A study on the behaviour of soil–geotextile systems in filtration tests

E.M. Palmeira, R.J. Fannin, and Y.P. Vaid

Abstract: The behaviour of soil–geotextile systems in filtration tests is reported for nonwoven geotextiles under unidirectional flow. A new apparatus was developed to perform filtration tests under an applied vertical stress, and tests were then conducted with different soils and nonwoven geotextiles in order to evaluate the clogging potential and retention capacity of these materials under rather severe combinations of geotextile and soil characteristics. Results show that the geotextiles perfomed well and that observed permeability losses were acceptable even for gradient ratios close to 3. No progressive piping was observed, and it is believed that the retention capacity of the geotextiles may be influenced by their manufacturing process. In general, theoretical predictions for the maximum particle size passing through the geotextile compared well with measurements.

Key words: geotextiles, filtration, gradient ratio, permeability, soil retention, clogging.

Résumé : Le comportement des ensembles sol–géotextile dans des essais de filtration est présenté pour le cas de géotextiles non tissés sous un écoulement unidirectionnel. Un nouvel appareil a été développé pour réaliser des essais de filtration sous une contrainte appliquée verticalement, et des essais ont alors été conduits avec différents sols et géotextiles non tissés dans le but d'évaluer le potentiel de colmatage et la capacité de rétention de ces matériaux sous des combinaisons plutôt sévères de géotextiles et de caractéristiques de sols. Les résultats montrent que les géotextiles se comportent bien et que les pertes de perméabilité sont acceptables même sous des rapports de gradients proches de 3. Des renards progressifs n'ont pas été observés, et l'on croit que la capacité de rétention des géotextiles peut être influencée par le processus de fabrication. En général, les prédictions théoriques pour la grosseur maximale des particules passant à travers le géotextile se comparait bien aux valeurs mesurées.

Mots clés : géotextiles, filtration, rapport de gradient, perméabilité, rétention de sol, colmatage.

[Traduit par la rédaction]

Introduction

The use of geotextiles in drainage and filtration works is becoming routine. Filtration tests, like the gradient ratio test (GRT), are performed to evaluate the clogging potential and retention capabilities of geotextiles in contact with soils (Calhoun 1972; Scott 1980; Haliburton and Wood 1982; Fannin et al. 1994, 1995). The general assumption of the gradient ratio test is that a geotextile clogging level can be inferred from the ratio of hydraulic gradients in different zones of the soil–geotextile system. The gradient ratio is defined as

$$[1]\quad \mathrm{GR}_{\mathrm{ASTM}} = \frac{i_{57}}{i_{35}}$$

where $\mathrm{GR}_{\mathrm{ASTM}}$ is the gradient ratio according to the American Society of Testing Materials (ASTM 1992), i_{57} is the gradient in the soil–geotextile composite zone between ports 5 and 7 (see Fig. 1), and i_{35} is a reference gradient in the soil zone between ports 3 and 5, which are considered sufficiently distant from the geotextile interface not to suffer any influence from the filtration mechanism developed in that region.

Fannin et al. (1994) have introduced a modified definition for the gradient ratio, intended to capture more precisely the mechanism close to the geotextile itself, given by

$$[2]\quad \mathrm{GR}_{\mathrm{mod}} = \frac{i_{67}}{i_{35}}$$

where i_{67} is the gradient between ports 6 and 7 in Fig. 1.

Limit values can be defined to bound the behaviour at the soil–geotextile interface. A value of $\mathrm{GR}_{\mathrm{ASTM}}$ equal to one would suggest that the presence of the geotextile does not affect the head loss distribution across the sample, or that it affects equally the reference zone (ports 3–5, Fig. 1) and the zone close to the geotextile. A value of $\mathrm{GR}_{\mathrm{ASTM}}$ less than one indicates that some piping of the base soil has taken place and that the permeability of the soil immediately above the geotextile has increased. Values of $\mathrm{GR}_{\mathrm{ASTM}}$ greater that one indicate that some level of clogging has ocurred near or within the geotextile. A $\mathrm{GR}_{\mathrm{ASTM}}$ value of 3 has been adopted as an upper limit for the acceptance of soil–geotextile compatibility (U.S. Army Corps of Engineers 1977; Haliburton and Wood 1982).

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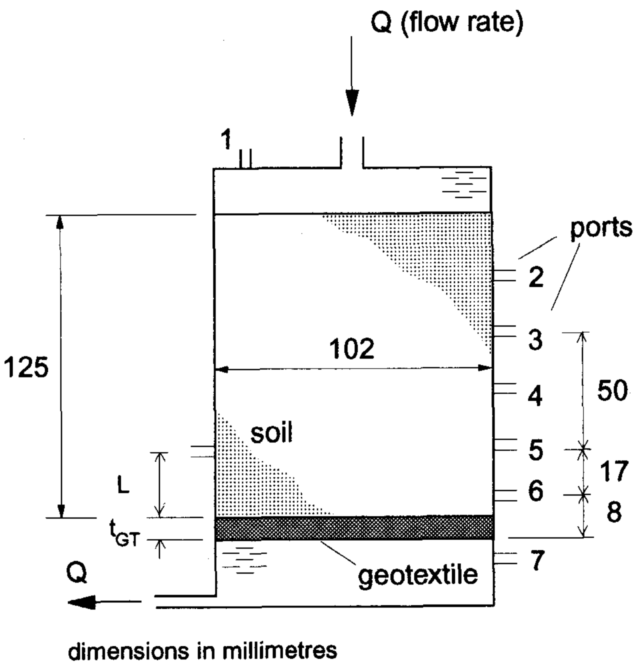
Fig. 1. Schematic view of the gradient ratio test.



Retention criteria for geotextiles have been proposed based on comparisons between characteristic particle size diameters of the soil to be protected and the geotextile opening sizes. A critical evaluation of these criteria and methodologies used to obtain geotextile opening sizes is given by Faure et al. (1989).

A new filtration test apparatus was developed at The University of British Columbia (Shi 1994; Fannin et al. 1995), and a series of filtration tests was then conducted to investigate some factors that might affect the behaviour of soil–geotextile systems. Specific objectives of the work were to observe the performance of soil–geotextile systems tested under confining pressure and interpret the results in terms of GR values and capacity for soil retention.

Some theoretical considerations regarding filtration tests

Considering the port located at a distance L from the top of the geotextile in Fig. 1, the following expression can be defined:

$$[3]\quad \mathrm{GR} = \frac{i_{\mathrm{LG}}}{i_{35}}$$

where GR is a general definition of the gradient ratio depending on the distance L chosen, and i_{LG} is the hydraulic gradient across L and the geotextile.

Equating Darcy's law, the continuity law, and head losses in different regions of the soil mass, one can obtain the following expression for the value of GR (see Appendix 1):

$$[4]\quad \mathrm{GR} = \frac{k_{35}}{k_{\mathrm{G}}}\,\frac{\dfrac{k_{\mathrm{G}}}{k_{\mathrm{L}}} + \dfrac{t_{\mathrm{GT}}}{L}}{1 + \dfrac{t_{\mathrm{GT}}}{L}}$$

where k_{35} and k_{L} are the permeability coefficients of the soil between ports 3 and 5 and within the distance L, respectively, k_{G} is the geotextile coefficient of permeability normal to its plane, and t_{GT} is the geotextile thickness.

Based on eq. [4], it can be observed that the value of GR depends on the length L, the hydraulic properties of the soil, and the geotextile properties (permeability and thickness). Under stress levels that are typical of construction works, the permeability of dense soils will vary little compared with the variation in values of k_{G} and t_{GT}. Thus, the smaller the distance L, the greater the influence of the ratio t_{GT}/L. Therefore, according to the definitions presented above, $\mathrm{GR}_{\mathrm{mod}}$ is likely to be more sensitive to compression of the geotextile than $\mathrm{GR}_{\mathrm{ASTM}}$. The variation of soil permeability (k_{35} and k_{L}) due to the movement of fines and the variation of k_{G} due to normal stresses or clogging will also affect the value of GR. In the case where $t_{\mathrm{GT}}/L \cong 0$, eq. [4] reduces to

$$[5]\quad \mathrm{GR} = \frac{k_{35}}{k_{\mathrm{L}}}$$

Equation [4] also suggests that in situations of internally stable and dense soils, little geotextile clogging, and usual geotextile thicknesses, the value of GR should not be sensitive to vertical stresses. The value of GR is dependent on the retention capability of the geotextile, since it affects the value of k_{L}, and on any geotextile permeability losses due to the combined effect of stress and clogging. So, the value of GR obtained in a filtration test is a measure of a combination of factors whose influences cannot be evaluated separately unless additional (and usually more complex) investigations are performed on both the soil and geotextile.

