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Research Paper

Evaluating the effect of slope angle on the distribution of the soil–pile pressure acting on stabilizing piles in sandy slopes

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ABSTRACT

In the past, the response of stabilizing piles subjected to lateral soil movement or lateral force loading has been analysed assuming that the piles are embedded in horizontal semi-infinite soil grounds. In this study, a limit equilibrium method analysing the lateral force (soil–pile pressure per unit thickness) on stabilizing piles embedded in semi-infinite slopes is presented. In addition, the soil arching effects between two neighbouring stabilizing piles are analysed, and the lateral active stress in the rear of the piles is obtained. Furthermore, the squeezing effect between two piles proposed by Ito and Matsui is combined with the lateral active stress in the slope to evaluate the distribution of the soil–pile pressure per unit length of the stabilizing piles in sandy slopes. A numerical simulation using FLAC^{3D} is used to evaluate the proposed approach. The simulation shows that the proposed model could reasonably predict the shape of the distribution of the soil–pile pressure acting on the stabilizing piles, while some discrepancy exists between the numerical results and predicted values. Furthermore, the prediction of the proposed model is also evaluated through comparison to the experimental data from the published literature. Parametric analysis is carried out to investigate the influence of the slope angle on the distribution of the soil–pile pressure. The shape of the distribution of the soil–pile pressure acting on the piles is shown to vary with the angle of the slope, while the magnitude of the soil–pile pressure remains in the same order.

1. Introduction

In the past several decades, installing rows of drilled shafts for slope stabilization has proved to be a reliable and effective technique to prevent excessive slope movement [14,7,19,20,10]. Piles are installed through the unstable soil layer and embedded into the stable layer below the sliding surface. The slope is stabilized by piles, which are able to transfer part of the force from the failing mass to the stable soil layer. For passive piles, the soil–pile pressure applied on the piles by the unstable layer is dependent on the soil movement, which is in turn affected by the presence of the piles [28].

Evaluating soil–pile pressure acting on stabilizing piles is of great significance for the study of slope stabilization. In previous research, a horizontal semi-infinite soil ground was typically used for the theoretical analysis of the soil–pile pressure on piles [14,24,26]. Satisfactory results have been predicted by these methods. In subsequent research [15,16,12,5,29,18,13], these methods have been adopted and developed. The interaction between piles is governed by the so-called arching effect. Durrani et al. [8] suggested that the Rankine passive and active pressure coefficients should be employed to estimate the maximum spacing resulting in arching between piles. Viggiani [26] suggested designing slope stabilizing piles using the limit equilibrium method. With such an approach, the stabilizing contribution given by a single pile depends on the pile characteristics (diameter, length, and ultimate bending moment), the soil strength and slide thickness [20].

Poulos [24] presented an analysis method in which a simplified form of the boundary element method (Poulos 1973) was employed to study the response of a row of passive piles incorporated in limit equilibrium solutions of slope stability. This method revealed the existence of three modes of failure: (i) “flow mode”, (ii) “short-pile mode”, and (iii) “intermediate mode”. This finding contributed to the practical design of stabilizing piles. Poulos [24] highlighted that the flow mode created the least damage effect of soil movement on the pile; if the piles required protection, efforts should be made to promote this mode of behaviour.

Norris [22] developed a strain wedge (SW) model to predict the response of a flexible pile under lateral loading. Generally speaking, the SW model allows the assessment of the nonlinear p–y

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curve response of a laterally loaded pile based on the envisioned relationship between the three-dimensional response of a flexible pile in the soil to its one-dimensional beam on elastic foundation parameters [1]. The SW model has been improved and modified to accommodate a laterally loaded pile embedded in multiple soil layers [1,2]. Undoubtedly, great improvements have been made on the SW model to predict the response of flexible piles under lateral loading [2,3]. In the SW model, the "flow mode" mechanism [24] mentioned previously was adopted in Ashour and Ardalan's research [4]. Such a slope-pile displacement mechanism is also adopted in the model presented here.

In this paper, the authors propose a simple method for estimating the ultimate soil–pile pressure per unit length of the pile, which is induced by flowing soil, assuming that the soil displacement is larger than the pile deflection (Fig. 1). The theory of plastic deformation [14] is modified, and the soil arching effects between two neighbouring piles are considered, which leads to the nonlinear distribution of the soil–pile pressure per unit length of piles. Furthermore, the theoretical analysis of the effect of the slope angle on the soil–pile pressure distribution in sandy slopes is carried out.

