Technical Paper by D.T. Bergado, R. Manivannan and A.S. Balasubramaniam

FILTRATION CRITERIA FOR PREFABRICATED VERTICAL DRAIN GEOTEXTILE FILTER JACKETS IN SOFT BANGKOK CLAY

ABSTRACT: Filtration tests on soil-geotextile filter systems were conducted in the laboratory in order to evaluate the filtration and clogging performance of prefabricated vertical drain (PVD) geotextile filter jackets in soft Bangkok clay. Initially, the flow was very slow for all types of PVD geotextile filter jackets and the soil permeability characteristics controlled the flow behavior. Subsequently, flow increased with time followed by a loss of fine particles. Finally, flow decreased and reached an equilibrium stage. As a result of the laboratory filtration tests, filtration and clogging criteria are proposed for geotextile filter jackets on PVDs in soft Bangkok clay.

KEYWORDS: Filtration, Clogging, Permeability, Soft clay, Prefabricated vertical drain, Geotextile, Apparent opening size.

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PUBLICATION: *Geosynthetics International* is published by the Industrial Fabrics Association International, 345 Cedar St., Suite 800, St. Paul, Minnesota 55101, USA, Telephone: 1/612-222-2508, Telefax: 1/612-222-8215. *Geosynthetics International* is registered under ISSN 1072-6349.

DATES: Original manuscript received 11 August 1995, revised version received 17 January 1996 and accepted 22 January 1996. Discussion open until 1 September 1996.

REFERENCE: Bergado, D.T., Manivannan, R. and Balasubramaniam, A.S., 1996, "Filtration Criteria for Prefabricated Vertical Drain Geotextile Filter Jackets in Soft Bangkok Clay", *Geosynthetics International*, Vol. 3, No. 1, pp. 63-83.

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1 INTRODUCTION

An effective prefabricated vertical drain (PVD) has two basic filtration functions: first to retain soil particles; and second, to allow water to pass from the soil into the PVD core. For PVDs, these two filtration functions are performed by a geotextile filter jacket wrapped around a drain core. For monolithic PVDs, on the other hand, filtration occurs at the surface of the drain core, either by means of holes punched in the drain core, or by the natural permeability of the drain core material. In order to evaluate the filtration and clogging performance of PVDs, filtration tests were conducted on various soil-geotextile filter systems. Most of the results presented in this paper were derived from the work of Manivannan (1995).

2 PERMEABILITY

Hansbo (1979) proposed that the openings of a geotextile filter jacket should be fine enough to prevent soil particles from passing through. These fine soil particles can cause siltation and reduce the discharge capacity of the PVD (Hansbo 1981). Geotextile filter jackets are quite thin, and even if they have a low permeability, the overall effect on the PVD performance is minimal. This condition can be analyzed by considering the geotextile filter jacket to be a smear zone of reduced permeability. Hansbo (1983) believed that PVD geotextile filter jackets used at that time were too permeable to prevent clogging and siltation of the drain core. The only situation in which a high permeability geotextile filter jacket would be an advantage is the case where PVDs are installed in very deep deposits of clay with intermediate sand seams which would serve as horizontal drainage layers: a less permeable geotextile filter jacket in this situation may have undesirable high head losses.

In order for a geotextile to be considered an effective filter, it should not clog or blind (Figure 1). Clogging can occur if soil particles move and become trapped within the fabric structure, reducing its permeability. Blinding occurs when soil particles are prevented from entering or passing through the geotextile and coat the geotextile surface forming a filter cake which can significantly reduce the permeability of the geotextile.

A geotextile filter jacket may function as illustrated in Figure 2. A small amount of particle movement occurs into or through the geotextile filter jacket leaving the coarser

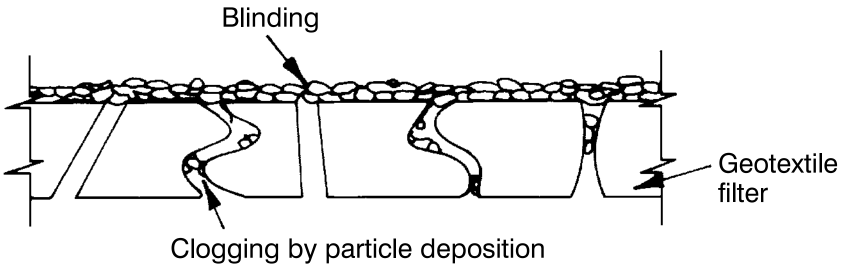

Figure 1. Definition of clogging and blinding (after Bell and Hicks 1980).