Equation [4] can be rewritten to allow for an estimate of the permeability of the soil close to the geotextile layer (k_{L}) as

$$[6]\quad k_{\mathrm{L}} = \frac{k_{35}}{\left(1 + \dfrac{t_{\mathrm{GT}}}{L}\right)\mathrm{GR} - \dfrac{t_{\mathrm{GT}}}{L}\dfrac{k_{35}}{k_{\mathrm{G}}}}$$

These relationships are discussed again later in association with experimental results reported below.

Test apparatus, materials, and experimental methodology

Apparatus

A permeameter was designed and built at The University of British Columbia to perform gradient ratio tests with a vertical stress ($\sigma_{\mathrm{v}} \leq 200$ kPa) applied to the top of the soil–geotextile system (Shi 1994). A schematic view of the equipment is given in Fig. 2. The body of the permeameter is made of anodised aluminium and accommodates a soil sample of 102 mm in diameter and 125 mm high. Seven manometer ports are located at different points on the permeameter for measurement of the water head distribution. Filtered deaired water with algaecide (concentration of 1/15 000 in volume) was used in all of the tests performed. A pneumatic Bellofram piston transfers vertical load to the specimen. Vertical load and compression of the sample are measured by a load cell and a displacement transducer fixed to the loading piston. A collection trough is located

Table 1. Characteristics of the soils.

Soil type	Code	D_{15} (μm)	D_{50} (μm)	D_{85} (μm)	C_u	$k_{35}{}^a$ (cm/s)	e_0	G	I_D (%)
Glass beads 1	UGGB1	29	48	64	2.1	8×10^{-4}	0.64	2.48	83
Glass beads 2	UGGB2	57	116	140	2.2	7.1×10^{-3}	0.64	2.48	83
Uniform sand	UGS	124	226	266	2	3.1×10^{-3}	0.61	2.74	85
Silty sand 1	BGSS1	9	214	257	25	1.4×10^{-4}	0.56	2.70	84
Silty sand 2	BGSS2	5	158	251	105	1.3×10^{-5}	0.54	2.65	85

Notes: C_u, coefficient of uniformity (D_{60}/D_{10}); e_0, initial void ratio; G, specific gravity; I_D, relative density.

[a]Typical value.

Fig. 2. Filtration apparatus used in the tests (after Shi 1994).

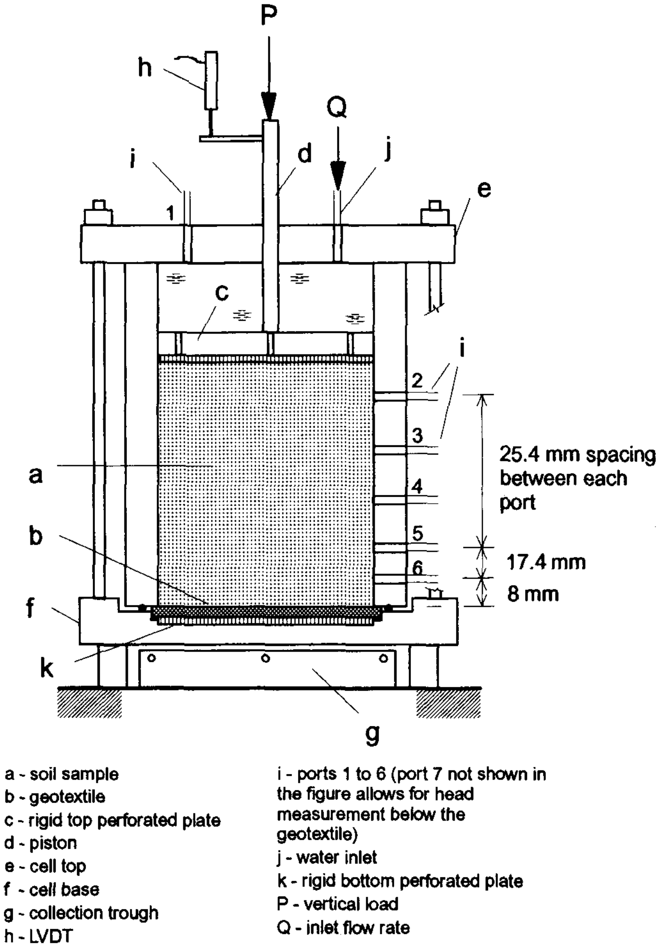
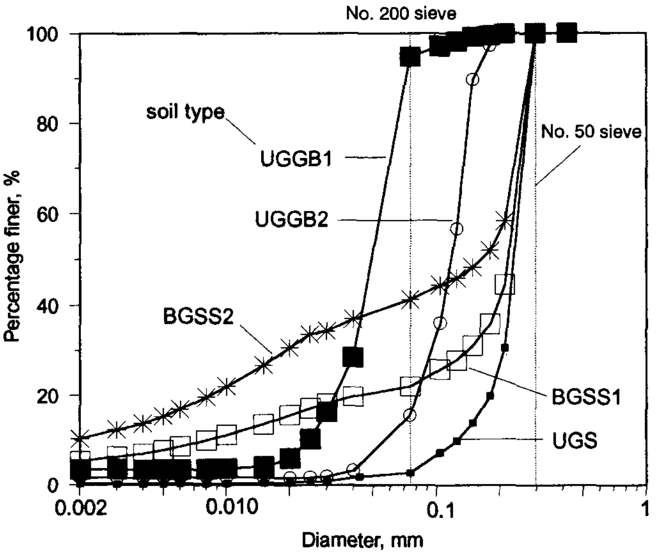


Fig. 3. Grain size distributions of the soils used.



below the permeameter cell to catch any soil particles that pass through the geotextile for a subsequent weight determination and grain size analysis.

Materials

Five fine-grained materials were used in testing, ranging in size distribution from uniform to broadly graded. These materials consisted of a uniformly graded sand, designated as UGS, two silty sands (broadly graded), designated BGSS1 and BGSS2, and two sizes of uniform glass beads, designated UGGB1 and UGGB2. The silty sands were obtained by adding different quantities of a silt to the uniform sand UGS. The glass beads were used as reference because, in retention criteria and filtration opening size tests, soil particles are commonly assumed to be spherical. Table 1 presents the main characteristics of the materials, and grain size distributions are reported in Fig. 3. The permeability varied between 1.3×10^{-5} and 7.1×10^{-3} cm/s, and the coefficient of uniformity (C_u) between 2.1 and 105 (Table 1). The materials were previously saturated by boiling and allowing them to cool at room temperature under a vacuum for a minimum of 12 h. Sample preparation consisted of water pluviation for the uniform materials and slurry mixing for broadly graded materials followed by vibration until a targeted dense void ratio was achieved (Vaid and Negussey 1988; Kuerbis and Vaid 1988).

Three types of needle-punched nonwoven geotextiles made of polyester were used. The mass per unit area varied between 180 and 600 g/m^2, and the filtration opening sizes (FOS) from hydrodynamic tests varied from 60 to 140 μm. Table 2 summarizes the characteristics of the geotextiles used. The geotextile samples were previously saturated by submerged flushing with a deaired water jet, followed by 1 h of boiling and 12 h of cooling at room temperature under a vacuum.

Fig. 4. Filtration test results for the system uniformly graded glass beads 1 (UGGB1) – geotextile G1 (test 3). (*a*) *GR* and *Q* vs. time. (*b*) Permeability coefficients vs. time. (*c*) Head loss variation along the sample height.

