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Parametric study of the stability of slopes reinforced with piles

Etude paramétrique de la stabilité de pentes renforcées par pieux

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ABSTRACT
This paper analyses the stability of a two-layers slope reinforced with a row of piles. The theory of Poulos (1973, 1995) is used to evaluate the pile response to a uniform lateral free-field displacement. A parametric study is carried out in terms of the ratio between the safety factor of the reinforced slope to the safety factor of the slope without piles, by varying geometric and mechanical dimensionless factors. For different shear strength of the soil a range of pile position is found, at which the piles offer the maximum contribution to slope stability. The length of piles is found to slightly influence the safety factor. The results also indicate that the critical slip surfaces do not always intersect the piles and that the thickness of the shallow layer can significantly influence the effectiveness of the passive piles.

RÉSUMÉ
Cet article analyse la stabilité d'une pente formée par deux couches et renforcée par des pieux. En employant l'approche de Poulos (1973, 1995) pour évaluer la réponse des pieux sollicités par des mouvements latéraux du sol, un étude paramétrique est présenté a travers le rapport entre le facteur de sécurité de la pente avec et sans les pieux. On montre que les pieux offrent la plus grande contribution à la stabilité pour une déterminée intervalle de position en fonction de la résistance au cisaillement du terrain. La longueur des pieux a peu d'influence sur le facteur de sécurité. Les résultats obtenus révèlent aussi que les surfaces critiques de glissement ne coupent pas toujours les pieux et que l'épaisseur de la couche superficielle peut influencer de façon significative l'efficacité des pieux.

1 INTRODUCTION

Passive piles are often used in order to stabilize moving slopes or as a preventive measure in stable slopes. Different approaches have been proposed in the literature to study single piles or pile groups subjected to lateral soil movements (Poulos, 1973; Ito and Matsui, 1975; Viggiani, 1981; Winter et al., 1983; Chow, 1996; Chen et al., 1997; Hassiotis et al., 1997; Liang and Zeng, 2002). Some approaches are valid only in cohesive soils (Viggiani, 1981; Winter et al., 1983) and refer only to the ultimate state. Other methods assume piles of infinite length, which may not represent the actual piles in the field (e.g. Ito et al. 1979; Hassiotis et al., 1997). The methods of Poulos (1973, 1995) and Chow (1996) seem to be more versatile, allowing to evaluate the pile response at any stage of soil movement, regardless of pile length. Comparison between well-documented case histories suggest that the approaches of Poulos (1973, 1995) and Chow (1996) enable satisfactory prediction of the behaviour of the pile in unstable slopes. For these reasons the method of Poulos was chosen in the present work.

As far as the stability of pile reinforced slopes is concerned, traditional equilibrium methods (e.g. Ito et al., 1979; 1981; Lee et al. 1995; Hassiotis et al., 1997) and finite element methods (Cai and Ugai, 2000; Ng et al., 2001) are generally used. Very simplified methods have been also proposed (e.g. Poulos and Davis, 1980; Broms, 1981; Anagnostopoulos and Georgiadis, 2000). In stability analysis in presence of passive piles the key factor is the proper estimation of the pile stabilizing force dependent on the lateral pile-soil interaction pressures which are in turn affected by soil movements. These pressures are intended as the difference on both sizes of a pile and they vary from an initial value (generally assumed equal to zero) in case of no movement to an ultimate value when the soil-pile system reaches its maximum strength. Ito and Matsui (1975) derived a theoretical equation to estimate the lateral pressure in one row of piles taking into account of group effect. Despite some limitation this approach is widely used in practice (e.g. Hassiotis et al., 1997).

The review of previous studies indicates that in a pile reinforced slope the critical slip surface does not necessarily coincide with that of the unstabilized slope. The assumption that the critical surface does not change with the addition of piles would lead to non-conservative answers for the factor of safety of the slope. Only in a active landslide it is reasonable to suppose that the critical slip surface remains unchanged, because the shear strength parameters in this zone are likely lower than those in other zones of the slope.

The safety factor of a slope stabilized with piles was found to depend on many factors including pile location, spacing and fixity condition of the pile head. However the results of published works are not always in agreement. For example, the optimal location of piles in a slope is not well established. Lee et al. (1995) individuated the toe and the crest in a homogeneous cohesive slope as the most effective pile location. Hassiotis et al. (1997) found that in a homogeneous c-ϕ slope the optimal location tends to move to the top of the slope for increasing slope inclination.

