Numerical study of infiltration into unsaturated clay slopes with nonwoven geotextile drains sandwiched in sand cushions: Featuring the capillary barrier effect

Article · January 2014

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Numerical study of infiltration into unsaturated clay slopes with nonwoven geotextile drains sandwiched in sand cushions: featuring the capillary barrier effect

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ABSTRACT: Economic and environmental constrains have required the use of marginal fills as backfill in geosynthetic-reinforced soil (GRS) retaining structures. The main challenge in the use of marginal fill as backfill material is their inability to quickly drain water, leading to building up of pore water pressures. The use of nonwoven geotextile drains within these backfills has been suggested but it is also recognized that the nonwoven geotextile may retard water due to capillary barrier effect under unsaturated soil conditions and start to act as a drainage material only once the soil immediately above it becomes nearly saturated. In this study, the numerical model is first calibrated using experimental results of one-dimensional clay column underlain by nonwoven geotextile system subjected to infiltration to validate its suitability of modeling capillary barrier effect. Thereafter, numerical models of unsaturated clay slopes with nonwoven geotextile drains are developed to investigate the unsaturated hydraulic behavior of such systems and to evaluate the effect of sandwiching nonwoven geotextile drains in thin layers of sand (i.e., sand cushions) on the development of the capillary barrier. The numerical results indicate that inclusion of sand cushions reduced the development of capillary barrier by acting as a transition zone of pore pressure difference between clay and geotextile. As a result, the accumulation of pore water pressure within soils above nonwoven geotextiles can be dissipated downward effectively. In addition, the sand cushions also act as additional drain layers to facilitate the drainage of water within the slope system and subsequently enhance system stability.

Keywords: Unsaturated flow, infiltration, marginal fill, rainfall, nonwoven geotextile, sand cushion

1 INTRODUCTION

To eliminate the need for expensive granular soil, reduce transportation cost, and minimize environmental impact due to disposal of local excavated soil, the locally available fine grained soils (silt and clay usually referred to as marginal fills) with low hydraulic conductivity have been often used to replace conventionally recommended granular fill in geosynthetic-reinforced soil (GRS) structures. However, it has been reported that low draining capacity of fine soils compromise the performance of reinforced soil walls under rainfall infiltration (Koerner and Koerner 2012; Mitchell and Zornberg 1995; Yoo and Jung 2006; Zornberg and Mitchell 1994) due to building up of pore water pressures. The use of nonwoven geotextile drains to improve the drainage capacity of marginal fills has been suggested and a number of studies on hydraulic behavior of nonwoven geotextile (intended to drain water from low draining soils) has been conducted in an attempt to better understand the performance of fine grained soil-nonwoven geotextile system subjected to infiltration.

In the field, considering that during construction of earth retaining structures, backfill soils are compacted at optimum moisture content or dry of optimum (Liu et al. 2012; Yoo and Jung 2006), these soils are usually unsaturated and typically generate suction. However, in unsaturated soils, where pore pressure is under suction, nonwoven geotextiles have been reported to work as a moisture barrier rather than as drainage material (Iryo and Rowe 2004, 2005; Zornberg et al. 2010). It was found out that the nonwoven geotextile did not provide drainage as originally expected. The water flow from fine grained soil into nonwoven geotextile was not continuous. A measureable amount of water did not flow from the soil into the underlying drainage layer until a critical condition was reached when the soil was nearly saturated owing to a phenomenon described to as capillary barrier effect. Capillary barrier effect was observed to increase the water storage of fine grained soils beyond the level that would normally drain under gravity. In this condition, nonwoven geotextile acted as a water barrier and led to increased pore water pressure contrary to its behavior under saturated conditions. Thus, Iryo and Rowe (2004) suggested considerable care is required when selecting nonwoven geotextiles for use within soil structures to avoid the undesirable development of increased water content.

The concept of geogrid or nonwoven geotextile sandwiched in thin layers of sand (i.e., sand cushions) has been proposed to enhance the shear strength of clay (Abdi et al. 2009; Unnikrishnan et al. 2002) and to accelerate pore water pressure dissipation and to increase system drainage capacity under saturated conditions (Raisinghani and Viswanadham 2011). However, no study has been reported to address the hydraulic behavior of such systems under unsaturated conditions.

Above discussions prompted the current numerical study of infiltration into unsaturated clay slopes with nonwoven geotextile drains sandwiched in sand cushions. The main objectives of this paper are twofold: to examine the suitability of finite element formulations for modeling capillary barrier effect and to investigate unsaturated soil hydraulic behavior when geotextile is sandwiched in sand layers, specifically to evaluate the effect of sand cushions on the development of the capillary barrier. First, a one-dimensional model was developed and calibrated using experimental results of one-dimensional homogeneous clay-nonwoven geotextile system subjected to a series of infiltration. Second, numerical experiments were conducted for clay with nonwoven geotextile drains with and without sand cushions to provide discernment into the hydraulic behavior of such systems. Finally, based on the findings of this numerical study, hydraulic behavior of unsaturated fine grained soil-nonwoven geotextile systems subjected to infiltration and effect of inclusion of sand cushion are discussed. The results obtained from this study hope to provide insightful information for the design of GRS structures.

