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NUMERICAL INVESTIGATION OF PERFORMANCE OF CAPILLARY BARRIER SYSTEM WITH TRANSPORT LAYER

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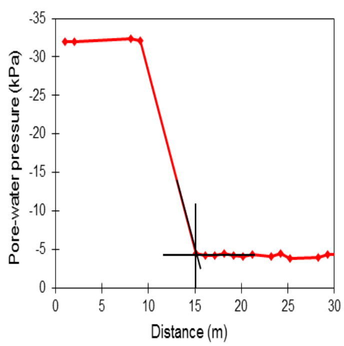
Graphical abstract



Abstract

A capillary barrier system is a promising alternative measure for controlling rainfall infiltration into unsaturated residual soil slopes. Although, system with capillary barrier effect has been successfully applied to avert rainfall infiltration in dry and semi-dry climates, its application in humid climates with high precipitation rate is still unsatisfactory. Therefore, this paper evaluates the performance of a modified capillary barrier system with transport layer under humid climatic conditions. The capillary barrier system and the transport layer were simulated with Grade V and Grade VI soils and gravel, respectively. The system was subjected to various rainfall intensities using saturated/unsaturated seepage analysis. When the initial suction of 32 kPa was assigned to the system and subjected to the worst rainfall condition for 24-hour duration, the breakthrough time increases with increase in the thickness of grade VI residual soil layer in the conventional capillary barrier system and the maximum diversion length achieved is less than 2 m. However, when a transport layer was placed at the interface of the grade V and grade VI soils, the diversion length increases to 15 m and avert breakthrough occurrence under the same condition. Therefore, the inclusion of transport layer in a residual soil capillary barrier system improved its performance and prevent breakthrough occurrence.

Keywords: Capillary barrier, transport layer, seepage analysis, diversion length, breakthrough time

1.0 INTRODUCTION

A capillary barrier system is a two-layered soil system of fine-grained soil layer overlying a coarse-grained soil layer [1-3]. The contrast in particle sizes results in variation of hydraulic properties between the two soil layers and creates a capillary break at the interface, which impedes downward movement of water into the coarse-grained soil layer. The infiltrating water can only enter the lower coarse-grained soil layer when the matric suction at the interface decreases to a value equal to the water-entry value of the coarse-grained soil layer [4, 5].

A system with Capillary barrier effect can be formed due to the natural soil arrangement as a result of weathering process and can as well be engineered and constructed from selected soil materials [6-8]. Most of previous studies on the use of capillary barrier system, give more preferences to the engineered capillary barrier system. In fact, it has successfully been applied as surface cover in dry and semi-dry climates to prevent rainfall infiltration into waste containment systems such as landfills and tailing dams [5, 9, 10].

Rainfall-induced slope failure is a natural disaster usually associated with loss of lives and properties in various parts of the world. Previous alternative methods of preventing this type of failure, such as the use of horizontal drains and geotextile have yielded unsatisfactory results. Hence, the principle of capillary barrier was recently extended as slope stabilization method and is successfully being applied to avert rainfall infiltration into the unsaturated slope under humid climatic conditions [11-15]. Rainwater that

Infiltrates a capillary barrier system is retained in the upper fine-grained soil layer by capillary forces, and is removed by evaporation, evapotranspiration, percolation or by lateral drainage through the slope [2, 14].

The major shortcoming of using capillary barrier system for slope stabilization in humid climates with high precipitation rate is breakthrough occurrence. A breakthrough is percolation of infiltrating water (retained in the upper fine-grained soil layer) into the coarse-grained soil layer. A breakthrough may occur once the fine-grained soil layer approaches saturation or due to poor lateral drainage along the interface. Morris and Stormant [16] proposed the use of unsaturated drainage layer (or transport layer) to prevent breakthrough occurrence and to extend the application of capillary barrier to humid climates. Zhan *et al*. [17] have shown that capillary-barrier cover with an unsaturated sand layer as transport layer performed much better than the conventional capillary-barrier cover in humid climate of China.

The concept of transport layer in capillary barrier is to facilitate lateral flow and delay breakthrough occurrence and is placed at the finer/coarser interface of a conventional capillary barrier system. The advantage of using transport layer includes; to increase the diversion length and breakthrough time and also to allowed vegetative soil to be used as fine-grained soil layer [12, 18]. The use of vegetative soil as the upper layer promotes plant growth which facilitates evapotranspiration process for water removal from the system.

