THE EFFECT OF CAPILLARY BARRIER ON MITIGATING RAINFALL-INDUCED SLOPE FAILURE

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ABSTRACT: Soil cover with capillary barrier layer is a potential method for limiting the deep infiltration of rain water into soil mass. The method is widely applied in the construction of landfill and lately was considered for mitigating rainfall induced slope failure. This paper presents the results of numerical analysis carried out using SEEP/W to study the effect of changing permeability on the effectiveness of soil cover as capillary barrier. Analyses were performed for different configurations of where transport layer was placed on original soil and overlaid by compacted soil cover. The slope was subjected to various rainfall intensities obtained from Intensity-Duration-Frequency (IDF) curve of Johor Bahru. The properties of original soil used for the analysis were derived from the results of laboratory test on sandy silt soil found at Universiti Teknologi Malaysia (UTM) Skudai Campus. Concrete sand was used for transport layer while compacted original soil was used for slope cover system. It is assumed that all layers are completely separated and both intrusion of coarse particle and pumping of fine particles do not occur. Numerical analysis shows that the configuration used in this study is able to inhibit deep infiltration of rainwater into slope. The optimum configuration comprises 25 cm soil cover 5 cm transport layer.

Keyword : Rainfall-induced slope failure, Capillary barrier, Numerical simulation

1. INTRODUCTION

It has been well accepted that rainfall infiltration impairs slope stability. Shallow slope failures are dominated by the combination of transient pore pressure in response to rainfall infiltration and soil erosion.

The rainfall infiltration produce downward flux and change the water content and pore water pressure gradient with depth. The in an increase of water content of the soil increases the driving force and together with the change in pore water pressure, it reduces the shear strength hence the resisting force in sloping ground. The response of the material involved is largely dependent on the ability of soil to retain water in its mass (soil water characteristics) and the ability of soil to transmit water or air through its pores (permeability). Both properties are related to soil suction (Fredlund and Rahadjo, 1993). The relationship between volumetric water content (θ) and matric suction (ψ) is presented as soil water characteristic curve (SWCC) while the relationship between permeability and soil suction is presented as hydraulic conductivity curve or permeability function. Maximum permeability is reached when the soil becomes saturated. The importance of permeability in the suction distribution was pointed out by Pradel and Raad (1993).

Slope resistance against shallow failure can be enhanced by limiting the infiltration of the rainwater into the slope simply placing impermeable material or by applying bioengineering method. A more recent approach was by utilizing the capillary barrier. The effect of capillary barrier on controlling the rainfall infiltration has been studied by several researchers (e.g. Stormont *et al.* 1999, and Khire *et al.* 2000) for the purpose of the design of as soil covers for landfill and mining waste. The possibility of utilizing the capillary barrier on slope was studied through physical model and numerical analysis by Tami *et al.* (2004) as well as Parent and Cabral (2005).

Capillary barrier consists of a finer grained layer overlying a coarse grained layer. There are two types of capillary barrier: without transport layer and with transport layer. The first type is generated by placing a fine grained soil on top of coarse grained soil layer. The second type is where a layer with higher permeability is sandwiched between soil cover and original soil (Fig 1).

Rainwater infiltration through the fine grained layer will enter the coarser soil only when the matric suction at the surface of the coarser layer decreases to the value near the water entry point (Stormont and Anderson, 1999). Since the water entry point of coarse grained soil occurs at much lower suction (Fig. 3), significant amount of water need to accumulate at the interface before it can pass through the coarse layer. The contrast in unsaturated hydraulic properties between the finer and coarser-grained layers in a capillary barrier forms the hydraulic impedance that limits downward water movement (Khire *et al*, 2000). Previous studied showed that effect of capillary barrier reaches optimum when the upper layer is designed at a specific thickness and the difference in the permeability of surface layer and the bottom layer is about 3 to 5 orders of magnitude (Rahardjo *et al*, 2006).

The objective of this study is to evaluate the effect of capillary barrier with transport layer on the rainfall infiltration through sloping ground by numerical analysis using Seep/W program from GeoStudio (GEO-SLOPE International Ltd, 2007). In this analysis, all layers are assumed to be completely separated and both intrusion of coarse particle and pumping of fine particles do not occur.