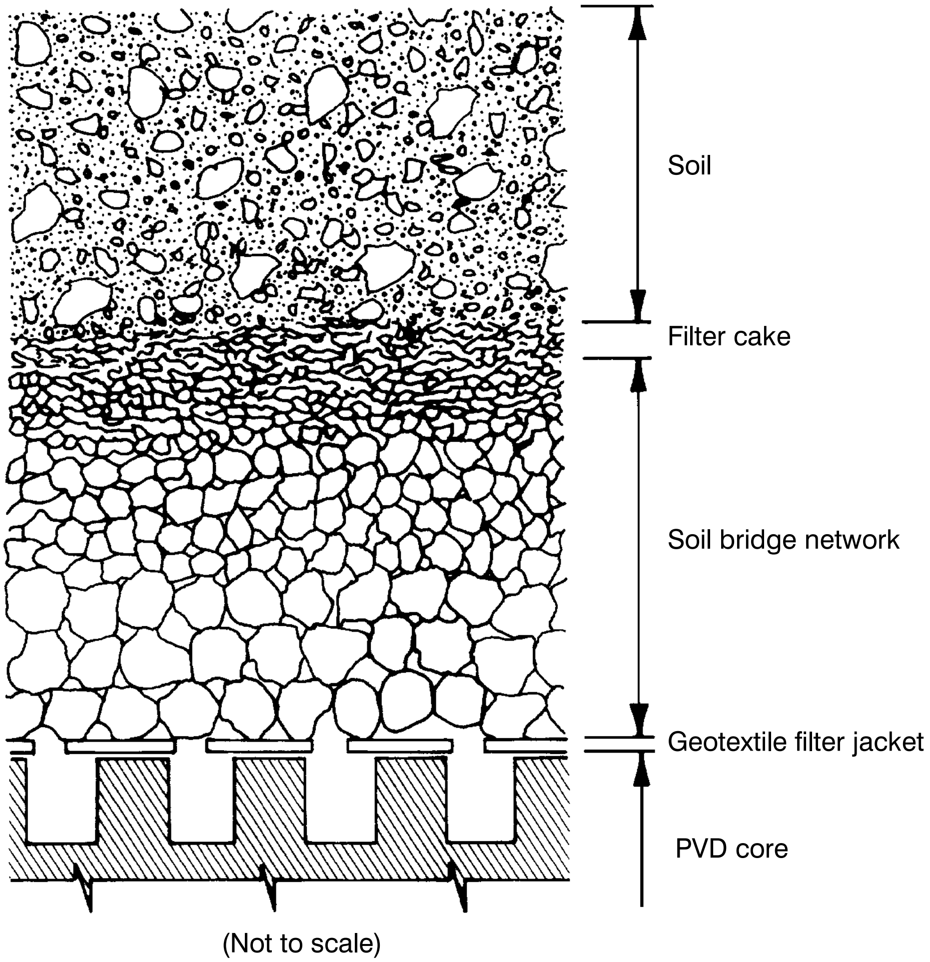

Figure 2. How a geotextile filter jacket works (after McGown 1976; Bell and Hicks 1980).

particles to bridge and arch. The zone of fine particles immediately behind the soil bridge network is sometimes called a "filter cake". Once the soil filter is established, no further particle movement will occur and the soil-geotextile jacket system is in equilibrium; hence, the geotextile filter jacket retains the soil and prevents its migration into the drain core. While it may not actually filter the pore water, the geotextile filter jacket does act as a catalyst for the formation of a soil filter in the adjacent soil. The establishment of a stable and effective soil filter by the geotextile filter jacket depends on the following (McGown 1976):

(1) The physical and mechanical properties of the geotextile filter jacket, e.g. pore size and pore size distribution, porosity, geotextile filter thickness, and compressibility.

(2) The characteristics of the soil to be protected, e.g. particle size and particle size distribution, porosity, permeability, and cohesiveness.
(3) External stresses and strains imposed on the soil-PVD system, e.g. traffic and structural loads.
(4) The prevailing hydraulic conditions, e.g. laminar or turbulent flow, unidirectional or reversible flow, and dynamic or pulsating flow.

The first attempts to develop geotextile filter criteria were based on experience using graded granular filters. However, there are obvious problems in extending graded filter criteria to geotextile filter design because the particle size distribution of the geotextile filter is unknown. It is more appropriate to consider the pore size distribution of the geotextile filter, yet there is no simple method to measure it (Falyse et al. 1985; Chen and Chen 1986). As with soils, the relationship between pore size distribution and permeability for geotextile filters is not yet established. It may be postulated that the permeability, clogging potential, and piping resistance of a geotextile filter depends on the type of fibre, structure, and porosity.

A high permeability for the geotextile filter jacket is desirable, but at the same time loss of small soil particles through the geotextile filter jacket should be minimized. The most important permeability criterion is that the geotextile filter must be and must remain more permeable than the adjacent soil (Holtz and Christopher 1987). This criterion can be expressed as follows:

$$k_g > k_s \tag{1}$$

where: k_g = permeability of the geotextile in the direction normal to the plane of the geotextile; and, k_s = permeability of the soil.

For critical applications, Holtz and Christopher (1987) suggest that the permeability of geotextile filters should be at least ten times the permeability of the soil. This geotextile filter hydraulic property is typically imposed during the selection phase. Ingold (1988) suggests that the designer has to forecast the long term performance to ensure that the geotextile filter will fulfill its design function. Rollin and Lombard (1988) have indicated that a geotextile filter may be partially clogged but still offer good performance. The work of Giroud (1982) suggests that the permeability of geotextile filters with clogging taken into account need only be 10 times greater than the soil permeability.

3 SOIL RETENTION ABILITY

The performance of PVDs is strongly influenced by small soil particles that accumulate within or near the geotextile filter jacket as a result of the flow of displaced pore water. An effective geotextile filter jacket should not allow too much soil to pass through, otherwise piping may occur in the adjacent soil and the drainage path of the PVD core may become clogged, thereby decreasing its discharge capacity. Therefore, in selecting an appropriate geotextile for a geotextile filter jacket, the particle size distribution of the soil should be considered. The geotextiles typically used for PVD filter jackets are nonwovens with nonuniform pore sizes.

Current soil-geotextile filter system retention criteria are generally based on relationships developed between a representative pore size of the geotextile and particle size of the soil. The parameters used for geotextile filter criteria proposed by many authors are: characteristic soil particle sizes, e.g. D_{85}, D_{10}; soil coefficient of uniformity, $C_u = D_{60}/D_{10}$; soil permeability, k_s; geotextile filter permeability, k_g; and, pore size characteristics of the geotextile filter, e.g. apparent opening size of the geotextile filter (AOS).

According to Kellner et al. (1983), several factors should be considered when evaluating the retention ability of geotextile filter jackets: chemical properties of the geotextile fibers; and soil composition. Several empirical relationships have been proposed to simplify geotextile filter selection and these criteria are presented in Table 1.

Table 1. Summary of filtration criteria for geotextile filters.

Source	Criterion	Remarks
Bergado et al. (1992)	$O_{90}/D_{85} \leq$ 2 to 3 $O_{50}/D_{50} \leq$ 18 to 24	Nonwovens, clay recommended
Ogink (1975)	$O_{90}/D_{90} \leq 1.8$	Nonwovens, type of soil not specified
Carroll (1983)	$O_{95}/D_{85} \leq$ 2 to 3	For both wovens and nonwovens, type of soil not specified
Christopher and Holtz (1985)	$O_{95} \leq 1.8\ D_{85}$ Steady state $AOS < 0.3\ D_{85}$	Nonwovens, for soils with greater than 50% particles passing the 75 μm sieve
Holtz and Christopher (1987)	For steady state $O_{95} \leq 0.5$, $D_{85} \leq 0.3$ mm For dynamic flow $O_{50} \leq 0.5\ D_{85}$	Nonwovens, for silts and clay
Calhoun (1972)	$O_{95}/D_{85} \leq 1$	Suitable for geotextile filters with a high percentage of large pores
Chen and Chen (1986)	$O_{90}/D_{85} \leq$ 1.2 to 1.8 $O_{50}/D_{50} \leq$ 10 to 12	
Sweetland (1977)	$O_{15}/D_{85} \leq 1$ $O_{15}/D_{85} \leq 1$	Nonwovens, soils with $C_u = 1.5$ Nonwovens, soils with $C_u = 4$
Rankilor (1981)	$O_{50}/D_{85} \leq 1$ $O_{50}/D_{50} \leq$ 25 to 37 $O_{15}/D_{15} \leq 1$	Nonwovens, soils with $0.02 \leq D_{85} < 0.25$ mm Nonwovens, cohesive soil Nonwovens, soils with $D_{85} > 0.25$ mm