2 MODEL CALIBRATION FOR CAPILLARY BARRIER EFFECT

2.1 *Experiment*

McCartney and Zornberg (2010) performed a one-dimensional soil column infiltration test to investigate the hydraulic behavior of soil underlain by geotextile, in particular the conditions necessary for establishment of capillary barrier effect. The test soil column comprised of a 203 mm diameter cylindrical polyvinyl chloride (PVC) tube filled with unsaturated clay underlain by a geocomposite drainage layer (GDL). The soil specimen was 1350 mm high, compacted in 25 mm lifts using a pneumatic piston compactor, and subjected to a series of uniform infiltration of water from the top at a rate less than the hydraulic conductivity of the soil. The soil used for this experiment was classified as low plasticity clay (CL) according to USCS. Figure 1 shows hydraulic characteristics of clay and geotextile used in this experiment. It can be observed in Figure 1(b) that at near saturation conditions, geotextile has high hydraulic conductivity compared to marginal fills (clay) but as suction increases, the hydraulic conductivity functions of the soil and the nonwoven geotextile cross at a suction of about 0.4kPa. This suggests that the soil acts as a more permeable material than the geotextile for suctions greater than 0.4kPa since marginal fills retains more water in the pores, they have more pathways for water flow, they are more conductive than geotextile. Moisture content profiles in the soil column were monitored using time domain reflectometry (TDR) and capacitance probes while matric suction changes were monitored using flushing tensionmeters at location shown in Figure 2.

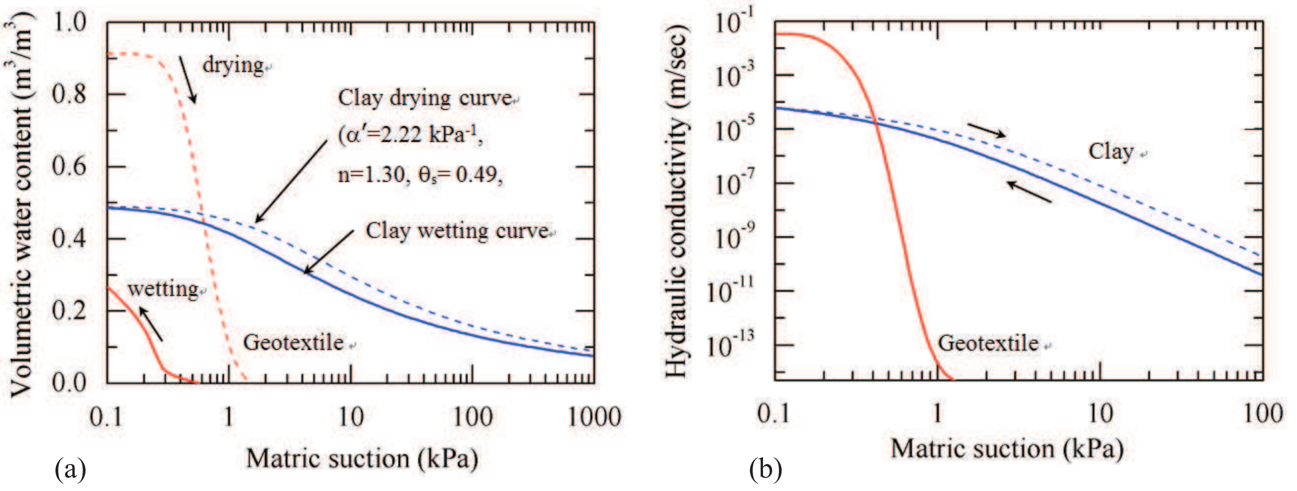

Figure 1. Hydraulic characteristics for clay and nonwoven geotextile: (a) soil water retention curves; (b) hydraulic conductivity functions

