STABILITY ANALYSIS OF DRILLED SHAFTS REINFORCED SLOPE

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ABSTRACT

Drilled shafts have been used as an effective means to stabilize a soil slope with marginal safety factor. A limit equilibrium based slope stability analysis technique is presented in this paper that would allow for the determination of the safety factor of the reinforced slope and the forces acting on the drilled shafts. Specifically, the finite element analysis generated load transfer characteristic curves were incorporated into the traditional method of slice approach to account for the soil arching effects. Mathematical formulation of the proposed analysis method is given in detail, followed by validation of the approach with other analysis methods. Examples of the slopes with or without the drilled shafts are given to illustrate the reasonableness of the solution provided by the proposed approach. The efficiency of using drilled shafts to stabilize a slope is discussed by examining the influence of the shaft location, shaft size and spacing on the calculated safety factor. Finally, a practical case involving the use of the proposed approach is presented.

Key words: drilled shafts, slope stabilization, stability analysis (IGC: E6)

INTRODUCTION

Drilled shafts have been used in cuts and bridge abutments for many decades. Recently, there has been an increasing interest in the use of drilled shafts for the purpose of slope stabilization. The increased popularity of such a slope stabilization technique may be attributed to the following factors: (1) various construction techniques are available for installing drilled shafts in almost any type of soil conditions; (2) numerous standard tests, such as lateral load test, can be readily performed to verify the load resistance capacity of the drilled shafts; (3) the use of drilled shafts seems to offer a reliable and economic solution with long-term resistance to environmental effects, such as corrosion.

The design of a drilled shaft supported wall calls for an adequate global stability to prevent excessive movement of the supported soil mass, and sufficient structural capability to resist bending moments developed in the shafts due to the earth pressure. The successful applications of drilled shafts in slope stabilization have been described by several investigators (e.g., Sommer, 1977; Ito et al., 1981, 1982; Nethero, 1982; Morgenstern, 1982; Gudehus and Schwarz, 1985; Reese et al. 1992; Rollins and Rollins, 1992); Yamagami et al. (2000), however, the methods used for the design and analysis of the stabilizing system varied widely. Furthermore, some of these methods appeared to be of doubtful validity as pointed out by Poulos (1995). Actually, the drilled shafts used for stabilizing a slope are often referred to as passive shafts. In the passive shaft analysis, the lateral force acting on the shaft is related to the movement of the slope and the interaction between the shaft and the surrounding soils. Ideally, the stabilization mechanisms of drilled shafts should be investigated based on three-dimensional consideration, incorporating nonlinear and plastic nature of soil constitutive behavior as well as the soil-shaft interactions. At the present time, it is extremely difficult to explicitly take into account of these true three-dimensional phenomena. In most instances, some simplifying idealizations of the problem are made.

The most common approach is based on the classic earth pressure theories to estimate the load or pressure acting on the shafts. Chelapati and Finn (1963) are the two primary investigators using the elastic theory. The derived analytical results, by use of elasticity methods in soils, are only valid for small deformations and strains; whereas, the behavior of the soil mass in the vicinity of the shafts usually involves large and nonlinear deformations. Recent developments in the subject area are represented by the method proposed by Ito et al. (1975, 1979, 1981), where rigid-plastic soil behavior was taken into account. The mathematical deductions of analytical formulations for calculating the acting pressure were based on a certain number of simplifying assumptions, including (i) the soil becomes plastic only in the area just around the drilled shafts; (ii) two vertical sliding surfaces will occur along the lines making an angle \((45 + \phi/2)\) with the direction of soil movement; (iii) the friction force acting on the sliding surfaces is neglected; and (iv) the active...
earth pressure is assumed to act on the plane along the direction of a row of piles. Once the lateral force has been calculated, then the structural adequacy of the shafts and the stability of the slope can be analyzed separately. Several other similar works using this analytical approach can be found in Wang and Yen (1974), Bransby and Smith (1975), and Reese et al. (1992). The various assumptions mentioned above, however, limit the validity of the solutions to certain specific cases.

