Design and laboratory verification of a physical model of sloping capillary barrier

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Abstract: A physical model was designed and constructed to study the mechanisms associated with capillary barriers for slope stabilization purposes. Prior to construction of the model, various numerical analyses were conducted to determine the optimum dimensions and appropriate soil types for the materials of the capillary barrier model. This paper is divided into three sections: the first two sections are related to the design of the model and are to obtain the optimum dimensions of the model and to investigate the range of soil properties that are most suitable for experimental studies in the laboratory; and the last section is laboratory verification of the numerical analysis where the numerical simulation results are compared with the experimental data. Based on the numerical simulation results, the physical capillary barrier model was constructed using two different combinations of soils, namely silty sand over gravelly sand and fine sand over gravelly sand. From the comparison of the numerical results and experimental data, it was found that the numerical analysis was able to simulate the experiment on the physical capillary barrier model reasonably well.

Key words: physical capillary barrier model, unsaturated water flow, numerical simulation, pore-water pressure, volumetric water content, slope stability, infiltration.

Résumé : On a conçu et construit un modèle physique pour étudier le mécanisme associé aux écrans capillaires utilisés pour la stabilisation des talus. Avant la construction du modèle, on a réalisé diverses analyses numériques pour déterminer les dimensions optimales et les types de sols appropriés pour les matériaux du modèle d’écran capillaire. Cet article est divisé en trois sections : les deux premières sections traitent de la conception du modèle et à étudier la plage des propriétés qui sont les plus adéquates pour les études expérimentales dans le laboratoire ; et la dernière section comprend la vérification en laboratoire de l’analyse numérique où les résultats de la simulation numérique sont comparés aux données expérimentales. Sur la base des résultats de la simulation numérique, le modèle de l’écran capillaire a été construit en utilisant deux différentes combinaisons de sols : nonnément, un sable limoneux sur un sable graveleux, et un sable fin sur un sable graveleux. En partant de la comparaison des résultats numériques avec les résultats expérimentaux, on a trouvé que l’analyse numérique pouvait simuler raisonnablement bien l’expérience sur le modèle physique d’écran capillaire.

Mots clés : modèle physique d’écran capillaire, écoulement non saturé d’eau, simulation numérique, pression interstitielle, teneur en eau volumétrique, stabilité de talus, infiltration.

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1. Introduction

A capillary barrier is a cover system consisting of a fine-grained soil layer placed over a coarse-grained soil layer and is generally unsaturated and functions in response to changes in negative pore-water pressures. Capillary barriers have been studied and widely used in geoenvironmental engineering applications as soil covers for landfills and mining wastes to reduce water and gas infiltration into protected waste materials (Nicholson et al. 1989; Ross 1990; Stormont 1996, 1997, 1999; Khire et al. 1997, 1999, 2000; Yanful et al. 1999). Capillary barriers have potential application as a slope stabilization method by preventing infiltration into soil slopes during rainfall. This application for slope stabilization against rainfall-induced landslides has never been fully investigated, however, and hence is the focus of this research.

When the soil in a slope is in an unsaturated condition, the infiltration of rainwater into the slope can cause an increase in pore-water pressure. An increase in pore-water pressure decreases the shear strength of the soil, making the slope more susceptible to failure. The construction of a capillary barrier as a slope cover can significantly reduce the infiltration of water into the slope during rainfall and keep the slope in a safe condition.

As a landfill cover, capillary barriers have been constructed under relatively flat slope conditions in arid to semiarid climates. For slope stabilization purposes, however, the geometry of a capillary barrier will have to follow the surface of the protected slope, and the slope can be rather steep. Bussière et al. (2000) studied numerically the effects of...
slopes on the efficiency of the capillary barrier for a mine waste cover. In addition to slope stabilization purposes, capillary barrier application in the tropics may be subjected to high rainfall intensities, but the effectiveness of a capillary barrier under high precipitation intensities has not been fully investigated.

It might be possible eventually to use synthetic materials that function in a manner similar to that of a soil capillary barrier system. However, to first study the physical process associated with the storage of water, the transmission of water, and the release of water to the atmosphere for a two-layer soil system. The same behavioral mechanism can then be applied to other materials that could be placed on the surface of the slope.

The optimum design of a capillary barrier for slope stabilization purposes can be evaluated through a series of parametric studies. The effectiveness of a capillary barrier for slope stabilization in tropical climates can be studied using a suitable numerical model for saturated–unsaturated water flow. It is also important to verify that the mechanisms used in the numerical model are physically correct. In circumstances such as homogeneous saturated systems, the physics of groundwater flow is sufficiently known to evaluate whether a solution is reasonable. When the soil system is layered and involves the complexities of geometry and soil properties, however, it is not sufficient to use an intuitive approach to verify the model.

There are several ways in which a numerical model can be verified, such as an analytical solution, a field investigation, or a laboratory model. Because of the complexities of the problem associated with a capillary barrier system (e.g., geometry, nonlinearity of the soil parameters, and antecedence conditions), an analytical solution is difficult to obtain. However, there are several parameters that cannot be easily controlled when conducting a field investigation. Many of the uncertainties can be accommodated through the use of an experimental model in the laboratory with the selection of appropriate materials. Therefore, performing experimental studies in the laboratory appears to be the most feasible means of verification.

