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Harnessing Green Cover Systems for Effective Slope Stabilization in Singapore

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Abstract: Slope stability is crucial in civil engineering, especially in urban areas like Singapore, where heavy rainfall may result in catastrophic slope failures. This study aims to evaluate the effectiveness of three rectification methods, i.e., vegetation covers, GeoBarrier Systems (GBS), and Capillary Barrier Systems (CBS), in reducing rainwater infiltration for maintaining slope stability. Numerical analyses were conducted using finite element seepage and limit equilibrium slope stability software incorporating various rainfall and soil conditions to simulate real-world scenarios, focusing on the Factor of Safety (FOS) and Overdesign Factor (ODF) variations during and after rainfall events. The results from numerical analyses indicate that all three rectification methods significantly reduced negative pore pressure across slope layers under different rainfall scenarios, with CBS being slightly less efficient compared to other methods. Compared to simulations of slopes without rectification methods, the negative pore pressures of the rectified slope are improved by 50 kPa, demonstrating the effectiveness of the rectification methods in mitigating rainwater infiltration. The rectification methods showed similar trends in FOS values, with significant improvements over bare slope simulations. The FOS of the bare slope dropped by 0.7, reaching 1.0 under short, intense rainfall and 0.94 under prolonged heavy rainfall. The FOS of the slope with rectification methods remained stable, with only a 0.05 drop under different rainfall scenarios. The ODF showed similar results. Simulations with high-permeability soils revealed the same trends, confirming the rectification methods' reliability in representing negative pore pressure and FOS accurately. These findings suggest that all three rectification methods are highly effective in maintaining slope stability under heavy rainfall, making them viable options for slope stabilization in Singapore.

Keywords: Capillary Barrier System; slope cover; numerical analysis; unsaturated soil; slope stability

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1. Introduction

In Singapore, the combination of a tropical climate and the city-state's topography makes slope failures a common occurrence. The region experiences high temperatures, heavy rainfall, and elevated humidity levels year-round, leading to soil saturation, reduced cohesion, and increased susceptibility to erosion [1,2]. Additionally, the hilly landscape amplifies the risk of slope instability, particularly in areas with steep slopes. Mburu et al. [3] stated that the infiltration of rainwater during precipitation affects negative pore-water pressure, causing a reduction in shear strength within the unsaturated zone. Consequently, the slope becomes more vulnerable to failure, particularly during rainy periods. This phenomenon is prevalent in unsaturated soils, notably in tropical regions characterized by frequent and intense rainfall events. The instability of slopes during rain is a common occurrence in areas with unsaturated soils, particularly in tropical climates prone to severe rainfall.

Rainfall is a critical factor affecting slope stability, mainly due to its influence on soil water content and pore-water pressure. Rahardjo et al. [4] suggested that slope failures are frequent in steep residual soil slopes with a high groundwater table during rainfall. These slopes, characterized by a substantial unsaturated soil zone above the groundwater table, rely on maintaining negative pore-water pressures or matric suctions for stability. Rainwater infiltration raises the groundwater table, reducing matric suctions and weakening the soil's shear strength along potential slip surfaces. Due to climate change, rainfall has generally become more intense but less frequent, contributing to the increased frequency of slope failures. The primary measure for assessing slope stability is the Factor of Safety (FOS), which represents the ratio by which the shear strength of the slope material needs to be divided to reach the point of failure [5]. Kim et al. [6] stated that there is a significant decrease in the FOS of slopes due to fluctuations in rainfall and that an increase in rainfall intensity would continue to decrease the FOS by a marginal amount. This implies that the likelihood of slope failures increases as rainfall intensity increases. To mitigate rainfall-induced landslides, a common issue in Singapore, protecting slopes from rainwater infiltration is essential. Implementing preventive measures becomes essential to minimize this risk in areas with steep residual soil slopes and deep groundwater tables.

Common mitigation strategies often involve the use of concrete soil nails to stabilize slopes after rectifications and subsoil pipes to facilitate the drainage of rainwater. However, these approaches raise concerns about sustainability, as they use materials such as concrete and steel. As Singapore strives for sustainable urban development, there is a need to explore alternative and eco-friendly solutions that not only enhance slope stability but also align with the principles of environmental conservation and resilience in the face of changing climatic conditions. Alternatively, several strategies can rectify slope failures through sustainable means, such as vegetation covers [7,8], Capillary Barrier Systems (CBS) [9,10], and GeoBarrier Systems (GBS) [11]. Vegetation covers involve planting vegetation to reinforce slopes and prevent soil erosion or slope failures. This approach capitalizes on the natural binding properties of plant roots, providing reinforcement that enhances slope stability [12,13]. CBS consists of two layers, fine and coarse, each with distinct hydraulic properties, aiming to impede water infiltration into the underlying soil using unsaturated soil mechanics. This system is versatile, allowing the incorporation of various materials for the layers, including the use of recycled materials. GBS combines reinforced soil walls with capillary barriers to stabilize slopes and protect against rainfall infiltration. It uses geobags with geosynthetic pockets to support sustainable plant growth on the wall's surface. Similar to CBS, GBS allows for the use of different types of materials to create a hydraulic barrier to prevent rainwater infiltration.

These preventive measures are essential for Singapore to maintain a highly viable built environment and a resilient, sustainable city. While numerous experimental studies have been conducted by researchers on individual sustainable preventive measures, there remains a lack of comprehensive numerical research comparing the effectiveness of these measures for residual soil slopes in Singapore. This research gap underscores the need to prevent catastrophic failures that could endanger public safety and damage public property.

Therefore, this study focuses on the feasibility and functionality of the proposed slope stabilization methods of Vegetation Covers (VC), Capillary Barrier Systems (CBS), and GeoBarrier Systems (GBS) through numerical simulations. An undisclosed slope failure site in Singapore was incorporated to ensure that the numerical analysis conducted is calibrated to local settings, allowing for accurate and context-specific assessments. The simulations were conducted using Geostudio 2024 software (v. 2024.2.1), incorporating the standards set by Eurocode, to assess the effectiveness of the solutions for enhancing slope stability, quantifying and analyzing the effectiveness of VC, CBS, and GBS in stabilizing slopes.

2. Available Green Cover Systems in Singapore

2.1. Vegetation Covers (VC)

Vegetation covers use the ability of plants, particularly deep-rooted species, to bind soil particles and absorb water, significantly reducing erosion and surface runoff. In a study on vegetation slope covers by Rahardjo et al. [7], it was stated that the interaction between roots and soil creates a new composite material characterized by roots with high tensile strength. The vegetation used for this experiment was selected based on their differing properties, with the Orange Jasmine being a small tropical evergreen shrub with a deep root system and Vetiver Grass having a deeper root system, typically 2 to 4 m (Figure 1). Slope stability analysis yielded that the vegetation slope covers were successful in achieving a higher Factor of Safety compared to the original slope, even when rainfall was considered in the experiment. In addition, Chok et al. [14] concluded that different computations of vegetation roots had a significant impact on the Factor of Safety. The analysis, focusing on scenarios where vegetation covers the entire ground surface with a root depth of 1 m, concluded at a root cohesion (cR) of 20 kPa for each effective cohesion value (c'). Notably, the increase in the Factor of Safety was more pronounced for slopes with lower effective cohesion (c' = 1 kPa) than for those with higher cohesion (c' = 5 kPa). Further investigation revealed that slopes with higher cohesion values typically failed along a deep-seated rotational slip surface, suggesting that vegetation has a reduced impact on such failures when the root zone depth (hR) is shallow.