Notes: O_{95}, O_{90}, O_{50}, O_{15} = geotextile filter opening size such that 95, 90, 50 and 15%, respectively, of pores are smaller than that size; D_{85}, D_{50}, D_{15} = soil particle diameter such that 85, 50 and 15%, respectively, of the soil particles, are smaller than that diameter.

4 CLOGGING RESISTANCE

The criteria for geotextile filter jacket clogging resistance depend on project criticality and the severity of the hydraulic loading conditions. Selection of a geotextile filter jacket for critical applications and severe conditions should be based on: the soil retention and permeability criteria for critical situations. In addition the geotextile must also satisfy clogging criteria for less critical applications and soil-geotextile filtration tests should be performed using representative samples of site soils.

The suggested filtration test for soils with $k_s > 10^{-7}$ m/s (silts, clayey and silty sands) is the gradient ratio test and the recommended gradient ratio (GR) criterion is $GR < 3$ (Carroll 1983; Holtz 1986). For finer grained soils with $k_s < 10^{-7}$ m/s, long term filtration tests should be performed. It should be emphasized that the gradient ratio test is not yet fully standardized and that considerable experience is required to obtain reproducible results (Christopher and Holtz 1985).

A geotextile filter jacket clogs and its permeability reduces if soil particles become trapped within the geotextile fabric structure. Therefore, it is recommended that for nonwoven geotextile filter jackets, with a porosity greater than 30%, placed in a potential clogging environment, such as gap graded and silty soils, a porosity qualifier should be included (Holtz 1986). Optional porosity qualifiers are selected based on experience with the use of granular piles, and ensure that finer soil particles can pass through the geotextile filter jacket without clogging it. For example:

$$O_{95} \geq 3\ D_{15} \text{ and } O_{15} \geq 2\ D_{15} \text{ to } 3\ D_{15} \tag{2}$$

5 FILTRATION MECHANISMS

The permeability and pore size distribution of geotextile filter materials are selected to restrain particle migration while allowing water to pass through their structure. The long term performance of these geotextile filters can be affected by soil conditions, design of the filtration system, installation procedures and hydraulic conditions. It is important to understand that in order to perform its filtration function adequately, the geotextile filter must act as a barrier suitable to the formation of a natural filter by one of, or a combination of, the following mechanisms: auto filtration; blocking of particles at the filter surface; or, vault network formation (Rollin and Lombard 1988).

Vreeken et al. (1983) performed filtration experiments to investigate the retention capability of geotextile filters and the effect of suspended soil particles on geotextile filter resistance. It was found that the retention capability and clogging resistance of a geotextile filter are mainly dependent on the pore size distribution of the geotextile filter. The principal geotextile filter mechanisms can be distinguished as follows: (i) cake filtration; (ii) deep filtration; and (iii) blocking filtration.

Cake filtration occurs when the soil particles are larger than the geotextile filter pores. All particles are retained on the geotextile filter and the resistance of the filter cake to water flow increases. In the case of pure infiltration and an incompressible filter cake, there is a linear relationship between the amount of retained particles and the resistance to flow through the filter cake. Rollin and Lombard (1988) and Williams and Abouzakhm (1989) have indicated that the flow across the soil-geotextile filter system interface triggers the formation of a filter cake due to the migration of fine soil particles. This filter cake, or transitional filter, typically impedes water flow.

Blocking filtration, on the other hand, occurs when the particles have roughly the same diameter as the pores of the geotextile filter. The particles are retained in the geotextile filter and filter flow resistance can rise rapidly. If the pore size distribution of the geotextile filter is large, only the larger pores may become blocked after a cake is formed.

Deep filtration occurs when the particles are smaller than the geotextile filter pores and the particles adhere to the geotextile filter. When filtration begins, the geotextile filter resistance increases, and, as a result of the increasing pressure drop across the filter, the particles are detached and the geotextile filter resistance decreases.

6 LABORATORY TESTS

Ten different PVDs were tested. The product names and designations used in the current study are shown in Table 2. All PVD products had a geotextile filter jacket with the exception of Desol which is a monolithic PVD comprising a one piece plastic core.

6.1 Apparent Opening Size (*AOS*)

The method used to determine the *AOS* of a geotextile utilizes glass beads sieved through a geotextile following the ASTM D 4751 standard. The *AOS* indicates the approximate largest particle size that would effectively pass through the geotextile.

A mechanical sieve shaker was used to impart a vertical and lateral motion to the sieve, causing the particles to bounce and turn so as to present different orientations to the geotextile surface. Spherical glass beads were used in the appropriate size fraction to match the range of the geotextiles tested. Static eliminators were used to prevent the accumulation of static electricity when the beads were shaken on the surface of the geotextile.

6.2 Filtration Test

The filtration test apparatus used in the study consists of a 310 mm high lucite cylinder with a 150 mm internal diameter as shown in Figure 3. The cylinder can be detached into two portions and a geotextile which acts as a filter can be placed between the two sections of the cylinder. A valve was installed at the bottom of the cylinder to regulate the water flow. Before running a test, the geotextile filter specimen was saturated and then placed between the two sections of the cylinder. A thoroughly mixed clay was placed to a thickness of 100 mm over the geotextile filter jacket specimen. The valves were opened and water was allowed to flow through the soil and geotextile filter jacket specimen under constant head. The volume of water leaving the apparatus was measured with time.

