Infiltration into an embankment reinforced by nonwoven geotextiles

T. Iryo and R.K. Rowe

Abstract: The hydraulic behaviour of permeable geosynthetics within unsaturated embankments subjected to infiltration is examined using the finite element method. The van Genuchten – Mualem model is employed to evaluate unsaturated hydraulic characteristics for both the soil and nonwoven geotextile. Using pore-water pressures obtained from the finite element analysis, stability analyses are conducted for the embankments, and the contribution of the nonwoven geotextile to stability is evaluated with reference to the observed performance of instrumented embankments. A numerical study is also conducted to examine the effect of geotextile configuration on the performance of reinforced embankments subject to infiltration. This study shows that nonwoven geotextiles may retard water flow in situations where the pore pressure is negative, whereas they act as a drainage material in situations where pore pressures are positive. It is also shown that the contribution of the nonwoven geotextile to the stability of the embankment as a drainage material is much less substantial than its role as a reinforcing material.

Key words: nonwoven geotextile, drainage, unsaturated, embankment, stability.

Résumé : On examine au moyen de la méthode des éléments finis le comportement hydraulique des géosynthétiques perméables installés à l’intérieur de remblais non saturés assujettis à l’infiltration. Le modèle de van Genuchten – Mualem est utilisé pour évaluer les caractéristiques hydrauliques non saturées tant pour le sol que pour le géotextile non tissé. En utilisant les pressions interstitielles obtenues par l’analyse en éléments finis, on a réalisé des analyses de stabilité pour les remblais, et évalué la contribution à la stabilité du géotextile non tissé par rapport à la performance des remblais instrumentés. On a aussi réalisé une étude numérique pour examiner l’effet de la configuration du géotextile sur la performance des remblais armés sujets à l’infiltration. Cette étude montre que les géotextiles non tissés peuvent retarder l’infiltration d’eau dans les situations où les pressions interstitielles sont positives. On montre également que, comme matériau de drainage, la contribution du géotextile non tissé à la stabilité du remblai est beaucoup moins substantielle que son rôle comme matériau d’armature.

Mots clés : géotextile non tissé, drainage, non saturé, remblai, stabilité.

Introduction

Nonwoven geotextiles have been used to replace conventional granular material to provide drainage within soil structures. In this application they are expected to contribute to the stability of the soil structure by facilitating the dissipation of excess pore pressures during construction and minimizing the build up of pore pressure caused by subsequent infiltration events. There have been a number of full scale studies on the effectiveness of geosynthetic drainage layers in embankments, as described in the following paragraphs.

Mitchell and Zornberg (1995) reviewed 11 field cases of soil structures where poorly draining fill material was reinforced with nonwoven geotextiles. It was noted that the permeable geosynthetics increased the stability of soil structures by providing both mechanical reinforcing and increasing soil strength by facilitating dissipation of excess pore-water pressures in the fill material. Miki (1997) examined the performance of nonwoven geotextiles as a drainage material within three embankments. The first embankment was constructed using volcanic ash clay, the second used the same volcanic ash clay mixed with sandy silt, and the third gravely clay and sand soil containing 30–50% fines content. Several layers of nonwoven geotextiles were installed within the fill material. For these cases, pore pressure dissipation occurred during the construction period, and consolidation settlement of fill material was completed in a relatively short period of time. It was inferred that the nonwoven geotextiles worked effectively as a drainage material within the embankment.

Kamon et al. (2001) examined three full-scale clayey soil embankments reinforced with a variety of geosynthetic horizontal drains (GHDs) including a composite nonwoven geotextile reinforced with a high tensile strength yarn. It was
found that two embankments remained stable for several years after the completion of construction, while one embankment failed under surcharge loading. GHDs were found to be effective at promoting consolidation and increasing the shear strength of the fill material.

Tan et al. (2001) conducted a laboratory test on a 2D soil–geosynthetics layered system. A horizontal layer of nonwoven geotextile reinforced with a grid network of polyester yarn was laid between two layers of residual soil and a surcharge loading was applied to the top of the upper layer of soil. It was found that the nonwoven geotextile effectively reduced excess pore-water pressures caused by the loading. The dissipation of pore-water pressure was evaluated using Terzaghi’s consolidation theory.

The studies described above related to the hydraulic behaviour of permeable geosynthetics within soil experiencing positive pore-water pressures. However, in many practical applications the water content of the fill material is relatively low and pore-water pressures are negative during and following construction. Thus it is also necessary to examine the hydraulic behaviour of permeable geosynthetics within unsaturated soil when subjected to infiltration from a water source such as rainfall. Nishigaki et al. (1993) conducted experiments to examine the hydraulic behaviour of geotextiles under infiltration loading. A geotextile layer was placed at an inclination of 12° within a fine-grained soil, and artificial rainfall was applied to part of the top surface. The infiltrated water accumulated above the geotextile layer, and the wetting front advanced along the geotextile layer, until the wetting front reached the end of the geotextile layer. It was concluded that seepage water did not drain from the geotextile layer but, rather, from the soil immediately above it. This is very similar to the hydraulic behaviour reported by Miyazaki (1988) of a sandy loam containing a thin layer of gravel. Several different angles of inclination of the gravel layer were examined, and Miyazaki (1988) found that the advancement of the wetting front was stopped at the interface between the upper sandy loam and the gravel layer, and that water then flowed along the interface.

