Numerical Simulation of Capillary Barrier System under Rainfall Infiltration in Singapore

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ABSTRACT: *Rainfall-induced slope failures commonly occur within residual soil slopes. One of the possible systems for slope preventive measure is capillary barrier system. A capillary barrier is a two-layer system of distinct hydraulic properties that is used to prevent water infiltration into the soil below the capillary barrier system by utilizing unsaturated soil mechanics principles. This paper presents the numerical simulation of the capillary barrier system as a slope preventive measure against rainfall-induced slope failures. The capillary barrier was constructed on a slope which experienced several shallow failures due to rainfall. In this study, the capillary barrier system was designed to repair the slope and at the same time to provide preventive measures for further failures due to heavy rainfall conditions of the tropics. The capillary barrier system was constructed using fine sand as the fine-grained layer and granite chips as the coarse-grained layer. Both layers were contained in geocells. The slope was instrumented with tensiometers and piezometers. The tensiometers were installed at different depths from about 0.5 m to 2.0 m below the slope surface. In addition, the adjacent original slope without the capillary barrier system was also instrumented using tensiometers in order to investigate the performance and effectiveness of the capillary barrier system in reducing rainwater infiltration and maintaining negative pore-water pressure in the slope. Results of field measurements from a one-year monitoring period and numerical analyses of the slope with and without capillary barrier system are presented in the paper. The results of numerical analyses of the slopes with and without capillary barrier system indicated that the capillary barrier system performed well in minimizing rainwater infiltration into the underlying soil layer. In addition, the numerical results showed that the factor of safety of a slope with a capillary barrier system was significantly higher than that of an original slope without the capillary barrier system. The field measurement and numerical analyses results were in good agreement, demonstrating the successful application of unsaturated soil mechanics principles in the design and construction of a capillary barrier system.*

KEYWORDS: Capillary barrier system, Fine Sand, Granite Chips, Finite Element, Rainfall

SITE LOCATION: **Geo-Database**

INTRODUCTION

Rainfall-induced landslide is one of the most common natural disasters that occur in many residual soil slopes in tropical areas. Residual soils cover about two-thirds of the land in Singapore (Pitts 1984; Rahardjo et al., 2004). The mechanism of failure for a rainfall-induced landslide can be described as follows: infiltrating water from rainfall events goes into the slope, resulting in a decrease of matric suction due to an increase in the pore-water pressures. The reduction of matric suction in unsaturated residual soils is equivalent to a decrease in shear strength of the soil along the potential slip surface (Fredlund and Rahardjo, 1993). Since rainwater infiltration into soil slopes is the major cause of rainfall-induced landslides, it is of value and interest to study preventive measures that can prevent or minimize rainwater infiltration into soil slopes.

A capillary barrier is an earthen cover system using a fine-grained layer of soil overlying a coarse-grained layer of soil (e.g. Ross 1990a,b; Stormont 1996). The principle of the capillary barrier system is based on the contrast in unsaturated hydraulic

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properties (soil-water characteristic curves and permeability functions) of both materials. Under unsaturated conditions, the difference in permeability between the fine-grained layer and the coarse-grained layer limits the downward movement of water through capillary barrier effect. The infiltrated water is then stored in the fine-grained layer by capillary forces. This infiltrated water is ultimately removed by evaporation and transpiration, lateral drainage through the slope or percolation into the underlying layer. When percolation (breakthrough) takes place, the capillary barrier no longer impedes water from infiltrating into the slope.

Previous research works have indicated the effectiveness of the capillary barrier system as a soil cover in reducing rainfall infiltration (Rahardjo et al., 2016; Tami et al. 2004; Khire et al. 2000; Morris & Stormont 1997a,b; Stormont 1996). Rahardjo et al. (2007) conducted a 1-D laboratory test to investigate the infiltration characteristics through a capillary barrier system and the storage of the fine-grained layer. The performance of capillary barrier models constructed using different materials (i.e. geosynthetic material and gravelly sand) as coarse-grained layer was also studied. Harnas et al. (2016) constructed a 2-D infiltration box to investigate the performance of capillary barrier system using fine and coarse recycled asphalt in minimizing the simulated rainwater infiltration in laboratory.

In this study, a capillary barrier system (CBS) using fine sand as the fine-grained layer and granite chip as the coarse-grained layer was designed as a slope repair and preventive measure of slopes which experienced numerous rainfall-induced slope failures in the past. The investigated residual soil slope from Bukit Timah Granite is located at Ang Mo Kio. Scars on the face of the slope indicated previous slope failures and movements. Numerical analyses were carried out on slope with capillary barrier system and the adjacent original slope without capillary barrier system to study the effectiveness and performance of the capillary barrier system as a slope cover.

