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Yield acceleration and permanent displacement of a slope reinforced with a row of drilled shafts

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ABSTRACT

In this paper, a method for estimating yield acceleration of a slope reinforced with a row of equally spaced drilled shafts under a seismic excitation is presented. The method is based on a concept of soil arching due to rigid inclusions of drilled shafts on slope, which in turn reduces the driving force on the down-slope side of drilled shafts. Considering soil arching effects and earthquake-induced inertia forces, a limiting equilibrium based formulation was derived. A computer program was coded to allow for calculations of yield acceleration of a drilled shafts reinforced slope with complex slope geometry and soil profiles. Once yield acceleration is determined, then Newmark's method can be evoked to estimate permanent displacement of a slope reinforced with a row of drilled shafts under an earthquake excitation. A total of seven cases were presented to show that the proposed Newmark type calculation is adequate when compared to 3-D finite element analysis results.

1. Introduction

Traditional seismic slope stability analysis is based on the use of pseudo-static approaches that apply the seismic coefficients to a conventional limit-equilibrium analysis to calculate factor of safety. This method, however, has been criticized due to lack of information of displacement of a slope [1–3]. To estimate slope displacement due to earthquake, the most often used method is the Newmark's sliding block method [4]. The Newmark method calculates the permanent displacement of a slope under earthquake excitation by integration of acceleration above yield acceleration. Calculation for yield acceleration for a slope is carried out by the limiting equilibrium method of slices. In recent years, several modifications of the Newmark's method have been made to account for the influences of site soil conditions as well as dynamic response characteristics of a slope [5,2,6]. Bray and Rathje [6] presented a nonlinear decoupled one-dimensional dynamic analysis method to estimate slope displacement based on dynamic response of the site, dynamic resistance, and ground motion parameters.

Stabilization of an unstable slope either in static or seismic conditions has been an important issue in geotechnical engineering. Among a variety of slope stabilization methods, a concept of using a row of drilled shafts has been well accepted and used successfully over the years. Some of the advantages offered by drilled shafts include: (a) drilled shafts are permanent structures that can provide significant resistance to earth thrust from a moving slope, (b) drilled shafts can be constructed in almost all soil and rock conditions, (c) drilled shafts can be constructed in difficult site conditions without the need for additional right-of-way in most highway applications, and (d) drilled shafts can be combined with other types of slope stabilization methods, such as tiebacks, drainages, and grade changes, etc., and finally (e) drilled shafts can be load tested to verify the resistance capacities. Design methods for using drilled shafts to stabilize an unstable slope have been developed by numerous researchers. Among them is the method based on the soil arching concept proposed by Liang and his associates [7–16]. However, there has been no previous study related to calculation of permanent displacement of a slope reinforced by a row of equally spaced drilled shafts under an earthquake excitation. The concept of soil arching proposed by Liang could lend itself for the determination of yield acceleration of a drilled shafts reinforced slope. Once such yield acceleration is determined, then permanent displacement of a drilled shaft reinforced slope system under an earthquake could be estimated using the well-known Newmark's method.

Presented in this paper is a method for determining yield acceleration of a slope reinforced with a row of equally spaced drilled shafts under an earthquake excitation. The concept of soil

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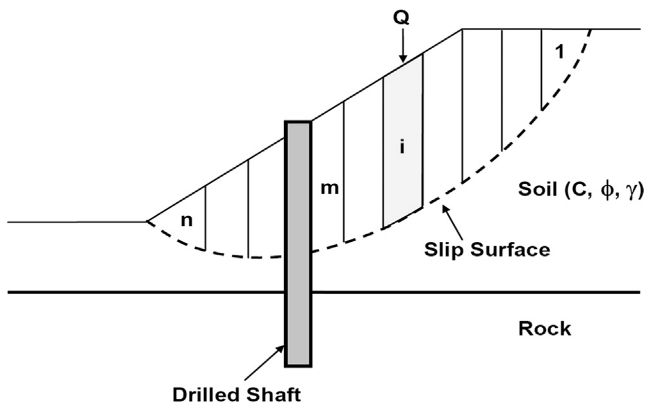

Fig. 1. Slope with sliding soil mass divided into n vertical slices.

arching in a drilled shafts/slope system is described. The limiting equilibrium method of slices for slope stability calculation considering soil arching effects due to drilled shafts is formulated through the load transfer factor. Parametric study results of 3-D finite element simulations using strength reduction techniques are used to obtain a semi-empirical equation for predicting load transfer factor. An example is given to show the validity of the proposed method for calculating yield acceleration. In addition, a modified Newmark method is introduced for calculating permanent displacement for a slope reinforced with a single row of equally spaced drilled shafts using the calculated yield acceleration and charts developed by Bray and Rathje [6]. A total of seven cases are performed to show good comparisons between the proposed simplified method and 3-D finite element simulation results.