Miyazaki (1988, 1993) conducted several laboratory experiments to study infiltration characteristics and wetting-front development in a fine-grained layer over a coarse-grained layer, which is essentially a capillary barrier system, using several infiltration boxes of different dimensions. The laboratory model consisted of a sandy loam as the fine-grained layer and gravel as the coarse-grained layer. Miyazaki observed that the advance of the wetting front from a constant infiltration rate occurred at the interface between the fine-grained and coarse-grained layers, and water entered the underlying layers at lower edges of the slopes. Miyazaki highlighted that water flow from the fine-grained layer to the coarse-grained layer was diverted laterally along the interface.

Ross (1990) studied the capillary barrier concepts and its potential use as a downward water movement barrier in a surface cover. Ross developed an analytical solution for diversion length and diversion capacity of sloped capillary barriers. This solution is considered one of the most widely referred analytical solutions to calculate the diversion capacity and diversion length of sloped capillary barriers. Ross derived the equations using several assumptions, such as steady-state infiltration; semi-infinitely thick soil layers; and a quasi-linear approximation for the relationship between relative permeability, $k_{rel}$, and pressure head, $h$ (defined as $k_{rel} = \exp(\alpha h)$, where $\alpha$ is a fitting parameter for the quasi-linear approximation). Steenhuis and Parlange (1991) improved Ross’ solution by considering different permeability functions to overcome the weaknesses of using the quasi-linear approximation for permeability functions, especially near saturation.

Oldenburg and Pruess (1993) conducted numerical simulations using finite difference methods to investigate the behavior of capillary barriers. Similar to Ross (1990), Oldenburg and Pruess used the quasi-linear approximation in describing the permeability functions. The work was compared to the theoretical solution proposed by Ross, and Oldenburg and Pruess concluded that Ross’ analytical solutions provided reasonable results. It was pointed out, however, that the breakthrough developed gradually and appeared to be much more complicated than Ross’ assumptions. In the simulations, the breakthrough region was characterized by a large downward flux through the interface. The amount of leakage increased with the increasing contrast in permeability ratio between the fine-grained and coarse-grained layers. The leakage occurred locally and tended to dry out the fine-grained layer in the downdip direction. As a result, the capillary barrier became effective again in preventing the downward movement of moisture.

Numerical simulations associated with the design and verification of a physical capillary barrier model are presented in this paper. The numerical simulation process can be divided into three sections. The first section is related to obtaining optimum dimensions for the capillary barrier model. The physical model cannot be too long because of laboratory space constraint but should be of sufficient length to avoid boundary effects associated with water flow within the capillary barrier model. The second section of the numerical simulation is performed to investigate the range of soil properties that can be used for the physical capillary barrier model studies to give meaningful experimental data (i.e., pore-water pressure, volumetric water content, runoff, lateral diversion, and breakthrough). Various soils with different soil-water characteristic curves (SWCC) and permeability functions were considered. Based on the results of the numerical study, several soils with appropriate hydraulic properties were selected for use in the physical capillary barrier model. The third section of the numerical simulation is a laboratory verification, in which the numerical simulation results from a series of experimental programs were compared with the experimental data.

2. Numerical analysis

The governing partial differential equation of water flow in an unsaturated soil for a transient problem (Fredlund and Rahardjo 1993) is shown as follows:

$$
\frac{\partial}{\partial x} \left( k_{wx} \frac{\partial h_w}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_{wy} \frac{\partial h_w}{\partial y} \right) = m_w \gamma_w \frac{\partial h_w}{\partial t}
$$
where \( h_w \) is the total head; \( \partial h_w / \partial x \) is the hydraulic head gradient in the \( x \) direction; \( k_w \) and \( k_w \) are the coefficients of permeability with respect to the water phase in the \( x \) and \( y \) directions, respectively; \( \gamma_w \) is the unit weight of water; \( m_w \) is the coefficient of water volume change with respect to the change in matric suction, which can be obtained from the slope of the SWCC; and \( t \) is time. In unsaturated undeformable soils, the coefficient of permeability is a function of matric suction, and the coefficient of permeability in saturated undeformable soils is considered constant. Equation [1] is highly nonlinear due to the nonlinearity of the SWCC and the permeability function for the unsaturated soil. The equation can be solved using an iterative numerical procedure in the finite element method. In this study, the finite element analyses were performed using the SEEP/W program (GEO-SLOPE International, Ltd. 2000) and a knowledge-based database system SVFlux for seepage modelling (SoilVision Systems Ltd. 2001).

3. Design of the physical capillary barrier model

Various lengths and thicknesses of the layers of materials in the physical capillary barrier model were analyzed using a steady-state seepage analysis under different precipitation rates. The length of the capillary barrier model was measured in the horizontal direction, and its thickness was measured in the vertical direction. Due to the large number of the analyses performed, only a few selected optimum models are presented in this paper.

3.1. Material description and its properties

A two-layer system capillary barrier model consisting of fine-grained and coarse-grained layers was used in the analysis. In the simulations, a silty sand or a concrete sand (i.e., sand that is commonly used as a concrete aggregate) was considered as the fine-grained layer, and pea gravel was used for the underlying coarse-grained layer. These materials were selected from Stormont and Anderson (1999) because their properties covered a large range of properties of materials that could be used as a capillary barrier. The grain-size distributions, saturated coefficients of permeability \( (k_s) \), and water contents at various matric suctions for these soils were measured by Stormont and Anderson.