METHODS AND MATERIALS

Analytical Solutions

The application of the capillary barrier as a landfill cover was initially investigated by Ross (1990b). Ross introduced the concepts of a down-dip limit and an up-dip limit which are related to the removal of moisture in the lateral direction and the no flow zone within the upper boundary of the coarse/fine interface, respectively. Ross (1990b) also established the mathematical solution for diversion capacity and diversion length of the inclined capillary barriers. The diversion capacity can be defined as the volume of water percolating laterally in the asymptotic down-dip limit which is the most that the barrier can divert. The diversion length can be defined as the length in the down-dip direction to a point where the barrier does not divert any additional water; a downward flux is experienced in both the fine and coarse soil. Ross's analytical solutions contribute significantly to the design of capillary barriers with respect to lateral diversion. Ross also observed that the horizontal flux is related to the distance above the fine/coarse interface. He proposed the mathematical relationship to predict the effective thickness of the fine layer based on the highest amount of the moisture which is laterally diverted. Ross' equations are developed based on several assumptions including semi infinitely thick soil layers, steady state infiltration, and the quasilinear approximation for the hydraulic properties of the soil.

The analytical solution from Ross (1990b) was extended by Steenhuis et al. (1991) for more accurate analyses on the diversion length of the capillary barrier. They observed that a stable wetting front does not always occur at the interface between the fine and coarse layers. In addition, the quasilinear approximation for hydraulic conductivity is also not appropriate for characterization of moisture contents near saturation. Ross' analytical solution for diversion length was revised using a different estimate of hydraulic conductivity as a function of matric suction. The modification of Ross' solution for the upper bound of the effective length of the capillary barrier is shown in Equation 1.

$$L \leq tan\phi \left[a^{-1}\left(\frac{k_s}{q} - 1\right) + \frac{k_s}{q}(h_a - h_w)\right] \tag{1}$$

where q = rate of water infiltration, ϕ = the inclination of the interface from the horizontal, h_w = water-entry value of coarse-grained layer, h_a = air-entry value of coarse-grained layer, a = sorptive number.

Numerical Analyses

The behavior of capillary barriers was studied comprehensively by Oldenburg and Pruess (1993) using numerical methods. The results of the analyses were in general agreement with the results of the analytical solution from Ross (1990b). Their results also validated the use of the quasi-linear approximation. Their numerical analyses also indicated that the breakthrough occurs gradually and the behaviour seems more complicated than the assumptions of Ross' analytical solution. Oldenburg and Pruess (1993) observed that the breakthrough is characterized by a large downward flux through the contact. This large leakage tends to dry out the fine layer, and the barrier becomes effective again in the down-dip direction.

Numerical analyses were conducted in this study to determine the thickness and length of fine- and coarse-grained materials of CBS. Rahardjo et al. (2006) concluded there are three factors that need to be considered in the selection of materials to be used as CBS materials. Those controlling factors are: the ratio of the water-entry value of the fine-grained and coarse-grained materials (ψ_m-ratio), the saturated coefficient of permeability (k_s) and the water-entry value (ψ_w) of the coarse-grained layer. The selection of CBS materials in this study was conducted based on the following criteria: ψ_m-*ratio* ≥ 10, k_s of material for the fine-grained layer must be larger than 10^{-6} m/s and ψ_w of the coarse-grained layer must be less than 1 kPa.

Composition of the Materials

Three different soils were investigated in this study, namely: fine sand for fine-grained material of CBS, granite chip for coarse-grained material of CBS and residual soil from Bukit Timah Granite at Ang Mo Kio. Based on the laboratory tests, the fine sand, granite chip and residual soil are classified as poorly-graded sand, poorly graded gravel and silty sand, respectively according to Unified Soil Classification System. The plastic limit and liquid limit of the soil are 37% and 50%, respectively. The specific gravity of the fine sand is 2.65 and the saturated coefficient of permeability is 2.7 x 10^{-4} m/s. The index properties of each soil are summarized in Table 1. In the field capillary barrier system, the fine sand and granite chip were compacted at dry densities of around 1.56 Mg/m^3 and 1.65 Mg/m^3, respectively. These dry densities were also used for laboratory tests to obtain the saturated coefficient of permeability, the soil-water characteristic curve (SWCC) and the saturated and unsaturated shear strengths of the investigated soils.

Table 1. Index properties of materials of CBS and residual soil from Bukit Timah Granite at Ang Mo Kio.

Index Properties	Fine sand	Granite chip	Residual soil
Specific gravity, G_s	2.65	2.69	2.66
Liquid Limit, LL (%)	-	-	60
Plastic Limit, PL (%)	-	-	37
Water content, w (%)	-	-	50
Dry density, ρ_d (Mg/m^3)	1.56	1.65	1.51
Gravel content (>4.75 mm; %)	5.4	98.5	0
Sand (%)	94.3	1.48	54
Fines (<0.075 mm; %)	0.3	0.02	46
Saturated coefficient of permeability, k_s (m/s)	2.7 x 10^{-4}	7.6 x 10^{-2}	6 x 10^{-6}
Unified Soil Classification System	SP (Poorly graded sand)	GP (Poorly graded gravel)	SM (Silty sand)

Tempe cell and pressure plate tests were carried out to obtain SWCC whereas multistage consolidated drained triaxial tests were performed to obtain the unsaturated shear strength parameter (ϕ_b). The permeability function was determined indirectly from the SWCC using a statistical model (Childs and Collis-George, 1955). SWCC for the CBS materials and the residual soil were fitted using the Fredlund and Xing (1994) equation (Equation 2), as presented in Figure 1.

$$\theta_w = C(\psi)\frac{\theta_s}{\left\{\ln\left[e+\left(\frac{u_a-u_w}{a}\right)^n\right]\right\}^m} \qquad (2)$$

where θ_w is volumetric water content, θ_s is saturated volumetric water content, $C(\psi)$ is correction factor, (u_a-u_w) is matric suction (kPa), e is natural number (2.71828…).

