Analyses of the lateral force on stabilizing piles in sandy slope

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ABSTRACT

In the past, horizontal semi-infinite soil grounds were utilized to analyze the response of the stabilizing piles due to lateral soil movement or lateral force loading. In this study, a limit equilibrium method analyzing the lateral force on stabilizing piles that embedded in semi-infinite slopes is presented. In addition, the soil arching effects between two neighboring stabilizing piles are analyzed, and the lateral active stress in the rear of the piles is obtained. Furthermore, the squeezing effect between the two piles proposed by Ito and Matsui is combined with the lateral active stress in the slope to evaluate the distribution of the lateral force of the stabilizing piles in sandy slopes. The numerical simulation using FLAC 3D is utilized to validate the proposed approach. The simulation shows that the proposed model could reasonably predict the lateral force acting on the stabilizing piles embedded in the slope.

Keywords: stabilizing piles, sandy slope, soil arching, slope angle, numerical simulation

1. INTRODUCTION

Evaluating the lateral force loading on the stabilizing piles is of great significance for the study of slope stabilization. In the past research, a horizontal semi-infinite soil ground is usually used for the theoretical analysis of the lateral force on piles. Ito and Matsui (1975) have analysed the squeezing effects when the plastic deformation occurs between two neighbouring piles. Note that this analysis is conducted in a horizontal soil ground. Thereafter the results are applied to the inclined soil mass. Other researchers (Poulos, 1995; Norris, 1986; He et al. 2014) have developed approaches for the design of reinforcing piles to increase slope stability, but the slope angle was not considered in their models. All the models mentioned above are able to provide some reasonable results for the design of stabilizing piles. However, the influence of the slope angle on the piles is still need to be studied for the purpose of figuring out the mechanism of pile-slope system.

In this study, the lateral force loading on stabilizing piles per unit thickness is analyzed in a semi-infinite sandy slope, which is shown as Fig. 1. The general analysis of the lateral forces on the piles involves three main steps: (1) determine the soil arch zone adjacent to the piles in the slope; (2) analyzing the active lateral stress in the soil arch zone between two neighboring piles; (3) substituting the active lateral stress into Ito and Matsui’s approach (1975) to estimate lateral force on each pile. The piles are assumed to be rigid, which is the same as the assumption used in Ito and Matsui’s research (1975). For step 1, when the unstable soil layer slides along the potential sliding surface (Fig. 1), the soil layer deforms. And meanwhile, the soil arch occurs adjacent to the two neighboring piles in the failing mass. The plan view of soil arch zone between two neighboring piles is shown by the shadowed portion in Fig. 2(a). A typical cross section, AA’ is employed and shown in Fig. 2(b). The area of the soil arch zone is dependent on the slope angle and soil property, which is discussed later in this paper. Step 2 analyzes the limit equilibrium condition of the differential element in the arch zone to obtain the active lateral stress between two piles. For step 3, the approach proposed by Ito and Matsui (1975) is adopted and the squeezing effects between piles are evaluated. After three steps the lateral forces on piles are obtained.

For the purpose of verifying the proposed model, a numerical simulation results is introduced. In addition, the shear strength reduction method (SRM) is utilized in the code FLAC 3D. In the present paper, authors use the three dimensional finite difference code FLAC 3D by SRM to analyze the lateral force acting on stabilizing piles during the slope slides. The numerical simulation result is compared with the prediction by the proposed model. It shows that the proposed approach provides a satisfactory solution on the estimation of lateral force of stabilizing piles.
Soil pressure

Potential sliding surface

Unstable soil layer

Stable soil layer

Stabilizing pile

Slope surface

Fig. 1 stabilizing pile embedded into the semi-infinite slope

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

2. THE SOIL ARCHING ZONE

In the semi-infinite inclined soil mass, the soil arching adjacent to stabilizing piles has been studied by Wang and Yen (1974). However, they didn't point out the area of the arching zone. Paik and Salgado (2003) assumed the slip plane behind the retaining wall makes angle of $45^\circ + \phi/2$, and the area between the slip plane and the wall is considered the arching zone. In the present paper, the soil arching zone is analyzed by geometry. In most of the slopes, there is a potential sliding surface as shown in Fig.1, which can be investigated in advance. It is assumed that when the unstable soil layer slides along the potential sliding surface, the soil layer deforms, and a slip plane occurs in the rear of piles, which slopes an angle $\theta$ with the slope surface (Fig. 3). The area ABC in Fig. 3 is considered as the soil arching zone. Assuming that the active earth pressure is applied on the on the plane AB (Fig. 3), the differential element (Fig. 4) and the corresponding Mohr’s circle (Fig. 5) are utilized to determine the geometry between the stresses. The process of working out the angle $\theta$ is shown as follows.