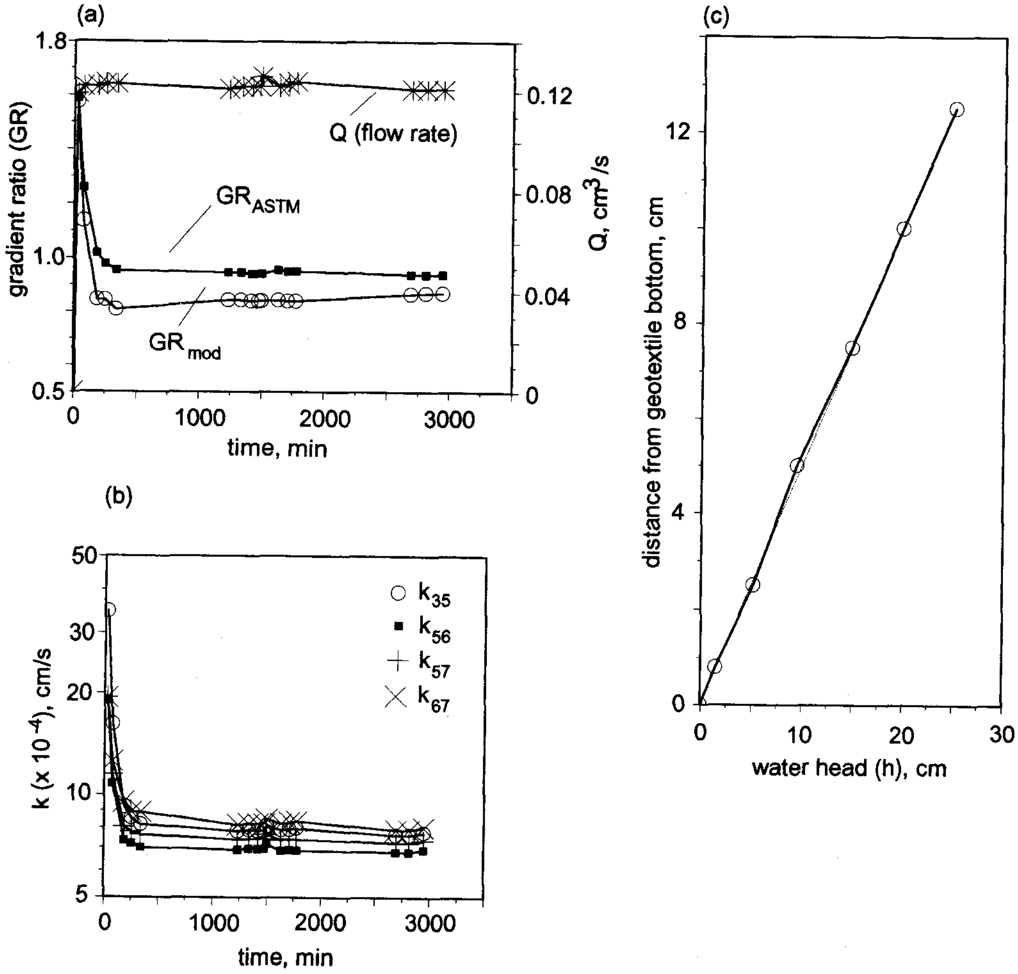


Table 2. Geotextile characteristics.

Geotextile code	Thickness[a] (mm)	Mass per unit area (g/m^2)	FOS[b] (μm)	k_{G_0}[c] (cm/s)
G1	1.9	180	140	0.70
G2	2.7	300	110	0.63
G3	5.6	600	60	0.28

[a] At 2 kPa vertical stress.

[b] Filtration opening size from hydrometer analysis (AFNOR G38017, CFG 1986).

[c] Permeability normal to the geotextile plane (no surcharge).

Additional details on the apparatus and experimental procedure can be found in Shi (1993) and Fannin et al. (1995)

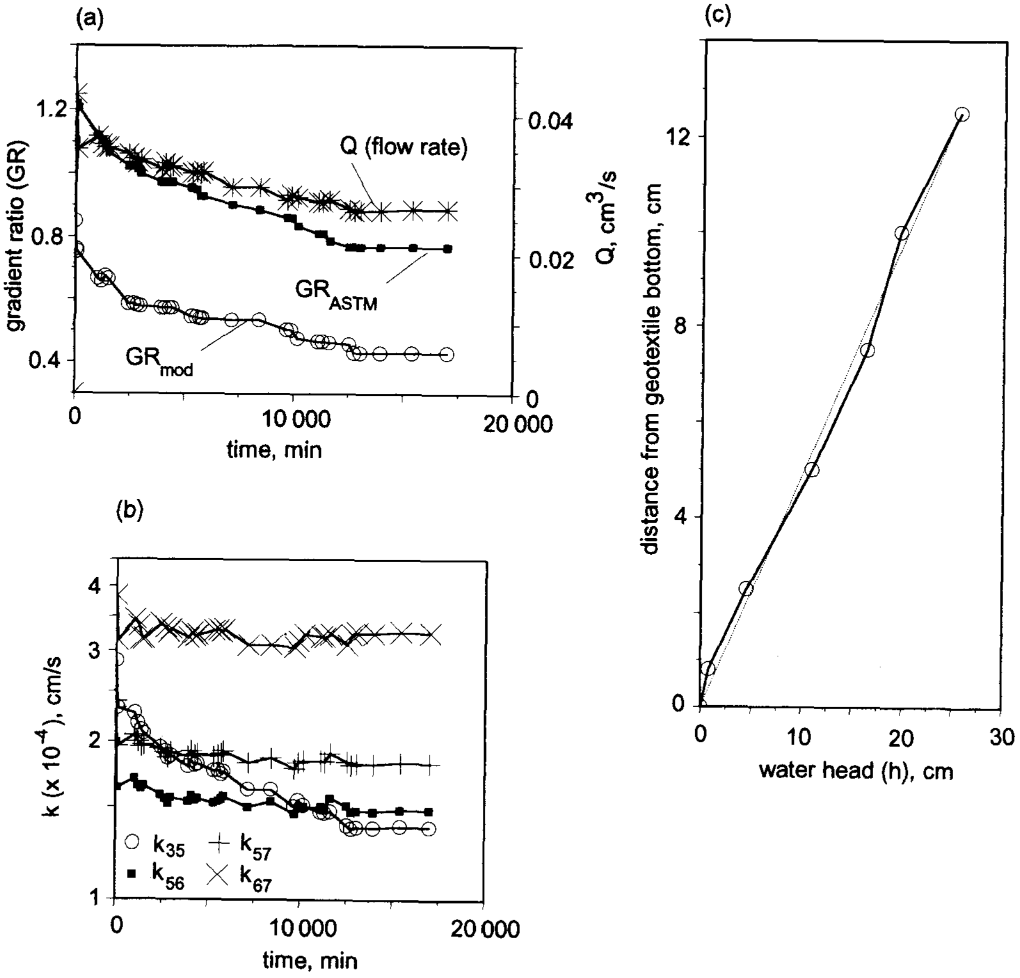
Methodology

The geotextile sits on a perforated rigid bottom plate. An unimpeded flow of water out of the geotextile is promoted by a coarse wire mesh placed between the geotextile and the rigid bottom plate. A top rigid perforated plate, again covered by a fine wire mesh, is used to apply a vertical stress to the soil sample. Double layers of plastic film and grease are placed at the interface between the soil sample and the internal surface of the permeameter cell, without blocking the manometer ports, in order to minimize sidewall friction due to vertical stresses on the sample. The permeameter was submerged in a reservoir bath during testing, and the water flow was controlled at a targetted system gradient provided by a constant head device on the inlet and outlet of the cell. With the exception of one of the tests where the gradient was varied, all other tests were performed with a system gradient of 2 (i_{17} in Fig. 1).

Grain size analyses of fine soil particles that passed through the geotextile were performed using a particle size analyser Sedigraph 5100, from the Micromeritics Instrumentation Corp. This equipment allows grain size distribution curves to be obtained in sedimentation tests by x-ray emissions in a very quick and accurate way.

To allow for a more comprehensive interpretation of the behaviour of the soil–geotextile system under pressure, the permeameter was also used to obtain values of normal permeabilty (k_G) and to deduce opening sizes (OS) of

Fig. 5. Filtration test results for the system broadly graded silty sand 1 (BGSS1) – geotextile G1 (test 10). (*a*) *GR* and *Q* vs. time. (*b*) Permeability coefficients vs. time. (*c*) Head loss variation along the sample height.