2. CONFIGURATION AND MATERIAL PROPERTIES

Fig. 1 shows the configuration of soil cover system used in this study which consists of compacted soil, transport layer and original soil.

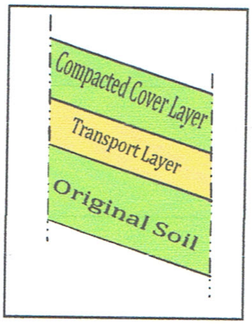


Fig. 1 Soil-cover system configuration used in this study

2.1 Soil Properties

The properties of original soil used for the analysis were derived from the results of laboratory test on soil samples collected at a location in Universiti Teknologi Malaysia (UTM) Skudai Campus. The soil is classified as highly plastic silt with sand (MHS) according to BS standard. The falling head test gives a saturated permeability of the original soil 3.25 × 10^{-8} m/s.

Concrete sand is used as transport layer. The properties of concrete sand were derived from Tami *et al.* (2004). Concrete sand was classified as uniform graded sand (SPu) according to BS standard. The concrete sand poses the lowest volumetric water content but highest permeability. The saturated permeability of concrete sand is 2.4 × 10^{-4} m/s.

Surface cover is naturally subjected to compaction; therefore compacted original soil is used. Marsilia *et. al.* (1998) indicated that compaction caused a significant increase in bulk density and decrease in saturated hydraulic conductivity and water retention curve (SWCC). Furthermore, Zhang *et al*. (2006) showed that the saturated hydraulic conductivity decreases as much as one order of magnitude for 20% increase in bulk density. Zhang *et al.* (2006) as well as Gao *et al.* (2008) showed a change in SWCC curve only in terms of volumetric water content but the shape stays the same. Since compaction of the soil used in this study induced only a slight change in bulk density (from 16.76 kN/m^3 to 17.24 kN/m^3), similar SWCC and hydraulic conductivity curve were employed. Adjustment was made only for the saturated permeability which was reduced by one order of magnitude to 3.25 × 10^{-9} m/s.

Fig. 2 shows the particle size distribution (PSD) of the original soil and concrete sand while Fig. 3 and 4 shows the SWCC and the hydraulic conductivity function of the soil respectively.