In this study, the soil–pile pressure per unit length of the stabilizing pile is analysed in a semi-infinite sandy slope, as shown in Fig. 2. The general analysis of the soil–pile pressure acting on the piles involves three main steps: (1) analysing the soil arching zone adjacent to the piles in the slope; (2) analysing the active lateral stress in the soil arching zone between two neighbouring piles; and (3) substituting the active lateral stress into Ito and Matsui's approach [14] to estimate the soil–pile pressure acting on each pile. The piles are assumed to be flexible. In step 1, when the unstable soil layer slides along the potential sliding surface, the soil layer deforms. Additionally, soil arching occurs adjacent to the two neighbouring piles in the failing mass. The plan view of the soil arching zone between two neighbouring piles is shown by the hatched area in Fig. 3(a). A typical cross section UU′ is shown in Fig. 3(b). The area of the soil arching zone is dependent on the slope angle and the properties of the soil, which are discussed later in this paper. In step 2, to simplify the analysis of the active stress on the plane AA′ (referring to Fig. 4), an assumption is made that when the active stress on the plane AA′ is analysed, the area between the parallel lines AG and AG′ is considered to be the soil arching area. This soil arching area is shown as the shadowed portion in Fig. 4, where σ_h is the active soil stress induced by the soil arching effects, D_1 is the centre-to-centre interval between two neighbouring piles, and D_2 is the clear interval between piles. In addition, the limit equilibrium condition of the differential element

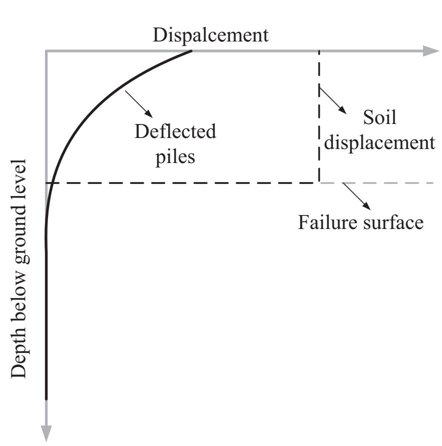

Fig. 1. Soil–pile displacement as employed in the model presented here (Ashour and Ardalan's research [4]).

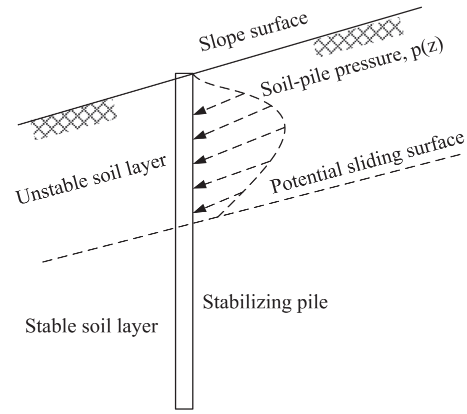

Fig. 2. Stabilizing pile embedded into a semi-infinite slope (adopted from Ashour and Ardalan [4]).

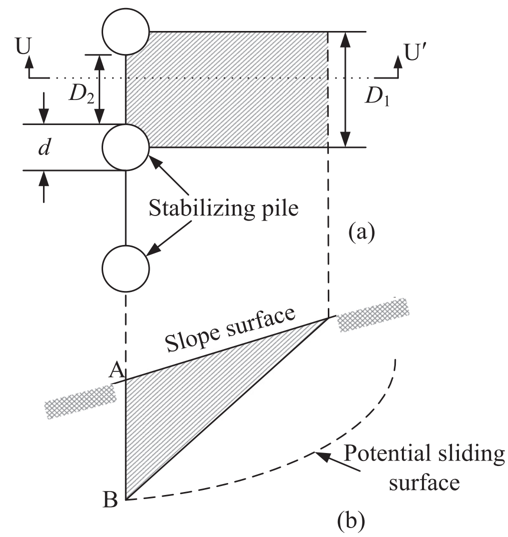

Fig. 3. Soil arching adjacent to the stabilizing piles in a slope: (a) plan view of the soil arching zone; (b) cross section of the soil arching zone in the slope.

in the soil arching zone is analysed to obtain the active stress. In step 3, the approach proposed by Ito and Matsui [14] is adopted, and the squeezing effects between the piles are evaluated. This procedure yields the soil–pile pressure per unit length of the pile.

For the purpose of verifying the proposed model, a numerical simulation was performed. The shear strength reduction method (SRM) is used in the code of FLAC^{3D}. SRM has been used in the stability analysis of slopes without piles by many previous researchers [30,25,9,28]. This method is extended to analyse the safety factor of a slope stabilized with piles. In the studies by Martin and Chen [21], Won et al. [29], Wei and Cheng [28], and Lirer [20], FLAC^{3D} is used to analyse the response of the stabilizing piles or the safety factor of the reinforced slope with piles. FLAC^{3D} is a widely used tool for estimating the response of the stabilizing piles. In this study, the authors use the three-dimensional finite difference code FLAC^{3D} by SRM to analyse the soil–pile pressure acting on stabilizing piles during slope slides. The numerical simulation results are compared to the prediction obtained from the proposed model. Furthermore, the laboratory experiments carried out by Chen et al. [6] and Guo and Ghee [11] are introduced to evaluate the proposed model.

Finally, the validated model is used to evaluate the effect of slope angle on the distribution of the soil–pile pressure per unit