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Behavior of Stabilizing Piles to Increase Stability of Residual Soil Slope

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***Abstract*-- The use of one-row of piles for stabilization of an unstable slope has been employed for many years. However, when one-row of piles are not able to stabilize complex slopes then multiple rows of piles should be adopted. This paper presents the feasibility of using multiple rows of stabilizing minipiles to increase the residual soil slope stability. Consolidated undrained triaxial (CIU) tests were conducted on reconstituted saturated samples of residual soil to determine the shear strength behavior. The response of residual soil slope stabilized with minipiles was carried out using a simplified pile-slope analysis method. The influencing factors on the behavior of residual soil slope stabilized with multiple rows of stabilizing minipiles were investigated. A parametric study was performed for utilizing the use of multiple rows of stabilizing minipiles mainly includes the pile row number, pile row position and slope geometry. The computed stabilizing minipile response shows that the residual soil slope stability with one-row of stabilizing piles is different from that with multiple rows of stabilizing piles. The present study could provide useful insight into the use of multiple rows of minipiles to increase the stability of residual soil slope.**

***Keywords*-- multiple rows of minipiles, residual soil slope, parametric analysis, factor of safety**

INTRODUCTION

In common practical cases, one-row of piles for stabilization of an unstable slope has been used over the past years [e.g., 1-4]. However, there may be conditions under which the use of one-row of piles may not be practical for complex slopes then multiple rows of piles should be used [e.g., 3, 5-6]. Li and Liang [5] showed that multi-rows of concrete piles could be more effective to achieve the required safety factor than one-row of concrete piles with less net load on the pile shaft resulting more economical pile shaft design.

The optimum pile position is an important factor used to stabilize slopes. Several researchers [e.g., 2-3] found that the optimum stabilizing pile position was close to the mid-slope.

According to the studies by Li et al. [7] and Wang et al. [8], the optimum pile position was placed within the mid-slope and slope crest. Some numerical studies [e.g. 9-10] showed that the optimum pile position was located near the slope toe. The results obtained for optimum pile position are quite different due to the resisting forces developed by the stabilizing piles on the slope depend mainly on the slope and pile properties.

In last decades, relatively large-diameter drilled shafts and precast reinforced concrete piles have been widely used in conventional slope remediation practices [e.g., 3-5]. Minipiles can be a more rapid, cost-effective, and simple alternative remediation system [e.g. 11-12] that can be used to stabilize relatively shallow failure conditions where access and space are very limited. Many of the transmission towers in Malaysia are located on residual soil slopes in mountain areas. A review of published case studies on residual soils and specifically residual soil slopes indicated that the important strength parameters (cohesion and friction) are needed to analyze and design of slope stability in residual soils [e.g., 13-15]. However, the use of multiple rows of minipiles for stabilization of an unstable residual soil slope has rarely been studied.

In the present study, consolidated undrained triaxial (CIU) tests were performed on reconstituted saturated samples of residual soil to determine the shear strength behavior. Parametric study was presented to evaluate the influence of the multiple rows of minipiles on residual soil slope stability using a simplified pile-slope analysis method. The analysis results are described and discussed. An attempt is made to give insights of into the use of multiple rows of minipiles to increase the stability of residual soil slope.

