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A semi-analytical methodology for development of woven geotextile filter selection criteria

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ABSTRACT: Geotextiles have been commonly used in geotechnical and environmental engineering projects to prevent erosion of soils in contact with the filter without impeding the flow of seeping water through the soil. Several empirical criteria incorporating varying factors of safety have been proposed for selection of geotextile filters. A probabilistic numerical filter model, named RETAIN, using image-based geotextile pore structure was developed for woven geotextile filters and is presented in this paper. The paper also summarizes a new methodology to propose filter selection criteria using the results of RETAIN. The proposed criteria based on this methodology and the existing empirical criteria from the literature were evaluated against the actual performance observed in the laboratory filtration tests on a silty sand specimen and a wide range of woven geotextiles. The results indicated that RETAIN can model the filtration behavior of silty sands and woven geotextiles, and the model output can be used to develop new geotextile selection criteria. The method is currently applicable to one type of soil; however, the method is rational, and the applicability of the methodology to other soils with a range of particle size distributions can be checked after conducting laboratory filtration tests on these soils.

KEYWORDS: Geosynthetics, Geotextile, Digital image analysis, Pore opening size, Filtration, Monte Carlo simulation

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1. INTRODUCTION

Geosynthetic filters (geotextiles) have been commonly used in geotechnical and environmental engineering projects for the last 20 years to prevent erosion of soils in contact with the filter without impeding the flow of seeping water through the soil. Several filtration criteria have been proposed in the past for selection of geotextile filters. These criteria are typically expressed in terms of a ratio of a characteristic geotextile pore size to a characteristic soil particle (grain) size (Carroll 1983; Christopher and Holtz 1985; Giroud 1988; Fischer *et al.* 1990; Moraci 1996; Austin *et al.* 1997; Mlynarek 2000). The criteria give limiting values for such a ratio so that the filter is not clogged and also the filtered materials are retained. Some ratios based on analogies with earthen filters were proposed in the early days of geotextiles (Calhoun 1972; Ogink 1975; Schoeber and Teindl 1979; Millar *et al.* 1980), and more recently they were based on long-term soil–geotextile filtration performance tests and have been evaluated by field observations (Christopher and Holtz 1985; Gabr and Akram 1996; Aydilek and Edil 2002). Safety factors are often incorporated into the criteria to account for material variability. In summary, empirical criteria based on tests of various soils with various geotextiles are available, but comparisons between them are difficult owing to arbitrary selection of factors of safety. Additionally, laboratory filter performance tests require several weeks and a sophisticated test set-up. Thus rational and quantitative methods for developing and testing these criteria are needed.

The main objective of this paper is to introduce a non-empirical, rational, and quantitative methodology for development of criteria for selection of woven geotextiles that are increasingly being used in filtration applications such as capping of contaminated sediments and dewatering of high water content geomaterials. The study has two parts. First, a probabilistic numerical filter model was developed and the pore size distributions (PSD) of various geotextiles based on image analysis were input to the probabilistic filtration model. Second, the results obtained from the numerical model were used to develop filter selection criteria. The proposed criteria and the existing empirical criteria from the literature were evaluated against the actual performance observed in the laboratory filtration tests on a silty sand specimen and a wide range of woven geotextiles.

2. MODELING FILTRATION PHENOMENA

The probabilistic numerical filter model mentioned above had two parts. The first part was directed at predicting soil retention and defining the structure of the bridging network (soil/geotextile interface layer), i.e. the number of soil particles of different diameters, and the location of particles. The second part of the model used this bridging network and calculated its hydraulic conductivity, which, in turn, predicted a clogging ratio, i.e. a permeability ratio.

2.1. Simulation of retention

A probabilistic approach was used to simulate the movement of soil particles through a geotextile using a newly developed algorithm called RETAIN. Simulated spherical soil particles were placed in layers onto a geotextile of given PSD and their progress through the geotextile as well as the resulting bridging network is investigated. RETAIN requires seven different parameters as input, including the geotextile pore size distribution (PSD), the initial percent open area (POA) and cross-sectional surface area of the geotextile, the specific gravity, weight, and particle (grain) size distribution (GSD) of the soil, and the thickness of the base soil. Illustrations of the base soil and filter element and the flow chart of RETAIN are given in Figures 1 and 2, respectively.

POAs and PSDs of the geotextiles had to be determined as they were model inputs. The commonly used dry sieving test (ASTM D 4751) can only provide the O_{95} (apparent opening size), but at its current status cannot define the complete PSD of a woven geotextile. Similarly, the light projection method, a method commonly used by the manufacturers for POA determination (US Army Corps of Engineers 1986), has potential problems in defining the open areas in a geotextile. Aydilek and Edil (2004) have discussed the shortcomings of these two methods and developed image-based methodologies to overcome these difficulties. They measured the POA and AOS of 17 geotextiles including the nine employed in the current testing program using image analysis, and showed that the results are highly comparable to those measured by light projection or dry sieving method. The same study also indicated that PSD of wovens can easily be determined by image analysis, owing to their two-dimensional structure. Following these suggestions, POAs and PSDs of the geotextiles tested in the current study were determined by using image analysis. For this, digital images of the geotextiles were captured via a charge-coupled device (CCD) camera, and POA was calculated by dividing the pore areas by the total area. For the PSDs, a range of geotextile opening diameters (i.e. comparable to the sieve sizes commonly used in a dry sieving test) was defined in a computer code, and each opening size was compared with the diameter of a circle fitted to the pore. The number of pixels given in the output was defined as the number of pore openings having a diameter greater than a given diameter, which simulated retaining percentages in the dry sieving test. The details of the two image analyses are given by Aydilek and Edil (2004).

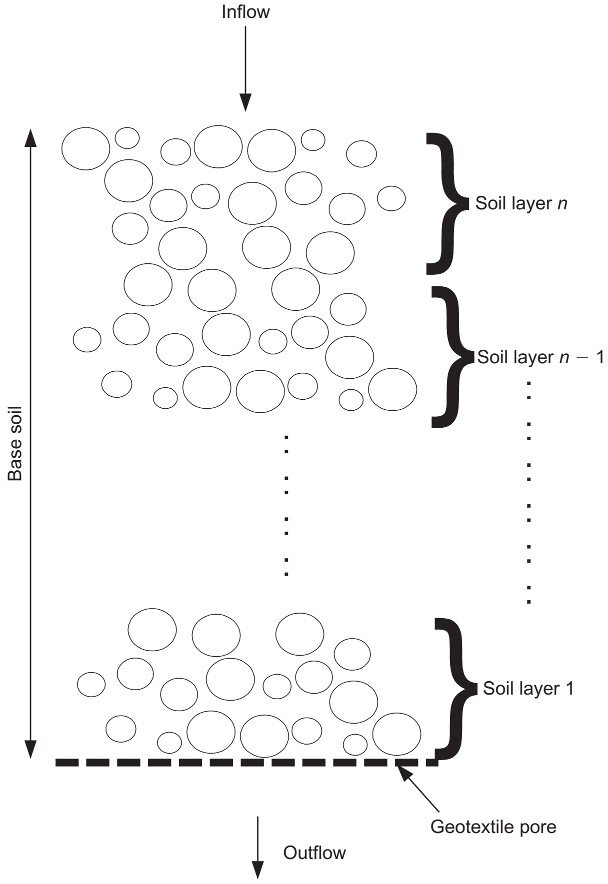


Figure 1. Illustration of base soil layers and the filter

Pore sizes obtained from the discretized PSD curve were written into an array, and the location of each pore was designated. The area of openings in the array was called the ‘cumulative pore area’ of the geotextile (CPA) and calculated as follows.

$$\mathrm{CPA} = A_c \times \mathrm{POA} \tag{1}$$

where A_c is the cross-sectional area of geotextile analyzed.