In this paper the stability analyses are performed by using the drained shear strength parameters of soil; a two-layer slope representing a typical soil profile is considered and the effect of a row of passive piles is analysed by varying geometrical and mechanical parameters.

2 METHOD OF ANALYSIS

The stability of the slope reinforced with piles is here analysed by a simplified approach based on an uncoupled formulation in which the pile response and slope stability are considered separately. In particular, the stability analyses are performed by a traditional limit equilibrium method, whereas the pile-soil interaction is studied assuming the soil to be elastic, but a nonlinear response can be obtained depending on the specified limiting lateral pile-soil stress (Poulos, 1995; Lee et al., 1995).

In order to study the pile response to a given external lateral movement (Fig. 1c), a Fortran 77 computer program, *CRIBEL*, has been devoloped based on Poulos theory (Poulos, 1973, 1995). The pile, of length L_p and diameter B, is divided into n elements of constant length ($h = L_p/n$). For each point of the mesh a constant soil-pile pressure is assumed to act over a rectangular area of height h and width B. Only for the head and tip points the pressure acts on a height of $h/2$ (Fig. 1b). The relationships between pressures and displacements are calculated by the equations of Douglas and Davis (1964). A linear system is obtained considering $n+1$ equations of compatibility of lateral displacements of the pile and soil at each point. The pile bending equation in finite difference terms uses deflections at three points above and at three points below the point being considered. Therefore six imaginary deflections are introduced, three at the top and three at the bottom of the pile, so that the overall unknowns are $n+7$. Further six equations are written by considering the pile head and tip boundary conditions and the horizontal and moment equilibrium. The overall system is solved by the routine proposed by Press et al. (1992) based on the technique of the singular value decomposition (Forsythe et al., 1977). Once the pile deflections have been calculated, the soil-pile pressures are evaluated from the bending equation of the pile. If the computed value exceeds the specified limiting pressure the compatibility equation for that element is replaced by the pile bending equation.

Because the maximum shear force is always developed at the level of the slide plane, particular attention has been paid in its calculation. In particular, the number n (> 40) is automatically selected in order to assure that the slip surface intersects the pile in the midpoint of the mesh, so that the soil-pile pressure has opposite sign above and below the slide plane (Fig. 1b). The maximum shear force is then calculated on the basis of the soil-pile pressures.

3 PARAMETRIC STUDY

3.1 *Geometry and soil parameters*

Figure 2 shows the geometry of the simple two-layers slope with a height H and an inclination β to the horizontal. It is assumed that the shallow layer has a constant thickness, H_1, and that the deeper layer has greater mechanical properties than shallow layer ($c_2/c_1 = 2$ and $tan\phi_2/tan\ \phi_1 = 1.2$). The water table is assumed to be horizontal at a depth H_1 from the base of the slope.

The Young modulus of the soil is assumed to linearly increase with depth from a value E_0 at the ground surface, with the same gradient in the two layers. The soil's Poisson ratio was assumed to be 0.3.

According to Poulos (1995), in the unstable zone the limiting lateral pressure is calculated by the theoretical solution of Ito and Matsui (1975), while in the stable zone the limiting lateral pressure is assumed to be 4.5 times the Rankine passive pressure.

3.2 *Pile parameters and stability analysis*

The diameter, B, the bending stiffness, EJ, and the yield moment of piles, M_y, were assumed equal to 1 m, 1230 MNm^2 and 2 MNm, respectively. An unrotated head condition is considered which can be obtained by connecting the pile heads with a reinforced concrete beam. Ito and Matsui (1975) showed that their theory is more accurate for a restrained pile head.

In the pile design it is conservative to consider a single pile, and a relatively large free-field movement at which the pile reaches the ultimate condition. However, it is well known (e.g. De Beer, 1977) that conservative assumptions for the pile stability are unconservative for the slope stability, because the maximum pile contribution is considered. Therefore it seems reasonable to calculate the pile response for an assigned allowable soil movement. In the following analyses the soil movement in the slide zone is assumed to be constant with depth (Fig.1c) and equal to 1% of the pile diameter.

A computer code, *STABPILE*, has been developed in order to perform stability analyses in the presence of passive piles. Given the pile length a preliminary soil-pile interaction analysis is made by *CRIBEL* considering the slip surface at various depths. For each position of the slip surface the maximum shear force and the bending moment are calculated. In the stability analysis, for an assigned slip surface intersecting the pile, the maximum shear force and bending moment are obtained by interpolating the values previously calculated.

