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Numerical Evaluation of Geogrid-Reinforced Slopes under Various Soil and Geometric Configurations

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ABSTRACT: This study examines the stability of geogrid-reinforced slopes under different soil and geometric conditions using SLOPE/W. The Morgenstern–Price method was used to analyze three homogeneous soil parameter sets: silty clay, clayey sand, and clayey silt. Four slope inclinations (25°, 30°, 45°, and 60°) were considered, along with total slope heights of 18, 24, 30, and 36 m. The reinforced slopes were modeled using UX1100 uniaxial geogrid at vertical spacings of 0.5, 1.0, and 1.5 m. Each reinforced model was compared with its corresponding unreinforced model under the same dry, drained, and static conditions, with pore-water pressure set to zero. The results show that FOS decreased as the slope inclination and total height increased. The calculated FOS also varied with the soil parameters. Silty clay generally produced the highest FOS, while clayey sand produced the lowest despite having a higher friction angle, due to the combined effects of cohesion, friction angle, and unit weight. As expected, the 0.5 m spacing produced the highest FOS among the three spacings because it provided more reinforcement layers within the same slope height. However, closer spacing did not provide adequate stability in every case. For the 36 m slope at 60°, the reinforced FOS values were 1.49, 1.06, and 1.17 for silty clay, clayey sand, and clayey silt, respectively, which were below the adopted requirement of 1.5. The findings show that geogrid spacing should be assessed alongside soil conditions and slope geometry. The results provide comparative trends for the idealized dry slope conditions considered and are not intended as site-specific design recommendations.

ABSTRAK: Kajian ini menilai kestabilan cerun bertetulang geogrid bagi keadaan tanah dan geometri yang berbeza menggunakan SLOPE/W. Kaedah Morgenstern–Price digunakan untuk menganalisis tiga set parameter tanah homogen, iaitu lempung berkelodak, pasir berlempung dan kelodak berlempung. Empat kecerunan, iaitu 25°, 30°, 45° dan 60°, dipertimbangkan bersama jumlah ketinggian cerun 18, 24, 30 dan 36 m. Cerun bertetulang dimodelkan menggunakan geogrid uniaxial UX1100 pada jarak menegak 0.5, 1.0 dan 1.5 m. Setiap model bertetulang dibandingkan dengan model tanpa tetulang yang sepadan dalam keadaan kering, tersalir dan statik yang sama, dengan tekanan air liang ditetapkan kepada sifar. Keputusan menunjukkan bahawa Faktor Keselamatan (FOS) menurun apabila kecerunan dan jumlah ketinggian cerun meningkat. Nilai FOS yang dikira turut berubah mengikut parameter tanah. Lempung berkelodak secara umumnya menghasilkan FOS tertinggi, manakala pasir berlempung menghasilkan FOS terendah walaupun mempunyai sudut geseran yang lebih tinggi, disebabkan oleh pengaruh gabungan kejelekitan, sudut geseran dan berat unit. Seperti yang dijangka, jarak 0.5 m menghasilkan FOS tertinggi antara tiga jarak yang dianalisis kerana lebih banyak lapisan tetulang digunakan pada ketinggian cerun yang sama. Walau bagaimanapun, jarak yang lebih rapat tidak memberikan kestabilan yang mencukupi bagi semua keadaan. Bagi cerun setinggi 36 m pada kecerunan 60°, nilai

FOS bertetulang ialah 1.49, 1.06 dan 1.17 masing-masing untuk lempung berkelodak, pasir berlempung dan kelodak berlempung. Semua nilai tersebut berada di bawah keperluan FOS 1.5 yang digunakan dalam kajian. Dapatan menunjukkan bahawa jarak geogrid perlu dinilai bersama keadaan tanah dan geometri cerun. Keputusan ini memberikan trend perbandingan bagi keadaan cerun kering yang diidealkan dan tidak dimaksudkan sebagai cadangan reka bentuk khusus tapak.

KEYWORDS: *Geogrid reinforcement, Slope stability, SLOPE/W, Slope geometry, Reinforcement spacing*

1. INTRODUCTION

Slope stability is an important consideration in geotechnical engineering, particularly for slopes associated with roads, embankments, and other infrastructure. Slope failure occurs when the driving forces on a slope exceed the available resisting forces, which are mainly governed by the soil's shear strength and the slope's geometry. Slope stability can also be affected by rainfall infiltration, changes in groundwater conditions, and human activities such as slope cutting and inadequate drainage. In tropical regions, prolonged or intense rainfall can increase pore-water pressure and reduce soil shear strength, thereby increasing the possibility of slope failure [1, 2]. Different failure mechanisms and ground conditions may require different slope stabilization measures [3, 4]. Therefore, proper assessment of slope stability and the selection of suitable stabilization measures are important to ensure the safety and long-term performance of slopes. Although rainfall and groundwater are important in field slopes, this study considers only dry, drained, static conditions. Rainfall infiltration and groundwater were not included because the analysis was intended to compare the effects of soil properties, slope geometry, and reinforcement arrangement without an additional hydraulic variable.

Various stabilization methods have been applied to improve slope stability, including soil improvement, soil nailing, retaining structures, ground anchors, and geosynthetic reinforcement [5, 6]. Among these methods, geosynthetics are widely used in geotechnical applications because they provide reinforcement while offering flexibility in construction and application [7]. Geogrids are commonly used as reinforcement due to their tensile strength and ability to interact with the surrounding soil. The reinforcement contributes additional resistance when a geogrid layer crosses a potential slip surface. Its contribution depends on the geogrid's tensile capacity, the spacing and length of the layers, soil–geogrid interaction, and the available anchorage beyond the slip surface [8, 9]. Geosynthetic solutions have also been considered an alternative to conventional stabilization methods because of their versatility and potential environmental benefits [7]. Previous numerical studies have shown that reinforcement measures can increase the Factor of Safety (FOS) of unstable slopes under suitable design conditions [8, 9].