The number of soil particles with a particular diameter was calculated by assuming a spherical shape for each particle:

$$\text{Number of particles} = \frac{W}{\frac{4}{3}\pi(d/2)^3 G_s} \tag{2}$$

where d is the diameter of the soil particle, W is the weight of soil with that particular diameter, and G_s is the specific gravity of the soil. Preliminary analysis indicated that the weight of the soil may have an effect on the speed of simulations. However, this problem was resolved by using a high-speed computer (2 GHz), and approximately 1000 g of soil was used to represent the entire GSD of the soil. This weight is comparable to the weight of soil placed in a typical laboratory hydraulic conductivity test cell. The base soil (or simply the soil) was divided into

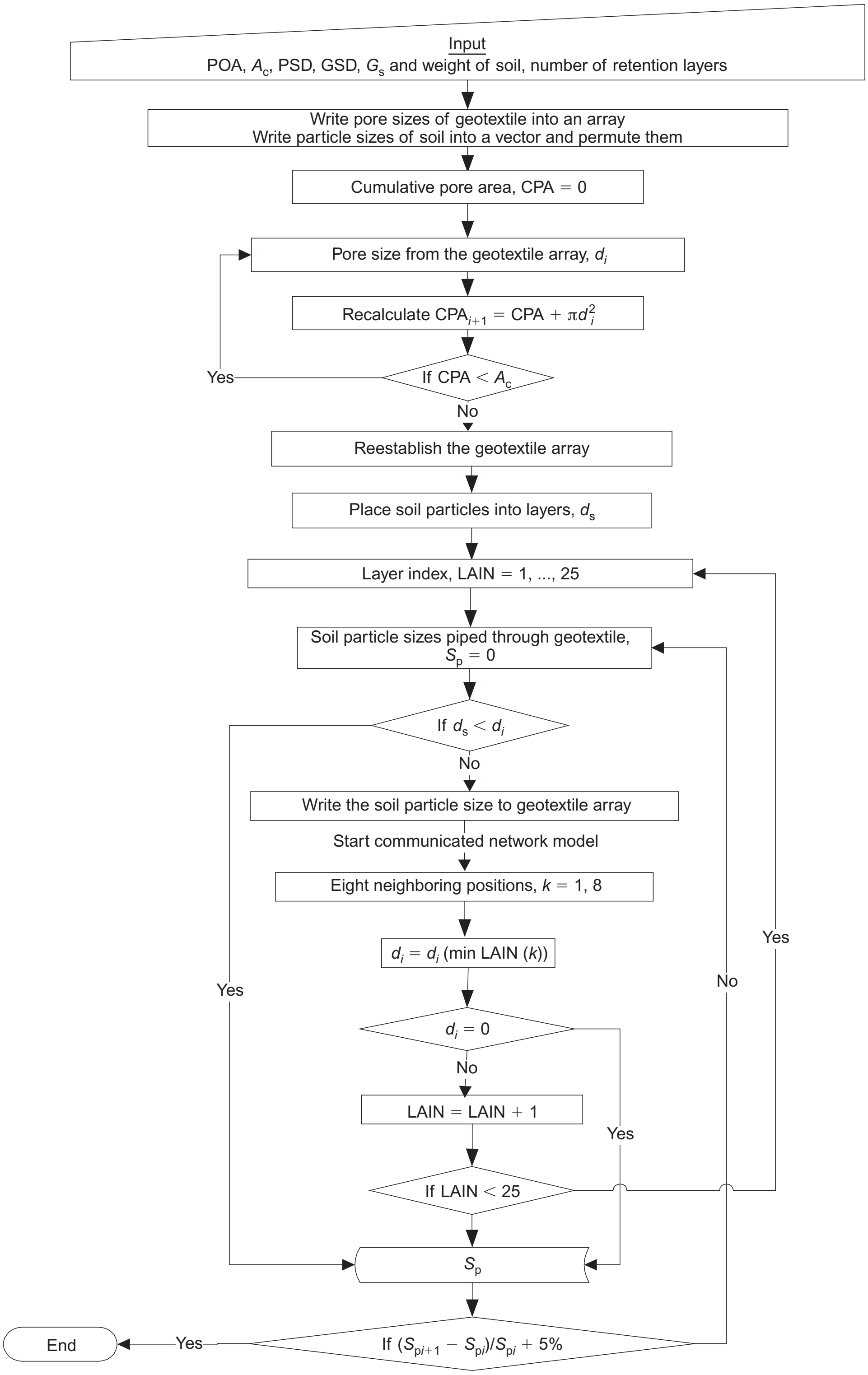


Figure 2. Flow chart of RETAIN

1 mm thick layers with equal thickness. Preliminary analysis indicated that the minimum required number of layers for the base soil is 15, and further increase in the number of layers had little effect on the results.

A Monte Carlo simulation was performed for placement of the soil, which was represented by its GSD. The soil particles at the geotextile interface were either smaller or larger than the geotextile pores, which determined whether a particle either piped or was retained under laminar flow conditions. Moreover, the diameter of the particles in the upper layers piped or retained depending on their size relative to the pore sizes of soil in the underlying layers as well as those of the geotextile. This process was repeated until the termination criterion was satisfied. The termination time was reached when the total piped amount in two consecutive steps varied by less than 5%. Because the number of particles piped through the geotextile and the number of retained particles in each layer were recorded, their masses could be calculated by assuming a spherical shape for each particle.

Preliminary simulations indicated that ‘tower-like’ accumulations formed on the geotextile during soil placement. This was because, when a soil particle blocked a geotextile pore, any particle randomly assigned to the position of the blocking particle would accumulate at that position (Figure 3a). This is specifically valid in the case of fine particles, because their numbers are of higher percentage and their probability of matching previously blocked pores is high. However, digital images of soil/geotextile interfaces taken by Bhatia and Huang (1995) have shown that, at most, three or four soil particles stay on top of each other in a bridging network. Even though this phenomenon was observed in testing of nonwoven geotextiles, it is unexpected that more than three or four particles will accumulate on top of woven geotextiles during filtration because of their more uniform PSDs as compared with nonwovens. A small recursive code was implemented in the current study to simulate the condition observed in the digital images, such as shown in Figure 3b. If three soil particles were stacked onto each other, the fourth particle that fell onto them relocated itself to a zone having fewer particles among the eight neighboring positions (Figure 4). This method was called ‘communicated network modeling’ herein. A sensitivity analysis (not shown herein) conducted on the number of neighboring positions indicated that a choice of eight positions is sufficient for the accuracy of the calculations.

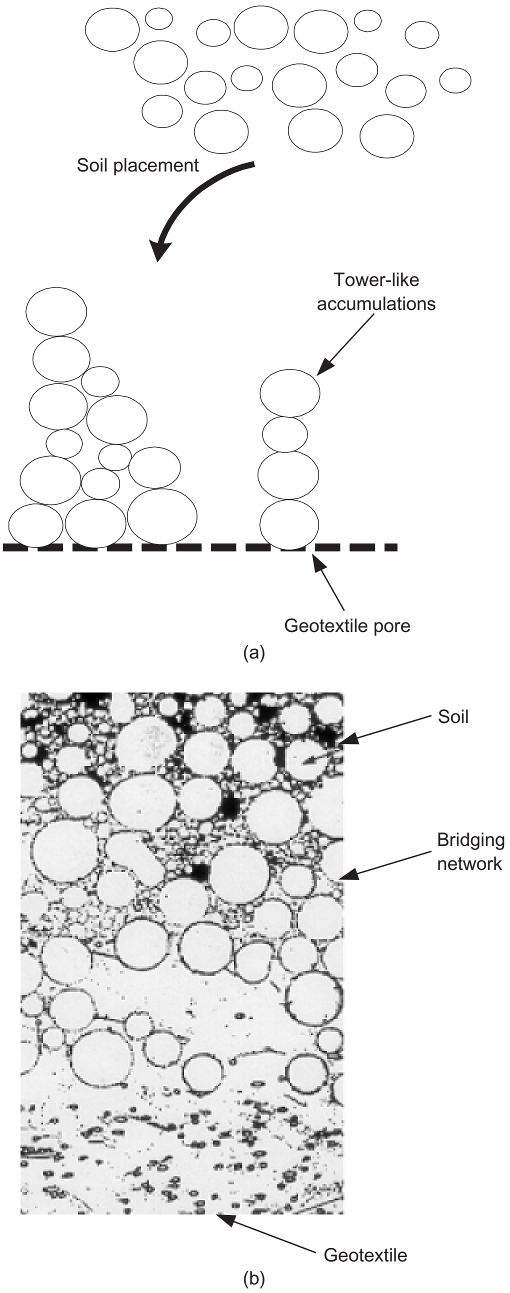


Figure 3. (a) Tower-like accumulations during soil placement; (b) micrograph of bridging network (after Bhatia and Huang 1995)

The variation of the applied hydraulic gradient and its effect on piping were simulated by using a simple approach, increasing the specific gravity of soil solids. As increased hydraulic gradient added seepage forces ($F_s = i_s \gamma_w$) onto the soil particles, this effect was reflected in the specific gravity of the soil:

$$G_{su} = G_s + i_s - 1 \tag{3}$$

where F_s is the seepage force per unit volume analyzed, G_{su} is the specific gravity under hydraulic gradient, and i_s is the applied hydraulic gradient during the test.

