Investigation on the Effect of Layer Thickness and Rainfall Intensity in Capillary Barrier System for Slope Protection

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Abstract: Rainfall-induced landslides have become very common on natural or man-made residual soil slopes in tropical regions during monsoon seasons. These slopes are found in unsaturated state as the groundwater table is positioned at a deeper depth. Rainwater infiltration into these slopes lowers the matric suction and raises the pore-water pressure, increasing the susceptibility to slope failure due to the reduction in shear strength. Capillary Barrier System (CBS) is one of the effective methods for enhancing slope stability against rainfall infiltration. It utilizes the contrast in hydraulic properties of a fine-grained soil layer (FGL) placed above a coarse-grained soil layer (CGL)under unsaturated state. The current study focuses on the effect of FGL and CGL thicknesses and rainfall intensity on the seepage and stability analyses of the slope covered with CBS, using finite element and limit equilibrium models. The results showed that the factor of safety of slopes increased with an increase in the thickness of CGL and FGL up to an optimum thickness as further increase in thickness could not yield improvement in terms of stability of the slopes. Thus, it is recommended not to increase the CBS thickness beyond the optimum value from the economic point of view. Understanding the optimum layer configuration within a CBS enhances its effectiveness as a remedial measure for mitigating rainfall-induced slope failures.

Introduction

Currently, tropical countries are experiencing extreme climatic conditions such as prolonged heavy rainfalls not only in the monsoons but also during other seasons, leading to slope instability, thereby causing rainfall-induced landslides. Generally, the ground water table in the tropical region is relatively deep [1]. It was observed that the rainfall-induced slope failures occur in unsaturated lateritic soil (residual soil) mainly due to the loss of suction as a result of the advancement of wetting front rather than the rise in ground water table [2]. Studies indicate that the infiltration of rainwater into these slopes increases the pore-water pressure and decreases the matric suction leading to reduction in the shear strength of the soil, making the slope more susceptible to failure [3].

Increasing population and rapid urbanization urge for developing new infrastructures and improving the existing highways and engineered soil slopes. As rainfall-induced landslides are observed both in natural slopes and in engineered soil slopes [2], it is essential to mitigate and protect the slopes for public safety and comfort.

Capillary Barrier system (CBS) is an effective preventive measure to landslide prone slopes. CBS is an unsaturated earthen cover system utilizing a fine- grained soil layer (FGL) overlying a coarse- grained soil layer (CGL). CBS works based on contrasting unsaturated hydraulic properties (soil-water characteristic curves and permeability functions) between FGL and CGL. The difference in the permeability between FGL and CGL limits water infiltration, generating the capillary barrier effect. Percolating ground water can be hydrostatically suspended, stored, or re-routed within the FGL. The water infiltrated is stored in the FGL by capillary forces, which will eventually be removed by evaporation, evapotranspiration, or lateral drainage. If the rate of evaporation, lateral drainage, or evapotranspiration from the FGL does not exceed the infiltration rate, then breakthrough occurs and water enters the coarse-grained layer leading to failure of CBS [4].

The focus of the present study is to understand the effect of FGL and CGL thicknesses and rainfall intensity on the seepage and stability characteristics of the slope covered with CBS, utilizing finite element and limit equilibrium models. Even though various other parametric studies have been conducted on CBS to understand its effect on the performance of slopes implemented with CBS, the effect of thickness was not extensively taken into consideration. Thus, the layer thicknesses have been varied to understand its effectiveness in terms of performance for mitigating rainfall-induced slope failures.

Methodology

A typical soil slope of 4m height with an inclination of 45^0 on an 8m high embankment, as adopted by Rahardjo et al.2019 [5], was considered in the present study to investigate the effect of layer thickness of CBS, as shown in figure 1. The model was validated by adopting the index, engineering, and hydraulic properties of the materials and rainfall data specified by Rahardjo et al.2019 [5].

Initially, a conventional slope stability analysis was performed on the soil slope, considering the saturated properties of the residual soil of the slope. This was performed to understand the necessity of utilizing unsaturated properties over saturated properties in the analysis to establish the stability of the slope.

The slope characteristics and the input data regarding unsaturated properties, (the soil water characteristic curves (SWCC) and the hydraulic conductivity functions (HCF)) were obtained from the Rahardjo et al.2019 [5]. The CBS consists of an upper layer of Fine Recycled Concrete Aggregate (FRCA), and a bottom layer of Coarse Recycled Concrete Aggregate (CRCA) placed above the residual soil of the slope. Transient seepage analyses followed by slope stability analyses were performed on the slope with and without CBS subjected to a rainfall intensity of 7.2mm/h.