The performance of a reinforced slope, however, depends on several factors and cannot be determined only by the presence of reinforcement. Soil shear strength parameters, particularly cohesion and internal friction angle, have a direct influence on slope stability, while changes in slope height and inclination can considerably affect the FOS [10]. As the slope becomes steeper, the downslope component of soil self-weight increases, resulting in a higher driving force and generally a lower FOS. An increase in total slope height may also increase the size and weight of the potential sliding mass. Reinforcement characteristics and arrangement also determine the stability of reinforced soil systems. Closer vertical spacing increases the number of geogrid layers that may cross the potential slip surface and contribute tensile resistance. However, the resulting improvement also depends on the soil strength and slope geometry. In addition, berms are commonly introduced in high slopes to modify the slope geometry and improve stability. Previous studies have shown that berms can affect the slope profile and potential sliding mechanism [11, 12]. These findings indicate that soil conditions, slope geometry, and reinforcement arrangement should be considered together when evaluating the performance of reinforced slopes.

Previous studies have investigated different slope stabilization techniques and the parameters affecting their performance. However, many studies have focused on a particular stabilization method or a limited set of parameters. For example, studies on soil nailing have examined the effects of nail length, inclination, and spacing [13], while studies involving geosynthetics have considered reinforcement properties and their effects on stability under specific conditions [7, 9]. The combined effects of soil condition, slope inclination, total slope height, stepped slope configuration, and geogrid spacing have received less attention. In the present analysis, the number of 6 m slope lifts increases together with the total slope height. Therefore, the analyzed cases represent the combined influence of slope height and stepped configuration rather than the independent effect of berm number.

This study numerically evaluates the stability of geogrid-reinforced slopes under different soil and geometric configurations using SLOPE/W. Three soil parameter sets, namely silty clay, clayey sand, and clayey silt, are considered, along with different slope inclinations and combined slope-height and stepped configurations. The reinforced slopes are analyzed using UX1100 uniaxial geogrid at vertical spacings of 0.5, 1.0, and 1.5 m. The calculated FOS values for the reinforced slopes are compared with those of the corresponding unreinforced slopes. The study aims to quantify the changes in FOS produced by the investigated geogrid spacings under different soil conditions, slope inclinations, and combined slope-height and stepped configurations. The analysis also identifies the configurations in which geogrid reinforcement alone is insufficient to achieve the adopted FOS requirement of 1.5.

2. METHODOLOGY

2.1. Numerical Modeling and Slope Geometry

The slope stability analyses were carried out using SLOPE/W to determine the Factor of Safety (FOS) of the unreinforced and geogrid-reinforced slopes. The Morgenstern–Price method was adopted in the limit equilibrium analysis. This method satisfies both force and moment equilibrium and considers the interslice shear and normal forces in the stability calculation [14].

Circular trial slip surfaces were generated using the Entry and Exit search method. The critical slip surface was taken as the trial surface that produced the lowest FOS. The same slip-surface search procedure was used for each unreinforced and reinforced model pair.

All models were analyzed under dry, drained, and static conditions. No groundwater function, rainfall infiltration, surcharge, or seismic coefficient was applied, and the pore-water pressure was set to $u = 0$. These conditions were kept unchanged throughout the analyses to allow direct comparison of the selected soil, slope geometry, and reinforcement variables.

Four local slope inclinations of 25°, 30°, 45°, and 60° were considered. Each slope lift was 6 m. Three, four, five, and six slope lifts produced total heights of 18, 24, 30, and 36 m, respectively. The 6 m slope-lift height and the range of configurations were selected based on the JKR Guidelines for Slope Design [15]. The same geometries were used for the corresponding unreinforced and reinforced models.

Because the number of slope lifts increased with total slope height, the analyzed cases were treated as combined slope-height and stepped configurations. Therefore, the analysis did not isolate the independent effect of berm number.

2.2. Soil and Geogrid Properties

Three homogeneous soil parameter sets were considered: silty clay, clayey sand, and clayey silt. The soil strength was represented using the Mohr–Coulomb model. The required input parameters were unit weight, effective cohesion, and effective friction angle, as listed in Table 1. The soil parameters were obtained from published secondary data [16] rather than laboratory testing for a specific project site. Each parameter set was applied uniformly throughout the corresponding slope model. Clayey sand has a higher friction angle than silty clay but lower cohesion and higher unit weight. Therefore, the FOS results were interpreted based on the combined effects of c', ϕ' and γ, rather than the friction angle alone.

Table 1. Soil properties used in the numerical analysis

Soil type	Unit weight, γ (kN/m³)	Cohesion, c′ (kPa)	Friction angle, φ′ (°)
Silty clay	18.0	4	30
Clayey sand	19.0	3	32
Clayey silt	19.5	3	28

For the reinforced slope analyses, Tensar UX1100 high-density polyethylene uniaxial geogrid was used. The geogrid properties were obtained from the manufacturer’s product information used in the numerical model. The nominal tensile strength was 58 kN/m. An approximate combined material reduction factor of 2.69 was applied to account collectively for creep, installation damage, and durability. This produced a reduced design tensile capacity of 21.58 kN/m, which was entered into SLOPE/W. Since the material reduction had already been included in the design tensile capacity, the model tensile reduction factor was set to 1.0 to avoid applying the reduction twice.