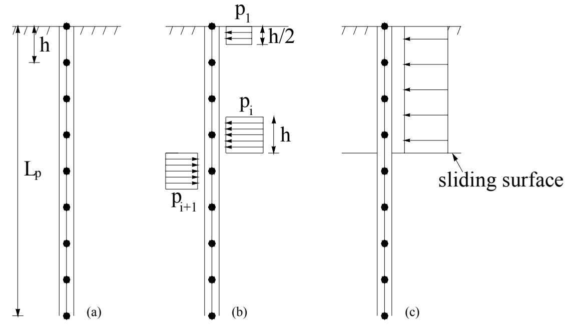

Figure 1. (a) Pile discretization (b) pressures on pile (c) assumed distribution of lateral soil movement.

The shape of the critical slip surfaces are assumed to be circular or to partly develop at the interface of the two layers, characterized by the shear strength parameters of the weaker layer. Because of not-circular shape of slip surface, the safety factor, $F_s^{(wp)}$, is calculated by the two-dimensional simplified Janbu method (Janbu et al., 1956) written in the generic form:

$$F_s^{(wp)} = \frac{F_{rs} + F_{rp}}{F_d} \tag{1}$$

where F_{rs} = resisting force due to the soil shearing resistance along the sliding surface; F_{rp} = resisting force due to the reaction force of a row of piles; F_d = driving force acting on the soil mass above the sliding surface.

For a given slip surface intersecting the pile, the contribution of one row of piles is obtained from the shear force (V) developed in the pile at the depth of the slip surface analysed is calculated taking into account of pile spacing:

$$F_{rp} = \frac{V}{D_1} \tag{2}$$

where D_1 = centre-to-centre spacing between the piles.

The search for the critical failure surface is performed with an automatic search routine described in Bellezza (2000), assuming a constant total unit weight to the entire slope.

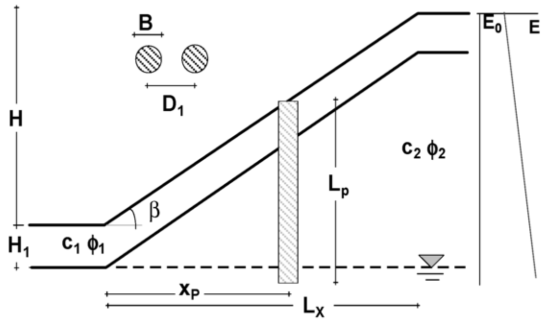

Figure 2. Geometry of a simple slope.

3.3 *Results and analysis*

All the solutions are presented in terms of an improvement ratio N_{ps} (Lee et al. 1995), defined as follows:

$$N_{ps} = \frac{F_s^{(wp)}}{F_s} \qquad (3)$$

where $F_s^{(wp)}$ = minimum factor of safety of the piled-slope; F_s=minimum factor of safety of the slope without piles.

Table 1 lists all the parameters involved in the analysis. In all the following figures distinction is made depending on the type of the critical slip surfaces: solid symbols and open symbols refer to critical slip surfaces intersecting and not intersecting the piles, respectively.

The values of the improvement ratio are plotted in Figure 3 against the dimensionless ratio of the horizontal distance between the slope toe and the pile position, x_p, to the horizontal distance between the slope toe and the slope shoulder, L_x, as shown in Figure 2. The effect of the pile position along the slope is evaluated for different values of shear strength of the shallow layer. It can be observed that the improvement ratio achieves its maximum value for a range of pile position. The width of this range is found to depend on soil strength; an increased cohesion results in a wider optimal range. For a shallow layer having low cohesion, when the piles are located near to the toe or crest of the slope (x_p/L_x< 0.4 or x_p/L_x > 0.7) the critical slip surface does not intersect the piles (open symbols in Fig. 3). A row of piles located at the middle of the slope (x_p/L_x = 0.5) always assures the maximum N_{ps} values. On the basis of these results all the following analyses refer to piles located in the middle of the slope (x_p/L_x = 0.5).

Figure 4 shows the combined effect of the slope inclination and thickness of the shallow layer on N_{ps} values, for a fixed pile length (L_p/H = 1). It is evident that the improvement ratio increases with increasing slope inclinations. For a thin shallow layer (H_1/H = 0.2) the effectiveness of piles is not appreciable, despite the increased length of piles embedded in the firm layer. This trend can be explained by considering that for H_1/H = 0.2 the critical slip surfaces do not intersect the piles, except for the steeper slope ($\cot\beta$ = 1), but they are merely located in front or behind the piles.

