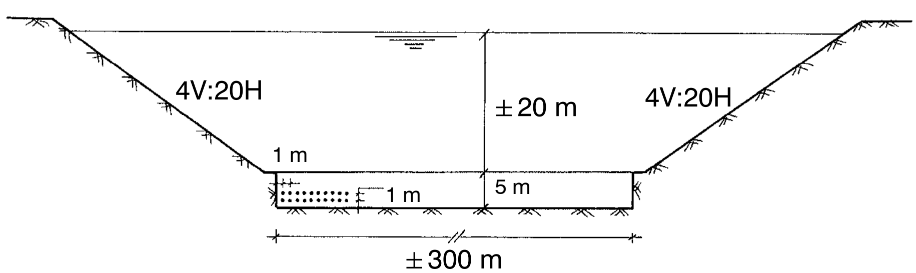

Figure 1. Schematic of a dredged sludge basin submerged under water.

Note: Slopes are exaggerated.

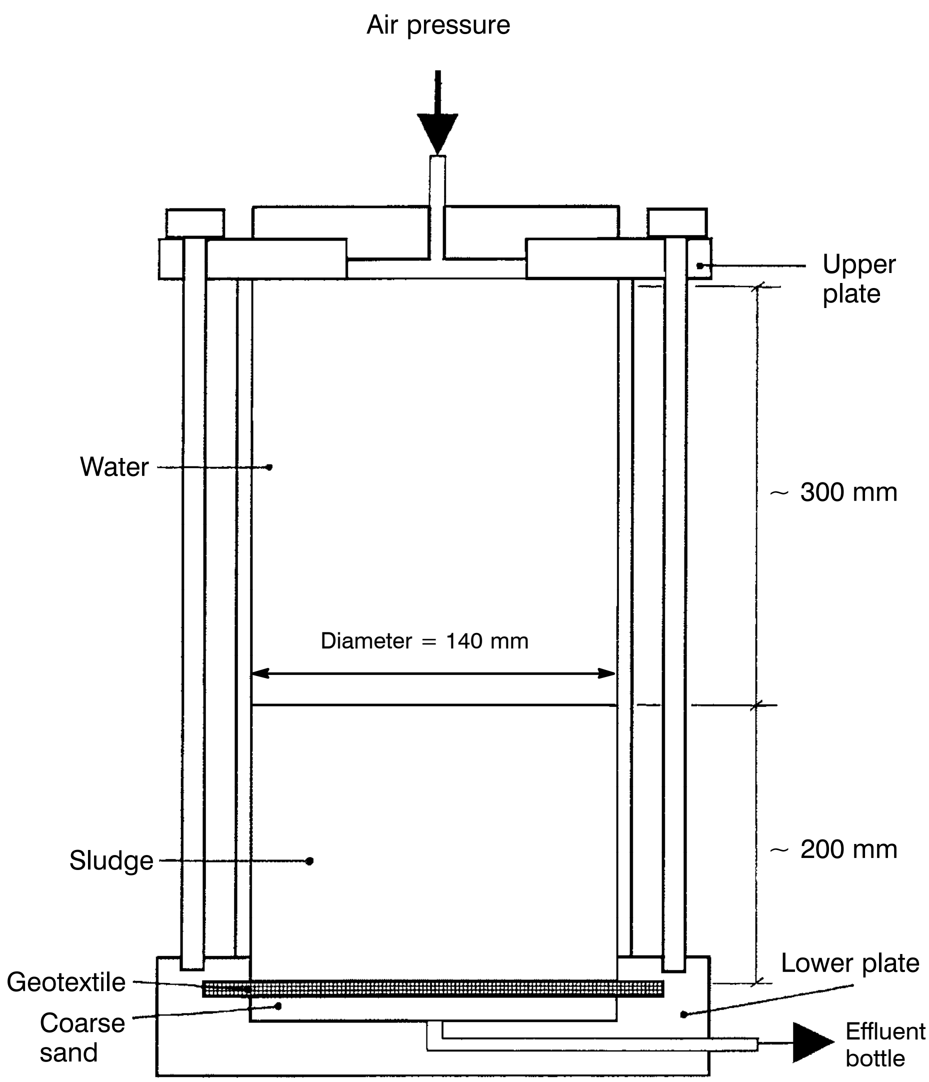

Figure 2. Schematic view of the filtration apparatus.