After validation, comprehensive numerical analyses were carried out to illustrate the stability of unsaturated soil slopes employed with and without CBS by varying the thicknesses of FGL and CGL, subjected to different rainfall intensities. At first, transient seepage analyses were conducted on slopes without CBS and subjected to different rainfall intensities (9mm/h, 36mm/h, and 80mm/h) for 3 days followed by slope stability analysis using the Morgenstern-Price method. The rainfall intensities of 9 mm/h, 36mm/h, and 80mm/h used in this study were obtained from Rahardjo et. al (2007), and Paulhus, J. L. H. (1965) [6&7] based on the intensity-duration-frequency (IDF) curve for Singapore. A similar procedure was carried out on slopes implemented with CBS, by varying the thickness of FGL and CGL. A total of 45 simulations were performed on slopes with CBS, incorporating the variations in the thicknesses of FGL, and CGL, and rainfall intensity.

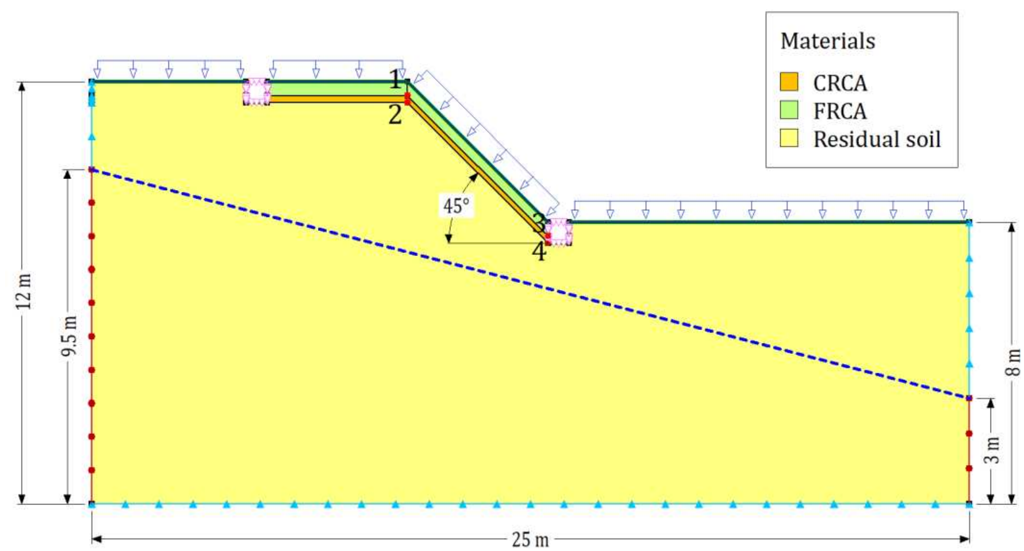

Figure 1: Numerical model with boundary conditions for slope with CBS

Numerical analysis

The two-dimensional seepage model (SEEP/W) utilized the saturated–unsaturated finite element analyses to simulate rainwater infiltration into the soil. It helps predict the change in porewater pressures throughout the slope profile due to the advancement of rain with respect to duration [8].

The input data required for the seepage model for conventional slope stability includes the geometry and soil profile of the slope, along with the saturated properties of each layer in the soil profile, and the boundary conditions of the slope [8]. Similarly, for the unsaturated slope stability analysis, instead of saturated properties of the residual soil of the slope, unsaturated hydraulic properties were given as the input to generate the seepage model.

Similarly, the input data required for the limit equilibrium-based slope stability model (SLOPE/W) encompasses the geometry and soil profile of the slope, the density, shear strength parameters of different soil layers in the slope, and the pore-water pressure distribution throughout the slope [8]. In the present study, the pore-water pressure distribution for the slope stability analysis was obtained from the parent analysis (seepage model).

The geometry and boundary conditions of the slope model adopted in the numerical analyses is shown in Figure 1. The boundary conditions used for the transient seepage analysis in this study included rainfall intensity, no flow boundary condition, total water head boundary condition, and implementation of drains. The rainfall intensity was applied on the ground surface as a flux (mm/h) with review and ponding was restricted on the ground by not allowing the pore-water pressure to rise beyond zero kPa. To simulate the No-flow Zone along the sides of the slope above the groundwater table, and at the bottom of the slope, a nodal flux equal to zero was applied. The total water head boundary condition was applied by assigning values for the total water head (h_w), along the sides of the slope below the groundwater table. The drains with a constant dimension of 0.6m×0.6m were provided at the crest, and at the toe of the slope to collect and drain out the water. This condition was established by applying flux equal to zero with review along the outer boundaries. The groundwater table was assumed to be situated at a typical known position, and the negative pore-water pressure in the slope was limited to 50 kPa, which reflects the typical values measured in the field, and to avoid any unrealistic field conditions with respect to higher suction values [5].

