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Enhancing Slope Stability in High-Rainfall Regions: Insights from Genting Highlands for Long-Term Geomaterial Performance

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ABSTRACT

Slope stability issues are a critical aspect of civil engineering, particularly in tropical regions like Malaysia, where extreme weather fluctuations and high rainfall frequently trigger slope failures. The combination of steep terrain and intense precipitation significantly increases the risk of landslides, threatening infrastructure, human settlements, and environmental sustainability. This research investigates the impact of heavy rainfall on slope instability at the Aminuddin Baki Institute, Genting Highlands, Pahang, Malaysia, an area characterized by complex topography and high precipitation. Using advanced geotechnical tools, SEEP/W for simulating rainfall infiltration and SLOPE/W for stability analysis, this study assesses slope performance under saturated conditions and evaluates three stabilization techniques: micro-helical anchors, soil nailing, and geotextiles. The analysis showed that rainfall-induced infiltration reduced the slope's Factor of Safety (FOS) to 1.257, indicating a failure-prone condition. Upon implementing reinforcement methods, FOS values improved to 1.685 (micro-helical anchors), 1.647 (soil nailing), and 1.605 (geotextiles), corresponding to percentage improvements of 34.0%, 30.9%, and 27.7%, respectively, relative to the unreinforced condition. All methods exceeded the JKR minimum safety threshold of 1.5 for reinforced slopes. Among them, micro-helical anchors demonstrated the best performance due to their deeper engagement and anchoring mechanism. These findings highlight the importance of selecting effective and site-appropriate reinforcement strategies. The study contributes valuable insights into cost-effective and sustainable slope stabilization techniques suitable for landslide-prone, high-rainfall environments.

Keywords: micro-helical anchor; soil nailing; geotextile; landslide; rainfall infiltration; slope stability; back analysis; seepage analysis

INTRODUCTION

Slope rehabilitation, the process of stabilization of displaced soil mass (Usluogullari et al. 2016), is critical in Genting Highlands, Pahang due to significant natural threats. These threats, driven by topography and weather conditions, necessitate effective stabilization methods to protect lives and property (Dewedree & Jusoh 2019). According to Fredlund et al. (2012), the unsaturated soil above the groundwater table can be described as a three-phase system comprising solids, air, and water with an additional contractile surface linked to soil matric suction. Rainfall infiltration changes soil matric suction, significantly affecting stress and contributing to slope instability (Lias et al. 2022; Mohamed Yusof et al. 2025; Mohd Noor et al. 2025)
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This research utilizes the two-dimensional (2D) Limit Equilibrium Method (LEM) in SLOPE/W for stability analysis and the Finite Element Analysis (FEA) in SEEP/W for back analysis of rainfall-induced seepage. The study aims to assess the stability of the existing slope before remediation using SEEP/W and SLOPE/W while also evaluating and comparing the effectiveness of proposed remediation techniques in SLOPE/W to determine the most suitable stabilization approach. According to Fredlund & Krahn (1978), identifying the critical slip surface is essential for an accurate slope stability assessment. To achieve this, the research integrates two specific approaches: back analysis of slopes using SEEP/W and the development of remedial solutions using SLOPE/W. SEEP/W employs the finite element method (FEM) to simulate water movement through porous media like soil, enabling a detailed representation of complex seepage conditions (Ltd., 2015).

By dividing the soil into small, discrete elements, FEM provides a precise model of seepage behavior (Fredlund et al. 2012). SEEP/W solves the governing equations of fluid flow to calculate pore water pressure distributions and hydraulic gradients within the soil, offering critical insights into the effects of seepage on slope stability (Ltd., 2015). This approach enables accurate prediction of water flow paths and seepage rates, which are essential for understanding the hydraulic behavior of slopes (Griffiths & Lane 1999). SEEP/W's FEA capabilities help identify critical areas where pore water pressure could lead to reduced soil strength and potential slope instability (Ltd., 2015). The software can model both steady-state and transient conditions, reflecting the real-time changes in water movement due to varying environmental factors (Fredlund et al. 2012). The integration of SEEP/W with other geotechnical analysis tools, like SLOPE/W, allows for comprehensive stability assessments by providing detailed hydraulic inputs for limit equilibrium methods (Ltd., 2015). This combined approach enhances the accuracy and reliability of slope stability evaluations, particularly in complex geological settings (Griffiths & Lane 1999).

Most researchers conduct slope stability analyses using traditional limit equilibrium methods, which typically involve slice methods (Griffiths & Lane 1999). Complicated stratigraphy, extremely irregular pore-water pressure conditions, different linear and nonlinear shear strength models, different slip surface forms, concentrated loads, and structural reinforcements are just a few of the more complicated assessments that limit equilibrium software like SLOPE/W can manage.

SLOPE REHABILITATION SOLUTIONS

A micro – helical is a type of deep foundation that consists of a central steel shaft with one or more welded helical plates (Lanyi-Bennett & Deng, 2019). Micro - helical are passive components that rely on soil displacement to activate shear strength along the nail (Goyal & Shrivastava, 2022) as shown in Figure 1. Micro – helical can mitigate slope failure by increasing shear strength, reducing shear stress, and improving drainage. Acting as soil nail anchors, they rely on bond stress along the cylindrical surface defined by the helix plates (Deardorff & Engineer, 2014). The ultimate pullout capacity of a multi-blade anchor results from both the shear forces along the soil cylinder between the blades and the load-bearing capacity of the uppermost blade.