In contrast to earth pressure methods, the displacement-based approaches emphasize on the assumptions of the magnitude and pattern of the lateral soil displacement of a free field, from which the resulting deflection and bending moment of the drilled shaft can be determined. Springman (1989) and Stewart et al. (1994) investigated the single pile behavior in an elastic soil layer subject to various types of assumed soil movements. Recent development was presented by Poulos (1994, 1995), in which the free field soil movement was used as input in a simplified boundary element method to compute the axial and lateral response of piles subjected to these prescribed soil movements. The influencing factors, such as positions of the drilled shafts, shear strength of the soil, soil layer thickness, the restraint at the pile head, and the installation sequence of piles, can be considered. Generally speaking, the displacement-based method is superior to the earth pressure method, because it reflects the true mechanism of soil-shaft interaction. However, it should be pointed out that accurate description of soil movements is a priori condition to the accuracy of the calculated loads applied to the drilled shaft. In most cases, such displacement description is very difficult to obtain in the field.

Limit equilibrium analysis in conjunction with the method of slices is the most widely used method for evaluating stability of slopes. The techniques can accommodate complex geometry and variable soil properties and water pressure conditions. The limit equilibrium analysis method can provide a global safety factor by which the safety of a slope can be quantitatively assessed. Numerous limit equilibrium methods for slope stability analysis have been proposed by several investigators, including the celebrated pioneers Fellenius (1936), Bishop (1955), Janbu (1954), Morgenstern and Price (1965), Spencer (1967), and Sarma (1973). Recent developments on application or enhancement of those methods can be found in Sharma and Moudud (1992), Fredlund et al. (1992), Espinoza et al. (1994), and Zhang and Chowdury (1995). These efforts, however, were related to a slope without drilled shafts. The analysis of a slope stabilized with the drilled shafts requires a development of an approach to account for the contribution of drilled shafts. The problem lies in the fact that the drilled shafts can only support a partial of resultant driving force, while the rest of earth pressure still transmitted to the downslope soil.

It has been recognized that discrete drilled shafts in a row embedded into a firm, non-yielding soil strata in a slope can provide significant additional stability to a slope if soil arching around the drilled shafts are developed. Soil arching, the transfer of stresses from a yielding mass of soil onto an adjacent non-yielding soil, is a phenomenon commonly encountered in the field. For a slope reinforced by the drilled shafts installed in a row, soil arching over the soil mass between drilled shafts may occur under certain circumstance as the soil attempts to move through the stiff drilled shafts which are firmly embedded in a non-yielding soil strata. There have been numerous literatures providing a wide range of information on the soil arching effects (e.g., Terzaghi, 1943; Cox et al., 1983; Bosscher and Gray, 1986; Adachi et al., 1989; Reese et al., 1992; Low et al., 1994; and McVay et al., 1995). Unfortunately, a generally accepted guideline to incorporate the arching effects into the design of drilled shafts in stabilizing a slope is not universally available due to the lack of adequate information on soil arching behavior. The key issues to be resolved in this context are: (a) What conditions should be met in order for soil arching to be fully developed, and (b) How much additional resistance force that can be provided by drilled shafts due to soil arching effect?

The main objective of the present study is to develop a practical methodology for stability analysis and design of drilled shafts reinforced slopes. The developed method utilizes the generalized procedure of slice for composite slip surfaces of any shape and incorporates the effect of the soil arching due to the installation of drilled shafts. Such integrated approach would allow for not only the determination of the safety factor of the reinforced slope, but also the forces acting on the drilled shafts. Parameters affecting the soil arching are investigated, and the load transfer curves characterizing the ability of soil arching mechanism are developed based on an extensive parametric study. The efficiency of stabilization of slope by drilled shafts is then discussed by examining the influence of shaft location, size and spacing on the computed factor of safety. Finally, a case study is presented.

GENERAL STATEMENTS

As shown in Fig. 1, drilled shafts of diameter d with spacing s are installed in a row through a moving soil into a firm, non-moving soil stratum underneath. As the soil mass moves through the drilled shafts, soil arching will occur, by which the stress in the yielding soil is redistributed unto the unyielding portion of soil and eventually unto the supporting piles. As a result, the driving force transmitted to the soil mass behind the drilled shafts is reduced to some extent, say by a reduction factor $R$, leading to a higher stability of the slope. The reduction factor, $R$, under certain circumstances, is related to both drilled shafts spatial parameters and soil conditions. Details about the determination of the reduction factor, $R$, will be given later in this paper.