Figure 1 shows that the water-entry values of fine sand, granite chip and silty sand are 3 kPa, 0.3 kPa and 150 kPa, respectively. The water entry values of granite chip (0.3 kPa) satisfied the criteria for coarse-grained material of CBS (<1 kPa). The ratio of the water-entry value of fine sand and granite chip (10) satisfied the criteria for the ratio of the fine-grained and coarse-grained materials (≥ 10). Figure 2 presents the permeability functions of fine sand, granite chip and silty sand. The measured saturated permeability of fine sand (2.7 x 10^{-4} m/s) satisfied the criteria for the saturated permeability of fine-grained materials for CBS (>10^{-6} m/s).

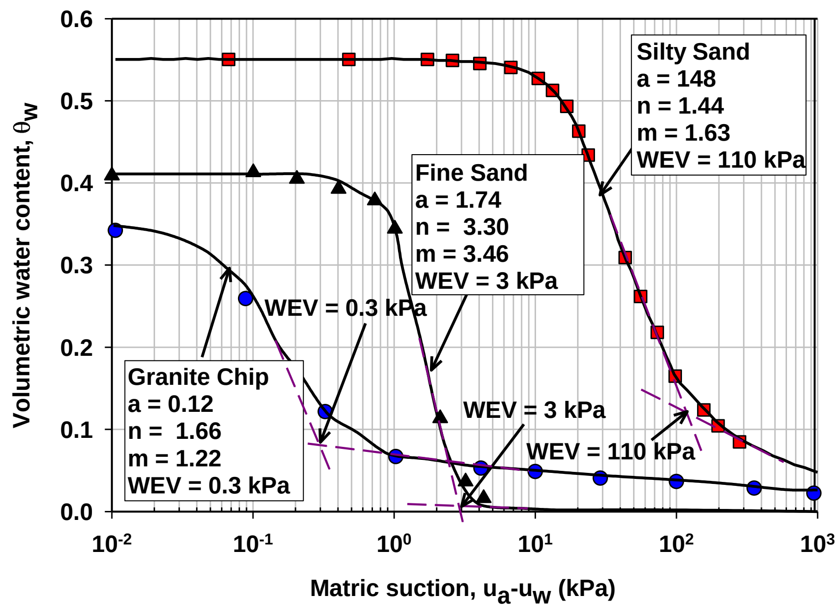

Figure 1. Wetting soil-water characteristic curves of fine sand, granite chips and residual soil at slope with capillary barrier system.

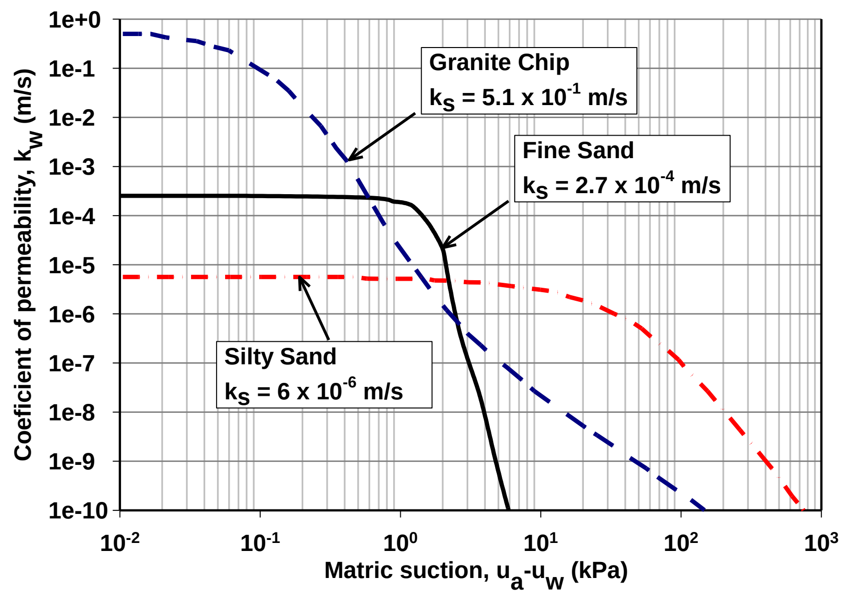

Figure 2. Wetting permeability function of fine sand, granite chips and residual soil at slope with capillary barrier system.

Diversion Length

Incorporating the properties of CBS materials into Equation 1, the lateral diversion of CBS is equal to 10.5 m. The CBS was designed with 9 m length (less than lateral diversion) in this study. The length of CBS should be less than the lateral diversion to avoid the breakthrough from the fine-grained layer to the coarse-grained layer of CBS. The thickness of fine- and coarse-grained layers in the CBS were 20 cm. Figure 3 shows the design of CBS to be used for protection of residual soil slope at Ang Mo Kio. The numerical analysis was performed to evaluate the thickness of each CBS material and the length of CBS to be constructed at Ang Mo Kio.