METHODOLOGY

Residual Soil Properties

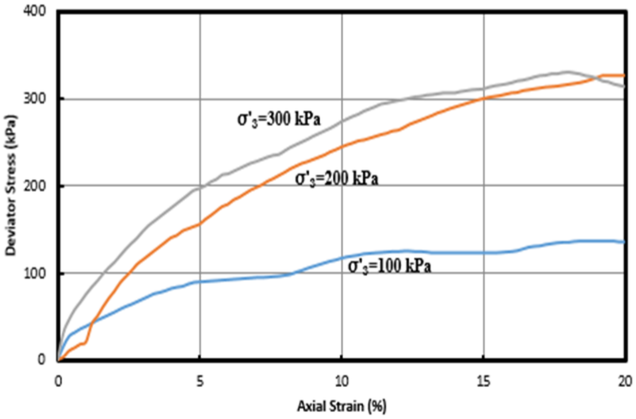
The residual soil samples used in the study were collected from a residual soil slope in Klang Valley, Malaysia. The typical physical parameters of the residual soil: specific gravity= 2.61, liquid limit= 65.2%, plastic limit= 38.5%, plastic index= 26.7% and dry density= 16.5 kN/m^3. The residual soil was classified as sandy silt of high plasticity (MHS).

Consolidated undrained triaxial (CIU) tests were conducted on reconstituted saturated samples of residual sandy silt soil. The soil samples were prepared on dry weight basis until they were observed to be visually homogeneous. The 50 mm diameter soil samples were prepared with different soil relative density. They were prepared by dry-tamping method, which was carried out by compacting the prepared soil samples in multiple layers to their required dry unit weight. After fully saturated, the soil samples were consolidated under effective confining stresses (100, 200 and 300 kPa). The soil samples were then sheared under undrained condition (CIU) at the rate of 0.05 mm/minute up to an axial strain of 20%.

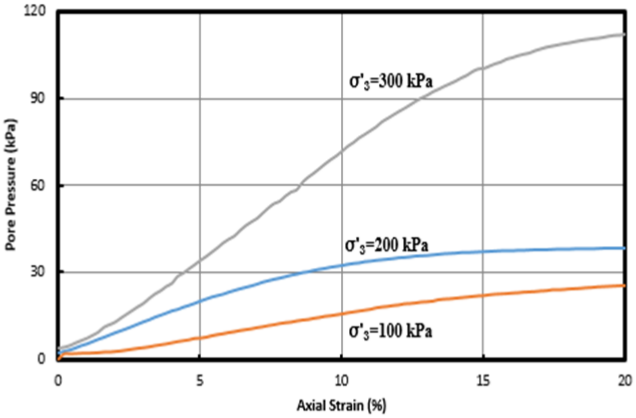
Typical variation of stress and pore pressure with strain under consolidated isotropically undrained triaxial (CIU) test of the residual soil samples is illustrated in Figure 1. The shear strength and pore water pressure of the residual soil samples increase with increasing confining pressures.

The relationship between soil parameters (c' and Φ') and relative density is shown in Table 1. In general, the test results demonstrate that the soil friction angle increases with increasing soil relative density but little change in the soil cohesion in the residual soil. The shear strength behavior is similar to some published residual soil results [e.g., 14-15].

The variation of soil strength parameters with fines content in the residual soils obtained from 11 project sites reported by Gue et al. [13] is shown in Figure 2. It is observed that the soil friction angle value falls between 26˚ and 36˚, and it appears to decrease with increasing fines content. It is also noted that the cohesion value is generally less than 10 kPa. The shear strength parameters obtained from the present study are also plotted on Figure 2 for comparison with the project site data. Generally, the present CIU test results are similar to those obtained from the project site data.



(a) Deviator stress versus axial strain



(b) Pore pressure versus axial strain

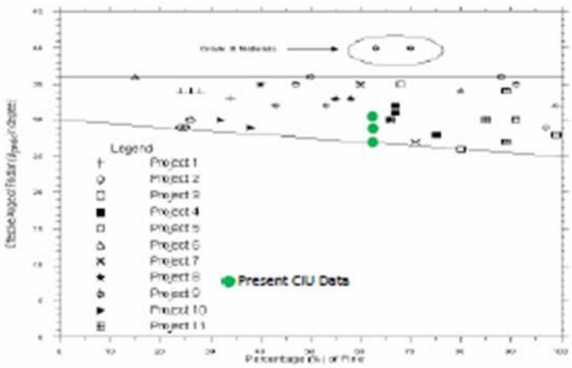
Figure 1 Typical variation of stress and pore pressure with strain of residual soil