For slope stability analysis, force and moment equilibrium equations together with the commonly adopted Mohr-Coulomb failure criterion are used in the method of slice technique. Some assumptions concerning
Stability Analysis of Reinforced Slope

Slip surface usually encountered in the field, the analysis should allow for a composite-type of failure surfaces. Thus, a generalized method of slices for composite slip surfaces of any shape is employed herein, and the resultant interslice force is assumed to be parallel to the base of the previous up-slope slice (see Fig. 2), with point of application located at one-third from the bottom of the interface.

At failure, the available shear strength on the base of the slice is governed by Mohr-Coulomb's failure criterion expressed in terms of effective stresses

$$\tau = c' + (\sigma - u) \tan \phi'$$  \hspace{1cm} (1)

where $\tau$ is shear strength; $c'$ is effective cohesion; $\phi'$ is effective internal angle of friction; $u$ is pore pressure at the base of the slice; and $\sigma$ is total normal stress acting on the base of the slice.

The safety factor $F$ is defined as the ratio of the available shear strength of the soil at failure to that mobilized for maintaining equilibrium. The mobilized shear stress $\tau$ necessary for equilibrium is

$$\tau = \frac{\tau}{F} = c'_m + (\sigma - u) \tan \phi'_m$$ \hspace{1cm} (2)

where

$$c'_m = \frac{c'}{F}$$ \hspace{1cm} (3)

$$\tan \phi'_m = \tan \phi'/F.$$ \hspace{1cm} (4)

Mathematical Formulation

Consider the static equilibrium of a soil slice $i$ overlying the slip surface segment of length $l$, as shown in Fig. 2. The forces acting on the slice are $W_i$, the weight of the slice; $P_{i-1}$, $P_i$, the resultant interslice forces on the $(i-1)$th and $i$th interfaces, respectively; $N_i$, the normal force reaction on the base of the slice; and $T_i$, the shear force reaction on the base of the slice. Also, $\alpha_{i-1}$ and $\alpha_i$ are the average slopes of the bases of the slices $i-1$ and $i$, respectively. As assumed, $P_{i-1}$ has orientation of $\alpha_{i-1}$ and $P_i$ of $\alpha_i$.

The force equilibrium of slice $i$ requires, in the direction parallel to $N_i$,

$$N_i - W_i \cos \alpha_i - P_{i-1} \sin (\alpha_{i-1} - \alpha_i) = 0$$ \hspace{1cm} (5)

Similarly, in the direction perpendicular to $N_i$

$$T_i + P_i - W_i \sin \alpha_i - P_{i-1} \cos (\alpha_{i-1} - \alpha_i) = 0.$$ \hspace{1cm} (6)

Based on the expression (2), the corresponding mobilized shear force $T_i$ is

$$T_i = \frac{c'_i l}{F} + \frac{N_i - u_i l}{F} \tan \phi'_i.$$ \hspace{1cm} (7)

Combining Eqs. (5) and (7) yields

$$T_i = \frac{c'_i l}{F} + \left[ W_i \cos \alpha_i + P_{i-1} \sin (\alpha_{i-1} - \alpha_i) - u_i l \right] \frac{\tan \phi'_i}{F}.$$ \hspace{1cm} (8)

Substituting (8) into (6) gives

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The interslice forces, and their directions or locations are needed to render the problem determinate. Different assumptions will lead to different analytical procedures for calculation of safety factor. For the drilled shafts reinforced slope considered here, the main objective of an analysis procedure is to incorporate the contributions exerted by the drilled shafts. To accommodate complex
\[ P_i = W_i \sin \alpha_i - \left[ \frac{c' l_i}{F} + (W_i \cos \alpha_i - u_i \phi_i') \frac{\tan \phi_i'}{F} \right] + k_i P_{i-1} \]  

(9)

where

\[ k_i = \cos (\alpha_{i-1} - \alpha_i) - \sin (\alpha_{i-1} - \alpha_i) \frac{\tan \phi_i'}{F} \]  

(10)

Equation (9), together with Eq. (10), applies to each slice and relates the interslice force \( P_i \) to the previous one \( P_{i-1} \). Thus, recursive formula for determining \( P_i \) with initial value \( P_0 \) being zero or prescribed boundary force, can be established. It is also noted from Eqs. (9) and (10) that \( P_i \) depends on the safety factor \( F \), thus an iterative computational scheme is required.