Iryo and Rowe (2003) compiled published data on unsaturated hydraulic functions of nonwoven geotextiles (water characteristic curve and hydraulic conductivity function) and reported that these geotextiles had characteristics similar to those of coarse materials, such as gravel. This suggests a similarity in behaviour for infiltration into soil–geosynthetics layered systems to that in fine–coarse soil layered systems, and implies that the study of the hydraulic behaviour of layered soil systems may be helpful in understanding the hydraulic behaviour of soil–geosynthetics layered systems. Iryo and Rowe (2004) numerically examined infiltration into a 1D soil column containing a nonwoven geotextile layer. It was reported that advancement of the wetting front from the top of the column was temporally halted, and a higher water content developed above the geotextile layer during the period that the wetting front was halted. This raises the possibility that geotextiles may retard water flow within unsaturated soil.

In a cooperative research effort the Public Works Research Institute of Japan (PWRI et al. 1988) examined the effect of artificial rainfall on the performance of one unreinforced embankment and three embankments reinforced with a variety of nonwoven geotextile configurations. It was reported that failure of the reinforced embankments started from erosion of the slope surface caused by higher water content in the vicinity of the geotextiles. However, these studies did not clearly define the role of the geotextile layers in the failure of these sand embankments.

The objective of this paper is to examine the hydraulic behaviour of permeable geosynthetics, particularly nonwoven geotextiles, within unsaturated embankments subjected to infiltration. Firstly, the infiltration into reinforced embankments conducted in PWRI et al. (1988) is numerically simulated using the finite element method. The van Genuchten – Mualem model (van Genuchten 1980) is employed to evaluate unsaturated hydraulic characteristics for both the soil and nonwoven geotextile. The suitability of such a numerical procedure for simulating infiltration into a 2D soil–nonwoven geotextile layered system is examined, and the hydraulic behaviour of the embankments is discussed. Secondly, using pore-water pressures obtained from the finite element analysis, stability analyses are conducted for the embankments, and the contribution of the nonwoven geotextile to stability is evaluated. Finally, a numerical study examines the effect of geotextile configuration on the performance of reinforced embankments subject to infiltration. The results of the numerical investigation are then used to provide insight into the use of geotextile layers.

### Table 1. Basic properties of sand (modified from PWRI et al. 1988).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel content (d ≥ 2 mm), (%)</td>
<td>1</td>
</tr>
<tr>
<td>Sand content (2 &gt; d ≥ 0.074 mm), (%)</td>
<td>91</td>
</tr>
<tr>
<td>Fine content (d &lt; 0.074 mm), (%)</td>
<td>8</td>
</tr>
<tr>
<td>Gravimetric water content, w (%)</td>
<td>24</td>
</tr>
<tr>
<td>Unit weight of soil, ( \gamma_t ) (kN/m³)</td>
<td>17.5³</td>
</tr>
<tr>
<td>Porosity, ( n_p )</td>
<td>0.465³</td>
</tr>
</tbody>
</table>

Note: \( d \), soil particle diameter.
*Deduced from PWRI et al. (1988).

### Table 2. Parameters used in the analysis of the embankment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated hydraulic conductivity, ( k_s ) (m/s)</td>
<td>1.3\times10⁻⁵</td>
</tr>
<tr>
<td>Friction angle, ( \phi' ) (°)</td>
<td>39</td>
</tr>
<tr>
<td>Cohesion in terms of effective stress, ( c' ) (kPa)</td>
<td>0</td>
</tr>
</tbody>
</table>

### Numerical simulation of infiltration into embankment reinforced with nonwoven geotextile

**Experiment outline**

To examine hydraulic behaviour under rainfall loading one unreinforced embankment (embankment 1) and three reinforced embankments (embankments 2, 3, and 4) were constructed by PWRI et al. (1988) and artificial rainfall was applied until all embankments failed. The embankments were 3 m high, 6 m long, and 4 m wide with a slope of 0.7H:1V. Sandy soil (Tables 1 and 2) was used as a fill material. Spunbond nonwoven geotextiles (Table 3) were used as a reinforcing drainage material. Three layers of nonwoven...
geotextiles were placed with a vertical spacing of 0.75 m and configurations as shown in Fig. 1. A 1.5 m long geotextile layer was also placed at the toe of each embankment to avoid the development of excess pore pressures at the base. As shown in Fig. 1, embankment 2 was reinforced with geotextiles of equal length. Embankment 3 was reinforced with a 4 m long geotextile in the upper layer and 1 m long geotextiles in the middle and lower layers. Embankment 4 was reinforced with 1 m long geotextiles in the upper and middle layers and a 4 m long geotextile in the lower layer. After the embankments were constructed, artificial rainfall with an intensity of 12.7 mm/h was applied to the slope and the top of the embankments. The rain was halted for about 1 h after the failure of embankment 1 and for about 13 h after the failure of embankment 3.

