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Laboratory and Numerical Studies of Rainfall Infiltration into Residual Soil Slope Improved by Biomediated Soil Cover

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Abstract: The capillary barrier system is a widely researched method used to control rainfall infiltration into soil slopes for mitigating rainfall-induced landslides. Conventional capillary barrier systems, however, are subjected to several weaknesses, such as the inability of the upper fine layer to function effectively under intense or prolonged rainfall, and sliding failure or erosion may occur in the fine layer as a result of excessive lateral seepage. This study aims to investigate the feasibility of using biomediated soil cover in a capillary barrier system to minimize rainfall infiltration into a residual soil slope. Firstly, the engineering properties of the original and biomediated residual soils were investigated. Secondly, an instrumented one-dimensional physical soil column was set up to investigate the infiltration behaviour of the tropical residual soil with and without biomediated soil cover. A numerical seepage model was simulated to compare the experimental and numerical results, as well as to verify the input parameters of the numerical simulation. Lastly, a two-dimensional slope model was simulated to investigate the effectiveness of the biomediated soil cover in minimizing infiltration under both intense (1-h, 4-h, 8-h, 24-h extreme rainfalls) and prolonged (72-h extreme rainfall) rainfall conditions. The results showed that the soil column with biomediated soil cover could effectively maintain the soil in an unsaturated state for a longer period of infiltration (i.e., 60 min) as compared with the original residual soil (i.e., 10 min only). The numerical simulation results agreed reasonably well with the experimental findings. The two-dimensional seepage analysis results indicated that the slopes with biomediated soil cover could reduce the infiltration of water into the underlying soil slope, and hence resulted in a shallower wetting front, particularly under short and intense extreme rainfall conditions.

Keywords: biomediated soil; capillary barrier; slope stability; unsaturated soil; residual soil

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1. Introduction

Rainfall-induced slope failure is a common geohazard in tropical countries, such as Malaysia. The capillary barrier system (CBS) is a widely researched mitigation method for rainfall-induced slope failures. The CBS is normally formed by two or more layers of alternating fine and coarse layers. Each layer has different unsaturated hydraulic properties that can be described through hydraulic conductivity function and the soil water characteristic curve (SWCC). Under an unsaturated condition, the upper fine layer may have a higher permeability than the underlying coarse layer [1]. Tapping on this unique unsaturated soil characteristic, the underlying coarse layer forms a hydraulic barrier and causes water to flow laterally in the fine layer, provided a breakthrough has not occurred. The water drifting in the top layer will be removed through evaporation or transpiration [2].

There are several factors affecting the performance of a CBS. Tami et al. [3] reported that the performance of a CBS under intense rainfall was primarily governed by the storage capacity of the upper fine layer. Damiano et al. [4] found that the initial condition of the soil profile strongly affected the performance of a CBS. The CBS was only effective in preventing vertical infiltration when the initial soil condition was dry, but not under an initially wet condition. A similar finding was reported by Capparelli et al. [5] in which the low unsaturated conductivity of the dry underlying coarse layer would require the building up of a high gradient of pressure in order to let the water penetrate through. Tallon et al. [6] conducted a field study to investigate the infiltration mechanism of a fine-coarse layered cover system. They concluded that even though the vertical infiltration into the inner part of a slope could not be entirely prevented, the use of the cover system was sufficient to minimize water from percolating through the cover system. Zhan et al. [7] investigated the performance of a three-layer CBS system formed by silt, sand, and gravel layers. They reported that the saturated hydraulic conductivity of the upper silt layer has to be kept lower than 5.3×10^{-7} m/s to effectively divert all infiltrated water laterally near the interface.

The previous studies on the CBS above suggested that conventional CBS does not perform well under intense rainfall [8]. The system is subjected to several shortcomings, such as the inability of the fine layer to retain the infiltrated rainwater for a sufficiently long duration and sliding failure in the fine layer as a result of excessive lateral seepage. Additionally, capillary barriers make the upper layer saturated, leading to loose bonds between soil grains, and hence forming a weak layer. A sliding failure could be initiated from the upper layer and trigger a deeper failure plane.

Microbial-induced calcite precipitation (MICP) treatment is an innovative soil improvement technology that utilises natural bacterial processes to produce calcite in the soil matrix for cementing and clogging soil particles. In geotechnical engineering, the applications of the MICP focus mainly on shear strength improvement [9], indestructible geophysical monitoring [10], and solidification at both laboratory and field scales. The harnessed microbial organisms are predicted to have a life of around 1.5 billion years [11]. Various microorganisms exist naturally in soil with concentrations of more than 10^9 cells per gram of soil on the surface and decrease gradually with depth [12].

The MICP soil treatment technique has been widely researched and applied to sandy material. Sharma et al. [13] conducted a comprehensive review of biogeotechnical methods for liquefaction mitigation in sands. They compared three biological approaches, i.e., MICP, microbially induced desaturation and precipitation (MIDP), and enzyme-induced calcite precipitation (EICP). They concluded that MICP is a suitable approach for mitigating sand liquefaction because the MICP technique uses the bioaugmentation of non-pathogenic bacteria, and the indigenous bacteria stimulated in the soil are not harmful to the environment. Besides *Sporosarcina pasteurii,* several other urease-producing bacteria have been explored, such as *Bacillus sphaericus, Bacillus subtilis, Bacillus lichenformis, Bacillus megaterium, and Proteus vulgaris*. The effectiveness of MICP treatment has also achieved similar success in recent studies on tropical residual soil and fine soil. According to Lee [14], the shear strengths of the MICP-treated residual soil could be increased by 40–164% depending on the soil density. A similar result was also reported by Ng et al. [15].

The present study investigates the feasibility of applying the MICP soil improvement technique in mitigating rainfall-induced slope failure. The conventional CBS is improved by introducing a biomediated soil cover to reduce water infiltration into the underlying residual soil, and hence to control suction loss caused by both intense and prolonged tropical rainfalls. The engineering properties of the biomediated soil are first studied, followed by conducting a one-dimensional infiltration test experimentally and numerically. Lastly, a series of two-dimensional seepage analyses are performed to predict the effectiveness of the biomediated cover in minimizing rainfall infiltration into residual soil slopes under various extreme rainfall conditions in Malaysia.

2. Materials & Methods

2.1. Materials

A typical granitic tropical residual soil was extracted from a site in Bandar Sungai Long, Selangor, Malaysia. The physical properties of the soil are tabulated in Table 1, while the particle size distribution of the residual soil specimen is presented in Figure 1. Based on the British Soil Classification System (BSCS), tropical residual soil was classified as Very Clayey Sand (SCL).