In the present study, simulations were conducted on slopes with and without CBS. Initially, for a rainfall intensity (9mm/h, 36mm/h, 80mm/h), transient seepage analysis was performed by varying the thicknesses of both FGL and CGL placed over the residual soil of the slope. The thickness of CGL was varied from 0.1m to 0.5m (0.1m CGL, 0.2m CGL, 0.3m CGL, 0.4m CGL, and 0.5m CGL), and that of FGL from 0.3m to 0.5m (0.3m FGL, 0.4m FGL, and 0.5m FGL) as the thickness of CGL is generally kept less than or equal to that of FGL [5],[9], [10] and also considering the CBS thickness (0.4m FGL over 0.2m CGL) adopted by Rahardjo et. al., (2019).

During the analysis, all the material, and unsaturated properties were kept constant while the geometry of the model was modified when the thickness was varied. Transient seepage analyses [11] were conducted and the pore water pressure distribution obtained from the seepage analysis was utilized to perform the slope stability analysis with respect to the Mohr-Coulomb model using the unsaturated parameters employing the Morgenstern-Price method [12]. The pore water pressure distribution and the variation in the degree of saturation with respect to time have been observed. The factor of safety vs time duration plots obtained from the stability analyses were compared amongst slopes employed with and without CBS.

Principle behind the numerical analyses

The materials used and the data regarding their properties were obtained from the literature [5]. These properties were used to model the slope in the seepage analysis. The fitted Fredlund

-Xing model parameters for establishing the pore water pressure distribution from the unsaturated property, SWCC [13], is as per the equation given in (1)

$$\theta_w = C_\Psi \frac{\theta_S}{\left\{ln\left[e + \left(\frac{\Psi}{a}\right)^n\right]\right\}^m} \tag{1}$$

where, θ_w is the volumetric water content corresponding to matric suction Ψ, C_Ψ is the correction factor, θ_S is the saturated volumetric water content, and a, n, m are the fitting parameters.

The hydraulic conductivity function for the seepage analyses may be derived from the saturated hydraulic conductivity, and the Fredlund-Xing parameters, using the Fredlund-Xing- Huang model [14], as per the equation given in (2).

$$k_w = k_s \frac{\sum_{i=j}^{N} \frac{\theta(e^y) - \theta(\Psi)}{e^{y_i}} \theta`(e^{y_i})}{\sum_{i=j}^{N} \frac{\theta(e^y) - \theta_s(\Psi)}{e^{y_i}} \theta`(e^{y_i})} \tag{2}$$

where, k_w is the hydraulic conductivity corresponding to the respective matric suction, k_s is the saturated hydraulic conductivity, θ_s is the saturated volumetric water content, *e* is the natural number, y is the dummy variable of integration, *i* is the interval between *j* to *N*, *j* and *N* are the minimum and maximum negative pore-water pressures decided by the final function. Ψ is the suction at the j^{th} interval. $\theta`$ is the derivative of equation (1).

The Mohr- Coulomb model with unsaturated parameters [15] was used in the stability analysis as given in equation (3).

$$s = c` + (\sigma_n - u_a)tan\varphi` + (u_a - u_w)\left[\left(\frac{\theta_w - \theta_r}{\theta_s - \theta_r}\right)tan\varphi`\right] \tag{3}$$

where, s is the shear strength of the soil, $c`$ is the effective cohesion, $(\sigma_n - u_a)$ is the net normal stress, $\varphi`$ is the angle of internal friction, $(u_a - u_w)$ is the matric suction, θ_w is the volumetric water content corresponding to the matric suction Ψ, θ_r is the residual volumetric water content, and θ_s is the saturated volumetric water content.

Results and Discussion

Validation of the model

The validation of the numerical model was performed by comparing the factor of safety obtained by the Rahardjo et al. 2019 and with the factor of safety obtained in the present study. Figure 2 shows the factor of safety values for the slope without and with CBS obtained from the present study. As per Rahardjo et al. the factor of safety obtained for slope without and with CBS are less than 1 and 1.36 respectively. The factor of safety obtained from the numerical simulation of the same slope in the present study are 0.95 and 1.32 respectively. The numerical simulation shows good agreement with Rahardjo et.al.2019. Therefore, the same model was adopted to investigate the effect of thickness of the CBS layers in the present study.