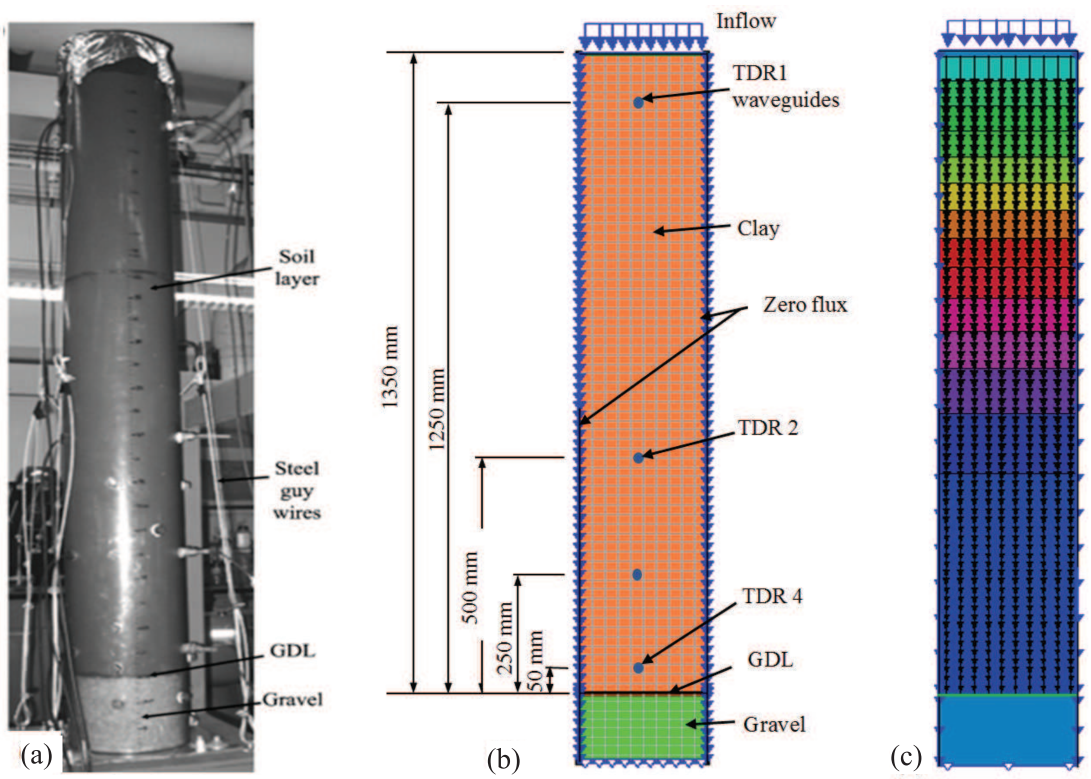

Figure 2. Experiment setup and numerical model of the soil column infiltration test: (a) Photo (McCartney and Zornberg 2010); (b) numerical model; (c) seepage velocity vectors

2.2 *Numerical Simulation*

Transient seepage analysis was conducted to examine the unsaturated hydraulic behavior of fine grained soil-nonwoven geotextile system subjected to infiltration, with a specific interest in the suitability of finite element formulations for modeling capillary barrier effect. Finite element computer program SEEP/W (Geo-Slope 2009) was used to solve a two-dimension form of the governing equation for transient flow within an unsaturated medium as was derived by Richards (1931) from Darcy's law and continuity. In this study, the soil and geotextile hydraulic characteristic curves were determined experimentally by McCartney and Zornberg (2010). The curve fitting parameters of drying curves were determined using RETC software (van Genuchten et al. 1991) and these parameters were used to approximate parameters of wetting curve following procedures suggested by Kool and Parker (1987). The column was modeled using 5694 four-node quadriteral elements with a global height of 0.01 m (Figure 2 (b)). To ensure that flow is only in the vertical direction, zero horizontal flux boundary condition to both sides of the column was applied. During this study, an automatically adjusted time increment between 1-100 s as needed to attain convergence was selected. The nonwoven geotextile was modeled as a line with interface elements assigned geotextile hydraulic properties. As suggested by Blake et al. (2003), modeling of antecedent hydrology (to generate initial pore pressure) was done by conducting a steady-state seepage analysis with a small prescribed unit flux on the surface boundaries. The values of prescribed unit flux were adjusted until the matrix suction did not exceed initial soil conditions. Through application of antecedent hydrology ensured that initial pore pressure head of -0.11m along the top of the column was established. A specified unit flux of 3.4 x 10^{-9} m/s for 3106 hours following the test condition was input to simulate infiltration.

2.3 *Comparison of Numerical and Experimental Results*

Figure 3 shows comparison of measured and predicted volumetric water content development at different locations. As shown in both the measured and predicted results, volumetric water content, θ, gradually increased with time due to the pass of wetting front and the development of hydrostatic pressure within the column when the wetting front reached the soil-geotextile interface. The latter was caused by the development of capillary barrier effect which prevented further drainage of water from the soil into the geotextile. Capillary barrier effect on an unsaturated soil-geotextile system increased the water storage capacity of soils beyond what the soil can store under gravity. In general, the numerical results showed a similar trend with the experimental results, which suggested the numerical simulation can capture the capillary barrier effect well. The difference between the measured and predicted values could be due to hysteresis nature of hydraulic characteristic of unsaturated soil and clogging of geotextile during infiltration which were not considered during numerical simulations.