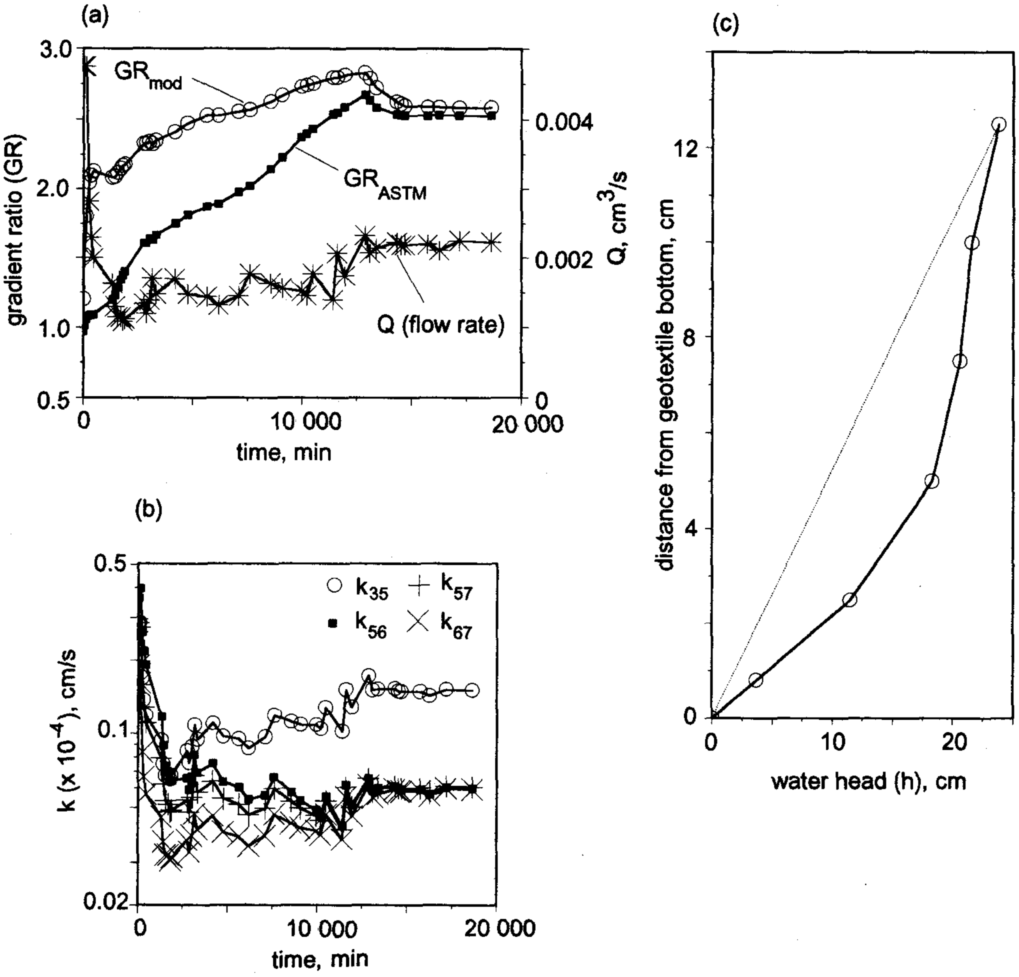


geotextiles under pressure. In the former case, several layers of geotextile were placed in the permeameter cell and subjected to normal flow under different levels of vertical stress. Measurements of geotextile thickness were also obtained using the same procedure. Tests with geotextile layers impregnated with predetermined amounts of soil were also carried out to investigate the effect of the level of soil impregnation on geotextile permeability under stress. Sample preparation involved laying an appropriate quantity of soil on the geotextile and vibrating it. In the case of OS tests, submerged glass beads were placed on top of the geotextile and the permeameter cell was vibrated for 3 min using a BVI-Vibro-Graver hand vibrator, model V-73-C, 8 W, at a frequency of 60 Hz. Glass beads that passed through the geotextile were then analysed to establish the diameter for which 95% of the particles were smaller. The results from these tests will be referred to throughout this work as OS rather than FOS to distinguish them from values that were obtained from standard FOS test procedures; although for the geotextiles used in the present work the results obtained with both techniques compare very well for tests under no vertical stress.

At the end of each gradient ratio test, the geotextile sample used was subjected to a permeability test in order to assess permeability losses. These tests will be referred to hereafter as geotextile residual permeability tests. The equipment employed in these tests was similar to the one presented in ASTM (1992). The total head loss was varied in preliminary tests to establish the range of laminar flow conditions for the geotextiles used. A total head loss of 10 mm was then adopted for all geotextile residual permeability tests carried out. An optical microscope was used to observe and photograph all geotextile samples after gradient ratio tests. The mass of soil particles retained in the geotextile was also assessed from the difference between its initial and final weights.

Combinations of soils and geotextiles that might result in an undesirable performance of the geotextile filter were examined in the test programme. To avoid tests that might be anticipated to yield good results, a series of tests always began with the worst combination for the geotextile in terms of the soil–geotextile system. The result of this test was then used to decide whether further tests should be conducted with that soil and other geotextiles. The results

Fig. 6. Filtration test results for the system broadly graded silty sand 2 (BGSS2) – geotextile G1 (test 12). (*a*) *GR* and *Q* vs. time. (*b*) Permeability coefficients vs. time. (*c*) Head loss variation along the sample height.



of the test programme are discussed in the following sections.

Results obtained

Gradient ratio test results

Typical results of gradient ratios (ASTM and modified), flow rate (*Q*), and permeability versus time for some of the tests are presented in Figs. 4–6, together with the variation of head loss at the end of the test. Depending on the soil type, stabilization of GR values and flow rates is seen to occur within intervals of time ranging from about 3 h to 10 days (Figs. 4*a* and 6*a*). All of the test results reported in the present work are those obtained after stabilization. Due to nature of the test and variability in properties of the materials (mainly the geotextile), a range of uncertainty of about 10% in the value of gradient ratio is expected in carefully conducted tests.

Figures 4*b*, 5*b*, and 6*b* show the variation of permeability at different locations in the sample during testing. Little variation is observed along the sample height for the uniform soil UGGB1. In contrast, tests with the broadly graded soils and geotextile G1 demonstrated a marked change in permeability close to the geotextile depending on both the amount of fines in the soil capable of migrating during flow and on the geotextile opening sizes (see Figs. 5*b* and 6*b*. The migration of fines through broadly graded soils can severely influence the variation of hydraulic head loss along the sample height (Fig. 6*c*), in comparison to the almost linear variation in the case of the uniform material presented in Fig. 4*c*. Indeed the extension of the region affected by fines migration may even reach the reference zone between ports 3 and 5 (Fig. 1), as seen in Fig. 6*c*.

Results of GR values obtained in all tests performed are summarized in Table 3. Very good agreement is obtained for two tests that were repeated (tests 11 and 12). It is observed that the value of GR_{ASTM} was close to one for all tests performed with uniform soils, while GR_{mod} tended to be slightly less than one, especially for uniform soils finer than the characteristic opening size of the geotextile. Bridges of soil particles are believed to have formed across the geotextile openings, even for a uniform soil with mean particle diameter approximately one third of the geotextile opening size (test 1), causing the geotextile

Table 3. Summary of filtration test results.

Test No.	Soil	Geotextile	i_{17}	σ_v (kPa)	σ_{vi}[a] (kPa)	GR_{ASTM}	GR_{mod}	k_G[b] (cm/s)	$\Delta k/k_{Go}$[c]
1	UGGB1	G1	2	0	0	1.0	0.8	0.48	0.31
			4			1.0	0.8		
			8			1.0	0.9		
2	UGGB1	G1	2	20	20	1.1	0.9	0.42	0.34
				50		1.1	0.9		
				100		1.1	1.1		
				200		1.1	1.2		
3	UGGB1	G1	2	50	50	0.9	0.8	0.39	0.44
				100		0.9	0.9		
4	UGGB1	G2	2	20	20	0.9	0.8	0.60	0.14
				50		1.0	0.9		
				100		1.0	0.9		
5	UGGB1	G3	2	0	0	1.0	0.8	0.28	0.14
				20		1.0	0.8		
				50		1.0	0.9		
				100		1.0	0.9		
6	UGGB2	G1	2	0	0	0.9	0.8	0.50	0.29
7	UGGB2	G2	2	0	0	1.0	0.9	0.51	0.19
8	UGS	G1	2	0	0	1.2	0.7	0.39	0.44
				20		1.2	0.7		
				50		1.2	0.7		
				100		1.2	0.8		
9	UGS	G2	2	0	0	1.0	0.9	0.20	0.32
				20		1.0	0.9		
				50		1.1	1.0		
10	BGSS1	G1	2	0	0	0.8	0.4	0.25	0.64
11	BGSS2	G1	2	0	0	2.7	2.6	0.28	0.60
12	BGSS2	G1	2	0	0	2.5	2.6	0.32	0.54
13	BGSS2	G2	2	0	0	1.8	1.8	0.40	0.37
14	BGSS2	G3	2	0	0	1.0	1.0	0.19	0.32

[a] Vertical stress when water flow starts.

[b] Residual geotextile permeability after the filtration test.