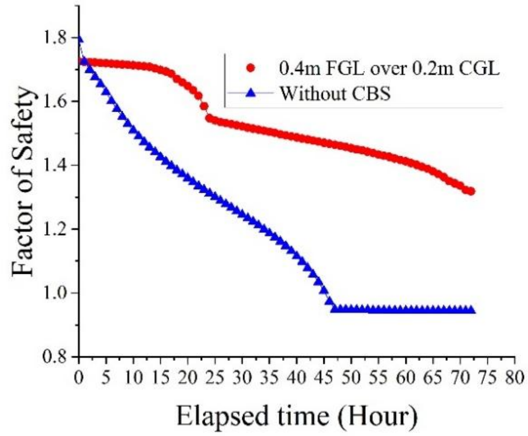

Figure 2: Difference in the factor of safety values for the slope without CBS and the slope with CBS (0.4m FGL over 0.2m CGL)

Conventional slope stability analysis on the original slope

The conventional slope stability analysis was performed on the original slope without CBS, considering the saturated properties for the seepage model in the seepage analysis prior to stability analysis. The factor of safety of the slope dropped suddenly below unity and became constant after 1 hour of 9mm/h intensity rainfall, as shown in Figure 3.

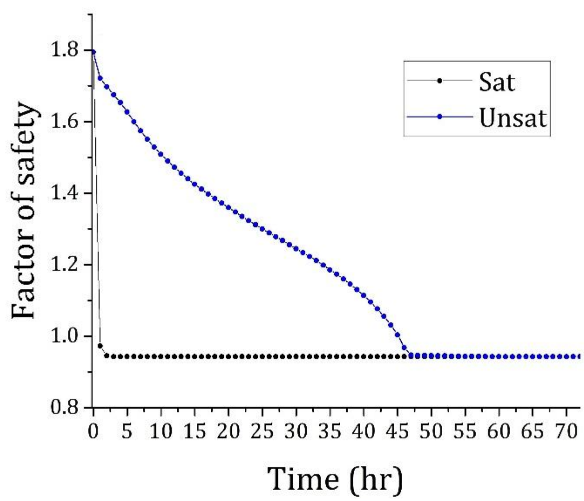

Figure 3: Factor of safety vs time plot for the slope with saturated properties (Sat) and unsaturated properties (Unsat)

The effect on the stability of the slope on utilizing unsaturated properties instead of saturated properties in the seepage analysis was studied. The seepage model was generated with unsaturated properties of residual soil and analysed followed by stability analysis. There was a gradual reduction in the factor of safety with time, when unsaturated properties were used. Figure 3 shows the variation in the factor of safety for original slope, when analysed to consider both saturated and unsaturated condition effects.

Effect of varying rainfall intensity and thicknesses of FGL and CGL with respect to factor of safety

The transient seepage analysis was performed followed by slope stability analysis on the slopes without CBS, by varying the rainfall intensities. It is found that, the slopes are susceptible to failure, as the factor of safety value was observed less than 1 irrespective of the rainfall intensities, as shown in Figure 5,Figure 6, and Figure 6. After analysing the slope without CBS, the seepage and stability analyses were conducted on slopes with CBS. The results show a significant improvement in the factor of safety when compared with that of the original slope without CBS.

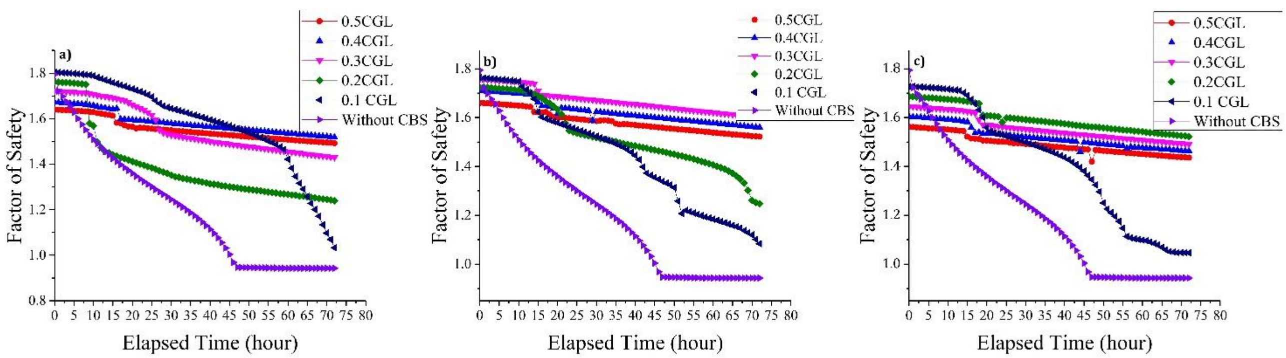

Figure 4: Factor of Safety vs Time duration plots for rainfall intensity of 9mm/h when a) 0.3m FGL b) 0.4m FGL c) 0.5m FGL were utilized in the CBS with variations in CGL