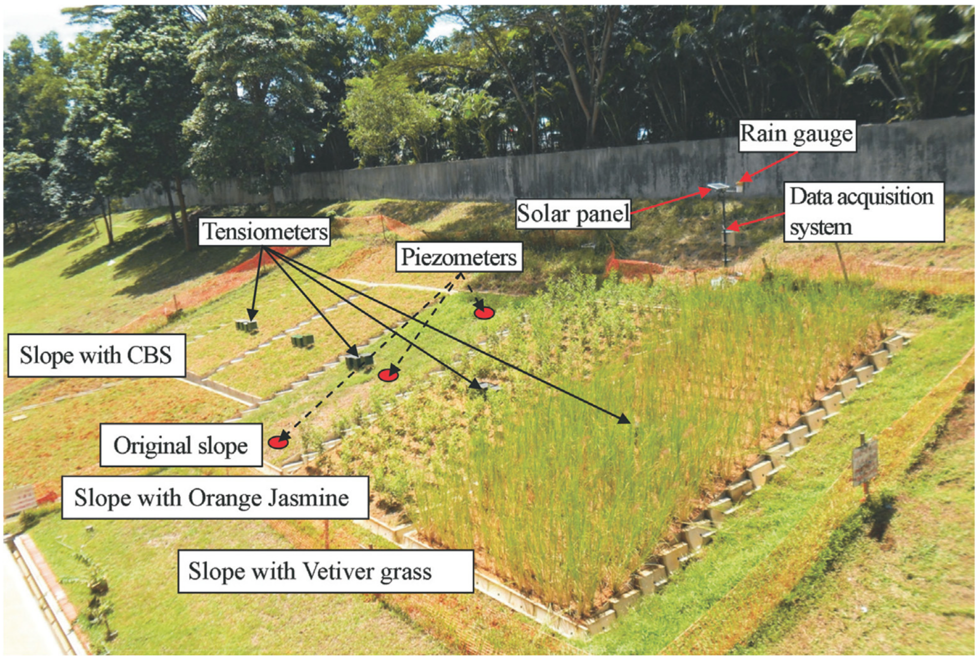


Figure 1. Vegetative covers in Singapore.

2.2. Capillary Barrier System (CBS)

A capillary barrier as a cover system is a two-layer system with distinct hydraulic properties designed to prevent water infiltration into the underlying soil by utilizing unsaturated soil mechanics principles. Rahardjo et al. [9] developed that CBS comprises two layers: one of non-cohesive fine-grained soil and another of coarse-grained soil (Figure 2). Under unsaturated conditions, the permeability of coarse-grained soil is lower than that of fine-grained soil. A barrier effect forms within the coarse-grained layer, directing water flow exclusively along the fine-grained layer. They concluded from the experiments that the Capillary Barrier System was effective in maintaining negative pore-water pressures during rainfall, particularly at the crest of the slope. Since rainwater infiltration is a prominent issue for slope failures, proper processes such as evaporation, transpiration, or lateral drainage situated at the slope's toe are essential. Therefore, recycled materials can be utilized for the fine and coarse layers, provided they meet the specified requirements for this approach.

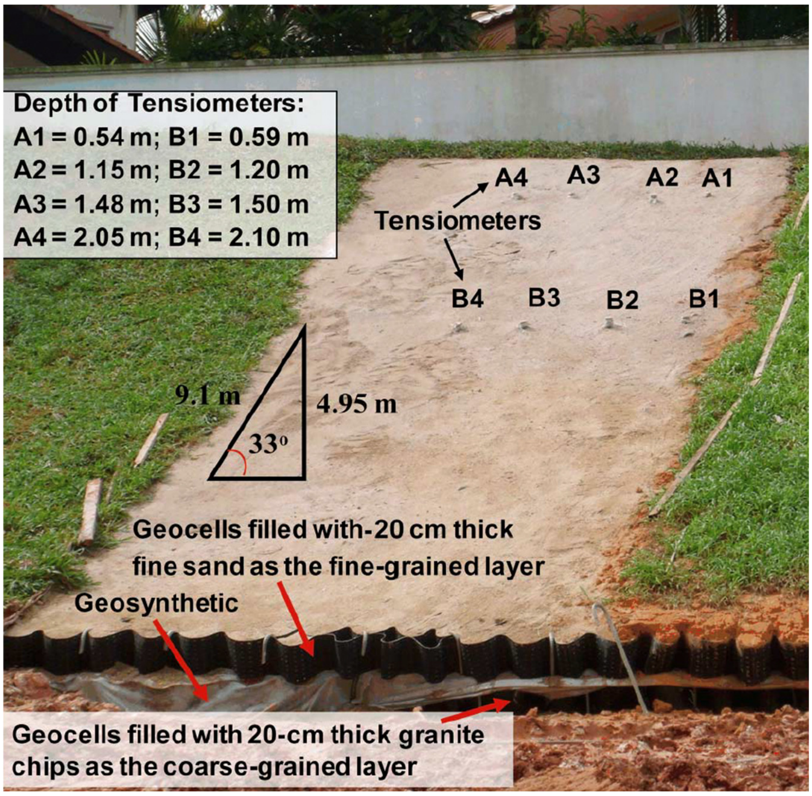


Figure 2. Capillary Barrier System in Singapore.

In addition, Scarfone et al. [15] stated that CBSs are effective when the slope angle falls between the friction angles of the underlying soil and the CBS materials. Slopes with very low angles are inherently stable without CBS, while those with very high angles may destabilize the CBS itself. Two primary operational principles of sloping Capillary Barrier Systems (CBSs) emerge based on the material used for the finer layer. Using finer materials like silty sand results in limited lateral water diversion, mimicking a horizontal CBS where rainwater is stored and then evaporates. This system is suitable for warm, dry climates with occasional heavy rains, where evaporation and rainfall are similar. A thicker, finer layer in this setup enhances water storage and evaporation efficiency. Alternatively, using a coarser material like fine sand allows the CBS to divert rainwater laterally down the slope via gravity, making it ideal for managing extreme rainfall events. In this case, a thicker, finer layer does not significantly boost diversion capacity because water diversion occurs within a thin sub-layer near the coarse layer interface.

2.3. Geobarrier System (GBS)

The GBS operates on the same principle as a CBS and serves two functions: as a retaining structure to support near-vertical excavated soil and as a slope cover to minimize rainwater infiltration and maintain slope stability during rainfall using the hydraulic properties of fine and coarse aggregates (Figure 3). Additionally, GBS reinforces the slope with geobags, which act as a retaining wall. Rahardjo et al. [11] reported that GBS combines reinforced soil walls to stabilize near-vertical cut slopes with capillary barrier principles to protect the wall from rainfall infiltration. Recycled materials are utilized instead of high-cost materials like steel or concrete. GBS also incorporates planting geobags with unique geosynthetic pockets for sustainable plant growth as the facing layer.

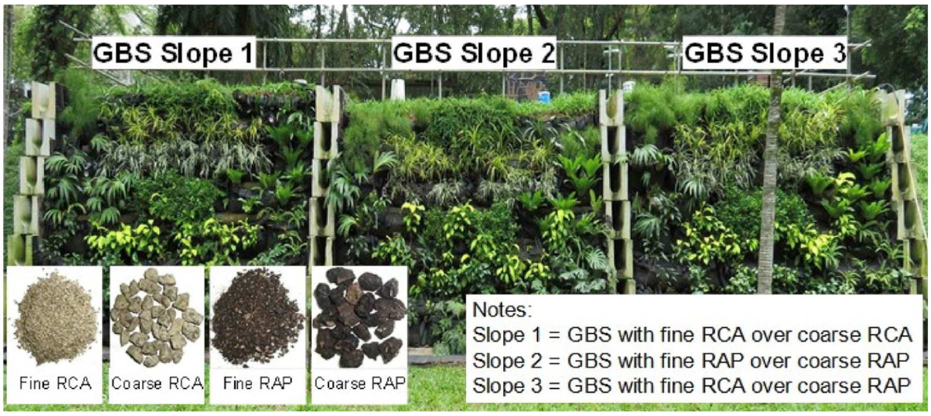


Figure 3. GeoBarrier Systems in Singapore.

In the same study, field and numerical investigations were conducted on a slope in Singapore to assess the feasibility of GBS. Rainfall and groundwater table variations within the GBS slope area were monitored using a rain gauge and piezometers. Changes in negative pore-water pressure (PWP) were monitored using tensiometers, while fluctuations in volumetric water content (VWC) were tracked with soil moisture sensors. The results showed that the PWP within the compacted residual soil remained nearly constant, suggesting minimal rainwater percolation during rainfall. Similarly, no changes in PWP were observed within the coarse-grained layer, indicating no breakthrough during heavy rainfalls. This suggests that the GBS effectively protected the slope from rainfall infiltration, maintaining its stability during heavy rainfalls.

In summary, the effectiveness of sustainable preventive measures, including vegetation covers, Capillary Barrier Systems, and GeoBarrier Systems, in enhancing slope stability through the application of unsaturated soil mechanics, as well as experimental and numerical approaches, has been documented in the literature.