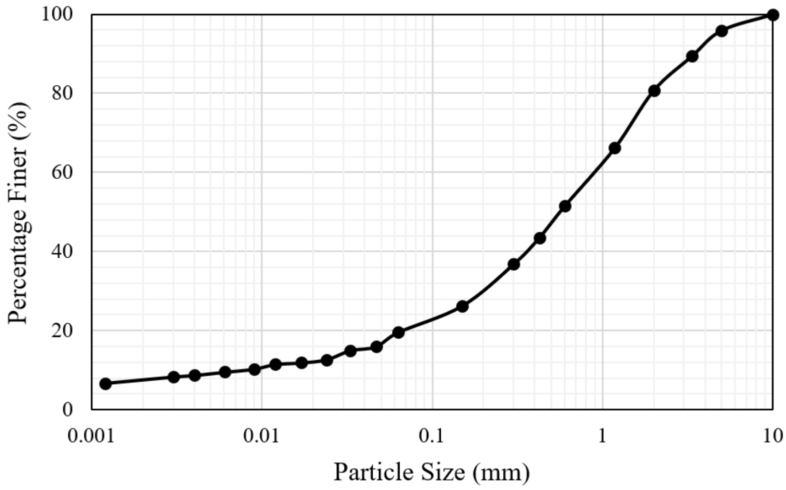

Figure 1. Particle size distribution of the studied tropical residual soil.

Table 1. Physical properties of residual soil.

Properties	Values
Gravel (%)	19
Sand (%)	61
Fine (%)	20
Liquid Limit, LL (%)	32.6
Plastic Limit, PL (%)	20.64
Plasticity Index, PI	11.98
Soil Classification BSCS	SCL
Maximum Dry Density, MDD (kg/m^3)	1799
Optimum Moisture Content, OMC (%)	15
Coefficient of Uniformity (C_u)	128.57
Coefficient of Curvature (C_c)	0.48
Saturated Permeability, k_{sat} (m/s)	9.0×10^{-5}

2.2. Alterations of Soil Properties by MICP Treatment

Sporosarcina pasteurii was used as the urease-producing bacteria for the MICP treatment. *S. pasteurii* is a common and widely studied species for MICP treatment in sands and other soils. The bacteria were cultivated and prepared in a concentration of approximately 1×10^8 cfu/mL. Both residual soil and biomediated soil specimens were prepared identically, with the only difference being that the amount of water used in the residual soil sample was replaced by the same amount of bacteria solution during compaction of the biomediated soil sample. The bacteria solution was mixed thoroughly into air-dried soil before compaction to ensure a uniform distribution of the bacteria in each soil specimen. The soil samples were compacted to 90% of their maximum dry density, with a moisture content of 15%. Upon compaction, cementation reagents were flowed directly into the soil at an interval of 6 h over a treatment duration of 72 h. The cementation reagent was prepared by mixing 55 g of calcium chloride and 30 g of urea to give a concentration of 0.5 M, which was selected based on the findings reported by Ng et al. [16], who suggested that the highest rate of calcite precipitation could be formed in the soil specimen at this reagent concentration. The calcite precipitation was responsible for reducing permeability and increasing shear strength of soil through bioclogging and biocementation mechanisms.

Table 2 summarises the shear strength properties for the untreated and biomediated tropical residual soils obtained from Consolidated Undrained (CU) triaxial compression tests. The tests were conducted on saturated samples of 50 mm in diameter and 100 mm in height in accordance with ASTM D4767-11 [17]. Upon the MICP treatment, the effective cohesion was increased from 5 kPa to 7 kPa, while the effective frictional angle was enhanced from 33 degrees to 36 degrees. Choi et al. [18] also reported a similar effective friction angle increment in the range of 2 to 4 degrees, although a more significant increase in the effective cohesion was realised in their studied Ottawa sand. These results suggested that the MICP treatment could effectively enhance the frictional resistance of soil, which is an essential parameter for slope stabilisation.

Table 2. Summary of triaxial test results.

Soil Properties		Original Residual Soil	Biomediated Soil
Total stress	φ	18	18
	c	8	24
Effective stress	φ'	33	36
	c'	5	7

The SWCCs for both original and biomediated residual soils were obtained using the capillary rise open tube method adopted by Yang et al. [19]. The readings of the volumetric water content were measured at various suction points, i.e., 0.01 kPa, 1.5 kPa, 8 kPa, 25 kPa, and 50 kPa. The SWCCs were then fitted to the measured data points using Fredlund and Xing's equation [20]:

$$(\varphi) = \theta_s \left[1 - \frac{ln\left(1 + \frac{\varphi}{h_r}\right)}{ln\left(1 + \frac{10^6}{h_r}\right)} \right] \times \left[\frac{1}{\left[ln\left[exp(1) + \left(\frac{\varphi}{a}\right)^n\right]\right]^m} \right] \quad (1)$$

where,
$\vartheta(\varphi)$ = volumetric water content at any specific suction,
h_r = residual soil suction (kPa),
a = a soil parameter that is related to the air entry value of the soil (kPa),
n = a soil parameter that controls the slope at the inflection point in the soil-water characteristic curve,
m = a soil parameter that is related to the residual water content of the soil.

The fitting parameters, a, n, and m, as tabulated in Table 3, were obtained by trial and error method. With the fitting parameters, the hydraulic conductivity functions were predicted using Fredlund et al.'s method [21].

Table 3. Fitting Parameters of SWCCs.

Fitting Parameters	Original Residual Soil	Biomediated Soil
a	3.00	25.00
n	3.00	3.00
m	0.20	0.20

Figure 2 shows the wetting soil water characteristic curve (SWCC) for the original and biomediated residual soils. Two apparent phenomena can be observed from Figure 2: (a) the volumetric water content at saturation for the biomediated soil (0.37) was marginally lower than that of the original soil (0.40); (b) the air entry values of the biomediated soil increased significantly from 1.5 kPa of original soil to 18 kPa. The results showed that the MICP treatment improved the pore water holding capability of soil. The pore volume of soil was filled by the precipitated calcite after the MICP process. As a result, water tended to be retained in the pores of biomediated soil. The amount of rainwater infiltrated into the soil was reduced, as the biomediated soil has a greater suction preservation capability. It was anticipated that the higher volumetric water content at saturation for the original residual soil was attributed to the larger pore volume within the soil matrix. In the biomediated residual soil, the pore volume decreased owing to the effect of cementation and calcite densification.

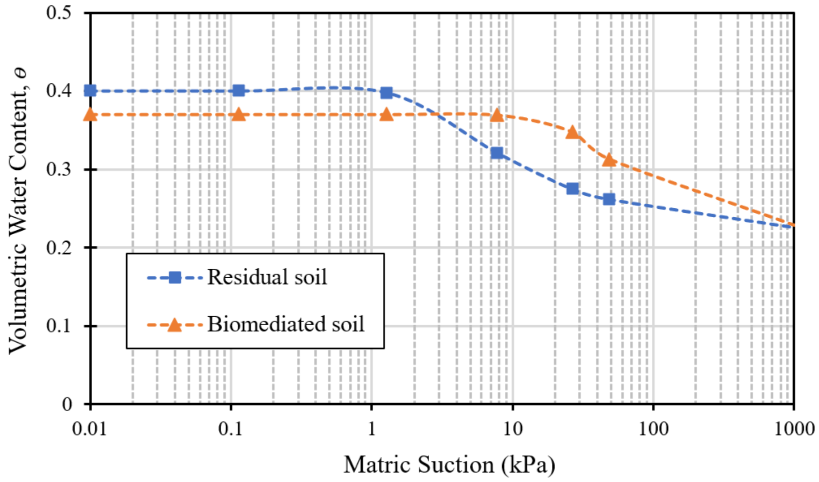

Figure 2. Soil water characteristic curves of original and biomediated residual soils.