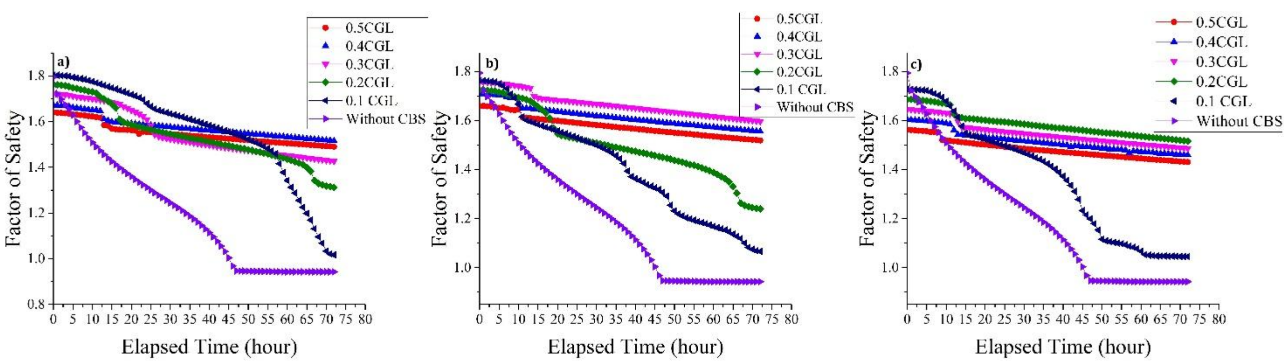

Figure 5: Factor of Safety vs Time duration plots for rainfall intensity of 36mm/h when a) 0.3m FGL b) 0.4m FGL c) 0.5mFGL were utilized in the CBS with variations in CGL

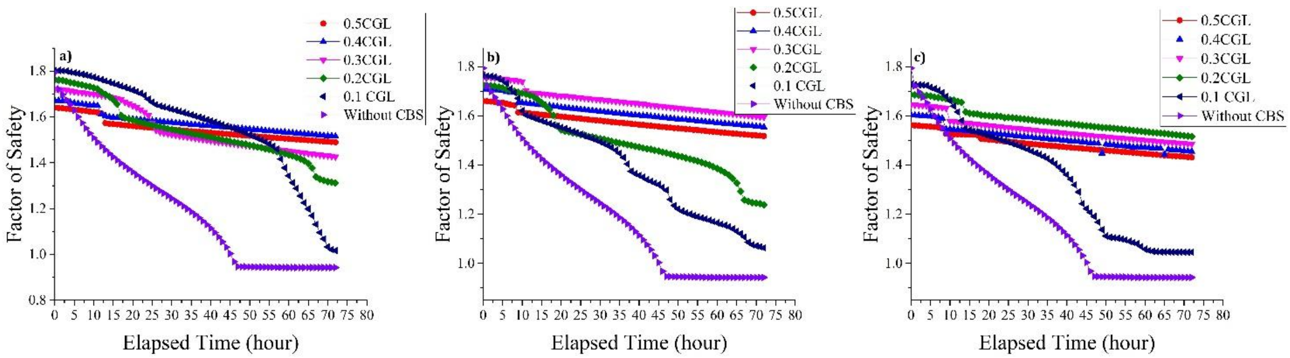

Figure 6: Factor of Safety vs Time duration plots for rainfall intensity of 80mm/h when a) 0.3m FGL b) 0.4m FGL c) 0.5m FGL were utilized in the CBS with variations in CGL.

The analyses were conducted on slope with CBS by varying the thickness of the CGL from 0.1m to 0.5m placed below FGL with thickness varying from 0.3m to 0.5m, and subjected to different rainfall intensities, which accounts to 45 different simulations in total. For CBS with 0.3 m FGL, and CGL with thickness varying from 0.1m to 0.5m, maximum factor of safety was observed for the CBS combination where 0.3m FGL was placed above 0.4m CGL, as shown in Figure 4a), 5a) and 6a). Similarly, when 0.4m FGL was analysed by varying the thickness of CGL (0.1 to 0.5 m CGL), the CBS combination of 0.4m FGL over 0.3m CGL yielded the highest stability, as shown in Figure 4b), 5b) and 6b). For 0.5m FGL when analysed by varying the thickness of CGL (0.1 to 0.5 m CGL), the CBS combination of 0.5m FGL over 0.2m CGL showed the highest factor of safety, as shown in Figure 4c), 5c) and 6c).

This points out that the CBS combination of 0.3m FGL with 0.4m CGL, 0.4m FGL with 0.3m CGL, and 0.5m FGL with 0.2m CGL are the optimum FGL-CGL combinations of the CBS for the materials and the conditions considered in the present study [5]. It was observed that the factor of safety of slope with CBS showed higher values when compared to slope without CBS. Also, the factor of safety of slope with CBS didn't drop down drastically, instead maintained stability without failure throughout the rainfall duration of 3 days as shown in Figure 4, 5 and 6. This is due to the presence of CBS which exhibits contrasting hydraulic properties between the materials used as FGL and CGL. This infers that the slope is less susceptible to rainfall-induced slope failures when the above-mentioned combinations of FGLs and CGLs are employed in the CBS system for the current study. From Figure 7, it was observed that the factor of safety of slope was increased with an increase in the thickness of CGL up to a certain limit for the FGL thickness of 0.3m, 0.4m, and 0.5m, after which an increase in the thickness of CGL could not yield improvement in the factor of safety. As a result, increasing the thickness of CGL beyond the optimum thickness might not provide an improved safety factor.

