NUMERICAL ANALYSIS OF REINFORCED SLOPE USING LIMIT EQUILIBRIUM METHOD

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ABSTRACT

Over the past few decades, the limit equilibrium method has dominated the usage of any other method for slope stability investigations for its case in use. High and steep cut slopes due to excavation are a common sight in building high-grade throughways. Such steep slope often requires reinforcement to stabilize it. In this study, GEO5 software was used to investigate the behavior of soil slope under different reinforcement conditions. The use of steel bars as reinforcement is increasingly becoming widespread in engineering practice. Consequently, this paper studies the effect of the incorporation of steel reinforcement in different manners using the limit equilibrium method. The parametric modeling was done to determine the effect of the inclination angle of reinforcing bars and their individual spacing on the factor of safety. From the analysis, it is observed that factor of safety of slope decreases due to the increase of slope angle.The effect of bar inclination angle in the reinforced slope is studied as well and it is noted that factor of safety of reinforced slope becomes maximum when the reinforcing bar inclination angle becomes 10°. It is also observed that factor of safety increases up to an optimum number of reinforcement layers and beyond this, factor of safety decreases even though the number of reinforcing bar layers increases. Higher values of factor of safety are obtained when equal spacing rather than random spacing of bar is used in the reinforced slope.

Keywords: *Slope stability, reinforcing bar, slope angle, reinforcing bar inclination angle, spacing.*

1. INTRODUCTION

Slope stability analysis is an enormously important deliberation in the design and construction of earth dams, embankments, bridge abutments, retaining walls and various other civil engineering structures. It may fail due to heavy rainfall, changes in topography, external forces, loss of shear strength, increase in ground water table, change in stress condition, etc. (Sazzad, Hie & Hossain, 2016). So, it is a big challenge to both researchers and professionals to estimate accurately the factor safety of slopes. Due to its engineering significance, it draws attentions to many researchers and numerous research works have been reported in the literature (Wei & Cheng, 2010; He & Zhang, 2012; Sazzad & Moni, 2017, Sazzad & Rahat, 2017). 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. Previous studies depicted that the shear strength of soil can be improved by using steel nails (Wei & Cheng, 2010; He, Ouyang & Luo, 2012; Sazzad, Hie & Hossain, 2016). 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). For example, a parametric study on the reinforced slope to investigate the effect of slope angle, inclined reinforcement bars and random and group spacing was carried out by Sazzad, Hie & Hossain (2016) using the FEM.

In this paper, the numerical analysis is carried out by using the limit equilibrium method (LEM) for its simplicity. The limit equilibrium method is used to analysis the stability of slope using soil reinforcing technique. Limit equilibrium methods have been widely adopted for slope stability analysis. A potential sliding surface is assumed prior to the analysis and a limit equilibrium analysis is then performed with respect to the soil mass above the potential slip surface. Many methods based on this approach are available in the literature. For example, the methods reported by Bishop (1955), Janbu (1957), Morgenstern and Price (1965), Spencer (1967) and so on are based on LEM. Although the approach is straightforward, these methods will not consider the stress–strain behavior of the soil mass while calculating the stresses. 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 the reinforcing bar number and spacing of reinforcing bar on the factor of safety of slope by LEM is studied using GEO5. The effect of regular and random spacing of reinforcing bars has been investigated. An attempt has also been made to find the optimum spacing and number of bar for the application of soil reinforcement in slope stability. The consequences of using different factors in the LEM based study have been investigated and the numerical results have been reported.

2. METHODOLOGY

2.1 Limit Equilibrium Method

Limit equilibrium method (LEM) is a powerful numerical tool for solving many problems of engineering and mathematical physics. Several limit equilibrium methods (LEM) have been developed for slope stability analysis. Fellenius (1936) introduced the first method, referred to as the Ordinary or the Swedish method, for a circular slip surface. Bishop (1955) advanced the first method introducing a new relationship for the base normal force. The equation for the factor of safety hence become non-linear. At the same time, Janbu (1954) developed a simplified method for non-circular failure surfaces, dividing a potential mass into several vertical slices. The generalized procedure of the same time as a further development of the simplified method was proposed by Janbu (1973). Later, Morgenstern-Price (1965), Spencer (1967) and several others made future contributions with different assumptions for the interslice forces. A procedure of general limit equilibrium was developed by Chuge (1986) as an extension of the Spencer and Morgenstern-Price methods, satisfying both moment and force equilibrium conditions (SLOPE/W, 2004 and Abramson et al., 2002). All limit equilibrium methods (LEMs) are based on certain assumptions for the interslice normal (E) and shear (T) forces, and the basic difference among the methods lies in how these forces are determined or assumed.