The numerical analyses were conducted using a finite element software, Seep/W (Geostudio, 2012a). The governing partial differential equation for transient seepage used in the numerical analysis is shown in Equation 3.

$$\frac{\partial}{\partial x}\left(k_w \frac{\partial h_w}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_w \frac{\partial h_w}{\partial y}\right) = m_w^2 \rho_w g \frac{\partial h_w}{\partial t} \quad (3)$$

where: k_w = coefficient of permeability with respect to the water phase for the x- and y-directions; h_w = hydraulic head; m_w^2 = coefficient of water volume change with respect to a change in matric suction; ρ_w = density of water; g = gravitational acceleration.

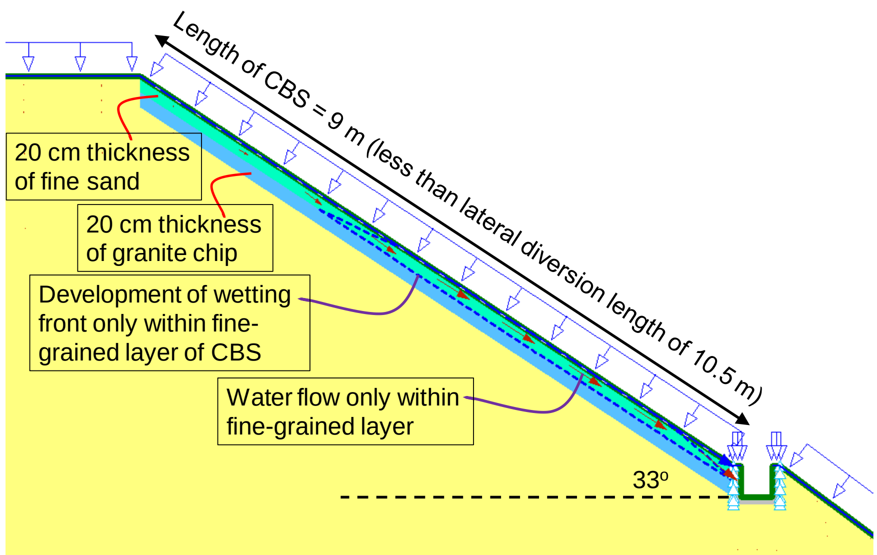

Figure 3. Thickness and lateral diversion of CBS.

The left side of the equation represents the flow of water through a soil element in the x- and y-directions based on Darcy's law, while the right side of the equation represents the change in the volume of water in the soil element based on the constitutive equation of water phase. The boundary conditions applied to the finite element model are illustrated in Figure 4. The boundary of the slope model was set at three times the height of the slope. The non-ponding condition was selected to avoid excessive accumulation of rainwater on slope surface. On the ground surface, surface runoff would occur because the increase in pore-water pressures was prevented and the maximum computed pore-water pressure was limited to zero. Nodal flux, Q, equal to zero was applied along the bottom of the slope model and along the sides of the slope model above the groundwater table to simulate a no flow zone. The constant total head, h_w, corresponding to each side was applied as the boundary along the sides of the slope model below the groundwater table. The rainfall intensity = 22 mm/h was applied to the surface of the slope as flux boundary (q) for 24 hours. This rainfall intensity was obtained based on PUB policy for design of drainage in Singapore.

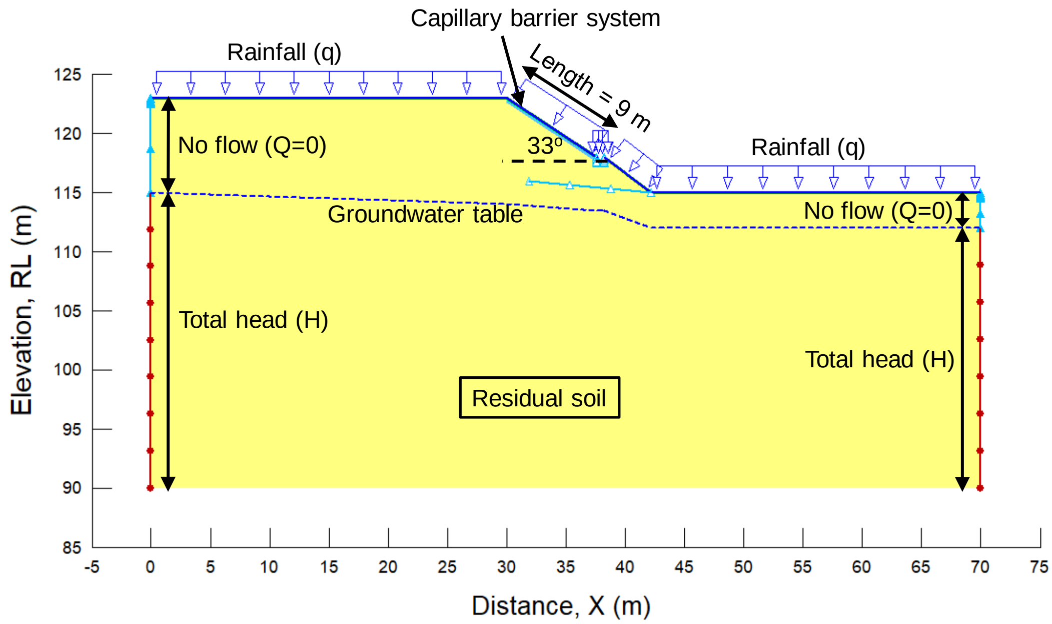

Figure 4. Numerical model for slope with CBS at Ang Mo Kio.