Silty sand (Unified Soil Classification System (USCS) group SM) had a clay fraction (<0.002 mm) less than 8% with a low plasticity index (PI = 2). Concrete sand was classified as a poorly graded sand (USCS group SP) with less than 1% fines (<0.075 mm). Pea gravel was uniform in distribution, and more than 99% of the pea gravel had particle size between 4 and 20 mm (USCS group GP). The grain-size distribution curves of the soils used are shown in Fig. 1.

The SWCCs were fitted using the equation of Fredlund and Xing (1994). The SWCC has a typical sigmoidal shape, and some useful parameters of the SWCC can be defined from the curve (Fig. 2). The air-entry value \( \psi_a \) is defined as the matric suction at which air first enters the saturated pores of the soil along the drying path. On the other hand, the water-entry value \( \psi_w \) is defined as the matric suction at which water first enters the dry pores of the soil in the wetting path, and its value can be estimated from the inflection point on the SWCC (Fig. 2).

Permeability functions were calculated using a statistical permeability function model (Childs and Collis-George 1950), which used the SWCC and saturated coefficient of permeability of the soil. Calculation of the permeability function involves a complex integration of the SWCC as illustrated in Fredlund and Rahardjo (1993). It should be noted, however, that the use of a calculated permeability function from the SWCC can lead to inaccurate simulation of a coarse soil under a dry condition, where the volumetric water content of the coarse soil is lower than its residual value (Choo and Yanful 2000). In this case, the water phase of the coarse soil quickly becomes discontinuous upon drying and the water flow may occur in the form of vapor flow.

The main hydraulic properties of the materials used in designing the capillary barrier physical model are presented in Table 1, and their SWCCs and permeability functions are presented in Figs. 3 and 4, respectively. Only the drying
curves of the SWCC were available, and these drying curves were used in the analysis.

3.2. Geometry and boundary conditions of the capillary barrier model

The geometry and dimensions for the capillary barrier model used in this analysis are illustrated in Fig. 5. The effects of varying the length of the capillary barrier model from 1500 to 3000 mm with thicknesses of 300–600 mm (200–400 mm fine-grained layer and 100–200 mm coarse-grained layer) on the water flow in the capillary barrier model were analyzed. The inclination angle used in the capillary barrier model was 30°. Most of the residual soil slopes in Singapore have slope angles between 20 and 30°. Based on landslide data in Singapore (Toll et al. 1999), the majority of failed slopes had a slope angle of 30–34°. To reduce the boundary effects on the left and right sides of the model, the crest and toe of the capillary barrier model were extended up to 300 mm in the horizontal direction (Fig. 5). The sides and bottom of the capillary barrier model were set to be impervious (i.e., a zero-flux boundary). Only the surface of the capillary barrier model was exposed to precipitation and evaporation. The precipitation was modeled as a positive-flux boundary, and evaporation as a negative-flux boundary. The rates of precipitation were varied from 2 to 200% of the saturated coefficient of permeability of the fine-grained layer (i.e., concrete sand or silty sand). Since the top surface of the capillary barrier model was not covered with vegetation, evaporation took place only on the surface of the capillary barrier model. The water tables at the crest and toe of the capillary barrier model were modeled using a zero-pressure boundary condition (i.e., \( h_w \) equal to elevation). The boundary conditions for the model are also shown in Fig. 5.

3.3. Analysis of the modelling results

The pressure head profiles in the \( y \)-axis direction (vertical direction from the bottom of the capillary model) for every 200 mm interval along the \( x \) axis (horizontal direction) of the capillary barrier model and for precipitation rates of 5% and 8% of \( k_s \) of the concrete sand are shown in Fig. 6. A value of \( x = 0.0 \) m corresponds to the toe of the capillary barrier model, and a value of \( x = 2.0 \) m corresponds to the crest (\( x \) refers to the horizontal distance axis in Fig. 5). All pressure head profiles had similar shapes but different magnitudes. The upper part of the capillary barrier model (i.e., large \( x \) values) had a lower pressure head (or a higher matric suction) as compared with the lower portion of the capillary barrier model (i.e., small \( x \) values). A similar observation was made by Bussière et al. (2003) on an inclined cover model used as an oxygen barrier.

The shape of the pressure head profile was close to the hydrostatic condition when the applied precipitation rate was relatively low. When the precipitation rate was increased, the pressure heads in the concrete sand layer increased (or became less negative); however, the pressure head profiles in the pea gravel layer remained unchanged (Fig. 6). This observation indicates that the additional infiltrating water due to the increasing precipitation was held inside the concrete sand layer. When the applied precipitation rate was 8% of \( k_s \) of the concrete sand layer, the pressure heads in the concrete sand layer were almost constant along each cross section (Fig. 6b). The pressure head profiles shown in Fig. 6 were similar but differed near the upper and lower ends of the model. The horizontal distance at which pressure head profiles begin to

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Table 1. Hydraulic properties of the materials used in designing the capillary barrier physical model.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>( k_s ) (m/s)</th>
<th>( \theta_s )</th>
<th>( \psi_a ) (kPa)</th>
<th>( \theta_r )</th>
<th>( \psi_w ) (kPa)</th>
<th>( \alpha ) (kPa)</th>
<th>( n )</th>
<th>( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty sand</td>
<td>( 3.0 \times 10^{-6} )</td>
<td>0.38</td>
<td>0.02</td>
<td>0.11</td>
<td>14.00</td>
<td>2.86</td>
<td>2.23</td>
<td>0.77</td>
</tr>
<tr>
<td>Concrete sand</td>
<td>( 2.4 \times 10^{-4} )</td>
<td>0.35</td>
<td>0.50</td>
<td>0.06</td>
<td>1.30</td>
<td>0.64</td>
<td>3.33</td>
<td>0.80</td>
</tr>
<tr>
<td>Pea gravel</td>
<td>( 1.3 \times 10^{-1} )</td>
<td>0.33</td>
<td>1.10</td>
<td>0.05</td>
<td>0.05</td>
<td>0.03</td>
<td>3.04</td>
<td>1.03</td>
</tr>
</tbody>
</table>

Fig. 3. Soil-water characteristic curve of the soils used in capillary barrier simulations. Data from Stormont and Anderson (1999) shown as symbols, and fitted curves shown as solid lines.