Figure 3 shows the hydraulic conductivity functions of the original and biomediated residual soils. At full saturation, it could be seen that the permeability of the original soil (k_{sat} = 9 × 10^{-5} m/s) was higher than that of the biomediated soil (k_{sat} = 5 × 10^{-7} m/s). The permeability decreased owing to the precipitation of calcite crystals to induce a bio-clogging effect [22,23]. However, between the suction range of 15 kPa and 200 kPa, the unsaturated hydraulic conductivity of the residual soil turned out to be lower than that of the biomediated soil. This unique characteristic of unsaturated hydraulic conductivity was essential for forming the capillary barrier effect.

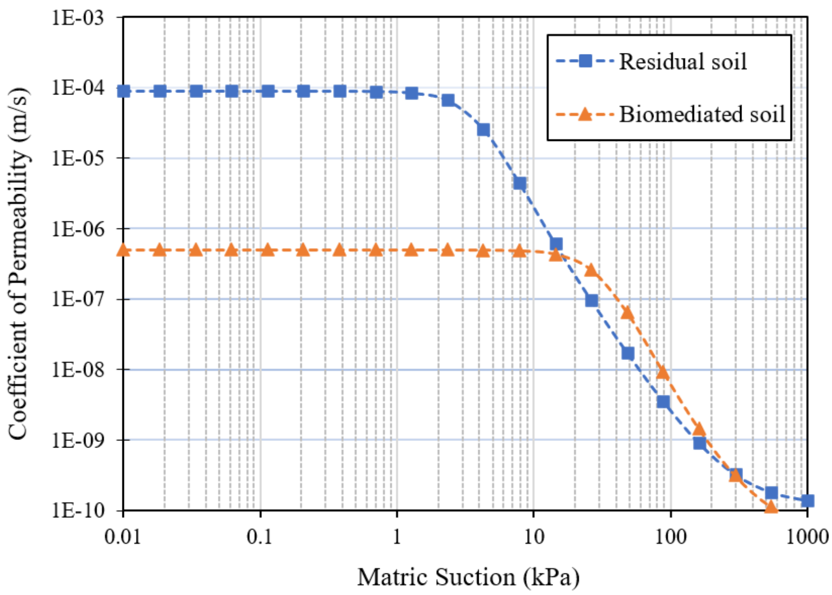

Figure 3. Hydraulic conductivity functions of original and biomediated residual soils.

2.3. Physical Soil Column Test

Laboratory infiltration tests were conducted using a polyvinyl chloride (PVC) pipe of 0.20 m diameter and 1.20 m height, as shown in Figure 4. A self-fabricated membrane was used to seal the bottom of the soil column while the top of the soil column was exposed to the atmosphere. The column was instrumented with three units of tensiometers (model: 2100F Soil moisture Probe). The details of the setup have been reported in the study by Tan et al. [22].

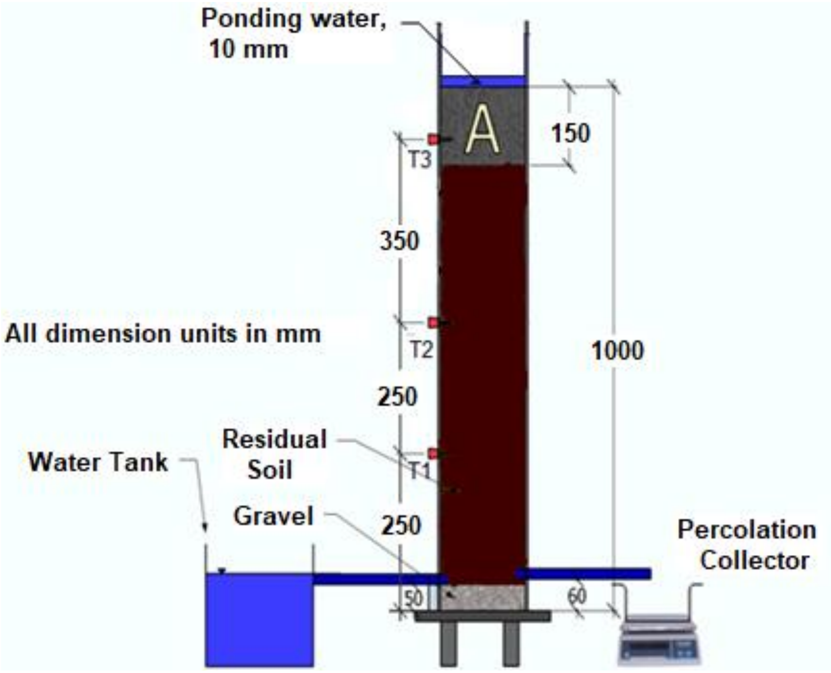

Figure 4. Schematic diagram of the physical one-dimensional soil column setup.

Two soil column infiltration tests were performed, i.e., original residual soil as a control test and a residual soil column covered by a 150 mm thick biomediated soil. The water applied to the soil column was kept constant by ponding the water on the soil surface for a duration of 60 min. The changes in pore-water pressure as well as water percolated through the columns were monitored.

2.4. Numerical Simulation

Transient seepage analyses for one-dimensional and two-dimensional slopes were carried out using Seep/W [24]. Figure 5 shows the one-dimensional soil column modelled in this study to simulate the soil seepage conditions in physical soil column tests. The model has a height of 1.1 m and a width of 0.2 m. The finite-element model was comprised of 405 nodes and 352 quadrilateral mesh elements (0.025×0.025 m). The left and right sides above the water level were modelled as a no flow boundary condition (Q = 0), while the side boundaries below the water table were assigned as head boundaries with the pressure head equalled to the elevation of the water table, i.e., 0.1 m. The top boundary was simulated as a unit flux boundary (equivalent to rainfall intensity), while the bottom boundary was assigned with no flow boundary. The contours in the soil column (Figure 5) represented the initial suction condition of the soil. The initial condition was created by applying a random transient unit flux on the soil column until a suction condition close to that of the actual experimental measurement was obtained. Upon obtaining the desired initial condition, transient seepage analysis was performed to evaluate the response of the soil column to water percolation. The simulated rainfall intensity was applied slightly larger than the saturated permeability of the soil to replicate the actual experimental condition. The time step interval used in the transient analysis was set at 30 s, with a total elapsed time of 60 min. The pore water pressure results obtained from the laboratory infiltration tests were compared with the numerical seepage analysis. This was important to ensure that the input parameters (SWCCs and hydraulic conductivity functions) for both residual soil and biomediated soil and modelling assumptions adopted in the numerical analysis were reproducible in the physical test.