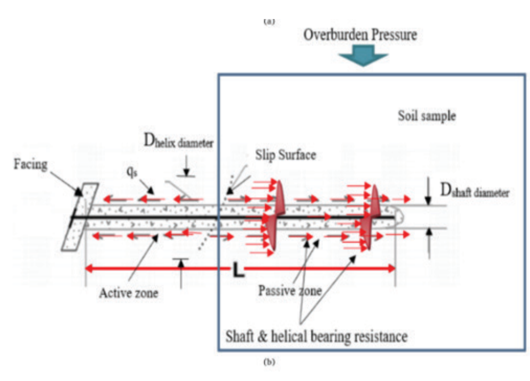


FIGURE 1. Micro - helical as slope rehabilitation solutions (Goyal & Shrivastava 2022)

Therefore, in a micro-helical system, the factor of safety (FOS) is influenced by the geometry of the helical anchors, the shear strength parameters of the soil, and the material properties used for the micro-helical anchors themselves. The FOS was calculated using the relation given:

$$FOS = \frac{Q_u}{Q_s}$$

Where:

Q_u = Ultimate capacity of the micro – helical (kN)

Q_s = Pullout load (kN)

According to Hu et al. (2010), the geotextile plays a crucial role in influencing the deformation of the slope, enhancing its stability, and impacting the modes of failure. Geotextile contributes to enhanced soil moisture levels by minimizing evaporation, increasing percolation, and increasing water retention within the soil (Shao et al. 2014). This proves particularly crucial in the context of slope in this case study, as soil layers in such areas typically display elevated bulk density, diminished porosity, and restricted infiltration capabilities. In stabilization methods, geotextile plays an important role as a reinforcement for increasing the tensile strength of the soil, thus enhancing the overall stability of the slope. By preventing soil particles from moving while allowing water to pass through, geotextiles effectively reduce pore water pressure and improve the slope's load – bearing capacity. According to Koerner (1994), there are three different mechanisms of geotextile which are membrane type, shear type, and anchorage type.

Soil nails are horizontal support elements installed through drilling and grouting to reinforce soil or soft and weathered rock excavations (Carlos, 2015). Their effectiveness is enhanced by interactions between soil and nails, increasing the resistance to soil changes and creating tensile forces on the nails (Dewedree & Jusoh, 2019). This interaction primarily develops tensile force. Budania (2018) explains that soil nailing improves slope stability by:

1. The normal strength of the shear plane is directly proportional to the shear resistance in frictional soil.
2. To enhance the stability of the slope, the driving force is reduced at the slip plane from the frictional and cohesive soil.

The soil-nail system has active and passive resistance to deformation in the active zone (Budania 2018). The system has two primary functions: first, it serves as a load bearer as shown in Figure 2, transferring loads generated by soil movement in the 'active' unstable zone at the front of the slope along the soil nail bar into the bond length of the bar, which is situated in the passive and stable 'resisting' zone of the slope (Lindsay et al. 2015). While reducing the applied shear force, the tension force increases the normal force on the slip plane. By using friction between the nails and the soil, soil nails anchored in the passive zone reduce pull-out pressures from the slope (Budania 2018). In light of these processes, it is necessary to put nails of a sufficient length in the resistant zone. Furthermore, the impact of the nail head strength and the tension force produced in the active zone must be coupled to guarantee the necessary nail tension at the slip surface (Shiu & Chang, 2004).

Previous studies on slope stability in tropical regions have primarily focused on general rainfall-induced failures without site-specific analysis or comparative evaluation of multiple stabilization techniques. This study addresses that gap by conducting a focused investigation at the Aminuddin Baki Institute, integrating advanced modeling tools and directly comparing the effectiveness of three stabilization methods under the same conditions.

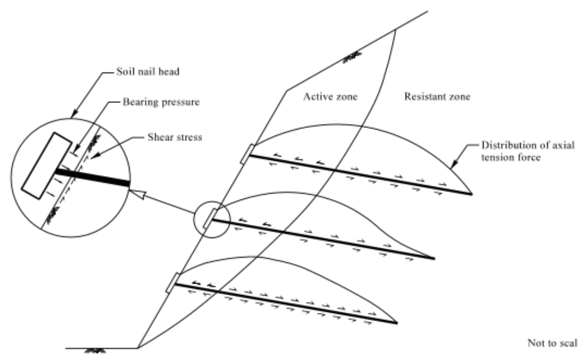


FIGURE 2. Mechanism of load transfer in a soil nail slope (Lindsay et al. 2015)

METHODOLOGY

At an elevation of 1800 meters, Genting Highlands is located at the top of Ulu Kali Mount in the Titiwangsa Mountains in the center of Peninsular Malaysia. The Genting Highlands' location, temperature, and human activity all have an impact on its geological state as shown in Figure 3. According to the Malaysian Public Works Department's (2022) site investigation report, the Genting Highlands location is primarily composed of granitic rocks from the Main Range batholith as shown in Figure 4, which have intruded into folded and regionally metamorphosed Paleozoic rocks because of its eastern Kuala Lumpur location. There are three major granitic rock bodies: Bukit Tinggi Granite, Genting Sempah Microgranite, and Kuala Lumpur Granite. A metasedimentary screen separates the primary rock mass, Kuala Lumpur Granite, from Genting

Sempah Micrograinite. Along the Bukit Tinggi Fault Zone in the northeastern portion of the research area, Bukit Tinggi Granite is an elongated body that comes into contact with Genting Sempah Microgranite. Therefore, the Aminuddin Baki Institute in Genting Highlands, Pahang, has been selected as the study's location. The site was selected due to its complex topography, history of slope failures, and consistently high rainfall levels, making it an ideal case for investigating the relationship between intense precipitation and slope instability.

The performance of the existing slope and proposed slope rehabilitation methods—micro-helical anchors, geotextiles, and soil nailing was evaluated using both finite element analysis (FEA) and the limit equilibrium method (LEM). SEEP/W was used to back analyze the current slope in order to assess the impact of rainfall events. In the meantime, SLOPE/W was used to examine the proposed slope rehabilitation methods. The performance of the existing slope was evaluated by comparing its Factor of Safety (FOS) before and after the rehabilitation work. The Malaysian Public Works Department (2022), carried out soil investigation at the failing slope, utilizing Mackintosh probe tests and boreholes to determine the soil characteristics of the impacted land. Along with the cross-section displayed in Figure 5, the Site Investigation (SI) report presents data from three boreholes, BH1, BH2, and BH3. In order to create a soil profile of the slope and ascertain the dimensions and properties of the soil layers, as shown in Figures 6 (for BH1 and B3) and 7 (for BH2), the SI data are crucial. While Table 1 summarized the soil parameters used in SLOPE/W whilst Table 2 summarized the parameters used in SEEP/W. The mechanical parameters (Table 1) ensure accurate simulation of shear strength and slope geometry. The hydraulic parameters (Table 2) enable realistic simulation of infiltration during rainfall, a key triggering factor for slope failure. These parameters are essential for performing limit equilibrium analysis of slope stability using the Mohr-Coulomb failure criterion, a widely accepted model for simulating the shear strength of soils. The Mohr-Coulomb model is selected for all materials due to its suitability in representing frictional and cohesive soils commonly found in tropical slopes. Phi-B is set to 0 due to assumed saturated conditions in SLOPE/W; a constant piezometric line value (1.00) simplifies modeling rainfall-driven saturation scenarios. The hydraulic parameters (Table 2) enable realistic simulation of infiltration during rainfall, a key triggering factor for slope failure. The Van Genuchten model is used for both soils because it effectively represents unsaturated hydraulic properties in fine-grained soils. Ky/Kx Ratio assumed as 1 to indicate isotropic flow conditions, simplifying the analysis while still capturing essential hydraulic response.

