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On the seismic stability and critical slip surface of reinforced slopes

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ABSTRACT

Seismic stability of reinforced slopes is investigated using Horizontal Slice Method within the framework of the pseudo-static force. These introduced by constant horizontal or vertical inertial forces and the equilibrium equations for all forces applied to each horizontal slice are considered. A new procedure is introduced which could determine the location and shape of failure surface. The slip surface is a multiplanar surface consisting of a number of inclined linear segments interconnected with various lengths and angles in a plane. The amount of reinforcement forces is used as the objective function in the optimization procedure to determine the shape and location of the critical slip surface. This approach is relatively simple and yields results which are in good agreement with previous findings. Final results revealed that with increase in horizontal seismic acceleration, the reinforcements force increases. With increase in slope angle, the failure surface changes from curve to planar shape.

1. Introduction

Stability analysis of natural and artificial slopes is an interesting issue in civil, geotechnical and mining engineering. In addition, the design and safety evaluation of reinforced structures subject to seismic loading is an important problem (Richardson and Lee [1], Bathurst and Cai [2], Jones and Clarke [3]).

In recent decades, a technique based on limit state approach has been employed in several studies (Ling et al. [4], Ling and Leshchinsky [5], Michalowski [6], Ausilio et al. [7]) to evaluate the seismic stability of slopes. Ling et al. [4] utilized the pseudo-static limit equilibrium approach for the seismic analysis of reinforced soil structures subject to seismic horizontal acceleration. Subsequently, Ling and Leshchinsky [5] extended their studies and examined the effect of vertical earthquake acceleration. Michalowski [6] and Ausilio et al. [7] used the kinematic approach of limit analysis to analyze the seismic stability of retaining structures.

Horizontal Slice Method (HSM) is a new analytical method based on limit equilibrium proposed by Lo and Xu [8]. This method has been used later by Shahgholi et al. [9] and Nouri et al. [10]. In this method, the sliding block is divided into several finite horizontal rigid slices parallel to reinforcements and then the equilibrium equations are considered for each slice. Effects of seismic loads are taken into account as pseudo-static forces. The crucial point in using HSM for stability analysis is how to find out the location and configuration of the slip surface. Different trial slip surface have been used by various researchers include planar (e.g., Saran et al. [11]; Narasimha Reddy et al. [12]), circular (e.g., Sengupta and Upadhyay [13]; Kalatehjari et al. [14]), non-circular (e.g., Zolfaghari et al. [15]; Nimbalkar et al. [16]).

For coarse-grained soil and also steep slopes, the slip surface is approximately planar [17]. Circular failure surface is used for cohesive and homogeneous soil slopes [18], and non-circular failure surfaces are occurred in non-homogeneous slope (e.g., Morgenstern and Price [19], Spencer [20]). Non-circular failure surface can be formed from arcs of a circle or log-spiral together with linear segments or just with straight line segments [21]. Prater [22] assumed sliding surface of circular and logarithmic spiral types and investigated the stability conditions for homogeneous soils. Although the different failure states are reported in the literatures, the real failure surface shape has not been obtained yet. For real cases, the location of slip surface is often unknown and sliding of a slope is not smooth and sometimes takes arbitrary shapes. In most of the studies, the shape of the slip surface is predefined. However, the configuration of the slip surface is affected by geotechnical and geometric characteristics of slopes [23]. There are various methods for obtaining the critical slip surface. Hu et al. [24] determined the noncircular slip surface using mutative scale chaos optimization algorithm. Nguyen [25] used the simplex reflection method to find critical slip surfaces. Malkawi et al. [26] adopted the Monte Carlo optimization procedure to identify the critical slip surfaces. Also, a number of researchers have used genetic algorithm to search for the slip surface (Goh [27]; Zolfaghari et al. [15]).

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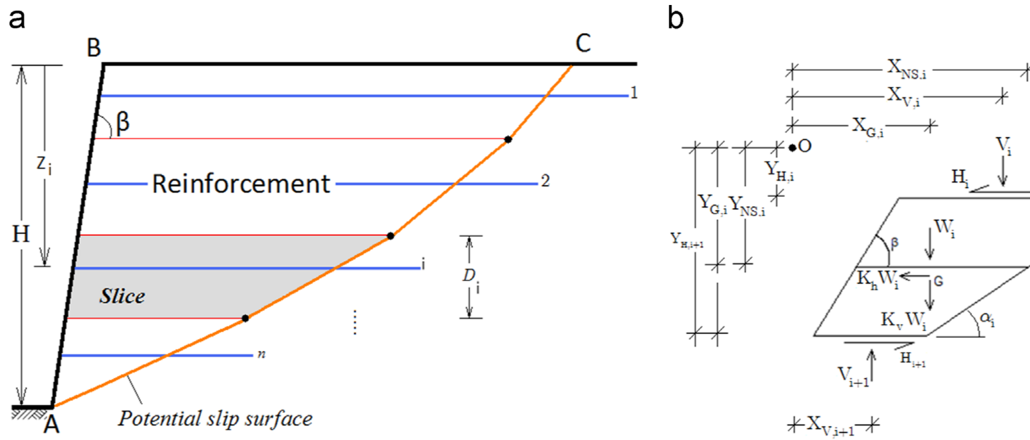

Fig. 1. (a) General slope configuration and (b) acting forces on each slice.

