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Stability analysis of reinforcement slope using FEM

MD. MAHMUD SAZZAD, A. B. K. M. ATFUL HIE, MD. SADDAM HOSSAIN
Department of Civil Engineering, Rajshahi University of Engineering & Technology, Bangladesh
Email: mmsruet@gmail.com, ah.shohag10.research@gmail.com, zsaddam15@gmail.com

Abstract: High and steep cut slopes due to excavation are a common sight in building high grade throughways. Currently, the usage of steel bars as reinforcement is increasingly becoming widespread in engineering practice. This paper studies the performance of reinforced slope under varying reinforcing bar inclination angle, slope angle, reinforcing bar number and spacing of reinforcing bars in regular, random and group forms using the finite element method (FEM). The geometric model of slope is arbitrary created with the variation of soil properties. The mesh effect is studied to ensure that the numerical solution by FEM converges. From the analyses, it is noted that mixed mesh is computationally efficient than that of 6-node triangular element. The factor of safety of reinforced slope increases with the increase of reinforcing bar inclination angle with respect to the horizontal axis which is followed by a decrease in the factor of safety with the further increase in reinforcing bar inclination angle. The maximum value of the factor of safety is a function of the slope angle. The relationship between reinforcing bar inclination angle and slope angle for maximum factor of safety is nonlinear. The maximum factor of safety of reinforced slope is possible when the bar inclination angle lies between 10° to 15° for the geometric model, soil and reinforcing bar properties considered in the present study. Maximum factor of safety is likely when equal spacing is adopted in reinforcing a slope. Group spacing also yields elevated factor of safety compared to that for the random spacing of reinforcing bar.

Keywords: *Slope stability, Reinforcing bar, Mesh effect, Reinforcing bar inclination angle, Group spacing.*

Introduction:

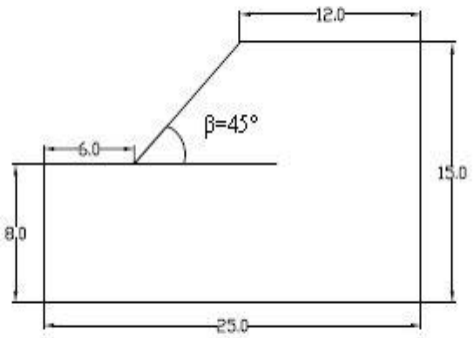
Detachment and sliding of a soil volume along a failure surface are often occurred due to heavy rainfall, increase in ground water table, change in stress condition, change in tropology, external forces, weathering, insufficient surface protection, infiltration, high seismic activity, etc. In order to prevent the sliding, different techniques have been developed to ensure the stability of slope. The reinforced soil is a decent technique and an economical alternative to stabilize the natural or artificial slopes as a part of civil engineering projects. It is in some cases used to construct stable slopes at much steeper angles than would otherwise be possible without reinforcing the slope [1]. Previous studies depicts that the shear strength of soil can be improved by using steel nails [2-5]. The stability of slope using soil reinforcing technique can be analyzed by using the conventional limit equilibrium methods or by using the finite element method (FEM). The conventional limit equilibrium methods require the assumption of failure surface and often deal with very simple geometry of slopes. In contrary, FEM needs no assumption of failure surface and can deal with any complex geometry of the model. FEM is a numerical technique for solving problems which are described by partial differential equations or can be formulated as functional minimization. A continuous physical problem is transformed into a discretized finite element problem with unknown nodal values. A domain of interest is represented as an assembly of finite elements. In addition, this method is able to run rigorous analysis on complex problems like stress analysis, fluid flow, heat transfer, etc. The development of finite element method leads to an effective approach for assessing the factor of safety of soil slopes within its strength reduction technique [5-8]. This procedure, coupled with the advanced optimization techniques, is adequate for regular slope stability problems [9]. This paper aims at performing a comprehensive numerical study of the stability of the reinforced soil slope. The influence of the variation of the reinforcing bar inclination angle along with the variation of reinforcing bar number and spacing of reinforcing bar on the factor of safety of slope by FEM is studied using GEO5 [10]. The effect of regular and random spacing of reinforcing bar and group spacing has been investigated. An attempt has been made to find the optimum spacing and number of bar in the application of soil reinforcement in slope stability. The consequences of using different factors in the FEM based study have been investigated and the numerical results have been reported.