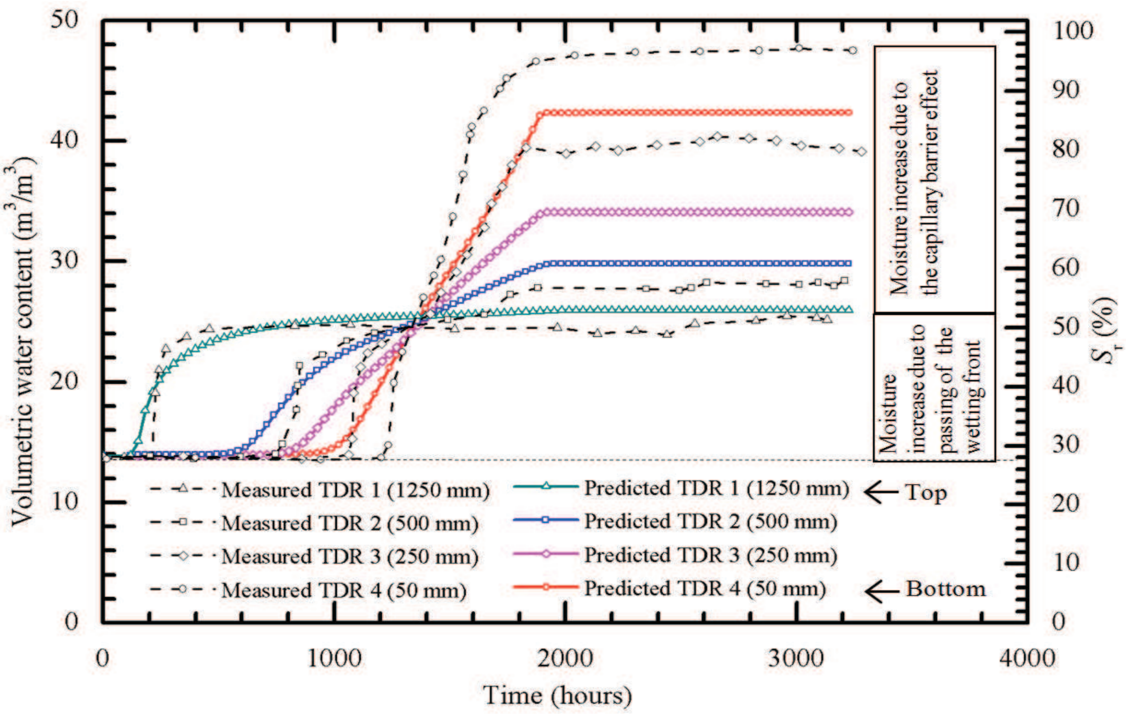

Figure 3. Comparison of measured and predicted moisture content histories at different elevations

3 NUMERICAL ANALYSES OF UNSATURATED CLAY SLOPES

3.1 *Numerical Simulation*

After the numerical model was validated, numerical experiments were conducted to two unsaturated clay slopes (Slope 1- reinforced clay slope with nonwoven geotextile drains and Slope 2- reinforced clay slope with nonwoven geotextile drains sandwiched in sand cushions) subjected to $q = 0.1\ k_{\text{clay}}$ (i.e. 22.3 mm/h). The slopes were 3 m high and 6 m long, with slope of 0.7H:1V similar to those constructed by Public Works Research Institute of Japan as described by Iryo and Rowe (2005). These slopes were modeled using 6445 six-node triangular elements arranged as shown in Figure 4. Vertical spacing of geotextile was set to 0.75 m and a 200 mm sand cushion was used to sandwich geotextile drains placed in Slope 2. A 1.5 m long geotextile layer was placed at the toe of each slope to avoid the development of excess pore pressures at the base. The element global height was set to 0.1m constrained to a third of global element size on top side and lower side of geotextile. Figure 5 shows the hydraulic characteristics of clay (deduced from McCartney and Zornberg (2010)), geotextiles (deduced from Iryo and Rowe (2004)) and sand. Hydraulic conductivity of saturated clay was 6.2e-005 m/sec while that of sand and geotextile were 0.01 m/sec and 0.0001 m/sec respectively. The initial pore water pressure condition in the domain was established using the numerical procedures suggested by Blake et al. (2003) as discussed previously. The calculated matric suctions were ensured did not exceed initial soil conditions (i.e., -20kPa).

To examine the effect of pore water increase in soil layers immediately above geotextile due to capillary barrier effect, limit equilibrium based slope stability analyses were conducted using SLOPE/W (Geo-Slope 2008). The pore water pressures predicted by SEEP/W were used as input water conditions using the built in interface between SLOPE/W and SEEP/W. Overall factor of safety for entire slope and local factor of safety for soil above the topmost geotextile layer were analyzed. The unsaturated soil shear strength was determined using the modified Mohr-Coulomb failure criterion proposed by Fredlund et al (1978). In this study, clay backfill material was modeled with a unit weight γ = 17.5 kN/m^3, effective friction angle ϕ'=30°, and zero effective cohesion. Sand was modeled with unit weight γ = 16.0 kN/m^3, effective friction angle ϕ'= 40°, and zero effective cohesion. A constant value of ϕ^b= 23°and 16°was selected for clay and sand respectively. The allowable long term design strength of geotextile T_a = 20 kN/m was used.