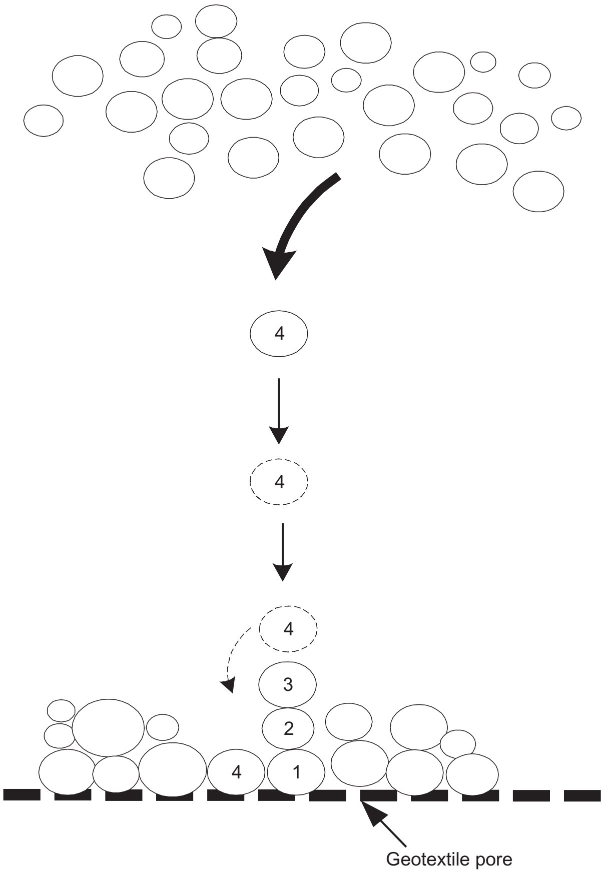


Figure 4. Communicated network modeling

2.2. Simulation of clogging

The retention model, RETAIN, provided valuable information about the pore structure of the soil/geotextile interface, commonly called a ‘bridging network’. This information was used herein to calculate the hydraulic conductivity of the network. Assuming laminar flow, the flow rate through a single circular tube, Q, can be calculated by Poiseuille’s law:

$$Q = \frac{\pi \gamma_{\mathrm{w}} i O^4}{128\mu} \tag{4}$$

where O is the diameter of the tube, i_{s} is the hydraulic gradient, and μ and γ_{w} are the viscosity and the unit weight of water, respectively. Fischer *et al.* (1996) extended the formula by simulating the structure with tubular pore channels, and approximated the number of pores of each size, O_j, by

$$m_j = \frac{4 p_j n A_{\mathrm{p}}}{\pi O_j^2} \tag{5}$$

where n is the porosity, p_j is the fraction of the total pore area associated with pore O_j, and A_{p} is the area of the porous zone simulated. Adding a tortuosity factor (C_{T}) of 1.2 and a viscosity value for a specific water temperature of 20°C, the hydraulic conductivity of the medium can be calculated by

$$k = 30.6 n^3 \sum p_j O_j^2 \tag{6}$$

Equation 6 was developed by Fischer *et al.* (1996) primarily for evaluating hydraulic conductivity geotextiles. In the current study, it was extended to soils by incorporating the pore size distribution of the soil formation and its porosity. Taylor (1948) showed that the pore size (O_j) between spheres of equal diameter, d, is $d/6.46$ for the densest packing and $d/2.42$ for the loosest packing. Soil-filtration tests, such as the gradient ratio test (ASTM D 5101), require a loose packing of soil in the test set-up; however, during the filtration process the density of the soil generally increases slightly. A pore size of $d/5$ was chosen for the calculations in consideration of this change in density. By knowing the number of pore sizes, their corresponding percentages (p_j) were calculated.

The porosity of the bridging network was calculated using the following equation, assuming a pure spherical shape for soil particles:

$$n = 1 - \frac{M_{\mathrm{b}}}{A_{\mathrm{b}} G_{\mathrm{s}} L} \tag{7}$$

where M_{b} is the mass of soil in the bridging network, G_{s} is the specific gravity of the soil, and A_{b} and L are the surface area and thickness of the bridging network, respectively. The thickness of the bridging network comprising s layers can be approximated by

$$L = \left(\sum_{j=1}^{s} d_j \right)_{\max} \tag{8}$$

where d_j is the diameter of the soil particles in the jth layer ($j = 1, 2, \ldots, s$). The hydraulic conductivity of the bridging network, K_{L}, was then calculated using Equations 6 and 7. The equivalent hydraulic conductivity of a soil–geotextile system, which is a composite hydraulic conductivity of the geotextile and overlying bridging network, can be calculated using the equation for stratified porous media:

$$K_{\mathrm{L-GT}} = \frac{L + t_{\mathrm{GT}}}{L/K_{\mathrm{L}} + t_{\mathrm{GT}}/K_{\mathrm{GT}}} \tag{9}$$

where t_{GT} and K_{GT} are the thickness and hydraulic conductivity of the geotextile, respectively, and K_{L} is the hydraulic conductivity of the bridging network. K_{GT} is defined as

$$K_{\mathrm{GT}} = \psi t_{\mathrm{GT}} \tag{10}$$

where ψ is the permittivity of the geotextile. By combining Equations 8, 9, and 10, the equivalent hydraulic conductivity of the soil/geotextile interface (bridging network/geotextile interface) is

$$K_{\mathrm{L-GT}} = \frac{\left(\sum_{j=1}^{s} d_j \right)_{\max} + t_{\mathrm{GT}}}{\left(\sum_{j=1}^{s} d_j \right)_{\max} \Big/ K_L + t_{\mathrm{GT}}/\psi t_{\mathrm{GT}}} \tag{11}$$

Equation 11 can be modified to calculate the $K_{\mathrm{s}ystem}$, an equivalent hydraulic conductivity for the soil, geotextile, and the bridging network:

$$K_{\mathrm{system}} = \frac{\left(\sum_{j=1}^{s} d_j \right)_{\max} + t_{\mathrm{GT}} + H_{\mathrm{soil}}}{\left(\sum_{j=1}^{s} d_j \right)_{\max} \Big/ K_{\mathrm{L}} + t_{\mathrm{GT}}/\psi t_{\mathrm{GT}} + H_{\mathrm{soil}}/K_{\mathrm{soil}}} \tag{12}$$

where H_{soil} is the thickness (15 to 25 mm) of the soil layer above the bridging network. The only unknown parameter in Equation 12 is K_{soil}, and it can be calculated using Equation 6. A pore size of $d/4$ was chosen for the soil above the bridging network, because previous research indicated that this layer is relatively more porous due to piping (Giroud 1996). The necessary soil porosity was determined from Equation 7. The hydraulic conductivities determined from Equations 6 and 12 were then used to calculate a clogging ratio, the permeability ratio (K_{R}) (Fischer 1994; Aydilek and Edil 2002):