Table 2. Geogrid properties and modeling settings

Parameter	Value or modeling setting
Product	Tensar UX1100
Material and type	HDPE uniaxial geogrid
Nominal tensile strength	58 kN/m
Combined material reduction factor	2.69
Reduced design tensile capacity	21.58 kN/m
Model tensile reduction factor	1.0
Pullout reduction factor	1.0
Reinforcement force option	FOS-dependent
Force direction	Axial along the horizontal geogrid layer
Vertical spacing	0.5, 1.0 and 1.5 m
Geogrid length for $H = 18$m	15 m
Geogrid length for $H = 24$m	20 m
Geogrid length for $H = 30$m	25 m
Geogrid length for $H = 36$m	30 m
Approximate L/Hratio	0.83
Layer extent	From the slope face into the stable soil zone
Anchorage	Portion extending beyond the critical slip surface
Tensile stiffness	Not used in the limit equilibrium model
Bond-slip stiffness	Not used in the limit equilibrium model

The geogrid was represented as horizontal axial reinforcement using the FOS-dependent option. It was not applied as a constant prestressing force. The available reinforcement force was controlled by the reduced tensile capacity and the pullout resistance mobilized along the anchorage length beyond the critical slip surface. The pullout reduction factor was set to 1.0.

No tensile stiffness or bond-slip stiffness was used because the limit equilibrium model calculates the global FOS rather than the geogrid deformation response. Table 2 summarises the geogrid properties and modeling settings.

The geogrid layers were placed horizontally from the slope face into the stable soil zone. The total geogrid lengths were 15, 20, 25 and 30 m for the 18, 24, 30 and 36 m slope configurations, respectively. These lengths gave an approximate reinforcement length-to-height ratio, L/H, of 0.83. The geogrid layers intersected by the potential slip surface contributed to the stability calculation, while the portion extending beyond the slip surface provided the available anchorage.

2.3. Analysis Configurations and Stability Assessment

The numerical analysis was conducted in two stages. First, each slope was analyzed without reinforcement to establish its baseline FOS. The same slope model was then reinforced with UX1100 geogrid and reanalyzed. The slope geometry, soil parameters, hydraulic condition, and slip-surface search procedure were kept unchanged within each unreinforced and reinforced model pair.

Three vertical geogrid spacings of 0.5, 1.0, and 1.5 m were investigated for different soil parameter sets, slope inclinations, and combined slope-height and stepped configurations. Table 3 summarizes the numerical analysis configurations.

Table 3. Numerical analysis configurations

Parameter	Conditions analyzed
Soil parameter set	Silty clay, clayey sand and clayey silt
Local slope inclination	25°, 30°, 45° and 60°
Number of 6 m slope lifts	3, 4, 5 and 6
Total slope height	18, 24, 30 and 36 m
Geogrid	Tensar UX1100 uniaxial geogrid
Geogrid vertical spacing	0.5, 1.0 and 1.5 m
Slip-surface search	Entry and Exit
Hydraulic condition	Dry and drained; $u = 0$
External loading	No surcharge or seismic coefficient
Stability parameter	Factor of Safety
Unreinforced-slope requirement	FOS = 1.3
Reinforced-slope requirement	FOS = 1.5

An FOS of 1.3 was adopted as the minimum requirement for unreinforced slopes, while an FOS of 1.5 was used for reinforced slopes, based on the adopted JKR slope design requirements [15]. These values were used to identify the configurations that satisfied the adopted stability requirement and those that remained below the required FOS.

2.4. Comparative Assessment of Reinforcement Performance

The contribution of the geogrid was evaluated by comparing the FOS of each reinforced slope with that of its corresponding unreinforced condition. The comparison considered the magnitude of the FOS change and whether the reinforced configuration achieved the adopted FOS requirement of 1.5.

The paired comparison provided an internal consistency check because the slope geometry, soil inputs, hydraulic condition, and slip-surface search procedure were kept unchanged. However, this comparison does not constitute independent validation against field monitoring, laboratory testing, or a published benchmark. The findings are therefore interpreted as comparative numerical trends rather than site-specific design values.

3. Results and Discussion

The numerical results were evaluated by first examining the unreinforced slopes and then comparing the changes after the inclusion of UX1100 geogrid. The discussion focuses on the influence of slope inclination, soil parameter set, combined slope-height and stepped configuration, and geogrid vertical spacing. The FOS was used as the main indicator of slope stability.

3.1. Stability of Unreinforced Slopes

The unreinforced analyses provided the baseline for evaluating the contribution of geogrid reinforcement. Fig. 1 shows a representative SLOPE/W output for the 18 m slope at 30° using the clayey sand parameter set. The critical slip surface produced an FOS of 1.28.