The iterative procedure is fairly straightforward. First, an initially postulated value of safety factor \( F \) is assumed. Next, the initial \( F \) is introduced in the recursive formulae (9) and (10), starting from the given \( P_0 \) to obtain \( P_1 \), then \( P_2 \), and finally \( P_n \). In most cases, the calculated \( P_n \) for the first try is not expected to satisfy the boundary conditions with respect to the force at the last slice. Thus, a different assumed value of safety factor is required and the iterative process continues until the calculated \( P \) matches the prescribed boundary forces within a specified accuracy.

It should be noted that if \( P_i < 0 \) occurs at any computation step while using Eq. (9), the calculated \( P_i \) is reset to be zero in next step for calculation of \( P_{i+1} \). This is to take into consideration that soils usually are weak in tension.

When drilled shafts are introduced in the slope, supposing installed in a line at the interface between slices \( i - 1 \) and \( i \), the computational scheme discussed above is still valid and Eq. (9) is used for all slices except for the slice \( i \) which is right behind the drilled shafts wall. The interslice force acting on the \( i - 1 \)th interface, with respect to the boundary of slice \( i \), is reduced to \( R P_{i-1} \), where \( R \) is the reduction factor due to the soil arching arising from the presence of the drilled shafts. As a result, substituting \( R P_{i-1} \) for \( P_{i-1} \) in Eq. (9) leads to

\[ P_i = W_i \sin \alpha_i - \left[ \frac{c' l_i}{F} + (W_i \cos \alpha_i - u_i \phi_i') \frac{\tan \phi_i'}{F} \right] + k_i R P_{i-1} \]  

(9a)

which can be used to calculate \( P_i \) for the slice \( i \), locating just behind the drilled shafts.

It should be noted that during the above process there is no physical slice designated to simulate the drilled shafts wall due to the uncertainties regarding the equivalent thickness of such slice for the discrete drilled shafts. Instead, the contributions of the drilled shafts are mechanically incorporated with the introduction of the reduction factor \( R \).

**SOIL ARCHING MECHANISM AND THE REDUCTION FACTOR**

Soil arching, defined as the stress transfer from a yielding soil mass into an adjoining non-yielding soil, is a phenomenon commonly encountered in geotechnical engineering. For a slope reinforced by the drilled shafts in a row, soil arching in the soil mass may occur as the soil moves through the opening between the drilled shafts, as depicted in Fig. 3. Based on laboratory model tests conducted by Bosscher and Gray (1986) and Adachi et al. (1989), the soil arching mechanism was found to be significant and the development of soil arching was affected by both the layout of the drilled shafts and the soil properties. In analysis and design of the drilled shafts stabilized slope, one requires an adequate information regarding the parameters most affecting soil arching. In particular, one needs to quantify the contribution of drilled shafts. For this purpose, a systematical parametric study has been carried out with the aid of a finite element computer program PLAXIS. Parameters varied included shaft diameter, shaft spacing, internal friction angle and cohesion of the soil. Details of FEM modeling techniques and validation results are summarized in a companion paper (Liang and Zeng, 2002), together with the pertinent results of a numerical parametric study.

For the soil strength, the internal friction angle was varied from 0 to 40° and the cohesion was varied from 0 kPa to 91.44 kPa. For the drilled shafts, three shaft diameters were studied: \( d = 30.48 \) cm, \( d = 60.96 \) cm and \( d = 91.44 \) cm, while the clearance (spacing) between the shafts was varied from 1 to 5 times of diameter. The development of soil arching was assessed by the degree to which the driving force was transferred to the drilled shafts, or by means of the residual stresses acting on the soil mass between the shafts. Here, the soil pressure acting on the soil mass between the piles due to soil arching effect was calculated and normalized with respect to the initial pressure to obtain a percentage factor \( R_p \). Obviously, if the value of \( R_p \) is 100%, it means that no arching effect exists at all and all soil pressure would be fully transmitted to the soil mass downslope.
Table 1. Percent of pressure acting on soil mass between piles (d = 91.44 cm)