Sarma and Tan [28] used a new method to determine the critical slip surface based on the limit equilibrium technique with added stress acceptability criterion, for both homogeneous and non-homogeneous slopes. No prior assumption of the shape of the surface is needed. In this method, the slip surface, which comprises a series of straight lines, was obtained slice by slice going uphill. The slip surface and the interslice boundaries were not predefined. But, the effect of reinforcement elements on stability was not considered. Then, Stamatopoulos et al. [29] extended the method proposed by Sarma [30] to dynamic problems using a developed multiblock model.

Therefore, determination of the critical slip surface is one of the key problems in slope stability evaluation.

In this study, Horizontal Slice Method is employed to analyze slope stability and also to achieve the position and configuration of the critical slip surface in slopes. The procedure yields a new multiplanar shape as an accurate approximation for the shape of the failure surface. Location of failure surface can be determined eventually.

2. Method of analysis

2.1. Horizontal Slice Method

In the comprehensive formulation proposed by Nouri et al. [10], the equilibrium of all vertical and horizontal forces and also the moment equilibrium in each slice of the logarithmic spiral slip surface are satisfied. They have called this formulation as rigorous formulation also known as $(5n-1)$ formulation. In this study a similar formulation, within the framework of the limit equilibrium technique of HSM is considered for homogeneous reinforced slopes.

The main difference between the present method and those of previous studies is that no prior configuration is assumed for slip surface. In order to obtain the equilibrium equations, consider a slope with general shape shown in Fig. 1.

T_i is the tension force in the i-th reinforcement layer. N_i and S_i are respectively the normal and shear forces acting on the base of each slice. W_i is the weight of the i-th slice, and α_i is the inclination angle of the slice base. k_h and k_v are the horizontal and vertical seismic coefficients for pseudo-static analysis, respectively. H_i and V_i are the shear and normal inter-slice forces acting on each slice, respectively. V_i denotes the vertical inter-slice force which is equal to the weight of upper soil layers.

For the interface forces, two approaches exist in the bibliography: (a) the first assumes that they have fixed inclination and that is defined through a scalar coefficient, and (b) the second

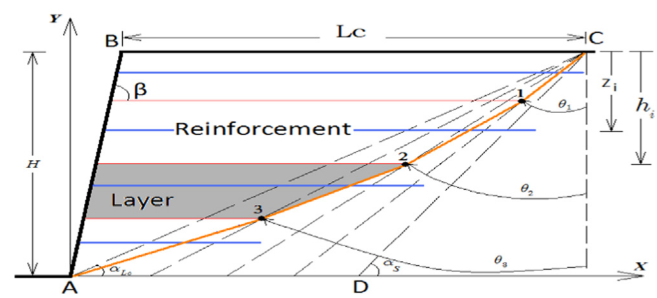

Fig. 2. The geometry of multiplanar sliding mechanism.

obtains the interface inclinations by minimizing the factor of safety. For non-circular slip surfaces, Morgenstern and Price [19] proposed the following relationship:

$$H_i = \lambda V_i \tag{1}$$

where λ is a coefficient ranging between 0 and 1.

In the method provided by Sarma [30], the shear strength was mobilized on the interslice boundaries and the inclination of slice interfaces is varied to produce a critical condition. The method provided by Sarma uses a shear strength equation. In addition, Sarma and Tan [28] have implicitly assumed that the Mohr–Coulomb criterion is satisfied along the vertical interfaces between slices. Nouri et al. [10] obtained the interslice forces via a trial and error procedure in the last piece. In the proposed method, the inclination of the inter-slice forces are taken to be independent of k_h and defined as $\lambda = (1 - \beta/100)\tan(\varphi)/F.S.$

Earthquake effects can be taken into account by assuming the sliding mass subjected to both vertical and horizontal pseudo-static forces. However, the vertical force is usually ignored in the standard pseudo-static analysis. This is due to the fact that the vertical seismic force acting on the sliding mass usually has negligible effect on the stability of a slope. The moment equilibrium equations require the location of the application of the normal force on the slip surface. The usual assumption of 'middle of the slice' is a good and reasonable one [10]. Hence, the equilibrium equations of the force and moment for each slice in x-y plane are proposed the by Nouri et al. [10], following relationship

$$\sum F_x = 0 \Rightarrow T_i + S_i\cos(a_i) - N_i\sin(a_i) - k_hW_i + H_{i+1} - H_i = 0 \tag{2}$$

$$\sum F_y = 0 \Rightarrow V_{i+1} - V_i - (1 + k_v)W_i + S_i\sin(a_i) + N_i\cos(a_i) = 0 \tag{3}$$