The cumulative rainfall, $R$ was reported to be 90 mm at failure for embankment 1, 132 mm for embankment 3, 217 mm for embankment 4, and 231 mm for embankment 2. The failure of embankment 1 occurred suddenly over the entire slope surface, while the other embankment failures developed from partial erosion on the slope surface.

**Outline of numerical simulation**

**Numerical procedure**

Richards (1931) derived the governing equation for tran-

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**Table 3. Basic properties of geotextile (PWRI et al. 1988).**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass per unit area, $m_a$ (g/m²)</td>
<td>310</td>
</tr>
<tr>
<td>Thickness of geotextile, $t_{geotextile}$ (mm)</td>
<td>3</td>
</tr>
<tr>
<td>Porosity, $n_p$</td>
<td>0.92</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity in plane direction, $k_{sat_\text{geotextile plane}}$ (m/s)</td>
<td>$2.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity in cross plane direction, $k_{sat_\text{geotextile cross}}$ (m/s)</td>
<td>$3.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Tensile strength in machine direction (kN/m)</td>
<td>21.6</td>
</tr>
<tr>
<td>Tensile strength in cross to machine direction (kN/m)</td>
<td>17.2</td>
</tr>
</tbody>
</table>

* Estimated value assuming unit weight of polyester $\gamma_{\text{polyester}} = 12.75$ kN/m³.
sient water flow within an unsaturated material from Darcy’s law and continuity. For the 2D homogeneous anisotropic material, the equation becomes

\[ k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} = \frac{\partial \Theta}{\partial t} = m_w \gamma_w \frac{\partial h}{\partial t} \]

where \( h \) is the total hydraulic head; \( k_x \) and \( k_y \) are the unsaturated hydraulic conductivities for the \( x \)- and \( y \)-directions, respectively; \( m_w \) is the coefficient of water volume change (slope of the water characteristic curve); \( \gamma_w \) is the unit weight of water; \( \Theta \) is the volumetric water content; and \( t \) is the time.

The parameters, \( m_w \) and \( k_x, k_y \) in eq. [1] are material specific and are functions of pore pressure. Thus the functions for hydraulic properties, water characteristic curve (volumetric water content versus pore pressure) and hydraulic conductivity function (hydraulic conductivity versus pore pressure) must be specified to solve eq. [1]. The van Genuchten – Mualem model (van Genuchten 1980) has been employed in many studies, and its validity has been examined for a wide range of soils. Iryo and Rowe (2004) also used this model to study infiltration into a 1D soil column containing a non-woven geotextile layer and found that it worked well for modelling the unsaturated response of the geotextile. Thus this model was used in the present study to characterize the hydraulic properties of both the soil and the geotextiles. Using the van Genuchten – Mualem model, the water characteristic curve is given by eq. [2], and the hydraulic conductivity function is given by eq. [3]. Based on van Genuchten (1980), \( m \) is assumed to be \( 1 - 1/m \).

\[ \Theta = \frac{\theta - \theta_t}{\theta_s - \theta_t} = \left[ \frac{1}{1 + \left( \alpha \frac{s}{\gamma_w} \right)^n} \right]^m \]

where \( \Theta \) is the normalized water content; \( \theta \) is the water content at a given suction; \( \theta_s \) is the saturated water content; \( \theta_t \) is the residual water content; \( s \) is the suction; and \( \alpha, n, \) and \( m \) are the fitting parameters.

\[ k_r(\Theta) = \frac{k(\Theta)}{k_{sat}} = \Theta^{1/2} \left[ 1 - (\Theta^{1/m})^{2} \right] \]

where \( k_r \) is the relative hydraulic conductivity; \( k(\Theta) \) is the hydraulic conductivity at a given \( \Theta \); and \( k_{sat} \) is the saturated hydraulic conductivity.