Fig. 4. Permeability function for the capillary barrier materials calculated using a statistical model.
be affected by the sidewalls was studied. For the selected dimensions of the capillary model, the distance of influence was found to be less than 200 mm from the ends of the model, as the pressure heads for $x = 0.0, 0.2, 1.8,$ and $2.0$ m have different shapes in terms of their profiles compared with those from other locations (Fig. 6).

The distance at which the upper and lower boundary conditions of the capillary barrier model influence the pressure head distributions depends on the precipitation rate, soil thickness, slope angles, and hydraulic properties of the capillary barrier materials. Generally, it can be concluded that the thinner the capillary barrier and the flatter the angle of inclination, the less will be the distance or width of influence of the upper and lower boundary conditions.

The selected geometry and dimensions for the physical capillary barrier model are presented in Fig. 5 (dimensions shown in parentheses). The total horizontal length of the capillary barrier model was set at 2600 mm, including a 300 mm horizontal extension at the crest and the toe, the width was set at 400 mm, and the slope angle of the capillary barrier model was $30^\circ$.

4. Selections and testing of material for the capillary barrier model

The three types of soil used in the first section of the analysis (Sect. 3) were also used in this analysis to investigate the range of material properties for the capillary barrier model. The shape and dimensions of the capillary barrier model used in these simulations were based on the result of the first analysis as shown in Fig. 5. The second set of simulations was conducted using a transient seepage analysis with different types of initial conditions, different intensities, and different durations of the simulated rainfall.

4.1. Boundary conditions

Four types of boundary condition were used to simulate the laboratory test model. Besides the three types of boundary condition used in the steady-state analysis, one additional boundary condition was used to model the drainage at the lower side of the capillary barrier model. This boundary condition was a unit hydraulic gradient boundary. The physical meaning of this boundary condition was that the amount of flux that passes through the boundary at a particular matric suction was equal to the coefficient of permeability of the soil corresponding to that matric suction. There were three drainage outlets in the laboratory model, two pipes on the left boundary of the model (i.e., located right at the bottom of the fine-grained layer and at the bottom of the coarse-grained layer) and one pipe at the bottom boundary, as shown in Fig. 5. Instead of the constant flux used in the steady-state analysis (i.e., first section analysis), a varied flux (i.e., flux $q$ as a function of time $t$: $q = f(t)$) was used in the transient analyses.

4.2. Initial conditions

The behavior of the physical capillary barrier model was analyzed using two different initial conditions. The first initial condition used was a wet condition. This condition was considered as the worst condition where the capillary barrier model had a low storage capacity. In this condition, a pressure head of $-0.1$ m was applied on both of the fine- and coarse-grained materials. The initial water content of the fine-grained layer (i.e., concrete sand) corresponding to the matric suction was 35.8% as obtained from its SWCC.
The second initial condition applied was a dry condition. In this condition, the capillary barrier system had a high storage capacity. This condition was achieved by applying a pressure head of –1.0 m to the model. The concrete sand layer had an initial water content of 16.5%, corresponding to an initial matric suction of 10 kPa as obtained from its SWCC.

4.3. Analysis of results

The results of the analysis in terms of velocity vectors are presented in Fig. 7. In this case, the capillary barrier model consisted of 400 mm of concrete sand underlain by 200 mm of pea gravel, and it was subjected to a precipitation rate of 10% of the $k_s$ of the concrete sand (i.e., 86.4 mm/h). It can be seen that the infiltrating water was diverted along the interface of the concrete sand and the pea gravel layers before it drained out through the drainage located at the left side of the model, right at the bottom of the concrete sand layer.

4.3.1. Effect of precipitation duration

Figure 8 presents the changes in pressure heads during the simulation for three different vertical cross sections located at $x = 0.25$, 1.00, and 1.75 m from the toe of the slope ($x$ refers to horizontal distance axis in Fig. 7). The applied precipitation rate and the calculated infiltration rate are shown at the top of Fig. 8. In this case, the capillary barrier model consisted of 400 mm of concrete sand underlain by 200 mm of pea gravel and was subjected to precipitation at a rate of 10% of the $k_s$ of the concrete sand (i.e., 86.4 mm/h). The duration of precipitation was 15 min for the first simulation and 42 min for the second simulation.

During the precipitation, the pressure head at the top surface of the model increased from an initial value of –0.54 m to –0.1 m in both simulations and then gradually decreased to –0.25 m after the precipitation ended. The pressure head increased in the middle of the concrete sand layer after 15–20 min of precipitation in both simulations. The pressure head changes were almost the same at the lower ($x = 0.25$ m) and middle ($x = 1.00$ m) cross sections at all depths. At the upper cross section ($x = 1.75$ m), however, the pressure head change occurred after some time, as indicated in Fig. 8.