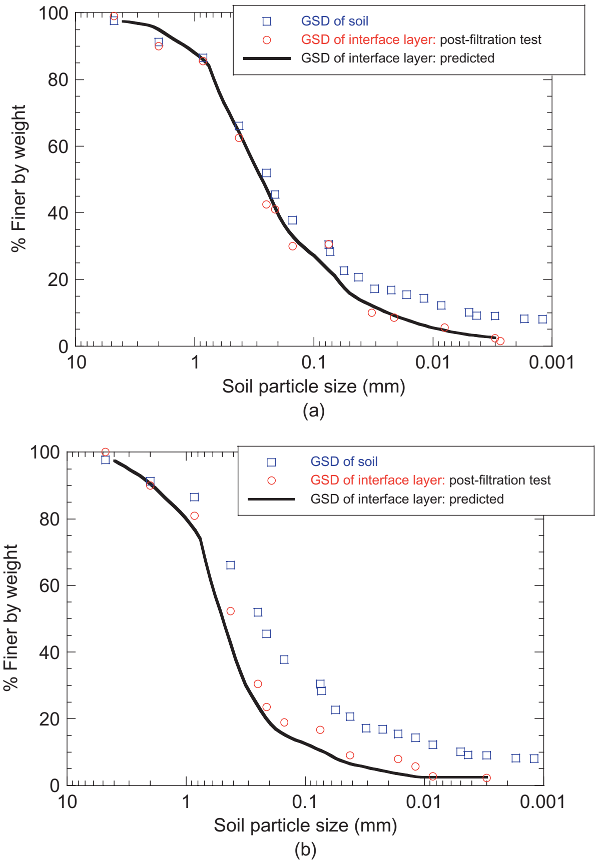
$$K_{\mathrm{R}} = \frac{K_{\mathrm{soil}}}{K_{\mathrm{system}}} \tag{13}$$

3. ACCURACY OF THE SIMULATIONS

RETAIN provides a description of the probabilistic structure of the bridging network formed on a geotextile during filtration. The number of particles that were spherical in shape but of different diameters was provided, and this information was used to deduce the weight of the soil piped through the filter. The calculated piping rates were compared with the ones measured in laboratory soil–geotextile filtration tests. The soil used in the laboratory study was silty sand (SM according to the Unified Soil Classification System (USCS)). The mean specific gravity of the soil was 2.67, and it included no organic materials. Nine woven geotextiles with a wide range of percent open area (POA) and permittivity values were used. The physical and hydraulic properties of the geotextiles are given in Table 1. Details of the laboratory soil–geotextile filtration tests are given by Aydilek and Edil (2002).

The simulations suggested that the variation of hydraulic gradient from 1.0 to 7.5 did not have a significant effect on the piping rates (not shown herein). The predicted piping rates at $i = 7.5$ were compared with those measured at the same hydraulic gradient (which is the final hydraulic gradient in the laboratory test). The piping rates summarized in Table 2 indicate that the values compare well for a range of geotextiles when end-of-testing conditions are considered.

In order to investigate the performance of the model, post-filtration test sieve analyses were performed on the silty sand specimens taken from the bridging network (soil/geotextile interface layer) in the test permeameters, and they were compared with the particle size distribution (GSD) of the network predicted by RETAIN. The results were comparable for a range of geotextiles tested. Figure 5 is given as an example to demonstrate these observations for two geotextiles with highly different POAs.



(a)

(b)

Figure 5. Measured and predicted GSD of bridging network for: (a) Geotextile E (POA = 0.6); (b) Geotextile G (POA = 25) when tested with silty sand

For further evaluation of the piping phenomena occurring in each layer of the base soil, the GSD distribution of

Table 1. Physical and hydraulic properties of woven geotextiles used in the study

Geotextile	Structure, polymer type	Mass/unit area (g/m^2)	Thickness (mm)	O_{95} (mm)	Percent open area, POA (%)	Permittivity (s^{-1})
A	W, SF, PP	263	0.462	0.130	0.6	0.05
B	W, MU, PP	257	0.645	0.444	13	1.50
C	W, MF, PP	207	0.613	0.233	8.1	1.36
D	W, SF, PP	291	0.603	0.416	2	0.09
E	W, SF, PP	102	0.163	0.256	0.6	0.15
F	W, SF, PP	165	0.316	0.150	0.6	0.05
G	W, MF, PP	204	0.664	0.340	25	2.14
H	W, MF, PP	205	0.272	0.231	17	1.50
U	W, MF, PP	120	0.533	0.665	53	NR

Notes: W = woven, SF = slit-film, MF = monofilament, MU = multifilament, PP = polypropylene. NR = not reported. All properties were measured according to the applicable ASTM standard except O_{95} and POA, which were determined via image analysis using the procedures outlined by Aydilek and Edil (2004).

Table 2. Measured and predicted piping rates and clogging ratios for silty sand

Geotextile name	Piping rate (g/m^2)		Permeability ratio, K_R	
	Measured	Predicted	Measured	Predicted
A	100–500	572	1.3	1.9
B	2,700	3,800	0.87	1.22
C	2,000	1,710	1.2	1.3
D	1,300	1,260	1.2	1.7
E	100–1,000	732	1.1	1.2
F	700	471	0.6	1.62
G	2,900	2,811	1.03	1.25
H	2,600	3,525	1.0	1.2
U	3,900	4,809	NA	1.26

Notes: NA = No laboratory test data were available to evaluate clogging performance.

each layer was plotted. Example plots are given in Figure 6 for two geotextiles with a range of POAs. To show the trends more clearly, the curves were developed using percent finer by number of particles instead of by weight. The results show that piping occurs as a result of movement of particles from the first and second layers. GSD curves of these layers shifted to the left because of piping. A distinguishable difference cannot be observed for the GSDs of layers 3 to 25. This verifies the assumption for the communicated network modeling that more than three soil particles do not accumulate at a point. The results also indicated that POA has a significant effect on the retention performance, and the shift is clearer for the geotextiles with higher POAs.

RETAIN simulates the microstructure of the soil bridging network. Using the information obtained from RETAIN and Equations 4 to 13, a clogging ratio (K_R) was calculated. The predicted clogging ratios are given in Table 2 along with the measured ones in the laboratory soil–geotextile filtration test. In general, the values are comparable, and demonstrate the effectiveness of RETAIN in evaluating the clogging performance of a woven geotextile. A comparison of the predicted values and laboratory measurements indicated that RETAIN can be effectively used to model the filtration phenomena and to develop woven geotextile filter selection criteria for a coarse-grained soil, such as silty sand.

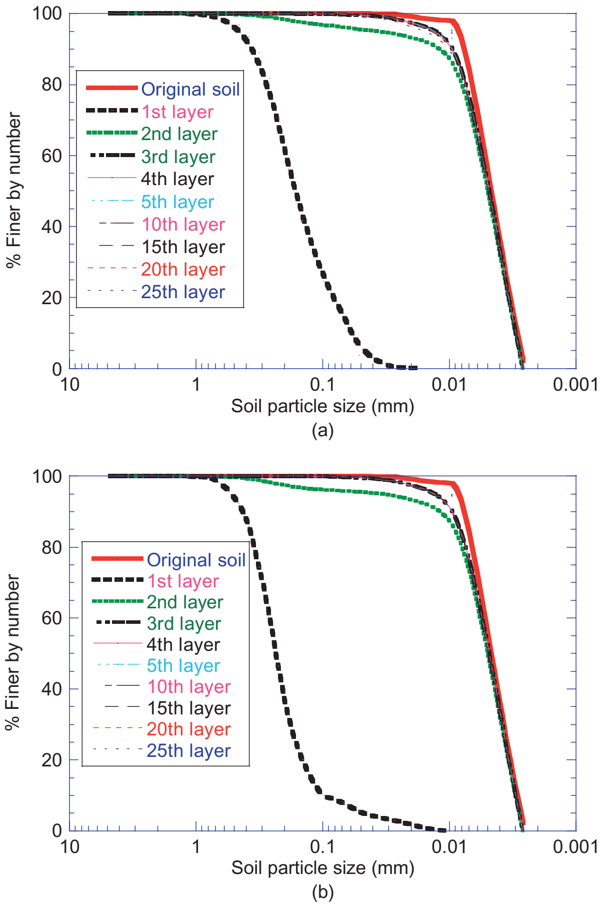


Figure 6. GSD of layers in the bridging network for silty sand–geotextile systems with: (a) Geotextile E (POA = 0.6); (b) Geotextile H (POA = 17)

4. DEVELOPMENT OF FILTER SELECTION CRITERIA

4.1. Background

The existing retention and clogging criteria use ratios of a characteristic geotextile pore size to a characteristic soil particle size. The general formula of the criteria can be written as

$$\begin{aligned} \frac{O_x}{D_x} &< A \\ \frac{O_y}{D_y} &> B \end{aligned} \qquad (14)$$

where A and B are constants, O_x and O_y are the characteristic retention and clogging pore sizes, and D_x and D_y are the characteristic retention and clogging soil particle sizes, respectively.