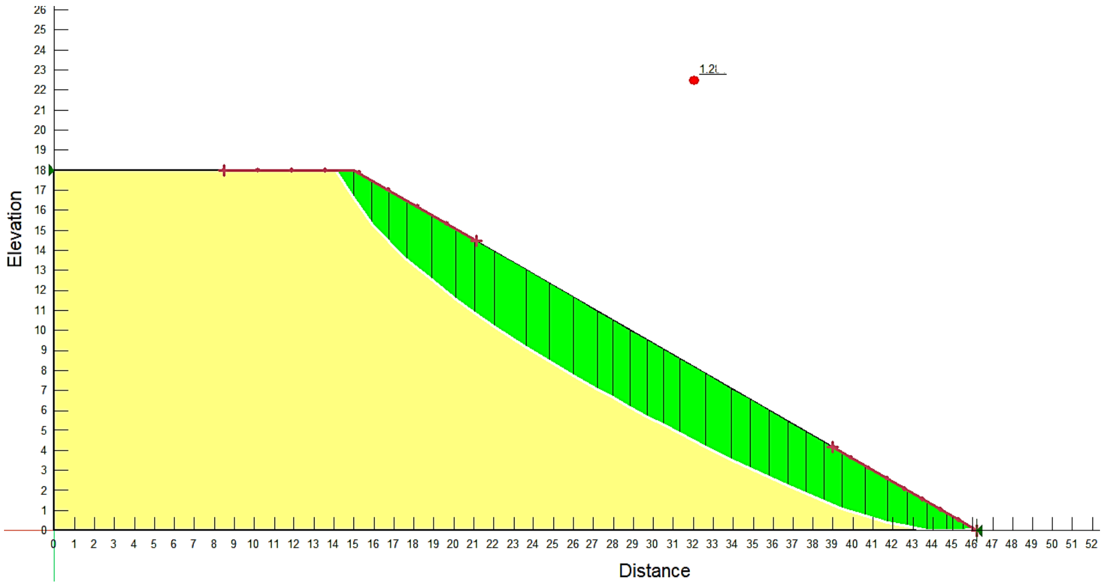

Figure 1. Representative critical slip surface for the unreinforced 18 m slope at 30° using the clayey sand parameter set (FOS = 1.28)

The FOS decreased as the slope inclination increased for all soil parameter sets and total slope heights. For the 18 m slope, the FOS of silty clay decreased from 2.41 at 25° to 1.10 at 60°. Over the same range, the FOS decreased from 1.53 to 0.58 for clayey sand and from 1.72 to 0.67 for clayey silt. A similar trend was observed for the other slope heights. For the 36 m configuration at 60°, the FOS values were 0.85, 0.50 and 0.57 for silty clay, clayey sand and clayey silt, respectively.

As the slope becomes steeper, a larger component of the soil self-weight acts downslope, increasing the driving force relative to the available shear resistance. The change in inclination may also affect the size and position of the critical sliding mass. Previous numerical studies have reported similar effects of slope inclination on FOS [9, 10, 17].

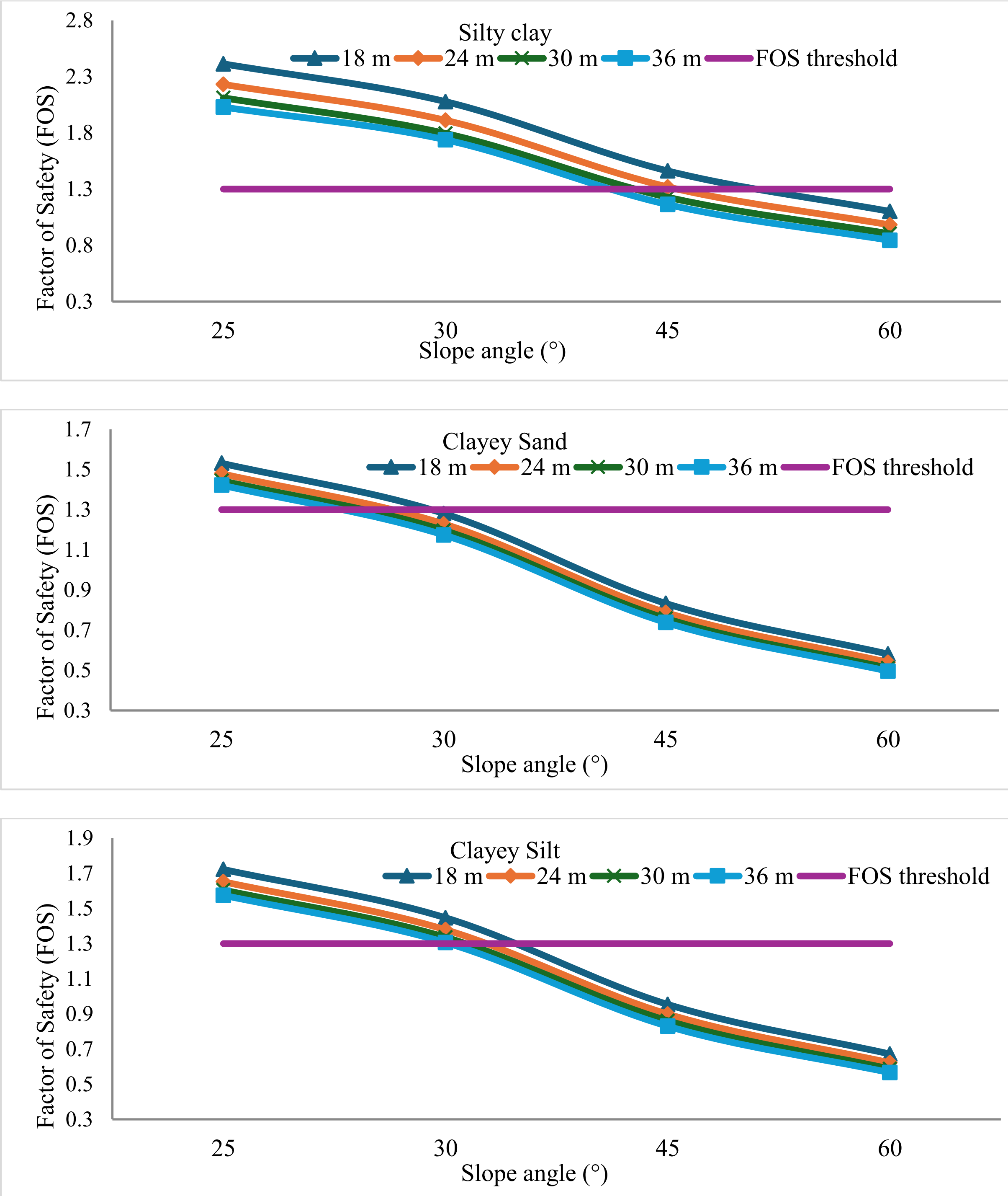

Figure 2. Variation of FOS with slope angle for unreinforced slopes at different slope heights

Fig. 2 compares the unreinforced FOS values with the adopted minimum requirement of 1.3. Several gentler configurations remained above the required value. However, the number of cases below FOS = 1.3 increased as the slope inclination and total height increased. The 60° slopes were the most critical, particularly for clayey sand and clayey silt.