(a) In a rectangular coordinate system, because the internal friction angle $\phi$ was investigated in advance, the strength envelope is determined as the line OP shown in Fig. 5.

(b) The two lines OL and OL’ are drawn above and below the $\sigma$ axis; the angle between each line and the $\sigma$ axis is $\beta$.

(c) On the line OL, we set $OA = \sigma_x = \gamma z \cos \beta$. Point A in Fig 5 represents the stress acting on the surface (Fig. 4(b)), including the normal stress and the shear stress.

(d) In the negative direction of the $\sigma$ axis, an arbitrary point $D'$ is set. A circle can then be drawn with center $D'$ and with tangency point $B'$ on the line OP'. The circle $D'$ and the line OE intersect at point A'.

(e) Parallel to $A'D'$, a line $AD$ is drawn with the point D located on the $\sigma$ axis. Taking $AD$ as the radius.
and point E as the center, a circle is drawn. This produces the circle D, which is tangent with line OP at point B.

(f) The angle between AD and BD is equal to θ.

According to the geometry shown in Fig. 5, it is obvious that

\[
\angle ADC = \arccos \frac{\sin \beta}{\sin \phi} \tag{1}
\]

\[
\theta = \frac{1}{2} (\varphi - \beta + \arccos \frac{\sin \beta}{\sin \phi}) \tag{2}
\]

\[
\theta_1 = \frac{1}{2} (\varphi + \beta + \arccos \frac{\sin \beta}{\sin \phi}) \tag{3}
\]

in which \(\varphi\) is the internal friction angle of soil, \(\beta\) the inclined angle of the slope surface.

3. THEORETICAL ANALYSIS

In the study of retaining wall, assuming the soil arch is an arc of a circle, Paik and Salgado (2003) has evaluated the active soil stress based on the soil arching theory. In this paper, the approach proposed by Paik and Salgado (2003) is adopted. What’s more, it is extended to the inclined soil mass. The rotation of the principal stress on the line AB (Fig. 3) is described as Fig. 6. The active earth pressure acting on the line AB includes two components: the active lateral stress on the differential element in the soil arch zone and the shear stress \(\tau\) in which \(\beta\) is the major principal stress on the arch. The trajectory of minor principal stress on the differential element is represented by the dotted lines, while the major principal stress is the normal of the arch. The lateral active earth pressure acted on the line AB is expressed as

\[
\sigma_\alpha = \frac{K_m \gamma H \cos \beta}{1 - (K_m \tan \varphi - K_m \tan \beta + m) \sin \theta \cos \theta_1} \cdot \left[\left(1 - \frac{z}{H}\right) \left(\frac{K_m \tan \varphi - K_m \tan \beta + m \sin \theta}{\cos \theta_1}\right) - \left(1 - \frac{z}{H}\right)\right] \tag{4}
\]

in which \(H\) is the height of the unstable soil layer, \(\beta, \theta, \theta_1\) are the angles shown in Fig. 3, \(\gamma\) the arbitrary height of the soil, \(K_m\) and \(m\) are the parameters respectively expressed as follow

\[
K_m = \frac{\cos (\varphi + \xi) \cos \beta \cdot 3 (N \cos^2 \theta_u + \sin^2 \theta_u)}{\cos (\beta + \xi) \cos \theta_u \cdot 3N - (N - 1) \cos^2 \theta_u} \tag{5}
\]

\[
m = \frac{K_m \sin \xi \cos \beta}{(N \cos^2 \theta_u + \sin^2 \theta_u) \cos (\xi + \beta)} \tag{6}
\]

where \(N = \tan^2 (45^\circ + \varphi/2), \theta_u = \pi/4 + \varphi/2\).