The finite element computer program SEEP/W Ver. 5 (GEO-SLOPE International Ltd. 2001a) was used to solve eq. [1]. Ju and Kung (1997) have shown that to obtain a stable numerical solution when solving Richard’s equation using linear finite elements, it is necessary to employ a capacitance matrix established with a lumped formulation. This approach was adopted (using SEEP/W Ver.5), and the embankments were modeled using 20 524 three noded triangular elements arranged as shown in Fig. 1. A series of numerical experiments with different mesh configurations and time steps were used to established a suitable numerical scheme. Based on this study, the 3 mm thick nonwoven geotextile was modeled using 6 three noded triangular elements across the thickness of the geotextile. The time increment was automatically adjusted between 0.1 s and 100 s as needed to achieve convergence. The reported intensity of rainfall, 12.7 mm/h per horizontal m (per m width in this 2D analysis), was applied to the top and side slope of the embankment as a specified flux boundary condition. To allow simulation of seepage from the embankment, once the pore pressure became positive at any nodes on the top surface and side slope surface the boundary condition was changed from specified flux to specified pressure head, \( h_p = 0 \) condition and the simulation was repeated until all boundary nodes had a pore pressure less than or equal to 0 kPa. The embankments were constructed on a solid concrete slab (PWRI et al. 1988) and so the base was taken to be a zero flux boundary. It is noted that the infiltration pattern around the toe and the effectiveness of the geotextile there might be different if the foundation were a permeable material. However, for the purposes of modelling the PWRI embankments, this boundary is considered to be the most realistic. PWRI et al. (1988) reported that about 10 cm of geotextile extended out from the slope surfaces. Thus, unlike most parts of the slope surface, the slope surface 10 cm below each geotextile layer was shielded from infiltration, and along these segments the boundary was treated as a no flux condition while pore pressure was negative and \( h_p = 0 \) when the pore pressure became positive (Fig. 2).

The soil was placed with a controlled water content and it was considered reasonable to assume that pore-water pressure was relatively uniform (with some statistical variability) at the end of construction. Thus a uniform distribution of pore-water pressure of ~3.5 kPa was assumed based on the average value reported for all of the embankments.

**Material parameters**

Since PWRI et al. (1988) did not provide any information regarding the unsaturated hydraulic properties of the soil, the van Genuchten – Mualem model parameters for the soil were obtained based on consideration of typical published values combined with a parametric study of the infiltration into unreinforced embankment 1. The values used for this study were: \( n = 1.5, 2.0, 2.5; \alpha' = (\alpha/\gamma_w) = 0.25, 0.4, 0.8 \) (1/kPa); \( k_{sat} = 1.0, 1.3, 2.0, 4.0, 6.0, 10.0 \times 10^{-3} \) (m/s); and \( S_r \) was evaluated from the reported properties. Different combinations resulted in quite different behaviour (e.g., the shape of the wetting front, the initial water content, and the rate of advance of the wetting front varied). The most significant parameters were \( n \) and \( \alpha \). A suitable combination was selected based on a comparison of the behaviour and volumetric water content profiles to the observed values. The saturated water content, \( \theta_s \), was evaluated from the reported properties. The water characteristic curve and the hydraulic conductivity function for the soil deduced from this study are shown in Figs. 3a and 3b, respectively. Profiles showing the degree of saturation for the soil, \( S_r \), at the failure of embankment 1 are shown in Fig. 4. The water content within the embankments was measured using the radio isotope method along three vertical observation lines. The left vertical axis of each graph in Fig. 4b is located at the line where the measurements were made. There was a fair agreement between the numerical and the experimental results and adjustment of pa-
parameters did not provide any improved fit between the two. Thus the parameters in Figs. 3a and 3b were used for further study.

The saturated hydraulic conductivity of the nonwoven geotextile, $k_{\text{sat geotextile}}$ was reported and its $\theta_s$ was estimated from the other reported physical properties of the geotextile. The other van Genuchten – Mualem model parameters for the nonwoven geotextile were chosen from the typical values evaluated from published data compiled by Iryo and Rowe (2003). The parameters and the functions obtained with these parameters are shown in Figs. 3a and 3b. Both the water characteristics curve and the hydraulic conductivity function of the nonwoven geotextile are steeper than those of the soil, and the hydraulic conductivity functions of the soil and the nonwoven geotextile cross at a suction of about 1 kPa. This implies that the nonwoven geotextile acts as a less permeable material than the soil for suctions greater than 1 kPa.

Comparison between experimental result and numerical simulation

The advancement of the infiltration front into embankment 2 is shown in Fig. 5. The change of water content of the soil is illustrated in terms of the degree of saturation, $S_r$ at critical locations. The distribution of $S_r$ over the entire embankment obtained from the numerical simulation is also shown by contour lines. The profiles and the distribution of the degree of saturation after cumulative rainfall $R = 90$ mm (at the point where failure of embankment 1 occurred) are shown in Fig. 5a, and those after 132 mm (failure of embankment 3) are shown in Fig. 5b. The experimental results indicate that a higher $S_r$ area occurred near the slope face and developed inward with increasing cumulative rainfall $R$. The numerical results showed the same trend, and they were in fair agreement with the experimental results. The $S_r$ profile from the numerical simulation showed that the geotextiles caused a discontinuity in water content distribution. This was most pronounced at locations not reached by the wetting front (e.g., the middle and lower layers at $R = 90$ and 132 mm) where the water content of the soil increased immediately above the geotextile layer and decreased slightly below it (from the initial value of about 63%). Thus the nonwoven geotextile acts as an impermeable layer. This occurred because the hydraulic conductivity of the geotextile, $k_{\text{geotextile}}$ was less than that of the soil, $k_{\text{sat soil}}$ at the negative pore pressure of soil around the geotextile layers. Even at locations where the wetting front had already passed, there was slight discontinuity in the $S_r$ of the soil around the geotextile (e.g., the upper layer at $R = 132$ mm). This is because the specified boundary flux, $q$ was smaller than $k_{\text{sat soil}}$, thus the pore pressure of the soil remained negative, and
Thus the geotextile acted as a less permeable material than the soil even after the wetting front had passed the geotextile layer. A similar trend was observed and discussed for infiltration into a 1D soil column containing a nonwoven geotextile layer (Iryo and Rowe 2004). While the numerical simulation showed discontinuities in $S_r$ profiles around the geotextile layers, the experimental results showed less variation in $S_r$. It is reported that the radio isotope method (which is based on neutron-scattering and thermalization process (Gardner 1986)) works on the basis of volume averaging and has limited resolution in water content measurements. This may be the reason why the experimental results did not exhibit discontinuities of $S_r$. More frequent measurement of water content with a technique that provides finer resolution of the data is recommended for further investigation of the hydraulic interaction between soil and geotextiles.