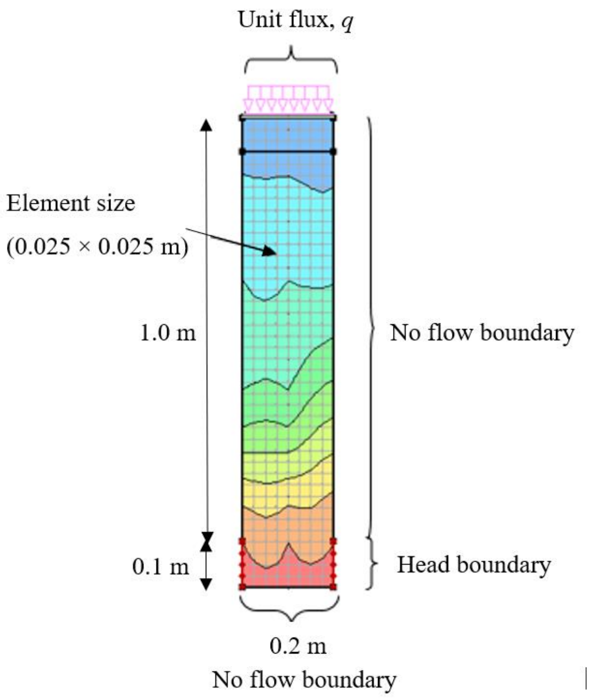

Figure 5. Element meshes and boundary conditions of the soil column numerical model.

Upon verification with the physical tests, the same input parameters (SWCCs and hydraulic conductivity functions) were used for the subsequent two-dimensional seepage analysis. This analysis aimed to investigate the effectiveness of biomediated soil cover in minimising infiltration at a sloping site under various extreme rainfall conditions. Figure 6 shows the two-dimensional seepage model used for the subsequent study. The seepage model was comprised of 4851 nodes and 4731 quadrilateral mesh elements (0.5 m $\times$ 0.5 m). Similar side boundary conditions as those in the one-dimensional analysis were applied to the two-dimensional model. The water table was located 15 m below the soil surface. The top boundary was assigned a rainfall (q) with no ponding option. Extreme rainfalls of a 10-year return period in Malaysia were adopted to investigate the infiltration response of the slope models under intense rainfall [25]. Table 4 summarises the extreme rainfall intensities for various durations considered in the present study.

Table 4. Extreme rainfall intensities for various durations.

Rainfall Duration (Hours)	Rainfall Intensity (m/s)
1	2.59×10^{-5}
4	1.12×10^{-5}
8	7.44×10^{-6}
24	4.25×10^{-6}
72	2.39×10^{-6}

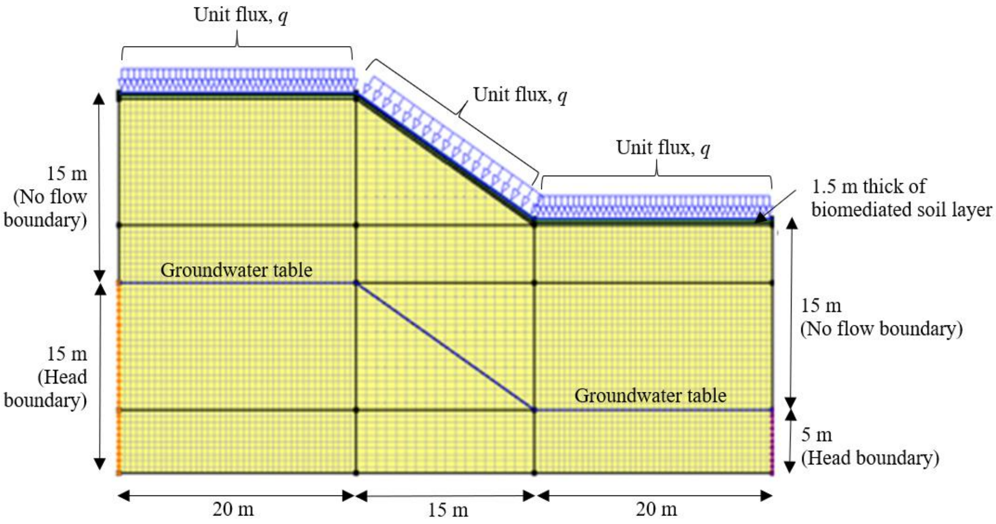

Figure 6. 2-dimensional seepage slope model.

3. Results

3.1. Results of 1-D Infiltration Tests

The significance of the biomediated soil cover towards controlling water infiltration as well as the suction distribution throughout the soil column could be visualized through the physical and numerical one-dimensional soil column infiltration tests. The experimental suction profiles of the soil column containing residual soil and residual soil with biomediated cover are presented in Figure 7. For each test, suctions at three measuring points were recorded. The markers in Figure 7 indicate the measured suction readings, while the associated curves represent the interpolated suction distributions. It should be noted that the initial conditions of the two soil columns (at t = 0 min) were slightly different, particularly at the middle of the columns, because of the difficulty in creating an initial suction condition identical to that of the original soil with the presence of the biomediated soil layer. As compared with the soil column filled with residual soil only, the soil column with biomediated cover could delay the saturation/suction loss in soil. At the beginning of the test, the initial suction near the top surface for both columns was reasonably identical at 36 kPa. With the passage of time, the biomediated cover could favourably retain suction in the soil column. The suction in the control original residual soil column was almost diminished after 14 min of infiltration, while a residual suction of 2.8 kPa still existed in the soil column encapsulated with biomediated cover even after 1 h of infiltration time. At an elevation of 0.55 m, the residual soil column started to experience suction loss as early as 2 min of elapsed time, while the suction of soil column protected by biomediated cover only started to reduce after 18 min of infiltration. These observations suggested that the biomediated cover could effectively preserve suction in soil and delay suction loss.

The numerical simulation results of the one-dimensional soil column test are presented in Figure 8. In general, the numerical results of the residual soil column showed reasonably good agreement with the experimental results (refer to Figure 7). Even though the suction distributions obtained from the experimental (Figure 7) and numerical simulation (Figure 8) were not completely identical, both results were capable of showing similar trends in terms of overall response of suction change with time. For instance, both the experimental and numerical simulation results showed that the suction of the original soil column diminished after about 14–18 min of infiltration. However, the shape of the suction profile predicted from the numerical simulation was slightly different from that of the actual experiment, particularly within 10 min of elapsed time, where the simulated suctions at the centre of the column were generally higher than that of the actual experiment. A possible reason for this discrepancy could be that some water may have infiltrated through the interface between column and soil in the actual experiment. For the soil column with biomediated cover, the simulated suctions were generally lower than that of the actual experiment, indicating that the biomediated soil cover in the actual experiment probably had a better water retention ability at a macroscopic scale than that of the numerical simulation. Nevertheless, the numerical simulation could still reasonably resemble the changes of suction obtained from the experimental infiltration test. The input parameters (SWCC and hydraulic conductivity function) adopted in the numerical simulation were thus validated.

