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Numerical Evaluation of Factor of Safety (FOS) and Anchor Pile Arrangement for Slope Stability Using GeoStudio (SLOPE/W)

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Abstract

Slope stability is very important for structural safety in civil engineering and infrastructure projects in Malaysia, where land development often needs steep slope cuts and supporting walls. This study presents a full numerical evaluation of slope stability and ground anchor pile performance under different soil conditions with a load at the top of the slope. Using GeoStudio (SLOPE/W) software based on the Morgenstern-Price method, five soil types ranging from weak, loose soils to strong, hard rock were analyzed at slope angles of 30°, 60°, and 90° (vertical) for a 6 m high slope. These selected angles cover real site conditions, including normal fill slopes (30°), steep cut slopes (60°), and deep vertical excavations (90°). To simulate real site conditions, a top surcharge load of 15 kPa was applied based on Public Works Department (JKR) standards to represent construction traffic, heavy machines, and vehicle loads. First tests on slopes without anchors showed that weak soils were very unsafe, giving a Factor of Safety (FOS) as low as 0.109, while strong rock stayed safe with an FOS up to 2.897. When active ground anchors were installed set at a 10° downward angle with 3 meters spacing they pulled back against the soil and increased the strength inside the slope. This reinforcement successfully increased the overall FOS above the required JKR minimum safety standard of 1.30 for 30° and 60° slopes. However, for 90° vertical slopes, active ground anchors alone were not strong enough to stop the heavy side soil pressure, giving a low post-reinforcement FOS of 0.788 under the 15 kPa load. For vertical cuts, the failure line forms very close to the slope face, which causes the anchor bond to fail by slipping out of the soil, leading to large movement at the top of the slope. In conclusion, ground anchor systems work very well to keep 30° and 60° slopes safe, but 90° vertical cuts need stronger combined retaining wall systems to stop total slope failure.

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1. Introduction

Slope stability is a critical aspect of geotechnical engineering, serving as a key safety determinant for the construction of infrastructure such as highways and urban developments. In Malaysia, the rapid pace of hillside construction driven by high demand for residential space has led to aggressive slope cutting and land reclamation, which often compromises natural stability [1]. These stability issues are primarily characterized by the slope mass being unable to withstand gravitational driving forces, leading to sudden collapses that cause massive property damage and loss of life [2]. Stability is often compromised by human intervention, to meet the high demand for residential space, and design-related deficiencies, which alone account for more than half of Malaysia's slope failure cases [1].

Persistent stability problems pose a severe threat to public safety, often resulting in tragic fatalities, massive economic losses, and the destruction of vital infrastructure [3]. Furthermore, the introduction of external surcharge loads from heavy machinery, buildings, and traffic significantly increases internal stresses, often pushing a critical slope toward failure [4].



Fig. 1 *Slope failure at Ampang, Selangor*

Figure 1 illustrates a critical slope failure happen in Ampang, Selangor, which serves as a prime example of the geotechnical challenges faced in Malaysian hillside developments.

To resolve these failures, various stabilization methods are conventionally employed, such as geometric modification cutting to gentler angles by remove the soil from the top of the slope to reduce heavy weight, installing drainage systems and berms at every 6 meters of height, or utilizing geosynthetics [1]. However, when a slope natural strength is insufficient to meet safety standards when the Factor of Safety (FOS) less than the mandated JKR minimum of 1.30 for untreated slopes soil reinforcement becomes essential by Jabatan Kerja Raya Malaysia. To prevent slope failure, engineers commonly combine traditional, innovative, and sustainable technique to reinforce the ground such as soil nailing, ground anchors, and micro-piles are widely used to enhance stability. These systems work by increasing interface friction and providing high pullout resistance with effectively creates a strong reinforced composite mass of earth [5].

To analysis these complex geotechnical conditions [6] utilizes SLOPE/W software to simulate failure mechanisms and calculate accurate FOS values [1][3]. Although numerous studied have investigated slope stability using numerical methods, limited studies have evaluated the optimization of anchor pile arrangement under different soil conditions and slope geometries subjected to surcharge loading. Therefore, this study aims to evaluate the Factor of Safety (FOS) of slopes under different soil types and slope angles using SLOPE/W simulation software, and to propose and optimize anchor pile arrangements for slopes subjected to external loads. The first objective examines how soil strength and slope geometry influence stability, while the second objective focuses on improving slope performance by designing reinforcement systems that can resist additional forces from operational loads such as vehicles or equipment. Together, these objectives ensure that slope stability is analyzed in a comprehensive manner and that practical reinforcement solutions are recommended to meet the minimum safety requirements set by the JKR Guidelines.