3. Numerical Models and Materials

3.1. Slope Design in Singapore

A real slope failure was simulated to assess the feasibility of each slope rectification method in accordance with the regulations established by the Building and Construction Authority (BCA) in Singapore, allowing for the worst-case scenario to be considered under climatic conditions. Under the framework for risk-based slope designs by BCA, it is stated that a global slope stability analysis must be conducted for both Design Approach 1 Combination 1 (DA1C1) and Combination 2 (DA1C2) following SS EN 1997-1 guidelines [16].

Eurocode 7 (EC7) for geotechnical design employs Limit State Partial Factors, which are applied to the characteristic values of loads, material properties, and geometric data to account for uncertainties. Singapore adopts DA1C1 and DA1C2, as prescribed in the Singapore National Annex (NA) to SS EN 1997-1, outlined below:

$$DA1C1 = A1 + M1 + R1 \quad (1)$$

$$DA1C2 = A1 + M2 + R1 \quad (2)$$

The partial factors for DA1C1 and DA1C2 are taken from EC7, which states that in some situations, unfavorable (or destabilizing) and favorable (or stabilizing) permanent actions may be considered as originating from a single source. If this is the case, a single partial factor can be applied to the sum of these actions or to the sum of their effects, which is also commonly referred to as the "single source approach".

DA1C1 emphasizes safety in situations where the applied loads do not exceed the design resistance calculated using characteristic material properties, while DA1C2 emphasizes safety regarding materials and resistance, ensuring that even under factored soil conditions, the resistance remains adequate to handle the characteristic loads. The two combinations work together to create a robust and balanced safety framework by addressing uncertainties in both loads and material properties.

3.2. Study Area

Multiple slope failures occurred in January 2023, mainly due to heavy rainfall during the Northeast Monsoon season, which spans from December to March [17]. Figure 4 shows one of the scarp zones, where immediate temporary mitigation and safety measures were taken to protect against additional water infiltration and erosion.

Figure 4. Failed slope (**left**) and mitigation work undertaken (**right**) in Singapore.

The slopes are located within residual soil from the Jurong Formation, experiencing localized subsurface slippage. The residual soils of the Jurong Formation in Singapore exhibit significant variability due to in situ weathering processes and depth-dependent changes in composition. These soils are predominantly fine-grained near the surface, gradually transitioning to coarser particles at greater depths. The percentage of fine particles (silt and clay) decreases with depth, influencing key geotechnical properties such as permeability, shear strength, and air-entry value (AEV).

The AEVs of Jurong Formation soils are generally higher at the surface due to the greater presence of fine particles and decrease with depth as the soil becomes coarser. This trend is also reflected in saturated permeability, which increases with depth, indicating improved drainage characteristics in deeper layers. The effective cohesion (c') of the soil follows a decreasing trend with depth, while the effective friction angle (ϕ') and unsaturated shear strength angle (ϕ^b) exhibit an increasing trend, suggesting that deeper soils have higher inter-particle friction and reduced cohesion.

The soil variability in the Jurong Formation is broader than in other geological formations, such as Bukit Timah Granite and Old Alluvium. This is because the composition of the residual soil from the sedimentary Jurong Formation is derived from the weathering products of the sedimentary rock formation [18].

3.3. Numerical Analyses

The slope for the simulation was configured based on the soil investigation report, which was set to be 3H of the crest and the toe of the slope, with H being the height of the slope, as shown in Figure 5. This was performed to ensure that the lateral boundaries did not affect the slope stability analysis. Table 1 shows the breakdown of the parameters of the soil profile seen in Figure 5, which was used in the numerical analyses. The soil properties used in the stability analysis were obtained from a site investigation report for the rectification work. The shear strength parameters of the soil fell within typical ranges [18]. The slope model had a 35-degree slope angle and a 10 m slope height.

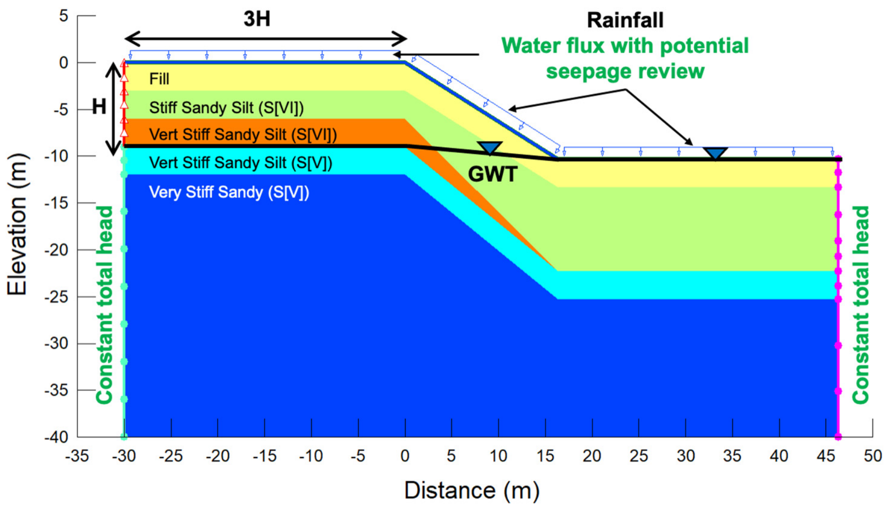


Figure 5. Geometry and boundary conditions for the simulated slope.

Table 1. Input parameters for the simulated slope.

Description	Unit Weight, γ (kN/m^3)	Effective Cohesion, c' (kPa)	Effective Friction Angle, ϕ' (°)	Unsaturated Shear Strength Angle ϕ^b (°)
Fill	18	3	28	21
Stiff Sandy Silt S(VI)	18	5	31	23
Very Stiff Sandy Silt S(VI)	20	8	32	24
Very Stiff Sandy Silt S(V)	20	10	32	24
Very Stiff Sandy S(V)	20	12	33	24

With the wide variety of functions available in GeoStudio, boundary conditions are necessary to streamline these functions to fit the objective of the analysis. According to BCA [16], an initial groundwater table (GWT), as illustrated in Figure 5, must be determined before starting a Seep/W analysis that includes rainfall infiltration. BCA assumes that the GWT will be at the surface at the toe of the slope and that the turning point of the GWT is located below the crest of the slope. These assumptions consider the worst possible scenario, which BCA intends the design to address.

For this project, the Water Standpipe (WSP) readings provided in the SI report indicate that the GWT is 9 m below the ground surface. There will be two separate sets of boundary conditions to control the flow of water in the soil, adhering to the requirements set by BCA. The first set of boundary conditions is established for the simulation of the initial GWT, which is set at a level of −9 m. The second set of boundary conditions is primarily for the rainfall infiltration simulations, which were applied to the surficial layer of the slope, as shown in Figure 5.

The rainfall events were incorporated into two cases. Rainfalls of 350 mm/day and 115 mm/5-day were applied uniformly to the soil surface in accordance with BCA requirements. In addition, the rainfall of 35.4 mm/day on the day of failure was uniformly applied. This value was extracted from NEA archives for rainfall data observed in the region where the failure site is located. The drainage systems used in these rectification methods were set to a no-flow condition to replicate rainwater draining and avoid any ponding situations.

For modeling vegetative covers on slopes, choosing the right types of vegetation is crucial for effective soil stabilization and erosion control. The selection criteria generally depend on the local climate, soil conditions, and the specific stabilization needs of the slope. In this study, the vegetative cover was planted at a depth of 0.6 m (Figure 6), and the simulations considered root lengths of 1 m [3]. The presence of plant roots with high tensile strength enhances the confining stress within the soil mass through their densely packed root matrix system. The impact of root reinforcement on shear strength is related to the role of cohesion, contributing significantly to the overall stability of the soil. Typical values of apparent root cohesion (cR) vary between 1 kPa and 17.5 kPa [15].

