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Limit equilibrium based design approach for slope stabilization using multiple rows of drilled shafts

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ABSTRACT

In this paper, a limiting equilibrium based methodology, incorporating the method of slices and arching effects of the drilled shafts, is developed for optimizing the use of multiple rows of drilled shafts. This proposed method is focusing on the number of rows, the location of each row, the dimension and spacing of the drilled shafts. Three design criteria are used for optimization: target global factor of safety, the constructability and service limit. A PC-based program called M-UASLOPE has been coded to allow for handling of complex slope geometry, soil profile, and ground water conditions. A design example is presented to illustrate the application of the M-UASLOPE program in the optimized design of multiple rows of drilled shafts for stabilizing the example slope.

1. Introduction

The practice of using drilled shafts to stabilize an unstable slope has been widely and successfully adopted [1–12]. However, most of the analysis and design methods are based on the limiting equilibrium approach, which considers the effects of drilled shafts to be an increase in resistance. The estimation of resistance from drilled shafts has been based on ultimate soil reaction pressure or displacement-based finite element analysis or an *LPILE* [13] type of computation to determine the displacement-dependent soil pressures against the drilled shafts. The alternative approach, within the concept of limiting equilibrium method of slices, has been proposed and developed by several researchers [14–28], in which the effects of the drilled shafts are considered as the reduction in the driving forces due to the soil arching between the adjacent drilled shafts. The estimate of the reduction in the driving force is based on empirical load transfer factor equation. The equation was derived from regression analysis of more than 40 cases of three-dimensional (3-D) finite element simulation results. This method has been coded into a PC based computer program (*M-UASLOPE*) for design applications.

When looking at the various proposed methods for slope stabilization using drilled shafts, it was found that all of them were concerned with the design of a single row of drilled shafts. The method proposed by Liang [17] allows for optimization of the size (diameter and length) of the drilled shafts, the spacing between the adjacent drilled shafts, and the location of the row of drilled shafts on the slope. However, in reality, the use of a single row of drilled shafts may not be feasible due to the dimensions of the failed slope and the large earth thrust applied to the drilled shafts, which would render the structural design of the drilled shafts nearly impossible. In these difficult conditions, the use of multiple rows of drilled shafts could be a feasible solution to both ensure that the global factor of safety of the stabilized slope meets the target factor of safety and that the size of drilled shafts and the amount of reinforcement used in the drilled shafts is constructible and economical. Specifically, multiple rows of drilled shafts are needed to arrest slope movement and enhance the safety margin of the failing slope for the following two scenarios: (1) one row of drilled shafts cannot satisfy the target factor of safety (FS_{Target}), regardless of the dimension of the drilled shafts and location of the drilled shafts; and (2) although the use of single row of drilled shafts can increase the global factor of safety of the slope to the target value, the net force applied to the drilled shafts is excessively large, which either precludes the design of a constructible reinforcement or produces a deflection of the shaft that may be too large to meet the service limit requirements.

In this study, an analysis and design approach for using multiple rows of drilled shafts to stabilize an unstable slope is presented. The method is based on the limit equilibrium method of slices, incorporating the concept of soil arching in determining the

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reduction of the driving force in the stability analysis. The formulation of this method, together with the empirical equations for determining the arching-induced reduction in the driving forces is described. Optimization of the number of the rows, the dimensions of the drilled shafts, and the locations of each row of the drilled shafts to achieve safety and service limit requirements are described. An example is presented to demonstrate the use of the proposed method to optimally design multiple rows of drilled shafts for the purpose of slope stabilization.

2. Multi-rows of drilled shafts for stabilizing a slope

Ideally, one would like to use only a single row of drilled shafts to stabilize an unstable slope. However, conditions exist that may require use of more than one row of drilled shafts. Usually, there are two major circumstances where multiple rows of drilled shafts are necessary: (1) cases where using one row of drilled shafts cannot satisfy the target FS regardless of the chosen dimension of the drilled shafts, the spacing of drilled shafts, and location of the row of drilled shafts, and (2) although the global factor of safety can be satisfied with the use of a single row of drilled shafts, the forces applied to the drilled shaft are excessively large such that either the reinforcement cannot be practically provided without causing constructability issues or the drilled shaft deflection is too excessive to meet the service limit requirements. Therefore, to address situations like these, there is a need to use multiple rows of drilled shafts.

