Performance of an instrumented slope under a capillary barrier system

Rahardjo, Harianto; Hua, Chai Juay; Leong, Eng Choon; Santoso, Vera Amalia

2011

Rahardjo, H., Hua, C. J., Leong, E. C., & Santoso, V. A. (2011). Performance of an instrumented slope under a capillary barrier system. Proceedings of the fifth International Conference of Unsaturated Soils, Barcelona, Spain, pp.1279-1284.

<https://hdl.handle.net/10356/93920>

<https://doi.org/10.1201/b10526-200>

© 2011 Taylor & Francis Group. This is the author created version of a work that has been peer reviewed and accepted for publication by Unsaturated Soils, Taylor & Francis Group. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [DOI: <http://dx.doi.org/10.1201/b10526-200>].

Downloaded on 26 Apr 2023 23:18:03 SGT

Performance of an Instrumented Slope under a Capillary Barrier System

H. Rahardjo , C.J. Hua, E.C. Leong, & V.A. Santoso

School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

ABSTRACT: A capillary barrier is a two-layer system of distinct hydraulic properties that is used as a cover system. The distinct hydraulic properties prevent water infiltration into the soil below the capillary barrier system by utilizing unsaturated soil mechanics principles. This paper illustrates the application of the capillary barrier system as a slope cover to prevent rainfall-induced slope failures. The capillary barrier was constructed on a slope which experienced a shallow slip surface. In this study, the capillary barrier system was designed as a cover system for slopes with a steep slope angle under 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. The measurement results showed that the capillary barrier system was effective in maintaining the negative pore-water pressures during rainfalls. Results of field measurements and numerical analyses are presented in the paper. The measurement and numerical results were in agreement, demonstrating the use of unsaturated soil mechanics principles in capillary barrier system.

Keywords: capillary barrier, pore-water pressure, matric suction, residual soil, slope instrumentation

1 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). 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 (Brand 1982). 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 properties (soil-water characteristic curves and permeability functions) of each material. 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 (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. Krisdani et al. (2006) also constructed a capillary barrier system soil cover using fine sand as the fine-grained layer and geosynthetic material as the coarse-grained layer on a cut slope which experienced a shallow slip.

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 constructed on a slope which experienced numerous rainfall-induced slope failures in the past. This slope with capillary barrier system and the adjacent original slope without capillary barrier system were monitored using tensiometers and piezometers to study the effectiveness and performance of the capillary barrier system as a slope cover.

2 CONSTRUCTION SEQUENCES AND FIELD INSTRUMENTATION

A slope which experienced numerous rainfall-induced slope failures was selected for the construction of CBS. Scars on the face of the slope indicated previous slope failures and movements. The total area of the slope to be covered with a capillary barrier system was approximately 140 m². 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 1. 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 (Fig. 1). 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.

Twenty four tensiometers were installed on the capillary barrier system, with 8 tensiometers being located on the capillary barrier system with topsoil and cow grass, 8 tensiometers on the capillary barrier system without topsoil and cow grass (Fig. 2),

Figure 1. Laying of separator layer and fine-grained layer.

Figure 2. Capillary barrier system without topsoil and cow grass.

Figure 3. Schematic diagram of capillary barrier system without topsoil and cow grass.

and 8 tensiometers on the original slope. From the 8 numbers of tensiometer for each area; 4 numbers of tensiometers were installed near the crest of the capillary barrier system representing Row A, and the other 4 tensiometers installed near the middle of the capillary barrier system representing Row B. Under the capillary barrier system with topsoil and cow grass; 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.

Similarly, under the capillary barrier system without topsoil and cow grass, tensiometers installed at the crest (Row A) were named A5, A6, A7 and A8 at 0.5 m spacing and insertion depths of 0.54 m, 1.15 m, 1.48 m and 2.05 m, respectively. Tensiometers installed at the mid slope (Row B) were named B5, B6, B7 and B8 at 0.5 m spacing and insertion depths of 0.59 m, 1.2 m, 1.5 m and 2.1 m, respectively. Under the original slope, tensiometers installed at the crest (Row A) were named A9, A10, A11 and A12 at 0.5m spacing and insertion depths of 0.5 m, 1.29 m, 1.6 m and 2.18 m, respectively. Tensiometers installed at the mid slope (Row B) were named B9, B10, B11 and B12 at 0.5 m spacing and insertion depths of 0.65 m, 1.31 m, 1.6 m and 2.18 m, respectively.

There were three numbers of 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 groundwater table.