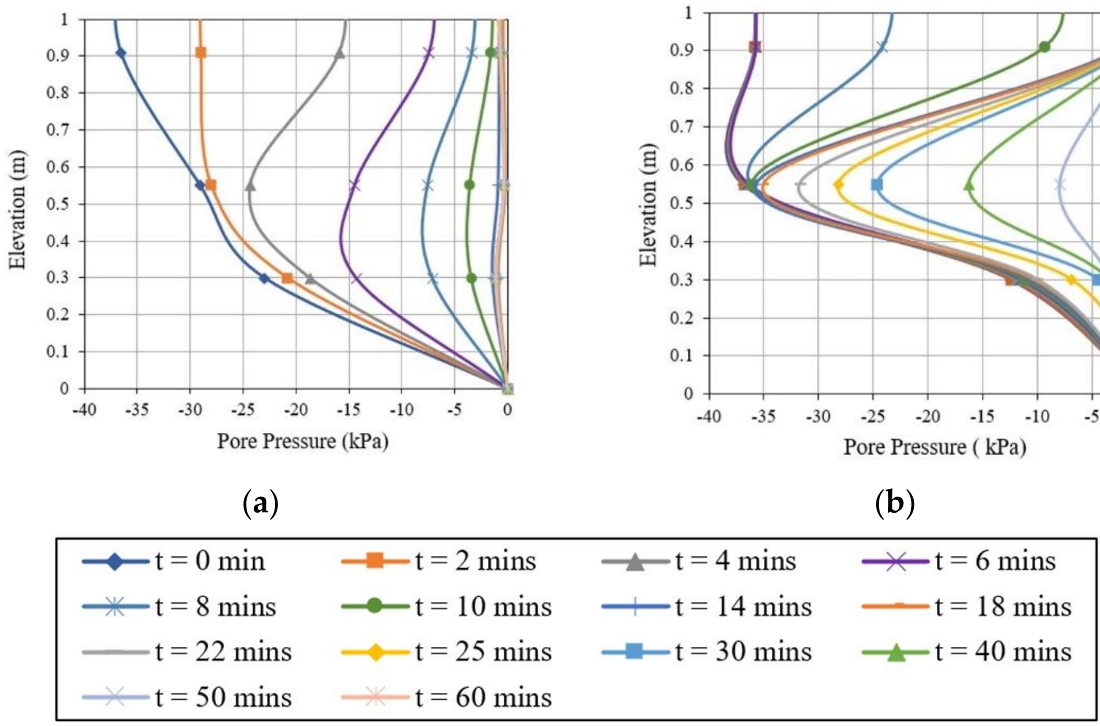

Figure 7. Suction profiles obtained from physical one-dimensional infiltration test on: (**a**) Original residual soil, (**b**) Residual soil with biomediated cover.

3.2. Results of 2-D Slopes under Various Extreme Rainfall Conditions

A series of two-dimensional seepage analyses were performed to predict the performance of the biomediated soil cover in actual slope embankment under extreme rainfall conditions. The comparisons of suction profiles in both the original soil slope and the slope with biomediated cover under 1-h, 4-h, 8-h, 24-h, and 72-h extreme rainfalls are presented in Figures 9–13, respectively. One of the key indicators to assess the effectiveness of the cover system was the advancement of the wetting front in soil under rainfall infiltration. Table 5 summarises the wetting fronts observed for various extreme rainfall conditions. Under continuous infiltration of extreme rainfall, the wetting front was observed to have advanced gradually with time into deeper soil deposits. Extreme rainfalls of a longer duration resulted in deeper wetting fronts. With the surficial MICP treatment, the soil slope was protected by a layer of low permeability material that effectively reduced rainfall infiltration. As such, short and intense extreme rainfall (i.e., 1-h, 4-h, 8-h and 24-h) tended to contribute more to surface runoff and resulted in a shallower advancement of the wetting front (almost 50% shallower) than the original soil slope. Under prolonged extreme rainfall (i.e., 72 h), the intensity of the extreme rainfall was lower than those of short-duration rainfalls. The biomediated cover became less effective as more water could infiltrate into the soil slope and a breakthrough would eventually occur under a prolonged infiltration. Nevertheless, the wetting front of the slope with biomediated cover was still shallower coupled with slightly higher suctions within the wetting front as compared with the original soil slope under the 72-h extreme rainfall.

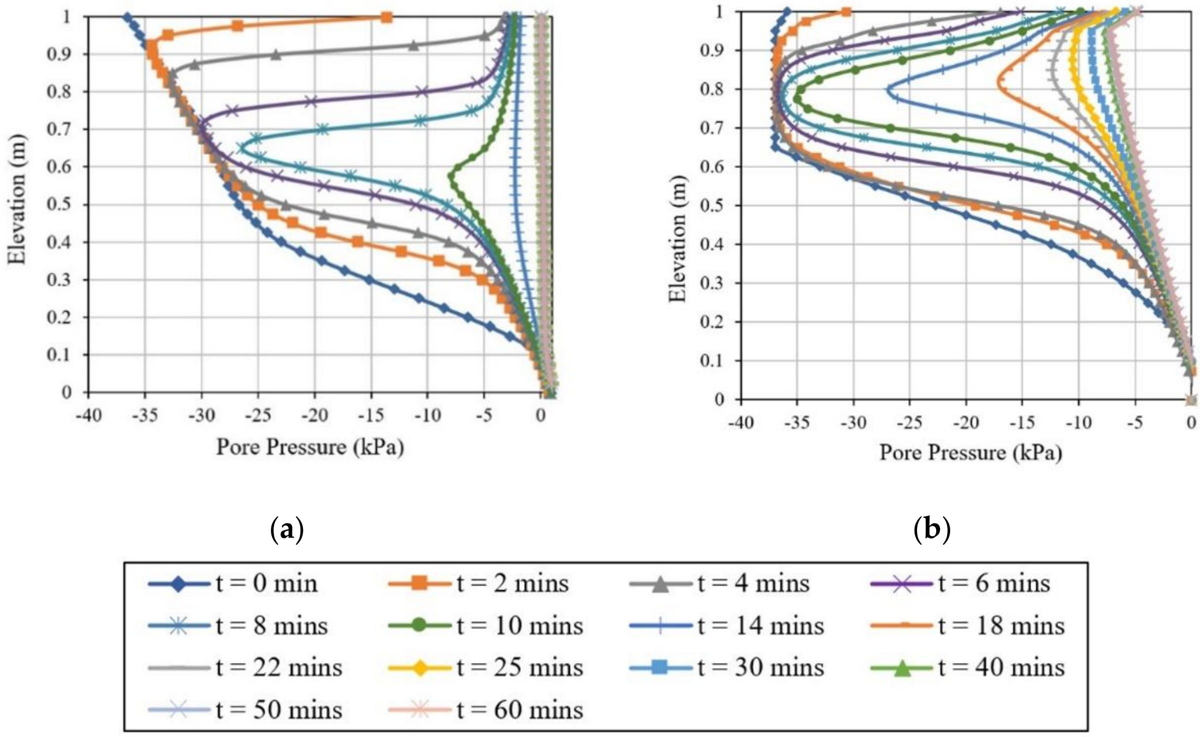

Figure 8. Suction profiles obtained from numerical one-dimensional infiltration test on: (**a**) Original residual soil, (**b**) Residual soil with biomediated cover.