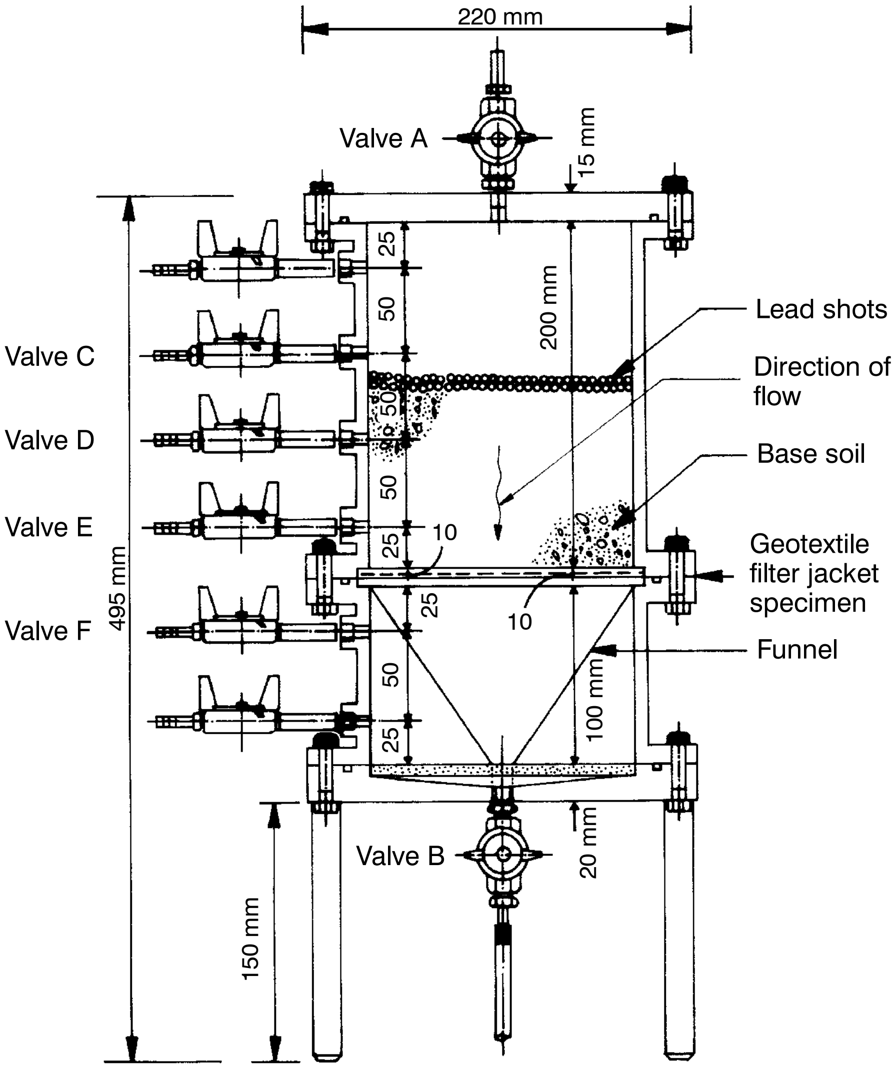

Figure 3. Filtration test apparatus.

7 RESULTS AND DISCUSSIONS

7.1 Apparent Opening Size (*AOS*)

The *AOS* of a geotextile filter, which is designated as O_{95} when tested in accordance with ASTM D 4751, corresponds to the particle size (bead size) in millimeters for which

5% or less by mass passes through the geotextile. The *AOS* value does not represent a reliable indicator of geotextile filter permeability or clogging resistance. The results of the *AOS* tests are given in Table 2. The selected geotextile filter jackets differ in material composition and in the method used to strengthen the geotextile.

The *AOS* method has limitations in measuring small pore sizes due to electrostatic forces and any surface coating on the geotextile. The build-up of static electricity causes the glass beads to cling to the geotextile rather than pass through, leading to erroneous results. Static eliminators added to the sieve frame walls reduce or eliminate the build-up of static electricity. In some instances, the geotextile manufacturing process leaves a surface coating on the geotextile which may clog some of the geotextile openings which also lead to erroneous test results. The use of *AOS* for nonwoven geotextiles (the most common geotextile filter jacket for PVDs) has been criticized (Holtz and Christopher 1985). It is impractical to specify an *AOS* smaller than 0.075 mm because it cannot be measured using the ASTM D 4751 standard test method.

Among the PVD geotextile filter jackets tested, PVD F with one geotextile layer (old design) gave the highest *AOS* of 0.6 mm. However, when PVD F with two layers of geotextile (improved design) was tested it gave an *AOS* of 0.075 mm. The PVD D and PVD H geotextile filter jackets gave *AOS* values less than 0.075 mm. Figure 4 presents the pore size distribution of the PVD geotextile filter jackets and the particle size distribution of the clay used in the current study.

Table 2. Apparent opening size (*AOS*) results.

PVD type		*AOS* (mm)	
Name	Designation	Manufacturer's data	Laboratory test results
Alidrain	A	0.12	0.160
Amerdrain 408	B	0.16	0.200
Castleboard CS	C	0.074	0.075
Colbond CX-1000	D	< 0.075	< 0.075
Desol *	E	0.20	N/A
Fibredrain	F	Not provided	0.60 (one layer), 0.075 (two layer)
Flodrain FD4-EX	G	< 0.090	0.075
Geodrain "L"	H	Not provided	< 0.075
Hongplast GD-75	I	< 0.075	0.075
Mebradrain MD-7007	J	0.075	0.075

Notes: * Monolithic one piece core without geotextile filter jacket. N/A = not applicable.

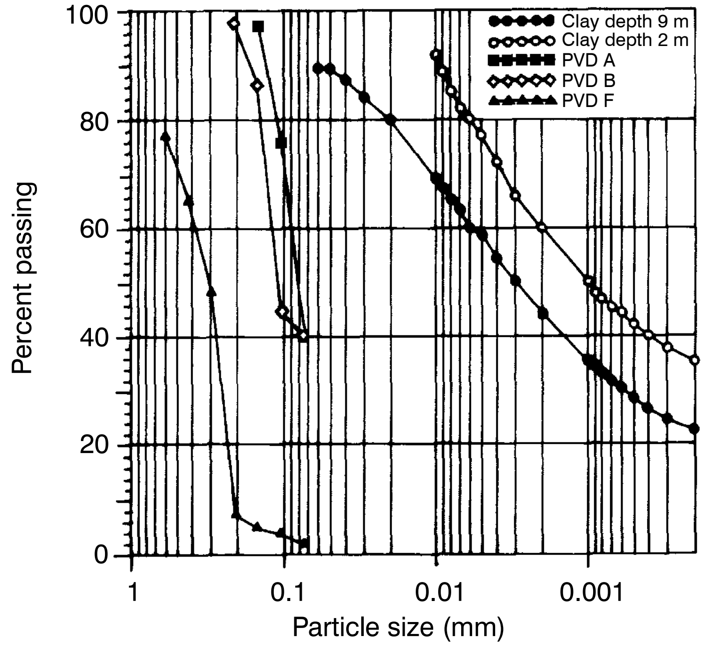

Figure 4. Particle size distribution of the Bangkok clay at two different depths and the results of apparent opening size (O_{95}) standard tests (ASTM D 4751) of three different PVD geotextile filter jackets.