Ito and Matsui (1975) have proposed a plastic deformation model to evaluate the squeezing effects between two neighboring piles. In this present paper, the concept used herein is similar to the method used by Ito and Matsui (1975). Furthermore, all the assumptions given by them are adopted. Eq. (4) is substituted for the active earth pressure obtained by Coulomb’s earth pressure theory in Ito and Matsui’s research (namely the active earth pressure, corresponding to the Eq. (8) in Ito and Matsui’s research (1975) is replaced by the proposed Eq. (4)), the lateral forces acting on stabilizing piles in a sandy slope is expressed as

\[
p = \frac{\gamma HK \cos \beta}{1 - (K_m \tan \varphi - K_m \tan \beta + m) \sin \theta \cos \theta_1} \cdot \left[\left(1 - \frac{z}{H}\right) \left(\frac{K_m \tan \varphi - K_m \tan \beta + m \sin \theta}{\cos \theta_1}\right) - \left(1 - \frac{z}{H}\right)\right] \tag{7}
\]

\[
	imes \left\{D_1 \left(\frac{D_2}{D_2^1}\right)^{1/2} \tan \varphi + N^{-1} \exp \left[\frac{D_1 - D_2}{D_2} N\right]ight\} \tan \varphi \tan \left(\frac{\pi}{8} + \frac{\varphi}{4}\right) - D_2 \right\}
\]

Fig. 6 Stress on the differential element in the soil arch zone

4. NUMERICAL VERIFICATION

A numerical model of the stabilized slope with piles was constructed in the numerical finite difference program FLAC\textsuperscript{3D}. Additionally, SRM was utilized to analyze the lateral forces on the piles when the slope fails. In the numerical model, the piles were modeled as the intrinsic structure element. The slope model was shown in Fig. 7 with a vertical: horizontal gradient of 1:2. 3 Piles with the length of 9 m were installed in a row in the middle of the slope with the interval \(D_1 = 3\) m and \(D_2 = 2.6\) m. The width of the model was 9 m. At the bottom boundary of the model mesh zero displacement was imposed. Stress boundary conditions were imposed at both the uphill and downhill truncation planes. The soil was modeled using the Mohr-Coulomb model. The material properties were shown in Table 1.

The model was firstly brought to equilibrium under gravity loading. After that, a gradual reduction of the
shear strength was imposed along the shear zone. In order to simulate the existence of an accumulation zone, the SRM was not imposed to the downslope final stretch of the shear zone, for a length of 10m. This method of simulating the resistance of the accumulation zone was proposed by Lirer (2012). Incorporating the soil properties, pile geometries and the height of the sliding soil above the shear zone, the lateral force loading on the piles was calculated by Eq. (7), and the results were shown in Fig. 8. For the purpose of comparison, a prediction by Ito and Matsui’s approach (1975) and the results by FLAC\(^{3D}\) were included in Fig. 8 as well.

![Fig. 7 Slope model used in FLAC3D](image)

**Fig. 7** Slope model used in FLAC3D

| Sliding properties adopted in Numerical model |
|---------------------------------------------|
| Sliding body | Shear zone | Stable layer | pile |
| γ(kN/m\(^2\)) | 20 | 20 | 20 | 60 |
| E(Pa) | 2.2e7 | 1.2e7 | 7.8e7 | 3e10 |
| μ | 0.3 | 0.3 | 0.3 | 0.2 |
| c(kPa) | 0 | 2 | 1000 | - |
| φ(°) | 37 | 37 | 37 | - |

**Fig. 8** Comparison among numerical results and the prediction by two different theoretical methods

Fig. 8 compares the results of the numerical approach with those of two theoretical methods and reveals that the distribution of the lateral force computed by the proposed model is non-linear, while the prediction by Ito and Matsui’s approach appears to be linear; however, the orders of magnitude of the two methods’ results are in line with each other. In Fig. 8, ignoring the negative force on the top of the piles, the distribution of the lateral force on piles predicted by the proposed approach shows the same trends to the numerical results. Especially on the sliding surface, the lateral forces calculated by Ito and Matsui’s approach are 8.64 t, while the numerical results and the predictions by the proposed method show that it should be 0. Using the result of FLAC\(^{3D}\) as a deterministic criterion, the proposed model of this study yields a more accurate estimation for the lateral force than that of Ito and Matsui’s approach.

5. CONCLUSION

In this paper, the interaction between stabilizing piles and granular soil is analyzed in a semi-infinite inclined sandy slope. A new theoretical model is proposed to evaluate the lateral force on stabilizing piles on a sandy slope. In the proposed model, the soil arching zone is analyzed using geometry. Soil arching effects are then considered to estimate the lateral active stress between two piles. Furthermore, as analyzed by Ito and Matsui (1975), the squeezing effects between two neighboring piles due to the deformation of the surrounding soil are adopted. To validate the proposed formulation, numerical simulations implemented by FLAC\(^{3D}\) are introduced. A comparison of the results from the proposed model, Ito and Matsui’s approach and the simulations reveals that Ito and Matsui’s approach gives a linear solution for estimating the lateral force, while a non-linear solution can be obtained by the proposed formulation and shows better agreement with the simulation results.

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