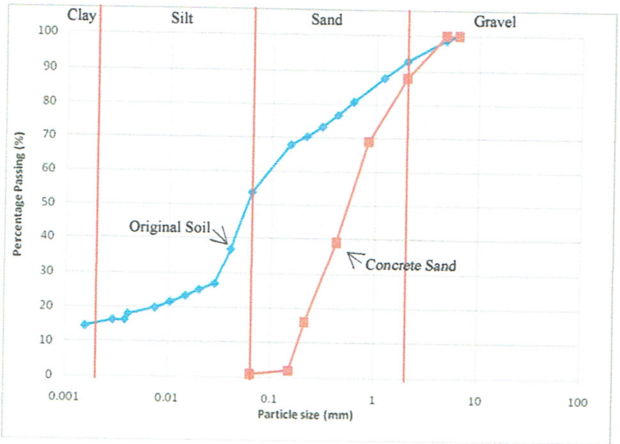


Fig.2 PSD of original soil and concrete sand

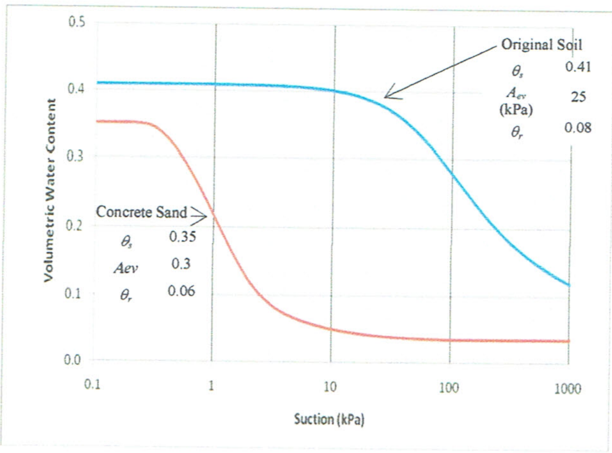


Fig. 3 SWCC of original soil and concrete sand

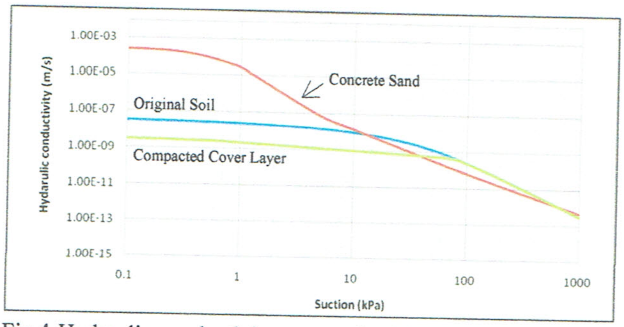


Fig.4 Hydraulic conductivity curve of original soil, concrete sand and compacted soil

3. FINITE ELEMENT MESH

The numerical model represents an imaginary slope stood at an inclination of 18°. The mesh comprises 2662 nodes and 2520 quadrilateral elements. Very fine first order quadrilateral elements (0.005 × 2 m) were designed for cover system. Quadrilateral elements (0.005 × 2 m) were used for the capillary barrier, quadrilateral elements (0.005 × 2 m) were used below the capillary barrier to depth 0.50m. Larger size quadrilateral elements (0.5 × 2 m) were used below 0.50m depth.

Four-noded elements were assigned to the entire mesh, except for the infinite elements on the left and right edges in which eight-noded quadrilaterals were required to form a decay function. Fig. 5 shows the element mesh designed for the numerical model to produce satisfactory result within a reasonable processing time.

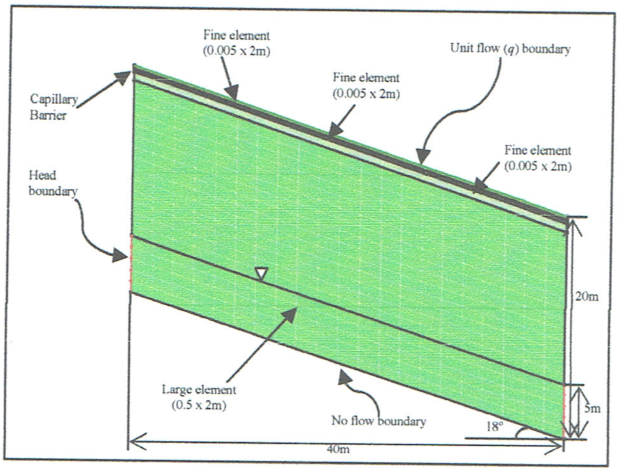


Fig. 5 Finite element mesh and boundary conditions for numerical simulation

A hydrostatic initial condition was established at the beginning of the transient seepage analysis. The water table assigned at 15 m below the ground surface therefore the negative pore-water pressure at the surface was almost 150 kPa.

The left and right edges above the water table were specified as a no flow boundary ($Q = 0$), while the edges below the water table were assigned as head boundary equal to the elevation of the water table. These boundary conditions might not simulate the actual conditions in a soil slope, but should give reasonable pore-water pressure distribution if the horizontal boundary is set at a sufficient distance to avoid saturation of the slope model due to the rise of the water table. Besides, it should be noted that the no flow boundary above the water table has forced the water flowed vertically into the soil, hence enabled the two-dimensional infinite model to be approximated to one-dimensional analysis (only the vertical flow was studied). On the exposed sloping surface, infiltration due to rainfall was simulated by applying a unit flux *(q)* with varying intensity. The bedrock located at 20 m from the ground surface was assumed to be an impermeable layer.

4. ANALYSIS

The numerical analysis was performed for five configurations of soil cover system. In this case, the thickness of transport layer was set constant at 50 mm while the thickness of compacted soil varies from 150 to 350 cm with interval of 50 mm as shown in Table 1.

