Influence of placement and configuration of small diameter steel pipe pile on slope reinforcement

Influence de la position et la configuration de pieux en acier a faible diametre sur le renforcement des pentes

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ABSTRACT: The main objective of this study is to elucidate slope failure preventive mechanisms of small diameter steel piles. In this research, model tests were conducted on such piles, using large-scale direct shear testing apparatus. Tests were performed under different test conditions: placement of piles in different rows, varying the installation angle of piles, connecting the head of piles, and combination of vertical and slanted piles (coupled piles). In addition, numerical analyses were also performed for the experimental models. The results show enhancement of the improvement effect in the case of piles with connecting heads. In the case of coupled piles, the shearing strength and the bending stiffness were found to be increased. Therefore, it can be inferred that the pile group constructed by combining vertical and slanted piles is the most effective solution for preventing slope failure.

RÉSUMÉ : La présente étude a pour objectif principal la clarification de mécanismes préventifs pour les pieux en acier à faible diamètre. Dans le cadre de cette recherche, les essais, réalisés à l'aide de l'appareil de cisaillement, sont menés sous différentes conditions, à savoir : la position des pieux, l'angle d'installation des pieux, les conditions de liaison des têtes des pieux et la combinaison de pieux verticaux et inclinés (dits pieux couplés). En outre, des analyses numériques sont effectuées pour le model expérimental. Les résultats obtenus démontrent que l'effet d'amélioration connait une augmentation pour le cas des pieux à tête reliée. Egalement en ce qui concerne les pieux couplés, pour lesquels des pieux inclinés sont installés en sus des pieux verticaux, la résistance au cisaillement ainsi que la rigidité de flexion ont amélioré. Ainsi d'après cette étude, le groupe de pieux construit par combinaison de pieux verticaux et inclinés peut être considéré comme la solution la plus efficace pour prévenir la rupture de pente.

KEYWORDS: box shear apparatus, coupled piles, multi rows pile, slope stabilizing method, small diameter steel piles.

1 INTRODUCTION

Natural disasters such as landslides and slope failures, caused by the heavy rainfalls and earthquakes, are problems of major concern to Geotechnical engineers. As a disaster mitigation measure, in many cases, engineers opt for the slope stabilizing methods using piles. Many methods of slope stabilization have been developed so far. Preventive method is one of the popular slope stabilizing techniques in which the sliding is prevented by using reinforcing materials. Basically two techniques are used in such slope failure prevention method: One is the reinforcing bar technique and the other is the steel pipe pile technique. In the former, reinforcing bars of less than 29 mm diameter are inserted into the ground, which prevent the sliding due to pullout resistance of the bars. In the latter, steel pipes of more than 300 mm diameter are installed in the slope, which prevent the sliding due to the flexural resistance of the piles.

In recent years, research has been focused on a new kind of preventive pile (Hori and Maeda, 2002) called the small diameter steel pipe pile, which has diameter ranging from 100 mm to 300 mm. Such piles possess both the flexural and pull out resistance, and they have been mostly used in a single row. However, depending on the scale of a project, sometimes installation of such piles in multiple rows is required for prevention of slope failures (Sugahara et al. 2014a; Tsukada et al. 2012).

The design method of such piles, when used in multiple rows, however, has not yet been established as the reinforcing effect and the preventive mechanism in such application have not been made clear yet. This research is directed towards establishing a new earth reinforcing method using small diameter steel pipe piles (Sugahara et al., 2014b), when they are installed in multiple rows. The purpose of this research is to determine the effective placement of the piles, their reinforcing effect and slope failure preventive mechanism. To achieve that goal, model tests were performed using a large-scale direct shear testing apparatus, in which the sliding movement of slope could be forced to generate along the shearing surface. Shearing along the sliding surface was simulated in the models under static loading, and the influence of placement of piles (single row to multiple rows), installation angle of piles, and fixing conditions of the head of the piles were examined. In addition, the preventive mechanism of the piles was made clear, through numerically examining the developed state of stress inside the model ground, using finite element analysis of the experimental model.

2 MODEL TEST

Model tests were conducted using the procedures described in Matsushima et al. (2005), and modifying those to be applied for the small diameter steel pipe pile introduced here.