3 FIELD PERFORMANCE RESULTS

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 4. 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 5 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.

Based on the manual monitoring, the water level in piezometer 3 was always at the toe of the slope as plotted in Figure 6. The graph of piezometer readings versus rainfall data (Fig. 6) illustrates that the pattern of the piezometer readings followed exactly the pattern of the rainfall data.

Figure 4. Pore-water pressures versus rainfall (slope with capillary barrier system).

Figure 5. Pore-water pressures versus rainfall (original slope).

Figure 6. Groundwater level versus rainfall.

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

Figure 8. Pore-water pressures versus groundwater level (original slope).

A rise in the intensity of rainfall was accompanied by a rise in the groundwater level as illustrated in Figure 6. It was suspected that during rainfall events, there was an internal water flow from the uphill part of the slope, contributing significantly to the rise of groundwater level. As a result, the pore-water pressure variations in both slopes with and without capillary barrier system were controlled by the fluctuations in groundwater level. In addition, the pore-water pressure variation in the original slope was also affected by rainfall infiltration from the slope surface. However, this was not the case for the slope with capillary barrier since the capillary barrier system minimized rainfall infiltration into the underlying soils. Therefore, during rainfalls, the pore-water pressures in the slope with capillary barrier system (Fig. 7) were generally lower than the pore-water pressures in the original slope (Fig. 8), demonstrating the effectiveness of capillary barrier system in minimizing rainfall infiltration into the slope.

4 NUMERICAL STUDIES

Two-dimensional seepage analyses were performed using finite element software, SEEP/W (Geoslope International Pte. Ltd. 2004).

4.1 Modelling of Slope with Capillary Barrier System

4.1.1 Slope Geometry

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 (Fig. 3). Test results indicated that the water content, specific gravity, liquid limit, and plastic limit range of the residual soil are 35~40%, 2.64~2.68, 53~66%, and 36~38%, respectively. The slope consisted of clayey silt with a unit weight of 20 kN/m³, an effective cohesion of 8 kPa, an effective friction angle of 33°, and a ϕ^b angle of 25°.

4.1.2 Soil Properties

Figures 9 and 10 show the soil-water characteristic curves (SWCCs) and permeability functions, respectively, for fine-grained, coarse-grained, and residual soils at Ang Mo Kio St. 21. The SWCC of the soils in the slope was best-fitted using Fredlund & Xing equation (1994):

$$\theta_w = C(\psi) \frac{\theta_s}{\left\{ \ln \left[e + \left(\frac{u_a - u_w}{a} \right)^n \right] \right\}^m} \quad (1)$$

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...). Correction factor is taken as 1 as suggested by Leong & Rahardjo (1997), while fitting parameters fitted are $a = 147.88$ kPa, $n = 1.44$, and $m = 1.63$.

The SWCCs of the fine sand and granite chips in Ang Mo Kio St. 21 slope were estimated using Fredlund & Xing equation (1994). The fitting parameters for the fine sand are $a = 1.74$ kPa, $n = 3.30$, $m = 3.6$, and those for the granite chip are $a = 0.12$ kPa, $n = 1.66$, $m = 1.22$. The measured saturated permeability of the clayey silt soil, fine sand, and granite chip of Ang Mo Kio St. 21 slope were 6×10^{-6} , 2.7×10^{-4} , and 7.6×10^{-2} m/s, respectively.

4.1.3 Boundary Conditions

The boundary conditions applied to the finite element model are illustrated in Figure 3. The boundary of the slope model was set at three times the height of the slope. The non-ponding condition was

Figure 9. Soil-water characteristic curves for fine-grained, coarse-grained and residual soils at slope with capillary barrier system.

Figure 10. Permeability functions for fine-grained, coarse-grained and residual soils at slope with capillary barrier system.

Figure 11. Rainfall data on 26 May 2008.

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 actual rainfall intensity and its duration were applied to the surface of the slope model as flux boundary, q .

Transient seepage analysis was performed on the slope for a natural rainfall from 26 May to 13 June 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 26 May to 13 June 2008 was 157.6 mm and the maximum rainfall intensity was 33.6 mm/h. The rainfall pattern from 26 May to 13 June 2008 is shown in Fig. 11.