TABLE 1
RESIDUAL SOIL PARAMETERS (CIU)

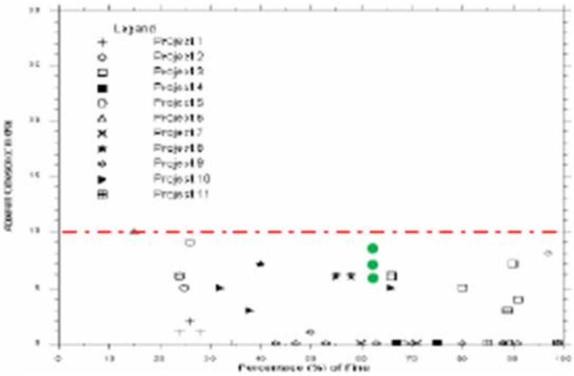
	Cohesion, c' (kPa)	Friction Angle. Φ' (˚)
Loose soil	7	27
Medium dense soil	5	29
Dense soil	4	32

Analysis Method

The residual soil slope stabilized with multiple rows of minipiles are analyzed using a simplified pile-slope analysis method [12]. A limit-equilibrium approach is employed to determine the slope stability, whereas the pile-soil system is represented as a simple beam on subgrade reaction foundation. Initially, the critical sliding surface and safety factor of a residual soil slope without stabilizing piles are determined using limit equilibrium solutions.



(a) Soil Friction angle (Φ') versus Percentage of Fines in Residual Soils



(b) Soil Cohesion (c') versus Percentage of Fines in Residual Soils

Figure 2 Variation of Shear Strength Parameters with Percentage of Fines Content in Residual Soils [13]

Figure 3 shows a residual soil slope stabilized with multiple parallel rows of piles used in the analysis. The slope is divided into an unstable upper layer (the passive part of pile subjected to soil horizontal movement) and a stable lower layer (the active part of pile).

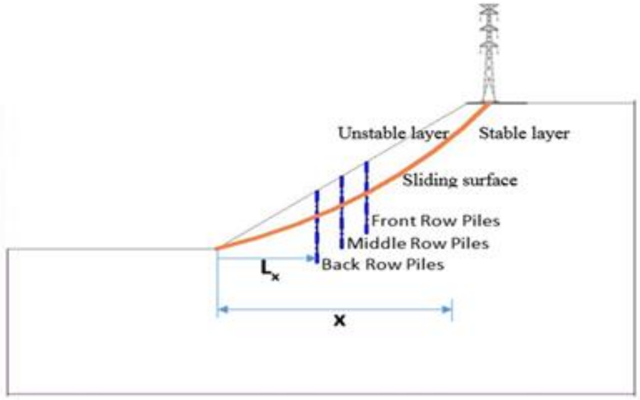


Figure 3 Simplified pile-slope analysis of residual soil slope stabilized with multiple rows of minipiles

The pile behavior in the active part of the slope is represented by the simple beam equation on subgrade reaction foundation expressed as:

$$EI\left(\frac{d^4y}{dz^4}\right) + k_h y = 0 \qquad (1)$$

where y= lateral pile displacement, k_h= subgrade reaction modulus, EI= pile flexural stiffness and z= pile depth.

For the pile behavior in the passive part of the slope, the forces developed from the horizontal soil displacements, w, and equation (1) can be modified as:

$$EI\left(\frac{d^4y}{dz^4}\right) + k_h y = k_h w \qquad (2)$$

In the study, the global stability of the residual soil slope is analyzed initially using the commercial Slope Stability program [16] based on limit equilibrium approach to determine the critical sliding surface position, the passive and active forces that have to act on the stabilizing piles to meet the required safety factor. These results are then used in the commercial Anti-Slide Pile program [17] based on a simple beam on subgrade reaction foundation to compute the stabilizing piles response.