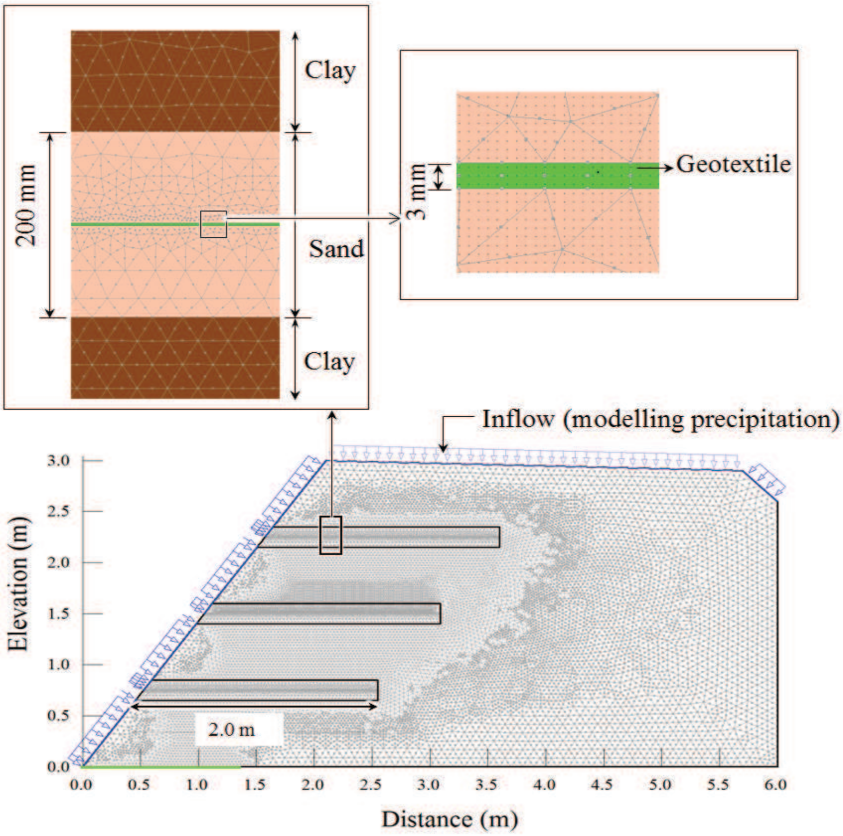

Figure 4. Numerical infiltration model of Slope 2 (with geotextile sandwiched in sand cushion)

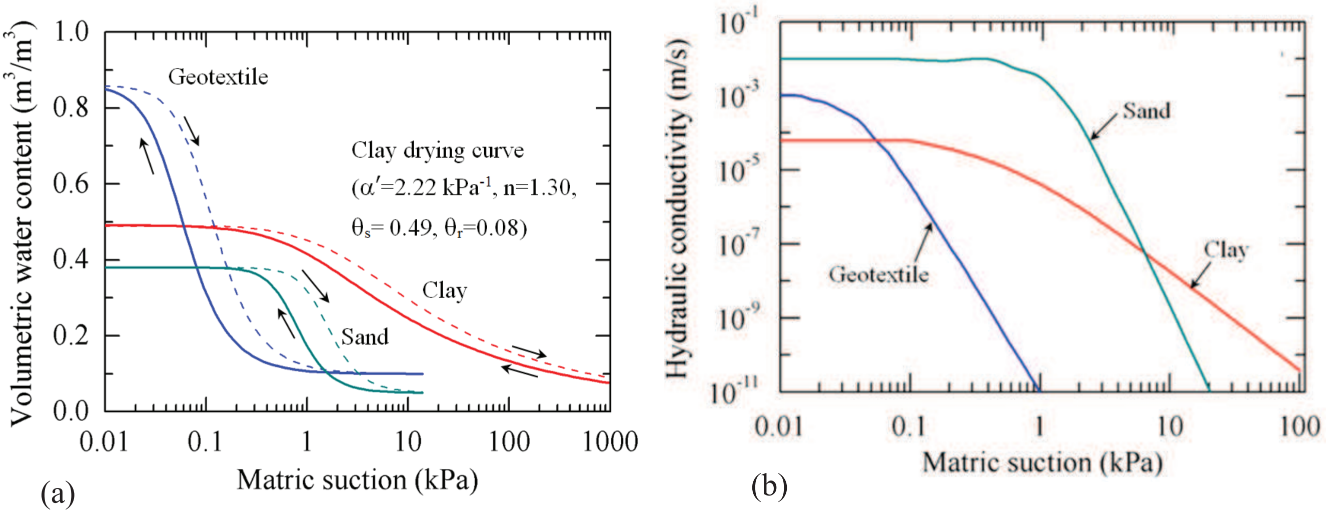

Figure 5. Hydraulic characteristics for clay, geotextile and sand: (a) water retention curves (WRC); (b) hydraulic conductivity functions