The body of the permeameter is a 140 mm diameter perspex cell, sealed with an anodised aluminium upper and lower plate that accommodates a sludge layer approximately 200 mm high, which is overlain by ± 300 mm of water. Through the top plate, an air pressure of 80 kPa is applied on the surface of the water to simulate a vacuum pressure in the sludge-geotextile system. A geotextile specimen is placed on top of a coarse sand layer and secured between the two sections of the lower plate. A layer of silicone gel is applied around the perimeter of the geotextile to minimize in-plane flow and leakage. Three collection ducts are located below the permeameter cell to catch the effluent and any soil particles that pass through the geotextile for a subsequent weight determination.

2.2 Materials

Sixteen borings were taken from a sludge disposal basin (field site) and undisturbed soil samples were taken for laboratory analyses. Nineteen laboratory tests were performed to determine the physical properties of the sludge and the results are presented in Table 1. The particle size distributions for the sludge specimens are given in Figure 3. Specimens of five brands of nonwoven geotextiles, supplied by the contractor, were used in the current investigation. The O_{90} (where O_{90} is the geotextile pore opening size such that 90% of the pores are smaller than that size) and thickness of the geotextiles were provided and the mass per unit area was measured (Table 2).

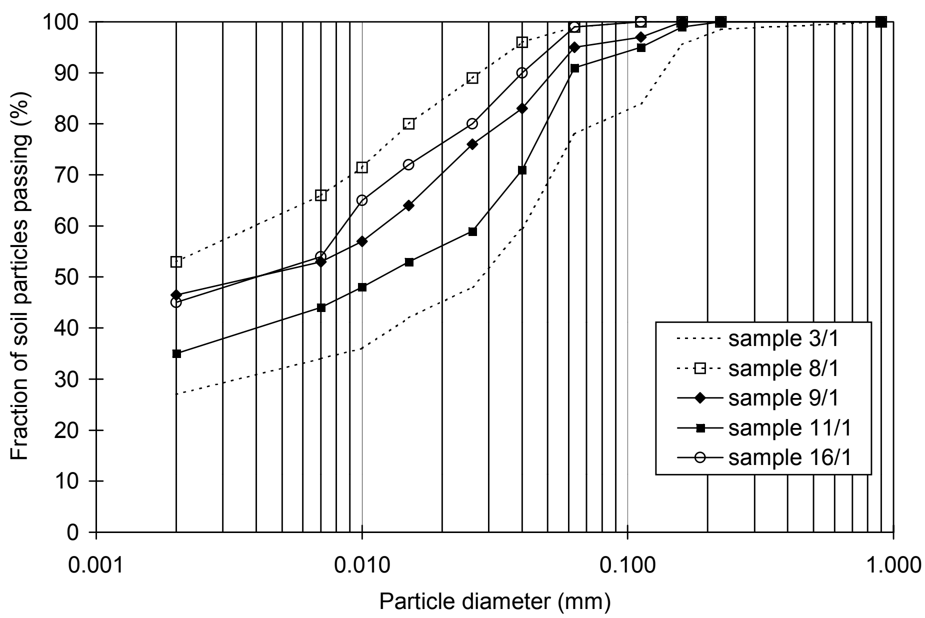

Figure 3. Particle size distribution of sludge specimens.

Table 1. Physical properties of the sludge.

Physical property	Value
Initial moisture content, w_o	91.7 to 160.3%
Liquid limit, w_L	86.3 to 157.3%
Plasticity index, I_p	71.4 to 110.7%
Total volumetric mass, ϱ_n	1,240 to 1,500 kg/m^3
Activity index, A_c	1.9 to 3.0
Organic content	3.8 to 7.4%
Carbon content	16.8 to 25.5%
Vane shear strength, c_u	1.3 to 3.1 kPa
Compressibility index, C_c (at 60 kPa)	0.63 to 1.32

Table 2. Physical properties of the tested nonwoven geotextiles.