2. Method

The stability of slopes under various soil types, slope angles, reinforcement, and external loads was examined in this work using numerical modeling. To ensure methodical and reliable results, the procedure followed a planned flow chart.

Progress in Engineering Application and Technology Vol. 7 No. 2 (2026) p. 49-59

2.1 Software and Analytical Method

The slope stability analysis was carried out using GeoStudio (SLOPE/W) with the Morgenstern-Price method, which is widely recognized for its ability to analyze complex non-circular slip surfaces and provide reliable Factor of Safety (FOS) values [6]. The overall simulation process followed a structured workflow, as shown in Figure 2 Flow Chart for Simulation, beginning with the identification of the problem, objectives, and literature review, followed by data collection and numerical modeling. The study was divided into several phases; Phase 1, Phase 2, Phase 3 examined slope stability without reinforcement, effect of soil properties and slope geometry variations, Phase 4 introduced anchor pile reinforcement, and Phase 5 applied external loads to evaluate performance under realistic conditions [4]. This phased approach ensured that the analysis was systematic and comprehensive, capturing the influence of soil strength, slope geometry, reinforcement, and external loads on slope stability.

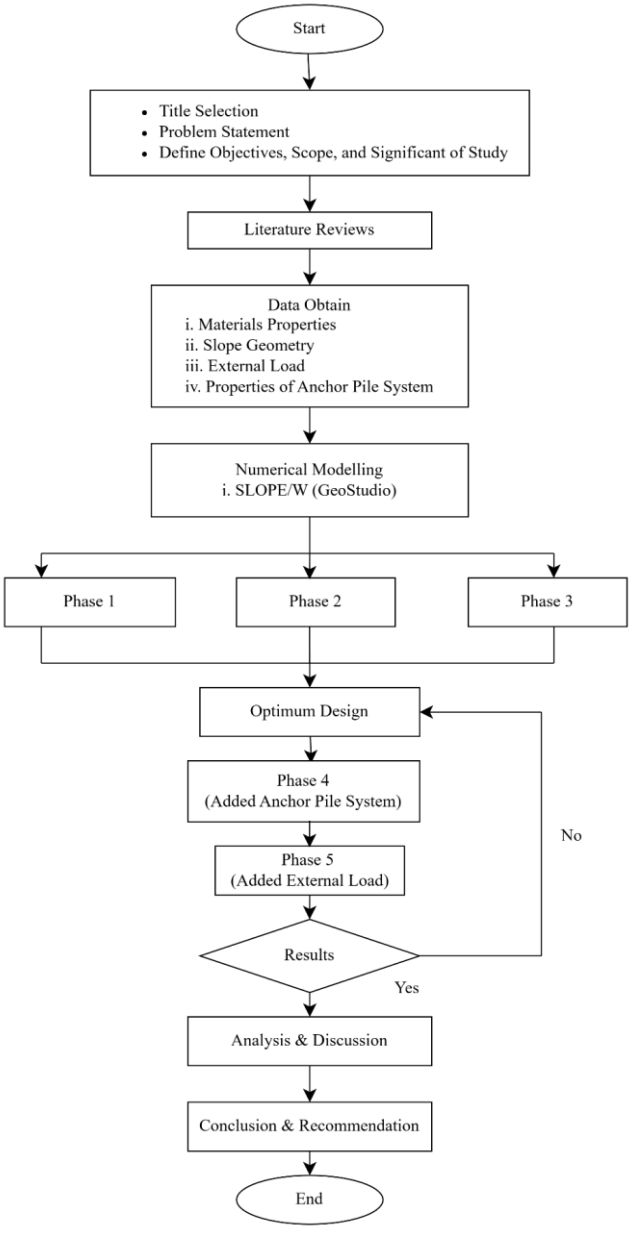


Fig. 2 *Flow chart for simulation*

2.2 Slope Geometry

The slope model was designed with a fixed height of six meters to represent typical hillside construction in Malaysia. Three slope angles were considered, 30° (gentle slope), 60° (steep slope), and 90° (vertical slope). These variations allowed the study to capture the influence of geometry on slope stability, ranging from relatively stable conditions to highly critical scenarios where slope failure is more likely [7]. Table 1 shows the beginning phases the slope geometry add into SLOPE/W software.