Figure 5 shows the effect of the pile spacing on the improvement ratio for four different values of the strength parameters of the shallow layer. As expected, the safety factor in presence of piles increases with reducing the pile spacing, owing to the increased lateral force reaction (eq. 2). However it can be seen that, depending on soil strength parameters, a threshold value of the spacing can exist, below which N_{ps} are independent on pile spacing. Indeed, for increasing value of F_{rp} in (1) the slip surfaces intersecting the piles are no longer those in which the safety factor is the minimum.

Table 1. Parameters considered in the analysis.

Parameter	symbol	base value
Slope height	H	10 m
Slope inclination	β	$\cot\beta = 2$
Thickness layer #1	H_1	0.5 H
Soil unit weight	γ	19.62 kN/m^3
Soil #1 frictional strength	ϕ_1	20°
Soil #1 cohesive strength	c_1	$0.02\gamma H$
Soil #2 frictional strength	ϕ_2	$\tan\phi_2 = 1.2 \tan\phi_1$
Soil #2 cohesive strength	c_2	$c_2 = 2c_1$
Young's modulus soil #1	$E_0+m_1z_1$	E_0=10 MPa m_1 = 1 MPa/m
Young's modulus soil #2	$E_2+m_2z_2$	$m_2 = m_1$
Poisson's ratio	ν	0.3
Pile diameter	B	1 m
Pile bending stiffness	EJ	1230 MNm^2
Pile position	x_p	0.5 L_x
Pile length	L_p	H
Centre-to-centre spacing	D_1	3B
Pile Yield moment	M_y	2 MNm
Free-field displacement	y_{ex}	0.01B

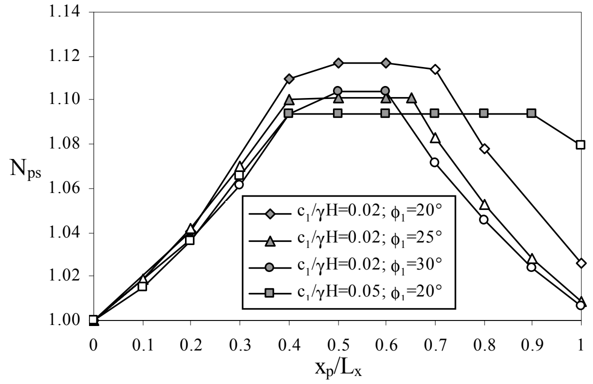

Figure 3. Effect of pile position on N_{ps}; $\cot\beta$ = 2; H_1/H = 0.5; L_p/H = 1; D_1/B = 3; y_{ex}/B = 0.01.

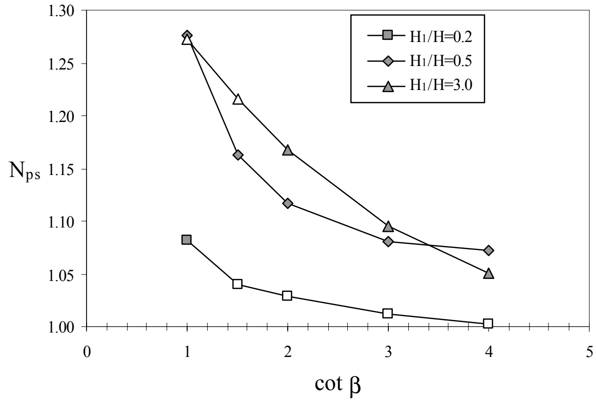

Figure 4. Effect of slope inclination on N_{ps}; x_p/L_x = 0.5; L_p/H = 1; D_1/B=3; ϕ_1 = 20°; $c_1/\gamma H$ = 0.02; y_{ex}/B = 0.01.