The soil parameter set also influenced the calculated FOS. Silty clay generally produced the highest FOS, followed by clayey silt, while clayey sand produced the lowest. For the 30 m slope at 25°, the FOS values were 2.11, 1.61 and 1.44 for silty clay, clayey silt and clayey sand, respectively. At 45°, the corresponding values decreased to 1.23, 0.86 and 0.76.

The available Mohr–Coulomb shear resistance depends on the combined contribution of effective cohesion and frictional resistance. Although clayey sand had a higher friction angle than silty clay, it also had lower cohesion and higher unit weight. Its lower FOS therefore resulted from the combined soil parameters and stress conditions rather than the friction angle alone.

Figure 3 shows the unreinforced results at 45° for the combined slope-height and stepped configurations. For silty clay, the FOS decreased from 1.46 for the 18 m configuration to 1.16 for the 36 m configuration. The FOS decreased from 0.83 to 0.74 for clayey sand and from 0.95 to 0.83 for clayey silt over the same range.

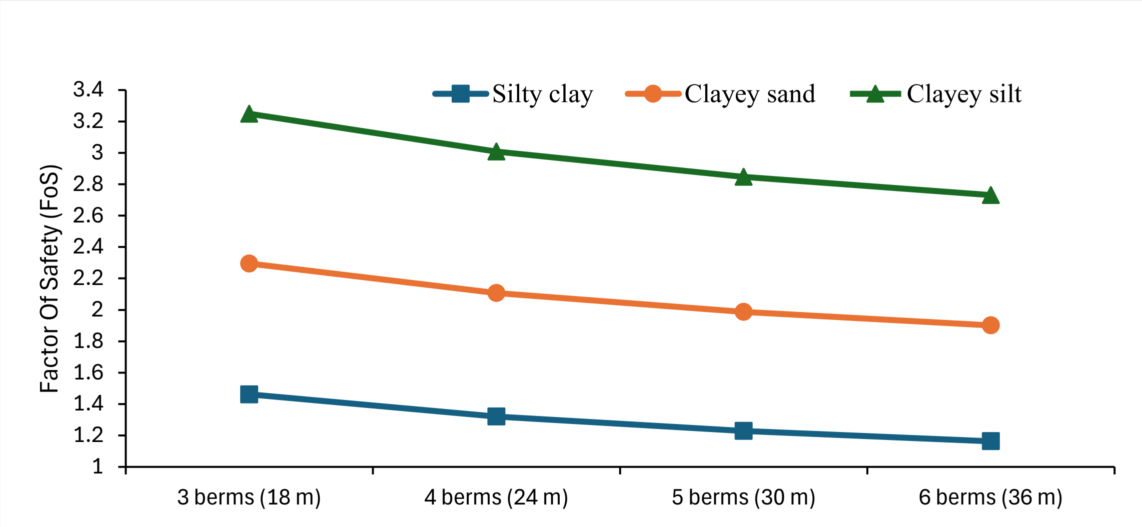

Figure 3. Variation of unreinforced FOS with the combined slope-height and stepped configuration at 45°

The reduction should not be attributed only to the number of berms because the number of slope lifts and total slope height increased together. The observed result represents their combined influence. A constant-height analysis in which the number and width of berms are varied independently would be required to isolate the effect of berm configuration.

3.2. Effect of Geogrid Reinforcement on Slope Stability

Including geogrid increased the FOS relative to the corresponding unreinforced slopes. However, the magnitude of improvement depended on the soil parameter set, slope inclination, total height, and reinforcement spacing. Fig. 4 shows a representative reinforced SLOPE/W model and its critical slip surface.

For the 18 m slope at 45°, the silty clay FOS increased from 1.46 without reinforcement to 2.15 with geogrid at 0.5 m vertical spacing. The clayey sand FOS increased from 0.83 to 1.51, while the clayey silt FOS increased from 0.95 to 1.67.

At 60°, the silty clay FOS increased from 1.10 to 2.12 at the same spacing. Clayey sand increased from 0.58 to 1.43, while clayey silt increased from 0.67 to 1.58. Although clayey sand showed a large percentage improvement, its final FOS remained below 1.5. Therefore, the percentage increase alone does not indicate whether the reinforced slope meets the adopted stability requirement. The final reinforced FOS must also be considered. Table 4 summarizes selected reinforced and unreinforced results to demonstrate the improvement provided by the geogrid.