<table>
<thead>
<tr>
<th>$d/s$</th>
<th>$\phi = 0^\circ$</th>
<th>$\phi = 10^\circ$</th>
<th>$\phi = 20^\circ$</th>
<th>$\phi = 30^\circ$</th>
<th>$\phi = 40^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$c = 0$ (kPa)</td>
<td>$c = 6.9$ (kPa)</td>
<td>$c = 13.8$ (kPa)</td>
<td>$c = 27.6$ (kPa)</td>
<td>$c = 41.4$ (kPa)</td>
</tr>
<tr>
<td>$s/d = 2$</td>
<td>100.00</td>
<td>40.13</td>
<td>10.44</td>
<td>10.07</td>
<td>9.65</td>
</tr>
<tr>
<td>$s/d = 3$</td>
<td>100.00</td>
<td>67.98</td>
<td>28.75</td>
<td>15.61</td>
<td>15.24</td>
</tr>
<tr>
<td>$s/d = 4$</td>
<td>100.00</td>
<td>78.18</td>
<td>48.30</td>
<td>23.30</td>
<td>17.91</td>
</tr>
<tr>
<td>$s/d = 2$</td>
<td>72.33</td>
<td>20.06</td>
<td>10.14</td>
<td>9.99</td>
<td>9.57</td>
</tr>
<tr>
<td>$s/d = 3$</td>
<td>85.33</td>
<td>45.68</td>
<td>16.01</td>
<td>15.52</td>
<td>15.18</td>
</tr>
<tr>
<td>$s/d = 4$</td>
<td>90.85</td>
<td>63.69</td>
<td>30.02</td>
<td>17.38</td>
<td>17.33</td>
</tr>
<tr>
<td>$s/d = 2$</td>
<td>49.80</td>
<td>14.18</td>
<td>10.09</td>
<td>9.57</td>
<td>9.39</td>
</tr>
<tr>
<td>$s/d = 3$</td>
<td>71.90</td>
<td>25.38</td>
<td>15.62</td>
<td>15.39</td>
<td>15.12</td>
</tr>
<tr>
<td>$s/d = 4$</td>
<td>81.48</td>
<td>50.98</td>
<td>16.86</td>
<td>16.56</td>
<td>15.02</td>
</tr>
<tr>
<td>$s/d = 2$</td>
<td>60.58</td>
<td>16.16</td>
<td>15.46</td>
<td>15.32</td>
<td>15.06</td>
</tr>
<tr>
<td>$s/d = 3$</td>
<td>74.02</td>
<td>41.09</td>
<td>16.43</td>
<td>15.46</td>
<td>15.00</td>
</tr>
<tr>
<td>$s/d = 4$</td>
<td>81.26</td>
<td>10.02</td>
<td>9.34</td>
<td>9.32</td>
<td>9.21</td>
</tr>
<tr>
<td>$s/d = 2$</td>
<td>53.54</td>
<td>19.54</td>
<td>15.32</td>
<td>15.18</td>
<td>14.94</td>
</tr>
<tr>
<td>$s/d = 3$</td>
<td>64.82</td>
<td>35.14</td>
<td>15.46</td>
<td>15.31</td>
<td>14.87</td>
</tr>
</tbody>
</table>

Thus, the net force acting on one drilled shaft is

$$F_{\text{shaft}}^\text{down} = P_{i-1}d$$

(12)

Expression (13) relates the drilled shaft force $F_{\text{shaft}}$ to the soil arching factor $R_p$. As it indicates, the stronger the soil arching effect (the smaller $R_p$), the more net force would act on the drilled shaft. For any reason, if the soil can freely move through the shafts without any traction or the soil mass and the drilled shafts experience no relative movement between them, then there would be no arching effect and no net force acting on the drilled shafts. This scenario can be represented by letting $R_p = 1$, the case of no arching effect, in expression (13), which leads to $F_{\text{shaft}} = 0$ as expected.