Referring to the contour lines shown in Fig. 5a-ii and 5b-ii, the $S_r = 70$% line developed above the geotextile along its length and a 90% saturation zone appeared close to the slope surface. On the other hand, immediately below the geotextile layer there was little to no increase in water content, and the distribution of $S_r$ was discontinuous at each geotextile layer. Infiltration from the slope surface developed above the geotextile layer. The hydraulic behaviour of this reinforced embankment can be explained by the difference of the hydraulic conductivity functions for the soil and the geotextile. At the beginning of infiltration, $k_{\text{geotextile}}$ is several orders of magnitude smaller than $k_{\text{soil}}$. Thus the geotextile acts as an impermeable material. When water infiltrating through the slope surface reaches the geotextile layer, a portion of the infiltrated water flows inward along the geotextile layer at the interface between the soil and the geotextile. As a consequence, a higher $S_r$ develops above the geotextile layer. As infiltration continues, water migrates into the geotextile and $k_{\text{geotextile}}$ increases. Eventually water starts flowing across the geotextile and the $S_r$ of the soil immediately below the geotextile begins to increase. Such an increase of $S_r$ was found near the slope for each geotextile layer. This behaviour was also observed for embankments 3
This mechanism resulted in increased water content (higher $S_r$) along almost the entire length of the upper geotextile layer for embankment 3. It was reported that the failures of the reinforced embankments started from slope surface erosion in the vicinity of the geotextiles (PWRI et al. 1988). The results of the numerical simulation showing higher $S_r$ above the geotextile layer are consistent with this observation. Thus, consistent with the finding of Nishigaki et al. (1993), it appears that the nonwoven geotextile did not provide drainage as originally expected in this experiment. This suggests that proper treatment of the water infiltrating from the slope surface is necessary to avoid such a failure.

### Stability analysis considering infiltration

In this section, the contribution of nonwoven geotextiles to the stability of the embankments studied in the previous section is examined. The stability analysis is conducted using the limit equilibrium method considering the tensile force developed in nonwoven geotextiles and the pore pressure distribution within the soil, including negative values. First, shear strength parameters of the soil were obtained from a back analysis for embankment 1. Then the stability of reinforced embankments is studied and the effectiveness of nonwoven geotextiles is discussed.

### Method and strength parameters

The limit equilibrium method employed in this study was the general limit equilibrium method (GLE) from Fredlund and Krahn (1977), wherein the factor of safety (F.S.) with respect to horizontal interslice forces is equal to that with respect to moment equilibrium. The computer program SLOPE/W Ver.5 (GEO-SLOPE International Ltd. 2001) was used for an effective stress analysis (considering negative pore pressures). The shear strength of unsaturated soil is given by Fredlund et al. (1978):

$$
\tau = c' \tan \phi' + (\sigma - u_w) \tan \phi^b
$$

where $\tau$ is the shear strength; $c'$ is the effective cohesion parameter; $\sigma$ is the total normal stress; $u_w$ is the pore-air pressure; $u_w$ is the pore-water pressure; $\phi'$ is the friction angle with respect to changes in $(\sigma - u_w)$ when $(u_w - u_u)$ is held constant; and $\phi^b$ is the friction angle with respect to changes in $(u_w - u_u)$ when $(\sigma - u_u)$ is held constant.

It has been reported that $\phi^b$ is equal to $\phi'$ at saturation and then decreases with an increase in suction (Fredlund et al. 1996). Vanapalli et al. (1996) noted that $\tan \phi^b$ in eq. [4] may be approximated by $\Theta \tan \phi'$. In this study, the shear strength of the fill material was estimated using this relationship with a certain value of $\Theta$. As a result, the required shear strength parameters were reduced to $c'$ and $\phi'$ for the saturated soil. The value of $\Theta$ used to estimate the shear strength in this study is discussed later in this section.