Table 1 *Slope Geometry*

Phase	Slope Angle, β (°)	Slope Height, H (m)
1	30	6
2	60	
3	90	

2.3 Soil Properties

To simulate realistic geotechnical conditions, soil parameters were varied across a wide range. Cohesion (c) values ranged from 0 to 20 kPa, while friction angle (φ) values ranged from 5° to 45°. The unit weight (γ) was adjusted according to soil type. The soils tested included poorly graded soil, medium-dense sand, dense silty sand, well-graded sand, and well-compacted soil or rock. This variety ensured that the analysis covered weak, moderate, and strong soil conditions, reflecting the diversity of ground materials found in Malaysian construction sites [3][1]. Table 2 shows the beginning phases that the soil properties add into SLOPE/W software.

Table 2 *Soil Properties*

Type of Soils		Friction Angle, φ (°)	Cohesion, c (kPa)	Unit Weight, γ (kN/m^3)
Very loose, poorly graded soil.		5	0	17
Loose to medium dense sand.		15	5	
Medium dense sand to dense silty sand.		25	10	
Well graded sand and gravel.		35	15	
Well compacted soil like rock.		45	20	

2.4 Anchor Pile System

An anchor pile system was introduced as a reinforcement measure to improve slope stability. The anchors were installed at a 10° downward inclination with a spacing of three meters. This arrangement was chosen to maximize pull-out resistance and increase interface friction between soil and reinforcement. By transferring loads deeper into the soil mass, the anchor piles acted as stabilizing elements that reduced the risk of sliding and enhanced overall slope safety [5]. These specifications define the active reinforcement elements used to provide immediate lateral confinement that shown in table 3.

Table 3 *Technical Properties of the Ground Anchor [8]*

Parameter	Specification
Borehole / Bond Diameter	115 mm
Prestressing Force	150 kN
Breaking Strength	260 kN
Elasticity Modulus	210 GPa

Progress in Engineering Application and Technology Vol. 7 No. 2 (2026) p. 49-59

Cross-Sectional Area (Single Strand)	143 mm^2
Grout Shear Resistance	560 kPa
Bond Skin Friction	560 kPa
Inclination Angle	10° (downward from horizontal)
Horizontal Spacing (m)	3.0 meters
Bound Factor of Safety	2.0

2.5 External Surcharge Load

An external surcharge load of 15 kN/m^3 was applied vertically at the slope crest. This load was intended to represent the effects of building structures, heavy machinery, and traffic, which are common external factors contributing to slope instability. Including surcharge loads in the analysis was important to evaluate how external forces influence slope safety, especially in urban hillside developments where additional loads are unavoidable [4].

2.6 Analysis Procedure

The analysis was conducted in several stages. First, baseline FOS values were calculated for slopes without reinforcement to establish natural stability. Next, anchor piles were installed, and FOS values were recalculated to measure the improvement in stability. Finally, the external surcharge load was applied, and FOS values were compared before and after reinforcement. This step-by-step procedure allowed for a comprehensive evaluation of slope stability under both natural and loaded conditions, providing insights into the effectiveness of anchor pile reinforcement across different soil types and slope geometries by Jabatan Kerja Raya Malaysia.

3. Results and Discussions

This section presents the findings of slope stability analysis under different soil types, slope angles, reinforcement systems and external loads. The results are explained in a phase-by-phase manner, followed by a discussion to highlight the key factors affecting slope safety and performance.

3.1 Results Phase 1

The baseline analysis at slope geometry (H = 6 m, β = 30°) showed that soil type strongly affects slope stability. Poorly graded soil recorded the lowest Factor of Safety (FOS) of 0.188, indicating critical failure due to weak grain interlocking and low shear resistance [7]. In comparison, medium-dense sand achieved an FOS of 1.072, while well-compacted soil or rock reached 4.116, showing that higher cohesion and friction angle values improve stability.

According to the JKR Guidelines, slopes with FOS below 1.50 are unsafe and require reinforcement. Based on this, poorly graded soil and medium-dense sand were identified as unstable, while medium-dense sand was chosen for further analysis since its FOS value was closer to the recommended limit.