Table 1 Parametric study

Layer	Properties	Thickness
Cover Layer	Compacted soil $k_{sat} = 3.25 \times 10^{-9}$ m/s.	150,200,250, 300,350 mm
Transport Layer	Concrete Sand (SPu) $k_{sat} = 2.4 \times 10^{-4}$ m/s.	50 mm
Original soil	Highly plastic silts with sand (MHS) $k_{sat} = 3.25 \times 10^{-8}$ m/s.	20 m or infinity

The slope is subjected to a constant rainfall intensity of 6.08×10^{-7} m/s for a duration of 1,2,3,4,5,6,and 7 days. The extreme rainfall intensity used for detail analysis, were 1-day intensity (2.53×10^{-6}m/s) for duration 3, 6, 9, 12, 15, 18, 21 and 24 hours, and 1-hour intensity (2.46×10^{-5}m/s) for duration 10, 20, 30, 40, 50 and 60 minutes. This rainfall intensity and duration is selected based on the intensity – duration - frequency (IDF) of ten-year return period for Johor Bahru (Gofar and Lee, 2008) as shown in Fig. 6.

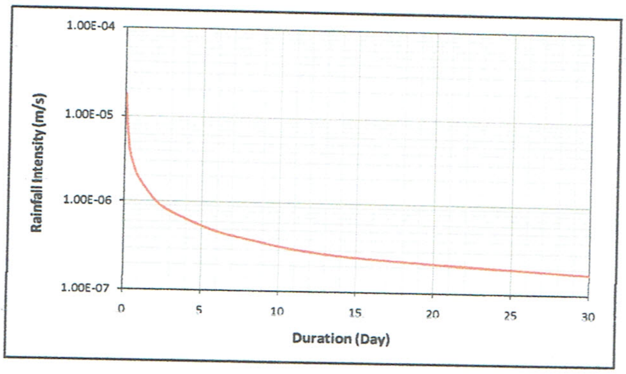


Fig.6 Intensity-Duration-Frequency (IDF) curve (Johor Bahru)

5. RESULTS AND DISCUSSION

Fig. 7 shows the advancement of rainfall infiltration and suction distribution in soil when subjected to infiltration of 6.08×10^{-7} m/s for a duration of 1,2,3,4,5,6,and 7 days. The figure indicates that the wetting front reaches 1m depth after only four days and 2m deep after 7 days.

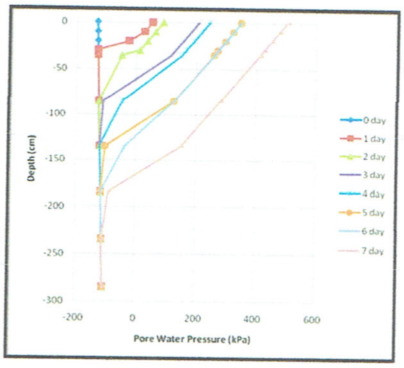
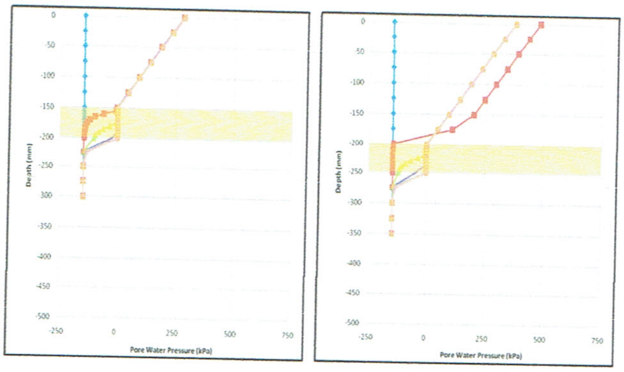
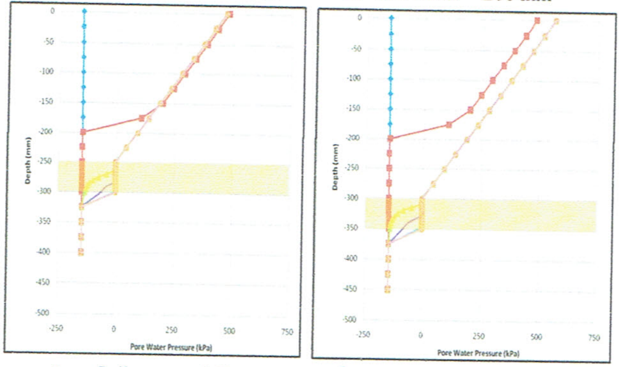