Further, the factor of safety of CBS with 0.1m CGL placed below 0.3m FGL, 0.4m FGL, and 0.5m FGL showcased lower stability compared to other combinations, as shown in Figure 7. This is due to the fact that, the FGL almost reached its maximum infiltration capacity (nearly saturated hydraulic conductivity) and indicated the onset of breakthrough. Usually, when the infiltrated water accumulates and reaches the fine-coarse interface, the matric suction of the CGL reduces, eventually, leading to the reduction in the shear strength of CBS. Once, the matric suction of CGL achieves its water entry value, the coefficient of permeability of CGL increases rapidly and overcomes the coefficient of permeability of FGL leading to the breakthrough. Since the thickness of CGL was 0.1m, it prompted to achieve the water entry value of CGL, leading to a reduced factor of safety.

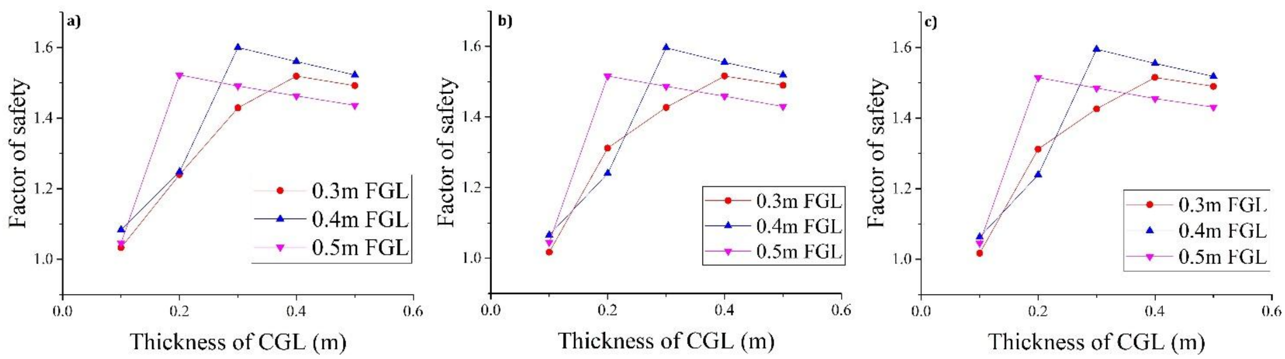

Figure 7: Factor of safety vs thickness of CGL for different thicknesses of FGL at a rainfall intensity of a) 9mm/h b) 36mm/h c) 80mm/h

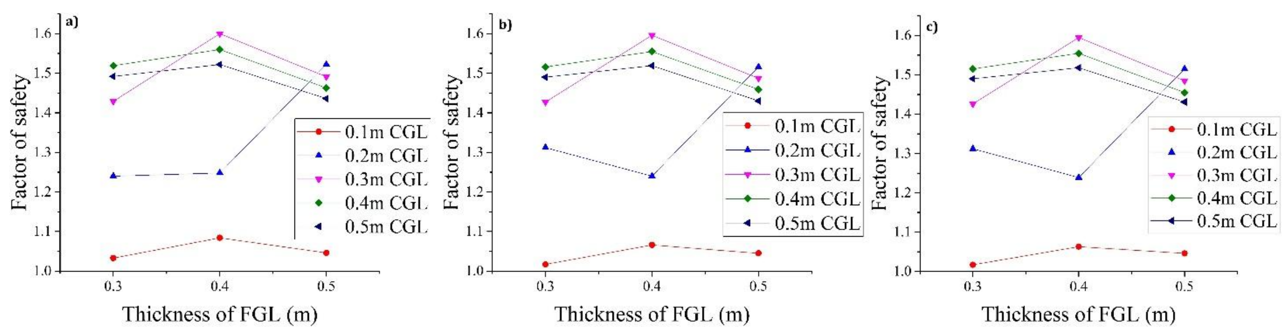

Figure 8: Factor of safety vs thickness of FGL for different thicknesses of CGL at rainfall intensities of a) 9mm/h b) 36mm/h c) 80mm/h

From Figure 8Figure 8, it was observed that the factor of safety of slope with CBS was the maximum when the thickness of FGL was 0.4m; irrespective of the variations in the thicknesses of CGL and rainfall intensities when compared to the CBS combinations of 0.3m FGL and 0.5m FGL.