The key elements of the many SLOPE/W approaches are encapsulated in a generic limit equilibrium method (Ltd., 2014). Two FOS equations are necessary for the formulation. Regarding moment equilibrium, the FOS equation is:

$$F_m = \frac{\Sigma(c'\beta R + (N - u\beta)R \tan\phi')}{\Sigma Wx - \Sigma Vf \pm \Sigma Dd}$$

The second FOS equation with respect to force equilibrium is:

$$F_f = \frac{\Sigma(c'\beta\cos\alpha + (N - u\beta)\tan\phi'\cos\alpha)}{\Sigma N\sin\alpha - \Sigma D\cos\omega}$$

Based on the equation, the terms are:

c'	=	effective cohesion
ϕ'	=	effective angle of friction
u	=	pore – water pressure
N	=	slice base normal force
W	=	slice weight
D	=	Concentrated point load
β, R, x, f, d, w	=	Geometric parameters
α	=	inclination of slice base

In all shear-type failures, the soil can be modeled as a Mohr-Coulomb material, where shear strength is defined by cohesion (c') and friction angle (ϕ') According to this theory, the shear strength of soil (τ) at failure is given by the equation;

$$\tau = c' + \sigma \tan(\phi')$$

where σ is the normal stress on the failure plane.

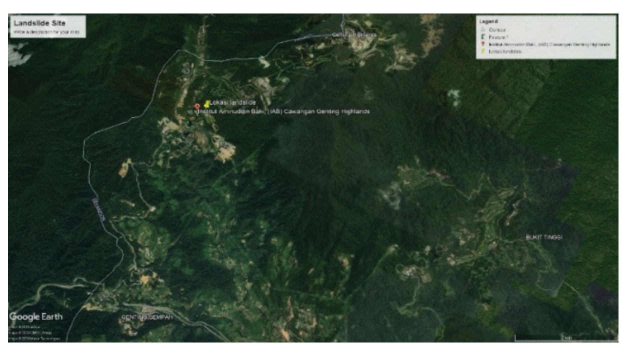


FIGURE 3. The landslide region captures via Google Earth, 2025.

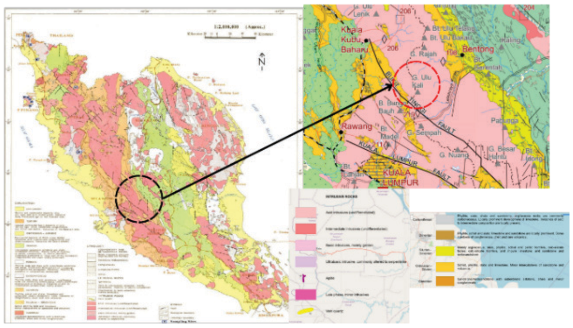


FIGURE 4. Site condition of slope failure based on site investigation (Malaysian Public Work Department, 2022)

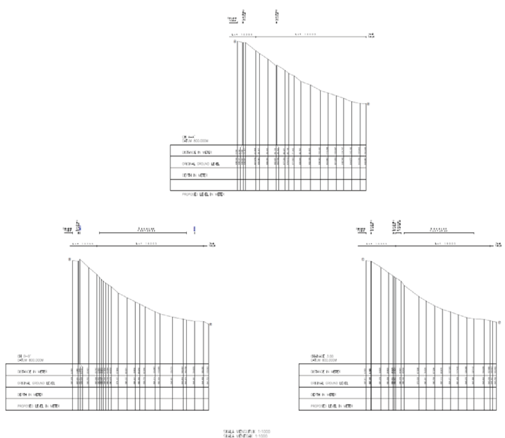


FIGURE 5. Cross - section of the slope based on the borehole log that extracted from SI report (Malaysian Public Work Department, 2022)

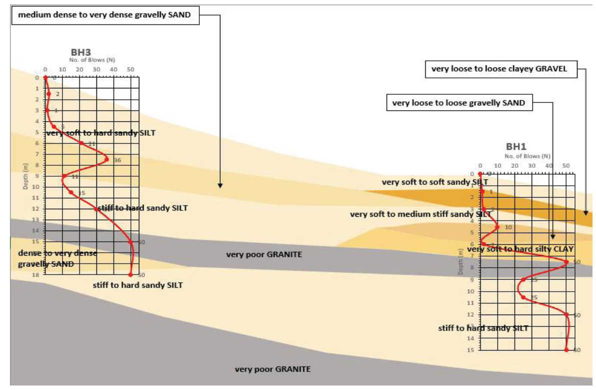


FIGURE 6. Soil profile of BH1 and BH3 in Section B – B (Malaysian Public Work Department, 2022)

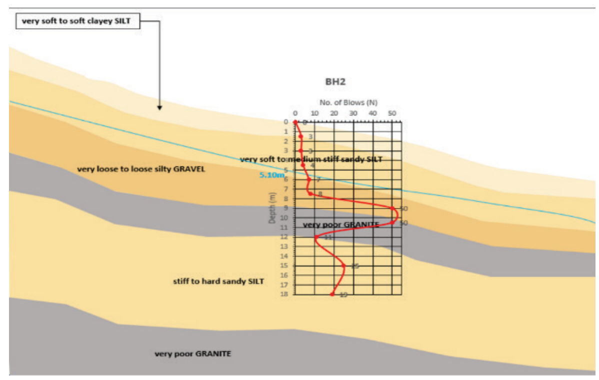


FIGURE 7. Soil profile of layer BH2 in section B – B (Malaysian Public Work Department, 2022)