Along the interface between the concrete sand and pea gravel layers, for the case with 15 min of precipitation, the pressure head started to increase gradually after 30 min of simulation and reached a value of –0.1 m after 60 min. The same phenomenon was observed in the case when the precipitation was applied for 42 min. The pressure head along the interface started to increase after 30 min of simulation; however, its increase occurred rapidly and reached 0.0 m after 40 min of simulation. This indicates that the capillary barrier material along the interface had become saturated.

There was no significant change in pressure head in the pea gravel layer with 15 min of precipitation. In this case, the capillary barrier was able to maintain the matric suction in the underlying soils and the infiltrating water was diverted along the concrete sand – pea gravel interface. When the duration of precipitation was 42 min, however, the pressure heads in the pea gravel layer increased gradually and reached positive values after 60 min of simulation (at cross section of $x = 0.25$ m). In this case, breakthrough had occurred and the capillary barrier became less effective as a moisture barrier. The average value of volumetric water content along the interface increased to 22%, indicating that the
breakthrough can occur even though the fine-grained layer is still in an unsaturated condition. For this particular capillary barrier, it was found that its effective length was 0.22 m (i.e., the distance from the crest of the capillary barrier) where the infiltrated water stored in the fine-grained layer began to penetrate into the coarse-grained layer.

Regardless of the duration of the applied precipitation, the infiltrating water reached the interface at the same time (i.e., first 30 min of the simulation), as indicated by an increase in the pressure head profiles at the concrete sand – pea gravel interface.

4.3.2. Effect of different initial conditions

Another set of simulations on the capillary barrier consisting of 400 mm of concrete sand underlain by 200 mm of pea gravel was conducted to observe the effect of initial conditions. Two different initial conditions were used, one to represent a wet condition and one to simulate a dry condition (see Sect. 4.3). The capillary barrier model was subjected to a precipitation rate of 10% of the $k_s$ of the concrete sand, and the duration of the applied precipitation was 30 min for each simulation.

Changes in volumetric water content relative to the initial values during the simulations are presented in Fig. 9 for three different vertical cross sections located at $x = 0.25$, 1.00, and 1.75 m from the toe of the slope. The applied precipitation rate and the calculated infiltration rate are also shown at the top of Fig. 9.

Figure 9 shows that the infiltration water moves fastest under an initially wet condition (Fig. 9a). This condition can be considered as the worst condition for a capillary barrier because of its low matric suctions (i.e., less negative pressure head) and low storage capacity. The volumetric water content along the middle of the concrete sand layer increased after 15 min of simulation. Along the concrete sand – pea gravel interface, however, the volumetric water content increased from the beginning of the simulation. This phenomenon occurred because the initial volumetric water content of the capillary barrier material was already high due to its low matric suction. The infiltrating water flowed down initially and later diverted laterally along the concrete sand – pea gravel interface. Breakthrough occurred after 25 min, as indicated by the rapid increase in volumetric water content of the pea gravel. Water that penetrated into the pea gravel layer subsequently flowed to the bottom of the pea gravel layer, as indicated by the increasing volumetric water content along the bottom of the layer following the same pattern as that in the middle of the layer. The effective length of the capillary barrier was found to be 0.22 m (i.e., the distance from the crest of the capillary barrier) where the infiltrated water stored in the fine-grained layer began to penetrate the coarse-grained layer.

For the case of an initially dry condition, there was no significant change in volumetric water content in the pea gravel layer during the 90 min of simulation (Fig. 9b). The infiltrated water was held inside the concrete sand layer and diverted laterally along the concrete sand – pea gravel interface. Along the surface of the concrete sand, the change in volumetric water content was high when precipitation was initially applied and decreased immediately after the precipitation ended. The infiltrated water reached the middle of the concrete sand layer and subsequently infiltrated the concrete sand – pea gravel interface after 30 and 60 min of simulation, respectively (Fig. 9b).

These simulation results indicate that a particular capillary barrier model subjected to similar precipitation rates works well for the case of an initially dry condition and becomes less effective for the case of an initially wet condition.
4.3.3. Effect of capillary barrier materials

To investigate the effectiveness of different materials for use in a capillary barrier model, three combinations of capillary barrier using three different materials were used. The capillary barrier models were silty sand over concrete sand, silty sand over pea gravel, and concrete sand over pea gravel. In each simulation, the capillary barrier model was subjected to an initially dry condition (i.e., an initial pressure head of –1.0 m was applied to both fine- and coarse-grained layers). A precipitation rate of 10 mm/h was applied for 30 min in each simulation.

The changes in pressure head during the simulations for three different vertical cross sections located at \( x = 0.25, 1.00, \) and 1.75 m from the toe of the slope are presented in Figs. 10a, 10b, and 10c, respectively. The applied precipitation rate and the calculated infiltration rate are shown at the top of Fig. 10.

For a simulation period of 100 min, the pressure head changes were almost the same in both capillary barrier models consisting of silty sand over concrete sand (Fig. 10a) and silty sand over pea gravel (Fig. 10b). During precipitation, the pressure head along the top surface was zero. Near the end of precipitation the pressure head decreased gradually to –0.4 m. In the middle of the silty sand layer, the increase in the pressure head occurred 30 min after the beginning of the simulation. The pressure head increased gradually from its initial value of –1.0 m up to –0.5 m in 25 min and then became constant until the end of the simulation. There was no change in pressure head along the interface of fine- and coarse-grained layers during the simulation. This indicates that the infiltration water did not reach the interface.