Geotextile designation	Brand of geotextile	O_{90} (μm)	Thickness (mm)	Mass per unit area (g/m^2)
G1	Geofelt 200	200	1.8	119.5
G2	Polyprop 300	300	5	601.3
G3	Polyprop 700	700	10	406.7
G4	Cocos	1,000	7.5	367.4
G5	Typar 3337	500	4	116.3

2.3 Methodology

Geotextile specimens were prepared with initial dry unit weights of approximately 4.9 to 6.5 kN/m^3. A geotextile specimen was placed on top of the coarse sand layer and secured between the two sections of the bottom plate. The sand and geotextile were back-saturated with de-aired water for a 24 hour period under low hydraulic head. The sludge was mixed at a natural water content until a homogeneous slurry was achieved. The slurry was then poured onto the geotextile specimen until a height of 200 mm was reached. Finally, the cell was completely filled with de-aired water and, after one day of consolidation, an air pressure of 80 kPa was applied to the top of the water-sludge-geotextile column. All tests were conducted at a temperature of 10°C. The volume of permeant, the room temperature, T, and the height of the sludge and water layer were recorded at different time intervals. The flow rate, q, through the sludge-geotextile system was calculated as a function of time, t, as follows:

$$q = \frac{m}{\rho_T \, \Delta t} \tag{1}$$

where: m = mass of the column effluent; ϱ_T = density of the column effluent at the recorded temperature; and Δt = time interval over which the column effluent was collected.

The variation of the hydraulic gradient during testing was calculated as the ratio of the hydraulic head difference across the sludge-geotextile system to the height of the system. The hydraulic gradient changed due to the changing water level and height of the sludge layer, and varied between 40 to 60.

Carroll (1983) and Akram and Gabr (1997) showed that the potential for piping and subsequent filter clogging, i.e. geotextile clogging, increases when soil-geotextile systems are exposed to high hydraulic gradients. The exposure of geotextile specimens to high hydraulic gradients in filtration tests forces fine particles toward the soil-geotextile interface and, thus, may expediently simulate long-term filtration behaviour. Consequently, it can be argued that, by testing under high hydraulic gradients, long-term filtration behaviour is simulated.

The hydraulic conductivity was calculated based on Darcy's law using the flow rate, geotextile specimen area, and hydraulic gradient. Fine particles passing through the geotextile specimen were retained in an effluent bottle (Figure 2), filtered, and weighed.

To assess the consolidation of the sludge layer during testing, the dry unit weight, γ_d , of the sludge specimens was calculated at different time intervals:

$$\gamma_d = \gamma_{di} \frac{h_i}{h} \tag{2}$$

where: γ_d = dry unit weight at time t; γ_{di} = initial dry unit weight; h_i = initial specimen height; and h = specimen height at time t.

If particles passed through the geotextile, the dry unit weight was corrected accordingly. No correction was made for particles retained in the geotextile because this was measured after testing. Finally, at the end of the filtration test, three sludge specimens were taken along the height of the consolidated sludge layer to determine the volume, mass, and water content and to verify the calculated dry unit weight.

3 RESULTS AND DISCUSSION

The variation of the system permeability with time for the five geotextiles and the variation of the dry unit weight of the sludge during testing are presented in Figure 4. In all cases, variations in the coefficient of permeability, k, occur in three distinct stages.

In the first stage, k decreases markedly to approximately 2×10^{-9} m/s for the G5, G4, and G3 geotextiles and approximately 1.1×10^{-9} m/s for the G2 and G1 geotextiles. This initial decrease is dominated by soil compaction (consolidation), soil adjustment to side wall effects, and initial geotextile modification. Some sludge embedded itself on the surface of, or within, the geotextile. This type of modification of the geotextile to the upstream soil, its stress state, its permeating liquid, and its hydraulic conditions are necessary and expected. However, it is believed that this first stage is predominantly dominated by consolidation of the sludge layer causing a decrease of the overall permeability of the sludge-geotextile system. This can also be seen in the variation of the dry unit weight of the sludge specimens in this initial stage: the decrease in k stops at the moment the dry unit weight becomes approximately constant (Figure 4).