Previous studies by Krisdani *et al*. [19] have demonstrated that residual soil can be used as capillary barrier material (fine-grained soil layer) and large deposits of this type of soil are normally found in abundance in tropical humid regions such as, Northern Brazil, Ghana, Malaysia, Nigeria, Southern India, Sri Lanka, Singapore and the Philippines [20]. For instance, more than seventy five per cent of surficial deposit in Malaysian Peninsular is covered by residual soils [21].

Therefore, from the previous studies, the use of capillary barrier system that formed in tropical residual soil due to natural soil arrangement from weathering process is not fully exploited. Hence, this study is aimed at exploiting the potentials of using this type of capillary barrier system to impede percolation of infiltrating water. The poor drainage and lateral diversion characteristics of this type of capillary barrier system will be alleviated by introducing a transport layer at the interface of the soils. A grade VI and a grade V soils are employed as fine-grained and coarse-grained soil layers, respectively. While, an unsaturated gravel was employed as a transport layer at the interface of the grade V and grade VI soil layers to improve its diversion capacity. A saturated/unsaturated commercial finite element software, Seep/w [22] was used for the numerical analysis. Two types of analysis, with and without the transport layer were performed to investigate the performance of a capillary barrier system with transport layer. The numerical analysis simulates suction distribution due to typical soil arrangement in the site. The soil arrangement is in such a way that the grade VI residual soil layer overlain the grade V soil layer. Therefore, during the simulations, the thickness of grade V soil was kept constant, while grade VI and transport layer thicknesses were varied.

2.0 MATERIAL AND METHODS

The study commenced by determining the relevant properties of the soil and the transport layer material for classification purposes. These properties include the particle size distribution, atterberg limits and specific gravity. They are determined using recommended procedure outlined in part 1 of BS 1337 [23]. Other input data required in the numerical analysis includes the saturated hydraulic conductivity (k_{sat}), soil water characteristics curve (*SWCC*), and unsaturated hydraulic conductivity functions. The k_{sat}(s) are determined using constant head and falling head methods as described in Head and Epps [24]. The *SWCC*s are determined in the laboratory using a pressure plate equipment in accordance with method C as described in ASTM [25]. The unsaturated hydraulic conductivity functions are predicted from the soil's *SWCC*s using van Genuchten [26] method.

Based on the preliminary tests conducted, the grade V and grade VI soils are classified as silty gravel of high plasticity (GMH) and sandy silt of very high plasticity (MVS), respectively. Moreover, the gravel is classified as uniformly graded gravel (GP_u). Another important parameter in the numerical analysis is the determination of the breakthrough suction values. It is a matric suction which once exceeded indicates a percolation of water into the coarse-grained soil layer. This values are determined as suction value where the hydraulic conductivity curve of the soils and the transport layer material intersect [1, 27]. It is determined as 5.0 kPa and 1.5 kPa for grade V and grade VI residual soils and grade V and gravel transport layer, respectively. The summary of the soil properties is shown in Table 1, while the particle size distribution curves, the *SWCC*s and the hydraulic conductivity functions are presented in Figures 1, 2 and 3, respectively.

2.1 Numerical Model

The transient suction distributions were simulated with commercial unsaturated/saturated seepage software, Seep/W [22]. In the first analysis without the transport layer, the thickness of grade VI residual soil layer is varied from 0.3 m to 1.5 m, while grade V soil layer is fixed as constant. However, based on findings of Yunusa *et al*. [28], the thickness of the grade VI and the transport layer were restricted to 0.5 m and 0.3 m, respectively, when a transport layer was considered in the analysis.

Table 1 Summary of soil properties

Description	Grade VI: Sandy Silt	Grade V: Silty Gravel	Transport Layer: Gravel
Moisture content, w_n (%)	28	26	-
Liquid limit, w_l (%)	78	65	-
Plastic limit, w_p (%)	35	46	-
Plasticity index (PI)	43	19	-
Classification (BSCS*)	MVS	MHG	GP
Specific gravity, G_s	2.64	2.66	2.70
Saturated coefficient of permeability, k_{sat} (m/s)	5.89 x 10^{-7}	1.24 x 10^{-6}	3.46 x 10^{-2}