When the capillary barrier model is constructed from concrete sand over pea gravel, the change in pressure head is more obvious (Fig. 10c). This observation could be attributed to the high permeability of the concrete sand layer. All precipitation was transferred into infiltration (i.e., no runoff occurred). As a result, the total infiltration that occurred in this combination was higher than that of the previous combinations (i.e., silty sand over concrete sand and silty sand over pea gravel). The pressure in the middle of the concrete sand layer increased to zero after 33 min of simulation and remained constant at –0.10 to –0.15 m until the end of the
The increase in pressure head along the concrete sand – pea gravel interface occurred after 40 min of simulation and the pressure head reached zero after 60 min of simulation. Inside the pea gravel layer, either in the middle or the bottom of the layer, a gradual increase in pressure head was observed after 45 min of simulation and a zero pressure head was reached after 90 min of simulation. At this instance, breakthrough occurred and the capillary barrier model became less effective in maintaining the negative pore-water pressure of the underlying soils.

The comparison of pressure head development in the capillary barrier model with different initial conditions and material combinations is shown in Fig. 11. The pressure head was calculated at 10 mm below the interface between the fine- and coarse-grained layers. It was observed that breakthrough occurred at the fastest rate in the case of the capillary barrier model consisting of concrete sand over pea gravel when compared with the other combinations of capillary barrier model. In this case, the change in pressure head occurred rapidly before breakthrough. On the contrary, the change in pressure head occurred gradually when silty sand was used as the fine-grained layer. The gradual pressure head change shown was due to the low permeability of the silty sand layer. As a result, the precipitation mainly became runoff instead of infiltration into the capillary barrier model.

The performance of two capillary barriers that use the same fine-grained material was different if different types of coarse-grained materials were used. The higher the water-entry value of the coarse-grained layer, the faster the breakthrough (Stormont and Anderson 1999). Once the matric suction in the coarse-grained layer reaches its water-entry value, the coefficient of permeability of the coarse-grained layer increases rapidly and may exceed the coefficient of permeability of the fine-grained layer. As a result, the infiltrating water begins to move through the coarse-grained layer. In this case, the coarse-grained layer becomes a drainage layer instead of providing a capillary break.

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From the results of the analysis, it is concluded that the coefficient of permeability of the silty sand was too low. As a result, the changes in pore-water pressure in this material were not significant. The silty sand, with a coefficient of permeability higher than that used in the numerical simulation, was selected to be used in the physical capillary barrier model. On the other hand, the particle size of the pea gravel was found to be too coarse. When a coarse material, like the pea gravel used in this analysis, was employed as a coarse-grained layer in a capillary barrier model, breakthrough occurred in terms of funnel flow or fingering (Baker and Hillel 1990). Therefore, gravelly sand was selected for use in the physical capillary barrier model instead of pea gravel to reduce the possibility of occurrence of the funnel flow in the experiment. A soil similar to the concrete sand (i.e., fine sand) was selected as the third material for the physical capillary barrier model.

5. Laboratory verification

In this section, the results of numerical analyses are compared with experimental data. The physical capillary barrier...
model was constructed inside an infiltration box, and simulated rainfalls of different intensities and durations were applied through a rainfall simulator located on top of the box. Various instruments consisting of tensiometers for pore-water pressure measurement, time-domain reflectometry (TDR) waveguides for volumetric water content measurement, flowmeters, and weighing balances for water balance measurements were used in the experiment. The numerical simulation of the laboratory tests was performed using soil properties (i.e., SWCC and permeability function) that were independently measured. Three different soils (silty sand, fine sand, and gravelly sand) were used to construct the physical model of a capillary barrier in the laboratory as suggested by the results of numerical simulations (Sect. 4). The silty sand was the original local (Singapore) residual soil, the fine sand was a sand used in the Changi reclamation projects, and the light grey to white gravelly sand was crushed from fresh granite that can be obtained commercially. A detailed explanation of the apparatus, materials used, and testing procedures in the physical capillary barrier model was given by Tami et al. (2004).

5.1. Experimental studies

A series of experiments involving a capillary barrier model with a 400 mm thick layer of fine-grained soil (i.e., fine sand) and a 200 mm thick layer of coarse-grained soil (i.e., gravelly sand) are presented and discussed in this paper. The fine sand is a white river sand, and the light grey to white gravelly sand is a crushed fresh granite. The fine sand has a coefficient of uniformity ($C_u$) of 2.1 and a coefficient of curvature ($C_c$) of 0.89. The gravelly sand is uniform and has a grain size range from 2.5 to 7.5 mm, with 50.1% of the particles passing sieve No. 4 (ASTM 1998). Both the gravelly sand and the fine sand are categorized as poorly graded sands (USCS group SP). The saturated coefficients of permeability ($k_s$) of the fine sand and gravelly sand are $2.7 \times 10^{-4}$ and $7.6 \times 10^{-2}$ m/s, respectively, for a dry density of 1.56 Mg/m$^3$ (with porosity equal to 0.38) for the fine sand and 1.62 Mg/m$^3$ (with porosity equal to 0.41) for the gravelly sand. The dry densities of the materials were controlled so that they were similar to those of the capillary barrier model. The experimental volumetric water content and matric suction data were fitted using the equation of Fredlund and Xing (1994) to obtain smooth drying and wetting SWCCs for each soil. The correction factor of the fitting equation, $C(\psi)$, was set to 1 (Leong and Rahardjo 1997). The main hydraulic properties of the materials used in the capillary barrier physical model are presented in Table 2, and their

![Fig. 11. Pressure head changes at 10 mm below the interface in the middle of the capillary barrier model for initially wet and dry conditions at $x = 1.0$ m.](image-url)
SWCCs and the permeability function are presented in Figs. 12 and 13, respectively (where W indicates wetting path and D indicates drying path).