The pore and soil particle sizes mentioned above are determined using the information obtained from RETAIN. The method is realistic, and also is based on a more rational approach, because it is not dependent solely on a series of laboratory tests, i.e. is not empirical like most of the existing criteria. It may be readily expanded to soils with different GSDs in conjunction with geotextiles having different PSDs; however, some of the limitations should be considered, as given later in this paper.

4.2. Retention criterion

A good filter is expected to retain a significant portion of solid particles, and therefore the largest pore size of the geotextile is expected to be smaller than the larger soil particles. Despite the fact that some researchers promote O_{100} as the largest pore size, accurate determination of this size is not possible owing to boundary effects. Therefore sizes between O_{85} to O_{95} are generally used (Giroud 1996). This is logical; however, the selection of this size is arbitrary in most cases. The output of RETAIN can be used to define this characteristic retention pore size.

The numerical simulations showed that the new model RETAIN can predict the filtration performance of woven geotextiles well. The model also provides the number of unblocked pores after filtration. Using this information, the contribution of each individual pore size to the retention performance was quantified. It is well known that the impediment of flow in woven geotextiles is due mainly to a phenomenon called ‘blocking’, in which the soil particles right above the geotextile pore openings relocate themselves and reduce the flow of water. Thus, considering the observations made in Figure 6, the movement of the soil particles at the soil/geotextile interface layer (the first layer) was analyzed. Two example plots for geotextiles with highly different POAs given in Figure 7 show that most of the small and medium size pores were able to retain soil particles, and piping usually occurred through the large pores. The size of these large pores that

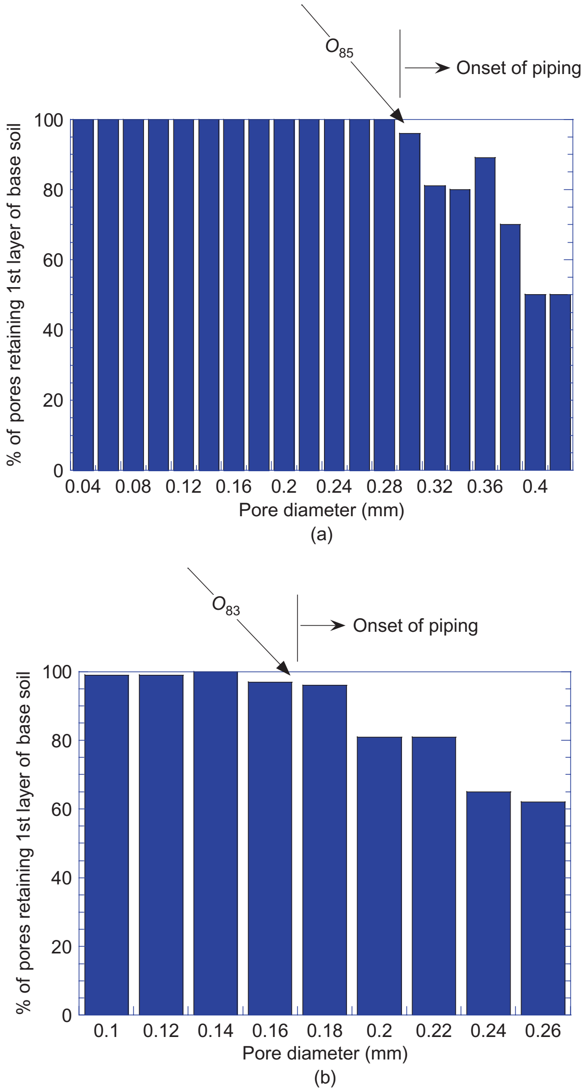


Figure 7. Prediction of retention pore opening size, O_x, for (a) Geotextile E (POA = 0.6), (b) Geotextile H (POA = 17), when tested with silty sand

initiated piping (onset of piping) ranged from O_{75} to O_{85}. Therefore an upper bound of the range, O_{85}, was chosen as the characteristic retention pore size for a conservative approach. The observed range is due mainly to the variability of the PSDs of woven geotextiles. Some of the woven geotextiles have more uniform PSDs than others, which may affect the O_x sizes. The images of two geotextiles with varying open areas are given as an example in Figure 8 to demonstrate this phenomenon.

Another component of the retention criterion is the characteristic soil particle size (D_x). D_x is the threshold particle size: any particles smaller than this size will pipe through the geotextile. A change in the shape of GSD after filtration can be used to identify D_x. For this purpose, the GSD of the virgin soil was compared with the predicted GSD of the bridging network. The particle at which the bridging network GSD first deviates from the virgin soil GSD is designated as D_x, as shown in Figure 9. The analyses indicated that D_x ranged from D_{50} to D_{80} for eight of the geotextiles, and a clear-cut trend was not observed when they were plotted against virgin geotextile POAs. For one geotextile (Geotextile U), D_x was equal to D_{95}; however, this fabric had significantly larger pore sizes than the other geotextiles (e.g. $O_{95} = 0.67$ mm and $O_{50} = 0.60$ mm) and could easily facilitate piping. Therefore this geotextile was ignored in the calculations. The mean value of D_x determined for the remaining eight geotextiles was D_{76}, which was comparable to the retention soil particle size of D_{75} suggested by Fischer (1994). However, the use of an average size would not be conservative for the geotextiles with a D_x of around D_{50}. Therefore D_{50}, the lower bound of the calculated D_x values, was chosen as the characteristic retention particle size.

The term A in Equation 14 is referred to as the 'retention ratio', and is usually multiplied by a factor of safety (FS), which ranges from 1.5 to 7.5 in various criteria proposed in the literature. An actual basis for the selection of a factor of safety without knowing the conditions in the field has not been documented. The new retention criterion proposed in this study is based on the worst-case scenario, and therefore a factor of safety was not applied. The magnitude of the factor of safety is typically based on the severity of the loading conditions and criticality of the project and, if necessary, should be applied by the designers. Therefore the recommended retention criterion for the silty sands tested in this study based on the new approach adapted here using RETAIN, without incorporating a factor of safety, is