Effect on pore water pressure and degree of saturation

To discuss the distribution of pore water pressure and the degree of saturation, the CBS combination with 0.4m FGL placed over 0.3m CGL was chosen, as this combination showed the maximum factor of safety out of the optimized combinations. Figure 1 shows the locations of the selected points at the crest and toe of the slope to study the variations in the pore water pressure and saturation of soil with respect to change in time.

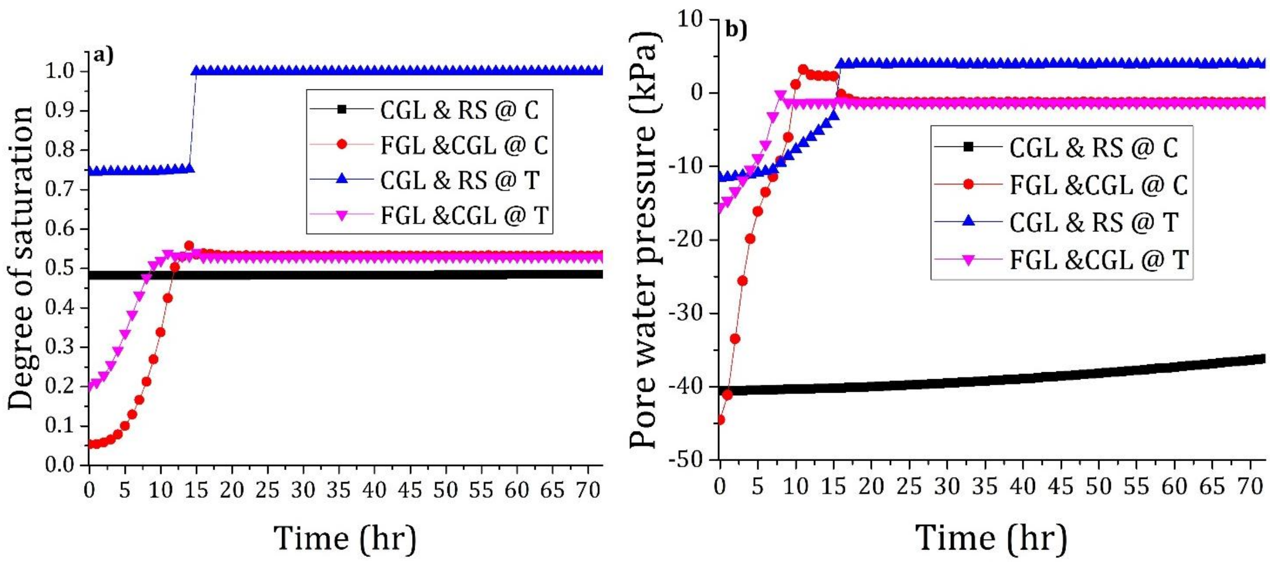

Figure 9: a) Pore water pressure distribution in CBS with respect to time for 0.4m FGL over 0.3m CGL at 9mm/h rainfall intensity. b) Degree of saturation vs time plot for CBS with 0.4m FGL over 0.3m CGL at 9mm/h rainfall intensity