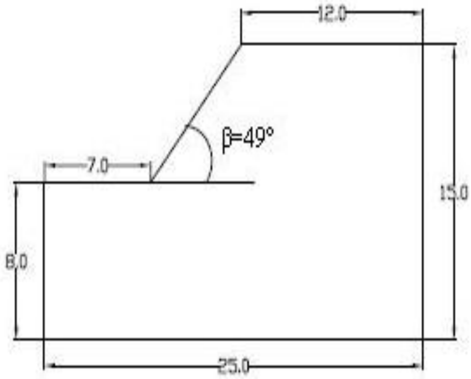
Brief Description of GEO5:

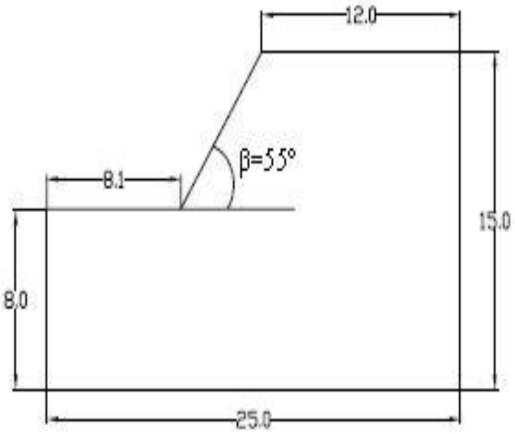
The numerical study of the reinforced slope has been carried out by GEO5 [10] based on Finite Element Method. This software enables the linear or nonlinear, time-dependent and anisotropic behavior of soil or rock from the most basic to the most advanced constitutive models. Since the behavior of slope can be defined as two dimensional analysis, geometry of slope as plane strain mode has been used for the finite element modeling. The soil profile has been modeled using definite nodded triangular element and the boundary conditions are defined by the standard fixities for static loading. In the standard fixities, vertical geometry lines for which the $x-$coordinate is equal to the lowest or highest $x-$coordinate in the model to obtain a horizontal fixity.

Geometric Modeling:

The geometric model used in the present study is depicted in Figure 1 with slope angle of 45, 49, 55 and 63.5 degrees, respectively, relative to the horizon. The dimensions in the slope model are given in meter. The geometric boundaries are horizontally constrained on the left and right sides and completely fixed at the bottom of the geometry. The whole domain is divided into sub domain of mesh size equal to 1 m. After the generation of mesh and assigning the properties of soil and reinforcing bar, the stability analysis is performed. The Mohr-Coulomb failure criterion is used as material model for non-linear behavior of the soils. Eleven layers of steel bar are reinforced in slope keeping the relative spacing same. Factor of safety (FS) of slope in GEO5 [10] has been calculated by reducing the strength parameters of the soil. The properties of the reinforcing bars and soil are given in Tables 1 and 2, respectively.







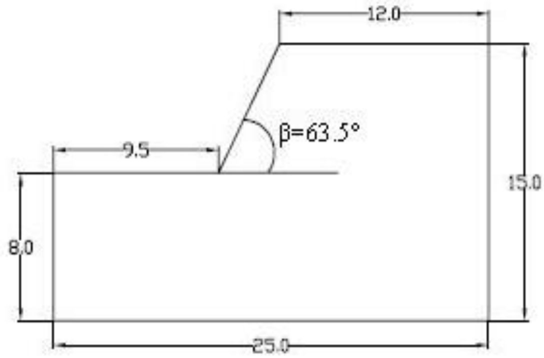


Figure 1: *The geometric model used in the present study with different slope angles*

Table 1: Properties of steel bar used in the present study

Properties of steel bar	Value
Stiffness of bar (kN/m) :	60
Total length of reinforcement bar in 1m width of slope (m)	121

Table 2: Properties of soil used in the present study

Properties of soil used	**Soil type**		
	Type-1	**Type-2**	**Type-3**
Unit weight (KN/m^3)	19	19	19
Saturated unit weight (KN/m^3)	21	21	21
Elastic modulus of soil (MPa)	7	8	8
Cohesion of soil (KPa)	7	10	14
Angle of friction (°)	25	25	25