Assuming that the net drilled shaft force $F_{\text{shaft}}$ is sustained by the drilled shaft itself, the interslice force transmitted to the next slice right behind the drilled shafts is reduced to

$$P_{i-1} = \frac{P_{i-1}s - F_{\text{shaft}}}{s}$$

(14)

Substituting expression (13) into (14) yields

$$P_{i-1} = \left[ \frac{1}{s/d} + \left( 1 - \frac{1}{s/d} \right) R_p \right] P_{i-1}$$

(15)

Recall the definition of reduction factor $R$ introduced in Eq. (9a), then the expression (15) implies

$$R = \frac{1}{s/d} + \left( 1 - \frac{1}{s/d} \right) R_p$$

(16)

As it can be seen from the above expression, the interslice force reduction factor $R$ is a function of the ratio of shaft spacing to shaft diameter and the arching effect factor $R_p$. For a given soil condition and drilled shafts layout (dimensions and spacing) with their parameters being within the range of the numerical values in Table 1, one could obtain the $R_p$ directly from Figs. 4 to 6 or Table 1. The reduction factor $R$ can then be calculated via Eq. (16). However, if some of the parameters are outside the range in Table 1, either interpolation or extrapolation can be exercised to determine the corresponding numerical values. It is important to perform additional numerical simulations to confirm the extrapolated numerical values.

EXAMPLE STUDIES

(1) Example One: Comparison of Methods of Analysis

Figure 7 shows an example problem considering a slope with a weak layer underneath. The presence of the phreatic ground water table was treated by either the constant water pressure ratio $r_g$ or a direct input of phreatic surface location. This problem has been studied by quite a few investigators (Fredlund and Krath, 1977; Baker, 1980; Donald and Giam, 1988; Zhang and Chowdhury, 1995). The validity of the present method was evaluated by comparing the calculated results with those obtained by other well-established methods.
Analyses were first performed for the case of circular slip surface. In this case, the slope was considered to be homogeneous with \( \gamma = 18.85 \text{ kN/m}^3, c' = 28.73 \text{ kPa} \) and \( \phi' = 20^\circ \). The height of the 2:1 slope is 12.2 m and the radius of the slip circle is 24.4 m. The calculated safety factors for three different water conditions: no water, constant pressure ratio \( r_p = 0.25 \) and specified phreatic line were 2.097, 1.720, and 1.844, respectively. The calculated results are listed in Table 2 along with those from various other methods.

For more complicated cases where the slope is underlain by a weak layer, a composite slip surface, consisting of parts of the above circle and a weak segment intersecting the circle, was used. The properties of the weak joint were \( \gamma = 18.85 \text{ kN/m}^3, c' = 0 \text{ kPa} \) and \( \phi' = 10^\circ \). Similarly, three possible water conditions were taken into account. The calculated factors of safety were 1.396, 1.165 and 1.255, as presented in Table 3.

The comparison results in Tables 2 and 3 show that the factors of safety obtained by the proposed method are generally similar to those computed by the simplified
Table 3. Comparison of factors of safety for example problem (composite slip surface)

<table>
<thead>
<tr>
<th>Methods of analysis</th>
<th>Without water</th>
<th>$r_0=0.25$</th>
<th>Phreatic line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary method</td>
<td>1.288</td>
<td>1.029</td>
<td>1.171</td>
</tr>
<tr>
<td>Simplified Bishop method</td>
<td>1.377</td>
<td>1.124</td>
<td>1.248</td>
</tr>
<tr>
<td>Spencer’s method</td>
<td>1.373</td>
<td>1.118</td>
<td>1.245</td>
</tr>
<tr>
<td>Janbu’s method</td>
<td>1.432</td>
<td>1.162</td>
<td>1.298</td>
</tr>
<tr>
<td>Morgenstern-Price method</td>
<td>1.378</td>
<td>1.124</td>
<td>1.250</td>
</tr>
<tr>
<td>Proposed method</td>
<td>1.396</td>
<td>1.165</td>
<td>1.255</td>
</tr>
</tbody>
</table>

Table 4. Comparison of results (plain slope)

<table>
<thead>
<tr>
<th>Methods of analysis</th>
<th>Factor of safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bishop’s method</td>
<td>1.03</td>
</tr>
<tr>
<td>Local minimum FS method</td>
<td>1.00</td>
</tr>
<tr>
<td>Proposed method</td>
<td>1.005</td>
</tr>
</tbody>
</table>