Capillary Barrier System for Construction in the Field

The total area of the slope at Ang Mo Kio to be covered with a capillary barrier system was approximately 140 m^2. Geodrain was laid on the soil once the slope has been trimmed to the correct depth. Steel wires were then used to secure the geodrain to the soil to prevent slippage. The purpose of the geodrain was to provide drainage if a breakthrough were to occur. Geocells were laid over the geodrain and granite chips were used to fill up the entire geocells to form the underlying coarse-grained layer as shown in Figure 5. Steel J-pins of length 550 mm were used to secure the underlying geocells onto the ground. Manual tamping was carried out to compact the coarse-grained layer to the desired density. In-situ density tests were conducted on several locations of the coarse-grained layer to ensure that the layer has been compacted to the desired density. A layer of geofabric was laid on top of the coarse-grained layer to act as a separator between the coarse-grained and the fine-grained layers. A second layer of geocells was then laid above the geofabric. Steel J-pins of length 750 mm were used to secure the overlying geocells onto the ground (Figure 5). Fine sands were used to fill up the geocells to form the fine-grained layer. Manual tamping was carried out to compact the fine-grained layer. Density tests were also conducted to ensure that the layer has been compacted to the desired density.

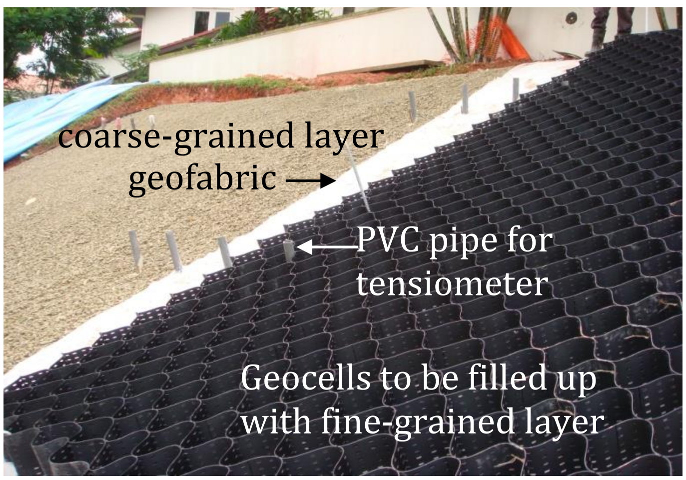

Figure 5. Laying of separator layer and fine-grained layer.

The slope constructed with the capillary barrier system lies on residual soils of Bukit Timah Granite and is located at Ang Mo Kio St. 21. The slope has a slope height of 8 m, slope angle of 37˚ at the toe of the slope and 33˚ at the repaired area (Figure 6). A total of twenty-four tensiometers were installed on the capillary barrier system and the original slope. Eight tensiometers were located on the slope with capillary barrier system (Figure 6) where tensiometers were installed near the crest of the capillary barrier system representing Row A, and the other 4 tensiometers were installed near the middle of the capillary barrier system representing Row B. Similarly, 8 tensiometers were also located on the original slope where 4 tensiometers were installed near the crest of the original slope and the remaining 4 tensiometers were installed near the middle of the original slope. Under the capillary barrier system; tensiometers installed at the crest (Row A) were named A1, A2, A3 and A4 with a spacing of 0.5 m and insertion depths of 0.69 m, 1.3 m, 1.59 m and 2.18 m, respectively. Tensiometers installed at the mid slope (Row B) were named B1, B2, B3 and B4 with a spacing of 0.5 m and insertion depths of 0.69 m, 1.27 m, 1.57 m and 2.12 m, respectively. There were three piezometers: piezometer 1, piezometer 2 and piezometer 3 located at the crest, middle and toe of the slope, respectively. A dip-meter was used to measure the level of the groundwater table.

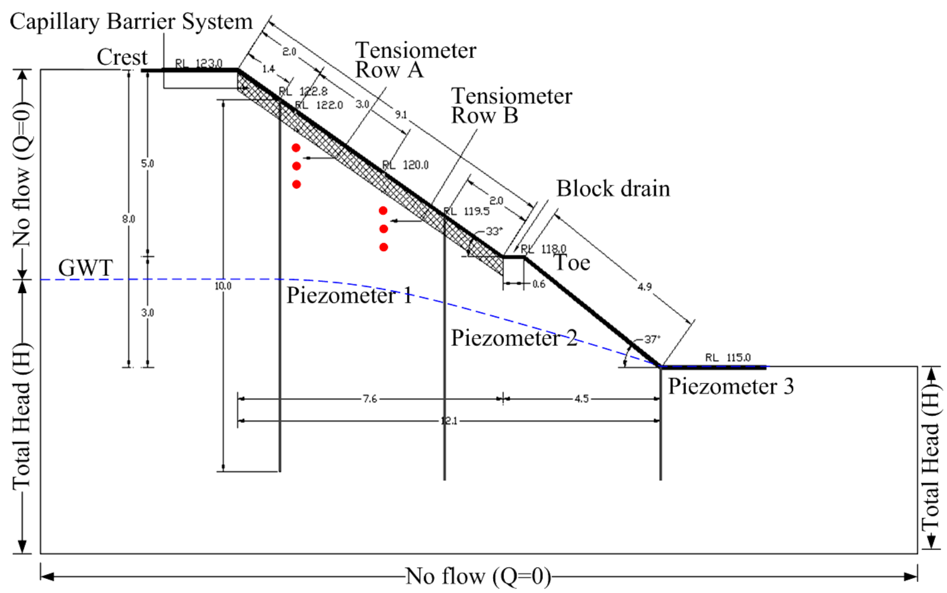

Figure 6. Schematic diagram of capillary barrier system at Ang Mo Kio.