TABLE 1. Soil parameters adopted into SLOPE/W

Cohesive Soil Name	Soil Parameter					
	Model	Unit Weight, Y (kN/m³)	Cohesion, C (kPa)	Internal Friction Angle, (°)	Phi - B (°)	Piezometric Line
soft sandy SILT	Mohr - Coulomb	18.70	9.50	30.40	0.00	1.00
stiff to hard sandy SILT	Mohr - Coulomb	18.80	10.00	33.80	0.00	1.00
very poor GRANITE	Mohr - Coulomb	24.00	100.00	50.00	0.00	1.00

TABLE 2. Parameters in SEEP/W

Cohesive Soil Name	Material Model	Vol. Water Content Function				Fill K Function			Ky/ Kx' ratio
		Volumetric Water Content vs. Water Pressure				Water X- Conductivity vs. Water Pressure			
		Compressibility (/kPa)	Estimation Model	Saturated WC	Maximum Suction (kPa)	Saturated Kx (m/d)	Estimation Method	Residual Water Content	
Soft sandy SILT	Saturated/ Unsaturated	0.0005	Sample functions	0.45	1000	0.0432	Van Genuchten	0.1	1
Stiff to hard sandy SILT	Saturated/ Unsaturated	0.0005	Sample functions	0.35	1000	0.000432	Van Genuchten	0.1	1
GRANITE	None	-	-	-	-	-	-	-	-

CODE OF PRACTICE

In this study, the slope stability analysis followed the specifications set by the Malaysian Public Works Department (2022) as outlined in Figure 9. Typically, two design components are considered: unreinforced slopes and reinforced slopes. Unreinforced slopes typically require a Factor of Safety (FOS) of 1.3, whereas reinforced or treated slopes are advised to have a value of 1.5. Stabilization measures are necessary if the Factor of Safety falls below these minimum recommended values. These thresholds are based on empirical observations and risk management practices suitable for tropical climates, where slopes are frequently subjected to intense rainfall and rapid changes in pore-water pressure.

FINITE ELEMENT ANALYSIS IN SEEP/W

SEEP/W is a numerical modeling tool capable of simulating the physical process of water flow through a particulate medium using mathematical methods. According to the Ltd. (2015), water flow in the transient state within a slope is analyzed by considering the changes in water storage over time, influenced by the soil's pore – water pressure and its hydraulic properties. Unlike steady – state conditions where the inflow equals the outflow, transient analysis accounts for the system's ability to store or release water. The key factors in this process are the hydraulic conductivity, which controls the rate of water flow, and the volumetric water content function, which defines the quantity of water retained in the soil.

LIMIT EQUILIBRIUM METHOD IN SLOPE/W

In SLOPE/W, the limit equilibrium method evaluates slope stability by dividing the potential sliding mass into individual slices and assessing equilibrium for each slice. This study applies the Morgenstern-Price method, which considers both force and moment equilibrium, providing a detailed analysis of the slip surface. By incorporating interslice forces through an assumed function, this method enhances accuracy in stability assessments. Utilizing the Morgenstern-Price method in SLOPE/W enables a comprehensive evaluation of slope failure slip surfaces. This approach ensures a thorough assessment of stability factors and helps identify critical slip surfaces, offering a more precise understanding of potential failure mechanisms (Ltd., 2014). Figure 8 shows a flowchart for the SEEP/W and SLOPE/W analysis.

MOHR – COULOMB MODEL AND IMPENETRABLE (BEDROCK)

In slope stability analysis, Mohr – Coulomb model without tension cracks is applied. Based on the SLOPE/W manual, using effective strength parameters provides the most accurate representation of the soil, especially in determining the position of the critical slip surface. The accuracy of predicting the critical slip surface location is highest when effective stress conditions are considered. In bedrock, the "impenetrable strength" option is not a strength model but rather a software setting that signifies the slip surface cannot penetrate this material. This approach indirectly influences the formation of trial slip surfaces and is occasionally known as the bedrock soil model type.