4.1.4 Seepage Analysis Results

Comparison of pore-water pressure profiles obtained from the numerical analyses and field measurements are presented in Figures 12 and 13 for the crest and the middle of the slope, respectively. At the start of the analyses, the groundwater table (measured by piezometers) was significantly high due to the previous rainfall events and a suspected source of water flow from the uphill part of the slope. For this reason, the initial groundwater table before applying the actual rainfalls for the period of analysis (i.e. 26 May to 13 June 2008), was not in a steady state condition. This explains the reason for the more negative pore-water pressures at elapsed times greater than zero (i.e. up to 4 days) as depicted in both numerical results and field measurements. The problem of high water table during rainfalls was later resolved by installing one row of horizontal drains near the toe of the slope on 24 November 2008.

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. The problem was overcome later by installing a rain gauge on the slope in May 2009 to measure the actual rainfalls on the slope. In addition, the SWCCs used in the analyses were estimated from the grain size distribution.

5 CONCLUSIONS

Based on the pore-water pressure data measured by the tensiometers, the capillary barrier system constructed on the slope was able to reduce the rainwater infiltration, therefore maintaining the negative pore-water pressures in the unsaturated zone. As a result, the shear strength in the unsaturated zone of

Figure 12. Comparison of pore-water pressure profiles obtained from numerical analyses and pore-water pressure data measured in the field near at the crest of the slope from the beginning of rainfall ($t=0$) until the end of rainfall ($t=18$ days) on 26 May 2008.

Figure 13. Comparison of pore-water pressure profiles obtained from numerical analyses and pore-water pressure data measured in the field at middle of the slope from the beginning of rainfall ($t=0$) until the end of rainfall ($t=18$ days) on 26 May 2008.

the slope with capillary barrier system can be maintained, causing the slope to be less susceptible to future instabilities. However, further measurements are required to have a better understanding of the performance of capillary barrier system as a slope cover including the effect of fluctuation in groundwater level on the effectiveness of the capillary barrier. The measurement results showed that the capillary barrier system was effective in maintaining the negative pore-water pressures during rainfalls. The numerical results 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.

ACKNOWLEDGEMENT

The work described in this paper is supported by the Housing & Development Board and Nanyang Technological University, Singapore.

REFERENCES

- Brand, E.W. 1982. Analysis and Design in Residual Soils, in *Proc. ASCE Specialty Conf. Eng. Ad Construction in Tropical and Residual Soils (Honolulu, HI)*: 89-143.
- Fredlund, D.G. & Xing, A. 1994. Equations for the Soil-Water Characteristic Curve, *Canadian Geotechnical Journal* 31: 533-546.
- Geoslope International Pte. Ltd. 2004. SEEP/W User's Guide for Slope Stability Analysis. Geoslope International Ltd., Calgary, Alberta, Canada.
- Khire, M., Benson, C., & Bosscher, P. 2000. Capillary Barriers: Design Variables and Water Balance, *J. of Geotech and Geoenviron. Engrg.*, ASCE 126(8): 695-708.
- Krisdani, H. 2006. The Use of Residual Soil and Geosynthetic Material in Capillary Barrier System. PhD thesis, School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.
- Leong, E.C. & Rahardjo, H. 1997. A Review on Soil-Water Characteristic Curve Equations, *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, December, 123(12): 1106-1117.
- Morris, C.E. & Stormont, J.C. 1997a. Capillary Barriers and Subtitle D Covers: Estimating Equivalency, *J. of Envir Engrg.*, ASCE 123(1): 3-10.
- Morris, C.E. & Stormont, J.C. 1997b. Capillary Barriers and Subtitle D Covers: Estimating Equivalency – Closure, *J. of Envir Engrg.*, ASCE 123(1): 3-10.
- Pitts, J. 1984. A Review of Geology and Engineering Geology in Singapore, *Quarterly Journal of Engineering Geology* 17: 93-101.
- Rahardjo, H., Krisdani, H., & Leong, E.C. 2007. Application of Unsaturated Soil Mechanics in Capillary Barrier System, in *Proc. 3rd Asian Conf. on Unsaturated Soils*: 127-137.
- Ross, B. 1990a. Reply to 'Comment on the Diversion Capacity of Capillary Barriers' by T.S. Steenhuis nad J.Y. Parlange, *Water Resources Research* 27(8): 2157.
- Ross, B. 1990b. The Diversion Capacity of Capillary Barriers, *Water Resource Research* 26(10): 2625-2629.
- Stormont, J.C. 1996. The Effectiveness of Two Capillary Barriers on a 10% Slope, *Geotechnical and Geological Engrg.* 14: 243-267.
- Tami, D., Rahardjo, H., Leong, E.C., & Fredlund, D.G. 2004. A Physical Model for Sloping Capillary Barriers, *Geotechnical Testing Journal*, ASTM 27(2): 173-183.