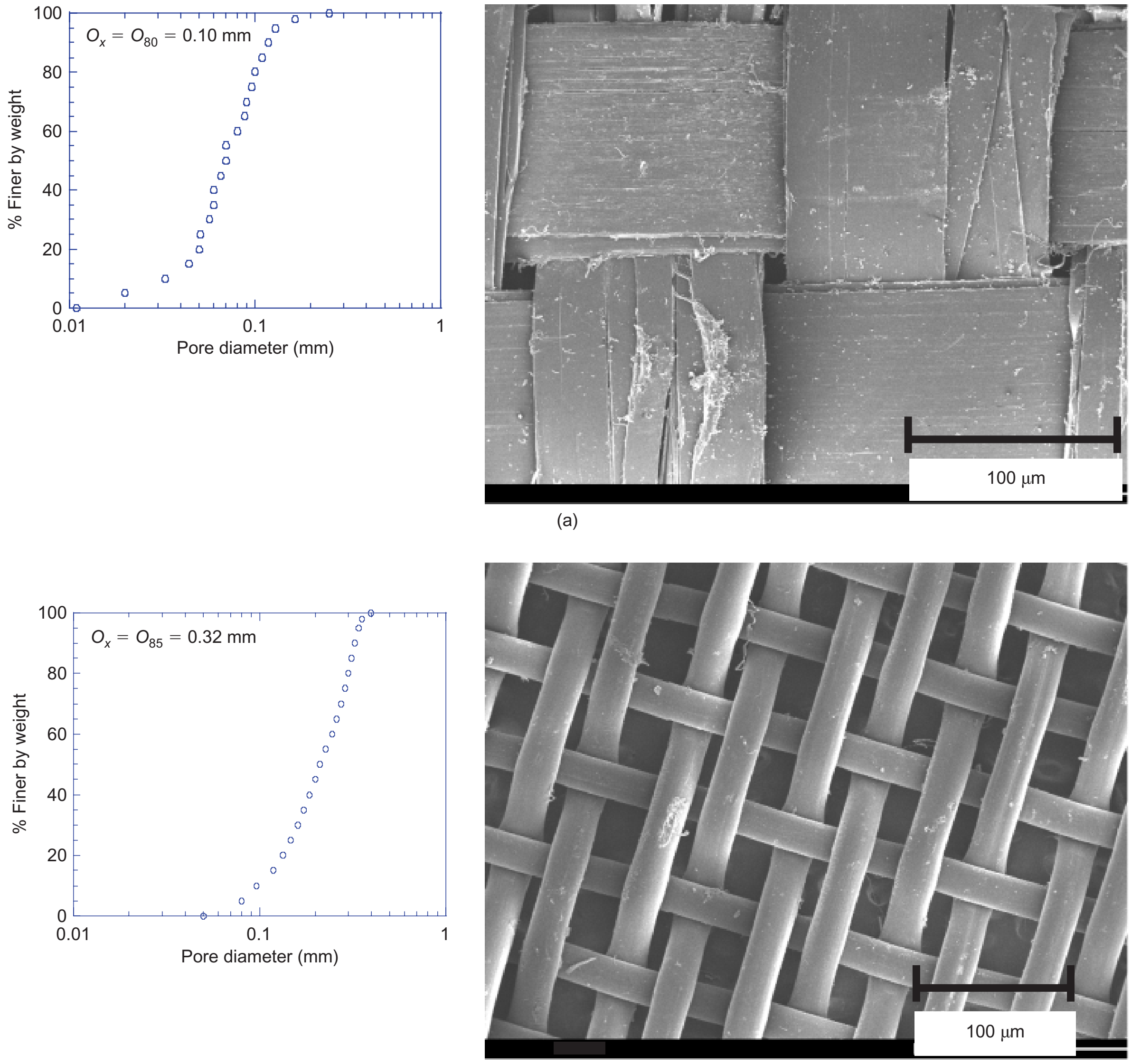
$$\frac{O_{85}}{D_{50}} < 1.0 \text{ for all POA} \tag{15}$$

4.3. Clogging criterion

The second important function expected from a good filter is that it has pore sizes large enough that it does not clog during filtration. Previous studies showed that the POA of woven geotextiles is one of the important pore structure parameters that affect clogging performance, and that it should be included in the design procedures (Austin *et al.* 1997; Aydilek and Edil 2002). Despite some of the existing clogging criteria, which use the largest pore size of the geotextile (O_{95}) owing to its availability, recent studies indicate that smaller pore sizes (i.e. O_{40}–O_{50}) are the controlling size for clogging (Bhatia *et al.* 1996; Aydilek and Edil 2002).

PSDs of virgin and post-filtration test geotextiles were compared to determine which pore sizes were most affected during the filtration process. For all the geotextiles tested, smaller pore sizes were blocked. Figure 10 shows two example plots. The characteristic clogging pore size, O_y, can be defined as the point where the PSD of the post-filtration test starts to deviate from the virgin curve. O_y values stayed in a narrow range (O_{40} to O_{45}) for the range of geotextiles tested. Therefore the lower bound of this range, O_{40}, was set for all geotextiles.

The hydraulic conductivity of a silty soil is controlled by the size of its fine particles, such as D_{10} or D_{15} (Peck *et al.* 1974; Cedergren 1989). Therefore smaller soil particle sizes have a significant effect on the clogging performance. It is necessary to allow the particles smaller



(a)

(b)

Figure 8. Images and corresponding PSDs of: (a) Geotextile A (POA = 0.6); (b) Geotextile G (POA = 25)

than those diameters to pass through the geotextile to prevent excessive clogging. To observe the movement of small soil particles through the geotextile, comparisons were made between the fine fractions of the original GSD curves and those of the bridging network. As mentioned previously, these curves started to deviate from the virgin soil GSD at a point called D_x. The shift continues to a point where the two curves become almost parallel, as shown in Figure 11. This point was chosen as the characteristic clogging particle size, D_y. Figure 11 shows that all of the particles smaller than D_y pipe through the geotextile.

Examination of Figure 11 as well as the GSD curves plotted for different geotextiles (not shown herein) reveals that D_y values are not uniform, and instead depend on the POA of the geotextile. To predict D_y more accurately, the difference between the virgin and post-testing soil particle sizes ($\Delta = D_{y\ \text{post-filtration test}} - D_{y\ \text{virgin soil}}$) are plotted against their corresponding percent finer by weight values in Figure 12. The trends are clear; Δ stabilizes around D_{15} for the geotextiles with POA < 8 and around D_{30} for geotextiles with POA > 8. Therefore two distinct D_y values were suggested for the geotextiles tested. The term B in Equation 14 is referred to as the ‘clogging ratio’ and is occasionally multiplied by a factor of safety (FS). Based on the considerations mentioned previously, a factor of safety was not included in the criterion. The recommended geotextile clogging criterion, for the silty sands tested in this study, is

$$\begin{aligned} &\frac{O_{40}}{D_{15}} > 1.0 \text{ for POA} < 8 \\ &\frac{O_{40}}{D_{30}} > 1.0 \text{ for POA} > 8 \end{aligned} \tag{16}$$

4.4. Predictions of the new filter criteria and comparisons with existing criteria

The results of long-term soil–geotextile filtration tests and image analysis PSDs were used to determine the applicability of widely used existing geotextile filtration criteria to the silty sand–geotextile systems tested in this research. A piping rate of 2,500 g/m^2, a limit suggested by Lafleur *et al.* (1989) for internal stability of soils, was chosen to discriminate the successful retention and piping (erosion).

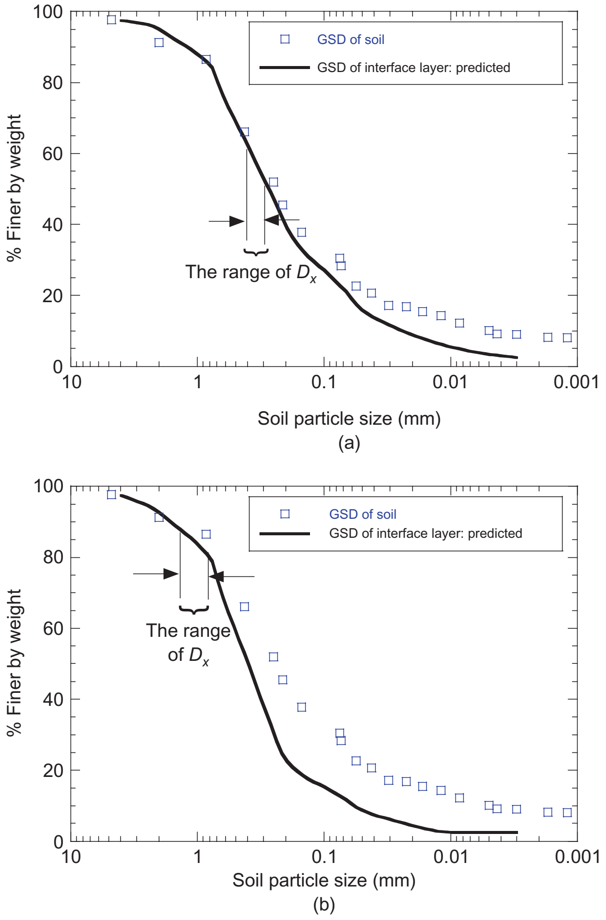


Figure 9. Identification of characteristic soil particle size, D_x, for retention of: (a) Geotextile E (POA = 0.6); (b) Geotextile H (POA = 17)