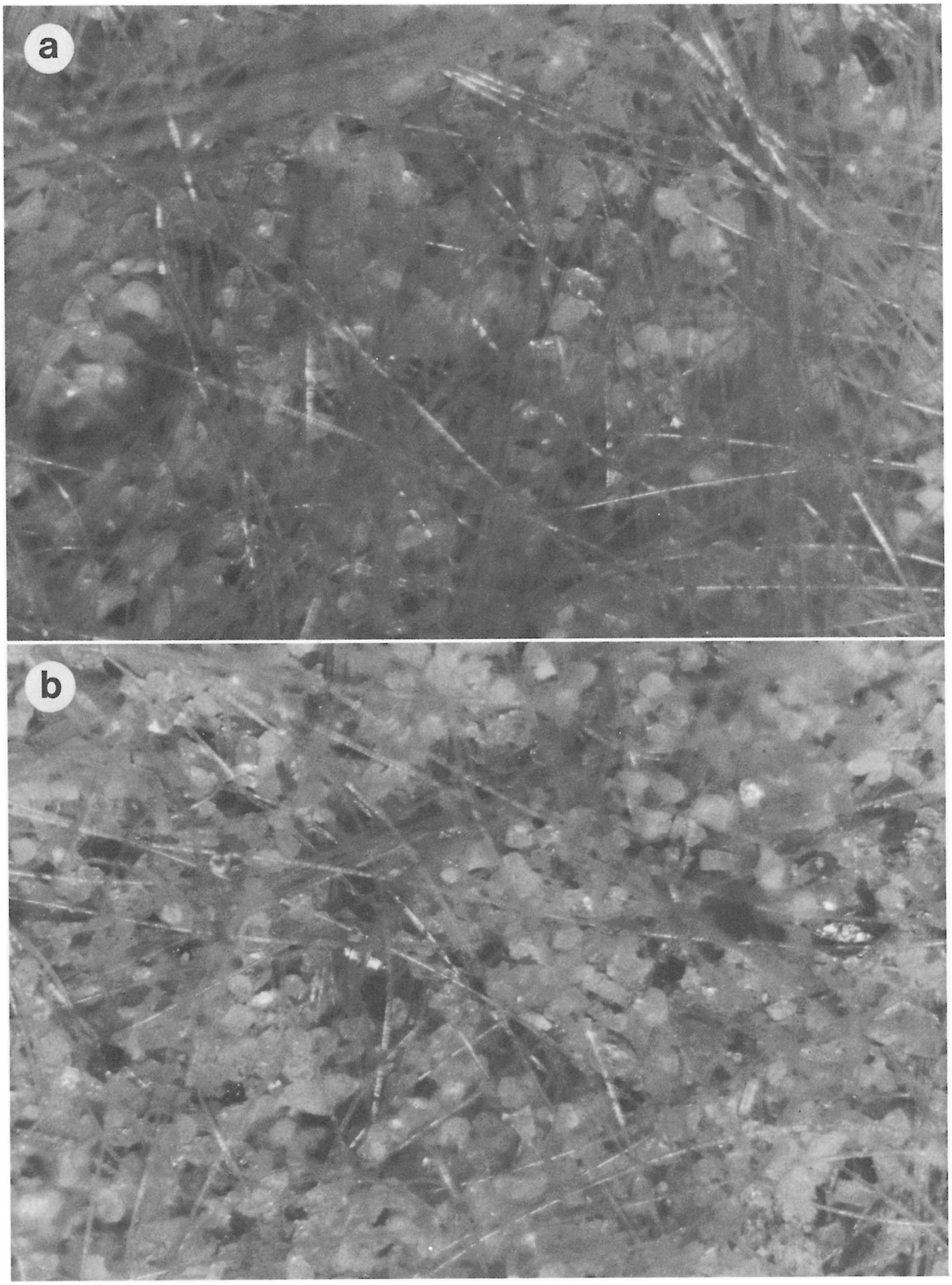
[c] $\Delta k = k_{Go} - k_G$, where k_{Go} is the original geotextile permeability coefficient.

to retain sufficient particles and develop a stable soil structure throughout the test. Differences between values of GR_{ASTM} and GR_{mod} are attributed to the latter being capable of better capturing the "bridging" mechanism of soil particles around geotextile openings and consequent increase of permeability in that region.

An interesting feature is noted for tests with geotextile G1 (FOS = 140 μm) and soils UGS, BGSS1, and BGSS2 (tests 8, 10, and 11 in Table 3). For these soils the values of C_u are 2.1, 25, and 105, respectively, and the percentage by weight of soil particles smaller than the geotextile FOS are 12, 29, and 47%, respectively. Finer particles will tend to migrate through the soil mass and, if mobile, may be retained by the geotextile depending on its opening size and potential to develop a bridging structure. In the test with soil BGSS2, the permeabilities of the soil close to the geotextile and of the geotextile itself diminished and the value of GR increased (Fig. 6*a*). This can be attributed to geotextile soil retention causing clogging of adjoining soil close to the geotextile. Geotextiles with smaller openings (G2 and G3) were less affected by this clogging action and exhibited lower values of gradient ratio (see tests 13 and 14 in Table 3). Tests with geotextiles G2 and G3 and soil BGSS2 presented similar distributions of head loss along the sample height, but in these cases the distributions were more uniform between ports 5 and 7 and 3 and 5 (Fig. 1). In contrast, some fine particles are washed out from the soil matrix in the test with soil BGSS1 and through the geotextile causing a significant reduction in the value of GR_{mod} (see Fig. 5*a*). The UGS soil has fewer particles smaller than the geotextile openings and experienced less washing out of fines (and reduction of GR). Despite this loss of fines, these soils behaved in a stable manner throughout the test duration in terms of constant values of GR, permeabilities, and amount of soil piped through the geotextile, as suggested by the results in Figs. 5 and 6.

Values of the geotextile residual permeability coefficient after filtration tests (k_G) and the permeability loss ($\Delta k/k_{Go}$) with regard to the initial permeability of the geotextile (k_{Go}) are given in Table 3. Larger losses occurred for the broadly graded soils (up to 64% reduction) with geotextile G1, the most open of the three geotextiles. The uniform

Fig. 7. Microscopic views of geotextiles (*a*) G1 (8×) and (*b*) G3 (8×) after filtration tests with soil BGSS2 (tests 11 and 14).



soil UGS also caused a rather large geotextile permeability loss (44%) with geotextile G1. It is interesting to note that the size of particle capable of migrating through this soil would be of the order of its D_{10}, which is a value very close to the geotextile FOS (140 μm).

A microscopic image of two geotextile samples (G1 and G3) after filtration tests with soil BGSS2 is presented in Fig. 7. In spite of the considerable quantity of soil particles entrapped in the geotextile, a reasonable number of voids can still be seen, an observation which is consistent

Fig. 8. Variation of gradient ratios with vertical stress: (*a*) GR_{ASTM} vs. σ_v, (*b*) GR_{mod} vs. σ_v.

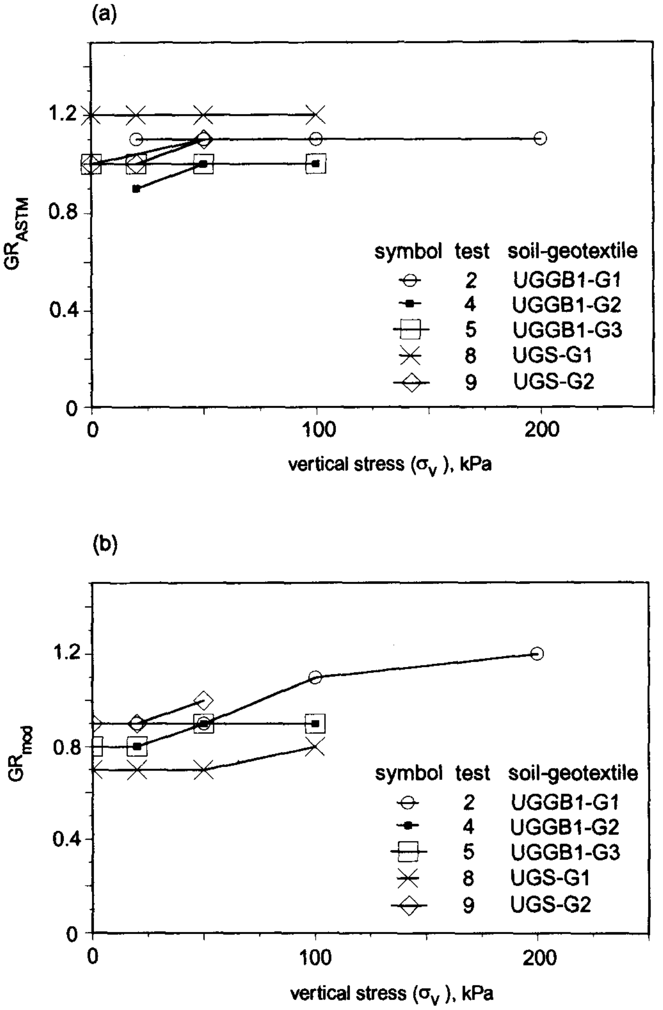
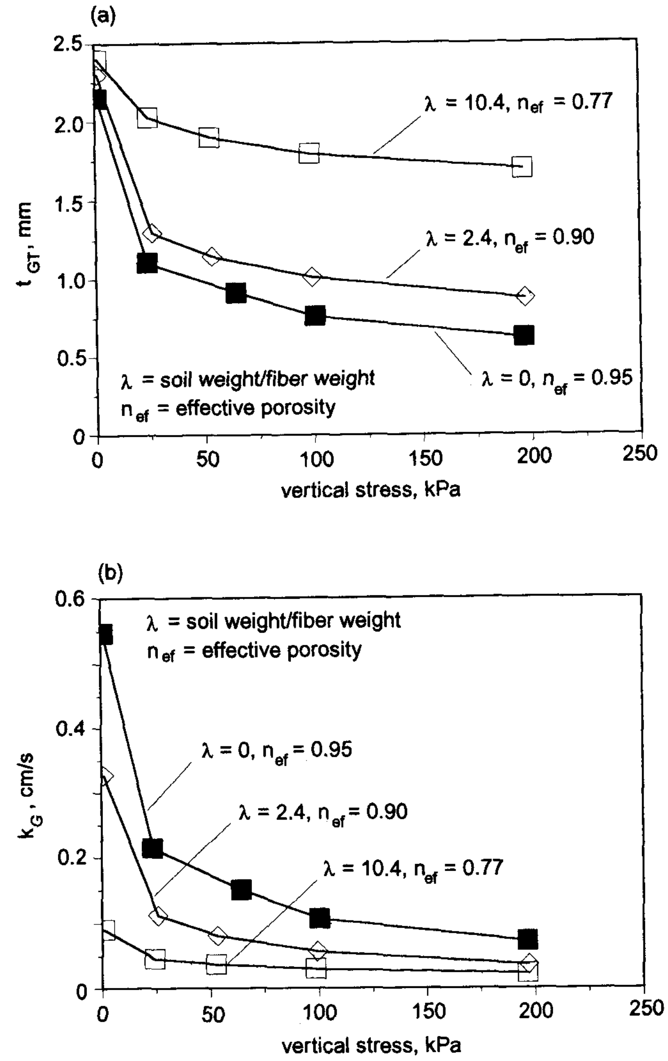