Results And Discussions

In order to examine the minipile row effect, pile spacing, s= 3d and pile row spacing, s_r= 0.1x (where d= pile diameter and x= slope width) are employed in the parametric study.

Some of important parameters that could influence the stabilizing piles to increase the residual soil slope stability are the slope geometry, pile row position, and number of rows of piles. The properties of the minipile used: diameter= 90 mm, wall thickness= 5 mm, length= 6 m and elastic modulus for steel= 2x10^{11} kN/m^2. The average residual soil properties: soil unit weight= 18 kN/m^3, soil cohesion= 5 kPa, soil friction angle= 35˚ and height of slope= 20 m. A transmission tower is assumed located at the slope crest with vertical load of 0.996 MN and water table was not considered.

Figure 4 illustrates the effect of the back-pile row position (L_x) on the residual soil slope safety factor on the stabilizing piles (F_p) for slope inclination (β=40˚) for three rows of piles. The relationship between the slope safety factor (F_p) and normalized back-row pile position (L_x/x) shows that the slope stability reduces when the minipiles are located further from the slope toe demonstrating that the stabilizing minipiles located nearer to the slope toe are more effective.

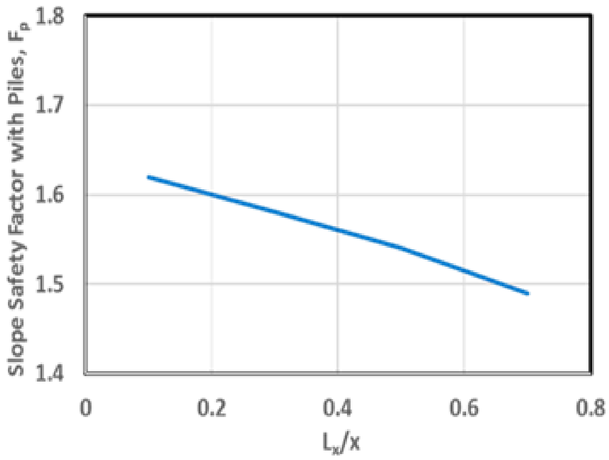


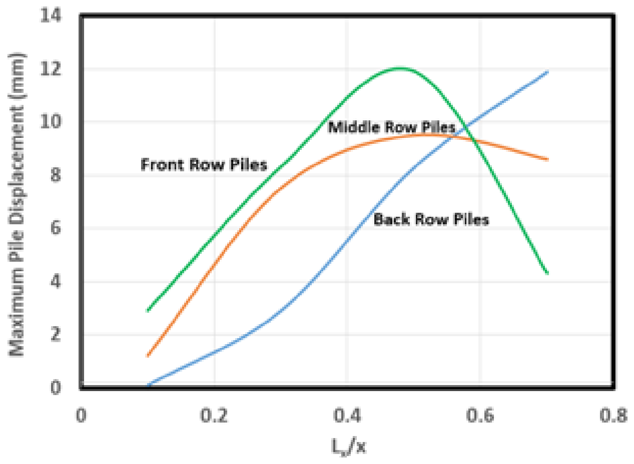
Figure 4 Effect of pile row position (L_x) on F_p for three rows of minipiles

Figure 5 shows the pile response (in terms of pile maximum displacement, shear force and bending moment) increases with increasing normalized pile position (L_x/x) for three rows of minipiles. However, they increase until the mid-slope and then decrease for the front and middle row of minipiles. For the three rows of minipiles close to the slope toe and crest subjected to shallow sliding depths, the sliding soil mass flows past the piles with little flexural distortion and group effects. However, the pile resistance increases significantly and the piles behave more flexible and group effects become more significant when the three rows of minipiles are placed close to the mid-slope subjected greater sliding depths. The front and middle row minipiles are subjected to larger soil pressure due to arching effect causing greater pile response than the back row minipiles.