Fig. 7 Advancement of wetting front in original soil

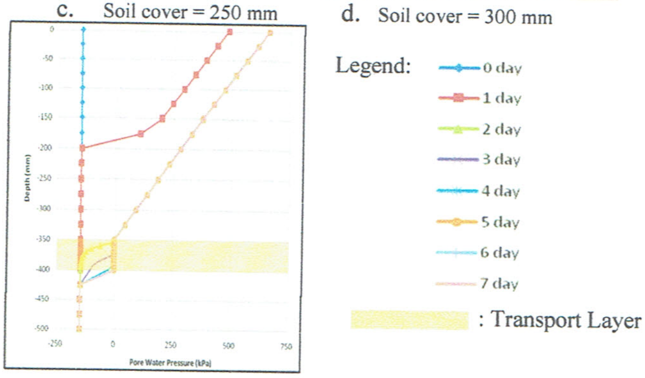
The presence of transport layer significantly reduces the wetting front (Fig. 8a-e). Fig 8a and 8b shows that for thickness of compacted soil 150 and 200 mm, the water seeps through the transport layer after day 3. However, when the thickness of soil cover is increased to 250mm, all water was retained and diverted through the transport layer even after 7 days. This phenomenon is shown in detail in Fig.9 (a-b) for thickness of surface layer 200mm and 250mm respectively. It is clear that for surface layer of 200mm, some amount of water still percolates into original soil after day 3, but when the surface layer is increased to 250 mm, no water is percolating to the original soil. No significant change in the mechanism when the thickness of soil cover was increased to 300 and 350mm. Thus, the configuration of 250mm soil cover and 50mm transport layer can be referred as the optimum configuration.



a. Soil cover = 150 mm b. Soil cover = 200 mm

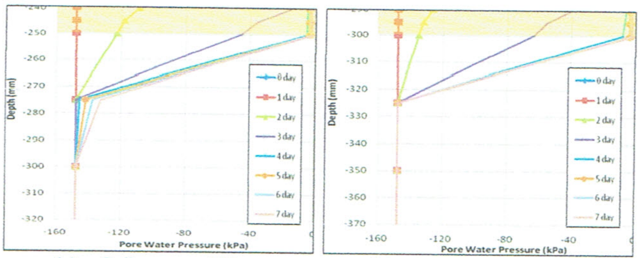


c. Soil cover = 250 mm d. Soil cover = 300 mm



e. Soil cover = 350 mm

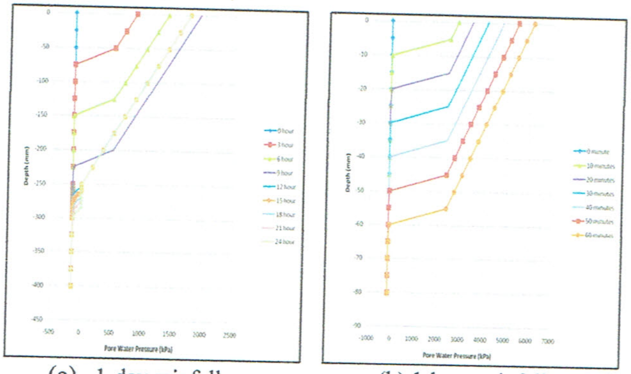
Fig.8 Effect rainfall duration on suction distribution for different configuration of compacted soil cover and transport layer.



(a) Soil cover = 200 mm (b) Soil cover = 250 mm

Fig.9 Effect rainfall duration on suction distribution at original soil under transport layer.

Detailed study was made for the optimum configuration of 250mm soil cover and 50 mm transport layer subjected to 1-day rainfall infiltration (2.53×10^{-6}m/s) for duration 3, 6, 9, 12, 15, 18, 21 and 24 hours. The result shown in Fig. 10a indicates that higher intensity rainfall does not influence the wetting front even until 24 hour. The highest intensity rainfall of 2.46×10^{-5}m/s applied for duration of 10, 20, 30, 40, 50 and 60 minutes resulted in shallow wetting front of 60mm only (Fig. 10b). The rainfall does not even reach the transport layer.