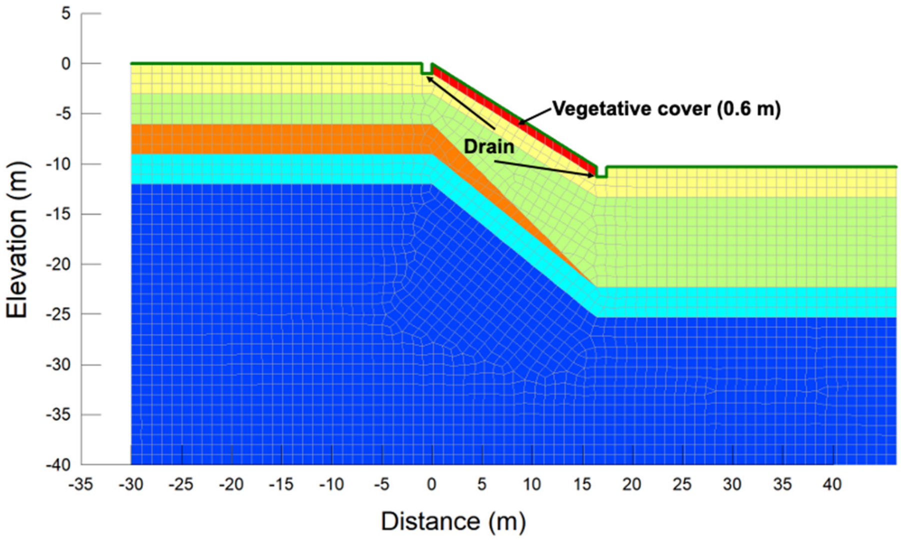


Figure 6. Finite element meshes for the vegetative cover.

For modeling CBS, recycled concrete aggregates (RCA) were used to form the coarse- and fine-grained layers of the CBS. The grain size analysis and classification of RCA were determined according to ASTM D2487-17e1 [19]. The coarse RCA could be classified as poorly graded gravel (GP), while the fine RCA is classified as poorly graded sand (SP). This suggests that the properties of fine RCA and sand do not differ significantly. Therefore, the properties used for this simulation were referenced from Figure 7, where the sand used in the analyses was assumed to be finely graded RCA. The dimensions used for the CBS model were 0.2 m for the fine layer and 0.4 m for the coarse layer. The coarser layer functions as an impermeable barrier until it reaches a critical condition known as a breakthrough, which typically occurs when the finer layer achieves a high degree of saturation [15]. The thickness of the coarser layer does not impact the performance of the CBS as long as it exceeds the minimum thickness of approximately 2 cm. In this study, a thickness of 40 cm was selected as the minimal realistic value that can be implemented on-site without causing significant tolerance issues.

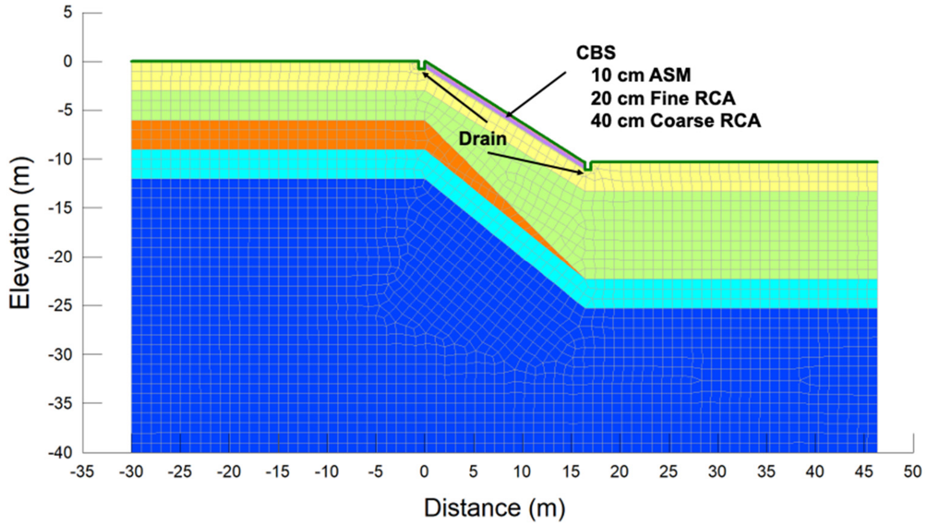


Figure 7. Finite element meshes for the CBS.

For the GBS, the concept is similar to the CBS, with additional components that were modeled in layers to represent each of the components (Figure 8). The GBS consists of compacted residual soil (the reinforced zone), geogrids, fine RCA, coarse RCA for the capillary barrier cover, and ASM for the sustainable green cover. The GBS is implemented on a steep slope of 70 degrees with additional reinforcement elements.

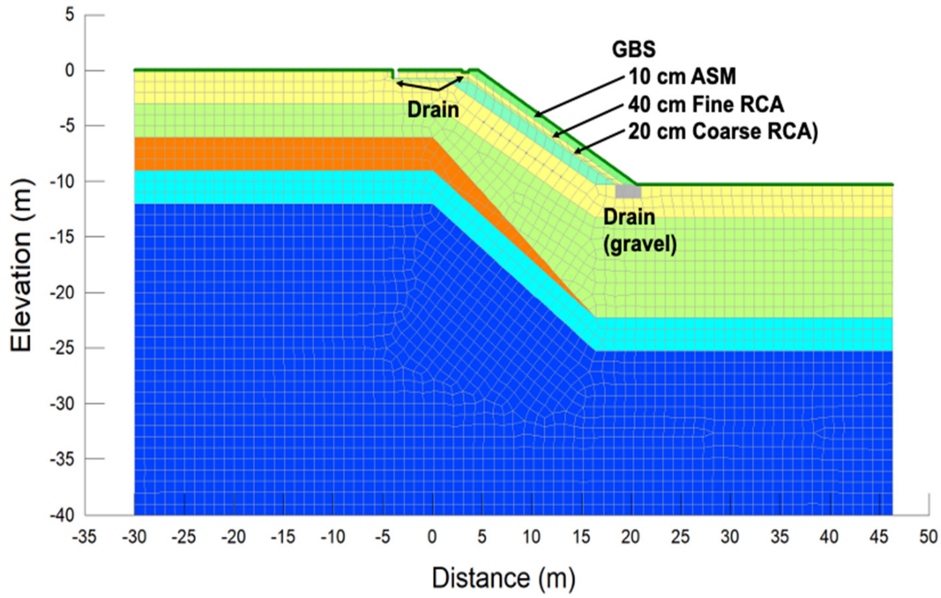
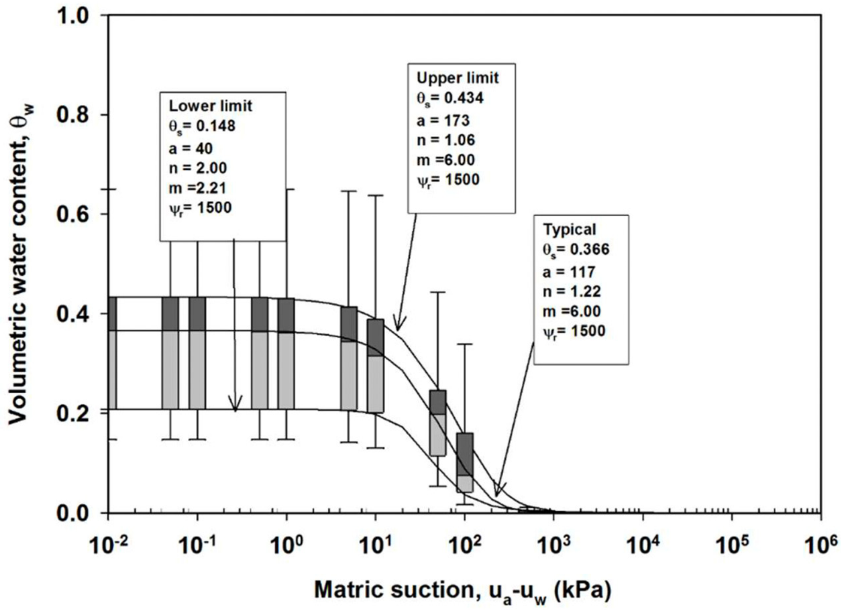


Figure 8. Finite element meshes for the GBS.