The shear strength of the soil was estimated at the base of each soil slice, and the pore pressure was obtained from the transient water flow analysis discussed in the previous section. As noted earlier, the shear strength parameters $c'$ and $\phi'$ were obtained from a back analysis for the failure of em-
First, combinations of $c'$ and $\phi'$ giving F.S. = 1.0 were obtained with the analysis along the observed failure approximated with a circular slip surface (step I). Then, the analysis of possible slip surfaces specified by a grid of the centre and tangential lines of circular slip surfaces was conducted with the combinations of $c'$ and $\phi'$ obtained earlier (step II). A suitable combination of $c'$ and $\phi'$ was obtained from the case of the slip surface closest to the approximated observed failure surface (Wesley and Leelaratnam 2001).

The observed failure surface for embankment 1 passed through the area of $S_r$ from 70 to 90% for the numerical result discussed in the previous section. Thus the back analysis for step I was conducted with a series of values of $\Theta$ (0.7, 0.8, and 0.9) to obtain shear strength parameters that considered the effect of $\Theta$. The combinations of $c'$ and $\phi'$ obtained from the step I analysis are shown in Fig. 8. It was observed that $c'$ decreased linearly with an increase in $\phi'$ for all $\Theta$, and $c'$ showed slightly lower values with higher $\Theta$. Using these combinations, the back analysis for step II was conducted. From the step II analysis, the failure circles closest to the observed failure with F.S. = 1 were obtained at $c' = 0$ kPa for all $\Theta$. Thus, in this study, the values of $\phi'$ and $c'$ chosen for the average value of $\Theta = 0.8$ (i.e., $\phi' = 39.3^\circ$ ($\phi' = 33^\circ$) and $c' = 0$ kPa) were used for further study of the reinforced embankments.

The elongations of the nonwoven geotextiles were measured for all reinforced embankments at each failure. The relationship between stress and strain on the geotextiles was also reported. It has been reported that the strain rate used in typical index tensile tests is several orders of magnitude higher than the loading rate in an actual soil structure (Walters et al. 2002). As a result, the stiffness of geotextiles obtained from a typical index tensile strength test tends to be larger than that for the geotextiles within actual structures. On the other hand, the stiffness of nonwoven geotextiles increases with an increase in confining pressure. As a result, a typical index tensile test, which is without any confining pressure, underestimates the stiffness (Walters et al. 2002). In this study, the effects of high elongation rate and no confining pressure of the index tensile strength test are assumed to be compensating. Thus, the tensile forces employed for the stability analysis for the reinforced embankments were estimated from the measured elongations of the geotextiles and reported stress–strain relationship. For embankment 2, this corresponded to a mobilized tensile force of about 0.5 kN/m for all geotextiles. For embankments 3 and 4, 0.7 kN/m was mobilized for the longer geotextiles, and 0.2 kN/m was mobilized for the shorter geotextiles (Figs. 6 and 7). Michalowski (1998) considered the reaction force on the reinforcement caused by small displacements at the failure zone and noted that the reinforcing force should be applied parallel to the original direction of placement. Thus, in this study the reinforcing forces were applied in the horizontal direction.

The F.S. for reinforced embankments was evaluated in two separate ways in this study: analysis 1 and 2. For analysis 1, both the pore pressure distribution from transient water flow analysis and the tensile force acting on the nonwoven geotextiles were taken into account to include the contribution from both the reinforcing and drainage functions of
nonwoven geotextiles. For analysis 2, the tensile resistance was neglected and only the pore pressure distribution was considered to examine the contribution of the drainage functions of the geotextile in isolation. The analysis is conducted with the pore pressure distribution at $R = 0$ (initially), 90 (failure of embankment 1), and 132 mm (failure of embankment 3) for all embankments. Although embankment 1 failed at $R = 90$ mm, its F.S. was calculated at $R = 132$ mm for comparison with the other calculated results.

Results of stability analysis for reinforced embankment and discussion

The slip surfaces obtained from analysis 1 and 2 for embankment 3 at $R = 132$ mm are shown in Fig. 9. The observed slip surface for embankment 3 at $R = 132$ mm and that for embankment 1 at $R = 90$ mm are also shown. Changes of F.S. for all embankments with increasing rainfall, $R$, are shown in Fig. 10.

While embankment 3 failed at $R = 132$ mm, the F.S. obtained from the stability analysis (analysis 1) was 1.025, and the calculated slip surface was deeper than that observed. It was reported that the failure of embankment 3 started from a surface erosion, (i.e., it failed because of a different mechanism than that reproduced in the stability analysis). This implies that embankment 3 could have been stable, if there had been the proper treatment of the slope surface for the surface erosion. The F.S. obtained from analysis 2 was 0.956. This implies that the reinforcing function of the geotextile was required to maintain stability and that the geotextile did not provide the drainage that would have been required to maintain embankment stability without the reinforcement function.