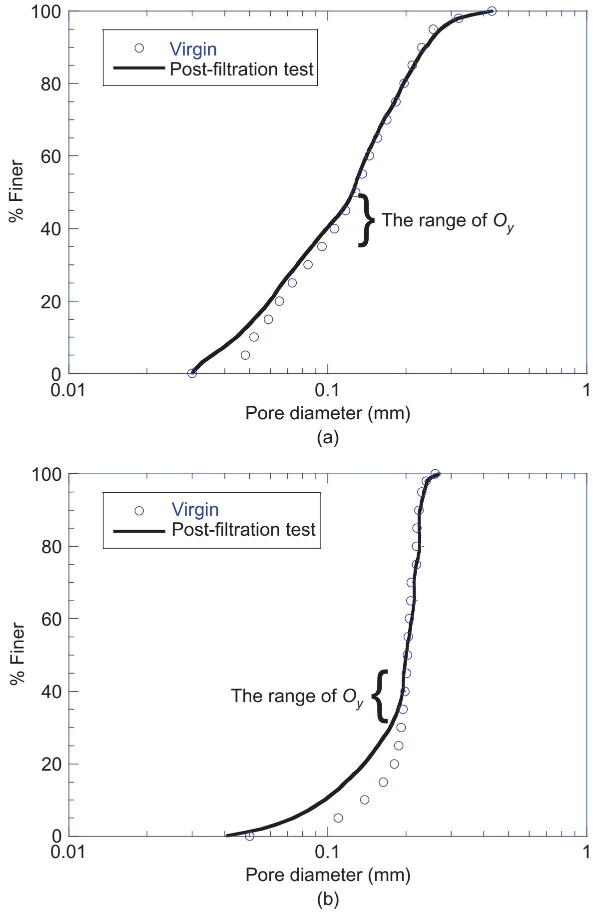


Figure 10 Prediction of clogging pore opening size, O_y, for (a) Geotextile E (POA = 0.6), (b) Geotextile H (POA = 17), when tested with silty sand

Tables 3 and 4 compare the actual performance observed in the laboratory tests with predictions of the new and existing filtration criteria.

Table 3 shows that the definitions used in the new criterion can handle the entire range of geotextiles tested in identifying their retention behavior. However, the existing empirical criteria did not always predict the retention performance observed in the laboratory tests. The Giroud (1988) criterion predicted 45% of the test results. The Calhoun (1972), Ogink (1975), Millar *et al.* (1980), Carroll (1983), Christopher and Holtz (1985), and Fischer (1994) criteria correctly predicted 56% of the test results. The prediction success of the Schoeber and Teindl (1979) and Fischer *et al.* (1990) criteria was 67%. The Austin *et al.* (1997) criterion, which incorporates POA instead of a retention ratio, was the best as it accurately predicted the performance observed in all tests.

All of the geotextiles performed successfully in the laboratory tests in terms of clogging performance, as the K_R was less than the US Army Corps of Engineers' criterion of 3.0 (Aydilek and Edil 2002). The new clogging criterion predicted the performance accurately (Table 4). The Calhoun (1972) and Koerner (1997) criteria, both highly regarded by designers, correctly predicted only 50% of the test results. More recently, Austin *et al.* (1997) have criticized this criterion and modified it for silty sands. Their criterion predicted that all of the tests would be successful. The remaining clogging criteria were satisfactory as well; however, their success is assured mostly because factors of safety are included.

5. LIMITATIONS OF THE PROPOSED METHODOLOGY

The probabilistic model RETAIN describes the microstructure of the bridging network. This information can be used to propose a woven geotextile filter selection criterion by using the methodology described in this paper. The main drawback of RETAIN is that it assumes the soil particles are pure spheres. Even though this assumption has been commonly made by various researchers (Faure *et al.* 1990; Indraratna and Vafai 1997), the model can be improved by adding a shape factor for characterization of the 'true' shapes of the particles. Shape factors have been used in previous studies, and image analysis is the most accurate measurement method. The approach has been successfully applied to coarse gravels (Masad *et al.* 2000); however, use of more complicated methods is necessary to determine the shape factors for sandy soils (Alshibli and Alsaleh 2004). Therefore such an analysis was not con-

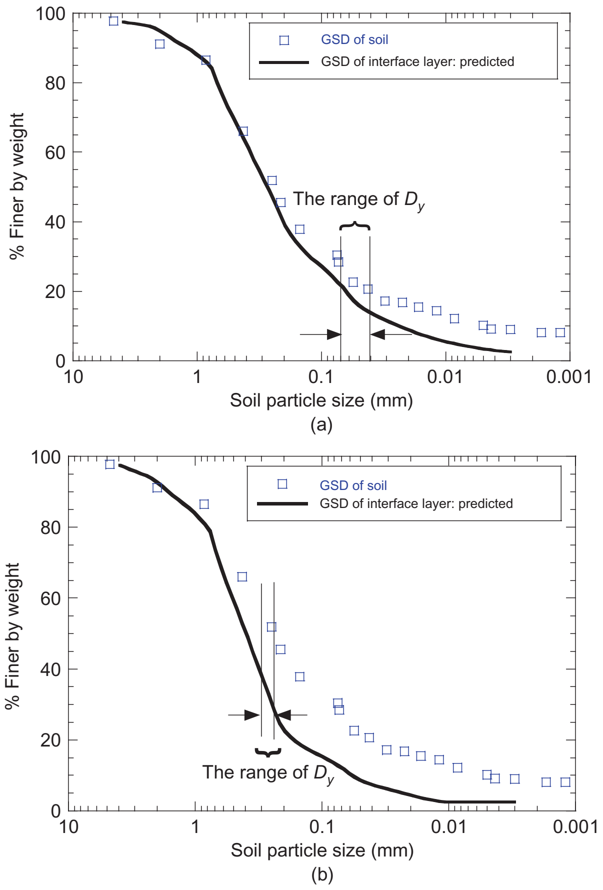


Figure 11. Possible range of critical clogging soil particle size, D_y, for (a) Geotextile E (POA = 0.6), (b) Geotextile H (POA = 17), when tested with silty sand

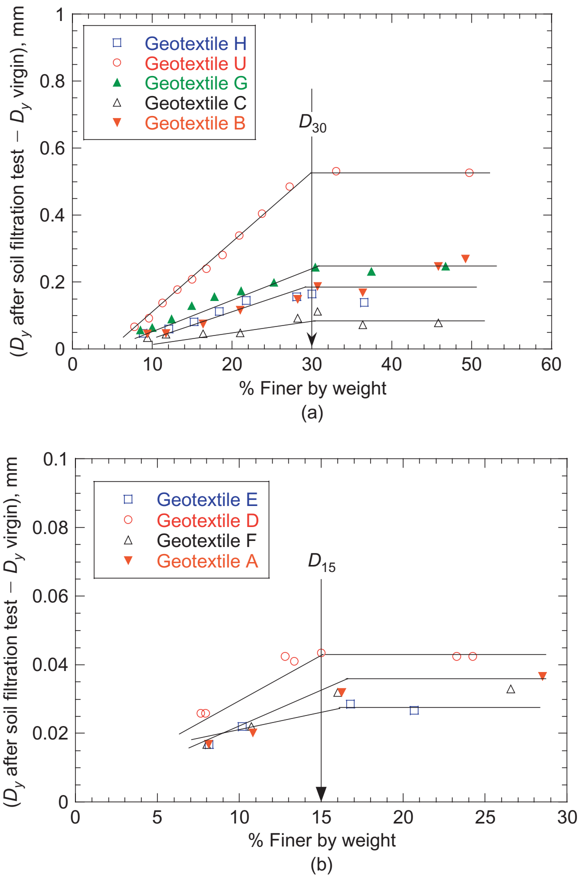


Figure 12. Determination of critical clogging soil particle size, D_y, for geotextiles with (a) POA > 8, (b) 0.6 < POA < 8, when tested with silty sand

ducted herein to define a shape factor for the tested geomaterial.