EVALUATION OF CAPILLARY BARRIER SYSTEM IN THE FIELD

Field Monitoring

Manual monitoring of the tensiometers and piezometers was done 5 times a week (Monday – Friday) at the same time for the first month. Subsequently, manual monitoring was carried out 3 times a week (Monday, Wednesday and Friday) at the same time. Rainfall data was obtained from the nearest rainfall station which was about 0.9 km away from the site. Manual monitoring was conducted for a period of 10 months, starting from February to November 2008. Pore-water pressures measured by the tensiometers were plotted against the rainfall data. In general, pore-water pressures under the slope with capillary barrier system were able to maintain negative pore-water pressures or matric suction under rainfall conditions as illustrated in Figure 7. Although there was a rise in pore-water pressure due to percolation, the pore-water pressure was still able to maintain negative values. This could be attributed to the lateral drainage in the fine-grained layer that reduced the amount of rainfall infiltration into the soil below the capillary barrier system significantly. As a result, the presence of negative pore-water pressure contributed to the shear strength of the soil, resulting in the slopes to be less susceptible to failure. On the other hand, the pore-water pressure under the original slope was easily affected by the rainfall infiltration. Figure 8 illustrates that the pore-water pressures under the original slope followed the rise and fall of rainwater infiltration. Pore-water pressures under the original slope were unable to maintain negative values when rainfall occurred.

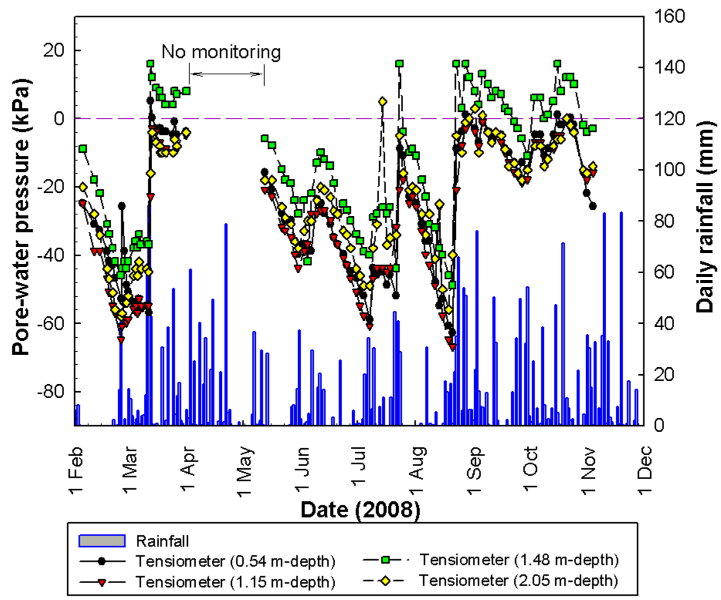

Figure 7. Pore-water pressures versus rainfall (slope with capillary barrier system).

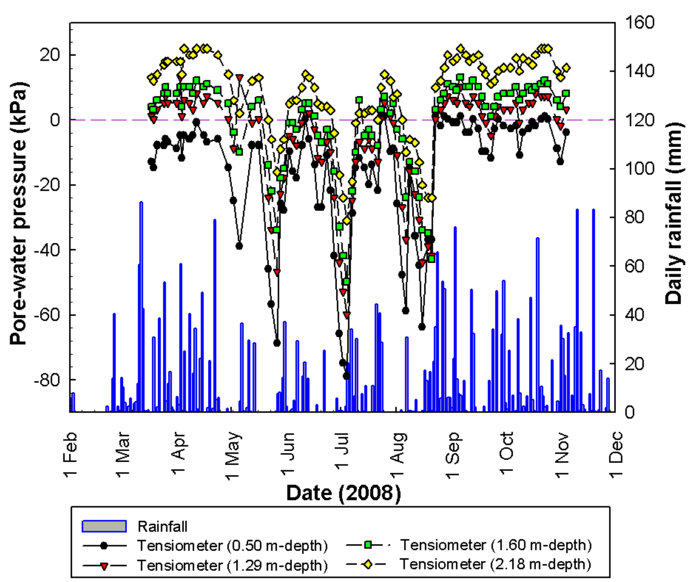

Figure 8. Pore-water pressures versus rainfall (original slope without capillary barrier system).