The F.S. from analysis 1 for the reinforced embankments (embankments 2, 3, and 4) reduced with an increase in
cumulative rainfall $R$. Thus, for the design of reinforced embankments, it is important to examine stability when the area is subjected to high infiltration.

As noted earlier, the difference in F.S. between embankment 1 and that from analysis 2 for embankments 2, 3, and 4 represents the contribution of the geotextile as a drainage material to the stability of embankments, and the difference in F.S. between analysis 1 and 2 for embankments 2, 3, and 4 represents the contribution of the geotextile as a reinforcement material. It appears that the contribution as reinforcement is considerably larger than that as a drainage material. Thus, it is concluded that the nonwoven geotextile contributed to the stability of embankments as a reinforcing material rather than as a drainage material.

While the geotextiles worked mainly as a reinforcing material for the embankments discussed above, they are also expected to work as a drainage material within soil structures in some cases. Therefore further study of the hydraulic behaviour of geotextiles within soil is necessary to examine under what conditions they provide drainage and under what conditions they act as a barrier to drainage. An examination of this issue is presented in the following section.

**Numerical experiments for infiltration into reinforced embankment**

The effectiveness of nonwoven geotextiles as a drainage material subjected to infiltration is studied in this section through numerical experiments. The embankments were assumed to have the same geometry and material properties as the PWRI embankment examined earlier. The effects of geotextile layout and boundary conditions are examined.
Outline of numerical experiments

Eight cases (see Table 4) were examined with four different geotextile layouts and two types of boundary condition. Cases 1 and 2 did not have any geotextile. Cases 3 and 4 had a 1.5 m long geotextile at the toe. Cases 5 and 6 had a 1.5 m geotextile layer at the toe and three 2 m long geotextiles in the fill. While the reinforcing materials were placed at an inclination of several percent in some cases (e.g., Miki 1997), there has been no published study of the effect of geotextile inclination on its performance as a drainage layer. Thus, to study the effectiveness of sloped geotextiles, cases 7 and 8 had a 1.5 m long geotextile at the toe and three layers of geotextiles in the fill with a 10% inclination. The odd-numbered cases had a specified flux boundary condition both on the slope and the top of the embankments. The flux, \( q \), was 12.7 mm/h, which is the same value used for the previous numerical simulation of the PWRI embankments. These cases represent relatively light rainfall that did not cause ponding. The even-numbered cases had a specified pressure head boundary condition both on the slope and the top of the embankments. The pressure head, \( h_p \), applied to the top was 0.1 m and that to the slope was 0.0 m. This corresponds to heavy rainfall with ponding on the top of the slopes and water running down the slope. The initial condition was a uniform distribution of the pore pressure of –3.5 kPa. Rain was applied continuously for the duration of the numerical experiments.

Results and discussion

The results of this numerical experiment are discussed in terms of the pore pressure distribution and the Darcy flux (Darcy velocity) within the geotextiles at the time when the wetting front had advanced from the top to the middle of the embankment. For the no ponding cases (cases 1, 3, 5, and 7 – specified flux), this occurred at \( 6.0 \times 10^4 \) s (16.7 h) and the results are shown in Fig. 11. For the ponding cases (cases 2, 4, 6, and 8 – specified head boundary condition cases), it occurred at \( 2.0 \times 10^4 \) s (5.6 h) and the results are shown in Fig. 12.

Effect of geotextile layer at toe

While positive pore pressure developed around the toe for case 1, there was no positive pressure developed around the toe for case 3 (Figs. 11a and 11b). Additionally, outward flow was predicted within the geotextile at the toe for case 3. Thus, the geotextile at the toe effectively worked as a drain-
Fig. 11. Darcy flux in geotextiles and pore pressure distribution in the embankment for cases with infiltration caused by $q < k_{sat \text{ soil}}$ ($t = 6.0 \times 10^4$ s): (a) case 1, (b) case 3, (c) case 5, (d) case 7.
Fig. 12. Darcy flux in geotextiles and pore pressure distribution in the embankment for cases with infiltration caused by $h_p = 0.1$ m on top ($t = 2.0 \times 10^4$ s): (a) case 2, (b) case 4, (c) case 6, (d) case 8.
age material and prevented the pore pressure from becoming positive at the toe. The effectiveness of the geotextile at the toe was also observed for the ponding cases (compare cases 2 and 4). For case 4 (with a geotextile at the toe), the pore pressure around the toe became positive, but it was much smaller than that of case 2 (without a geotextile) (Figs. 12a and 12b). Outward flow was also observed in the geotextile. Thus, whether ponding occurs or not, the geotextile at the toe worked effectively as a drainage material and reduced the pore pressure development around the toe.