7.2 Filtration Test Results

Filtration test results for the soil-geotextile filter jacket systems are plotted in Figures 5, 6 and 7. As shown in these figures, the flow rate (m^3/year) was computed per square meter surface area using a hydraulic gradient, $i = 1$. Immediately after the installation of the geotextile filter, the initial flow rate for all systems was very slow. This indicates that initial flow behavior is dominated by the hydraulic properties of the soil, while the long time flow behavior is dominated by the hydraulic properties of the geotextile filter (Lawson 1982). Figures 5, 6 and 7 show that the flow rate across the soil-geotextile filter system then decreases with time, indicating movement of fine particles towards the geotextile filter and initial clogging of the geotextile filter openings. Once the fine particles adjacent to the geotextile filter were removed in the filtration process, an increase in the flow rate was observed. The subsequent retention of soil particles on the geotextile filter led to cake formation, resulting in a reduction of flow rate until an equilibrium condition was reached.

As shown in Figure 5, the flow rate for the PVD A geotextile filter jacket did not become stable even after it decreased from a peak flow rate. Afterwards, the flow rate for the PVD A geotextile filter jacket increased due to loss of fine particles which indicates that soil-geotextile filter system equilibrium was not reached. Similarly, for the PVD F geotextile filter jacket (one geotextile filter layer) the flow decreased initially and increased suddenly to a high value. The fine soil particles lost during this increment of

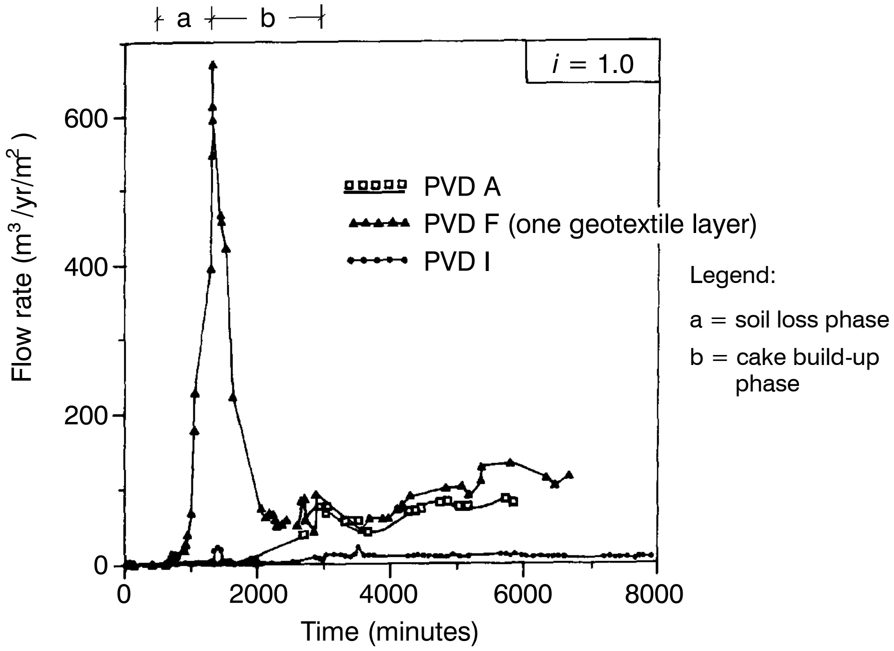

Figure 5. Variation of flow rate with time for PVD geotextile filter jackets from filtration tests.

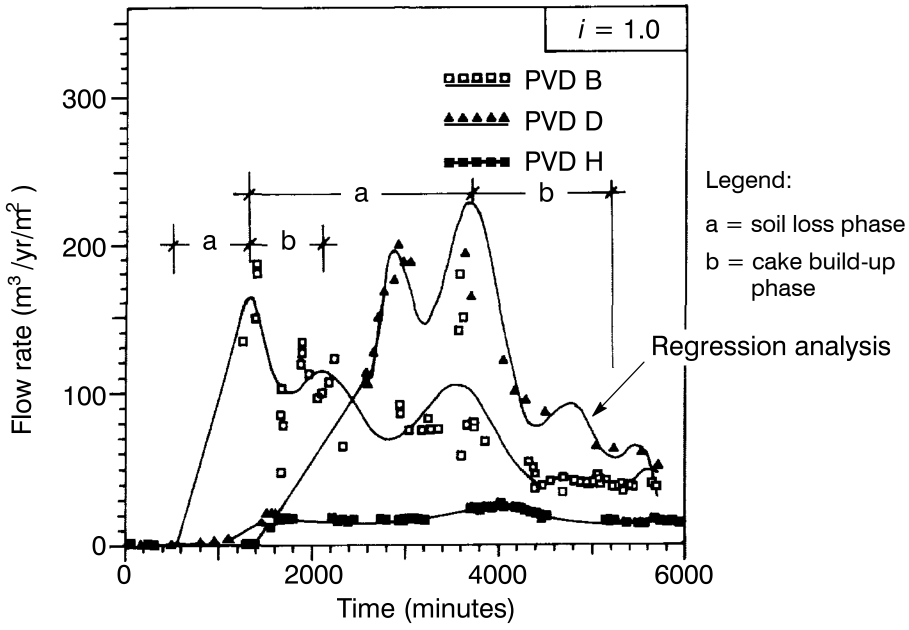

Figure 6. Variation of flow rate with time for PVD geotextile filter jackets from filtration tests.