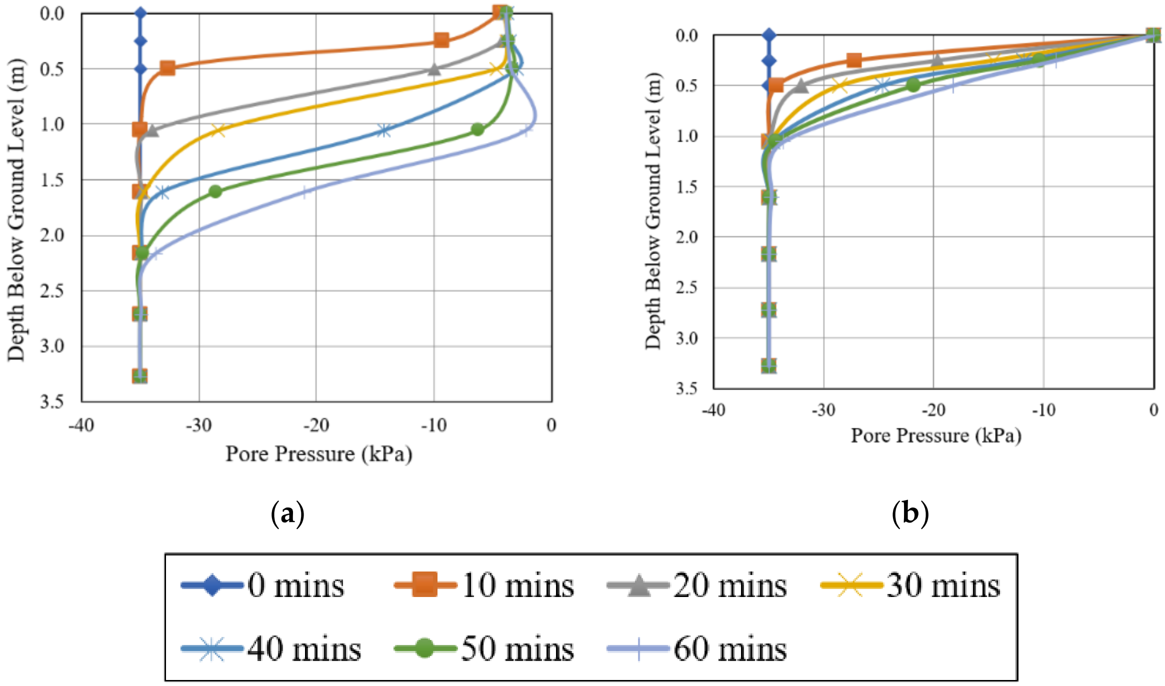

Figure 9. Changes in pore water pressure with time under 1-h extreme rainfall for (**a**) Original soil slope, (**b**) Slope with biomediated soil cover.

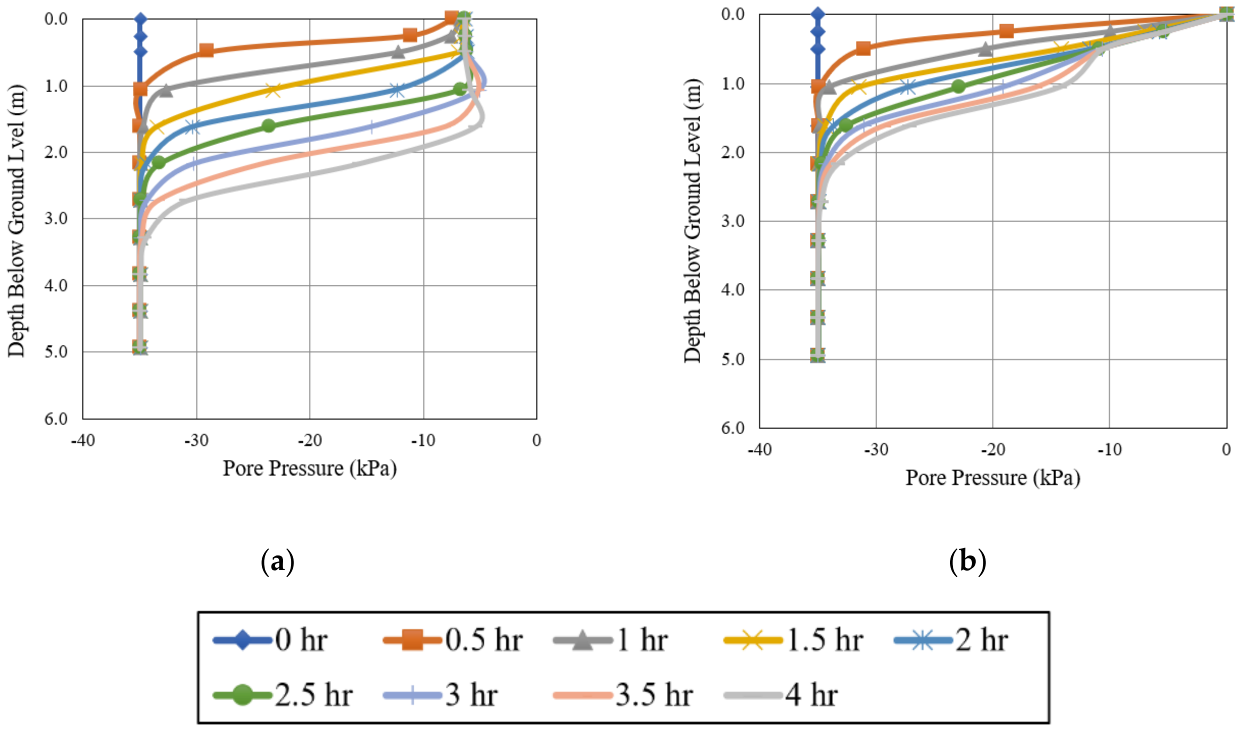

Figure 10. Changes in pore water pressure with time under 4-h extreme rainfall for (**a**) Original soil slope, (**b**) Slope with biomediated soil cover.

