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Modeling of Seismic Stability of Reinforced Soil Slopes Using Horizontal Slice Method

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ABSTRACT

Reinforced soil has been abundantly used in the building of soil slopes because of benefits that are provided due to its behavior. In this paper, seismic stability of reinforced soil slopes has been analyzed using pseudo-dynamic technique. Horizontal, vertical, and the moment equilibrium equations of horizontal slices have been used for any shape of failure surfaces in recent researches, but in the current paper failure surface has been considered as log-spiral. Newton-Raphson method has been applied to solve the nonlinear equilibrium equations. To achieve this purpose a MATLAB program has been prepared. The critical failure surface and time have been optimized using the genetic algorithm method. This program has been used to analyze a vertical slope with different soil friction angle and pseudo-static horizontal and vertical coefficients, and the results are in an excellent accordance with other researches. The results of formulation in current work have an acceptable accordance with the other research results.

KEYWORDS: Pseudo-dynamic, Reinforced soil slopes, Optimization, Genetic algorithm, Log-spiral

1. INTRODUCTION

The seismic stability analysis of soil slopes has been one of the most significant problems in the field of geo-technique engineering. Today reinforced soil has been abundantly used in the building of soil slopes due to its behavior and reasonable cost. The number of studies on this topic and its applications and introduction of novel techniques of studying is the witness of this statement. Therefore, the study of slope's seismic stability is greatly significant. Many methods have been applied to survey the seismic stability of soil slopes, among them vertical and horizontal limit equilibrium method (LEM) [1], stress characteristic [2,3] and numerical solutions such as finite difference and finite element can be mentioned [4,5,6].

When using limit equilibrium methods, it is necessary to determine the optimized failure surface before the slope analysis. Genetic algorithm (GA) [7,8], particle swarm method (PSM) [9], and fish swarm [10] are the techniques which can be used for the optimization of failure surface.

Nowadays pseudo-dynamic analysis of seismic stability of soil slopes is more common than pseudo-static ones, since the outcome of pseudo-dynamic analysis is more accurate and reasonable in comparison to pseudo-static ones [11,12].

Log-spiral failure surface has been introduced as one of the most optimized failure surfaces in various studies [11,12]. But it is worth nothing that in such researches the failure surface has been considered as a slice in slope seismic stability calculations [13,14].

In the current work the seismic stability of soil slopes has been studied using horizontal limit equilibrium and log-spiral surface failure. The log-spiral surface failure was optimized using GA. The equilibrium of forces for horizontal slices was similar to the equilibrium which is used by Keshavarz [2], while in this work the analysis of forces is the pseudo-dynamic type, and the dynamic effects of earthquake forces have been considered in stability equations.

THEORY OF ANALYSIS

In pseudo-static analysis, dynamic forces are considered as pseudo-static forces, and dynamic nature of earthquake forces are studied without their time effects. But in pseudo-dynamic method, the time and the phase difference dependence of seismic forces are of great importance.

In pseudo-dynamic method, dynamic effects of earthquake forces are calculated as vertical and horizontal inertial forces exerted the on each element of surface, where these forces are replaced by vertical and horizontal pseudo-static constant coefficients in equilibrium equations. Vertical and horizontal inertial forces are calculated for each element as the equations of 1-4 [12]:

$$Qh_i = \int_{y_i}^{y_{i+1}} m_i a_h(y,t)dy \tag{1}$$

$$Qv_i = \int_{y_i}^{y_{i+1}} m_i a_v(y,t)dy \tag{2}$$

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$$a_h(y,t)=\left\{1+\frac{H-z}{z}(f-1)\right\}k_h g\sin(2\pi)\left\{\frac{t}{T}-\frac{H-z}{T\upsilon_s}\right\} \quad (3)$$

$$a_v(y,t)=\left\{1+\frac{H-z}{z}(f-1)\right\}k_v g\sin(2\pi)\left\{\frac{t}{T}-\frac{H-z}{T\upsilon_p}\right\} \quad (4)$$

Where Qh_i and Qv_i are horizontal and vertical inertial forces for each slice respectively, $a_h(y,t)$ and $a_v(y,t)$ are horizontal and vertical acceleration as a function of depth and time, T is the period, f is amplification factor (which is assumed to be one in this paper), k_h and k_v are horizontal and vertical seismic acceleration coefficients respectively, and v_s and v_p are shear wave velocity and primary wave velocity, respectively.