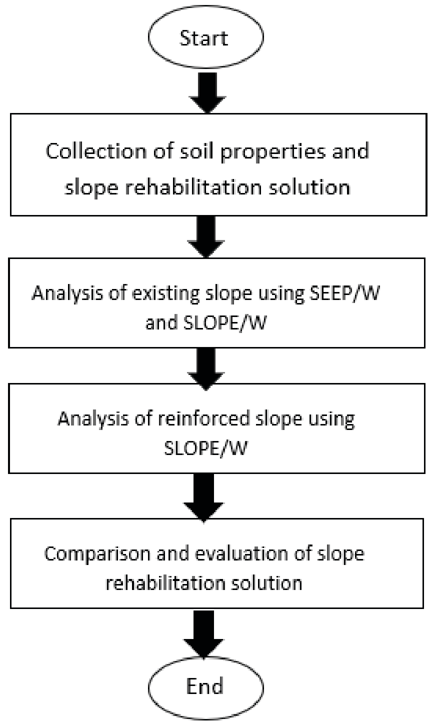


FIGURE 8. Flowchart for the SEEP/W and SLOPE/W analysis

LAMPIRAN A

TYPICAL GEOTECHNICAL DESIGN CRITERIA

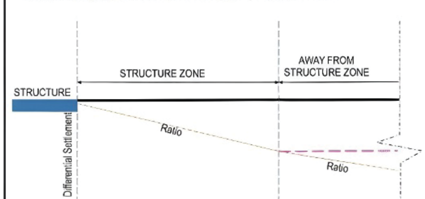
No	DESIGN COMPONENT			DESIGN CRITERIA		MINIMUM F.O.S/ SETTLEMENT (mm)		DESIGN LIFE (Durability of Material)	REMARK
1	Embankment	Not on soft Ground	Unreinforced	1.1	Local & Global Stability	1.3		75 Years	i) 90% of primary consolidation shall be achieved during construction unless otherwise agreed by JKR. ii) For item 1.10 &1.11 - **Structure Zone** is defined as a length not less than 50m within the approach to any structure (bridges, culverts, non-floating piled embankment, etc). - Immediate settlement after structure should be allowed up to maximum 15mm. 
				1.2	Bearing (Fill)	2.0			
			Reinforced	1.3	Local & Global Stability	1.5			
				1.4	Bearing (Fill)	2.0			
		Soft Ground		1.5	Local & Global Stability (Short term)	1.3			
				1.6	Local & Global Stability (Long Term)	1.5			
				1.7	Bearing (Short term)	1.4			
				SETTLEMENT(mm)					
						ROAD PROJECT	BUILDING PROJECT		
				1.8	5 Years Post Construction Settlement	<250	< 10% of primary consolidation or max 100mm		
				1.9	Total post construction settlement	-	<250		
				DIFFERENTIAL SETTLEMENT RATIO (vertical: horizontal)					
				1.10	Within the structure zone	1:500	1:500		
				1.11	Away Structure Zone	1:300	1:300		
2	Cut Slope	Unreinforced / Natural Slope		2.1	Local & Global Stability	1.3		75 Years	i) Analysis shall always consider transient condition. ii) For item 2.2, project with a complete geological data set & 10 years rainfall data, minimum F.O.S for reinforced cut slope can be considered as 1.4. Hong Kong Geotechnical Manual For Slope Second Edition Fifth reprint, Jan 2011.
		Reinforced		2.2	Local & Global Stability	1.5			
3	Anchors / Soil Nail			3.1	Tensile Resistence	2.0		75 Years	**Periodic inspection** i) Monitoring and maintenance shall be conducted once a years for the first 3 years after installation. After 3 years, it shall be conducted in every 3 -5 years. ii) For extremely important anchors and old type of anchors, inspection shall be conducted every 12months. **Integrity Investigation** i) Shall be conducted once within 5 years of installation. ii) For extremely important anchors, it shall be conducted once in every 2-3 years. Japan Anchor Association - Inspection & Maintenance Manual for Ground Anchors (English Version), June 2015
				3.2	Resistance at soil grout	3.0			
				3.3	Interface creep/ corrosion	3.0			
4	Rigid Retaining Structures			4.1	Overturning	2.0		75 Years	i) Hong Kong Geoguide 1 updated e-version, June 2020 ii) BS EN 1997: 1-2004, Eurocode 7
				4.2	Sliding	1.6			
				4.3	Overall Stability	1.5			
				4.4	Bearing	2.0			

FIGURE 9. Guidelines for slope design (Malaysian Public Work Department 2022)

SOIL PROPERTIES

It is necessary to identify the key geotechnical properties of the soil that will be input into SLOPE/W, as shown in Table 3. These parameters were obtained from the site investigation (SI) report. The properties and geometric configuration of the micro-helical reinforcements, including shaft diameter, shaft length, shaft inclination, helical plate diameter, and horizontal spacing, were derived from previous studies on helical soil nailing or the Geocon (M) Sdn. Bhd. (GMSB) product catalog. Additionally, characteristic initial strength, roll width, roll length, and roll weight for geotextile, sourced from the Alpha Pinnacle Sdn. Bhd product catalog. Information on soil nailing was also obtained from Keller Group. Table 3 summarised the properties of Micro-Helical, Soil Nailing and Geotextile adopted in this study.

TABLE 3. The properties of Micro-Helical, Soil Nailing and Geotextile

Parameters	Micro-Helical Anchors	Soil Nailing	Geotextile
Length, ℓ (m)	15	16	-
Pullout Resistance, F/Area (kPa)	200	100.5	200
Tensile Capacity (kN/m)	200	321.68	200
Shear Force (kN)	200	100	-
Bond Length (m)	10	-	-
Bond Diameter (m)	0.1	0.1	-
Out-of-Plane Spacing (m)	1.5	1.5	-
Characteristic Initial Strength (kN/m)	-	-	200
Roll Width (m)	-	-	20
Roll Length, ℓ (m)	-	-	100
Roll Weight (kg)	-	-	230
Reduction Factor	1.5	1.2	1.5

MODEL SETUP

The entire model utilized the Mohr – Coulomb model without considering tension cracks. This involves outlining a stratigraphic layer to create a closed polygon and selecting only the critical soil layer to form three critical regions, as done in this study which 108m height in y axis and 173m in x axis. The material properties for these regions are based on soil parameters derived from the soil profile. Moreover, the interaction between the soil and the reinforcement can evolve in response to deformation, like how soil strength is mobilized as the soil deforms.

As the soil deforms, it mobilizes its inherent strength. Reinforcement mechanisms counteract destabilizing and gravitational forces while enhancing shear resistance, ultimately improving the factor of safety. According to Ltd. (2014), SLOPE/W structures its equilibrium equations around the shear mobilized at the base of each slice. The mobilized shear (Sm) is determined by dividing the shear strength by the factor of safety, providing a measure of stability within the slope analysis. In equation form, this relationship can be expressed as follows:

$$S_m = \frac{S_{soil}}{FOS}$$

When incorporating reinforcement to improve shear resistance, the forces from the reinforcement must also be divided by the factor of safety. Therefore, the mobilized shear (S_m) is calculated as follows:

$$S_m = \frac{S_{soil}}{FOS} + \frac{S_{reinforcement}}{FOS}$$

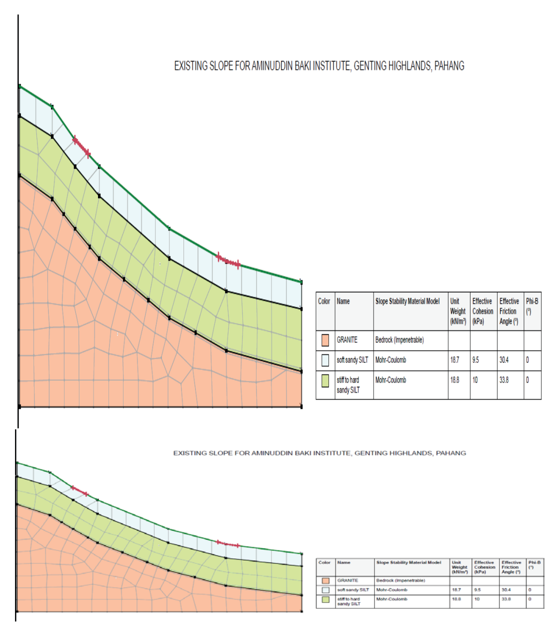


FIGURE 10. Slope geometry and their regions for back analysis and unreinforced slope

According to Kinde et al. 2024, the assessment of groundwater's influence on slope stability involves considering pore water pressure. Therefore, an infiltration analysis was conducted using SEEP/W to determine the cause of the slope failure, as depicted in Figure 11. The slope model is based on water table data from the borehole log in the SI report, and the boundary conditions were used to analyze the cumulative water infiltration over time. This simulation illustrates varying pore water pressure conditions, showing the impacts of rainfall events (Wang et al. 2023). The analysis involved two different boundary conditions: for the initial phase (day 0 to day 1), the data from the initial phase each layer had zero pressure as shown in Figure 10, while during the rainfall event, the boundary conditions for the stiff to hard sandy silt layer were adjusted to the water unit gradient conditions Figure 12.