Result and Discussion:

1 Effect of mesh:

Generation of mesh in the finite element model is the most important step because the number of element in a given model affects the accuracy and the computational economy of the analysis. Two types of mesh are generated: (i) six node triangular element (TE6) and (ii) mixed mesh which is the combination of 6 node triangular element and 8 node quadrilateral element. The factor of safety for different mesh geometries with varying mesh sizes are listed in Table 3. It is noted in Table 3 that, for 6 node triangular element, when the slope model is divided into 83 to 163 elements, the factor of safety decreases slowly and with further increasing of element number from 219 to 3252, the factor of safety changes a little. It also exhibits that in mixed mesh (combination of triangular element and quadrilateral element), element number from 92 to 139, the factor of safety decreases slowly and with further increase of element number from 229 to 335, factor of safety changes a little and from 654 to 1897, factor of safety remains constant. In both the cases, the trend is same. The more the element number the less the factor of safety until the factor of safety yields an almost equal value. From the table, it is also obvious that it is suitable to choose mixed mesh for yielding consistent factor of safety with less element number.

Table 3: Effect of mesh on the factor of safety

Approximate global size (m)	6 node triangular element			Mixed mesh		
	Factor of safety	Elements number	Nodes number	Factor of safety	Elements number	Nodes number
0.5	0.90	3252	6061	0.90	1897	4622
1.0	1.00	938	1661	0.90	654	1407
1.5	1.04	485	830	1.08	335	664
2.0	1.05	322	537	1.08	229	434
2.5	1.09	219	358	1.17	176	321
3.0	1.14	163	264	1.18	139	244
3.5	1.15	129	208	1.37	116	201
4.0	1.17	113	182	1.40	101	174
4.5	1.20	100	159	1.48	92	157
5.0	1.39	83	134	1.48	92	157

2 Effect of inclination angle of reinforcement:

One of the objectives of the study is to investigate the effect of the inclination angle of reinforcing bar on the stability of slope of varying slope angles. In this study, eleven rows of soil reinforcement (steel bar), each 11m length having stiffness of 60 kN/m, are placed in a regular interval in the slope. The factor of safety of slope with the incorporation of reinforcement bar is computed and reported in Table 4. Note that the factor of safety of slope increases with the increase of bar inclination angle which is again followed by a decrease in the factor of safety. It should be noted that the maximum value of the factor of safety is a function of the slope angle. The relationship between the bar inclination angle (θ) and the slope angle (β) for the maximum value of factor of safety is depicted in Figure 2. Note that the relationship between bar inclination angle and slope angle for maximum factor of safety is nonlinear. The same relationship for soil type-2 and soil type-3 is depicted in Tables 5 and 6 and in Figures 3 and 4, respectively.

Table 4: Factor of safety (FOS) of reinforced slope of soil type-1 with varying slope and bar inclination angles

Bar inclination	Slope angle, β (^{0})			
	45	49	55	63.5
θ (^{0})	FOS	FOS	FOS	FOS
0	1.67	1.09	1.21	0.90
5	1.85	1.46	1.60	1.69
10	1.73	1.74	1.60	1.77
15	1.73	1.23	1.69	1.77
20	1.60	1.33	1.54	1.64
25	1.66	1.11	1.50	1.59
30	1.21	1.00	1.03	1.03

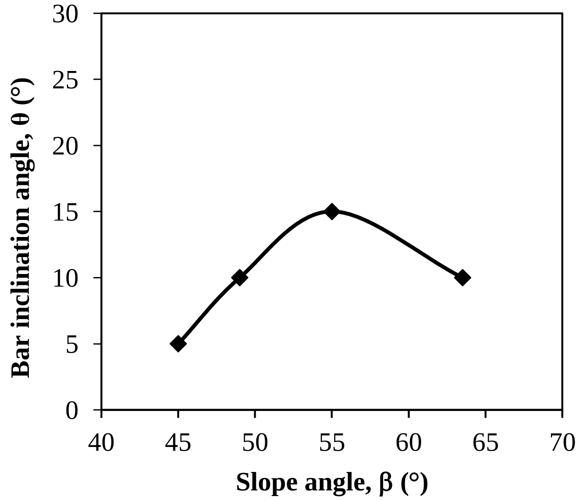


Figure 2: *Relationship between bar inclination angle and slope angle for maximum factor of safety*