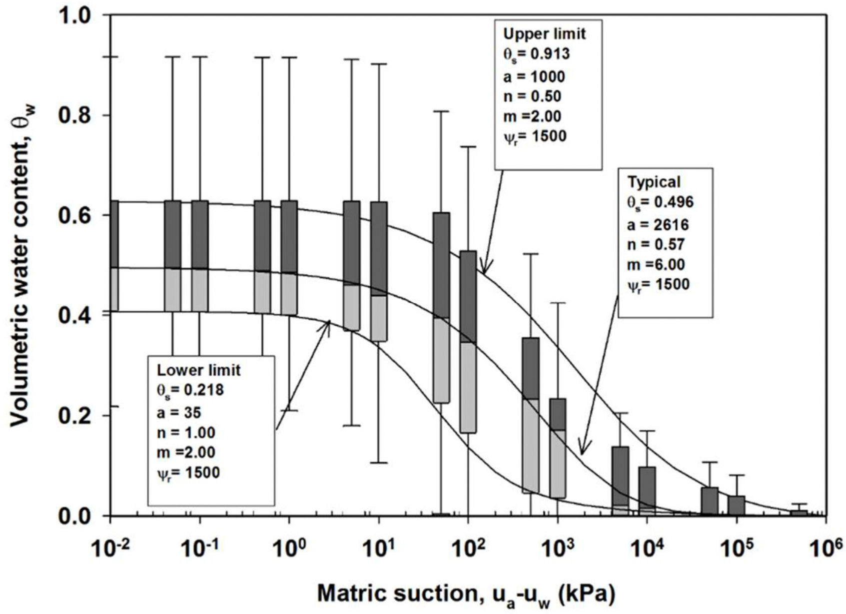
In this study, the natural slope reinforced with the GBS was analyzed for a comparative study. The software allows users to utilize a wide range of methods to calculate slope stability. It employs the method of slices to evaluate slope stability under various conditions, including complex scenarios. Slope/W supports multiple analysis methods, making it a vital tool for assessing and designing slope stabilization measures in diverse geotechnical projects. Each method has its own statistical equations employed for calculations. In this study, Bishop's simplified method was used for the simulation, following the study by Kim et al. [6].

Some assumptions were made for the parameters of the soil properties, as some of these data would only be attainable through specific laboratory testing. The key parameters that were assumed were the Soil Water Characteristic Curve (SWCC) and ϕ^b used for each of the soil layers. SWCC defines the relationship between water content and the suction (negative pore-water pressure) of the soil [20]. This relationship is used for modeling water flow through saturated-unsaturated systems and for estimating the engineering properties of unsaturated soil, such as permeability and shear strength.

In relation to the soil investigation report provided, the SWCC curves used for these soil layers in the model are shown in Figure 9. Based on the index properties of the investigated soil, the typical SWCC (middle line) of clayey, silty sand was deemed relevant for use as the unsaturated properties in the seepage analyses.



(**a**)



(**b**)

Figure 9. Typical SWCC for seepage analyses. (**a**) Clayey silty sands for the fill layer. (**b**) Sandy silts for the rest of the soil layers.

The value ϕ^b refers to the angle of the increase in shear strength due to matric suctions. Since the ϕ^b value is not specifically provided for each of the soil layers, an assumption was made at 75% of the ϕ' angle. The parameters used for the vegetative cover layers, CBS, and GBS are summarized in Table 2.

Table 2. Input parameters used in the simulation for vegetation cover, CBS, and GBS.

Description		Unit Weight, γ (kN/m^3)	Effective Cohesion, c' (kPa)	Effective Friction Angle, ϕ' (°)	Unsaturated Shear Strength Angle ϕ^b (°)
VC	Vegetative cover	21.4	10	34	19
CBS	Fine RCA	19.0	0	34	0
	Coarse RCA	25.0	0	35	0
GBS	ASM	16.6	2	30	15
	Fine RCA	20.0	0	34	17
	Coarse RCA	21.0	0	35	17
	Gravel	21.0	0	35	17
	Compacted soil	20.0	5	38	14

4. Results

In the SeepW simulation, four sets of simulations were conducted for each of the rectification methods. The first simulation was performed to generate the GWT of the site in accordance with BCA standards. The following two sets of simulations were carried out in accordance with the load cases set by BCA, with Load Case 1 being 350 mm/day for 24 h and Load Case 2 being 115 mm/day for 5 days. The third set of simulations, Load Case 3, used the same rainfall amount that caused the failure on-site, set at a flux load of 35.4 mm/day. This was performed to evaluate the effectiveness of the rectification methods under rainfall conditions.

An initial set of simulations was conducted on the bare slope without any rectification methods. This was performed to facilitate comparative studies between the rectification methods and to evaluate the effectiveness of each method. The figures below show the results of the SeepW simulation for the bare slope. It is evident that the pore-water pressure above the GWT increases once rainwater infiltration is applied. The initial simulation indicated a negative pore pressure of −100 kPa to −50 kPa in the regions above the GWT. In the following simulations, it can be seen that the pore pressure in the same region has increased from approximately −50 kPa to 0 kPa, as shown in Figure 10. The GWT has also risen in height compared to the initial analysis. This indicates a decrease in negative pore pressure, signifying a reduction in shear strength, making the slope more susceptible to failure.

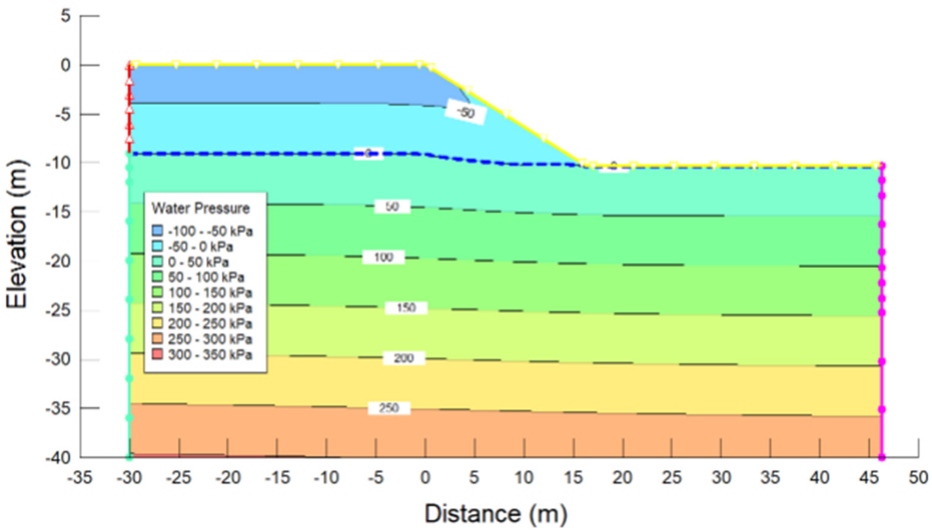


Figure 10. Pore-water pressure distribution after the rainfall of 35.4mm/day for 24 h.

Figure 11 shows one of the results for the rectification method under Load Case 1. The pore-water pressure has improved, as the region above the GWT has managed to retain a pore pressure of −50 kPa, with some regions still in the range of −100 kPa to −50 kPa. The level of the GWT has also remained unchanged, indicating no increase in GWT. Portions of the ground surface at the crest of the slope still indicate water pressures of −50 kPa to 0 kPa. However, these portions are not part of the slip surface of the slope and can be mitigated through surface drainage.

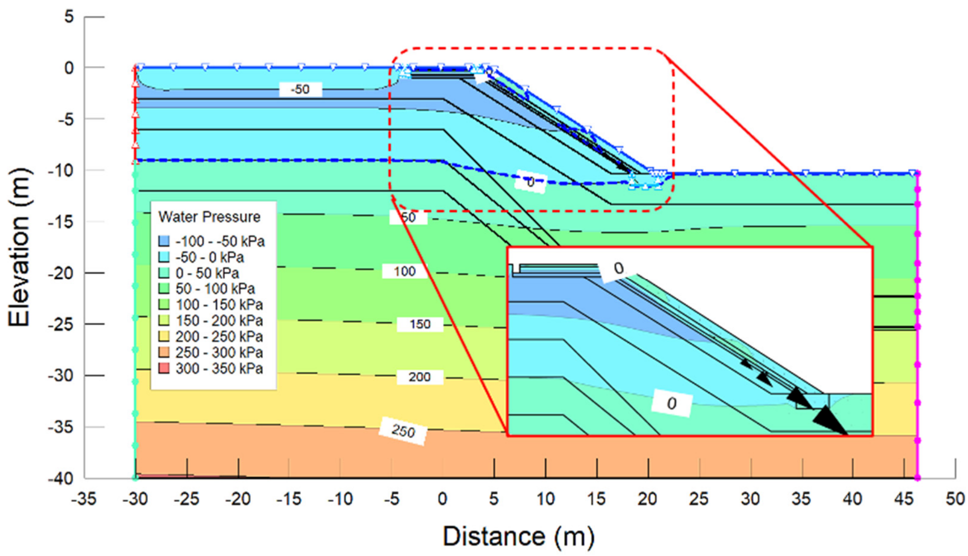


Figure 11. Pore-water pressure distribution after rainfall of 350mm/day for 24 h (GBS).