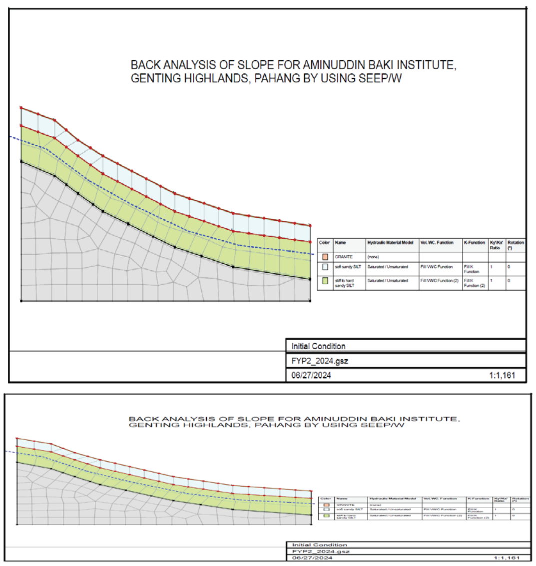


FIGURE 11. Boundary conditions of the initial phase, and the piezometric surface (pore water table)

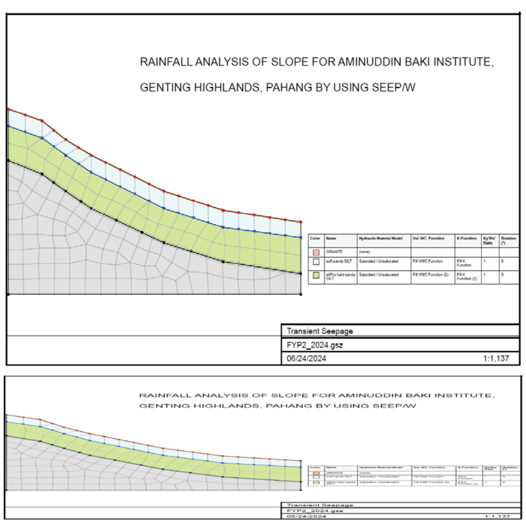


FIGURE 12. Boundary conditions change into water unit gradient for rainfall event.

The proposed rehabilitation solutions—micro-helical anchors, geotextiles, and soil nailing—were modeled using their respective reinforcement types in SLOPE/W. The slope was designed with a 2:1 (H:V) gradient while maintaining the original unit weight, shear parameters, and pore water table to reflect the existing slope conditions. The Critical Slip Surface was determined through the analysis of the unreinforced slope. Micro-helical anchors and soil nails were implemented with a length of 20 meters and a horizontal spacing of 3 meters. Each layer included five micro-helical anchors and five soil nails within a 6-meter slope height, totaling five reinforcement layers. Geotextile reinforcement was applied in layers spaced at 3-meter intervals, using three rolls per layer, each with a width of 20 meters.

RESULTS AND DISCUSSION

BACK ANALYSIS FOR EXISTING SLOPE

Figure 13 illustrates the water flow within the slope based on the SEEP/W back analysis results. The starting circumstances show the spread of the pore water table in the slope before to the rainfall event (Day 0 to 1). Water flow at this time is determined by variables like hydraulic conductivity (K function) and volumetric water content (VWC). The steady flow patterns, which are mostly determined by the soil's natural hydraulic qualities and current moisture content, give an initial assessment of the slope's state prior to external water penetration. The data demonstrate that the slope experiences notable changes in pore water pressure as a result of the commencement of rainfall, which causes enhanced water penetration, after the heavy rainfall event begins (Figure 14; Day 1 onwards). Water infiltration and redistribution within the soil over time are demonstrated by the transient seepage study carried out using SEEP/W. As the soil gets increasingly saturated, this causes a discernible increase in pore water pressure. The hydraulic gradient and flow dynamics are changed when the increasing pore water pressure lowers the effective stress in the soil. As a result, there is increased water flow on the slope, which may indicate weak spots and unstable sections, underscoring the crucial role that rainfall plays in slope stability.

Figure 15 illustrates the progression of water pressure head over time in response to a rainfall event. From Day 0 to Day 1, the water pressure head remains stable, indicating pre-rainfall conditions where the soil's hydraulic properties and flow patterns remain undisturbed. However, after Day 1, as rainfall begins, there is a noticeable increase in water pressure head, signaling water infiltration into the soil and a rise in pore water pressure due to increased saturation. The subsequent rise and fluctuations in the graph highlight the dynamic response of the soil to continuous rainfall. This trend demonstrates how infiltration affects slope stability by altering pore water pressure levels. As water pressure increases, the effective stress within the soil decreases, potentially leading to reduced stability and a higher risk of slope failure.

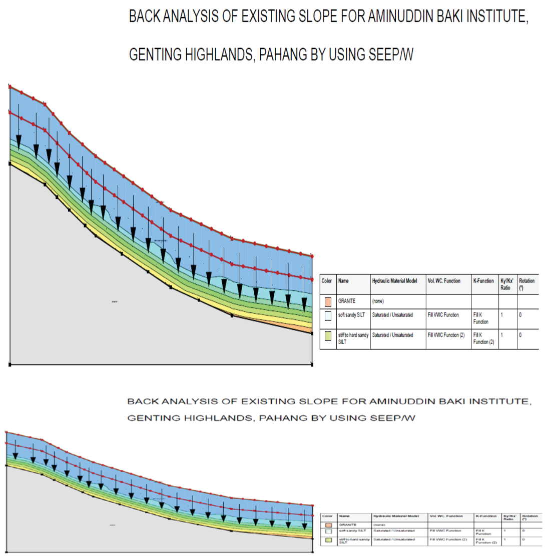


FIGURE 13. Back analysis before rainfall event.