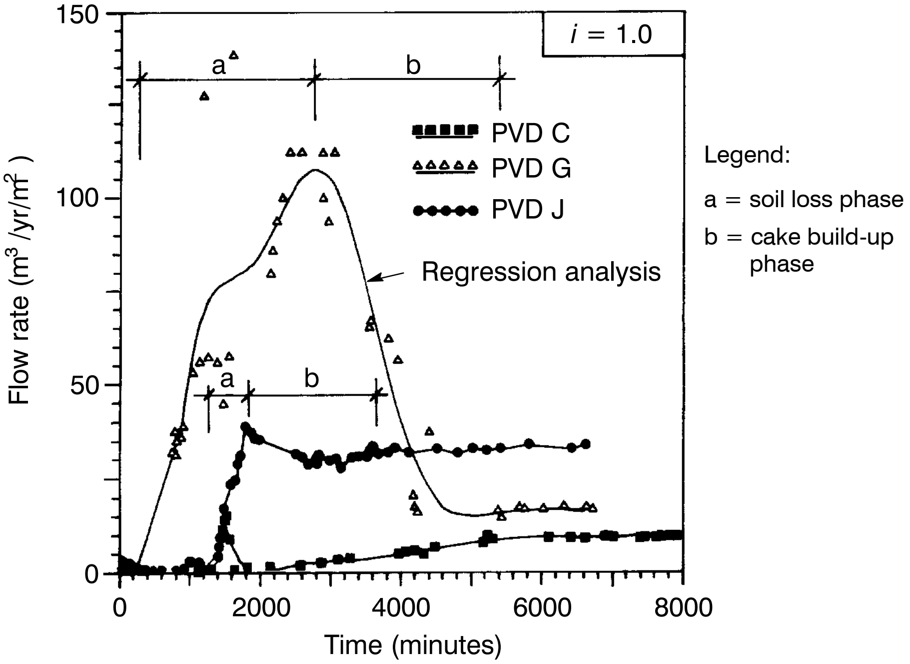

Figure 7. Variation of flow rate with time for PVD geotextile filter jackets from filtration tests.

flow for the PVD F geotextile filter jacket was also very high due to its large pore sizes (Figure 4). Thus, when using a geotextile filter jacket with relatively large pore sizes, such as the PVD F geotextile filter jacket, a large amount of soil can be deposited in the PVD core leading to the obstruction of its flow channels and clogging. The PVD I geotextile filter jacket, on the other hand, did not show a significant change in flow rate with time.

For the PVD B geotextile filter jacket (Figure 6), the flow rate was erratic for approximately 4000 minutes before it reached a quasi-stable flow state. This could be attributed to the loss of fine particles or internal rearrangement of soil particles. The flow rate for the PVD D geotextile filter jacket increased significantly for approximately 3750 minutes becoming stable after the loss of fine particles. For the PVD H geotextile filter jacket, there was a slight increase in flow rate after approximately 1200 minutes which remained stable until the end of the test.

Figure 7 shows that the flow rate for the PVD C geotextile filter jacket did not increase significantly during the early stages of the test. After the specimen reached a peak flow rate, the flow rate decreased abruptly and then remained steady until the end of the test. The flow rate for the PVD G geotextile filter jacket increased abruptly reaching peak flow at approximately 3000 minutes and then decreased suddenly and became stable with time. During the early stages of testing, the flow rate for the PVD J geotextile filter jacket remained constant, then increased abruptly at 1300 minutes, and then decreased slightly and remained steady until the end of the test.

Among the geotextile filter jackets tested, PVD I, H and C exhibited the lowest flow rates (Figures 5, 6 and 7). The flow in these geotextile filters did not change significantly with time unlike the other geotextile filters, which reached peak flow, decreased for some time, and then became stable.

When the design criteria (Table 3) are applied to the PVD A geotextile filter jacket (Figure 5) they indicate that its pore size distribution is course and that it cannot prevent soil loss and subsequent clogging of the PVD core. A similar conclusion is reached for the PVD B geotextile filter jacket since the scattered points (Figure 6) indicate that the variation in flow rate was caused by soil loss. The large pore sizes of the PVD B geotextile filter jacket prevented the flow rate from reaching an equilibrium condition quickly. Therefore, the results of filtration tests on the PVD A and B geotextile filter jackets demonstrate that the geotextile filter jacket pore size must be able to prevent the loss of fine particles.

For the PVD C geotextile filter jacket (Figure 7), the flow rate reached equilibrium after the fine soil particles were removed. However, it took quite some time to increase the flow rate through the PVD D geotextile filter jacket (Figure 6). In the case of the PVD H geotextile filter jacket (Figure 6), the flow rate was initially negligible and then suddenly increased unlike the gradual increase in flow rate of the other PVD geotextile filter jackets. The flow rate were varied and did not show any regular behavior. This may be due to pore size changes during the test period. It should be noted that the PVD H geotextile filter jacket is very thin compared to the other PVD geotextile filter jackets. The flow rate for the PVD J geotextile filter jacket, on the other hand, became stable very rapidly, at approximately 2600 minutes.

Table 3. Relationship between pore size of PVD geotextile filter jackets and soil particle size.

Source	Criterion	PVD designation				
		A	B	F	G	J
Bergado et al. (1992)	$O_{90}/D_{85} \leq 2-3$ $O_{50}/D_{50} \leq 18-24$	4.7 - 17.5 26.7 - 80	5.3 - 20 33.3 - 100	20 - 46.2 13.3 - 44	2 - 7.5 16.7 - 50	2.5 - 9.4
Ogink (1975)	$O_{90}/D_{90} \leq 1.8$	2.8 - 15.6	3.2 - 17.8	12 - 66.7	1.2 - 6.7	1.5 - 8.3
Carroll (1983)	$O_{95}/D_{85} \leq 2-3$	5.33 - 20	6.67 - 25	20 -75	2.3 - 8.75	2.5 - 9.4
Rankilor (1981)	$O_{50}/D_{50} \leq 25-37$	26.7 - 80	33.3 - 100	20 - 75	16.7 - 50	-
Christopher and Holtz (1985)	$O_{95} \leq 1.8\ D_{85}$ Steady State $AOS \leq 0.3\ D_{85}$	5.33 - 20	6.67 - 25	20 - 75	2.3 - 8.75	2.5 - 9.4
Holtz and Christopher (1987)	Steady State $O_{95} \leq 0.5\ D_{85} \leq 0.3$ mm	5.33 - 20	6.67 - 25	20 - 75	2.3 - 8.75	2.5 - 9.4
Calhoun (1972)	$O_{95}/D_{85} \leq 1$	5.33 - 20	6.67 - 25	20 - 75	2 3 - 8.75	2.5 - 9.4
Chen and Chen (1986)	$O_{90}/D_{85} \leq 1.2-1.8$ $O_{50}/D_{50} \leq 10-12$	4.7 - 17.5 26.7 - 80	6.67 - 25 33.3 - 100	20 - 46.2 133.3 - 400	2 - 7.5 16.7 - 50	2.5 - 9.4 -

8 SPECIFICATIONS

8.1 Filtration

It can be observed that as the filtration time increased, the permeability of the soil-geotextile filter systems decreased. The general trend is that in the initial time period of approximately 15 to 30 hours (900 to 1800 minutes), the flow increases, then gradually decreases, and finally reaches a constant value.