2 .1 *Model description and materials used*

The apparatus used in this research was a large size direct shear testing apparatus with box size of width 200 mm, length 400 mm and height 300 mm (Fig. 1). It is assumed that by forcing the sliding to take place along the shearing surface of the shear box, the reinforcing effect will be manifested through the mobilization of shear strength. Also, through measurement of the earth pressure acting on the piles and the strain developed in the piles, the preventive mechanism can be ascertained. The scale effect was taken into consideration by adopting a model to prototype ratio of 1/10.

The model piles were made of hollow aluminum bar (thickness 1 mm) with width 10 mm, length 10 mm and height 260 mm. In one row, three model piles were installed with a pile spacing of 75 mm as shown in Fig. 2. As seen in Fig. 3, model piles were fixed at the bottom of the lower shear box.

Model ground was prepared using dry sand with a relative density of 80%. The earth pressure acting on the piles and strain developed were measured during the tests to examine the preventive effect of the piles. For that purpose, eight earth pressure cells (EC) and ten strain gauges (SG) were installed in both sides of the piles as shown in Fig. 3.

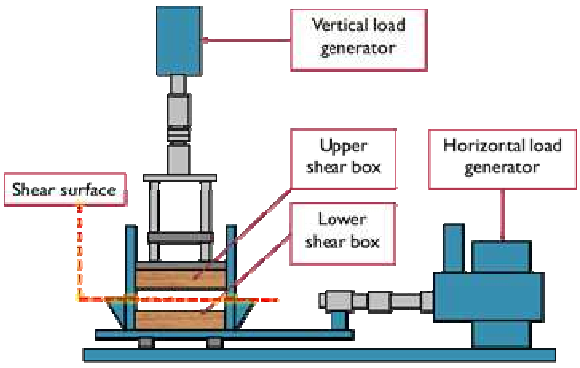

Figure 1. Lower movable large scale shear box.

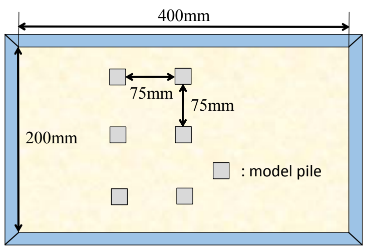

Figure 2. Placement of piles (example of two rows).

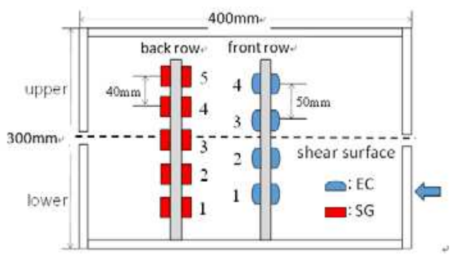

Figure 3. Instrumentations.

2 .2 *Test conditions*

Various placement and configurations of the piles and pile groups were considered in the model testing: 1) changing the rows of piles (1 row to 3 rows); 2) varying the installation angle (±20°as shown in Fig. 4a); 3) fixing the head of piles installed vertically (as shown in Fig. 4b) as well as slanted (not shown in figure); and 4) formation of pile group (called coupled piles) using the combination of vertical piles and slanted piles, as shown in Fig. 4c.

A 3 mm thick hollow aluminum rod of length 260 mm was used to fix the heads of the piles. A prototype depth of 10 m below the ground was considered, and, accordingly 25 kN/m^2 of confining stress was applied in each test. Static loading at a rate of 1 mm/min was applied to the model, and the reinforcing effect was compared by observing the measured shear strength.

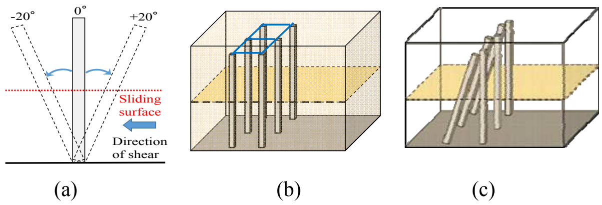

Figure 4. Placement and configurations of piles (a) Pile inclination (b) Heads connected (c) Coupled piles.

3 TEST RESULTS

In the following subsections results of the tests are described through discussions as to how and why the slope failure prevention methods work in reinforcing the slope. The discussion is based on the asumption that by evaluating the maximum shear strength and the initial stiffness, it is possible to compare the effectiveness of reinforcement in each placement and configuration described in Fig. 4.