Table 5: Factor of safety of reinforced slope of soil type-2 with varying slope and bar inclination angles

Bar inclination	Slope Angle, β (^{0})			
	45	49	55	63.5
θ (^{0})	FOS	FOS	FOS	FOS
0	2.03	1.98	1.98	1.97
5	2.07	2.03	2.03	1.91
10	2.14	2.03	2.03	1.80
15	2.09	2.06	2.06	1.75
20	1.93	2.00	2.00	1.74
25	1.96	1.95	1.95	1.64
30	1.98	1.44	1.44	1.77

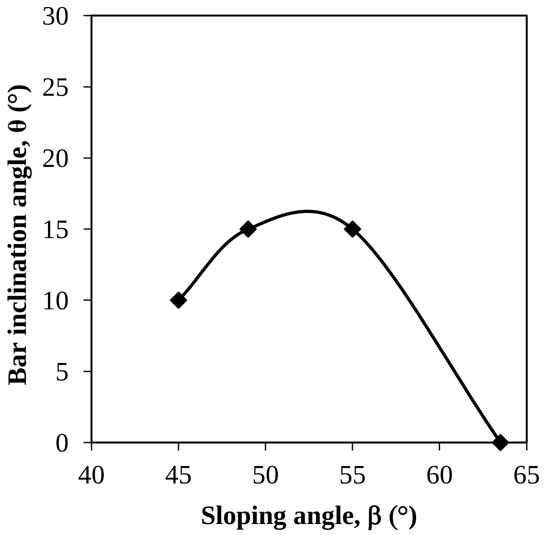


Figure 3: *Relationship between bar inclination angle and slope angle for maximum factor of safety*

Table 6: Factor of safety of reinforced slope of soil type-3 with varying slope and bar inclination angles

Bar inclination	**Slope Angle, β (^{0})**			
	45	**49**	**55**	**63.5**
θ (^{0})	FOS	FOS	FOS	FOS
0	2.20	2.20	2.16	2.23
5	2.20	2.38	2.31	2.17
10	2.32	2.26	2.34	2.23
15	2.32	2.38	2.43	2.14
20	2.28	2.09	2.54	1.62
25	2.28	2.40	2.75	2.18
30	2.29	1.80	2.18	1.93

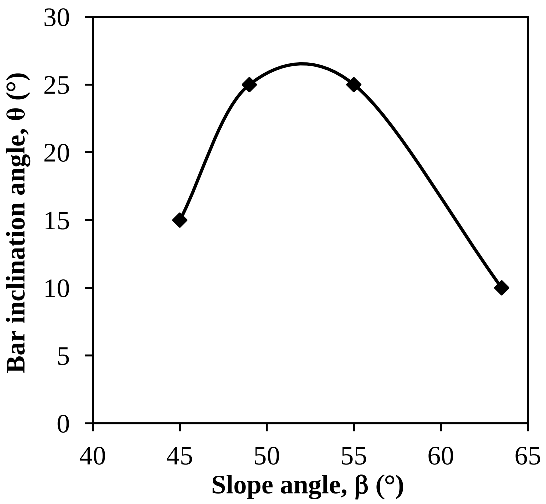


Figure 4: *Relationship between bar inclination angle and slope angle for maximum factor of safety*

Figure 5 depicts the comparison of the factor of safety for different bar inclination angles at a particular slope inclination angle, $\beta = 49^\circ$. Note that the factor of safety increases with the increase of the cohesion of the soil, as one might expect. However, the interesting point is that the peak factor of safety of the average curve for different types of soil lies between the bar inclination angle of 10° to 15°. Similar behavior is also noticed for other slope angles.