Fig. 9. Compressibility and permeability test results for geotextile G1 with and without impregnation with soil UGGB2.



with the level of residual permeability remaining in the geotextile samples tested (Table 3). It should be noted that the larger holes apparent in the geotextile in Fig. 7 are those left by needles in the needle-punching process during manufacture. The size of these holes may affect the filtration opening size of the geotextile, as commented upon later. It is believed that tests to determine the residual permeability of the geotextile and use of microscopic observations after filtration tests where high values of GR are obtained can be useful tools to a sound interpretation of the extent of geotextile clogging.

Figure 8 shows the variation of GR values with vertical stress (σ_v) on the sample top. It is observed that the value of GR_{ASTM} is almost unaffected by the vertical stress, while GR_{mod} tends to increase slightly with vertical stresses above 25 kPa. These results support the comments presented earlier in this work. The value of applied stress on the sample when flow of water was initiated in tests with UGGB1 and geotextile G1 did not show any appreciable influence on the measured gradient ratios, as seen from the results of tests 1, 2, and 3 in Table 3.

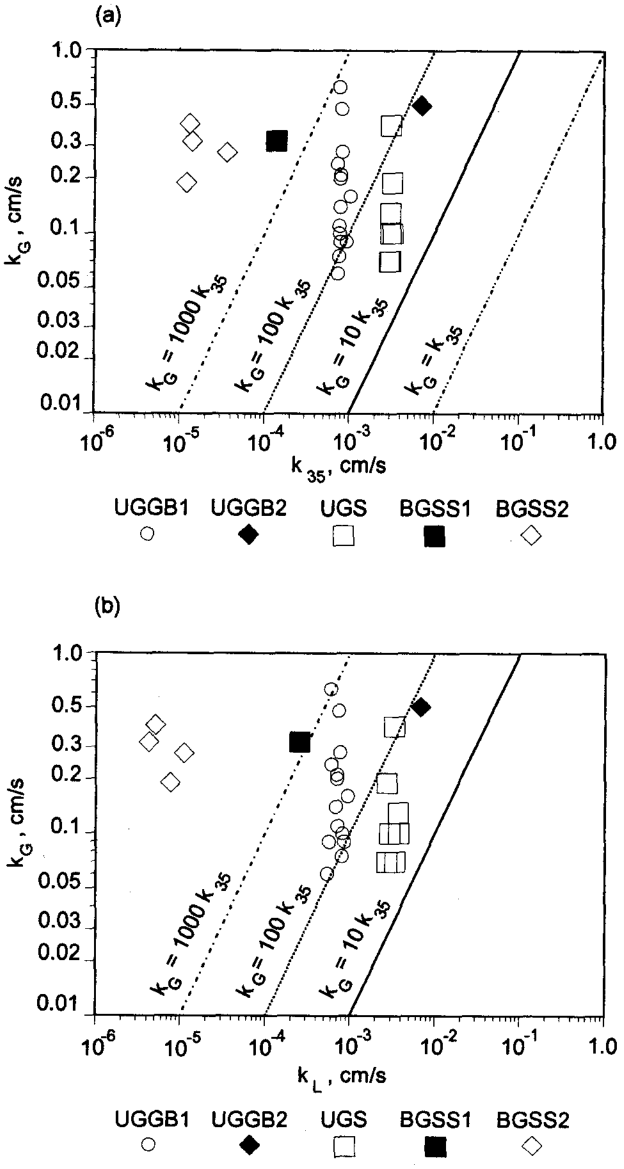
It is important to recognize the extent to which placement of soil on the geotextile during sample preparation in the filtration tests, or during construction for that matter, causes some initial clogging of the geotextile and reduces the original filtration opening size to an effective value that is difficult to assess. The behaviour is likely to be more severe for broadly graded soils with particle size ranges enveloping the geotextile filtration opening size.

Fine-grained soils and internally unstable soils are believed to be the most challenging materials in filtration design with geotextiles. However, the results presented above show that the value of GR for unstable soils can be severely affected by the way in which fine particles migrate through the soil and where they may be retained within the sample. A large value of GR may not necessarily indicate unacceptably severe clogging of the geotextile.

Comparison between soil and geotextile permeabilities

From eq. [6] and the values of GR obtained in the filtration tests, the average soil permeability (k_L) along the length L (Fig. 1) can be deduced, and a comparison made with the geotextile permeability (k_G). The length $L + t_{GT}$ to be used

Fig. 10. Comparison between geotextile and soil permeabilities for all tests performed. (*a*) k_G vs. k_{35}. (*b*) k_G vs. k_L for $L + t_{GT} = 8$ mm.



is 25.4 or 8 mm, depending on the port location and the definition of GR that is considered (GR_{ASTM} or GR_{mod}, respectively).

For tests with no surcharge on the sample top, the values of k_G used were those obtained in the geotextile residual permeability tests. For filtration tests with surcharge on the sample, the variation of k_G and t_{GT} with pressure is required in eq. [6] for a proper determination of k_L. These relationships may be obtained from filtration tests performed under vertical stresses on clean geotextile packings about 8 cm thick without any soil in the same apparatus, for which some results are reported using geotextile G1 in Fig. 9. However, geotextiles in the filtration tests become impregnated with particles of the soil, leading to a reduced permeability. For an accurate representation of the geotextile state under these circumstances, a large number of repetitions of the same filtration tests would be necessary (in some cases more than 15 repetitions) to collect a reasonable number of geotextiles to form the packing for permeability tests under stress. Rather than using geotextile permeability test results under virgin conditions, which would be favourable to the geotextile, the results of permeability tests on similar 8 cm thick geotextile packings impregnated with soil to a targetted value, as described earlier in this work, were used in eq. [6] for the estimate of k_L. Results of permeability tests on impregnated samples with ratios of impregnating soil mass to geotextile fiber mass (λ) equal to 2.4 and 10.4 are also shown in Fig. 9. These ratios are associated with values of geotextile effective porosity in the geotextile (n_{ef}) of 0.90 and 0.77 under no surcharge. It is observed that the presence of soil particles in the geotextile voids can significantly reduce its permeability and compressibility. By measuring the values of λ obtained for each geotextile sample after a filtration test, it was possible to establish the values of t_{GT} and k_G for substitution in eq. [6] for the interpretation of k_L in tests under pressure. Inspection of the results obtained with this approach, Fig. 10, shows that the requirement $k_G > 10\ k_L$ was satisfied in all cases.

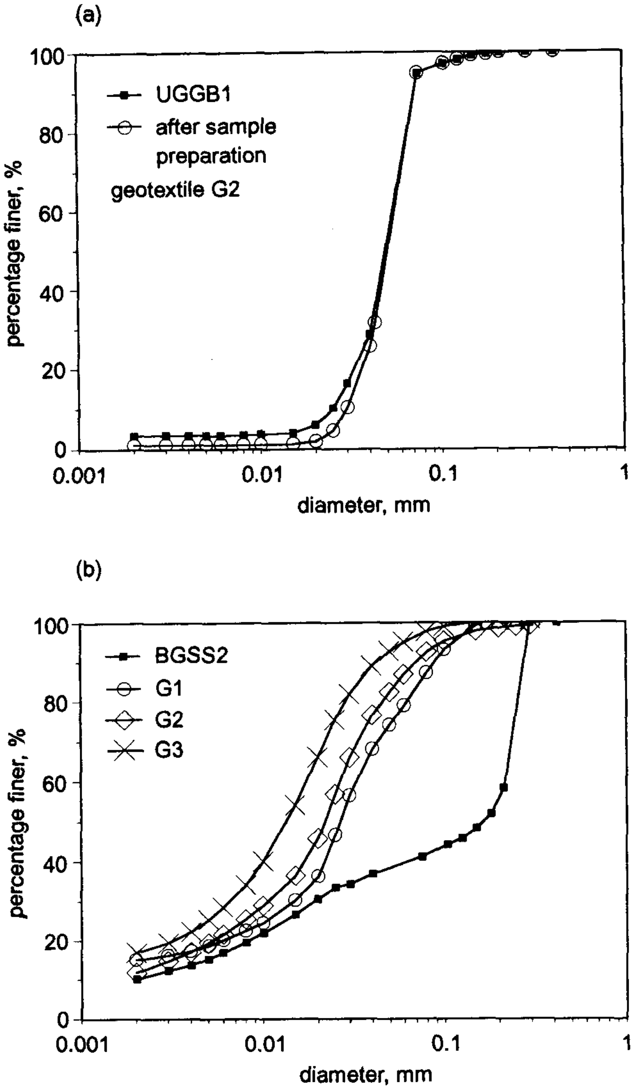
It is recognized that impregnation of the geotextile with soil as described above addresses the reduction in k_G that occurs. However, it may not completely replicate conditions in the field.