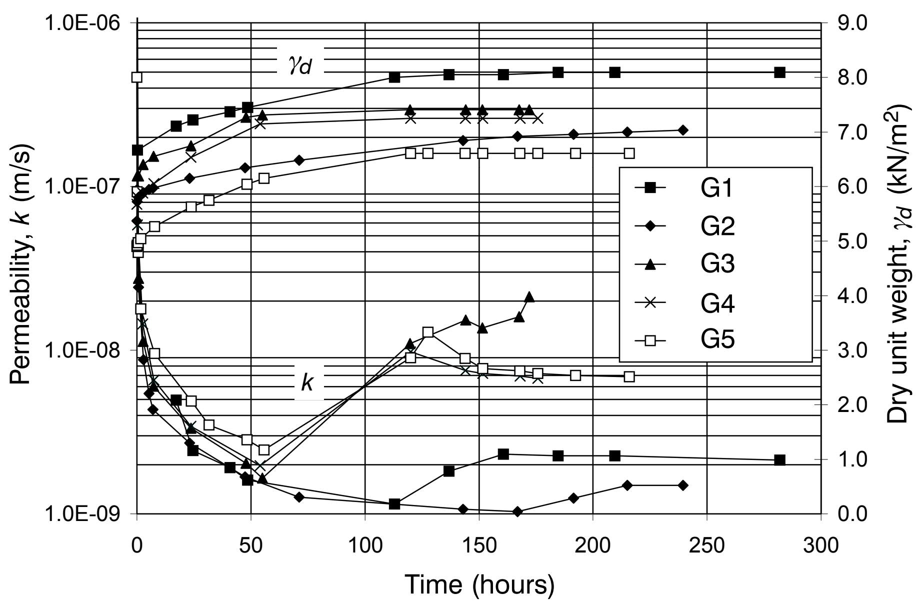

Figure 4. Variation of system permeability and dry unit weight during testing.

The second stage, at the end of consolidation, was marked by an increase in *k*. The upward seepage due to consolidation no longer acted against the downward seepage of the hydraulic gradient, thus, *k* gradually increased.

Finally, four sludge-geotextile systems appear to stabilise and *k* exhibits a steady-state behaviour (Figure 4). For the G4 and G5 geotextiles, the start of the stabile stage shows a decrease in *k*, which marks the onset of filter cake formation upstream of the sludge-geotextile interface. The steady-state values of *k* for the G5, G4, G1, and G2 sludge-geotextile systems are 7×10^{-9} m/s, 6.7×10^{-9} m/s, 2.1×10^{-9} m/s, and 1×10^{-9} m/s, respectively, which were attained after 150 hours of testing for the G5, G4, and G1 sludge-geotextile systems and after 215 hours for the sludge-G2 system**.**

The G3 geotextile showed almost a continuous increase in *k*, and after 172 hours the test had to be stopped due to a lack of water. It was not believed that this tendency signified a soil piping condition because no soil particles passed through the geotextile.

Regarding the retention characteristics of the geotextiles, three potential phases of soil passage were identified, particles that passed during preparation of the sludge layer, during application of the surcharge air pressure, and during water permeation. Only in the two tests with the G3 and the G4 geotextile was a quantity of soil collected a few minutes after application of the surcharge. Thereafter, the system stabilised and no further piping was observed. The mass of the piped soil was 71.6 g (4,650 g/m^2) and 43.7 g (2,840 g/m^2). No soil piping was noticed during water permeation in any of the tests. This behaviour was confirmed by measurements of sludge-layer height during testing.

The particles that passed through the geotextiles during application of the surcharge, however, caused a rapid decrease in the sludge layer height of 15.3 and 12.3% and an increase in the hydraulic gradient during the first hour of the test. This can also be seen in Figure 5, which shows the variation of the hydraulic gradient and sludge layer height during testing.

The quantity of soil that passed through the geotextiles was also taken into account when calculating the variation of sludge dry unit weight during testing (Figure 4).