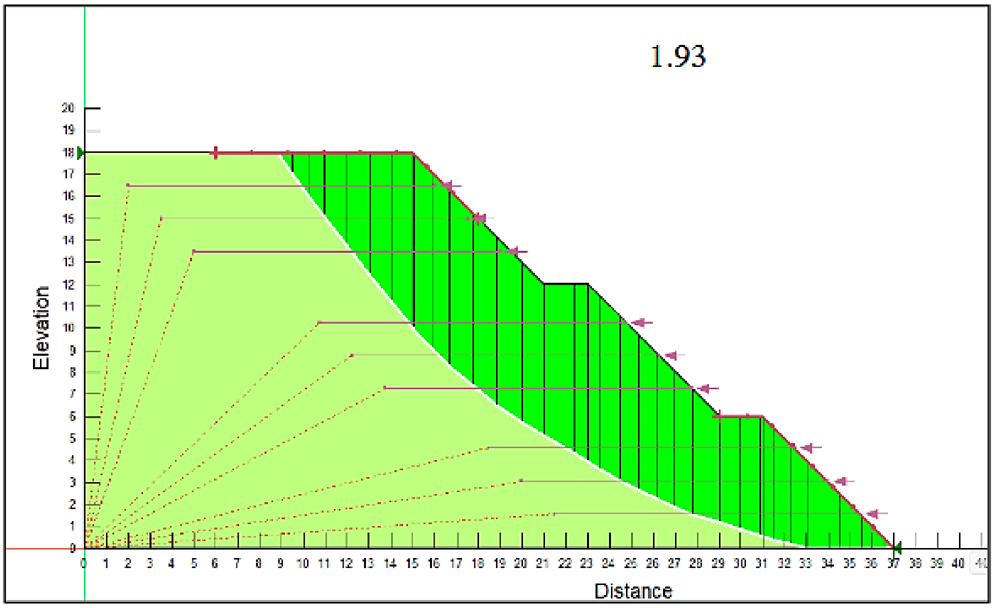

Figure 4. Representative SLOPE/W analysis of a slope reinforced with UX1100 geogrid.

Table 4. Comparison of representative FOS values for unreinforced and reinforced slopes

Height	**Angle**	**Soil type**	**FOS without geogrid**	**FOS with geogrid, 0.5 m**	**Increase in FOS (%)**
18 m	45°	Silty clay	1.46	2.15	47.1
18 m	45°	Clayey sand	0.83	1.51	81.8
18 m	45°	Clayey silt	0.95	1.67	75.4
18 m	60°	Silty clay	1.10	2.12	92.2
18 m	60°	Clayey sand	0.58	1.43	145.8
18 m	60°	Clayey silt	0.67	1.58	135.7

The geogrid contributed axial tensile resistance where the reinforcement layers intersected the potential slip surface. This resistance was transferred through soil–geogrid interaction and the available anchorage beyond the sliding mass. The magnitude that could be mobilized was limited by the reduced tensile capacity and pullout resistance. This mechanism is consistent with the improvement observed in previous reinforced-slope studies [8, 9, 18].

The effect differed between the soil parameter sets because the soil controlled both the unreinforced shear resistance and the interaction with the reinforcement. The relatively low initial FOS of clayey sand allowed a high percentage increase after reinforcement, but the resulting FOS was not always sufficient to reach 1.5. This distinction is important when interpreting reinforcement performance.

3.3. Effect of Geogrid Vertical Spacing

The FOS increased as the vertical spacing between the geogrid layers decreased. Among the three spacings investigated, 0.5 m produced the highest FOS, followed by 1.0 and 1.5 m.

This expected trend occurred because the closer spacing provided more reinforcement layers within the same slope height, allowing more layers to intersect the potential slip surface.

Fig. 5 shows the effect of geogrid vertical spacing on FOS for the 18 m slope at 45°. For silty clay, the FOS decreased from 2.15 at 0.5 m spacing to 2.10 and 1.93 at 1.0 and 1.5 m spacing, respectively. For clayey sand, the corresponding values were 1.51, 1.36, and 1.22. Clayey silt produced FOS values of 1.67, 1.52, and 1.37.

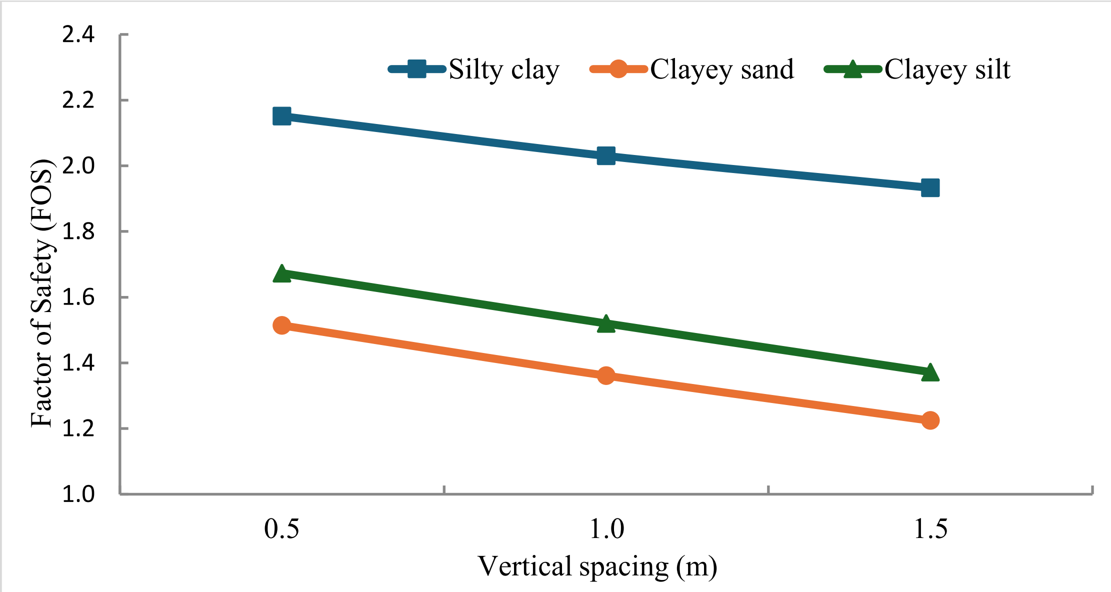

Figure 5. Effect of geogrid vertical spacing on FOS for the 18 m slope at 45°

Spacing also influenced the results at 60°. The silty clay FOS decreased from 2.12 at 0.5 m spacing to 1.68 at 1.0 m and 1.54 at 1.5 m. For clayey sand, the corresponding values were 1.43, 1.06 and 0.94, while clayey silt produced FOS values of 1.58, 1.19 and 1.06.