Figure 12 shows one of the results for the rectification methods under Load Case 2. The soil is increasingly saturated due to the longer duration of water infiltration. However, when compared to the previous simulations, there is a significant improvement in negative pore pressure, with an increase of approximately 50 kPa. The GWT has also remained at its initial level, with slight variations in certain portions.

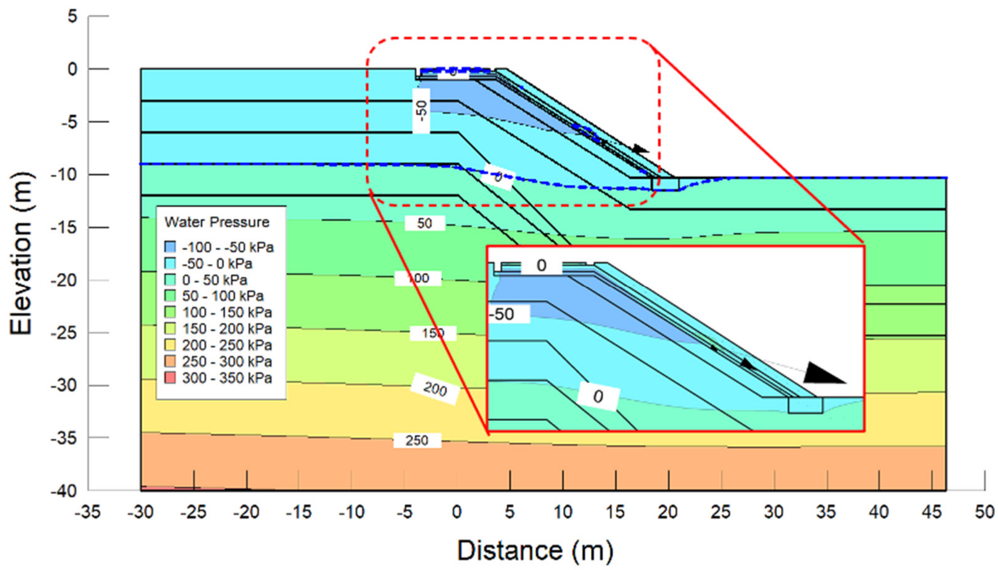


Figure 12. Pore-water pressure distribution after transient simulation with 115mm/day rainfall for 5 days for GBS.

Figure 13 shows one of the results for the rectification methods under Load Case 3. With a lower amount of rainfall, the soils are not as saturated compared to the previous two load cases. The negative pore pressure has also significantly improved by approximately 50 kPa.

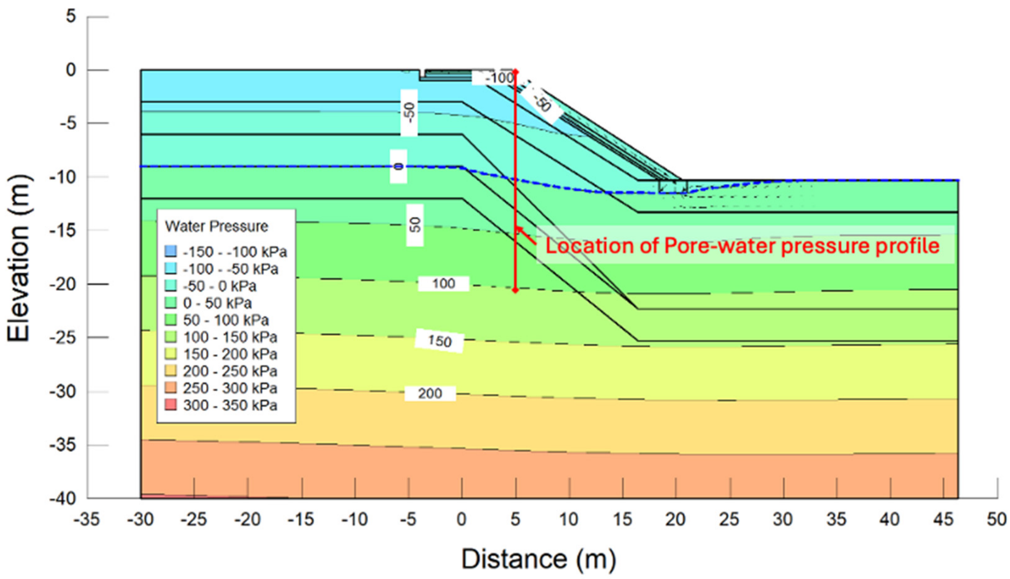


Figure 13. Pore-water pressure distribution after transient simulation with 35.4mm/day rainfall for 24 h for GBS.

Figure 14 shows pore-water pressure profiles of the simulated slopes through 20 m of depth for the two load cases. It is evident that the pore pressure of the bare slope is significantly higher compared to the rectification methods. This indicates that the rectification methods are successful in mitigating rainwater infiltration, as the pore pressures remain in the high negative regions.

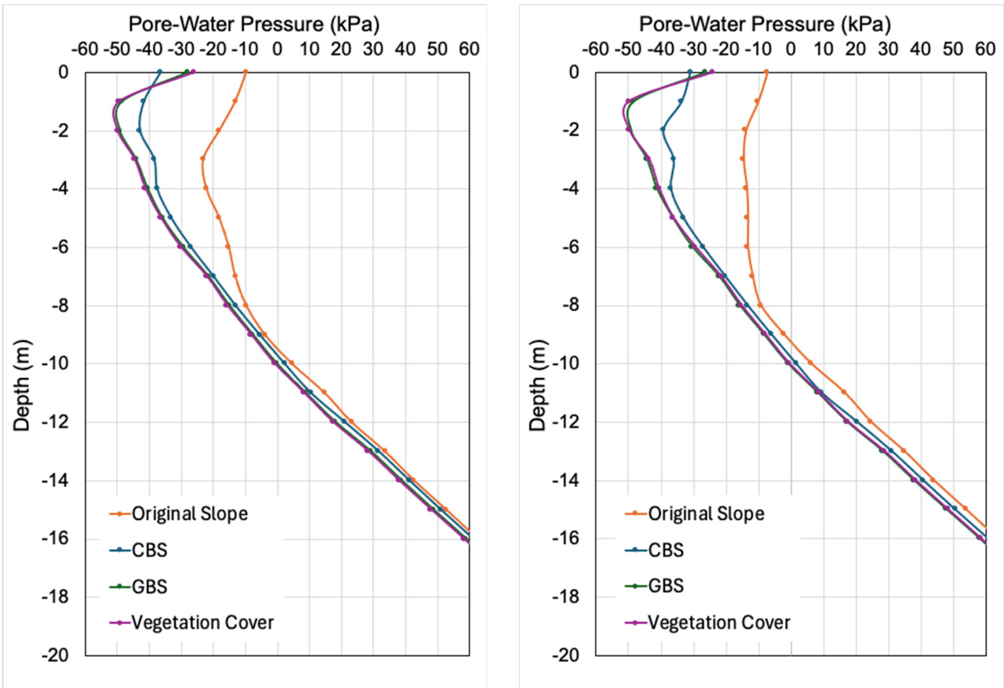


Figure 14. Pore water pressure profiles under different load cases. (**a**) Rainfall of 350 mm/day (Load Case 1). (**b**) Rainfall of 115 mm/5-day (Load Case 2).

It is also shown that the pore-water pressures at the surface for CBS are slightly higher compared to the other methods. However, the other methods are slightly more effective in maintaining negative pore pressure throughout the depth. The results from the three load cases show very similar trends, demonstrating that all the rectification methods exhibit comparable effectiveness in maintaining negative pore pressure on the slope surfaces.

The results from the SeepW analysis serve as the parent analysis for the SlopeW analysis, where the Factor of Safety (FOS) and Overdesign Factor (ODF) for Eurocode 7 (EC7) were determined. There are two methods for generating results in SlopeW: the Entry and Exit method and the Grid and Circle method. Both methods were used to verify the accuracy of the simulation. There is a slight difference between the two methods, but only by 0.1 to 0.2. The deviation in results is primarily due to the way settings are configured for the simulation. The Entry and Exit method assumes every slip circle is within the ranges defined by the user, while the Grid and Radius method requires the user to specify the center point of the slip circle through a grid and define the limits of the circle through tangent lines. These differences are not significant enough to cause major variations in results, as the values produced remain very similar.