2.1. Method of slices for two-row of drilled shaft/slope system

The global factor of safety of two or more rows in a drilled shaft/slope system can be calculated based on the limit equilibrium method of slices. The method of slices for two rows of drilled shafts incorporating the arching-induced reduction in driving force on the downslope side of drilled shafts is formulated herein. The basic assumptions made in the calculation of the method of slices are enumerated below:

(1) FS was considered to be identical for all slices.
(2) Normal force on the base of the slice was applied at the midpoint of the slice base.
(3) The location of the thrust line of the interslice forces was placed at one-third of the average interslice height above the failure surface, as in the study by Janbu [29].
(4) The inclinations of the interslice forces were assumed as follows: the right-interslice force $\left(P_i^R\right)$ was assumed to be parallel to the inclination of the preceding slice base (i.e., α_{i-1}), and the left-interslice force $\left(P_i^L\right)$ was assumed to be parallel to the current slice base (i.e., α_i).
(5) There is no group pile effect between the two adjacent rows of drilled shafts. The group pile effect will be produced if the two rows or more rows of drilled shafts are too close, which will affect the p-y curve analysis. In this paper, group pile effect is assumed non-existent, and the minimum spacing of two adjacent rows of drilled shafts is chosen as 5 m.
(6) Soil arching for each row of drilled shafts is considered as independent from each other. The soil arching has been expressed as load transfer factor in this paper. In practical engineering, when the two adjacent rows of drilled shafts are quite close, the soil movement induced by the deflection of up-slope row of drilled shafts may affect the down-slope row of drilled shafts. Therefore, the load transfer factor of down-slope row of drilled shafts may be affected. In this paper, however, the limit equilibrium method of slices has been employed, which means no soil movement will be produced. Therefore, soil arching for each row of drilled shafts can be considered as independent from each other.

Referring to Figs. 1 and 2 and applying the force equilibrium for any slice i of the slope, the force summations in two directions, the normal and tangential directions to the base of the slice, result in the following two equations:

$$N_i - w_i \cos\alpha_i - P_i^R \sin(\alpha_{i-1} - \alpha_i) = 0 \tag{1}$$

$$T_i + P_i^L - w_i \sin\alpha_i - P_i^R \cos(\alpha_{i-1} - \alpha_i) = 0 \tag{2}$$

Using Mohr–Coulomb strength equation of the soil to the base of the slice, the following relationship is obtained.

$$T_i = \frac{c_i l_i}{FS} + [N_i - u_i l_i]\frac{\tan\varphi_i}{FS} \tag{3}$$

Substituting Eqs. (1) and (2) into Eq. (3), one obtains the following equations:

$$T_i = \frac{c_i l_i}{FS} + \left[w_i \cos\alpha_i + P_i^R \sin(\alpha_{i-1} - \alpha_i) - u_i l_i\right]\frac{\tan\varphi_i}{FS} \tag{4}$$

$$P_i^L = w_i \sin\alpha_i - \left[\frac{c_i l_i}{FS} + (w_i\cos\alpha_i - u_i l_i)\frac{\tan\varphi_i}{FS}\right] + k_i P_i^R \tag{5}$$

$$k_i = \cos(\alpha_{i-1} - \alpha_i) - \sin(\alpha_{i-1} - \alpha_i)\frac{\tan\varphi_i}{FS} \tag{6}$$

where w_i is weight of slice i, N_i is force normal to the base of slice i, T_i is force parallel to the base of slice i, P_i^L is interslice force acting on the left side of slice, P_i^R is interslice force acting on the right side of slice, α_i is inclination of slice i base, α_{i-1} is inclination of slice $i-1$ base, u_i is the pore pressure at the base of slice i, c_i is soil cohesion at the base of slice i, φ_i is soil friction angle at the base of slice i. It is noted that c and φ are in terms of effective stress throughout this paper.

After the drilled shafts are inserted into the slope, the interslice force on the downslope side of the drilled shaft will be reduced due to soil arching, i.e., it will be reduced by a multiplier called the load transfer factor (η) from the previous interslice force P_i^R. Referring to Figs. 1–3 and applying the force equilibrium while invoking Mohr–Coulomb's strength criterion for any slice i of the slope, the interslice force shown in Fig. 3 can be written as the following expressions:

$$P_i^L = w_i \sin\alpha_i - \left[\frac{c_i l_i}{FS} + (w_i\cos\alpha_i - u_i l_i)\frac{\tan\varphi_i}{FS}\right] + k_i \eta_1 P_{i-1}^L \tag{7}$$

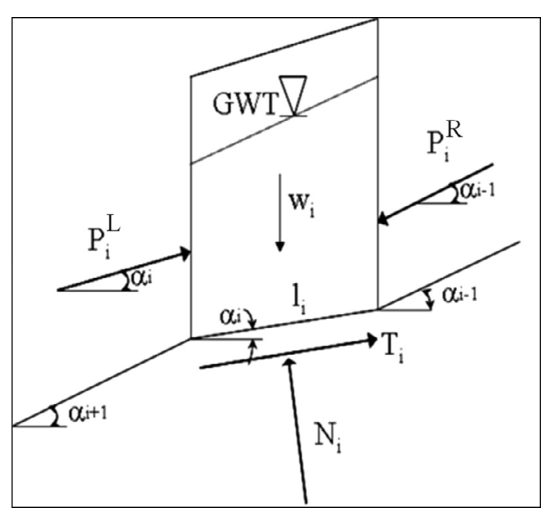

Fig. 1. A typical slice showing all force components.