Lafleur et al. (1990) discussed the stability of granular filters for soil retention applications. They stipulated a stability limit at 2,500 g/cm^2 for granular filters. This stability limit has been used by other researchers to define the stability of soil-geotextile systems, e.g. Siva and Bhatia (1993) and Akram and Gabr (1997). It was found that both systems exceeded this stability limit at the beginning of the test.

Although the initial height of the sludge layer for the G5, G1, and G2 geotextiles was the same, the time for consolidation increased from 55 to 167 hours. It could also be seen that the lower the steady-state value of the permeability, the larger the consolidation time. The height of the sludge layer with the G4 geotextile was lower due to the initial piping, but the consolidation time was similar to the consolidation time of the G5 system. This led to the conclusion that the consolidation time and steady-state permeability was dominated by the combined sludge-geotextile system and not only by the sludge layer. No relation could be found between the dry unit weight of the sludge and the measured steady-state permeability.

After the filtration tests, the geotextiles were removed, dried, and weighed to measure the weight of the soil particles retained in or at the upstream face of the geotextile in the form of a filter cake. The initial and final mass of the geotextiles are presented in Table 3. This data suggests again that a filter cake formed at the upstream face of the G4 and G5 geotextiles.

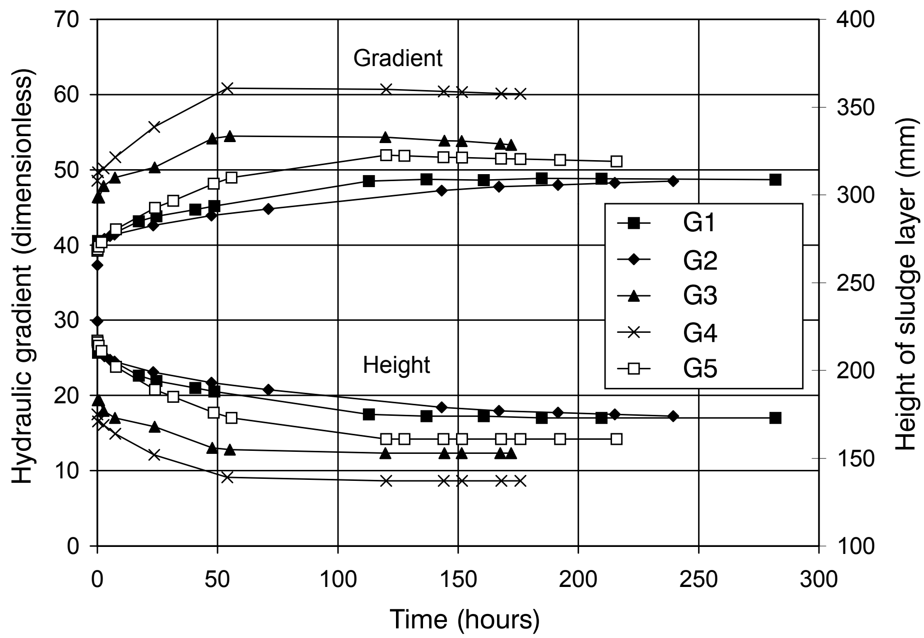

Figure 5. Variation of hydraulic gradient and sludge layer height during testing.

Table 3. Soil particles retained in or on the upstream face of the geotextile.

Geotextile (diameter = 180 mm)	Initial mass of geotextile (g)	Final mass of geotextile (g)	% increase
G1	3.04	7.33	141
G2	15.30	30.62	100
G3	10.35	51.73	400
G4	9.35	109.96	1,076
G5	2.96	10.90	268

The calculation of the dry unit weight of the geotextiles, using Equation 2, gave an indication of the piping or consolidation of the system. Figure 6 shows the calculated dry unit weight versus the measured dry unit weight of the geotextiles at the end of the tests. Only the dry unit weight of the sludge-G4 system is overestimated. This may be due to the large amount of soil particles that migrated into the geotextile, or the formation of a filter cake; both were not taken into account when calculating the dry unit weight.