SlopeW allows for time-step analysis, which shows the FOS and ODF at specific time intervals set by the user. These data can then be extracted and plotted into a graph for comparative studies, as shown in Figures 15–17. The SlopeW stability analyses indicated that the slip surface was observed within the first soil layer and classified as a circular failure surface. Therefore, the variations in FOS were calculated based on this circular failure surface. The orange lines represent the FOS trend for the bare slope. It is evident that the rectification methods successfully maintain the FOS throughout the simulations, demonstrating their effectiveness in ensuring slope stability under different rainfall conditions. However, the results reveal that the FOS for the GBS was the lowest among the rectification methods. This is primarily due to assumptions made above material parameters used in the GBS, which resulted in increased driving forces compared to those of other materials. However, the FOS of GBS remained constant even during rainfall, indicating that GBS performs well in maintaining slope stability.

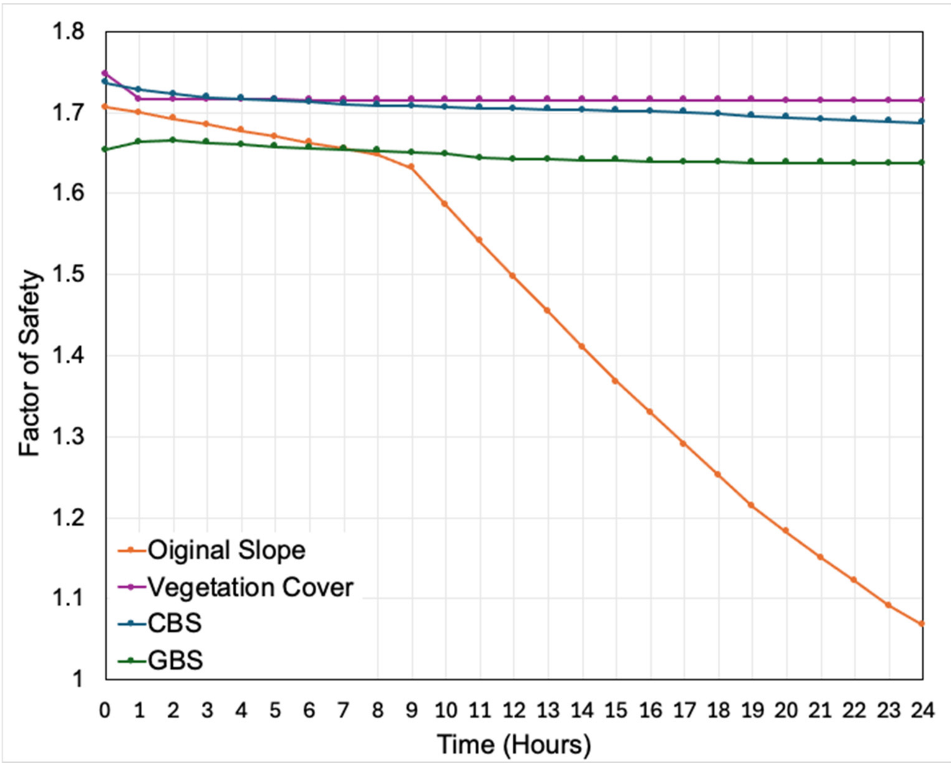


Figure 15. Factors of safety for Load Case 1.

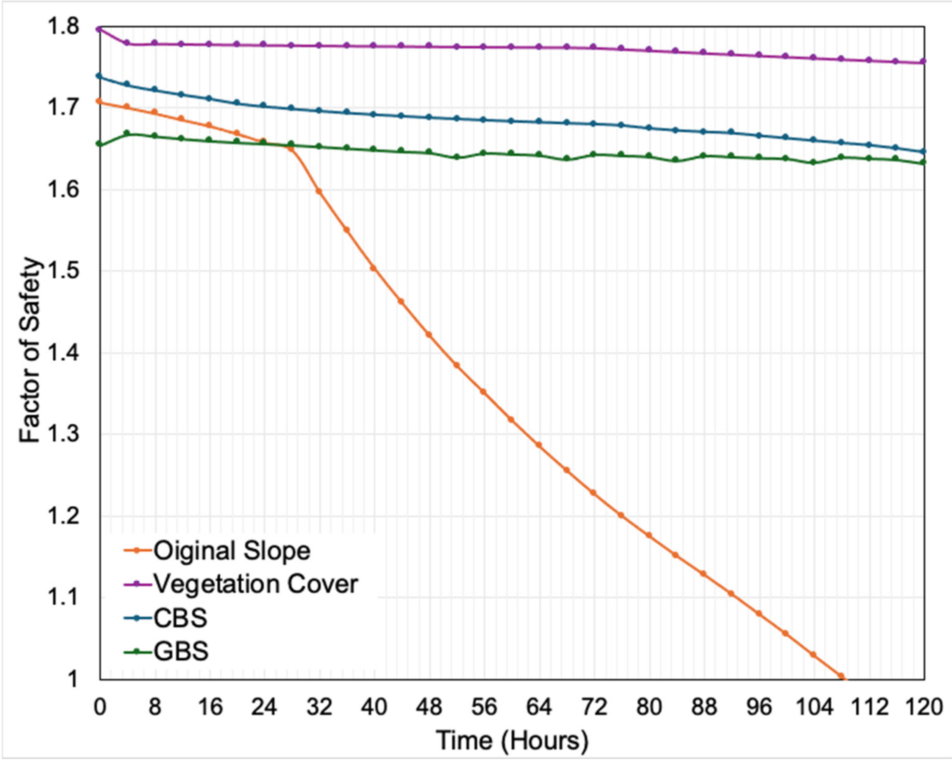


Figure 16. Factors of safety for Load Case 2.

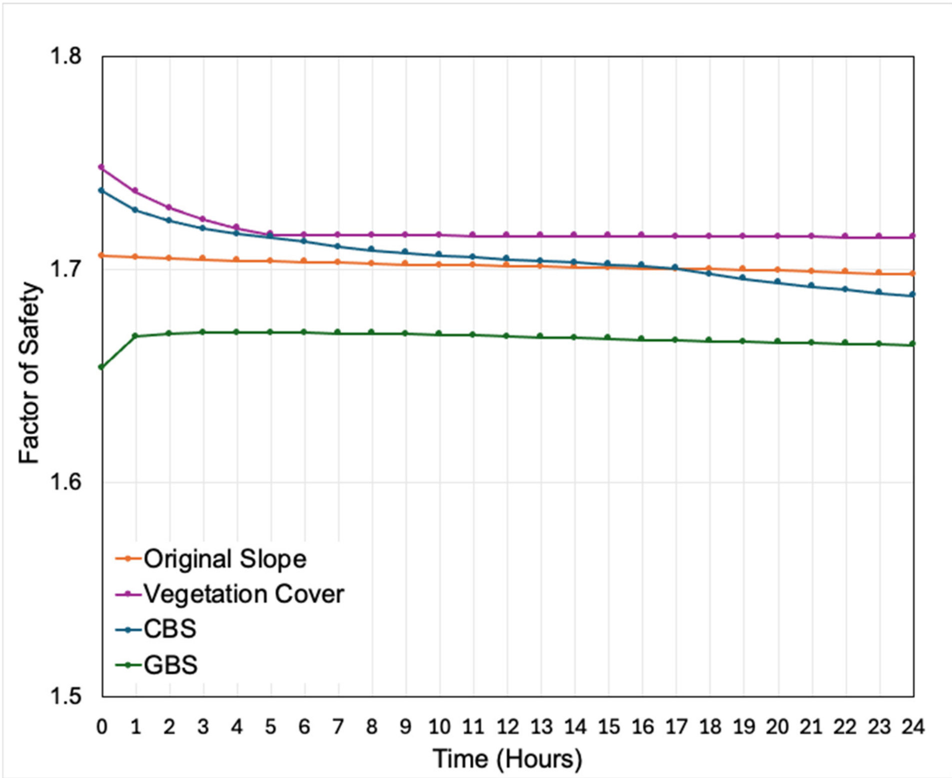


Figure 17. Factors of safety for Load Case 3.

The general trend of decrease in the ODF is similar to the trend of FOS, where the ODF is maintained throughout the rainfall simulation, as shown in Figures 18 and 19. This confirms that the rectification methods are effective in maintaining slope stability using sustainable approaches. The results also highlight that each rectification method offers distinct advantages through simulations. The comparative analysis indicates that CBS provided significant moisture control, as the pore pressure for CBS was relatively lower compared to the other rectification methods. The simulation also indicates that GBS provides moisture control, although not as effectively as CBS. While vegetation covers are less effective in moisture control, they contribute to erosion control and ecological benefits.