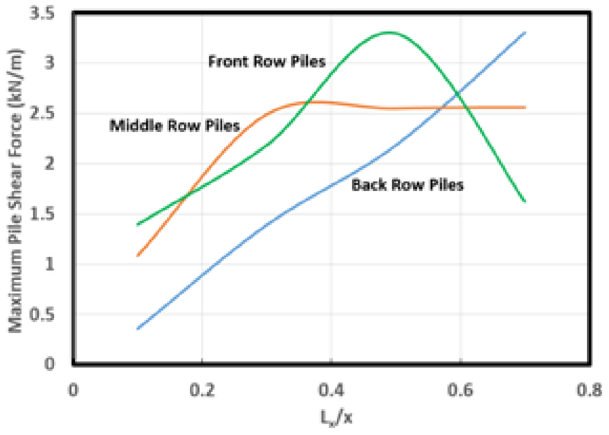
The effect of the residual soil slope inclination (β) on the slope safety factor (F_p) for three rows of minipiles is shown in Figure 6. As expected, the slope safety factor (F_p) decreases with respect to increasing slope inclination (β) as the slope driving force increases and hence, lower the pile resisting force developed causing F_p to decrease.

The effect of the residual soil slope inclination (β) on the response of the three rows of minipiles is shown in Figure 7. The minipile response increases with increasing pile position (L_x/x) until mid-slope and then decrease. The three rows of minipiles near the mid-slope are subjected to greater sliding depths and the piles behave more flexible causing larger pile response.

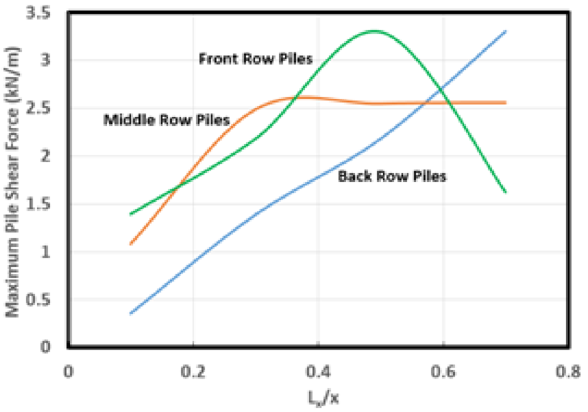
Figure 8 shows the effect of number of minipile rows on the slope safety factor (F_p). Multiple rows of minipiles can increase the stability of a residual soil slope resulting smaller net force developed on the piles to optimize the wall thickness (or rigidity) of minipiles to meet the optimum design requirement.



(a) Maximum pile displacement



(b) Maximum pile shear force



(c) Maximum pile bending moment

Figure 5. Effect of pile row position (L_x) on response of three rows of minipiles

Figure 9 shows that the number of pile row and pile row position have significant effect on the three rows of minipiles response. When the minipiles are placed in the lower-slope region, the minipile response increase with increasing number of rows. However, the minipile response increase with decreasing number of rows when the piles are positioned in the upper-slope region.