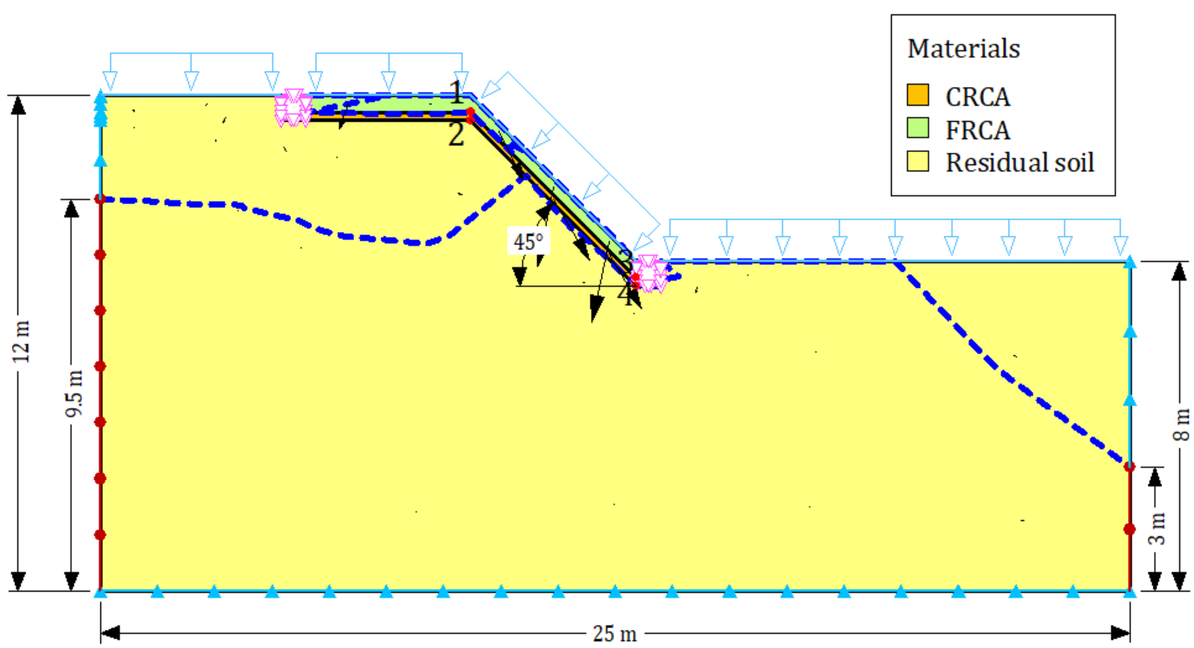

Figure 10: Result of numerical analysis showing the variation in ground water table

Figure 9, shows the pore water pressure distribution in CBS with respect to time for 0.4m FGL over 0.3m CGL for 9mm/h rainfall intensity. The points 1,2,3, and 4 shown in Figure 1 and 10 are represented as FGL & CGL @ C, CGL & RS @ C, FGL & CGL @ T, and CGL & RS @ T. FGL & CGL @ C represents the interface between FGL and CGL at the crest, 0.4m below the ground surface (Point 1). CGL & RS @ C represents the interface between CGL and residual soil at the crest, which is 0.7m below the ground surface (Point 2). FGL & CGL @ T represents the interface between FGL and CGL at the toe, 0.4m below the ground surface (Point 3), and CGL & RS @ T represents the interface between CGL and residual soil at the toe, 0.7m below the ground surface (Point 4).

From Figure 9, it is observed that at the interface between FGL and CGL at the crest (0.4m below the ground surface), negative pore water pressure of 1kPa prevailed and the degree of saturation was 53%. This indicates that sufficient matric suction was offered by the contrasting hydraulic characteristics of CBS layers to prevent slope failure. At 0.7m below the ground surface, at the interface between CGL and residual soil, the negative pore water pressure of 36 kPa was observed. This points out that lateral drainage occurred along the top layer of FGL, preventing infiltration into the CGL and residual soil of the slope. The degree of saturation at this location (point 1) was 48%.

At the interface between FGL and CGL at the toe (0.4m below the ground surface), negative pore water pressure of 1kPa was observed throughout, ensuring the efficient drainage of rainwater through the FGL as the degree of saturation was found to be 53%. At 0.7m below the ground surface, at the interface between CGL and residual soil at the toe, the negative pore water pressure of 5kPa was observed till 14 hours of continuous rainfall. Later, as time elapsed, the rise in the natural ground water table reduced the matric suction, leading to increasing pore water pressure. The degree of saturation was observed to be 100%, as the soil became completely saturated with the rising ground water table as shown in Figure 10.

Conclusion

The present study investigated mainly two factors i.e., rainfall intensity and thickness of FGL and CGL layers of CBS, that influenced the stability of the slopes. The following conclusions were made:

1. The factor of safety dropped suddenly and became constant for conventional stability analyses on original slope when the saturated properties were considered. There was a gradual reduction in the factor of safety when saturated properties were replaced with unsaturated properties. It shows that the stability analysis considering unsaturated soil properties is more effective and realistic.
2. The results of stability analyses pointed out that the factor of safety of slopes employed with properly designed CBS can be maintained well above unity, inferring the slopes with CBS have better stability against rainfall infiltration.

3. The factor of safety of slopes increased with an increase in the thickness of CGL placed below FGL up to an optimum value, further increase in the thickness of CGL could not yield improvement in the factor of safety.
4. The factor of safety of slope with CBS in the present study showed the maximum value when the thickness of FGL was 0.4m, irrespective of the variations in the thicknesses of CGL and rainfall intensities when compared to the CBS combinations of 0.3m FGL and 0.5m FGL.
5. The pore water pressure was negative at the interface between FGL and CGL throughout the rainfall duration, as the soil was partially saturated or unsaturated. This indicates the effectiveness of CBS in preventing rainfall infiltration.

The obtained optimum thickness of FGL and CGL for the CBS is suitable for protecting the slopes considered in the present study as per Rahardjo et al. 2019. Besides, increasing the thickness of either CGL or FGL beyond the optimum thickness is not recommended from economic point of view. This points out that, as the highest factor of safety is obtained at the optimum thickness, further increase in the thicknesses of either FGL or CGL does not yield better performance in terms of stability of the slopes. The study recommends to conduct extensive laboratory experiments accompanied with numerical simulations for finding the optimum thickness of CBS for different material combinations due to the variations in their properties.

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