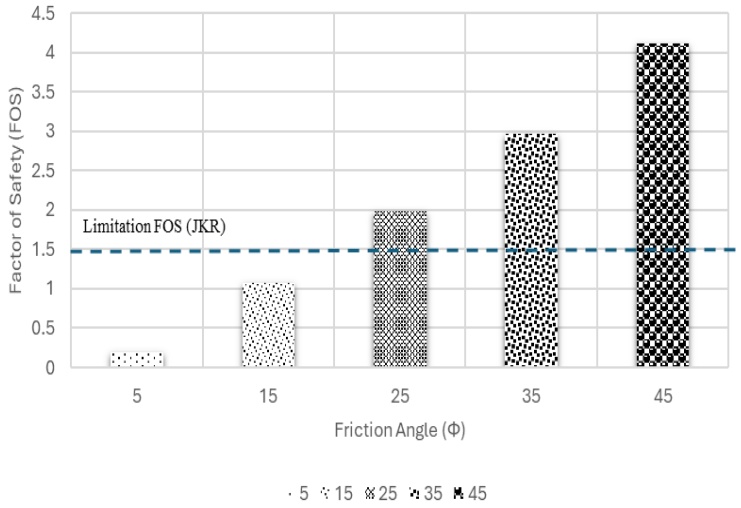


Fig. 3 *Effect of friction angle on factor of safety (FOS)*

Figure 3, effect of friction angle on FOS The graph shows that FOS increases consistently with friction angle (φ). At φ = 5°, FOS was only 0.188, but once φ reached 25° and above, the FOS exceeded 1.50, indicating stable slope conditions. This improvement occurs because the internal shear resistance of the soil at the potential slip surface increases directly with increasing friction angle. As a result, both the overall resistance and the associated resisting moment acting against slope failure increase. In addition to reducing regional shear failure and ensuring stability for moderate slopes, the enhanced interlocking between particles simultaneously improves the stress distribution within the soil mass.

3.2 Results Phase 2

The analysis in Phase 2 (H = 6 m, β = 60°) showed that slope stability decreased as the slope angle became steeper. Poorly graded soil recorded the lowest Factor of Safety (FOS) of 0.130, indicating a highly unstable slope with high failure potential due to weak grain interlocking and low shear resistance [7]. In comparison, medium-dense sand achieved an FOS of 0.734, while dense silty sand reached 1.355, showing moderate improvement but still below the recommended safety limit.

Higher strength soils performed better, with well-graded sand and gravel recording an FOS of 2.034, and well-compacted soil or rock reaching 2.897, reflecting the positive effect of higher cohesion and friction angle on slope stability [9]. However, the results confirm that poorly graded soil, medium-dense sand, and dense silty sand remain unsafe under steeper slope conditions. Among these, medium-dense sand was selected for further analysis because its FOS value was closer to the required stability limit set by JKR.

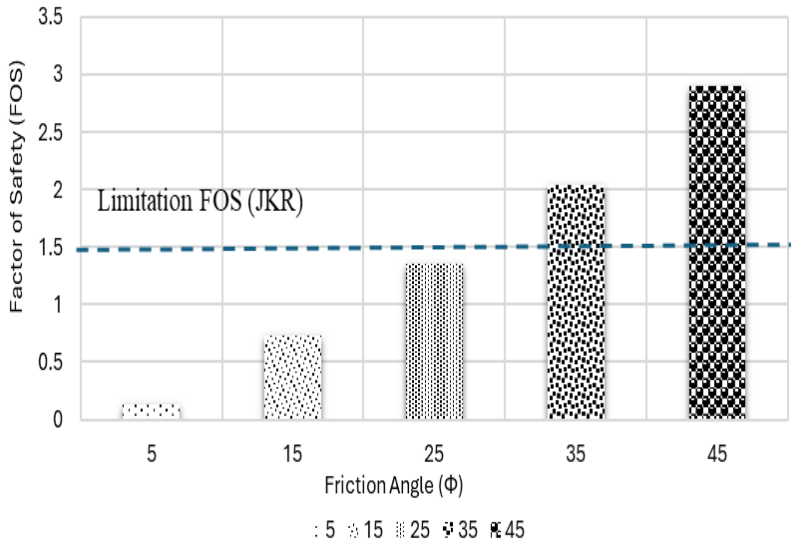


Fig 4. *Effect of friction angle on FOS for Phase 2*

Progress in Engineering Application and Technology Vol. 7 No. 2 (2026) p. 49-59

The graph shows that FOS increases with friction angle (φ), but values are lower compared to Phase 1. At φ = 5°, FOS was only 0.130, while at φ = 15° it rose to 0.734. At φ = 25°, FOS reached 1.355, which is close to the acceptable limit but still unsafe. Only at higher friction angles (35°–45°) did the FOS exceed 1.50, indicating that stronger soil properties are required to maintain stability as slope angles increase.

3.3 Results Phase 3

The analysis in Phase 3 (H = 6 m, β = 90°) showed the most critical slope condition, with overall low Factor of Safety (FOS) values. Poorly graded soil recorded the lowest FOS of 0.109, indicating extreme instability due to weak grain interlocking and low shear strength. Medium-dense sand produced an FOS of 0.502, while dense silty sand reached 0.951, showing slight improvement but still below the recommended safety limit. Higher stability was observed for well-graded sand and gravel with an FOS of 1.463, and well-compacted soil or rock with 1.942, reflecting the positive effect of stronger soil properties.