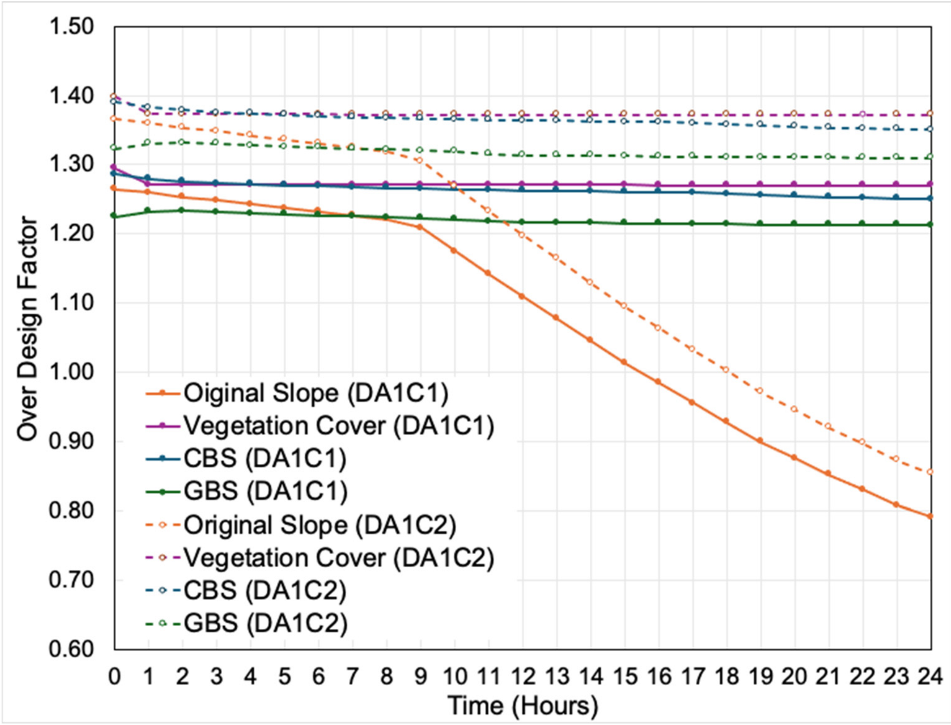


Figure 18. Over design factor for Load Case 1.

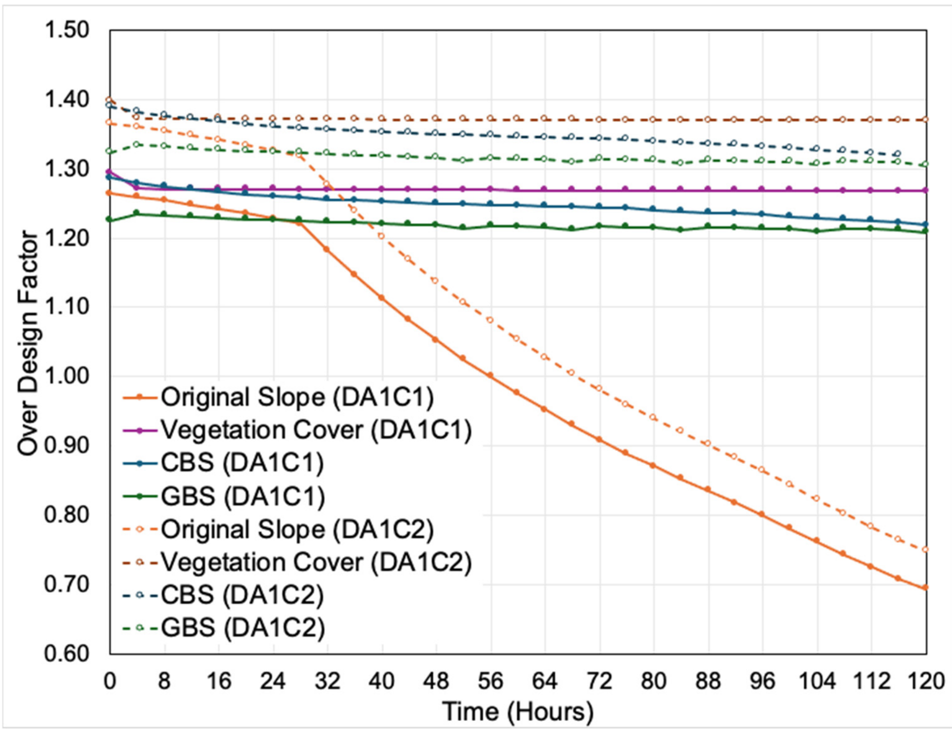


Figure 19. Over design factor for Load Case 2.

5. Discussion

The study confirms the effectiveness of vegetation covers, Capillary Barrier Systems (CBSs), and GeoBarrier Systems (GBSs) as eco-friendly methods for slope stabilization under varying rainfall intensities in Singapore. Each method demonstrated a unique approach to enhancing slope stability. The vegetation cover method showed its advantages in erosion control and ecological sustainability, utilizing plant roots to bind soil particles and improving water absorption. This method, however, was less effective in moisture control under prolonged rainfall conditions compared to CBS and GBS. Nevertheless, vegetation is valuable for its simplicity and lower maintenance, offering a sustainable approach for slopes in areas with moderate rainfall.

The CBS, constructed with fine and coarse aggregate layers, effectively mitigated rainwater infiltration by creating a barrier that channels water along specific paths. This study demonstrates that the CBS achieved greater moisture control than vegetation alone, making it suitable for areas prone to heavy rainfall. The CBS design limits water infiltration by maintaining unsaturated conditions in the soil, reducing the likelihood of slope failures. However, it is essential to consider that CBS performance can vary based on the thickness and properties of the materials used, such as grain size and hydraulic characteristics. This variability suggests the need for site-specific adjustments to ensure optimal performance in different geographic locations.

GBS combines the principles of CBS with a structural component, adding reinforced soil walls and geobags to stabilize near-vertical slopes effectively. The study showed that GBS performed well under intense rainfall, retaining its structural integrity and preventing significant shifts in pore pressure. This method is particularly advantageous for steep slopes, where traditional methods might fail, as the reinforced geobags provide additional support. Despite its effectiveness, GBS may require a higher initial investment and more maintenance than vegetation covers. However, it could be a preferable option for slopes with higher risk factors or slopes near infrastructure, where additional stability is critical.

Comparative analysis of the three methods reveals that CBS and GBS are highly efficient at moisture control, while vegetation covers excel in ecological contributions. The integration of vegetation with CBS or GBS could provide a balanced approach, where the structural integrity offered by CBS or GBS is complemented by the erosion control benefits of vegetation. This combined strategy aligns with sustainable urban planning goals, as it would allow for reduced soil erosion and enhanced aesthetic value while maintaining slope stability under various rainfall conditions.

Future research should focus on long-term field studies to evaluate the durability and maintenance needs of CBS and GBS in Singapore's tropical climate. Additionally, it would be beneficial to examine how varying plant species in vegetation covers influence overall slope stability and erosion control. Such insights could guide the selection of stabilization methods best suited for specific environmental conditions and contribute to developing more resilient urban landscapes. Moreover, as the combination of CBS and GBS has already been implemented in Singapore, a comprehensive assessment of their synergistic effects is necessary. This should involve quantifying the infiltration behavior and deformation response of integrated CBS-GBS systems under extreme rainfall conditions and prolonged wetting-drying cycles. Advanced numerical modeling and in situ monitoring techniques should be employed to refine design parameters and improve predictive capabilities for slope stability management.

6. Conclusions

The analysis has demonstrated the efficacy of CBS, GBS, and vegetation covers in enhancing slope stability, utilizing GeoStudio software for simulations. The comparative analysis indicates that each method offers distinct advantages, with CBS providing significant moisture control, GBS ensuring robust structural integrity, and vegetation covers contributing to erosion control and ecological benefits. Integrating these systems can offer a holistic approach to slope stabilization, where the strengths of each method are harnessed to address various aspects of slope failure mechanisms. The simulations underscore the importance of considering site-specific conditions and combining methods to achieve optimal results.

In conclusion, the implementation of CBS, GBS, and vegetation covers, supported by advanced simulation tools like GeoStudio, offers a comprehensive and effective approach to slope stability, addressing both immediate and long-term challenges in geotechnical engineering.

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