2.2 Brief Description of GEO5

The numerical study of the reinforced slope has been carried out by GEO5 (2017) based on limit equilibrium 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. The effectiveness of GEO5 has already been recognized (e.g., Sazzad, Hie & Hossain, 2016; Sazzad & Moni, 2017). For further details, readers are referred to GEO5 (2017).

3. GEOMETRIC MODELING

The geometric model used in the present study is depicted in Figure 1 where β is the sloping angle and θ is the reinforcing bar inclination angle with the horizontal axis. All the dimensions in the model slope are given in meter. After the generation of model and assignment of the properties of soil and reinforcing bar, the stability analysis is performed.

The stability analysis is carried out by using five basic methods of LEM. Eleven layers of steel bar are reinforced in slope keeping the relative spacing same.

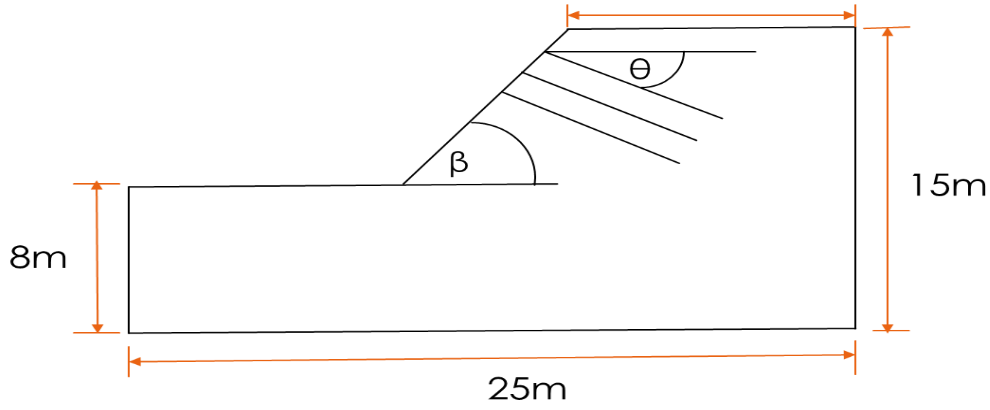

Figure 1: Geometric model of soil slope

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

Properties of steel bar	**Values**
Stiffness of bar (kN/m)	60
Coefficient of interaction	0.80
Total length of reinforcement bar in 1m width of slope (m)	121

Table 2: Properties of soil used in the present study

Soil properties	**Values**
Dry unit weight (kN/m^3)	18
Cohesion of soil (kPa)	7
Angle of friction (°)	25
Saturated unit weight (kN/m^3)	21

4. NUMERICAL RESULTS AND DISCUSSION

4.1 Effect of the variation of slope angle in reinforced slope

The stability of slope was analysed with the help of GEO5 software. Different slope angles (45°, 49° and 54°) were considered during the numerical analysis. In this study, eleven rows of soil reinforcement (steel bar), each 11m length having stiffness of 60 kN/m, are placed at a regular interval in the slope. For each slope angle (β), different Limit Equilibrium Methods such as Bishop (1955), Fellenious (1936), Spencer (1967), Janbu (1957) and Morgenstern and Price (1965) were used to obtain the factor of safety of slope with a fixed bar inclination angle (θ). This will help to compare the factor of safety of slope obtained by different methods for a particular slope angle and bar inclination angle. It is observed that Fellenious (1936) method gives the lowest factor of safety regardless of the slope angle for a constant value of bar inclination angle. On the other hand, the higest values of factor safety are obtained when either Spencer (1967) or Janbu (1957) or Morgenstern and Price (1965) method is used. It should be noted that the increase of the bar inclination angle has negligible effect on the development of the above discussed pattern. It is interesting to note that factor of safety of slope is the highest when the bar inclination angle is 10° regardless of the values of slope angle.