Retention characteristics of the geotextiles

Soil particles that passed through the geotextile during a filtration test were collected in the trough below the permeameter, and a gradation curve was estabilished from grain size analysis. Three potential phases for soil passage were identified: particles that passed during preparation of the soil sample, during application of the surcharge pressure (if any), and during water permeation. In all tests the greatest quantity of soil was collected after deposition and vibration of the soil sample to a targetted density during sample preparation. Significant quantities of soil were only collected for soils with a considerable number of particles smaller than the opening size of the geotextile. Even so, the mass of the soil piped in the worst case (test UGGB1-G1) was only 1.5% of the total mass of the soil sample. It was common to observe that, after sample preparation, some soil accumulated directly beneath the needle-punched holes of the geotextile. This behaviour is believed to depend on the presence of well-defined cylindrical holes in the geotextile layer, found to be more clearly apparent in the heavier geotextile layers (G2 and G3). However, this piping action ceased in the subsequent stages of a test (surcharge loading and water flow).

In general, for the uniform soils, the D_{95} obtained from grain size analysis of the material that passed through the geotextile after sample preparation compared well with the geotextile opening size obtained from hydrodynamic testing. For soils finer than the geotextile FOS, the resulting grain size curve of the soil that passed through the geotextile is very much the same as that of the original soil (Fig. 11*a*). However, with the broadly graded soils, only a finer fraction of the particles was able to pass through the geotextile (Fig. 11*b*).

Fig. 11. Typical grain size distributions of soil particles passing through the geotextile during sample preparation: (*a*) test 4; (*b*) tests 12, 13, and 14.



Although some soil particles are likely to be displaced and to pass through the geotextile during surcharge loading of the sample, the quantity collected in the trough was negligible compared with that after sample preparation and water flow. Further, the quantity of soil collected during water permeation was also generally small, particularly in tests with a vertical stress greater than 20 kPa and for coarse and broadly graded soils. Indeed with some broadly graded soils, the amount of soil collected was so small that the procedure used for grain size analysis was not sensitive enough for an accurate definition of grain size distribution. As might be expected, the smaller the geotextile opening size, the finer were the particles that piped through it (Fig. 12). Experience in other tests has shown that variability of the geotextile characteristics (distribution of opening sizes and needle-punching technique) may influence the nature of these results and partially obscure the effect of other relevant variables (vertical stress, for instance).

Fig. 12. Grain size curves of material piped through geotextiles G1, G2, and G3.

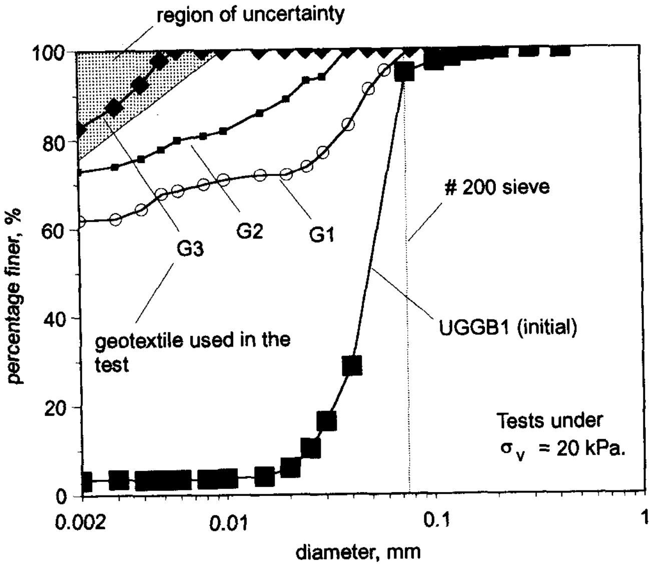
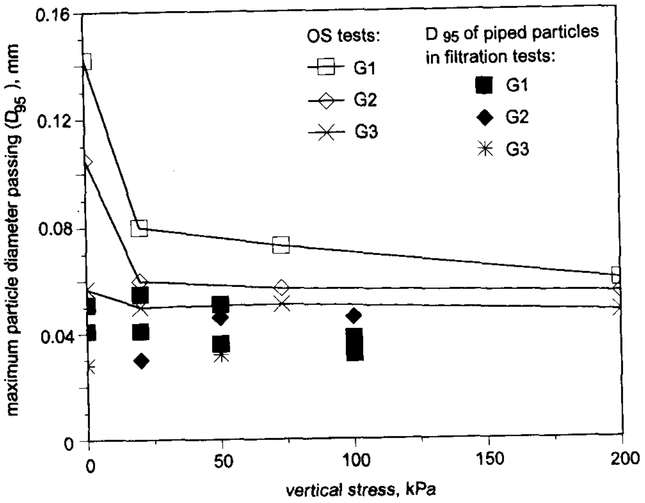


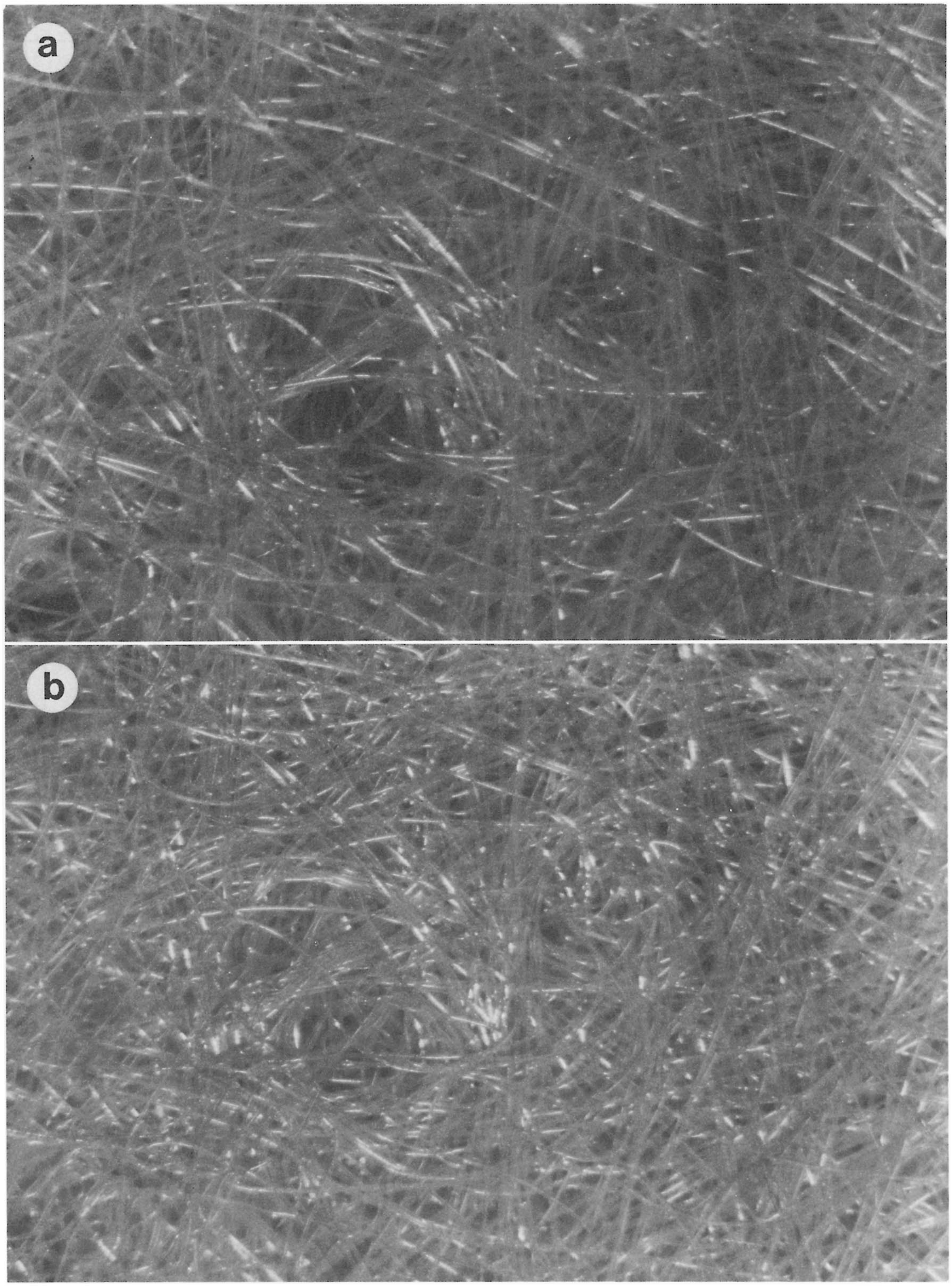
Fig. 13. Maximum particle diameter piped in OS tests and filtration tests under vertical stress.