2. Yield acceleration for a slope reinforced with drilled shafts

The arching mechanism occurs when the soils on a slope move through the opening between the drilled shafts, particularly when the opening is small and the drilled shafts are fixed deep enough into a stable stratum. As a result of arching, the earth pressures would transfer to the drilled shafts, which are resisted by the portion of the drilled shafts in the unyielding stratum (i.e., rock). Eventually, soil movements would slow down between the drilled shafts when equilibrium was reached. Thus, it is apparent that arching helps reduce the driving forces on the down-slope side of drilled shafts. In a seismic condition, a factor of safety of a drilled shafts reinforced slope can be set to equal to one to compute dynamic resistance (or yielding acceleration). The mathematic formulation of the method of slices for analyzing the dynamic resistance of a drilled shafts/slope system for a given seismic excitation is presented in this section.

Fig. 1 shows a schematic diagram of a slope with one row of equally spaced drilled shafts, with each slice acting as an unique sliding block affected by a general system of forces as depicted in Fig. 2. If each individual slice is assumed to be in a state of equilibrium, then there are ($8n$–3) unknowns as listed in Table 1. The total number of equations is $3n$; therefore, the solution is statically indeterminate. The following assumptions are made in order to render the problem determinate.

There is only one constant yield acceleration, thus reducing the total number of unknowns by (n–1) to ($7n$–2).

The normal force on the base of the slice acts at the midpoint of the slice base, thus reducing the total number of unknowns by (n) to ($6n$–2).

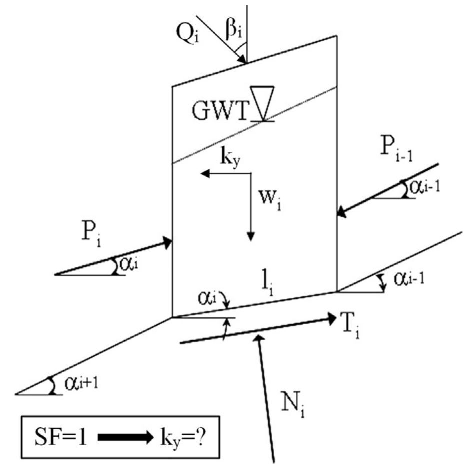

Fig. 2. General system of forces acting on a typical slice *i*.

Table 1
Equations and unknowns associated with the method of slices.

Equations	Condition
$2n$	Force equilibrium in two directions for each slice
n	Mohr–Coulomb relationship between shear strength and normal effective stress
$3n$	*Total number of equations*
Unknowns	**Variables**
n	K_y at center of density of each slice
n	Inclination of K_y
n	Normal force at base of each slice (N)
n	Location of normal force (N)
n	Shear force at base of each slice (T)
$n-1$	Interslice forces
$n-1$	Inclination of interslice forces
1	eta factor
$n-1$	Location of interslice forces
$8n-3$	Total number of unknowns

The location of the thrust line can be placed generally at one-third of the average interslice height (h_i) above the failure surface as in [17]. The thrust line as indicated in Fig. 2 connects the points of application of the right- and left-interslice forces. This assumption reduces the total number of unknowns by (n–1) to ($5n$–1).

The assumption by [7] regarding the inclination of the interslice forces is adopted. The right-interslice force is assumed to be parallel to the inclination of the preceding slice base (i.e., α_{i-1}), and the left-interslice force is assumed to be parallel to the slice base (i.e., α_i). Thus, the total number of unknowns is reduced by (n–1) to $4n$.

Inclination of the K_y is considered as horizontal. Thus, the total number of unknowns is reduced by (n) to $3n$.

Referring to Figs. 1 and 2 and applying the equilibrium method of slices for any slice of the slope, the summation of the forces in the direction normal to the base of the slice and in the tangential direction yields the following two equations, respectively:

$$N_i - w_i \cos \alpha_i - P_{i-1} \sin(\alpha_{i-1} - \alpha_i) + w_i K_y \sin(\alpha_i) - Q_i \cos(\beta_i - \alpha_i) = 0 \quad (1)$$

$$T_i + P_i - w_i \sin \alpha_i - P_{i-1} \cos(\alpha_{i-1} - \alpha_i) - w_i K_y \cos(\alpha_i) + Q_i \sin(\beta_i - \alpha_i) = 0 \quad (2)$$

Also, applying the Mohr–Coulomb strength equation of the soil to the base of the slice, one would obtain the following