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

Bar inclination	Slope angle (°) 45					49					54				
	Bishop	Fellenious	Spencer	Janbu	Morgenster -price	Bishop	Fellenious	Spencer	Janbu	Morgenster-price	Bishop	Fellenious	Spencer	Janbu	Morgenster-price
0	1.59	1.51	1.77	1.77	1.77	1.17	1.14	1.22	1.22	1.19	1.20	1.15	1.12	1.12	1.12
5	1.82	1.73	1.98	1.98	1.98	1.43	1.34	1.48	1.48	1.48	1.59	1.49	1.61	1.61	1.61
10	1.76	1.69	1.81	1.81	1.81	1.72	1.64	1.89	1.89	1.89	1.73	1.64	1.80	1.80	1.80
15	1.74	1.68	1.81	1.81	1.81	1.63	1.56	1.71	1.71	1.71	1.68	1.65	1.72	1.71	1.72
20	1.61	1.54	1.79	1.78	1.78	1.45	1.36	1.52	1.52	1.52	1.44	1.37	1.45	1.54	1.55
25	1.47	1.32	1.54	1.54	1.54	1.11	1.06	1.12	1.12	1.12	1.17	1.15	1.08	1.08	1.08

4.2 Effect of the number of reinforcement layer

The effect of the number of reinforcement layer number is studied in this section. It sholud be noted that the total length of bar (11@11 m =121 m) is kept conatant while studing the effect of the number of reinforcing layer on the stability of slope. The total bar length is kept constant because it otherwise may have effect on the overall result. The bar inclination angle is also fixed at 10°. This is because the bar inclination angle of 10° gives the highest factor of safety. Since the total length of the reinforcing bar is fixed, the increase in the number of reinforcing layer decreases the length of each reinforced bar as also noticed in Table 4. It is interesting to note that the factor of safety of reinforced slope becomes maximum when 13 no. of bars with a bar length of 9.30 m each is used.

Table 4: Factor of safety of reinforced slope for the variation of the number of reinforcement layer

Numbers of layer	Length of each bar	Factor of safety: Bishop	Fellenious	Spencer	Janbu	Morgenster-price
10	12.10	1.18	1.12	1.33	1.33	1.34
11	11.00	1.31	1.27	1.47	1.47	1.47
12	10.08	1.44	1.41	1.59	1.59	1.59
13	9.30	1.77	1.69	1.83	1.83	1.83
14	8.64	1.74	1.62	1.81	1.81	1.81
15	8.10	1.68	1.57	1.74	1.75	1.74
16	7.56	1.59	1.44	1.62	1.62	1.62
17	7.10	1.54	1.47	1.59	1.59	1.61
18	6.72	1.46	1.42	1.54	1.53	1.53

4.3 Effect of the spacing of reinforcing bar

The effect of different spacing styles such as equal spacing and random spacing for reinforced slope is given in Table 5. It is noted that the elevated values of factor of safety is obtained when equal spacing rather than random spacing of bar is used in the reinforced slope.

Table 5: Factor of safety for the variation of bar spacing

Type of Spacing	Factor of safety				
	Bishop	**Fellenious**	**Spencer**	**Janbu**	**Morgenster-price**
Equal spacing	1.76	1.65	1.82	1.81	1.81
Random spacing	1.44	1.34	1.54	1.53	1.54

5. CONCLUSIONS

Different Limit Equilibrium Methods were used in this study to evaluate the factor of safety of slope with varience of slope angle, bar inclination angle and spacing style. Some of the important findings of the study are summarized below:

i. The factor of safety of reinforced slope decreases with the increase of slope angle regardless of the values of reinforcing bar inclination angle.
ii. Fellenious (1936) method gives the lowest factor of safety regardless of the slope angle for a constant value of bar inclination angle.
iii. The factor of safety of the reinforced slope becomes maximum when the reinforcing bar inclination angle becomes 10° regardless of the value of slope angle.
iv. Factor of safety increases up to an optimum number of reinforcement layer and beyond this, factor of safety decreases even though the number of reinforcing bar layers increases.
v. Elevated values of factor of safety is obtained when equal spacing rather than random spacing of bar is used in the reinforced slope.

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