Overall, poorly graded soil, medium-dense sand, and dense silty sand remained unsafe under vertical slope conditions. Among these, dense silty sand was chosen for further analysis because its FOS value was closer to the required stability level.

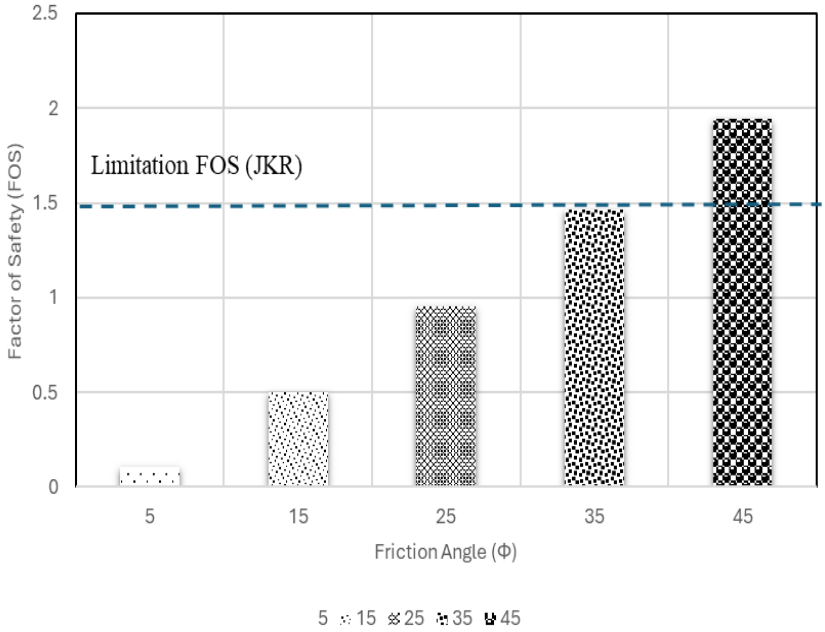


Fig 5. *Effect of friction angle on factor of safety (FOS)*

Figure 5 effect of friction angle on FOS for Phase 3 The graph indicates that FOS increases with friction angle (φ), but values remain low compared to previous phases. At φ = 5°, FOS was only 0.109, while at φ = 15° and 25° it rose to 0.502 and 0.951, both below the safe limit. Even at higher friction angles (35°–45°), FOS values of 1.463 and 1.942 were achieved, but stability remained limited. The driving force far exceeds the natural moment of resistance of the unreinforced soil in the vertical (90°) slope profile when it reaches its maximum limit. The self-weight of the soil produces a high driving force that the soil strength alone cannot safely balance, although the increased friction angle increases the internal shear resistance and distributes the stress over the failure zone. Therefore, to achieve a safe condition, additional structural strengthening measures (such as anchor piles) are required to overcome the external pull-out resistance, actively reduce the driving force, and provide the necessary structural moment of resistance.

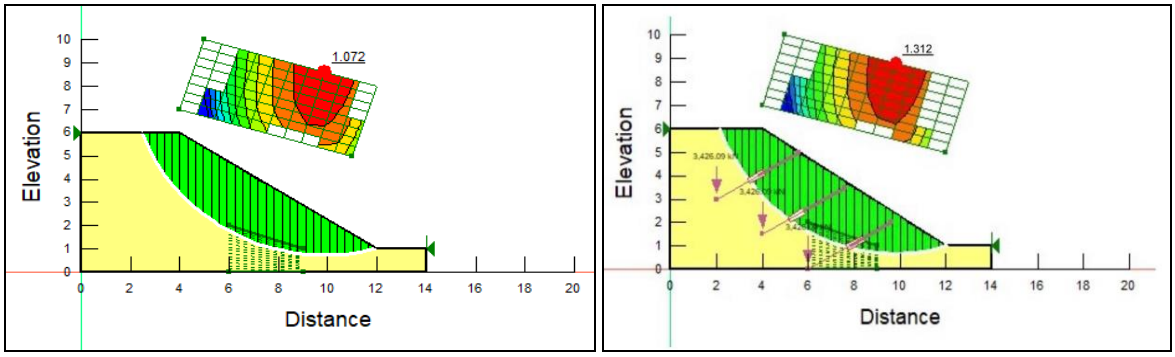
3.4 Results Phase 4

This phase shows the effect of anchor pile installation on slope stability. Comparisons were made between conditions before and after anchors were installed at slope angles of 30°, 60°, and 90°. The results prove that anchors can increase the Factor of Safety (FOS) on moderate slopes, but for very steep slopes the effect is limited, and additional methods are required to achieve safe levels.