Based on the analyses of all the tests performed, three types of filtration behavior can be identified:

- Type I, cake build-up and soil stabilization;
- Type II, continuous loss of soil particles; and
- Type III, cake build-up with the loss of few soil particles and soil stabilization.

It was also found that geotextiles can act as effective filters as long as their filtration behavior is of Types I and III. The change in the interface layer of the soil-geotextile filter systems can be summarized by the occurrence of the following five mechanisms: migration of soil particles; loss of soil particles; cake build-up; trapping of soil particles within the geotextile filter; and soil stabilization.

It is very difficult to determine the contribution of clogging to the reduction in flow rate from the filtration tests because the flow rate is initially controlled by the hydraulic properties of the soil, not by the soil-geotextile filter system. Moreover, it takes time to reach equilibrium conditions. In order for a geotextile filter jacket to be effective, it must prevent soil particles from moving towards the PVD core and flow rate must reach equilibrium. The PVD J geotextile filter jacket had a very small amount of soil particle loss and reached an equilibrium condition quickly, indicating a good soil-geotextile filter system. The PVD F geotextile filter jacket (one layer geotextile filter jacket), quickly reached a quasi-stable flow condition, but the loss of soil particles continued which could eventually clog the PVD core. A flow reduction factor can be defined that is the ratio of the steady state flow rate to the peak flow rate. The flow reduction factors for the PVD B, C, D, F, G, I and J geotextile filter jackets are 4.0, 1.7, 3.3, 3.0, 6.8, 2.0 and 1.3, respectively.

Koerner and Ko (1982) have performed long term filtration tests on soil-geotextile filter systems and obtained flow reduction factors in the range of 2.84 to 4.2. The results indicated that the soil-geotextile filter systems reached equilibrium after 100 hours. Rao et al. (1994) also performed long term filtration tests for soil-nonwoven geotextile filter systems. The flow reduction factors which they obtained varied from 2.5 to 6.7 with the largest values due to increasing soil fines content. In their tests it took 150 to 300 hours to reach equilibrium using a slurry soil. Thus, the flow reduction factor due to filtration and clogging is thought to be in the range of 1.3 to 6.75, with an average value of 3.5.

Various filtration criteria have been checked against the data obtained for the pore size distribution of the geotextile filter jacket and the particle sizes of Bangkok clay (Figure 4). Table 3 includes the relationships between the soil particle size and the pore size distribution of the PVD A, B, F, G, and J geotextile filter jackets.

For PVD A, all of the filtration criteria indicate that the pore sizes of the geotextile filter jacket are large and it cannot prevent soil loss. Figure 5 indicates that the PVD A geotextile filter jacket experienced a large loss of fine soil particles and that it did not reach equilibrium conditions quickly. The PVD B geotextile filter jacket exhibited similar behavior and the scattered points in Figure 6 indicate flow rate variation due to soil loss. The PVD B geotextile filter jacket pore sizes are large (Figure 4), and thus equilibrium conditions could not be reached quickly.

The PVD F geotextile filter jacket gave higher values for all of the filtration criteria, including a high loss of soil particles, which may lead to clogging of the PVD core. The filtration test, clearly indicated that a large amount of fine particles were removed. Pore size distribution and filtration test results for PVD A, B and F geotextile filter jackets indicate that the loss of fine soil particles increases with increasing pore size distribution.

The filtration test results for PVD G and J geotextile filter jackets indicate that flow rates became stable quickly even though some fine soil particles were lost. The data obtained from these PVD geotextile filter jackets are close to values recommended by Bergado et al. (1992), Carrol (1983) and Calhoun (1972).

The D_{85} of Bangkok clay varies from 0.030 mm to 0.008 mm depending on the depth of soil. If the aforementioned criteria are used for Bangkok clay, the *AOS* must be within the range of 0.024 mm to 0.090 mm; however, it is very difficult to find geotextile filters having an *AOS* less than 0.024 mm. This criterion is somewhat conservative when considering that Bangkok clay is cohesive and that the concentration of fine particles in the clay increases with depth. Thus, the *AOS* should not be larger than 0.090 mm. Using a maximum D_{85} value of 0.03 mm, and a O_{95} (*AOS*) value of 0.090 mm, the geotextile filter and soil should have a O_{95}/D_{85} value less than or equal to 3.0 in order to satisfy this retention criterion.

8.2 Permeability

There are various expressions for filtration criteria for granular filters. Typical classical expressions for the permeability and retention criteria of granular filters, respectively, are as follows:

$$D_{15(filter)} > 5\, D_{15(soil)} \tag{3}$$

$$D_{15(filter)} < 5\, D_{85(soil)} \tag{4}$$

The permeability of a granular filter material with a uniform particle size distribution is proportional to the square of the diameter of the particles. When the particle size distribution is not uniform, classical theory assumes that the permeability is proportional to D_{10}^2 or D_{15}^2 .