Although closer spacing increased the FOS, several cases at 60° remained below the reinforced-slope requirement of 1.5. The 0.5 m spacing should therefore be interpreted only as the spacing that produced the highest FOS among the three values investigated. It does not represent an optimum spacing. Determining an optimum would require additional spacings, along with deformation, constructability, and economic considerations.

3.4. Combined Influence of Slope Geometry and Soil Condition

The same reinforcement spacing did not provide the same level of stability for every slope configuration. At 25°, the reinforced slopes generally maintained relatively high FOS values, including the taller configurations. For the 36 m configuration at 0.5 m spacing, the FOS values were 2.46, 1.84, and 2.02 for silty clay, clayey sand, and clayey silt, respectively. All three values exceeded 1.5.

At 60°, substantially lower FOS values were obtained. For the 36 m configuration at the same 0.5 m spacing, the FOS values were 1.49, 1.06, and 1.17 for silty clay, clayey sand, and clayey silt, respectively. None of the three soil parameter sets achieved FOS = 1.5. Thus, closer reinforcement spacing alone was insufficient for this combination of total height and slope inclination. Table 5 compares the reinforced FOS values for the 18 m and 36 m configurations at 60° using the same geogrid spacing of 0.5 m.

Table 5. Reinforced FOS for the 18 m and 36 m configurations at 60° using 0.5 m geogrid spacing

Combined configuration	Soil parameter set	Reinforced FOS
3 lifts; $H = 18$m	Silty clay	2.12
3 lifts; $H = 18$m	Clayey sand	1.43
3 lifts; $H = 18$m	Clayey silt	1.58
6 lifts; $H = 36$m	Silty clay	1.49
6 lifts; $H = 36$m	Clayey sand	1.06
6 lifts; $H = 36$m	Clayey silt	1.17

For silty clay, the reinforced FOS decreased from 2.12 for the 18 m configuration to 1.49 for the 36 m configuration. Clayey sand decreased from 1.43 to 1.06, while clayey silt decreased from 1.58 to 1.17. These comparisons show that reinforcement performance was influenced by the slope geometry and initial soil resistance.

The results should not be interpreted as showing that berms reduce slope stability. The number of slope lifts and total slope height were varied simultaneously. Therefore, the observed reductions cannot be separated into independent berm and height effects. The results only describe the combined slope-height and stepped configurations considered in the study.

3.5. Overall Performance, Limitations and Practical Implications

Fig. 6 presents the variation of reinforced FOS with slope inclination at a vertical spacing of 0.5 m. For the gentler inclinations of 25° and 30°, reinforcement generally produced FOS values above the adopted requirement. As the inclination increased to 45° and 60°, the final FOS became more dependent on the soil parameter set and total slope height. Table 6 summarises the main findings and their implications for assessing geogrid-reinforced slopes.

The study was limited to homogeneous soil parameter sets under dry, drained, and static conditions. The study did not include groundwater, rainfall infiltration, surcharge, seismic loading, drainage performance, or spatial soil variability. The calculated FOS values should therefore not be applied directly to wet, loaded, or site-specific slopes.

The paired reinforced and unreinforced models provided an internal comparison because they maintained the same geometry, soil inputs, and analysis procedure. However, the models were not independently validated using field measurements, laboratory tests, or a published benchmark. The results should therefore be used to describe comparative numerical trends rather than as direct design values.

The results indicate that geogrid spacing should be considered alongside soil conditions and slope geometry. Although the 0.5 m spacing produced higher FOS values than the 1.0 and 1.5 m spacings, it remained insufficient for some of the taller and steeper configurations. This was most evident for the 36 m slope at 60°, where none of the three soil parameter sets achieved FOS = 1.5 at 0.5 m spacing.