Table 7*: Factor of safety (FOS) for the variation of bar number with soil type-1*

Number of layer	**Length of each bar**	**FOS**
10	12.10	1.25
11	11.00	1.74
12	10.08	1.67
13	9.31	1.75
14	8.64	1.78
15	8.10	1.68
16	7.56	1.69
17	7.10	1.69
18	6.72	1.53

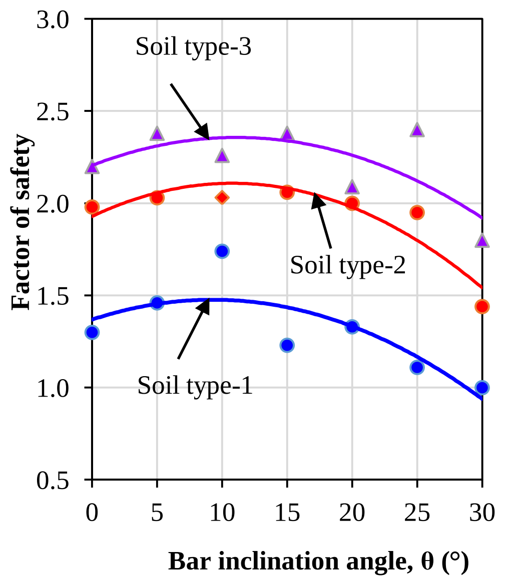


Figure 5: *Relationship between factor of safety and bar inclination angle for $\beta = 49^\circ$ for three types of soil considered in the present study*

3 Effect of variation of bar number:

The effect of the variation of bar number with a fixed bar inclination angle (10°), slope angle ($\beta = 49^\circ$) and total length of bar (121 m) is studied in the present study for soil type 1. The factor of safety is computed and the results are presented in Table 7. Note that the maximum factor of safety is obtained when 14 nos. of bar with a bar length of 8.64 m each is used.

4 Effect of variation of bar spacing:

Since maximum factor of safety is obtained when 14 nos. of bar with a bar length of 8.64 m each is used, in this section, 14 nos. of bar is selected keeping total bar length of 121 m by varying their relative spacing. Factor of safety for bar inclination of 10 degree at different spacing (i.e., equal spacing, random spacing, group spacing type-1 and group spacing type-2) are given below. Note from Table 8 that maximum factor of safety is possible only when equal spacing is adopted in reinforcing a slope. Group spacing also yields elevated factor of safety compared to that for the random spacing of bar.

Table 8: Factor of safety (FOS) of reinforced slope with different types of spacing of reinforcing bar keeping total bar length of 121 m

Spacing type	FOS
Equal spacing	1.78
Random spacing	1.44
Group spacing 1	1.72
Group spacing 2	1.74

The contour of the equivalent plastic strain for different type of bar spacing (i.e., equal spacing, random spacing, group spacing type-1 and group spacing type-2) are depicted in Figures 6, 7,8 and 9, respectively.