*BCSC - British Standard Classification System

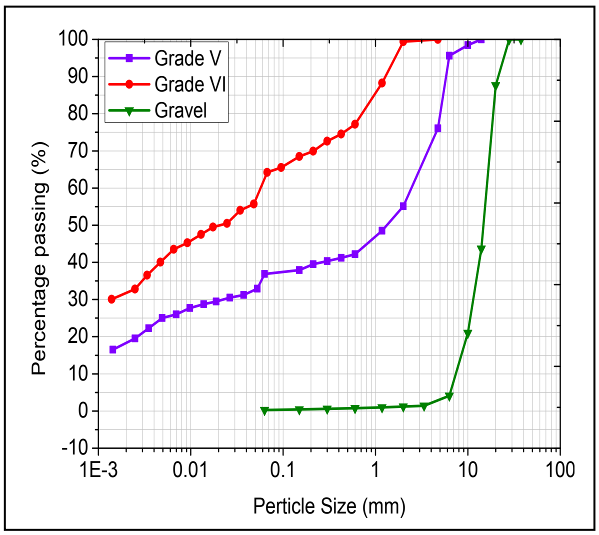


Figure 1 Particle size distribution curves of soils

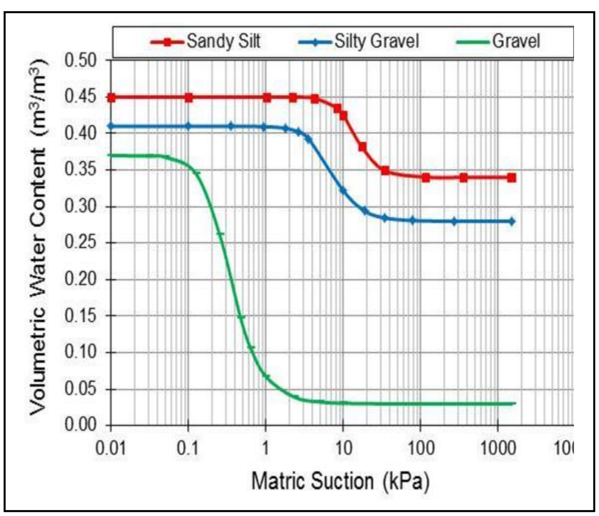


Figure 2 SWCCs of soils used in the analysis

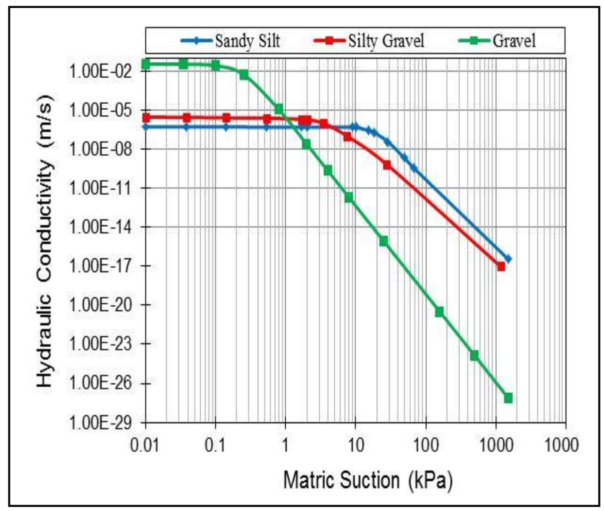


Figure 3 Hydraulic conductivity functions of soils

Figure 4 shows the numerical slope model used for the numerical analysis. The slope is inclined at an angle of 21° with a model sloping length of 30 m. However, to ascertain the effect of slope inclination on suction distribution due to the transport layer, four additional slope angles (i.e. 0°, 18°, 27° and 33°) were tested in the study. The finite element mesh for the numerical slope model with transport layer is a combination of very fine quadrilateral elements (0.05 m x 0.5 m) assigned near the ground surface up to 0.3 m depth to represent grade VI residual soil layer. Fine quadrilateral elements (0.1 m × 0.5 m) were assigned within the 0.2 m thickness of the transport layer. Large quadrilateral elements (0.25 m x 0.5 m) were assigned at 0.5 m below the transport layer. Due to the fact that the coarse-grain content increases with increasing depth in the residual soil mantle and in order to reduce the total number of nodes and invariably the time required to solve each simulation, a relatively very large quadrilateral elements compared to the remaining elements (i.e. 0.5 m x 0.5 m) were assigned at 1.0 m below the crest and toe of the modelled slope. In general, the finite elements mesh of the numerical slope model consists of 6222 nodes and 6060 quadrilateral mesh elements to represent the slope geometry.

Groundwater table was located at 15 m below the ground surface and therefore, head boundaries were applied along the left and right edges below the water table with pressure head equal to the vertical distance from the water table. This allowed the initial groundwater level and the initial pore-water pressure profile to be established in the modelled slope. The left and right edges above the water table were assigned as zero flux boundaries (i.e. *Q* = 0). Finally, rainfall intensity is modelled as unit flux *(q)* and is applied as infiltration on the exposed sloping surface.