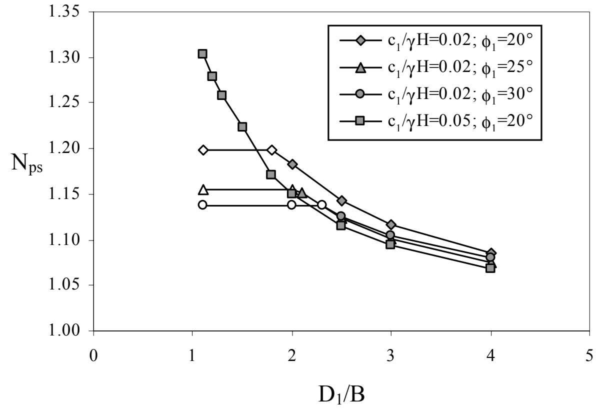

Figure 5. Effect of pile spacing on N_{ps}; $\cot\beta$ = 2; H_1/H = 0.5; L_p/H = 1; y_{ex}/B = 0.01

Figure 6 shows the dependence of the improvement ratio on the pile length for different shear strengths of the weaker layer (H_1/H = 0.5). For piles embedded in the firm layer for at least 0.1H, the pile length is found to have little influence on N_{ps}. For L_p/H ranging from 0.6 to 1.2 a slight increase in N_{ps} is appreciable; for greater length (L_p/H > 1.2) the variation of N_{ps} is negligible. From a practical point of view this result suggests that, for the assigned soil profile and the assumed soil movement, a further increase in pile length does not result in an increase in slope stability.

Figure 7 shows the values of the improvement ratio plotted against the normalised free-field soil movement (y_{ex}/B). For the investigated range of soil strength, the improvement ratio is found to increase with increasing ground movements up to a maximum N_{ps} value for ground movements of about 1.5-2.5% of the pile diameter. However, two different behaviours are evident: for low shear strength of the shallow layer the critical slip surfaces always intercept the piles and the maximum value of N_{ps} is due to full mobilisation of the assumed resistance of the pile-soil system; for high shear strength of the shallow layer the safety factor initially increases with the ground movement because of the increased pile response; however a limiting value of the pile shear force exists, beyond which the critical slip surface is no longer the same, but it is relocated along the slope without intersection with the piles; this implies also a reduction of the maximum values of the improvement ratio.

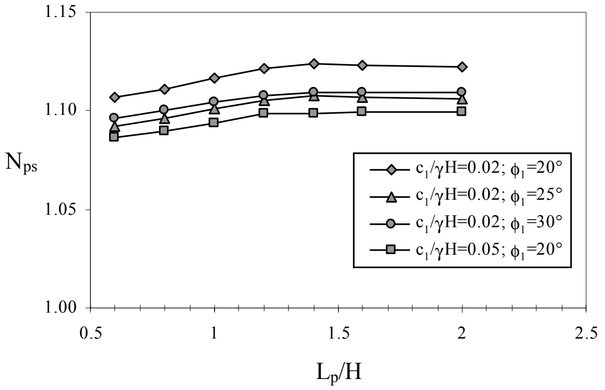

Figure 6. Effect of pile length on N_{ps}; $cot\beta$ = 2; H_1/H = 0.5; D_1/B = 3; y_{ex}/B = 0.01.

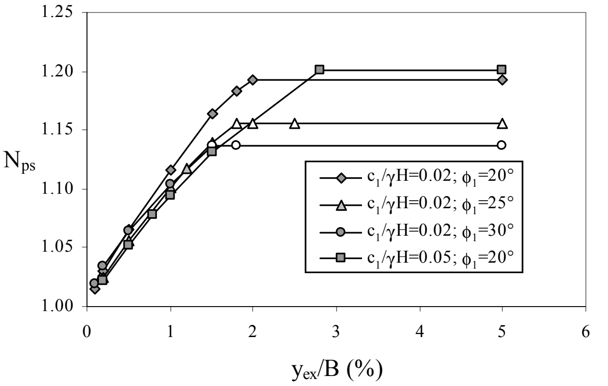

Figure 7. Effect of ground movements on N_{ps}; $cot\beta$ = 2; H_1/H = 0.5; L_p/H = 1; D_1/B = 3.

4 CONCLUSIONS

With reference to a two-layers slope a parametric study has been carried out in order to evaluate the influence of passive piles on slope stability. Based on the results obtained in the parametric analyses, for a slope height of 10 m and a pile diameter of 1 m, the following conclusions can be drawn:

- a row of piles offers an appreciable contribution to slope stability only for thickness of the shallow layer greater than 50% of the slope height; if the shallow layer is thin, the increase in the safety factor is negligible, especially for gentle slopes;
- to obtain the maximum benefit the piles must be located approximately in the middle of the slope, although an interval of the optimal location has been individuated;
- for the analyzed cases the pile length is found to have a little effect on slope stability, provided that a minimum embedment in the firm layer is assured.

The stability analyses also demonstrate that for the assumed soil profile a relocation of the critical slip surface can occur along the slope without intersection with the piles. The use of a multiple rows may represent an useful and effective alternative.

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