Table 5. Influence of shaft location on shaft force and global factor of safety

<table>
<thead>
<tr>
<th>$x$-coordinate (m)</th>
<th>Lateral force on shaft (kN)</th>
<th>Global factor of safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0</td>
<td>1.005</td>
</tr>
<tr>
<td>8</td>
<td>7.109</td>
<td>1.019</td>
</tr>
<tr>
<td>10</td>
<td>69.118</td>
<td>1.159</td>
</tr>
<tr>
<td>12</td>
<td>153.594</td>
<td>1.364</td>
</tr>
<tr>
<td>14</td>
<td>267.129</td>
<td>1.812</td>
</tr>
<tr>
<td>16</td>
<td>273.263</td>
<td>2.322</td>
</tr>
<tr>
<td>18</td>
<td>321.331</td>
<td>3.026</td>
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<tr>
<td>20</td>
<td>314.335</td>
<td>3.032</td>
</tr>
<tr>
<td>22</td>
<td>297.490</td>
<td>2.803</td>
</tr>
<tr>
<td>24</td>
<td>185.479</td>
<td>1.719</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
<td>1.005</td>
</tr>
</tbody>
</table>

Bishop, Spencer and Morgenstern-Price methods for the case of circular failure surface. On the other hand, for the composite slip surface, the calculated results are much closer to those from Janbu’s method. In all cases considered for possible combinations of water conditions, soil properties and various failure surfaces, the proposed method led to acceptable accuracy, with the average difference being within a narrow range of less than 3% when compared to the corresponding well-established methods.

(2) Example Two: Drilled Shafts Reinforced Slope

To evaluate the validity of the proposed method for drilled shaft stabilized slopes, it was applied to a slope where the reinforcement measures were required to stabilize the slope. The example selected was a 2:1 slope of a height of 8 m investigated by Hung and Yamasaki (1993), as shown in Fig. 8. The ground water table was assumed to be far below the failure surface so that there was no pore water pressure involved. The failure surfaces determined by the local minimum factor-of-safety approach and Bishop’s method were found to be very close and had factors of safety of 1.00 and 1.03, respectively, with the assumed soil properties of $c = 10$ kPa, $\phi = 10^\circ$ and $\gamma = 19.6$ kN/m$^3$.

Using a reduction factor $R = 1$ in Eq. (9a), meaning there are no drilled shafts in the slope, the calculated factor of safety is 1.005. This value compares favorably with 1.00 and 1.03 obtained by other methods, as listed in Table 4. The closeness of the safety factor to unity suggests the need of slope stabilization.

The stabilization effect of the installation of drilled shafts was investigated by calculating the factor of safety of the reinforced slope using the proposed stability analysis procedure. To evaluate the influence of the layout of the drilled shaft on slope stability, the locations and spacings of the drilled shafts were varied in the analyses.

Table 5 lists the factors of safety of the drilled shafts reinforced slope and the corresponding net lateral force acting on one shaft with respect to the location of the drilled shafts, with shaft diameter $d = 0.5$ m and shaft spacing $s = 1.0$ m. The results are also shown in Figs. 9 and 10 in normalized forms. As expected, the contribution of drilled shafts to the slope stabilization is comparatively less significant if the drilled shafts are located in the upper end of the slip surface, as characterized by a small increase on the factor of safety and drilled shaft force. The most effective location for the drilled shafts to improve slope stability is near the location of one-third of dimensionless distance from the toe.

For a specific position $x = 20$ m, which is within the most effective location based on the sensitivity study discussed above, the effect of drilled shaft spacing was analyzed. The calculated results with the shaft spacing ratio varying from 1.5 to 5.0 for shaft diameters of $d = 0.5$, $d = 0.75$ and $d = 1.0$ m were listed in Table 6. The factors of safety against the ratio of shaft spacing to diameter are plotted in Fig. 11 for the case of $d = 0.5$ m. It can be seen that the stability of the slope considered can be significantly enhanced by the installation of drilled shafts in a row with appropriate spacing ratio. The factor of safety increases rapidly from 1.4 to 5.0 as the ratio $s/d$ decreases from 3.5 to 1.5. This is a concomitant result of soil archi-
Fig. 9. Distribution of the ratio of drilled shaft lateral force $F$ over the maximum $F_{\max}$