3.4.1 Medium-dense Sand (β = 30°)

Figure 6 shows that after anchors were installed, the slope became more stable with an FOS of 1.312 compared to the lower value before reinforcement. The anchor system improved stability by mobilizing interface friction and providing pull-out resistance, which acted as an additional anti-sliding force. However, the stability

remained moderate, suggesting that further improvement may be needed depending on design requirements [10].

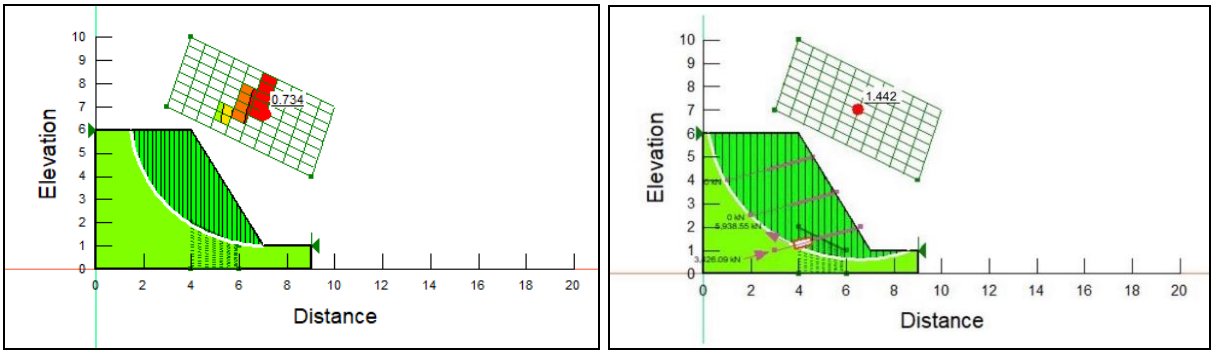


(a) (b)

Fig 6. *(a)Before added anchor pile system; (b) After added anchor pile system*

3.4.2 Medium-dense Sand (β = 60°)

In Figure 7, before anchors were installed the slope had an FOS of 0.734, which was unsafe. After reinforcement, the FOS increased to 1.442, showing that the slope became stable. The anchor piles provided extra resistance against sliding, and the combination of anchors with medium-dense sand improved the slope's ability to carry loads and reduced the chance of failure.



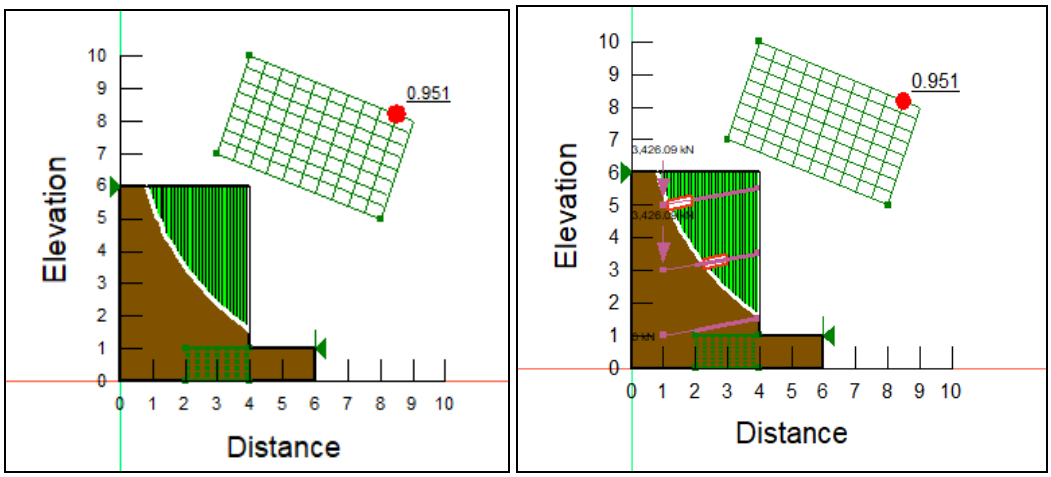
(a) (b)

Fig 7. *(a)Before added anchor pile system; (b) After added anchor pile system*

3.4.3 Dense Silty Sand (β = 90°)

Figure 8 shows that for vertical slopes, the FOS remained at 0.951 both before and after anchor installation. This indicates that anchors did not significantly improve stability at 90°, as the slope geometry itself controlled failure. Even though dense silty sand normally has good strength, the vertical slope angle was too critical. This demonstrates that for very steep slopes, anchors alone are insufficient, and other methods such as reducing slope angle or adding retaining structures are required to achieve stability.