The materials for the capillary model were placed layer by layer with an approximate thickness of 15–20 mm per layer. Each layer was placed parallel to the slope surface and subsequently compacted using a 200 mm × 200 mm vibrator plate. The compaction energy applied to each soil layer was calibrated a priori to achieve the desired density. The tensiometers and the TDR wave guides were installed during the placement of the soils to ensure full contact with the soil. A total of 25 tensiometers were installed in five cross sections, and 21 TDR wave guides were installed in seven cross sections. There were minor adjustments to the dimensions of the model and the locations of the drain during the construction of the model. The final arrangement of the capillary barrier materials and locations of measuring devices and drains are shown in Fig. 14.

An experiment consisting of two infiltration tests was conducted and analyzed. Prior to the experiment, a relatively small rate of precipitation of 2.5 mm/h was applied for more than 50 h to obtain a steady-state condition when there were no further changes in pore-water pressure and volumetric water content observed in the capillary barrier model. Therefore, the start of the experiment can be considered to be essentially a steady-state condition. In each test, a 24 h experiment was conducted starting with a wetting part (i.e., application of a simulated rainfall of 16 mm/h for 6 h) that was subsequently followed by 18 h of restoration (i.e., draining) where no rainfall was applied. Figure 15 presents the rates and durations of the precipitations applied in the tests.

5.2. Simulation of laboratory experiment

Two numerical simulations were conducted for each series of experiments. One simulation used the drying SWCC and permeability function, and the second simulation used the wetting SWCC and permeability function. The appropriateness of each set of data in simulating the different processes during the laboratory tests was investigated by comparing the simulation results and experimental data.

In this paper, numerical simulation results and experimental data from test II are presented. The simulation consisted of a 6 h precipitation event at a rate of 16 mm/h, followed by 18 h of draining with no precipitation applied. The initial condition used in the analysis was taken from the pressure head data obtained from the results of numerical simulation of test I (i.e., elapsed time of 24 h as shown in Fig. 15).

5.3. Comparison of experimental and numerical simulation results

Figures 16 and 17 show the variation of matric suction and volumetric water content for two cross sections along the fine-grained (i.e., fine sand) and coarse-grained (i.e., gravelly sand) layers of the capillary barrier model during test II. At the top of the figures, the applied rate of precipitation and the discharge flow rate from the model are shown. There was no runoff and breakthrough observed during the experiment, therefore runoff and breakthrough rates $q_R$ and $q_B$, respectively, are not shown in the figures. Cross section A was located at the lower part of the model, and cross section B at the upper part of the model (Fig. 14). Tensiometers T-22 and T-42 measured the matric suction in the gravelly sand layer and were located 50 mm below the fine sand – gravelly sand interface. Tensiometers T-23, T-24, T-25, and T-26 measured matric suction in the fine sand layer 50, 150, 250, and 350 mm above the fine sand – gravelly sand interface.

### Table 2. Hydraulic properties of the materials used in the capillary barrier physical model.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>$k_s$ (m/s)</th>
<th>$\theta_s$</th>
<th>$\psi_a$ (kPa)</th>
<th>$\theta_r$</th>
<th>$\psi_w$ (kPa)</th>
<th>Curve</th>
<th>Best-fit parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine sand</td>
<td>2.7×10^{-4}</td>
<td>0.41</td>
<td>1.40</td>
<td>0.03</td>
<td>2.69</td>
<td>Drying</td>
<td>$a$ (kPa) 6.30 $n$ 0.87</td>
</tr>
<tr>
<td>Gravelly sand</td>
<td>7.6×10^{-2}</td>
<td>0.38</td>
<td>0.11</td>
<td>0.02</td>
<td>0.29</td>
<td>Wetting</td>
<td>$a$ (kPa) 4.44 $n$ 1.13</td>
</tr>
</tbody>
</table>

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interface, respectively, in cross section A. Tensiometers T-43 to T-46 were arranged as tensiometers T-23 to T-26 but in cross section B.

TDR wave guides located at points TDR-31 and TDR-71 measured the volumetric water content of the gravelly sand layer and were located 100 mm below the fine sand – gravelly sand interface. Volumetric water content in the fine sand layer was measured using TDR-32 and TDR-72 (located 100 mm above the fine sand – gravelly sand interface) and TDR-33 and TDR-73 (located 300 mm above the fine sand – gravelly sand interface).

The numerical simulation results, calculated at the same locations as the instrumentation locations, are also plotted in Figs. 16 and 17, where D and W indicate the drying and wetting paths of SWCCs used in the simulations.