Fig. 10. Distribution of the global factor of safety

Table 6. Influence of shaft layout on global factor of safety

<table>
<thead>
<tr>
<th>Spacing ratio ($s/d$)</th>
<th>$d=0.5$ m</th>
<th>$d=0.75$ m</th>
<th>$d=1.0$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>5.001</td>
<td>4.999</td>
<td>4.434</td>
</tr>
<tr>
<td>2.0</td>
<td>3.032</td>
<td>2.745</td>
<td>2.522</td>
</tr>
<tr>
<td>2.5</td>
<td>2.017</td>
<td>1.946</td>
<td>1.882</td>
</tr>
<tr>
<td>3.0</td>
<td>1.652</td>
<td>1.615</td>
<td>1.581</td>
</tr>
<tr>
<td>3.5</td>
<td>1.440</td>
<td>1.425</td>
<td>1.411</td>
</tr>
<tr>
<td>4.0</td>
<td>1.318</td>
<td>1.307</td>
<td>1.298</td>
</tr>
<tr>
<td>4.5</td>
<td>1.230</td>
<td>1.224</td>
<td>1.218</td>
</tr>
<tr>
<td>5.0</td>
<td>1.168</td>
<td>1.164</td>
<td>1.159</td>
</tr>
</tbody>
</table>

Fig. 11. Global factor of safety versus the ratio of spacing to diameter

The influence mechanism where the closer drilled shafts are placed in a row, the stronger a soil arching effect would develop and consequently more transferred arching load to the drilled shafts would occur.

CASE STUDY

The case history selected was a slope stabilization analysis/design of the Pomeroy landslide at US RT 33 project. Shown in Fig. 12 is a typical cross-section of the slope together with the corresponding soil properties for each layer. The program STABL5M, a stability analysis program developed by the U.S. Federal Highway Administration, was applied to locate the failure surface as shown in Fig. 12. The analysis gave a factor of safety of 1.221 based on the given soil conditions. Since the inclinometer readings and surface investigation data indicated that the slope might have experienced significant slide along the slip surface, the higher value of factor of safety suggested that the soil strength along the soil-rock interface or the failure surface should be reduced to some extent. For this reason, a parametric study was carried out to produce the back-calculated strength parameters along the soil-rock interface. The failure state determined by STABL5M had a factor of safety of 1.007 with the assumed soil-rock interface properties of $c=3.4$ kPa and $\phi=16.5^\circ$. The installation of drilled shafts was chosen as a remedy means for slope stabilization. Pertinent design recommendation for the drilled shafts is summarized as below.

- Diameter: 122 cm
- Length: goes through the slide surface with minimum rock socket length of 2 m.
- Spacing: 244 cm center-to-center
- Reinforcement: 14 #11 main bars with #4@15 cm ties
The application of the proposed method to the original slope condition yielded the factor of safety of 1.231. For the case with reduced strength parameters, the proposed method gave a factor of safety of 1.012. The comparison between the results obtained by the proposed method and the other proven technique was presented in Table 7. As shown in the table, the results are very close to each other for both cases. This provides a solid base to review the recommended stabilization design by using the proposed method thereafter.

For the given layout of drilled shafts and the specified location as shown in Fig. 12, the global stability of the reinforced slope was found to be improved, with the calculated global factor of safety of the slope increasing from 1.012 to 1.297. The corresponding lateral force acting on the drilled shaft is 565 kN, which leads to a maximum bending moment \( M_{\text{max}} = 1684 \text{ kN-m} \). Since the allowed bending moment of the drilled shaft is \( M_{\text{allow}} = 2881 \text{ kN-m} \), the factor of safety of the drilled shaft with respect to bending moment is:

\[
FS_{\text{shaft}} = \frac{M_{\text{allow}}}{M_{\text{max}}} = 1.71.
\]

It can be concluded that both stability conditions of slope and drilled shaft are satisfied.

**CONCLUSIONS**

An approach has been described for the analysis and design of drilled shafts stabilized slope. The developed method utilizes the generalized procedure of slice for composite slip surface of any shape and incorporates the effect of soil arching due to the installation of drilled shafts. Such integrated approach can readily determine the global factor of safety for the slope reinforced with drilled shafts and the lateral force acting on the drilled shafts as well. Comparative studies have shown that the proposed method can lead to reasonable assessments on the stability of natural slope and reinforced slope using the drilled shafts. It has been found that the drilled shafts embedded into a firm, non-yielding soil stratum can provide significant additional stability to a slope if conditions for developing soil arching are present. Among the factors that most affect the reinforcement contribution exerted by the drilled shafts are the location, the ratio of spacing to diameter, and the properties of the soil.

**REFERENCES**

3) Bishop, A. W. (1955): The use of the slip circle in the stability anal-