Seepage Analyses

Two-dimensional seepage analyses were performed using finite element software, SEEP/W (Geoslope International Pty. Ltd. 2012) to evaluate the performance of the slope with CBS at Ang Mo Kio. The boundary conditions applied to the finite element model are illustrated in Figure 3. The actual rainfall intensity and its duration were applied to the surface of the slope model as flux boundary, q. The initial condition for the slope model was generated using a spatial function based on the initially measured pore-water pressures from tensiometer and piezometer readings at Ang Mo Kio slope on 5 July 2008. The spatial function is a function in SEEP/W to assist the users in setting up the initial condition of the model according to the field condition. Transient seepage analysis was performed on the slope for a natural rainfall from 5 July to 15 July 2008 and the results were then compared with the results from the manual monitoring of pore-water pressures in the slope. The total amount of rainfall from 5 July to 15 July 2008 was 210 mm and the maximum rainfall intensity was 49.7 mm/h. The rainfall pattern from 5 July to 15 July 2008 is shown in Figure 9.

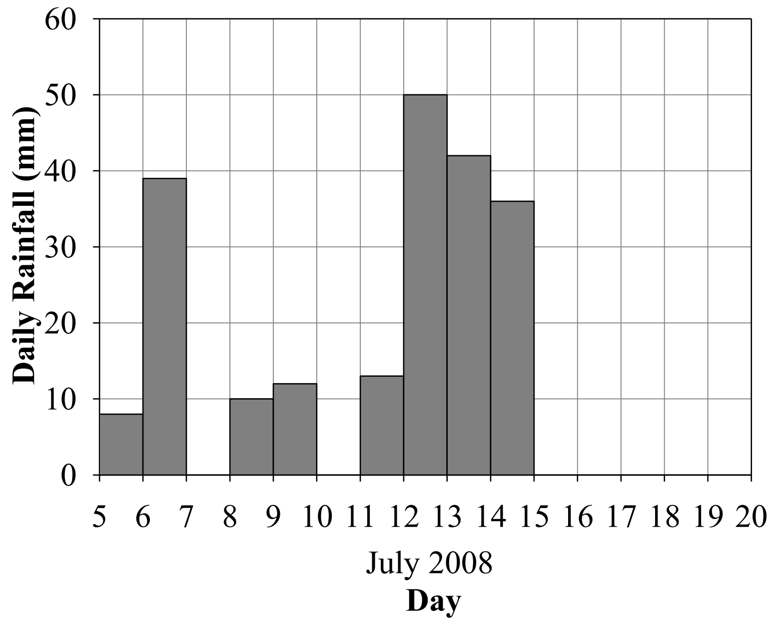

Figure 9. Rainfall data in July 2008.

The SWCCs (Figure 1) and the permeability functions (Figure 2) of the fine sand, granite chip and residual soil from Bukit Timah Granite at Ang Mo Kio were incorporated in the SEEP/W to obtain the pore-water pressure variations during dry and rainy periods. The finite element model within CBS layers surface had a mesh size of approximately 0.25 m, smaller than elements in other parts of the slope, in order to obtain accurate results within the CBS area.

Comparison of pore-water pressure profiles obtained from the numerical analyses and field measurements are presented in Figures 10a and 10b for the middle of the slope with CBS and the original slope without CBS, respectively. At the start of the analyses, the initial negative pore-water pressures within the slope with CBS (-40 kPa to -30 kPa) was higher than those within the original slope without CBS (-18 kPa to 2 kPa).

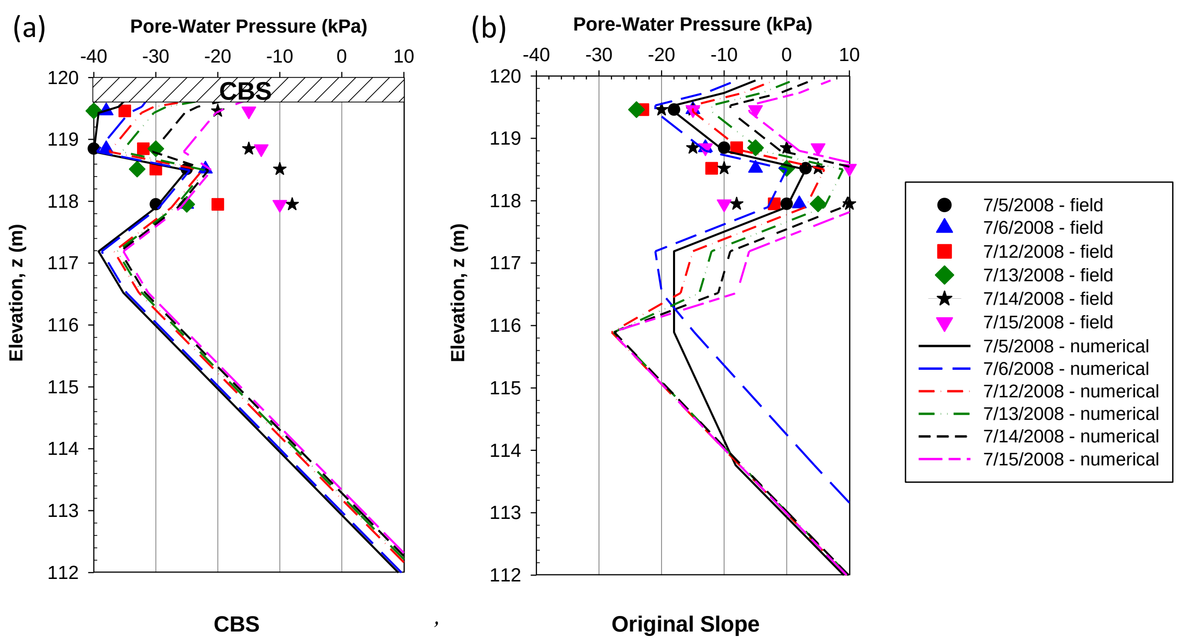

Figure 10. Comparison of pore-water pressure profiles obtained from numerical analyses and pore-water pressure data measured in the field at middle of (a) the slope with CBS and (b) the original slope.