Comparisons of the numerical simulation results and the experimental data show that the changes in matric suction and volumetric water content are similar. During the infiltration, the matric suction decreased while the volumetric water content increased. As expected, the numerical simulation results using the wetting SWCC and permeability function (namely, Numerical-W) showed better agreement with the experimental data for the fine sand layer during infiltration than with the simulation using the drying properties. The matric suction values reached during the numerical simulation of the infiltration process were similar to the experimental data at all measuring locations along the fine sand layer. The results from the numerical simulation using the drying SWCC and permeability function (namely, Numerical-D) showed higher matric suctions at almost all locations during the infiltration. This can be explained by considering the SWCC of the soil. For the same water content changes (from precipitation), the matric suction for Numerical-D is higher than that for Numerical-W.
In contrast to the infiltration process, changes in matric suction during the draining process (i.e., infiltration stopped) showed that the results from Numerical-D were in closer agreement with the experimental data. This phenomenon can be seen from the matric suctions at the end of the simulation (i.e., 24 h), where both the experimental data and the numerical simulation results from Numerical-D returned to the initial matric suction. This behavior was not observed in Numerical-W, since the magnitude of the matric suction at the end of simulation did not return to the initial values prior to the application of the precipitation. The wetting properties provide a better simulation of the infiltration process as the soil gains moisture, and the drying properties provide a better simulation of the drying process.

Unlike the comparison of matric suction in the fine sand, the comparison between the numerical results and the exper-
imental data in the gravelly sand layer did not show as good an agreement. It was suspected that the tensiometers cannot provide an accurate reading when used in gravelly soils, since the particle size of the gravelly sand was relatively large and full contact between the gravel and the tensiometer tip might not be achieved. The high nonlinearity of the relationship between matric suction and water content of gravelly sand could also contribute to this measuring error.

From the comparison of volumetric water contents between the experimental data and the numerical results along the fine sand layer, it was observed that in almost all measurement locations the results from Numerical-D matched better with the experimental data, both during the infiltration and during the draining processes (Fig. 17). Only at the location of TDR-72 did the results from Numerical-W and Numerical-D give the same level of agreement with the experimental data during the precipitation and draining processes, respectively. It appears that the hysteretic behavior affects the volumetric water content less than the pore-water pressures or matric suctions.

Unlike the comparison of matric suction in the gravelly sand layer, the comparison of numerical and experimental volumetric water contents showed a reasonably good agreement. The results from Numerical-D matched well with the experimental data, both during the infiltration and during the draining processes. The reason for this observation was that there was no water flow observed in the gravelly sand layer during the experiment. In other words, the gravelly sand layer experienced the drying condition during the experiment.

Figure 18 shows the variation of the flux components of the capillary barrier model as obtained from both experimental and numerical results. The rate of infiltration (i.e., input water) calculated in the Numerical-W simulation (i.e., using the wetting hydraulic properties of the soils) agreed with the experimental data. On the other hand, the rate of lateral diversion (i.e., output water) from the results of the Numerical-D simulation (i.e., using the drying soil properties) also agreed with the experimental data. The infiltration process is actually an adsorption process and should be modeled using the wetting SWCC. On the other hand, the draining process is actually a desorption process and should be modeled using the drying soil properties (i.e., Numerical-D).
6. Conclusions

6.1. Dimensions of the physical model of the capillary barrier

The objective of the first section of the numerical simulation was to observe the boundary influence on the physical capillary barrier model and obtain optimum dimensions for the model. From the results of the steady-state analysis using various shapes and dimensions for the physical capillary barrier model (Fig. 5), the boundary influence was found to be less than 200 mm from the left and right ends of the model. Therefore, for a capillary model with a horizontal length of 2 m, at least 1.6–1.7 m length of the capillary barrier model will not be influenced by the end boundary conditions.

6.2. Materials selected for the physical model of the capillary barrier

The objective of the second section of the numerical simulations was to determine the materials that should be used in the physical capillary barrier model. Three combinations of capillary barrier models were simulated using three different soils (i.e., silty sand, concrete sand, and pea gravel). The coefficient of permeability of the silty sand was found to be too low, and the particle size of the pea gravel was found to be too coarse, when they were used in the numerical model of capillary barrier. The silty sand, with a coefficient of permeability higher than that used in the numerical simulation, was selected as one of the materials for the physical capillary barrier model. Instead of pea gravel, a gravelly sand was selected as the second material for the physical capillary barrier model to reduce the possibility of the occurrence of funnel flow in the experiment. A soil similar to concrete sand (i.e., fine sand) was selected as the third material for the physical capillary barrier model.

6.3. Laboratory verification

A series of laboratory experiments was conducted on the capillary barrier model with a material combination of fine sand over gravelly sand layers. Comparisons were made between the numerical results and the experimental data for two-layered physical capillary barrier models where the soil properties were independently measured. In summary, it was found that for the fine sand layer the pore-water pressure head from the results of the numerical analysis that used the wetting SWCC and wetting permeability function matched well with the experimental pore-water pressure head during the precipitation process. Similarly, the pore-water pressure head from the results of the numerical simulation that used the drying properties matched well with the experimental pore-water pressure head obtained during the draining process. It then can be concluded that the hysteretic behavior of
the soils needs to be accounted for in the modelling of the
unsaturated flow systems to provide realistic results.

It can also be concluded that the numerical simulation that
used the drying properties can predict the magnitude of out-
flow (e.g., lateral diversion) reasonably well, and the nu-
merical simulation that used wetting properties can predict the
magnitude of inflow (e.g., infiltration) quite accurately. Fur-
ther experimental studies are presently underway to better
understand the mechanisms of capillary barriers, particularly
under the influence of high precipitation rates. Parametric
studies will also be conducted to extend the laboratory
model into full, field-scale models with various soil condi-
tions and rainfall loading to link material properties, initial
conditions, and precipitation rates with the efficiency of the
capillary barrier to act as a water-diversion barrier.

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