Progress in Engineering Application and Technology Vol. 7 No. 2 (2026) p. 49-59



(a) (b)

Fig 8. *(a)Before added anchor pile system; (b) After added anchor pile system*

3.5 Results Phase 5

To simulate realistic operational conditions, an external load of 15 kN/m^3 was applied to represent live loads from vehicles or equipment [3]. The analysis showed that the presence of this load increased the driving force acting on the slope, creating more critical conditions compared to unloaded cases. With reinforcement, the anchor pile system provided additional resisting force by transferring loads beyond the slip surface. This improved the Factor of Safety (FOS) and helped the slope withstand external loading. Overall, the reinforced slope demonstrated better performance under operational loads, but in some cases the FOS still dropped below the recommended minimum of 1.50 as specified in JKR.

3.5.1 Slope (β = 30°) with External Load

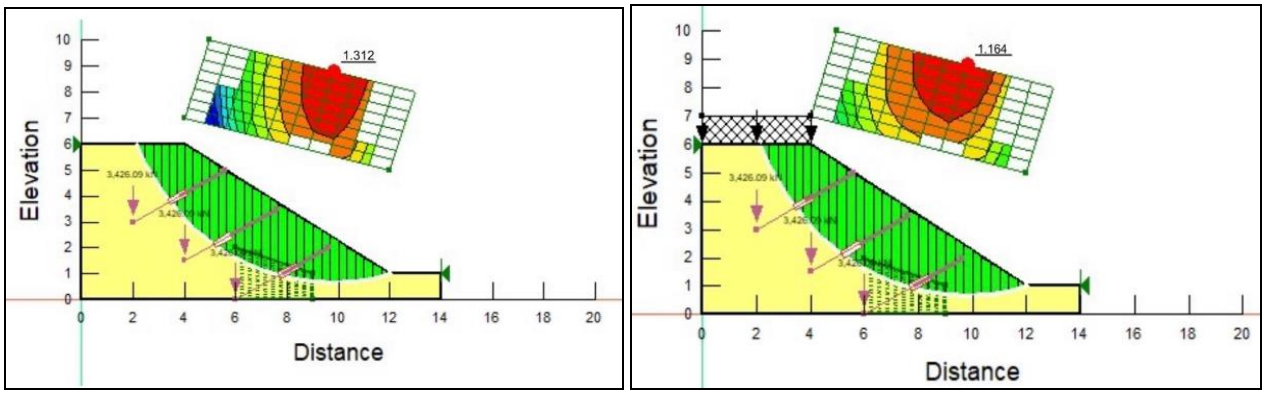


Fig 9. *Before vs after application of external load for slope 30°*

Figure 9 shows that the slope made of medium-dense sand with a 30° angle was initially stable with anchor support, recording an FOS of 1.312. After adding the external load, the FOS decreased to 1.164, which is below the required minimum value. This indicates that while anchors improved stability, the slope became unsafe under loading conditions and further reinforcement or redesign is needed.

3.5.2 Slope (β = 60°) with External Load

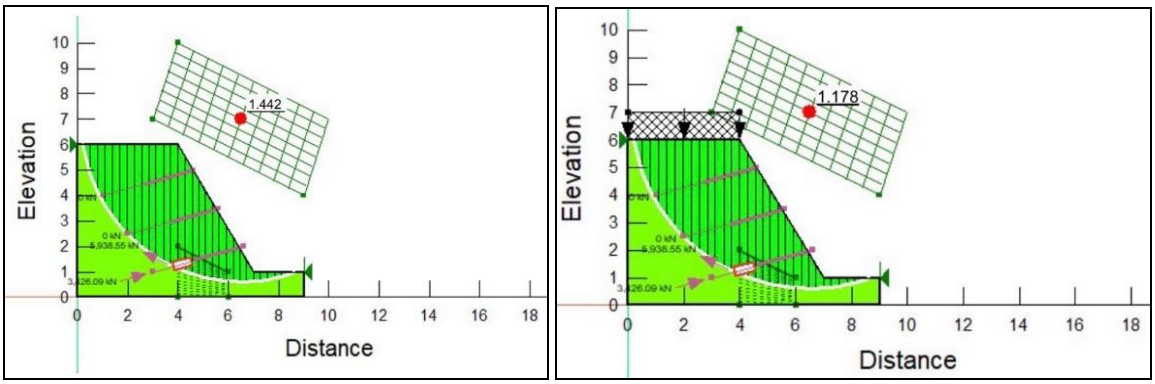


Fig 10. *Before vs after application of external load for slope 60°*

Figure 10 shows that before loading, the slope with anchor support had an FOS of 1.442, which was safe. After applying the external load, the FOS dropped to 1.178, falling below the minimum requirement. The steeper slope angle combined with the surcharge load increased the driving force, making the slope unstable even with anchors.