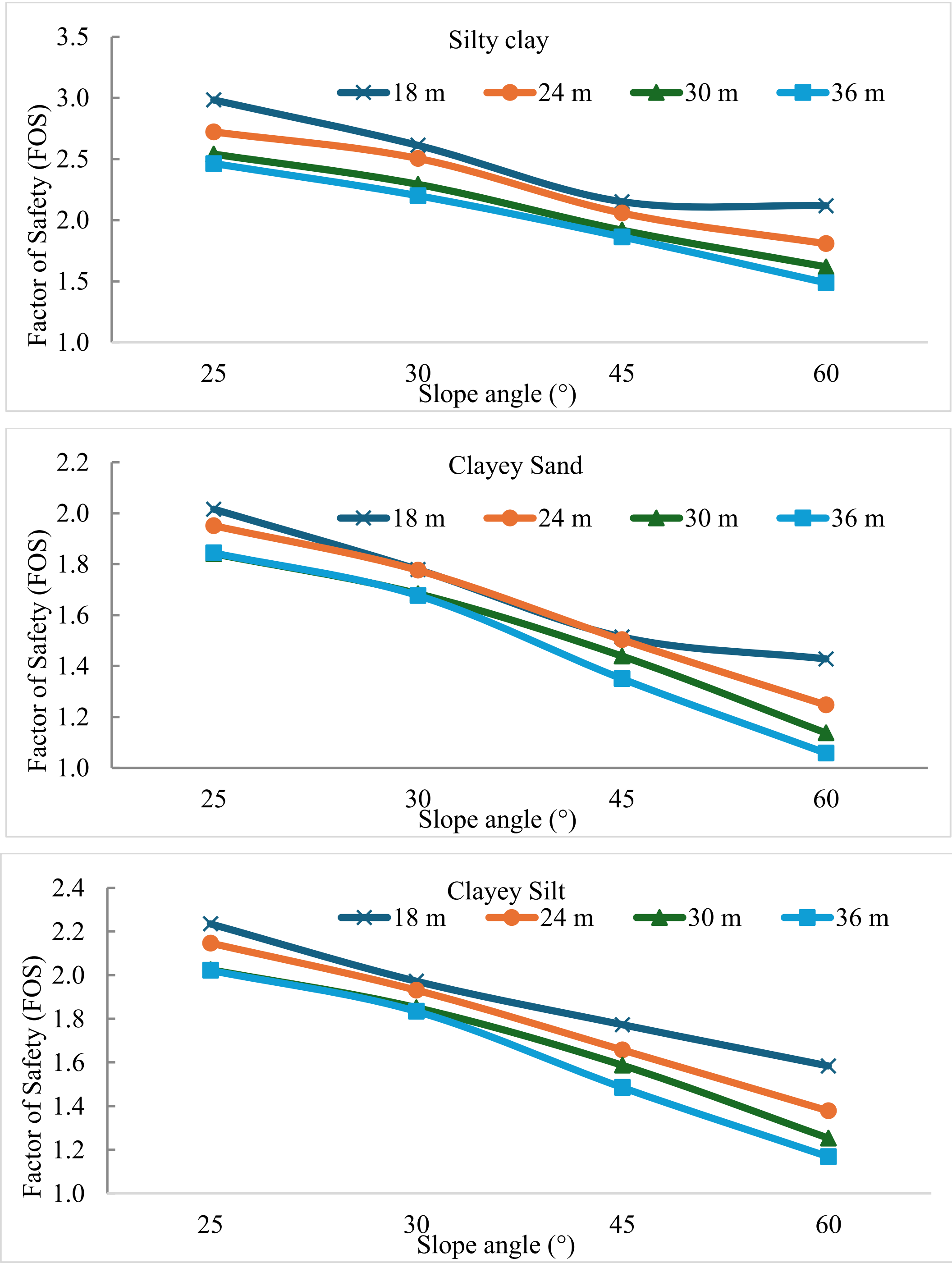

Figure 6. Variation of reinforced FOS with slope inclination at 0.5 m geogrid spacing for different total heights.

Further work should include coupled seepage–stability analysis, surcharge and seismic conditions, soil-property variability, and independent model validation. A constant-height factorial analysis in which berm number and geometry are varied separately is also required to isolate the influence of berm configuration. Additional reinforcement spacings and deformation or economic criteria would be required before an optimum geogrid arrangement could be established.

Table 6. Summary of the main findings and engineering implications

Parameter	Main finding	Engineering implication
Soil parameter set	Silty clay generally produced the highest FOS, while clayey sand produced the lowest	Reinforcement performance depends on the combined soil-strength parameters and stress condition
Slope inclination	FOS decreased as the slope became steeper	Steeper slopes produced a higher driving demand
Geogrid spacing	The 0.5 m spacing produced the highest FOS among the three spacings investigated	The result reflects the larger number of reinforcement layers and is not an optimization result
Combined slope-height and stepped configuration	Taller configurations generally produced lower FOS	The independent effect of berm number cannot be determined from the present analysis
Critical configurations	Reinforcement increased FOS, but some taller and steeper configurations remained below 1.5	An increase in FOS does not necessarily mean that the adopted stability requirement has been achieved

4. CONCLUSIONS

This study evaluated the stability of geogrid-reinforced slopes under different soil and geometric configurations using SLOPE/W. The analyses considered three soil parameter sets, four slope inclinations, four combined slope-height and stepped configurations with total heights ranging from 18 to 36 m, and geogrid vertical spacings of 0.5, 1.0 and 1.5 m. The reinforced and unreinforced slopes were compared under the same dry, drained, and static conditions.

The unreinforced results showed that the FOS generally decreased as the slope inclination and total height increased. Soil condition also influenced the calculated FOS. Silty clay generally produced the highest FOS, while clayey sand produced the lowest. Although clayey sand had a higher friction angle than silty clay, its lower cohesion and higher unit weight contributed to its lower FOS. The results therefore reflected the combined soil parameters rather than the friction angle alone.

Geogrid reinforcement increased the FOS for all the configurations investigated, but the magnitude of improvement varied with the soil parameter set and slope geometry. As expected, the 0.5 m spacing produced the highest FOS among the three spacings because it provided more reinforcement layers within the same slope height. This result should not be interpreted as an optimum spacing. More importantly, higher FOS did not always result in acceptable stability. For the 36 m slope at 60°, none of the three soil parameter sets achieved FOS = 1.5, even at the closest spacing of 0.5 m. This shows that closer reinforcement spacing alone may be insufficient for taller and steeper slope configurations.

The study does not establish the independent influence of berm number because the number of slope lifts and total height increased together. The results represent the combined influence of slope height and stepped configuration. A constant-height analysis with independently varied berm geometry would be required to determine the effect of berm number.

The findings are limited to homogeneous soil parameter sets under dry, drained, and static conditions, with no groundwater, rainfall infiltration, surcharge, or seismic loading. The paired reinforced and unreinforced models provided an internal comparison but were not independently validated using field measurements, laboratory tests, or a published benchmark. Therefore, interpret the findings as comparative numerical trends rather than site-specific design values. Future work should include independent model validation, wet and loaded slope conditions, constant-height berm configurations, and additional geogrid spacings supported by deformation, constructability, and economic considerations.

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