In horizontal slice method, considering an assumed log-spiral failure surface, soil is divided into horizontal slices. A soil slope with its log-spiral failure surface is illustrated in figure 1. Log-spiral failure surface equation can be written as equation 5:

$$r=r_0\exp\left[\left(\theta-\theta_0\right)\tan\phi\right] \quad (5)$$

Where φ is the soil friction angle. If the soil beneath the slope is firm enough, the failure surface will not continue to slope and therefore:

$$\theta_0\le\theta_h\le\frac{\pi}{2}+\phi$$

$$r_0=\frac{H}{\sin(\theta_h)\exp\left[(\theta_h-\theta_0)\tan\phi\right]-\sin(\theta_0)} \quad (6)$$

The forces which are exerted on a slice are depicted in figure 2. When the horizontal equilibrium, the vertical equilibrium, and the moment around the assumed O point are established, the equilibrium equations are written as below:

$$V_{i+1}-V_i-\left(W_i-Qv_i\right)+S_i\sin\alpha_i+N_i\cos\alpha_i=0 \quad (7)$$

$$T_j+S_i\cos\alpha_i-N_i\sin\alpha_i-Qh_i+H_{i+1}-H_i=0 \quad (8)$$

$$\begin{aligned}&V_{i+1}\left(x_{i+1}-x_0-L_{i+1}+x_{v,i+1}\right)-V_i\left(x_i-x_0-L_i+x_{v,i}\right)+T_j(y_0-y_{r,j})+\\&H_{i+1}\left(y_0-y_{i+1}\right)-H_i\left(y_0-y_i\right)+\left[S_i\sin\alpha_i+N_i\cos\alpha_i\right](x_{m,i}-x_0)+\\&\left[S_i\cos\alpha_i-N_i\sin\alpha_i\right](y_0-y_{m,i})-\left(W_i-Qv_i\right)(x_{G,i}-x_0)-Qh_i\left(y_0-y_{G,i}\right)=0\end{aligned} \quad (9)$$

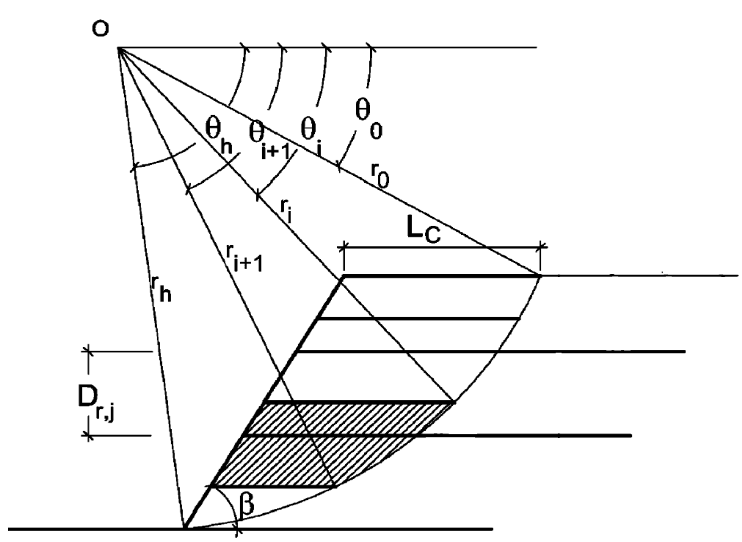

Figure 1: schematic of a log-spiral failure surface

Where *H* and *V* are the horizontal and the vertical forces on the slice boundary. These two forces are related to each other by the following equation [15]:

$$H_i = \lambda f_i V_i \tag{10}$$

Where λ is a scalar parameter, which is considered constant for all of the slices and f_i is an arbitrary function, which is taken to be one in this article. Considering Mohr–Coulomb criteria, then it would be:

$$S_i = \frac{N_i \tan\phi + cb_i}{F_s} \tag{11}$$

Where *C* is the soil adhesion, F_s is the confidence coefficient, and b_i is the width of slice bottom surface ($b_i = \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2}$). Here the soil adhesion and the confidence coefficient are assumed to be zero and one, respectively, and the location of point *O* does not have any significance to the results of calculations.