(a) 1-day rainfall (b) 1-hour rainfall

Fig.10 Effect rainfall on wetting front and suction distribution

6. SUMMARY AND CONCLUSION

The mechanism of rainfall infiltration through soil with capillary barrier was studied numerically by seep/w (GEO-SLOPE International Ltd, 2007). In this study, the thickness and properties of transport layer is constant i.e. the permeability of transport layer is four order of magnitude higher than the original soil and 5 order of magnitude higher than the compacted surface layer. The influence of the surface material was evaluated by varying the thickness from 150 mm to 350 mm with interval of 50 mm. The slope is subjected to 1 hour, 1 day, and 7 day extreme rainfall from IDF curve of Johor Bahru.

The study showed that the combinations of surface cover and capillary barrier inhibit the rainfall infiltration in sloping ground through the following mechanisms:

1. Surface layer having low saturated permeability will generate more runoff, hence; less infiltration and less percolation into soil mass.
2. Thicker surface layer generally yield in less percolation because of greater storage capacity therefore: the thickness of surface layer should be selected carefully. Analysis showed that the minimum thickness of surface layer is 250 mm.
3. The thickness of transport layer is less important because its effectiveness is controlled by the permeability. Analysis showed that 50 mm thick coarser layer is adequate to divert most water from infiltrating into the original soil mass.

7. REFERENCE

Fredlund, D.G. and Rahardjo, H. (1993). *Soil Mechanics for Unsaturated Soils*. New York: John Wiley & Sons, Inc.

Gao, L.-X., Luan, M.T., Yang, Q. (2008) Experimental Study on Permeability of Unsaturated Remolded Clay, *Electronic Journal of Geotechnical Engineering*, 14 E.

GEO-SLOPE International Ltd. (2007). SEEP/W for finite element analysis, version 7. Calgary, Alta., Canada. GEO-SLOPE International Ltd.

Gofar, N., Lee, M.L., 2008. Extreme Rainfall Characteristics for Surface Slope Stability in the Malaysian Peninsular. *Journal of Assessment and Management of Risk for Engineered Systems and Geohazards (Georisk)*, 2(2):65-78.

Khire, M.V., Craig H.B., and Peter J.B. (2000). Capillary Barriers: Design Variables and Water Balance. *Journal of Geotechnical and Geological Engineering*, ASCE, 126(8):695-709.

Marsilia, A., Servadioa, P., Pagliaib, M., Vignozzib, N. (1998), Changes of some physical properties of a clay soil following passage of rubber- and metal-tracked tractors, *Soil & Tillage Research*, Elsevier, 49:185-199.

Parent,S.E. and Cabral, A. (2005). Design of inclined covers with capillary barrier effect. *Journal of Geotechnical and Geological Engineering*, 24:689-710.

Pradel, D. and Raad, G. (1993). Effect of Permeability on Surficial Stability of Homogeneous Slopes. *Journal of Geotechnical Engineering, ASCE*.119(2):315- 332.

Rahardjo, H., Li X. W., Toll D. G. and Leong E. C. (2001). The Effect of Antecedent Rainfall on Slope Stability. *Journal of Geotechnical and Geological Engineering*. Netherlands. 19: 371-399.

Ross, B. (1990). The Diversion Capacity of Capillary Barriers. *Water Resources Research*. 26(10), 2625-2629.

Stormont, J. C., and Anderson, C.E. (1999). Capillary barrier effect of fine-overcoarse soil layers. *ASCE J of Geotech. and Geoenv. Eng.*. 125(8): 641-648.

Tami, D., Rahardjo,H., Leong, E. C., and Fredlund, D. G. (2004). A Physical Model for Sloping Capillary Barriers. *Geotechnical Testing Journal*, 2: 173-183

Tsaparas I., Rahardjo, H., Toll D.G. and Leong E.C. (2002). Controlling Parameters for Rainfall-Induced Landslides. *Computers and Geotechnic*. 29: 1-27.

Van Genuchten, M.T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*. 44: 892–898.

Zhang, S., Grip, H., Lovdahl, L., (2006) Effect of Soil Compaction on Hydraulic Properties of Two Loess in China. *Soil& Tillage Research*, Elselvier, 90, 117-125.