The rainfall intensities used in this study were determined from a recorded rainfall data in a rain gauge station located in Universiti Teknologi Malaysia, Johor Bahru campus. It was sorted out of 76 rainfall events recorded from September, 2014 to January, 2015. This period falls within the wet season were critical rainfall values are anticipated. Five rainfalls events were eventually selected from these rainfall records and used in the numerical analysis. These rainfall intensities are 46.8 mm/hr, 29.2 mm/hr, 18.8 mm/hr, 14.6 mm/hr, and 9.8 mm/day for 1-hour, 2-hour, 8-hour, 24-hour, and 7-day, respectively. However, previous study on suction distribution due to rainfall infiltration by Kassim [29] have shown that a 24-hour rainfall intensity is the critical intensity leading to the lowest matric suction. Hence, a 24-hour rainfall intensity was also considered as critical intensity in this study.

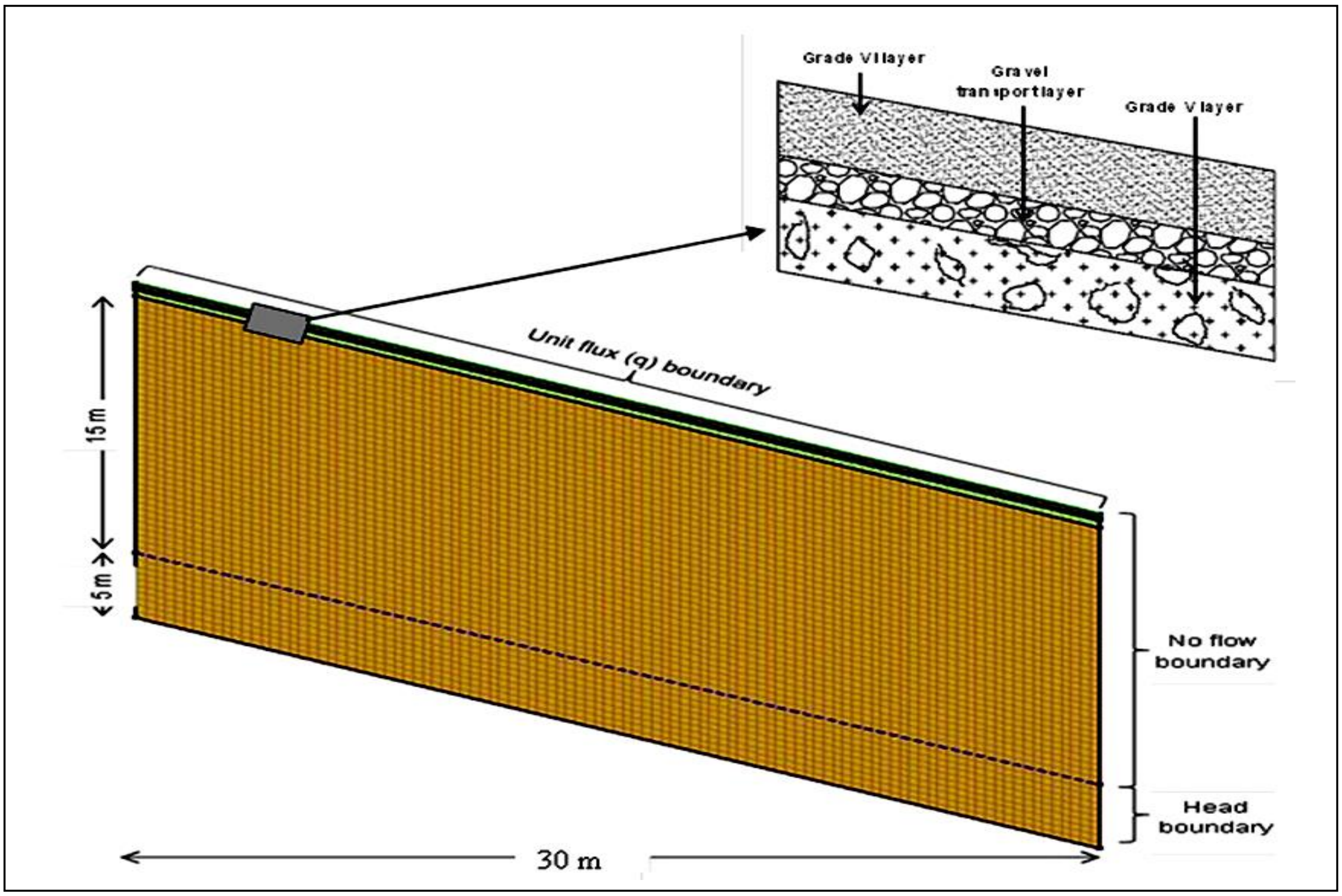


Figure 4 Numerical slope model

3.0 RESULTS AND DISCUSSION

3.1 Variation of Pore-water Pressure in a Capillary Barrier System Without Transport Layer

In order to justify the used of the transport layer at the interface of grade V and grade VI soil layers, a numerical analysis was performed with grade VI residual soil as the upper layer and grade V residual soil as the lower layer which typically forms a system with capillary barrier effect that exist in the tropical residual soil mantle due to weathering process. It is assumed that the interface between the two soil layers varies up to 1.5 m depth. This assumption conformed to what happen in reality regarding the thickness of grade VI residual soil layer. In fact, previous study by Rahardjo *et al*. [30] have shown that the depth to the interface (i.e. thickness of the grade VI soil layer) has great influence to the stability of the residual soil slope. Therefore, the variation of the thickness of grade VI soil layer depends on the extent of weathering process. As stated earlier, the thickness of the grade VI residual soil layer (i.e. fine-grained