Analysis of soil that piped through the geotextile at different times during the test duration showed that the piping mechanism tended to occur in the earlier stages of a test (first hour). Thereafter the system stabilized, and no significant further piping was observed. This behaviour was confirmed by measurements of sample height during testing.

Test data like those presented in Fig. 12 for the UGGB1 material were used to establish the "largest soil particle diameter" (assumed equal to D_{95}) that passed through the geotextile during flow. Values of D_{95} for some of the tests are reported in Fig. 13. Results of the geotextile opening size (OS) tests under vertical stress, described earlier in this work, are also presented in the figure. It is observed that the value of D_{95} of the soil piped is about 50–60% of the measured opening size. This response is attributed to geotextile impregnation during sample preparation prior to

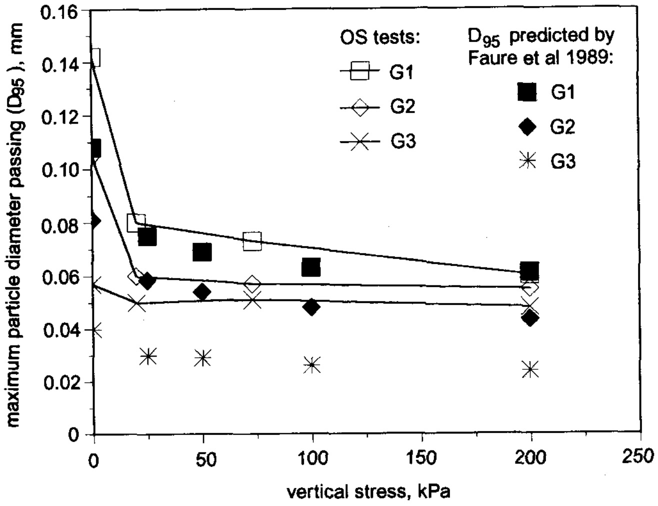
Fig. 14. Microscopic view of needle-punched holes under different vertical stresses for geotextile G1: (*a*) under zero vertical stress (8×); (*b*) under 150 kPa (8×).



initiation of flow and to the difference in energy applied to agitate soil particles in the OS tests and seepage forces in the filtration tests. It is noted that the OS and D_{95} values exhibit little variation for surcharge pressures greater than 20 kPa. This type of behaviour has also been observed in pore size measurements by image analyser (Gourc et al. 1982), and in the present case it may have resulted from a limited contraction of the needle-punched holes under stress. The size of these holes is believed to be the limiting factor controlling the diameter of soil particles capable of passing through the geotextile. A microscopic examination of the geotextile structure under a range of vertical stresses showed that the needle-punched hole, although decreasing in size, represents the largest aperture in the fabric for stresses varying from 0 to 150 kPa, as illustrated in Fig. 14. It is recognized that, under field conditions, soil compaction and geotextile impregnation are likely to partially reduce or block the needle-punched holes.

Faure et al. (1989) introduced an interesting theoretical approach to estimate the pore size of nonwoven geotextiles based on statistics. Figure 15 presents a comparison between predictions based on their theoretical approach and the observed values of maximum piped particle diameters (D_{95}) in OS tests under different vertical stresses. Very good agreement was observed for tests with geotextiles G1 and G2, but the method underestimated the values of D_{95} for the thicker geotextile G3.

Fig. 15. Comparison between predicted and observed maximum piped particle diameters in OS tests.



Conclusions

The behaviour of soil–geotextile systems in filtration tests has been examined. A new test apparatus was described that allows filtration tests to be conducted on relatively large samples under vertical stress and accommodates the collection of any soil particles that pass through the geotextile for grain size analysis. The main conclusions of the work are summarized below:

In spite of the rather severe combinations of soil and geotextile used in testing, the geotextiles performed well in terms of clogging potential, soil retention capacity, and permeability loss.

The gradient ratio value obtained in filtration tests is dependent on several factors related to the soil and geotextile characteristics. It is also dependent on preparation of homogeneous samples and the potential for unforeseen developments during testing such as blinding or clogging of the manometer ports. Aspects of fines migration through broadly graded soils, or sample preparation itself, can cause heterogeneities in the soil sample that may lead to large GR values. In these cases it is recommended that the filtration test be complemented by an analysis of the evolution of the flow rate during the test, microscopic observations of the geotextile structure, and a measurement of geotextile residual permeability. Due to the typical size of geotextile specimen used in testing, a variability of hydraulic and geometrical characteristics as well as nonuniform opening size distributions can also affect the value of gradient ratio.

The values of GR_{ASTM} and GR_{mod} were found to be rather insensitive to the applied vertical stress. For the conditions examined in this work, the combination of geotextile impregnation during sample preparation and later application of normal stress did not influence the value of GR. Results of permeability tests with impregnated geotextile samples alone showed that the permeability of the geotextile may have diminished by up to 20 times. However, the compressibility of the geotextile is smaller for such impregnated samples. The value of GR_{mod} is seen to be more sensitive to vertical stress than the GR_{ASTM} because the former is more affected by its proximity to the geotextile. Both definitions should be routinely used for the interpretation of filtration tests.

Permeability tests carried out on the geotextile samples after filtration tests showed reductions in geotextile permeability up to 44% for tests with uniformly graded soil, and up to a maximum loss of 64% for broadly graded soils.

Most of the soil particles that piped through the geotextile did so during sample preparation. The geotextile opening size was measured at several vertical stresses and compared with soil particles that passed through the geotextile during flow. It was observed that the largest particles carried by the water (at a system hydraulic gradient of 2) through the geotextiles were of the order of 50–60% of the geotextile OS under the same vertical stress. Although it is recognized that the value of OS is sensitive to the specifics of the test procedure, the results suggest that the retention capability of nonwoven geotextiles can be significantly greater than that predicted by current soil retention criteria.

The diameter of the largest soil particle capable of passing through the geotextile may be influenced by the size of holes in the geotextile left by the needle-punching manufacturing process. Under field conditions this influence is likely to be minimized by soil compaction and impregnation of the geotextile prior to flow. Acknowledging the few data reported in this study, the results obtained suggest that the Faure et al. (1989) method may be a useful tool for predicting pore sizes of geotextiles under vertical stresses.

Laboratory filtration tests do not simulate properly the operating conditions found in geotextile filters in the field. The construction procedure including compaction, impregnation of the geotextile with soil particles, and eventual geotextile damage are all likely to influence its performance. They may also increase its retention capacity. Nevertheless, the results obtained in this study would suggest that serious geotextile clogging tends to occur only under very severe conditions and imply that the current retention criteria are conservative. Further research is required to obtain a better understanding of the clogging potential and retention characteristics of geotextiles under working conditions, with more emphasis on retrieving samples from in-service constructions.

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Appendix

Demonstration of expression 4

The expression for the equivalent permeability coefficient for successive layers of soils submitted to water flow normal to the bedding planes can be found in most soil mechanics textbooks (see Terzaghi 1948, for instance). Assuming that the soil layer with thickness L and the geotextile in Fig. 1 form a two-layer system under those conditions, one can write:

$$[\text{A1}] \quad k_{\text{LG}} = \frac{L + t_{\text{GT}}}{\dfrac{L}{k_{\text{L}}} + \dfrac{t_{\text{GT}}}{k_{\text{G}}}}$$

where k_{LG} is the equivalent permeability coefficient of the soil–geotextile system, k_{L} and k_{G} are permeability coefficients in the sample region defined by length L and in the geotextile layer, respectively, and t_{GT} is the geotextile thickness.

The gradient ratio (GR) can be defined as:

$$[\text{A2}] \quad \text{GR} = \frac{i_{\text{LG}}}{i_{35}} = \frac{\dfrac{Q}{k_{\text{LG}}A}}{\dfrac{Q}{k_{35}A}} = \frac{k_{35}}{k_{\text{LG}}}$$

where Q is the flow rate, A is the sample cross-sectional area, and k_{35} is the soil permeability in the soil layer between ports 3 and 5 (Fig. 1).

Combining eqs. A1 and A2 yields eq. [4]:

$$\text{GR} = \frac{k_{35}}{k_{\text{G}}} \, \frac{\dfrac{k_{\text{G}}}{k_{\text{L}}} + \dfrac{t_{\text{GT}}}{L}}{1 + \dfrac{t_{\text{GT}}}{L}}$$