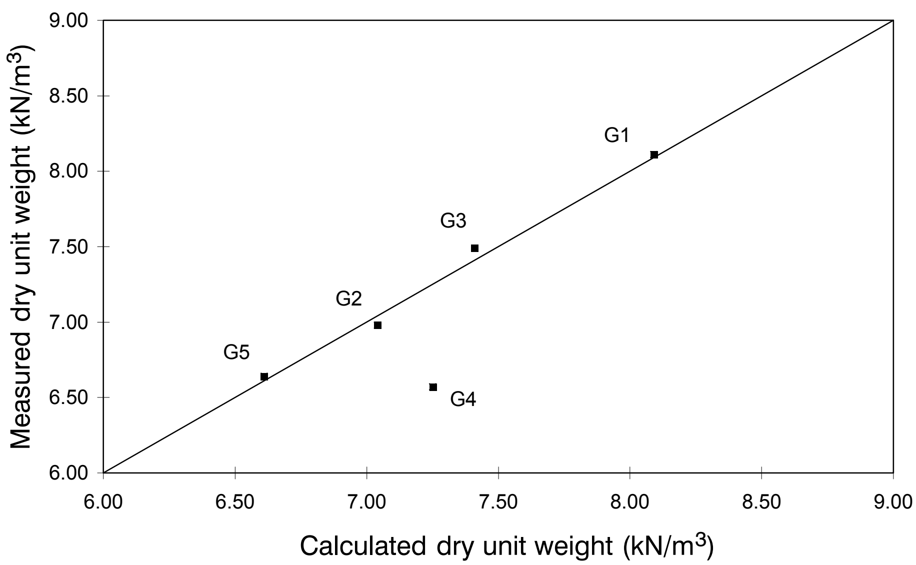

Figure 6. Calculated versus measured dry unit weight of the sludge-geotextile systems at the end of the tests.

4 CONCLUSIONS

The filtration behaviour of five geotextiles under vacuum-consolidation and overlain by a layer of sludge was investigated. A new test apparatus was described that allows filtration tests to be conducted on relatively large samples under high gradients and accommodates the collection of soil particles that pass through the geotextile. The main conclusions of the current work are summarised below:

1. In spite of the rather severe combinations of sludge and geotextiles used in the tests, three geotextiles performed well in terms of clogging potential, soil retention capacity, and permeability loss.
2. The flow pattern across the sludge-geotextile systems occurred in three distinct stages. The initial decrease of permeability was mainly due to the consolidation of the sludge layer. Four systems appeared to have been stabilised after 200 hours with k exhibiting a steady-state behaviour. The permeability of one geotextile progressively increased.
3. The soil particles that piped through the geotextile, did so during the application of the surcharge air pressure.
4. Due to the piping behaviour of the sludge-G3 and the sludge-G4 systems, and the low steady-state permeability of the sludge-G2 and sludge-G1 systems, the sludge-G5 system proved to be the most effective for the given test configuration.

Laboratory filtration tests do not fully simulate the operating conditions found in the field. The construction procedures, such as construction induced damage, may influence performance. Nevertheless, the results obtained in the current study suggest that the G5 geotextile, i.e. drain, is the most suitable for use in this particular vacuum-consolidation application knowing that other parameters such as cost, strength, and ease of installation might influence the final choice of geotextile.

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NOTATIONS

Basic SI units are given in parentheses.

A_c	=	activity index of sludge (dimensionless)
C_c	=	compressibility index of sludge at 60 kPa (Pa)
c_u	=	vane shear strength of sludge (Pa)
h	=	height of sludge layer at time t (m)
h_i	=	initial height of sludge layer (m)
I_p	=	plasticity index of sludge (%)
k	=	permeability of geotextile (m/s)
m	=	mass of effluent (kg)
O_{90}	=	geotextile pore opening size such that 90% of pores are smaller than that size (m)
w_L	=	liquid limit of sludge (%)
w_o	=	initial water content of sludge (%)
q	=	flow rate through sludge-geotextile system (m^3/s)
Δt	=	time interval over which column effluent was collected (s)
γ_d	=	dry unit weight of specimen at time t (N/m^3)
γ_{di}	=	initial dry unit weight of specimen (N/m^3)
ϱ_n	=	total volumetric mass of sludge (kg/m^3)