soil layer) was varied from 0.3 m to 1.5 m under this soil arrangement. The complete set up was subjected to rainfall intensity of 14.6 mm/hr for 24-hours.The variation of negative pore-water pressure at the interface of the two soil layers due to variation of the grade VI residual soil layer thickness is presented in Figure 5. Figure 5(a) shows that the breakthrough time increases with increase in the thickness of grade VI residual soil layer. This observation indicated that as the thickness of the grade VI residual soil layer increases, the time for the infiltrating water to reach the interface will also increase. This implies that the depth of wetting front increases with increase in grade VI residual soil layer thickness. The variation of breakthrough time with thickness of the grade VI residual soil layer is shown in Figure 5(b). This Figure is deduced from Figure 5 (a) and it shows that the breakthrough time increases with increase in grade VI residual soil layer thickness.

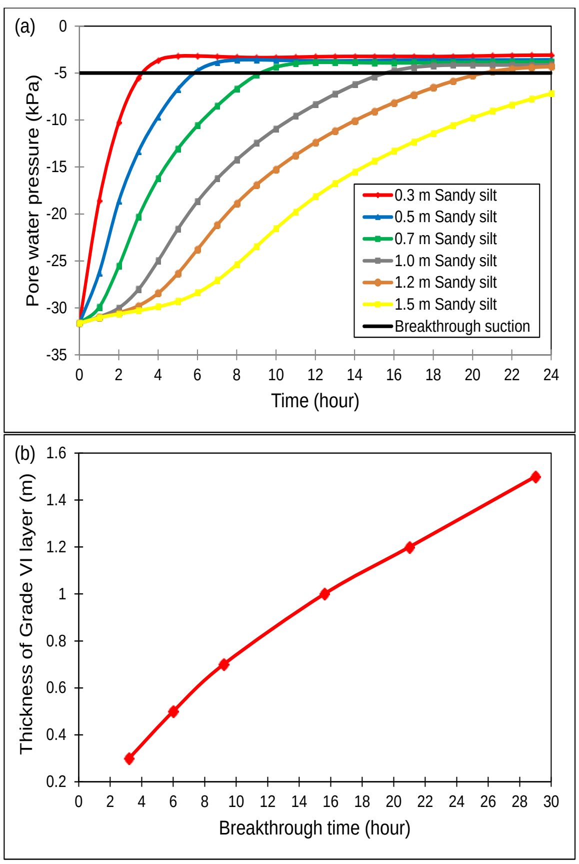


Figure 5 (a) Variations of pore-water pressure with time for various thickness of grade VI residual soil layer and (b) Variations of breakthrough time with thickness of grade VI residual soil layer

The variation of negative pore-water pressure with lateral distance along the interface of the two soil layers at the end of the 24-hour rainfall duration is presented in Figure 6(a). This Figure shows that the infiltrating water has reaches the interface of the two soil layers and uniformly reduces the negative pore-water pressure below the breakthrough suction value of 5.0 kPa. The uniform decrease in the negative pore-water pressure was observed even when the thickness of the grade VI residual soil layer was increased to 1.5 m. However, the negative pore-water pressure is above the breakthrough suction when the thickness of grade VI residual soil layer is increased to 1.5 m. Therefore, the diversion length for this combination of grade VI residual soil thickness is approximately 1.5 m as shown in Figure 6(b).