3.2 *Results and Discussions*

Figure 6 shows the degree of saturation (S_r) contours and profiles, and pore water pressure profiles when the wetting front reached the second geotextile layer (at time t = 15.0 h and the corresponding accumulate rainfall R = 335 mm) for Slope 1 (clay-nonwoven geotextile system) and Slope 2 (clay-sand-nonwoven geotextile system). It can be observed that discontinuities of the S_r and pore pressure profiles occurred at each geotextile layer in both Slopes 1 and 2. These discontinuities were most pronounced at the second geotextile in Slope 1. Also in Slope 1, the seepage velocity vectors of the infiltration front on reaching the geotextile drain indicated that the water dispersed along the soil-geotextile interface above the second geotextile layer and little to no water traveled in soils below the second geotextile layer. This observation suggests the capillary barrier occurred at the second geotextile layer in Slope 1. In Slope 2, the water traveled within upper and lower sand cushions, suggesting the sand cushions reduced the development of capillary barrier. Additionally, the sand cushions also acted as additional drain layers to facilitate the drainage of water within the slope system.

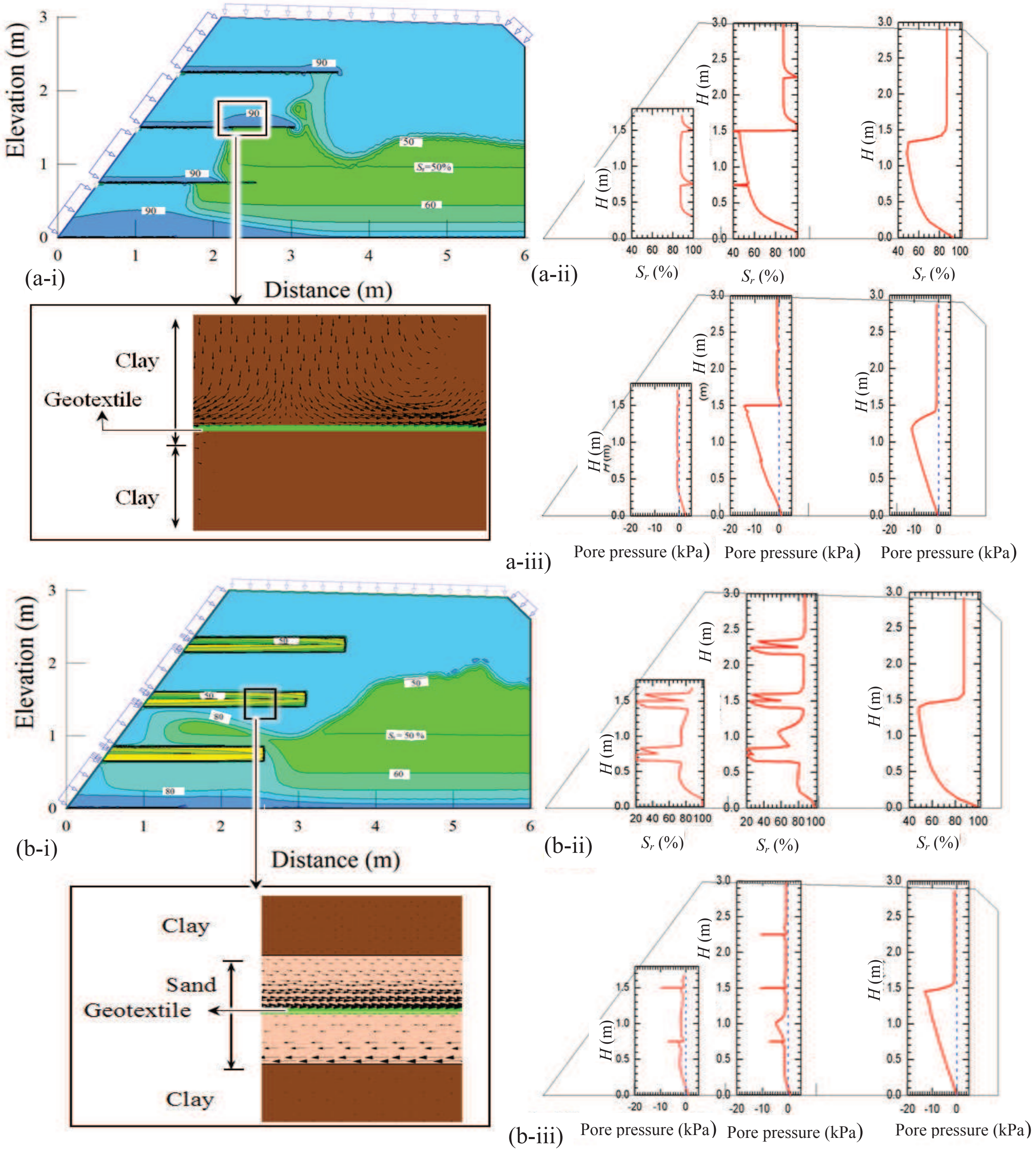

Figure 6. Advancing of infiltration when maximum pore pressure occurred at the second geotextile layer when t =15.0 h and the corresponding R = 326 mm: (a) Slope 1: (i) S_r contours; (ii) profiles of S_r; (iii) pore pressure profiles; (b) Slope 2: (i) S_r contours; (ii) profiles of S_r; (iii) pore pressure profiles