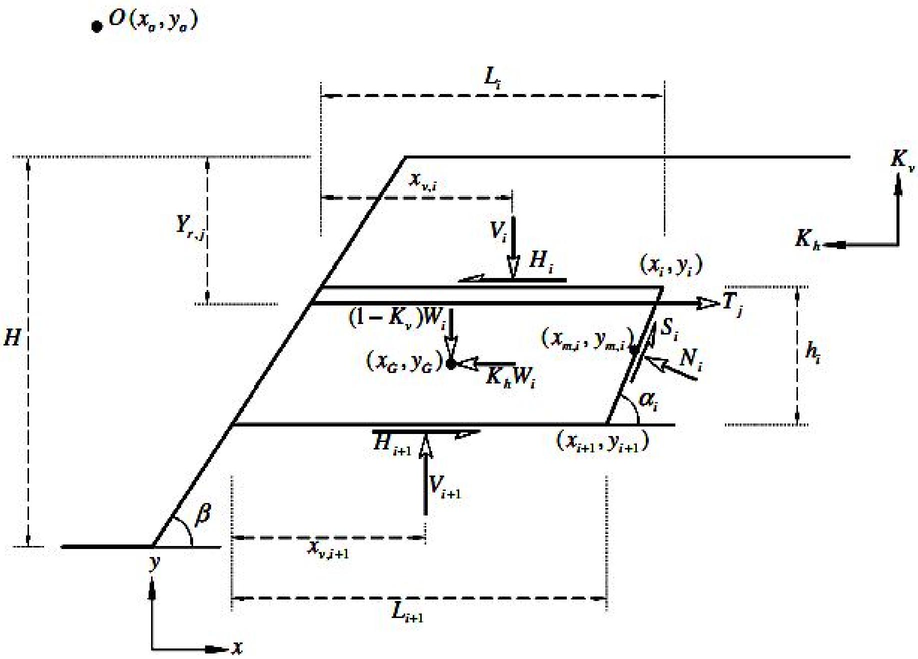

Figure 2: The distribution of forces on a slice

The force distribution per sum of forces in each of reinforcements is introduced by [16], where a similar distribution is used in the current work:

$$K = \frac{\sum_{j=1}^{m} T_j}{0.5\gamma H^2} \tag{12}$$

$$T_j = K\gamma Y_{r,j} D_{r,j}$$

Performing algebraic calculations, there will be two sets of equations for each slice [17]:

$$\begin{cases} A_1 K + (\lambda f - A_2)V_{i+1} + (A_2 - \lambda f)V_i + A_3 = 0 \\ \left[A_4 + x_{v,i+1} + \lambda f (y_0 - y_{i+1})\right]V_{i+1} - \left[A_5 + x_{v,i} + \lambda f (y_0 - y_i)\right]V_i + A_1 K(y_0 - y_{r,j}) + A_6 = 0 \end{cases} \tag{13}$$

Where:

$$A_1 = \gamma y_{r,j} D_{r,j}$$
$$A_2 = m_i \left(\frac{\tan\phi}{F_s} \cos\alpha_i - \sin\alpha_i \right)$$
$$A_3 = m_i A_i \left(\frac{\tan\phi}{F_s} \cos\alpha_i - \sin\alpha_i \right) + \frac{cb_i}{F_s} \cos\alpha_i - Qh_i$$
$$A_4 = x_{i+1} - x_0 - L_{i+1} - m_i B_i$$
$$A_5 = x_i - x_o - L_i - m_i B_i \qquad (14)$$
$$A_6 = m_i A_i B_i + \frac{cb_i}{F_s} \sin\alpha_i \left(x_{m,i} - x_0 \right) + \frac{cb_i}{F_s} \cos\alpha_i \left(y_0 - y_{m,i} \right) - (W_i - Qv_i)(x_{G,i} - x_0) - Qh_i \left(y_0 - y_{G,i} \right)$$
$$m_i = \frac{1}{\cos\alpha_i + \frac{\tan\phi}{F_s} \sin\alpha_i}$$
$$A_i = (W_i - Qv_i) - \frac{cb_i \sin\alpha_i}{F_s}$$
$$B_i = \left(\frac{1}{m_i} \right) \left(x_{m,i} - x_0 \right) + \left(\frac{\tan\phi}{F_s} \cos\alpha_i - \sin\alpha_i \right) \left(y_0 - y_{m,i} \right)$$

Newton-Raphson method has been used to solve these sets of equations. The solution is similar to pseudo-static method [17], while in pseudo-dynamic approach time is significant. Actually the required amount of reinforcement is the function of time; therefore both the failure surface and the time should be optimized.

In order to achieve the most appropriate log-spiral failure surface and the accurate occurrence time of seismic force GA approach has been applied. The significance of time is that it determines the most proper value for the reinforcement.

RESULTS AND DISCUSSION

Based on above mentioned theories a mathematical code was prepared in MATLAB® software environment, which provided the capability to study the pseudo-dynamic stability analysis of reinforced soil slopes using horizontal slice method. Here the assumption of log-spiral failure surface was considered in order to determine the most optimized failure surface in the most appropriate time. To achieve this goal, it is possible to change the log-spiral failure surface and time gradually to achieve approximate results. But the authors used GA optimization algorithm for more accurate results. In this work the period value is *0.3* (second) and the optimization was performed for the first *0.5* seconds of force influence [11,12].

The results of calculations for a 90^o angle slide with the height of *5m* are represented in table 1, where the values of horizontal pseudo-static coefficients are *0.1* and *0.2*, and friction angle value are 20^o, 25^o and 30^o.

These calculations were performed for different ratios of vertical to horizontal pseudo-static coefficients. As it can be seen, the optimized value which is obtained for *K* in this work is close enough to the results in literature [2,3], which also they are approximately higher than value which is reported in reference [17] and lower than the results of reference [11].

It is worth nothing that another formulation had been used in dynamic formulation of mentioned references. Figures 3 and 4 show the results obtained for the vertical acceleration value equal to zero and the horizontal pseudo-static accelerations of 0.1 and 0.2.

Table 1: comparison between the results of various studies

K value for k_h=0.1, H=5m, β=90, γ=19, T=0.3, t=0.5									
$\frac{K_V}{K_h}$	φ=20			φ=25			φ=30		
	[11]	[12]	This study	[11]	[12]	this study	[11]	[12]	This study
0	0.61	0.68	0.65	0.50	0.58	0.55	0.41	0.48	0.46
0.5	0.78	0.71	0.90	0.60	0.60	0.77	0.51	0.51	0.64
1	0.90	0.94	0.71	0.79	0.72	0.6	0.57	0.53	0.50
K value for k_h=0.2 ,H=5m, β=90, γ=19, T=0.3, t=0.5									
0	0.73	0.80	0.79	0.60	0.68	0.66	0.48	0.57	0.56
0.5	0.90	0.86	0.84	0.71	0.72	0.71	0.58	0.61	0.60
1	1.07	0.91	0.89	0.83	0.77	0.75	0.67	0.65	0.63