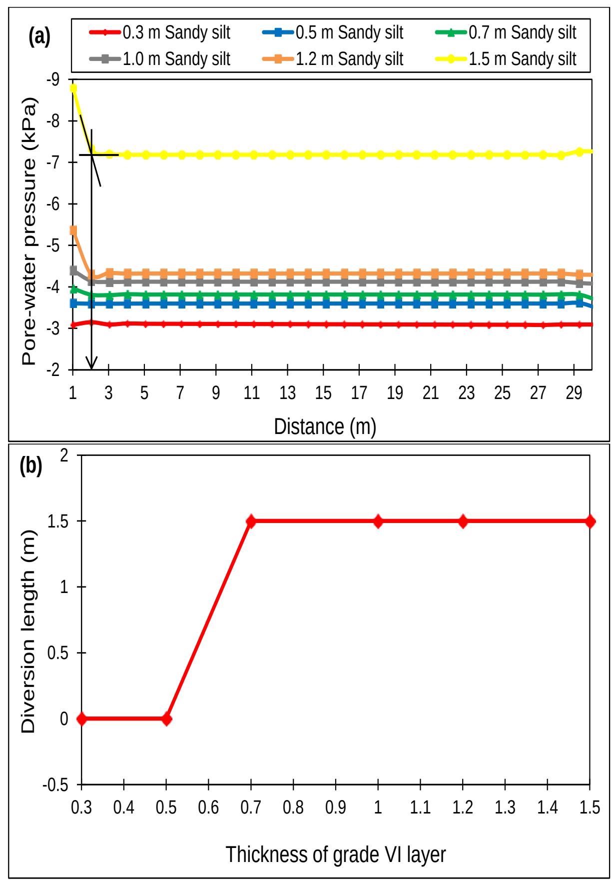


Figure 6 (a) Variations of pore-water pressure with lateral distance along the interface (b) Diversion length due to various thicknesses of grade VI residual soil layers

3.2 Variation of Pore-water Pressure in a Capillary Barrier System with Transport Layer

Previous studies by Yunusa *et al*. [31] have shown that gravel performed excellently as transport layer material due to its high hydraulic conductivity value. Therefore, in this section, a gravel layer is sandwiched between grade V and grade VI residual soil layers to act as transport layer. As stated earlier, the thicknesses of grade VI and transport layer used are 0.5 m and 0.3 m, respectively. The variation of pore-water pressure with time due to the 24-hour rainfall intensity of 14.6 mm/hr is presented in Figure 7. Unlike in the case of system without a transport layer where the negative pore-water pressure decreases to a breakthrough suction value instantaneously, the negative pore-water pressure is maintained as initial condition (i.e. 32 kPa) for almost 8 hours when a transport layer was sandwiched at the interface of the two soil layers. Within this time, the infiltrating water was laterally diverted towards the toe of the slope model. After 8 hours of rainfall infiltration, the negative pore-water pressure decreases to 22 kPa up to the end of the rainfall event. This shows that after 8 hours, the infiltrating water penetrates the gravel transport layer and diverted through it for the remaining analysis periods. From this observation, it is clear that the variation in the hydraulic conductivity of gravel and grade VI residual soil forms hydraulic impedance that limits downward movement of the infiltrating water. The infiltrating water is retained in the grade VI residual layer and flow laterally above the interface.

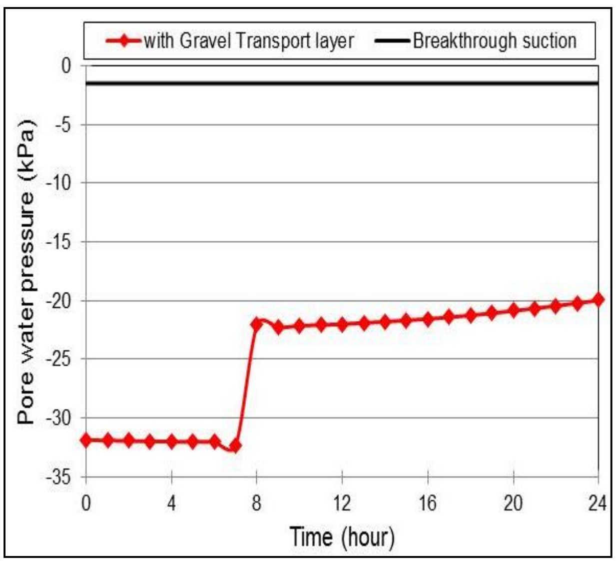


Figure 7 Variations of pore water pressure with time for a system with transport layer

3.3 Determination of the Diversion Length

The diversion length is the maximum distance from crest of the slope to a point along the interface where the negative pore-water pressure begins to disappear and the point is called a down-dip limit (*DDL*) [1, 4, 11, 32, 33].