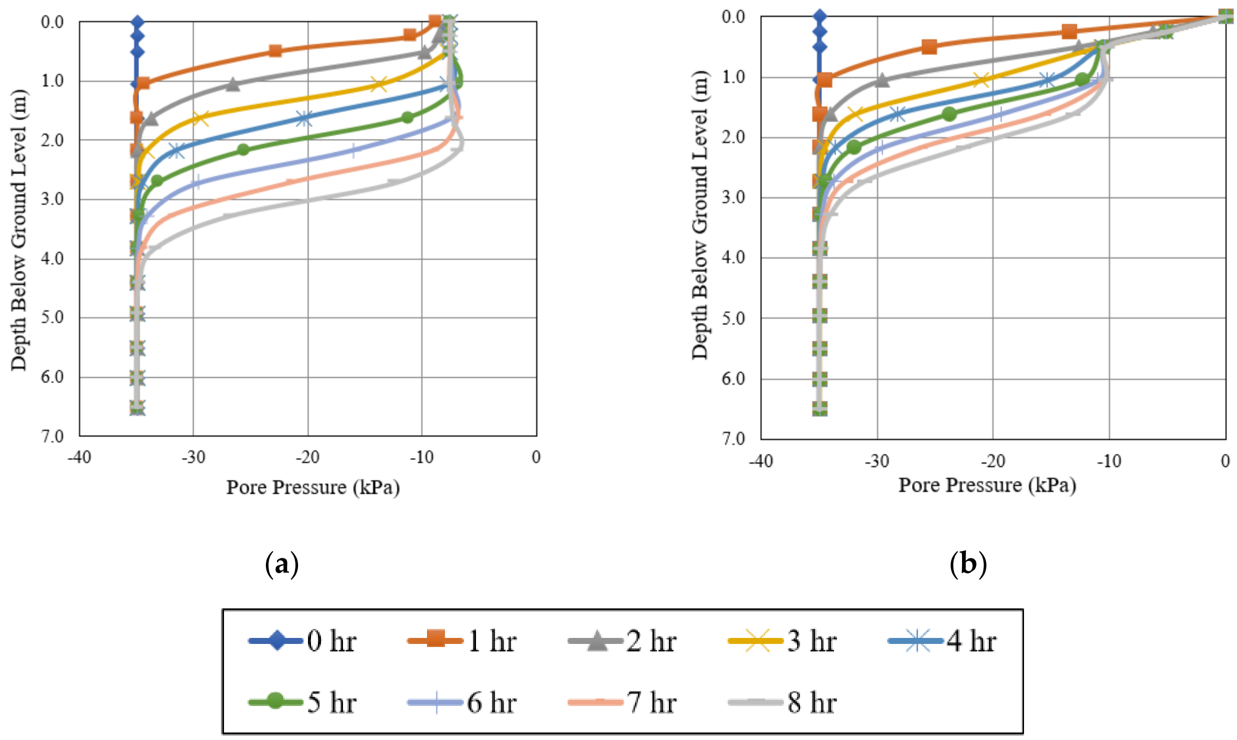

Figure 11. Changes in pore water pressure with time under 8-h extreme rainfall for (**a**) Original soil slope, (**b**) Slope with biomediated soil cover.

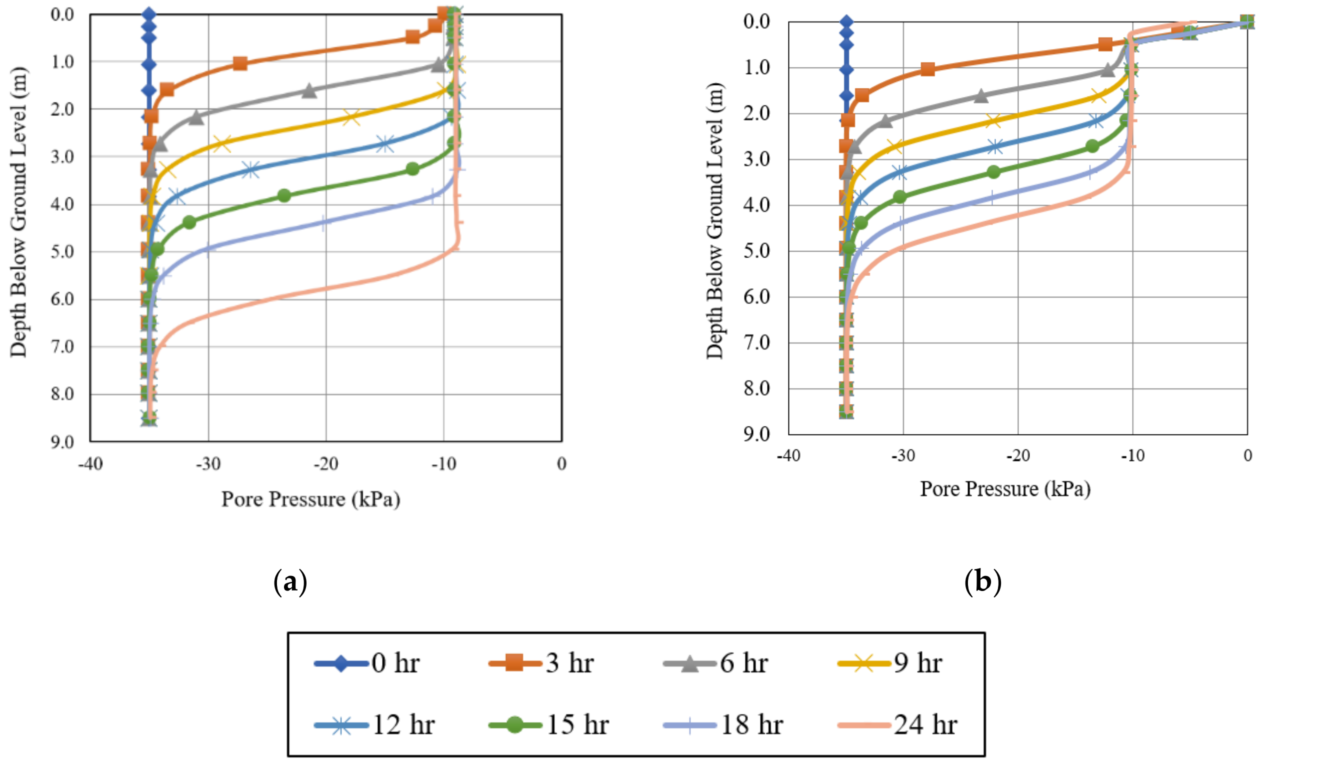

Figure 12. Changes in pore water pressure with time under 24-h extreme rainfall for (**a**) Original soil slope, (**b**) Slope with biomediated soil cover.