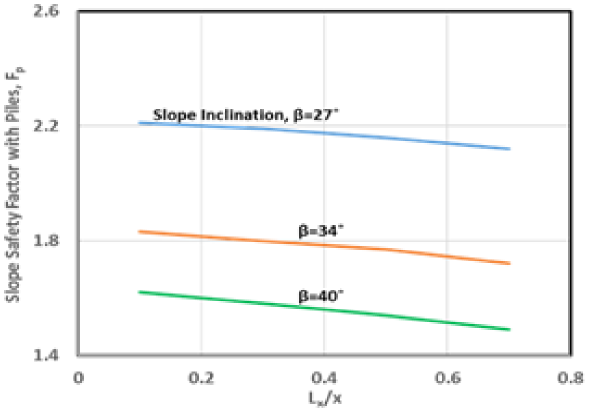
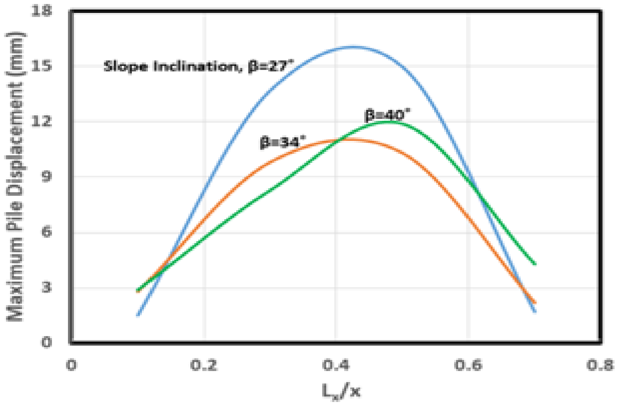
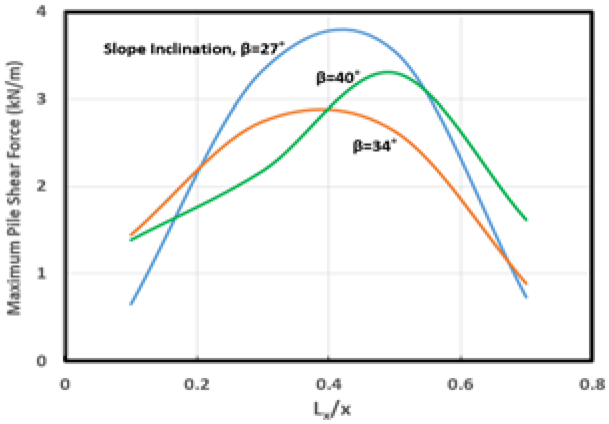


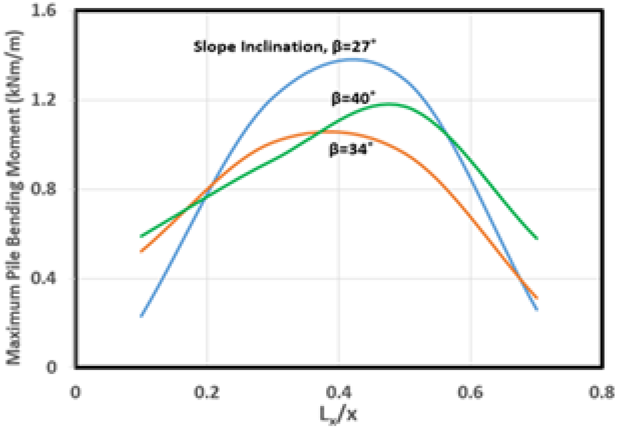
Figure 6 Effect of slope inclination (β) on F_p for three rows of minipiles