Figure 7 shows comparisons of pore pressure profiles of Slope 1 (clay-nonwoven geotextile system) and Slope 2 (clay-sand-nonwoven geotextile system) at a distance of 2.4 m from the toe. These profiles correspond to times before the wetting front approached the topmost drainage layer (t = 15,570s), when the wetting front was halted by the topmost drainage layer (t = 30,240s), when the wetting front was halted by second drainage layer from the top (t = 53,910s) and when the wetting front passed the third drainage layer from the top. In Slope 1, when the wetting front infiltrated into the soil layers, the pore water pressures increased to almost saturated conditions (i.e., -1kPa) signifying a great loss of matric suction. On reaching the geotextile the infiltration front was momentarily halted and positive pore pressures developed in soils immediately above geotextile. An obvious discontinuity of the pore pressures above and below the geotextile layer can be observed. After the wetting front passed the geotextile layer, the developed positive pore pressures on top side of geotextile dropped. The predicted pore pressure profiles in Slope 1 are similar to that reported by Iryo and Rowe (2005). In Slope 2, the maximum pore water pressures at each geotextile layer remained negative and the pore pressure profiles were less discontinuous compared to those in Slope 1. This observation suggests that the inclusion of sand cushions in Slope 2 reduced the development the capillary barrier effect by acting as a transition zone of the pore pressure difference between clay and geotextile; as a result, the accumulation of pore water pressure within soils above nonwoven geotextiles can be dissipated downward effectively. Figure 8 shows variation of overall and local factors of safety (FS) with cumulative rainfall (R). In Figure 8(a), the overall FSs of Slopes 1 and 2 decrease with cumulative rainfall. The FS of Slope 2 is greater than that of Slope 1 at a given cumulative rainfall. Because of the capillary barrier effect, the moisture was halted and positive pore pressures likely developed in soils immediately above geotextile, (Figure 7(a)).Thus, it is important to evaluate the local stability against soil sliding failure along each layer of soil-geotextile interface. Figure 8(b) shows the local FS (for soils above top geotextile layer) of Slope 1 at beginning of infiltration in Section (i) was greater than that of Slope 2. This is because the presence of high matric suction in clay maintained a high local stability for Slope 1. As infiltration continued, the matric suction decreased with the increasing cumulative rainfall and eventually the local FS of Slope 1 become less than that of Slope 2 when soils above top geotextile layer were saturated in Section (ii). It is interesting to point out in Figure 8(b), that at about R = 140 mm, local FS of Slope 1 reached its lowest value. This value corresponds to when the wetting front was momentarily halted by top geotextile layer due to the capillary barrier effect and the development of maximum pore pressures was observed. Afterward, the wetting front progressed past the geotextile, pore pressures on top of geotextile layer slightly dissipated, leading to gradual increase of FS. In Slope 2, the local FS value always decreased with cumulative rainfall; no increase of FS was observed. This decreasing trend also demonstrated the inclusion of sand cushions could reduce the capillary barrier effect efficiently.

