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Research Paper

Analysis of slope-stabilising piles with the shear strength reduction technique

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ABSTRACT

In this paper, the ultimate limit state (ULS) of continuous and discontinuous pile rows in a frictional soil slope is investigated by performing 2-D and 3-D numerical analyses, respectively. The 'phi-ci reduction calculation' implemented in PLAXIS was adopted to analyse the ULS conditions of a pile row embedded in an infinite slope, including a slipping layer under residual conditions, placed between unstable upper and stable lower soils. For a continuous pile row, pile displacements and soil stress at the pile interface that vary with the embedment ratio are discussed while highlighting the role of the unstable layer on the collapse of the system. Indeed, the results of parametric analyses with respect to changes in the slope inclination and residual frictional angle on the slipping surface are also represented in dimensionless form. The minor influence of these two variables on the problem is proven. For discontinuous pile rows, the soil arching effect was investigated with a focus on the influence of the pile embedded length on the critical spacing value beyond which soil arching vanishes. The different behaviours of a pile in a row between a continuous wall and isolated pile are also analysed in depth. The ultimate loads computed by the 2-D and 3-D analyses are compared to analytical rigid-plastic solutions obtained by extending the existing solution in frictional soils for a single pile and for a continuous wall to discontinuous pile rows. Finally, simple charts to design stabilising pile rows inside a landslide at the ULS are provided.

1. Introduction

The use of piles to stabilise slopes is widely acknowledged as effective, as reported in several theoretical studies and successful applications [1–5]. The piles resist the movement of a slipping soil mass by transferring the load from the unstable mass to the underlying stable stratum. Therefore, stabilising piles must be sufficiently deep to fulfil this purpose. As the slipping soil moves against the piles, the shear force and bending moment increase. The piles must be able to resist these loads without reaching the serviceability limit state (SLS) or ultimate limit state (ULS) [6]. ULSs are often investigated via the pressure-based method (i.e., [7–9]) or numerical methods to address any geometric imperfections and overcome the limitations of the existing simple methods (i.e., [8,10–13]). SLSs are usually analysed via the displacement-based method [14] or numerical methods [15].

Several methods proposed in the literature (e.g., rigid-plastic limit equilibrium in Viggiani [7], elasticity in Poulos [14], and the numerical finite difference method in Kanagasabai et al. [6]) investigate undrained conditions, which do not usually occur even in unstable clayey slopes, where the displacement rate is often very slow. The few applications in frictional soils [16–19] are often based on simplifying assumptions, such as horizontal soil surfaces and a single pile. Recently, Muraro et al. [8] proposed a rigorous analytical rigid-plastic solution for frictional soils by extending Viggiani's approach for single pile undrained conditions to drained conditions in either sloping or flat ground. Building from the results of Viggiani [7] and Muraro et al. [8], Di Laora et al. [9] proposed a comprehensive set of analytical solutions for both free and head-restrained isolated piles in drained and undrained conditions.

However, findings on this issue have been incomplete to date. A unique systematic approach valid for continuous walls, discontinuous pile rows and isolated piles is still lacking. Few studies have considered the effect of pile spacing on soil-pile interaction. Here, this behaviour is studied in depth up to the condition for which the arching effect vanishes and the piles tend to behave as isolated piles.

The ULSs of continuous and discontinuous pile rows in a frictional soil slope were investigated by performing 2-D and 3-D numerical analyses, respectively. The 'phi-ci reduction calculation' implemented in PLAXIS [20] was adopted to analyse the ULS of a pile row embedded in an infinite slope enclosing a slipping layer under residual conditions between the unstable upper soil layer and stable lower soil layer. Such conditions frequently occur worldwide (i.e., [3,21,22]). An example

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Notations

d	pile diameter
E	Young's modulus
FS	safety factor
L	length of domain analysed
M	bending moment
RPM	rigid-plastic method
T	shear force
c′	soil cohesion
i	pile spacing
l_{tot}	pile length
l_1	thickness of unstable layer
l_2	embedment length
k	earth pressure coefficient
k_a	Rankine active earth pressure coefficient
k_p	Rankine passive earth pressure coefficient
n	strength ratio
s	wall thickness
T_d	design force exerted by stabilising pile row on the slipping soil
u	soil displacement
$u_{headpile}$	head pile displacement
u_x	horizontal soil displacement
x_1, x_2	null points in pile-soil stress distribution
z	depth from the soil surface
α	slope angle
γ	soil unit weight
γ_s	shear strain
ν	Poisson ratio
σ_{x_u}	ultimate horizontal strength on the pile per unit length/diameter
σ'_x	horizontal effective stress
σ'_v	vertical effective stress
τ_f	soil shear strength
φ'_d	design soil friction angle
φ'	soil friction angle at critical state
φ'_{res}	residual soil friction angle

includes the typical earthflows in flysch formations of the Apennine chain in southern Italy [23,24].