**Effect of boundary condition and slope of geotextile**

For the no ponding cases, there was no flow in the geotextiles in the fill regardless of their inclinations (Figs. 11c and 11d). This arose because even after passage of the wetting front, the pore pressure remained less than $-1.0 \text{ kPa}$ (since the infiltration rate $q$ was smaller than $k_{\text{sat, soil}}$) and at these pore pressures the geotextile was less permeable than the soil ($k_{\text{geotextile}} < k_{\text{soil}}$ for suction greater than 1 kPa, as shown in Fig. 5b). Thus the geotextiles did not drain any infiltrated water outwards, and there was little difference in the pore pressure distributions between cases 5 and 7.

For the ponding cases (cases 6 and 8), after passage of the wetting front the pore pressure exceeded $-1.0 \text{ kPa}$ and often became positive (Figs. 12c and 12d). Thus, after the wetting front had passed the geotextile became saturated and $k_{\text{geotextile}}$ became greater than $k_{\text{soil}}$, and flow occurred within the geotextiles under some conditions. For case 6, outward flow occurred in the upper layer, no flow occurred at the middle layer, and inward flow occurred at the lower layer. The outward flow at the upper layer was caused by the pressure gradient along the geotextile from about 0.1 mH$_2$O on top of the geotextile to zero pressure on the slope face. Although the wetting front advancing from the top had passed the middle layer, the pressure along the geotextile was relatively constant at around 0 kPa. Thus, the hydraulic gradient was not large enough to cause flow within the horizontal geotextile layer. For the lower layer, the geotextile close to the slope became permeable as the wetting front advanced inward from the slope. As a result, the geotextile induced inward water flow because of the pressure gradient along it. On the other hand, outward flow occurred in all the inclined geotextiles for case 8. The flow in the geotextiles for case 8 resulted in the 0 kPa contour line remaining above the top geotextile layer, (i.e., the pore pressure within the fill material between the geotextiles remained negative), while the 0 kPa contour line passed the top geotextile layer for case 6, (i.e., the pore pressure within the fill material between the geotextiles became positive).

Thus, it is concluded that a geotextile acted as a drainage material at locations where pore pressure in the fill exceeded the threshold at which $k_{\text{geotextile}}$ becomes larger than $k_{\text{soil}}$ ($-1 \text{ kPa}$ in this study). It was also found that placing geotextiles with a 10% inclination made them more effective in draining the embankment under conditions of high infiltration.

**Practical implications**

The numerical results and discussion in the previous sections have a number of practical implications. With the development of pore pressure beyond threshold within an embankment (e.g., because of ponding on the top of the structure when the infiltration rate is larger than $k_{\text{sat, soil}}$), the geotextile will become more permeable than the soil and work as a drainage layer that will help in reducing the positive pore pressures and hence help maintain embankment stability. However, under other circumstances (e.g., when the infiltration rate is smaller than $k_{\text{sat, soil}}$), the pore pressure may increase but not exceed threshold, and the geotextile is less permeable than the soil and retards water flow. Thus, water content of the soil increases above the geotextile. As a result, the soil in the vicinity of the geotextile and the interface between the soil and the geotextile may weaken and cause undesired deformation or even failure. This could happen not only when the geotextile is used for drainage but also when it is used for other functions such as filtration, separation, or reinforcement. This could give rise to surface erosion as a consequence of wet soil around the geotextile, as observed in the experiments conducted by PWR-I et al. (1988). Thus, embankments need adequate surface treatment to avoid erosion in cases such as this. The numerical study indicates that for cases where the geotextiles are expected to drain infiltrated water, they would be expected to perform best if installed at an angle, as is done for other subsurface drainage systems.

**Conclusions**

The hydraulic behaviour of a series of test embankments was simulated using the finite element method and their stability was evaluated. Numerical experiments were conducted to examine the effect of geotextile arrangement and infiltration conditions as well to provide insight into the effectiveness of nonwoven geotextiles as drainage material. From the findings of this study, it is concluded that:

1. The finite element method, employing the van Genuchten – Mualem model for hydraulic functions of unsaturated soil and nonwoven geotextiles, reasonably simulated infiltration into the embankments reinforced with nonwoven geotextiles.

2. A numerical simulation showed that higher degrees of saturation developed above nonwoven geotextile layers. This is consistent with the higher water content in the vicinity of nonwoven geotextiles observed in the experiments.

3. A stability analysis using pore pressure distributions obtained from a finite element analysis showed that the contribution of the nonwoven geotextile as a drainage material was much less substantial than its role as a reinforcing material.

4. Nonwoven geotextiles placed at the toe of an embankment were effective at reducing pore pressure development regardless of rainfall intensity.

5. Nonwoven geotextiles acted as a drainage material where pore pressure exceeds the threshold at which geotextiles become more permeable than soil, and their performance was improved when they were installed with an inclination.

Many studies have shown that nonwoven geotextiles act as a drainage material in situations where pore pressures are positive. However, it is not so well recognized that these same materials may retard water flow and cause undesirable high water contents in their vicinity in situations where the
pore pressure is negative. Thus, in the design of these earth structures, it is necessary to consider the hydraulic behavior of a soil–geotextile layered system under unsaturated as well as saturated conditions.

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