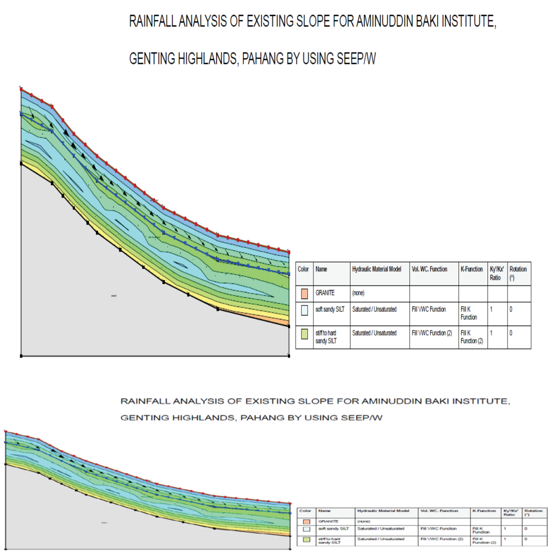


FIGURE 14. Back analysis during rainfall event (Day 1 onwards)

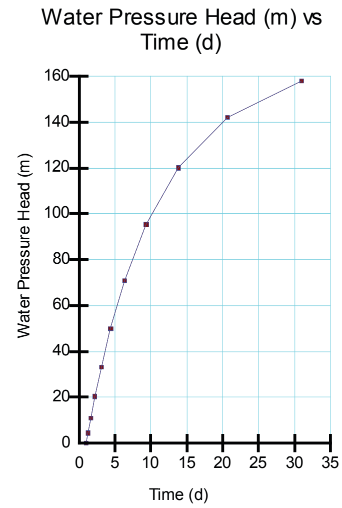


FIGURE 15. Result of water pressure head (m) increases over time (day)

The analysis of the existing slope using SLOPE/W incorporates pore water pressure data from SEEP/W (rainfall event) Figure 16. This stability analysis reveals a failed area with a Factor of Safety (FOS) of 1.257 with 41m in height. It demonstrates how changes in pore water pressure, caused by transient seepage during rainfall, affect the overall stability of the slope. This highlights areas prone to failure due to increased water infiltration and altered hydraulic conditions.

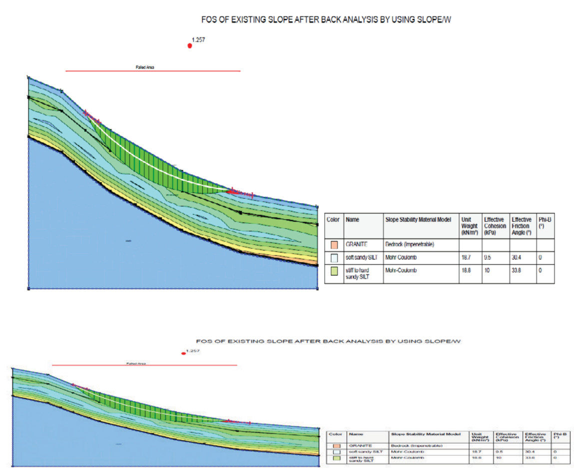


FIGURE 16. Stability analysis of existing slopes using SEEP/W pore water pressure data.

STABILITY ANALYSIS OF REINFORCED SLOPE

Based on the analysis result in Figure 17 the factor of safety (FOS) of micro–helical as an anchor is increased which is 1.685 passing the minimum of the JKR standard. The implementation of micro-helical as an anchor makes it evident that the remedial solution effectively addresses slope instability, resulting in an improved factor of safety (FOS). The implementation of micro-helical anchors, characterized by a high pullout resistance of 200 kPa and tensile capacity of 200 kN, significantly enhances the stability of the slope. The anchors, installed with a bond length of eighteen meters and a bond diameter of 0.1 meters, provide robust reinforcement by transferring loads efficiently through the soil strata. The spacing of 1.5 meters ensures uniform distribution of the stabilizing forces, mitigating the risk of localized failures.

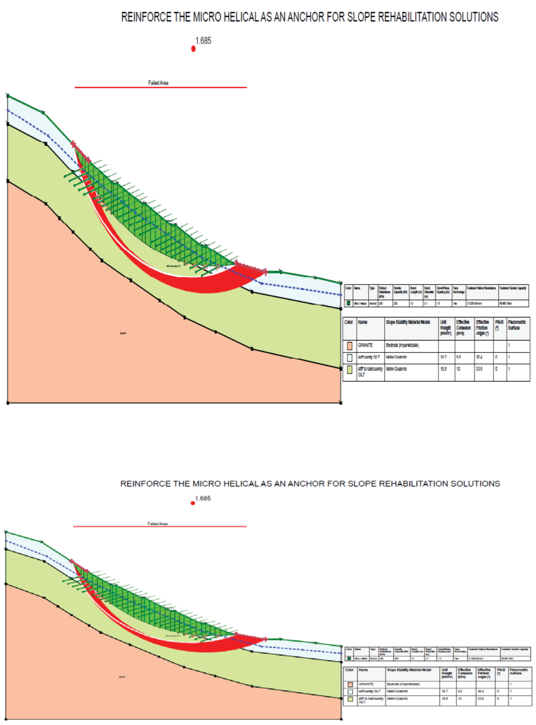


FIGURE 17. Stability analysis of slope reinforced with micro-helical as an anchor

Based on the findings in Figure 18, the FOS of the geotextile as a remedial solution is 1.605. These findings reveal that geotextiles are an effective solution for mitigating slope failures by enhancing stability and providing additional strength to the soil. Due to the high tensile capacity and pullout resistance, the FOS is significantly improved. The tensile capacity is 200kN and a pullout resistance of 200kPa with factored values of 133.33kN/m and 133.33 kPa respectively.