Assuming Darcy flow perpendicular to the surface of the granular filter, the following equations can be written:

- Flow rate per unit area with a granular filter;

$$Q/A = h/\left[d_f/k_f + d_s/k_s\right] \tag{5}$$

- Flow rate per unit area without granular filter;

$$Q'/A = hk_s/d_s \tag{6}$$

where: h = hydraulic head; d_s, d_f = soil and granular filter thickness; and k_s, k_f = permeability of the soil and granular filter.
Hence:

$$Q/Q' = 1/\left[\left(d_f k_s\right) + \left(d_f/k_f\right) + 1\right] \tag{7}$$

In order to minimize the flow disturbance caused by the granular filter, $(d_f)(k_s)/(d_s)(k_f)$ must be less than 1. In geotechnical engineering practice, a disturbance is usually considered negligible when the value of $(d_f)(k_s)/(d_s)(k_f)$ is less than 0.1. Furthermore, a factor of safety of 10 is recommended in the above calculation to compensate for the variability in soil permeability values. The above criterion can be stated as follows:

$$\left(d_f k_s\right)/\left(d_s/k_f\right) < 0.01 \tag{8}$$

A d_f value of approximately 1 m and a d_s value of 10 m can be used for granular filters. Thus, for granular filters:

$$k_f > k_s \tag{9}$$

Therefore, the permeability of a granular filter must be 10 times larger than the permeability of the soil. A similar recommendation is made by Giroud (1982) and Holtz and Christopher (1987) in the case of a soil-geotextile filter system.

In the case of a geotextile filter, the d_f value can be taken as 1 mm and a typical value for soil thickness, d_s, can be taken as 0.50 m. Therefore, Equation 9 becomes the following for a geotextile filter:

$$k_g > 0.2\ k_s \tag{10}$$

Vreeken et al. (1983) showed that the permeability of PVD geotextile filter jackets decreases by a factor of 4 to 5, either from clogging or from the formation of a filter cake. In Malaysia, a geotextile filter was excavated six years after installation and permeability tests were conducted to determine its long term performance (Loke et al. 1994). The test results indicated that the ratio of original permeability to the permeability of the exhumed geotextile varied from 1.7 to 3.3. In this case, while trimming the soil samples, sand lenses and pockets were observed indicating that horizontal drainage layers were present. Therefore, geotextile filter jackets should have a higher permeability than the surrounding clay. The factor of safety against clogging can be taken as 5 and an additional safety factor of 2 can be used to account for the possible presence of horizontal permeable (drainage) layers such as sand lenses and silt seams within the clay. The permeability criterion can then be expressed as:

$$k_g > 2\ k_s \tag{11}$$

Therefore, the permeability of geotextiles used as filters must be at least two times greater than the permeability of the soil.

8.3 Clogging Criteria

Clogging, which reduces the permeability of the geotextile filter jacket, is caused by fine particles penetrating into the geotextile filter jacket which were previously blocking the soil pore channels, or were caked on the upstream side of the geotextile filter jacket. Bangkok clay satisfies the clogging criterion expressed as $O_{95}\ (AOS) \geq n\, D_{15}$, where n varies depending on the particle size distribution. Holtz et al. (1995) suggests an n value of three. Due to the small size of the Bangkok clay particles and the large pore sizes of the geotextile filter jacket, the ratio of O_{95}/D_{15} is very high. The definition of clogging is closely related to the permeability criterion given in Equation 11 that is used to minimize clogging. Considering that permeability is proportional to D_{10}^2 or D_{15}^2 when the particle size distribution is not uniform, the clogging criterion can be expressed as $O_{15}/D_{15} \geq 1.5$.

9 CONCLUSIONS

Based on a literature review and analyses of laboratory test results on geotextiles used for filter jackets on PVDs in Bankok clay, the following conclusions are presented:

(1) Based on the average flow reduction factors obtained from the filtration tests that ranged from 1.3 to 6.75, the flow reduction value due to filtration and clogging can be taken as 3.5.

(2) The permeability of a geotextile filter jacket should be more than two times the permeability of the soil, i.e. $k_g \geq 2\ k_s$. Taking $D_{85} = 0.03$, which is the maximum value of D_{85} for Bangkok clay (varies from 0.030 to 0.008 mm) and $O_{95}\ (AOS) =$ 0.090 mm, the ratio $O_{95}/D_{85} \leq 3.0$ for the geotextile filter jacket and the soil is recommended to satisfy the soil retention function.

(3) Considering that the D_{85} of Bangkok clay varies from 0.030 mm to 0.008 mm, the apparent opening size, $O_{95}\ (AOS)$, of the PVD geotextile filter jacket should not be greater than 0.090 mm when the AOS of the geotextile is determined in accordance with ASTM D 4751 in order to satisfy the soil retention function.

(4) The definition of clogging is closely related to the permeability criterion of $k_g > 2\ k_s$ and, considering that the permeability is proportional to D_{10}^2or $D_{15}^2$when the particle

size distribution is not uniform, the geotextile filter jacket should satisfy $O_{15}/D_{15} \geq 1.5$ to prevent clogging.

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NOTATIONS

Basic SI units are given in parentheses.

A = area perpendicular to the flow direction (m^2)

C_u = soil coefficient of uniformity (dimensionless)

D_{10} = diameter such that 10% of the soil particles by mass are smaller than that diameter (m)

D_{15} = diameter such that 15% of the soil particles by mass are smaller than that diameter (m)

$D_{15(filter)}$ = diameter such that 15% of the soil particles by mass in a "granular filter" are smaller than that diameter (m)

$D_{15(soil)}$ = diameter such that 15% of the soil particles by mass (for a soil-granular filter system) are smaller than that diameter (m)

D_{50} = diameter such that 50% of the soil particles by mass are smaller than that diameter (m)

D_{85} = diameter such that 85% of the soil particles by mass are smaller than that diameter (m)

$D_{85(soil)}$ = diameter such that 85% of the soil particles by mass (for a soil-granular filter system) are smaller than that diameter (m)

D_{90} = diameter such that 90% of the soil particles by mass are smaller than that diameter (m)

d_f = thickness of filter layer (m)

d_s = thickness of soil layer (m)

h = hydraulic head (m)

i = hydraulic gradient (dimensionless)

k = permeability (m/s)

k_f = permeability of granular filter (m/s)

k_g = permeability of geotextile filter normal to the plane of the geotextile (m/s)

k_s = permeability of soil (m/s)

O_{15} = geotextile opening size such that 15% of pores are smaller than that size (m)

O_{50} = geotextile opening size such that 50% of pores are smaller than that size (m)
O_{85} = geotextile opening size such that 85% of pores are smaller than that size (m)
O_{90} = geotextile opening size such that 90% of pores are smaller than that size (m)
O_{95} = geotextile opening size such that 95% of pores are smaller than that size (m)
Q = flow rate through a granular filter and a soil layer (m^3/s)
Q' = flow rate through a soil layer (m^3/s)