(a) Maximum pile displacement



(b) Maximum pile shear force



(c) Maximum pile bending moment

Figure 7 Effect of β (slope inclination) on response of three rows of minipiles

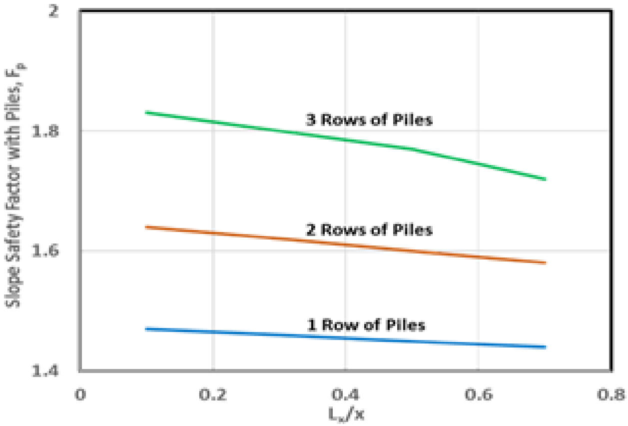
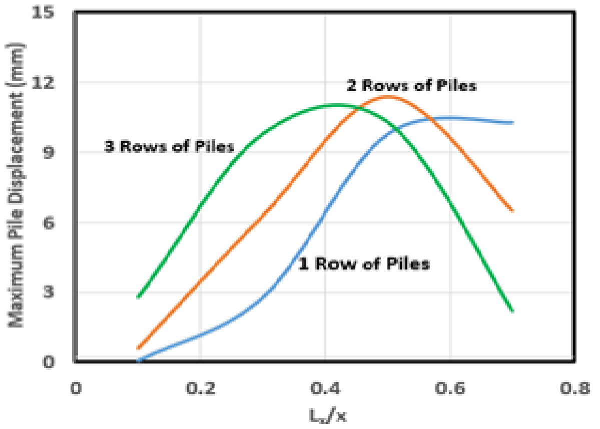
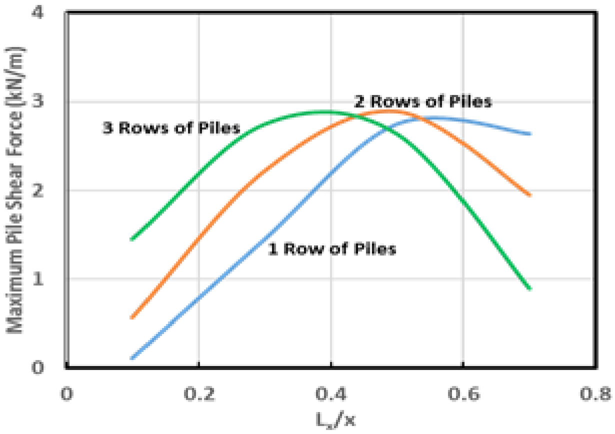


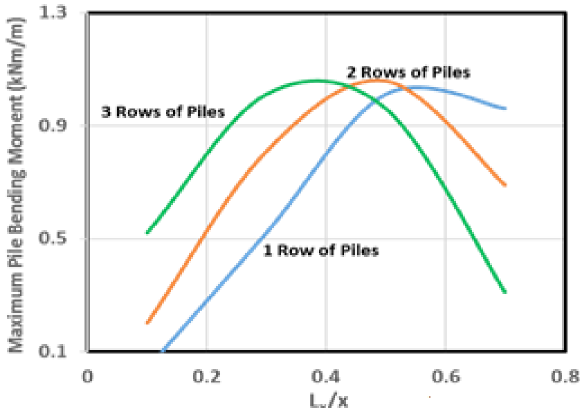
Figure 8 Effect of number of rows of minipiles on F_p (β=34°)



(a) Maximum pile displacement



(b) Maximum pile shear force



(c) Maximum pile bending moment

Figure 9 Effect of number of row of piles on response of three rows of minipiles (β=34°)

CONCLUSIONS

In the present study, consolidated undrained triaxial (CIU) tests were conducted on reconstituted saturated samples of residual soil to determine the shear strength behavior.

In general, the CIU test results show that soil friction angle increases with increasing soil relative density but little change in the soil cohesion. They were found to be similar to the published residual soil test results. A parametric study has been performed to examine the behavior of stabilizing minipiles to increase residual soil slope stability using a simplified pile-slope analysis method. From the numerical analysis, the pile row position on the slope, the number rows of piles and slope geometry could have a combined significant effect on the residual soil slope stability. Multiple rows of minipiles can increase the residual soil slope stability resulting smaller net force developed on the piles to optimize the wall thickness (or rigidity) of minipiles to meet the optimum design requirement. The stabilizing minipiles may subject to larger pile response when they are located near the mid-slope with greater sliding depth. The critical surface location and pile position in a residual soil slope can have considerable effect on stabilizing minipile behavior. The findings of the study can provide useful insight into the use of multiple rows of minipiles to stabilize residual soil slope where access and space are very limited.

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