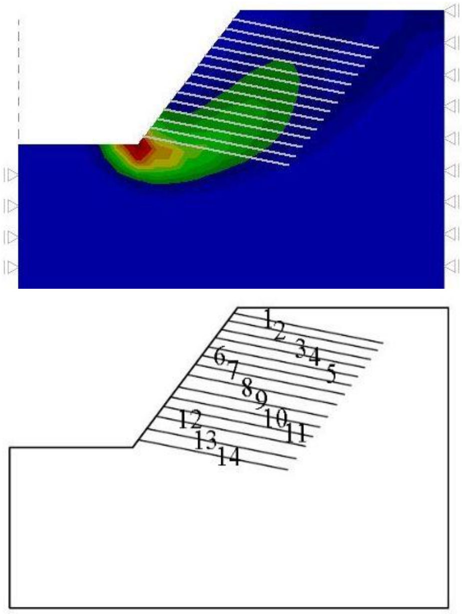


Figure 6: *Contour of equivalent plastic strain at equal relative spacing*

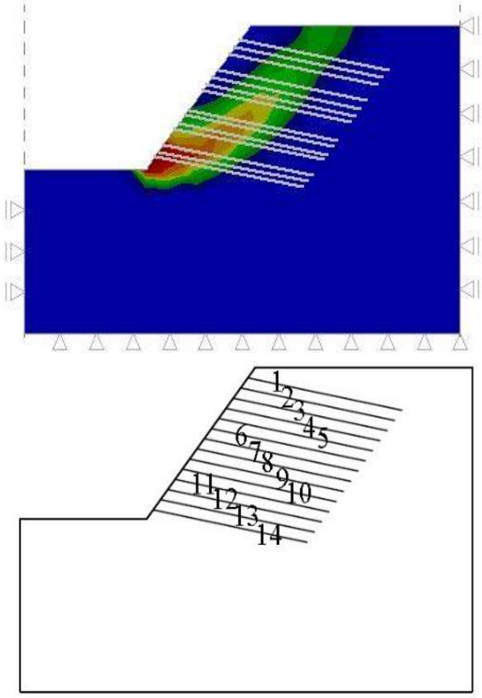


Figure 7: *Contour of equivalent plastic strain at random relative spacing*

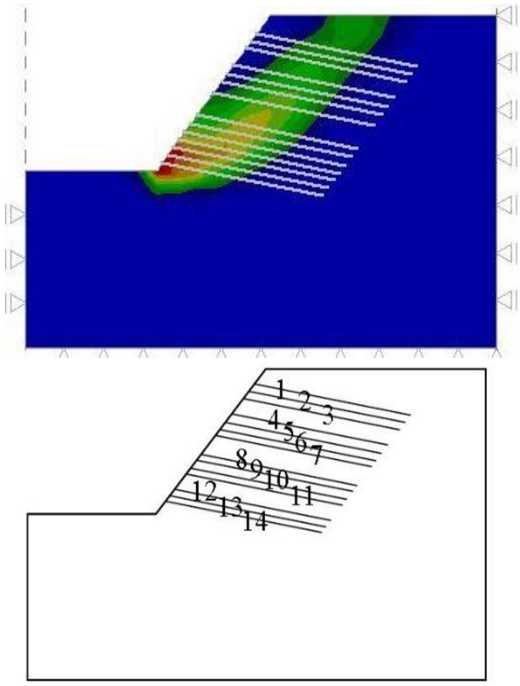


Figure 8: *Contour of equivalent plastic strain at group spacing 1*

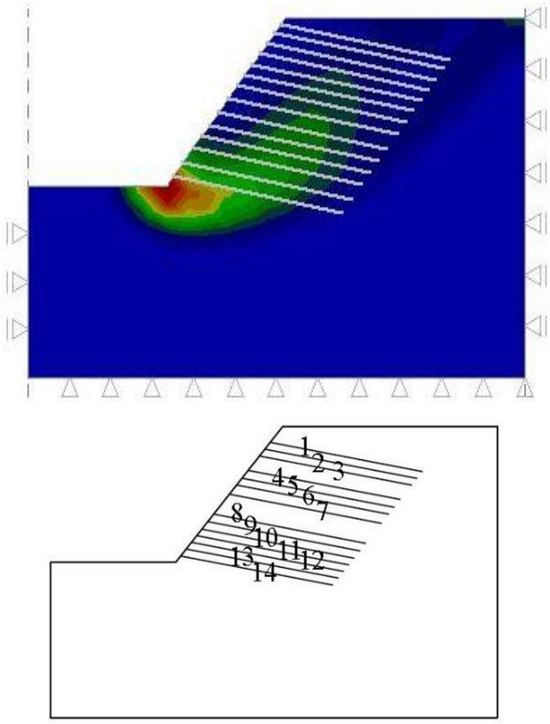


Figure 9*: Contour of equivalent plastic strain at group spacing 2*

In Figures 6 to 9, the red color indicates the highest equivalent plastic strain and the blue color indicates the lowest evolution of the equivalent plastic strain. The effect of the bar spacing is evident in Figures 6 to 9. The equivalent plastic strain is localized in a larger area when the group spacing is incorporated.

Conclusion:

i. Factor of safety varies up to an element number of 938 for TE6 and up to an element number of 335 for mixed mesh. Above the aforementioned number, the factor of safety remains almost constant. Mixed mesh is more suitable as it saves computational time.

ii. The factor of safety of reinforced slope increases with the increase of bar inclination angle which is followed by a decrease in the factor of safety. The maximum value of the factor of safety is a function of the slope angle.

iii. The relationship between bar inclination angle and slope angle for maximum factor of safety is nonlinear.

iv. The maximum factor of safety of reinforced slope is possible when the bar inclination angle lies between 10° to 15° for the geometric model, soil and reinforcing bar properties considered in the present study.

v. Maximum factor of safety is possible only when equal spacing is adopted in reinforcing a slope. Group spacing also yields elevated factor of safety compared to that for the random spacing of bar.

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