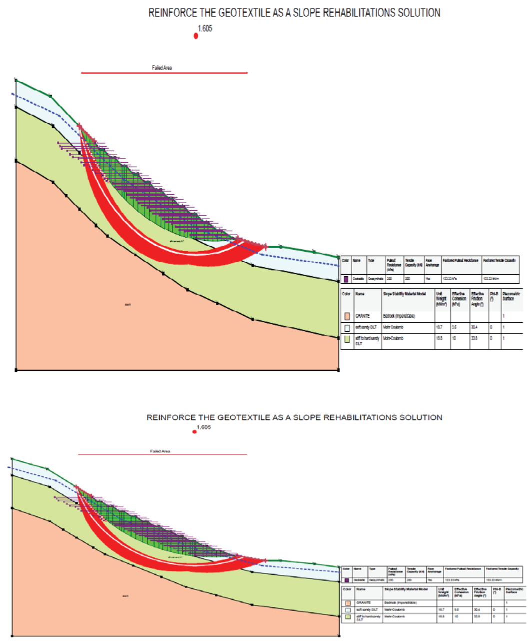


FIGURE 18. Stability analysis of slope reinforced with geotextile

The result in Figure 19 shows the evaluation of soil nailing analysis by using SLOPE/W. The FOS of soil nailing is 1.647 pass the minimum JKR requirement. The materials used in soil nailing typically include steel nails with high tensile capacity (321.68 kN) and significant pullout resistance (100.5 kPa). These nails are spaced out-of-plane by 1.5 meters and have a bond diameter of 0.1 meters, ensuring effective load distribution and slope stabilization. The nails' factored pullout resistance is 14.032 kN/m/m, while the factored tensile capacity reaches 178.71 kN/m, ensuring robust performance under load conditions.

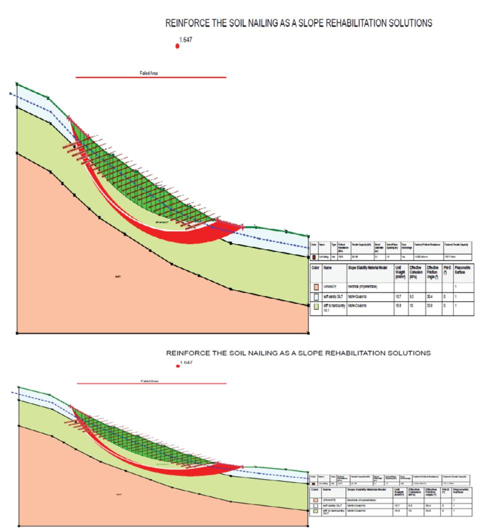


FIGURE 19. Stability analysis of slope reinforced with soil - nailing

In slope rehabilitation solutions, the Factor of Safety (FOS) serves as a crucial indicator of stability remedial works. Thus, the FOS of before and remedial works are shown in Table 4.

TABLE 4. The factor of Safety (FOS) for slope rehabilitation solutions

Material	FOS	Percentage Improvement Relative to Unreinforced Slope (%)
Unreinforced slope	1.257	-
Micro – helical	1.685	34.0
Soil Nailing	1.647	30.9
Geotextile	1.605	27.7

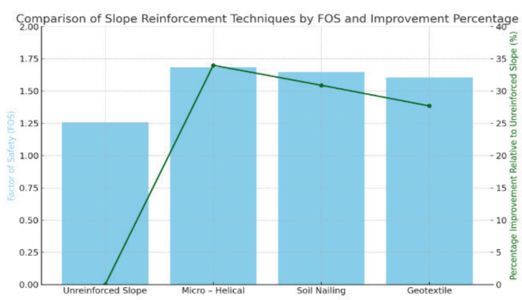


FIGURE 20. Comparison of slope reinforcement techniques by FOS and improvement percentage

Based on the improved FOS values, it is clear that the proposed rehabilitation measures substantially increase slope stability. Existing slopes often have reduced FOS due to elevated pore water pressure, which diminishes effective stress and shear strength (Wang et al. 2025). Among the methods evaluated, micro-helical anchors offered the greatest enhancement in stability. These anchors deliver deep, mechanically interlocked reinforcement with load transfer via both shaft friction and end-bearing resistance from the helical plates (Pessoa, 2024). In contrast, soil nailing improves stability by reinforcing the soil mass but depends primarily on friction between the nails and surrounding soil, which may be less effective in soft or layered soils. The dual advantage of frictional and bearing resistance makes micro-helical anchors particularly suited for silty and cohesive soil profiles seen at the study site. Meanwhile, geotextiles aid slope integrity by evenly distributing load and reducing surface erosion, though their performance varies with soil type and installation depth (Rahman et al. 2024). Local case studies further support these findings, for example, the use of soil nailing and geotextiles on existing slope at Taman Kelab Ukay, Ampang, Selangor resulted in factor of safety (FOS) values exceeding 1.5 (Idrus et al. 2023), while analysis of hydraulic conductivity and porosity confirmed the importance of subsurface flow behavior for slope failure potential (Mukhlisin & Taha, 2011)

CONCLUSION

Based on the analysis and design by using SEEP/W and SLOPE/W, the following conclusions are drawn:

1. Initial conditions before rainfall showed stable water flow patterns, but significant changes in pore water pressure during rainfall increased infiltration and highlighted weak zones. The analysis identified a failure-prone area with a factor of safety (FOS) of 1.257, demonstrating the impact of rainfall on slope stability.
2. Three slope reinforcement techniques were evaluated in this study. Micro-helical anchors achieved the highest Factor of Safety (FOS) of 1.685, showing a 34.0% improvement over the unreinforced slope. Soil nailing followed with an FOS of 1.647 (30.9% improvement), and geotextiles achieved an FOS of 1.605 (27.7% improvement). All three methods exceeded the JKR minimum requirement of 1.5 for reinforced slopes, confirming their effectiveness in improving stability.
3. The superior performance of micro-helical anchors is due to their larger surface area and deeper engagement. Micro-helical anchors demonstrate the highest stability among the evaluated remedial methods. While both micro-helical anchors and soil nailing utilize similar materials, their performance varies significantly. Micro-helical anchors act as true anchors, providing enhanced stability through mechanical anchoring. Their ability to generate immediate load-bearing capacity results from a combination of friction and bearing forces on the helix plates, making them a highly effective solution

Despite its strengths, this study has several limitations. The rainfall scenario used was based on historical intensity and did not include future climate variability or extreme weather projections. On-site construction effects and post-rehabilitation monitoring data were also beyond the scope of this simulation-based study. The use of a 2D modeling approach simplifies the actual 3D behavior of slopes and may not capture spatial variability or complex failure mechanisms.

As a recommendation for future works, field monitoring should be integrated to validate model predictions and capture real-time pore water pressure and deformation. Including climate change projections, durability analysis of reinforcement materials, and cost-performance evaluations of each method will also provide more comprehensive guidance for sustainable slope stabilization in high-rainfall environments.

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DECLARATION OF COMPETING INTEREST

None.

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