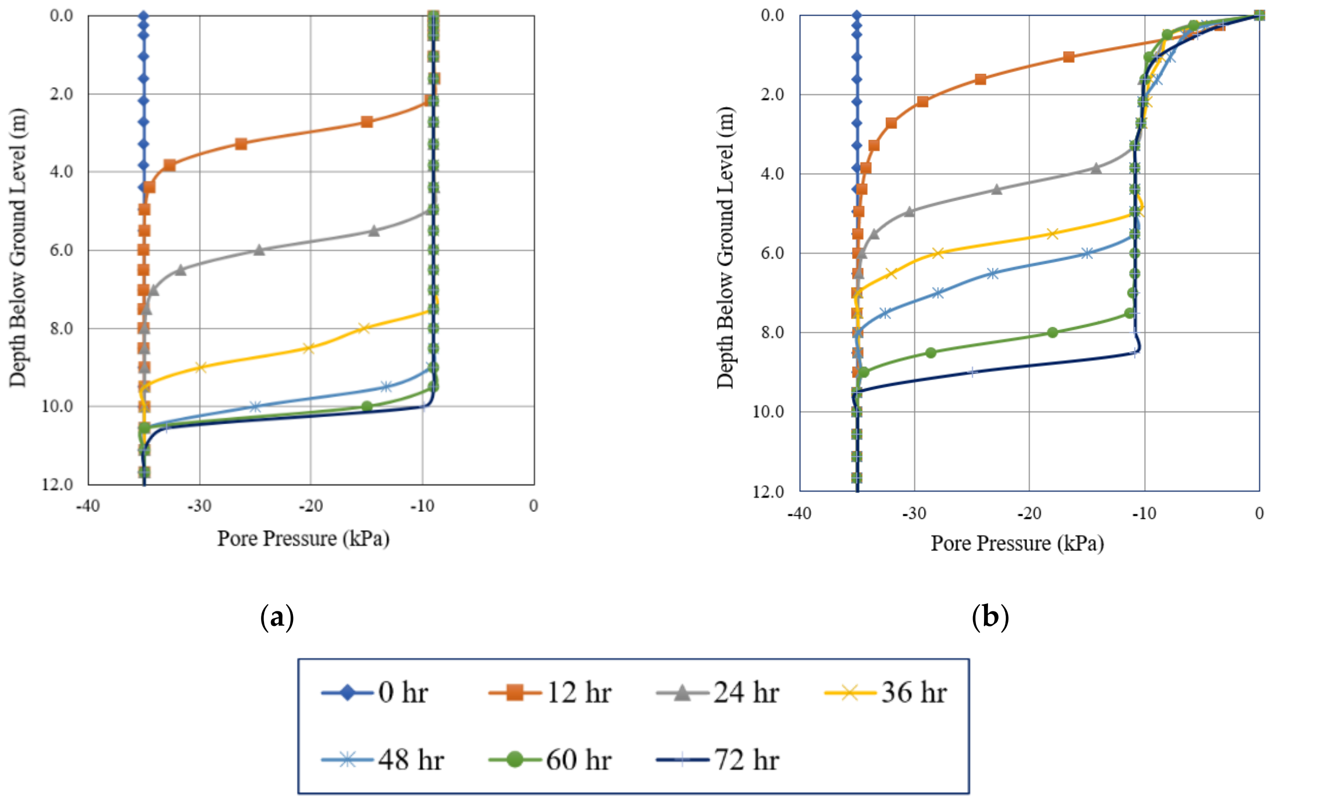

Figure 13. Changes in pore water pressure with time under 72-h extreme rainfall for (**a**) Original soil slope, (**b**) Slope with biomediated soil cover.

Table 5. Wetting fronts in soil slope under various extreme rainfall conditions.

Rainfall Duration (Hour)	Wetting Front of Original Residual Soil (m)	Wetting Front of Biomediated Soil (m)
1	1.0	0.0
4	1.8	1.0
8	2.3	1.2
24	5.0	3.1
72	10.0	8.5

4. Discussions

From the present experimental and numerical studies, the input parameters of the numerical model were calibrated carefully with the experimental results through a 1D soil column infiltration test. Some difficulties were encountered in experimentally creating an exactly identical initial condition for the original soil column and the soil column encapsulated with the biomediated soil cover because the biomediated soil has different hydraulic properties than its original counterpart. Nevertheless, the overall suction distribution trends predicted from the numerical simulation showed reasonably good agreement with the experimental observations, and hence verified the input parameters used. The MICP treatment was found to have reduced the saturated hydraulic conductivity of the soil by about two orders of magnitude, increased the air entry value of the soil by about one order of magnitude, and slightly increased the effective friction angle and effective cohesion of the soil by 3 degrees and 2 kPa, respectively. These alterations in soil hydraulic properties and shear strength parameters are essential in improving the water retention ability and sliding resistance of the upper layer of a CBS.

The 2D numerical simulation analyses were performed to evaluate the feasibility of applying the biomediated soil cover in an actual slope. The results obtained were pleasing, as the MICP-treated cover could effectively minimize vertical water percolation owing to its lower saturated permeability and higher water retention ability than the original soil. The use of soils with higher fine contents to form the upper fine layer in a CBS could replicate similar hydraulic properties. However, the use of excessive fine contents is not recommended, as it promotes the formation of desiccated cracks under repetitive wet-dry cycles. The use of biomediated soil could prevent this undesirable phenomenon, as the precipitated calcites are anticipated to bond the soil grains and maintain the soil structure.

Much of the recent research works on biomediated soil have centred on upscaling, exploration of its field applications, and solving practical applicability issues. The promising results from the present study have offered a novel idea on how biomediated soil can be potentially applied to mitigate slope stability problems. However, continued research must still address challenges associated with the applicability of the technique in an actual field slope, such as how to mass produce the bacteria and maintain its consistency. The preliminary idea is that the bacteria should be cultivated on-site and applied to the soil cover by the shallow mixing method since the required treated cover is relatively thin.

Despite the fact that MICP treatment is known to be a sustainable and environmentally friendly ground improvement technique, its influence on other land use has not been widely reported. It is common for the surface of a slope to be vegetated to prevent erosion. How the calcite precipitated in the soil matrix would affect the grass or plant growth warrants a standalone future study.

5. Conclusions

Three conclusions can be drawn from the present laboratory and numerical studies on the effectiveness of applying biomediated soil cover to minimize rainfall infiltration into residual soil slopes:

- The shear strength parameters (effective cohesion and friction angle) of the residual soil were enhanced by the MICP treatment, i.e., effective cohesion increased from 5 kPa to 7 kPa, and the effective friction angle increased from 33° to 36°. The SWCC of the biomediated residual soil was apparently different from that of the original tropical residual soil, in which the MICP treatment resulted in a lower volumetric water content (reduced from 0.40 to 0.37) and higher air entry value (increased from 1.5 kPa to 18 kPa). The significantly higher air-entry value makes the biomediated soil a favourable material to be used as the upper fine layer for a CBS.

- The residual soil column with biomediated cover minimized water infiltration at the upper zone of the soil column through a bioclogging mechanism. The suction loss in the middle part of the soil column was delayed with the application of the biomediated soil cover, indicating that less water had infiltrated into the soil column. The numerical simulation results generally agreed well with the experimental results, despite the former showing somewhat slightly more conservative predictions.
- The effectiveness of the biomediated soil cover could be acknowledged in the two-dimensional analysis of the slope model in which a section of the soil profile in the middle of the slope was investigated under various simulated extreme rainfall conditions. The wetting fronts of the soil slopes with biomediated cover have shallower (almost 50%) wetting fronts than those of the original soil slope under short and intense (<24-h) extreme rainfall. The system became less effective under prolonged (i.e., 72-h) extreme rainfall.

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