3.5.3 Slope (β = 90°) with External Load

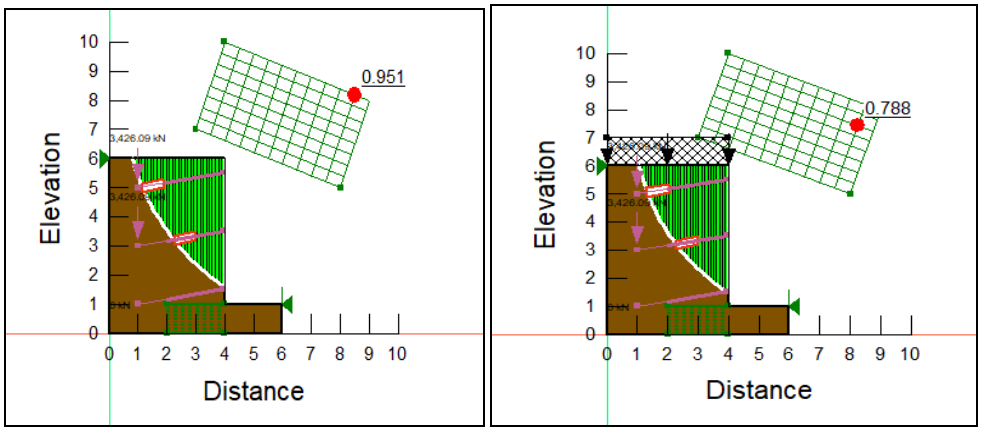


Fig 11. *Before vs after application of external load for slope 90°*

Figure 11 shows that the vertical slope made of dense silty sand was already unsafe before loading, with an FOS of 0.951. After applying the external load, the FOS decreased further to 0.788, confirming slope failure. This demonstrates that for vertical slopes, anchors alone are insufficient, and external loads worsen instability. Additional methods such as reducing slope angles or constructing retaining structures are required to achieve stability.

4. Discussion

The results show that slope stability depends on soil type, slope angle, reinforcement, and external load. Weak soils, such as poorly graded soil, gave very low Factor of Safety (FOS) values because of poor grain interlocking [8]. This shows that uniform soils are more likely to fail [8, 10]. Medium-dense sand and dense silty sand gave better stability, but reinforcement was still needed. When ground anchors were installed, slopes at 30° and 60° became stable. This finding agrees with previous studies showing that anchors increase resisting forces and improve the FOS in medium-dense soils [3, 10]. However, for vertical slopes at 90°, anchors did not help much because the extreme slope geometry controlled the failure mechanism [4]. This aligns with past research stating that reinforcement has little effect on very steep slopes [8]. Furthermore, when external surcharge loads were added, the FOS values dropped further, making the slopes unsafe. This is consistent with earlier findings that surcharge loads from vehicles or heavy equipment reduce overall slope stability, even when reinforcement is present [3].

Conclusion

This study analyzed slope stability using GeoStudio (SLOPE/W) with the Morgenstern-Price method across different soil types, slope angles, anchor piles, and top loads. The findings showed that weak, poorly graded soils had the lowest Factor of Safety (FOS) values and failed easily. Medium-dense sand and dense silty sand were

moderately safe, but they still needed anchors to meet safety standards [9]. Installing ground anchors improved stability for 30° and 60° slopes, raising the FOS above the required minimum level of 1.30. However, 90° vertical slopes remained unsafe even with anchors. This shows that anchors alone cannot hold extremely steep slopes. Finally, adding top loads reduced FOS values for all slopes, showing that real site loads must be included in slope design [3]. In conclusion, ground anchors work well for normal and steep slopes, but 90° vertical cuts need strong retaining walls to stay safe.

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Author Contribution

Authors should clearly specify the roles and contributions of each individual involved in the research to ensure proper attribution of credit and transparency regarding responsibilities. In this study, the specific contributions were as follows: conceptualization was carried out by Siti Nuramifarisya Mokhadis and Salina Sani; methodology was developed by Siti Nuramifarisya Mokhadis with guidance from Salina Sani; design arrangements, and data collection analysis were conducted by Siti Nuramifarisya Mokhadis; writing – original draft preparation was undertaken by Siti Nuramifarisya Mokhadis writing – review and editing were conducted by Salina Sani, supervision was provided by Salina Sani and Zaharah Mamat. All authors have read and agreed to the final version of the manuscript.

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