The diversion length indicates the maximum length through which the infiltrating water can be diverted before breakthrough occurrence. It was determined using a tangent method as explained by Aubertin *et al*. [4]. Figure 8 shows the diversion length for the modelled slope due to the 24-hour rainfall pattern.

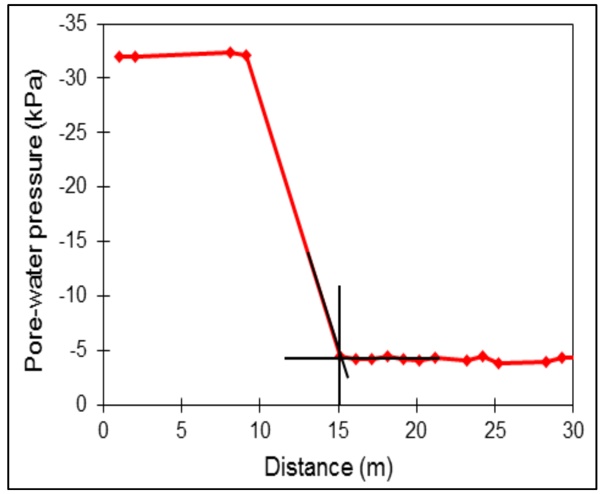


Figure 8 Diversion length of a capillary barrier system with transport layer

Figure 8 shows that the infiltrating water was diverted above the interface of the transport layer and the grade VI residual soil layer up to 15 m before it eventually percolates the grade V soil layer. By comparing this result with that of a capillary barrier system without transport layer where the diversion length was found to be 1.5 m as explained in the preceding section, this clearly shows a significant improvement in terms of water diversion and breakthrough time which are the two important parameters for assessing the performance of a system with capillary barrier effect.

3.5 Effect of Rainfall Intensity on Suction Distribution

The variation of negative pore-water pressures due to the 5 rainfall intensities explained in the preceding section are presented in Figure 9. This Figure shows that the infiltrating water was effectively diverted laterally above the interface of the grade VI residual soil layer and gravel transport layer without any breakthrough occurrence for all the five rainfall patterns.

Therefore, under these rainfall conditions the 15 m diversion length is fully achieved with gravel transport layer. This implies that the transport layer is capable of producing appreciable hydraulic impedance due to variation in hydraulic conductivities which causes lateral flow of the infiltrating water above the interface.

3.4 Effect of Slope Inclination on Suction Distribution

The effect of slope inclination on suction distribution is demonstrated using five different slope angles of 0°, 18°, 21°, 27° and 33° as shown in Figure 10.