In general, the numerical analysis shows a reasonably good agreement in the trend of the pore-water pressure profile with those obtained from field measurements. The discrepancies can be attributed to the fact that rainfall data were obtained from the nearest rainfall station and might not reflect the actual rainfalls on the slope. Figure 10 also shows that the changes of pore-water pressures within the soil layer beneath CBS materials were smaller as compared to those within the soil layer of the original slope without CBS. This phenomenon indicates that the rainwater infiltrated the soil layers of the original slope without CBS much faster than those below the CBS materials. In other words, the CBS performs well in minimizing rainwater infiltration into soil layer beneath CBS.

Slope Stability Analyses

Stability analyses of the slope with CBS and the original slope without CBS were carried out by incorporating the pore-water pressure variations from 5 to 15 July 2008. The variations in factor of safety for both slopes at Ang Mo Kio were determined using Bishop's simplified method of slices (Wright et al., 1973). Shear strength properties of the CBS materials and residual soil are summarized in Table 2. Figure 11 presents the variations of factor of safety with respect to time during and after the rainfall. It can be seen that the initial factor of safety of the slope with CBS and the original slope was 2.27 and 1.71, respectively. Although low intensity of rainfall (100 mm/day) occurred on 5 July 2008, the factor of safety for both slopes showed increasing trends from 5 to 6 July 2008. This might be attributed to the long dry period prior to the rainfall event. Therefore, the factor of safety is still in the upward trend until heavy rainfall occurred on 6 July 2008. The factors of safety of the slope with CBS remained constant whereas the factors of safety of the original slope without CBS varied during periods of small rainfalls between 7 and 12 July 2008. Figure 11 also indicates that the factor of safety of the original slope without CBS decreased whereas the factor of safety of the slope with CBS remained constant after the heavy rainfall on 6 July 2008. In addition, the factor of safety of the original slope decreased more significantly as compared to that of the slope with CBS during periods of heavy rainfalls from 12 to 15 July 2008. The results from stability analyses indicated that the CBS performed well in minimizing rainwater infiltration into soil layer.

Table 2. Shear strength properties of CBS materials and residual soil from Bukit Timah Granite at Ang Mo Kio.

Properties	Fine sand	Granite chip	Residual soil
Effective cohesion, c' (kPa)	0	0	2
Effective friction angle, ϕ' (°)	34	36	30
ϕ^b (°)	15	17	18

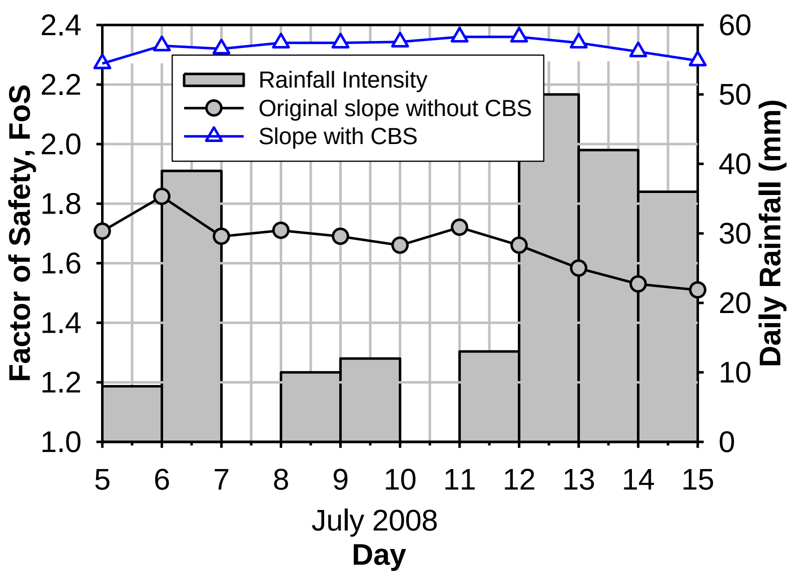

Figure 11. Factor of safety variations during and after rainfall event from 5 – 15 July 2008.

CONCLUSIONS

The conclusions of this study are as follows:

1. The design of CBS layers depends on the selection of materials and geometry of slope utilizing the principles of the unsaturated soil mechanics.

2. Based on the pore-water pressure data measured by the tensiometers, the capillary barrier system was able to reduce the rainwater infiltration, therefore maintaining the negative pore-water pressures in the unsaturated zone.

3. The numerical results from seepage analyses were able to simulate the field measurement reasonably, demonstrating the application of unsaturated soil mechanics principles in modelling capillary barrier system as a slope protection measures.

4. The stability analyses results indicated that the factor of safety for slope with CBS can be maintained, causing the slope to be less susceptible to failure.

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