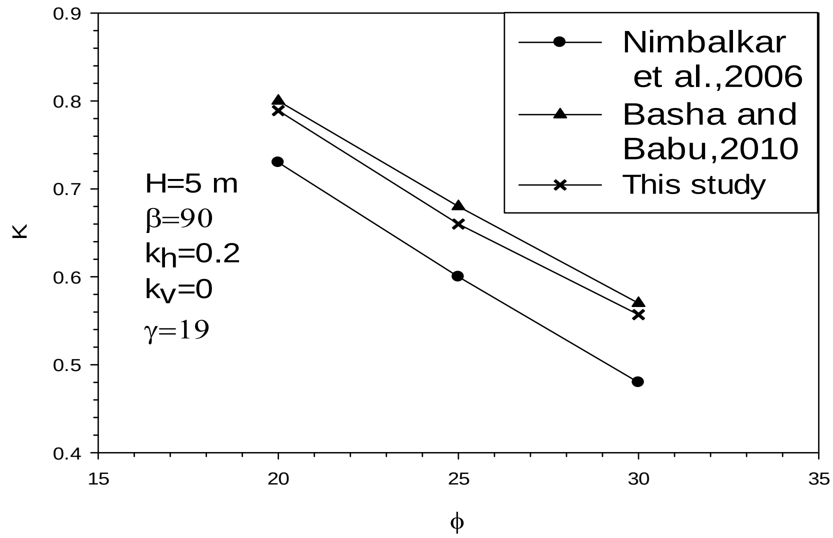

Figure 3: Comparison between the results of current study and others for k_h=0.1

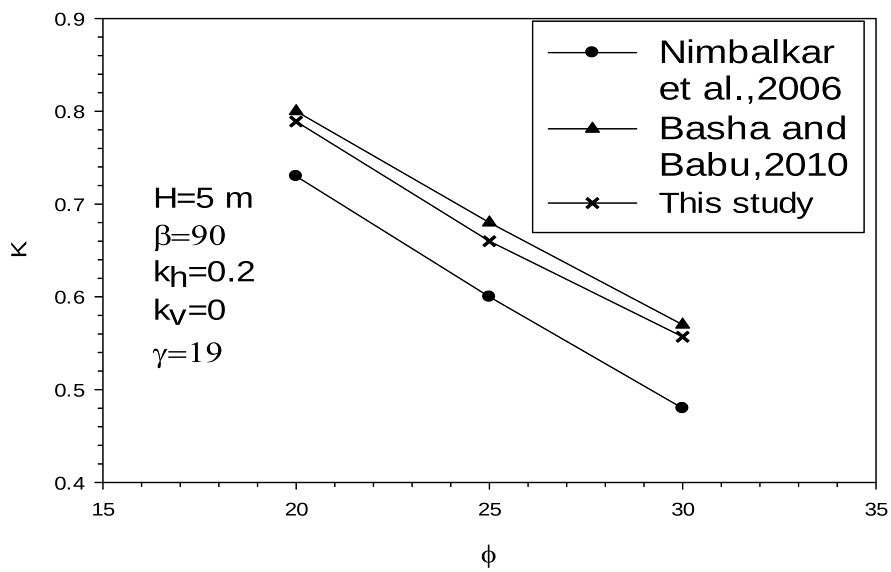

Figure 4: Comparison between the results of current study and others for k_h=0.2

CONCLUSIONS

The seismic stability analysis of reinforced soil slopes is of great importance in the field of geo_technique engineering. There have been various methods introduced for the analysis of reinforced soil slopes. In this work pseudo-dynamic method has been used to evaluate the required amount of reinforcement to stabilize the slope. Initially considering a static equilibrium for a horizontal slice (horizontal force equilibrium, vertical force equilibrium and the moment around a hypothetical point), the equilibrium equations achieved. Assuming a specific failure surface for solving the equilibrium equations by Newton-Raphson method [2], the required amount of reinforcement has been determined. The equilibrium equation for the total failure surface was written but the log-spiral failure surface was used here. A numerical code was written in MATLAB® software environment.

One of the challenges of pseudo-dynamic method is the determination of critical log-spiral failure surface and the critical time. This was done by exploration in a specific domain in previous researches, while they have been achieved by GA optimization algorithm. To evaluate the results, a specific vertical slope with different soil friction factor and horizontal and vertical pseudo-static coefficients were considered, and the results were compared to similar researches. The results have shown that the required amount of reinforcement which is predicted in this work is in an acceptable agreement with the other researches.

It is recommended to use optimize the failure surface generally, instead of log or surface failure surfaces. Additionally it is possible to compare its results to other failure surface's to acquire the most critical failure surface for soil slope design purposes.

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