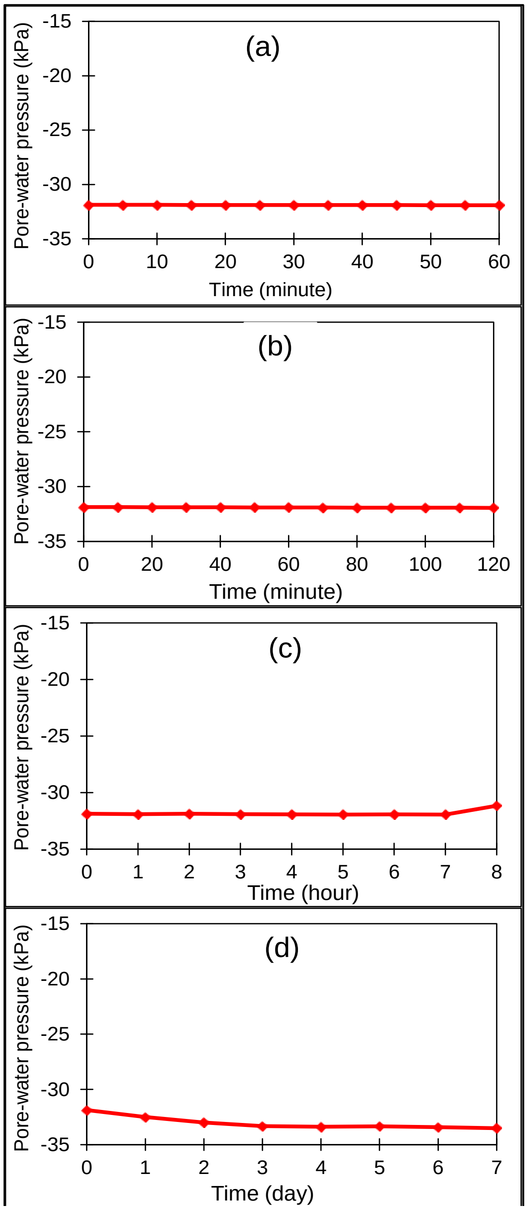


Figure 9 Variation of pore-water pressure with time due to (a) 1-hour (b) 2-hour (c) 8-hour and (d) 7-day rainfall intensity

The modelled slope was subjected to the 24-hour rainfall pattern (critical rainfall). Figure 10(a) shows the variation of pore-water pressure with lateral distance along the interface for these slope angles at the end of 24-hour rainfall event. Figure 10(a) shows that the negative pore-water pressure along the interface have been reduced considerably from the initial condition (32 kPa) to constant value of 4 kPa for 0° slope angle. This shows that the infiltrating water moves downward and dissipates the suction along the interface. However, for other slope angles, the negative-pore water pressure varies along the interface at the end of the rainfall and they eventually reduces the suction at the interface to a constant value at different locations along the interface. Similarly, the variation of the diversion length with the slope angle was deduced from Figure 10(a) using the tangent method. This relationship is shown in Figure 10(b). Figure 10(b) shows that the diversion length increases linearly with increase in slope angle up to 21° after which it decreases with increase in the slope angle. Therefore, this results shows that 21° is the effective slope inclination to achieve an optimum diversion length. This findings on the influence of the slope inclination on diversion capacity of a capillary barrier system with transport layer is in good agreement with previous findings such as that of Aubertin, *et al.* [4]; Li, *et al.* [11].

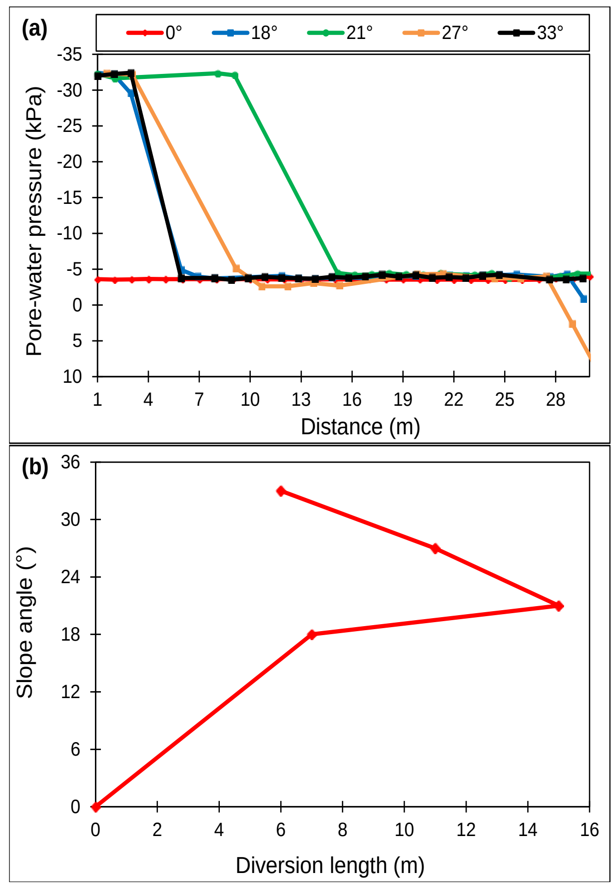


Figure 10 (a) Variation of pore-water pressure with distance and (b) Variation of diversion length with slope inclination for various slope angles

4.0 CONCLUSION

The performance of a capillary barrier system with transport layer was investigated in this study. Based on the outcome from this study, the following conclusions may be drawn:

With typical initial soil suction of 32 kPa, the capillary barrier system with transport layer perform well when subjected to four different rainfall patterns which are typical of the wet season and breakthrough does not occur due to all the four rainfall conditions.

Inclusion of transport layer at the interface of the grade V and grade VI soil layers results in increasing the diversion length up to 15 m, indicating more than 45% increase when a transport layer is not considered.

Under critical rainfall condition, lateral diversion of the infiltrating water above the interface increases with increasing slope inclination up to 21°. However, above this slope angle, the diversion length decreases with increasing slope angle.

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