Furthermore only one type of soil, silty sand, was tested in the laboratory, and the results were compared with the predictions of RETAIN. Therefore, at least in its current status, the model is applicable only to this particular soil. The predictive capability of RETAIN can be improved by conducting tests with clayey sands, soils with varying silt content, and pure sands. It is believed that the use of such a model can be efficient in predicting the performance of woven geotextiles in filtration applications, such as in designing silt fences or capping of contaminated sediments.

6. CONCLUSIONS

A new model was developed to predict the retention and clogging performance of woven geotextiles. The model is based on a probabilistic approach and uses the PSDs of geotextiles obtained via image analysis. Predicted performance was compared with laboratory observations, and the following conclusions were advanced.

- The piping rate predictions of RETAIN for various geotextiles filtering silty sand were successful. The rates were comparable to the ones obtained in the laboratory tests. An increase in the hydraulic gradient did not have a significant effect on piping rates. The model was also able to accurately predict the particle size distribution of bridging networks.
- The pore size distribution of a bridging network predicted by RETAIN was used to calculate hydraulic conductivities using Poiseuille's law to simulate pore flow as pipe flow. The permeability ratios calculated using the predicted hydraulic conductivities compared well with those determined in laboratory soil–geotextile filtration tests.
- The results of RETAIN were used to develop new geotextile design criteria for silty sand–geotextile systems. The predictive capability of the existing geotextile filter criteria was tested against behavior observed in laboratory tests. The existing clogging criteria generally predicted the behavior accurately, possibly because of the included factors of safety. However, predictions of retention by the existing criteria were generally poor. Some of the geotextiles, particularly the ones with high POA, failed in the laboratory tests; however, most of the existing retention criteria predicted that they would be successful.
- At its current status, RETAIN is applicable to the silty sand and geotextiles tested. However, the method is rational, and the applicability of the methodology to other soils with a range of GSDs

Table 3. Predictions of the existing and newly proposed retention criteria

Geotextile name	Performance observed in laboratory tests	Predicted retention performance										
		New criterion	Existing criteria									
		$O_{85}/D_{50} < 1$	Calhoun (1972): $O_{95}/D_{85} < 1$	Carroll (1983): $O_{95}/D_{85} < 2–3$	Christopher and Holtz (1985): $O_{95}/D_{85} < 1–2$	Giroud (1988): $O_{95}/D_{50} < (9–18)/C_u$	Ogink (1975): $O_{90}/D_{90} < 1$	Schoeber and Teindl (1979): $O_{90}/D_{50} < 2.5–4.5$	Fischer (1994): $O_{85}/D_{75} < 2$	Millar *et al.* (1980): $O_{50}/D_{85} < 1$	Fischer *et al.* (1990): $O_{50}/D_{85} < 0.8$,	Austin *et al.* (1997): POA < 8%
A	Retention	OK	OK	OK	OK	NO	OK	OK	OK	OK	OK	OK
B	Piping	NO	OK	OK	OK	NO	OK	OK	OK	OK	OK	NO
C	Retention	OK	OK	OK	OK	NO	OK	OK	OK	OK	OK	OK
D	Retention	OK	OK	OK	OK	NO	OK	OK	OK	OK	OK	OK
E	Retention	OK	OK	OK	OK	NO	OK	OK	OK	OK	OK	OK
F	Retention	OK	OK	OK	OK	NO	OK	OK	OK	OK	OK	OK
G	Piping	NO	OK	OK	OK	NO	OK	OK	OK	OK	OK	NO
H	Piping	NO	OK	OK	OK	NO	OK	OK	OK	OK	OK	NO
U	Piping	NO	OK	OK	OK	NO	OK	NO	OK	OK	NO	NO

Notes: Retention = satisfactory retention performance in the laboratory tests, no or acceptable amount of piping; Piping = unsatisfactory retention performance; OK = predicted a satisfactory retention performance; NO = failed owing to excessive piping.

Table 4. Predictions of the existing and newly proposed clogging criteria

Geotextile name	Performance observed in laboratory tests	Predicted retention performance						
		New criterion	Existing criteria					
		$O_{40}/D_{15} > 1$ for $0.5 < \text{POA} < 8$ $O_{40}/D_{30} > 1$ for $\text{POA} > 8$	Christopher and Holtz (1985): $O_{95}/D_{15} > 3$	French Committee on Geotextiles and Geomembranes (1986): $O_{90}/D_{15} > 4$	Millar *et al.* (1980) and Fischer (1994): $O_{50}/D_{15} > 1$	Fischer *et al.* (1990): $O_{15}/D_{15} > 0.8–1.2$	Calhoun (1972) and Koerner (1997) POA > 4–6%	Austin *et al.* (1997): POA > 0.5%
A	Not clogged	OK	OK	OK	OK	OK	NO	OK
B	Not clogged	OK	OK	OK	OK	OK	OK	OK
C	Not clogged	OK	OK	OK	OK	OK	OK	OK
D	Not clogged	OK	OK	OK	OK	OK	NO	OK
E	Not clogged	OK	OK	OK	OK	OK	NO	OK
F	Not clogged	OK	OK	OK	OK	OK	NO	OK
G	Not clogged	OK	OK	OK	OK	OK	OK	OK
H	Not clogged	OK	OK	OK	OK	OK	OK	OK
U	NA	OK	OK	OK	OK	OK	OK	OK

Notes: Not clogged = satisfactory anticlogging performance in the laboratory tests; OK = predicted a satisfactory anticlogging performance; NO = failed owing to excessive clogging; NA = no test data were available to evaluate clogging performance.

can be checked after conducting laboratory filtration tests on these soils.

NOTATIONS

Basic SI units are given in parentheses.

A	retention ratio (dimensionless)
A_{p}	area of porous zone simulated (m^2)
A_{b}	surface area of bridging network (m^2)
A_{c}	cross-sectional area of geotextile (m^2)
B	clogging ratio (dimensionless)
C_{T}	tortuosity factor (dimensionless)
C_{u}	coefficient of uniformity (dimensionless)
d	soil particle diameter (m)
D_x	characteristic soil particle size for retention (m)
D_y	characteristic soil particle size for clogging (m)
F_{s}	seepage force per unit volume analyzed (N/m^3)
G_{s}	specific gravity (dimensionless)
G_{su}	specific gravity under hydraulic gradient (dimensionless)
H_{soil}	thickness of soil layer above bridging network (mm)
i_{s}	hydraulic gradient during test (dimensionless)
K_{GT}	hydraulic conductivity of geotextile (m/s)
K_{L}	hydraulic conductivity of bridging network (m/s)
$K_{\mathrm{L\text{-}GT}}$	hydraulic conductivity of bridging network–geotextile (m/s)
K_{R}	permeability ratio (dimensionless)
K_{soil}	hydraulic conductivity of soil tested (m/s)
K_{system}	system hydraulic conductivity (m/s)
L	thickness of bridging network (m)
M_{b}	mass of soil in bridging network (m)
m_j	number of pores of each size (dimensionless)
n	porosity (dimensionless)
O	diameter of tube (m)
O_j	pore size (m)
O_x	characteristic pore size for retention (m)
O_y	characteristic pore size for clogging (m)
p_j	fraction of total pore area associated with pore O_j (dimensionless)
Q	flow rate (m/s)
t_{GT}	geotextile thickness (m)
W	weight of soil (kg)
γ_{w}	unit weight of water (N/m^3)
μ	viscosity of water (N-s/m)
ψ	permittivity of geotextile (s^{-1})

ABBREVIATIONS

AOS	apparent opening size
CPA	cumulative pore area
GSD	particle (grain) size distribution
POA	percent open area
PSD	pore size distribution

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