The wall and pile were modelled as perfectly elastic; thus, structural failure was not considered. In other words, soil failure was assumed to dominate the behaviour of the system. Nevertheless, this situation is likely when shallow landslides (slipping surfaces located at a depth less than 7–8 m) are analysed, as the moving soil is not sufficiently deep to impose a sufficiently large thrust to reach the ultimate structural capacity of the pile [11].

For the 2-D analyses, we considered the soil stress distribution at the pile-soil interface, the pile and soil displacements at the ULS, and the ultimate load transferred from the soil to the pile with variations in the embedment ratio, l_2/l_1, where l_1 is the thickness of the unstable layer and l_2 is the embedment length, and the effective friction angle of the stable layer, φ′. In addition, the results of parametric analyses involving changes in the slope inclination, α, and the residual frictional angle, φ_{res}, on the slipping surface are also reported in dimensionless form. The minor influence of these two variables on the problem is proven.

A series of 3-D analyses were also carried out to evaluate the arching effect and the evolution of the ultimate lateral load with increases in the pile spacing. The variations in the shear forces and bending moments with the embedment ratio, l_2/l_1, and normalised pile spacing, i/d (where i is the pile spacing and d is the diameter of the pile section), were calculated and reported. The distribution of the plastic shear strain at failure around the pile and the plan view of contours of the horizontal soil displacements are also shown to determine the failure mode and the arching effect.

To have a unique benchmark to interpret the computed results, we compared the ultimate loads computed by both 2-D and 3-D analyses to analytical rigid-plastic solutions, such as that obtained by Muraro et al. [8], extending these solutions to model a continuous pile row in frictional soils. Different rupture mechanisms detected along longitudinal and plan sections (for 3-D analyses) are discussed from a theoretical perspective.

With respect to the latest works on this topic, the present paper focuses mainly on the application of the 'phi-ci reduction calculation', as implemented in finite element codes, for pile design and reliability assessment to investigate the ULSs of both continuous and discontinuous rows and isolated piles in an infinite slope. A theoretical solution valid in drained conditions for the three geometric situations mentioned above is also obtained. The three geometric situations were considered using different soil strengths at the soil-pile interface according to the failure mode and pile spacing.

2. Numerical modelling

2.1. Geometry, mesh and boundary conditions

Several 2-D and 3-D numerical analyses were carried out by using the commercial finite element codes PLAXIS 2-D and PLAXIS 3-D Foundation, respectively. Fig. 1(a), (b) and (c) show the geometry, two-dimensional and three-dimensional finite element meshes used to schematise the infinite slope stabilised by the pile row, respectively. The stability of the overall slope was investigated; the model length is 120 m, and the mesh boundary is set sufficiently far away (approximately 60 m) to avoid impacts to the results of the analysis in the middle part of the domain (Fig. 1a).

The 2-D mesh consists of fifteen-node elements with a typical vertical element size of 0.25 m (Fig. 1b). The thickness of the continuous wall is 1.00 m, and the investigated ground surface inclinations are 14° and 20°. The thickness of the sliding upper layer is 8.00 m, and the embedment length in the unstable layer ranges between 1.0 and 12.0 m. Hence, an embedment ratio varying from 0.25 to 1.5 was considered (Table 1). The wall is modelled as a 'plate' consisting of 5-node beam elements with three degrees of freedom [25]. As for the boundary conditions, the nodes on the base of the mesh are restrained in both the horizontal (-x-) and vertical (-y-) directions, while the nodes on the upper and lower faces are prevented from moving in the -x- direction.

The 3-D mesh consists of 15-node wedge elements comprised of 6-node triangles in the horizontal direction and 8-node quadrilaterals in the vertical direction. The average element size is 0.25 m (Fig. 1c). The following parameters are adopted: a sliding layer thickness of 8.00 m, a ground surface inclination of 14°, embedment lengths of 4 and 12 m, a pile diameter of 1 m, and a normalised pile spacing ranging between 2 and 8 m (Table 1). The piles are modelled by the 'embedded piles' tool. The embedded piles are beam elements with 3-node line elements having six degrees of freedom per node [26]. Around the pile, an elastic cylindrical volume is automatically generated by the code. The nodes on the base of the mesh are restrained in both the -x- and -y- directions, while those on the top face are unrestrained. The nodes on the lateral face represent the planes of symmetry, and the nodes on the upper and lower faces are prevented from moving in the direction normal to the planes.

2.2. Piles and soil properties

A linear elastic perfectly plastic constitutive model with the Mohr Coulomb failure criterion is used for the dry soil layers. All the analyses