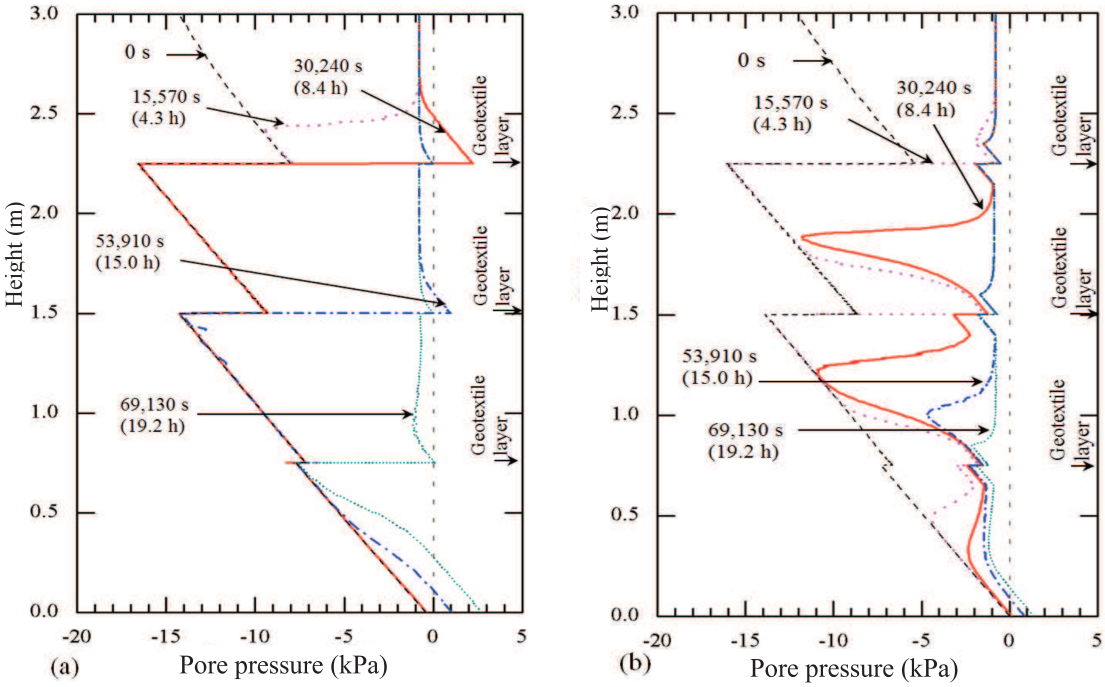

Figure 7. Development of pore pressure profiles at a distance of 2.4 m from the toe: (a) Slope 1; (b) Slope 2

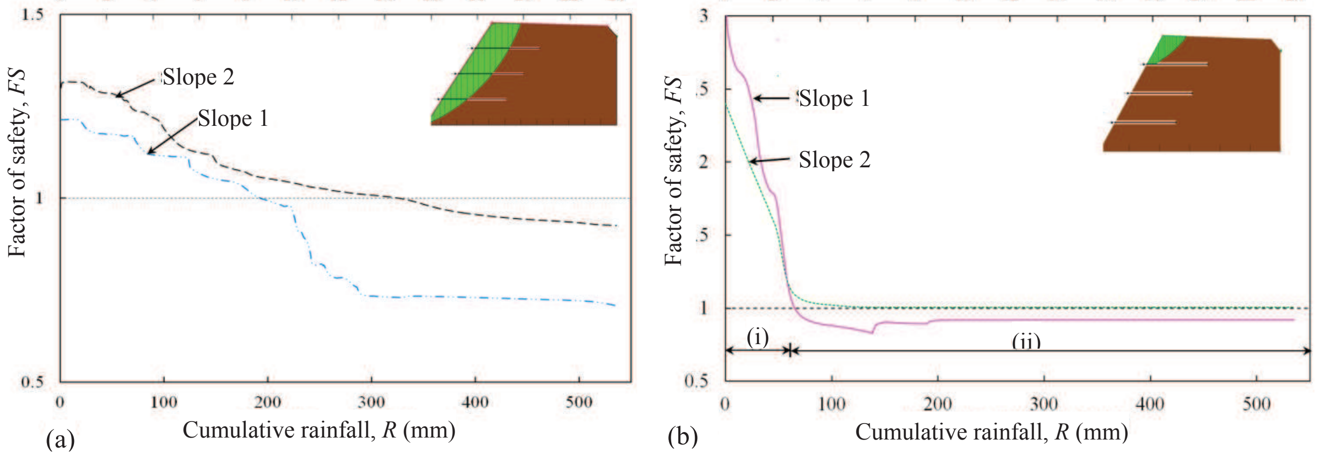

Figure 8. Variation of slope stability with cumulative rainfall: (a) overall FS; (b) local FS for soils above top geotextile layer

4 CONCLUSIONS

This study conducted a series of numerical analyses to investigate the unsaturated seepage behavior of fine-grained soil slopes with nonwoven geotextile drains. The effect of sand cushions on the development of the capillary barrier was evaluated and discussed. The conclusions drawn from this study are summarized below:

- The numerical model was validated for its suitability of modeling the capillary barrier effect using the experimental results of one-dimensional soil column infiltration test,
- For the clay slope with nonwoven geotextile drains (Slope 1), the numerical results indicated the wetting front was momentarily halted due to development of capillary break at the interface of soil and underlying geotextile and positive pore pressures developed in soils immediately above geotextile. An obvious discontinuity of the pore pressures above and below the geotextile layer can be observed. In this case, nonwoven geotextile acted as a moisture barrier instead of drainage material as expected,
- Sandwiching of geotextile drains in sand cushions in Slope 2 reduced the development of the capillary barrier effect. The maximum pore pressures at each geotextile layer remained negative and the pore pressure profiles were less discontinuous compared to those in Slope 1. In this case, sand cushions acted as a transition zone of the pore pressure difference between clay and geotextile; as a result, the pore pressure within soils above nonwoven geotextiles can be dissipated downward effectively, and
- Local soil sliding failure along each layer of soil-geotextile interface may occur in unsaturated clay-geotextile system due to the capillary barrier effect. In this study, the local slope stability was evaluated considering pore pressure changes at each infiltration stage. The numerical results showed as infiltration continued the sand cushions enhanced local slope stability.

Considering the application of geosynthetics in reinforced structures with low-permeable backfill soils, a suitable geosynthetic with thin layers of sand cushion is recommended to reduce the capillary barrier effect under unsaturated conditions.

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