3 .1 *Relationship between shear strength and shear deformation*

Figs. 5-7 show the shear strength and shear deformation relationship for various test conditions. If we observe the effect of the number of rows (Fig. 5), it is clear that with increasing number of rows, the shear strength is also increased. However, the numbers of rows seem have no influence on the initial stiffness. Comparing the rate of increase of shear strength with number of rows, it is clear that the shear strength increases with increase in number of rows, however, the increase does not exhibit a linear trend. The reason for such increase in the case of two rows and three rows can be attributed to the increase of confinement of soils between the inner piles.

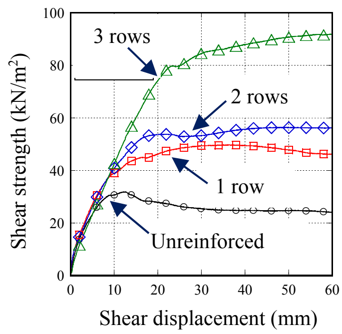

Figure 5. Effect of pile row variation.

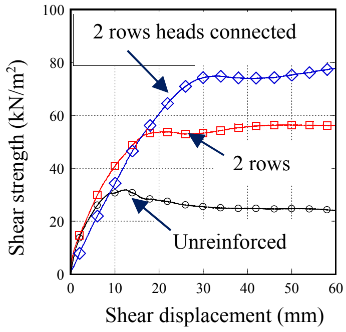

Figure 6. Effect of pile head restraining.

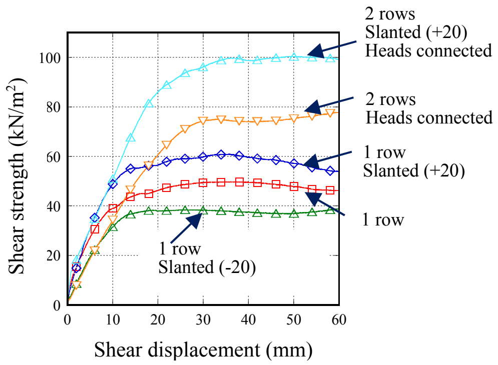

Figure 7. Effect of pile inclination.

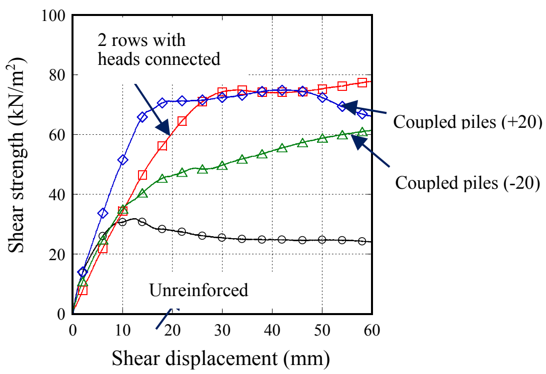

Figure 8. Effect of pile configuration.

If we look at the effect of fixities of the pile heads (Fig. 6), it is clear that fixing the pile heads leads to the increase of the maximum shear strength. Such increase could be confirmed in both vertical piles and slanted piles, however, the increase is significant in case of the slanted piles. This is due to the fact that fixing of the pile head results in a kind of monolithic structure, and as a result, the piles deform uniformly. Because of this, the load acting on the individual piles are dispersed evenly, which leads to effective mobilization of the reinforcing action of each pile.

If we observe the influence of inclination angle of piles on the reinforcing effect (Fig. 7), it can be seen that, when the piles are inclined in the positive direction, the shear strength is increased along with the increase of the initial stiffness. When the piles are inclined in the negative direction, the shear strength is decreased along with the decrease of the initial stiffness. This difference could be attributed to the development of pull out resistance. Also, when multiple rows of piles are installed in the positive direction, a constant increase of shear strength could be seen. Piles inclined in the negative direction results in the compressive reinforcement. Compressive reinforcement destroys the manifestation of reinforcing effect, which results in the decrease of shear strength. Based on these results, it can be said that installing the piles with positive inclination will lead to enhancement of the reinforcing effect.

The effect of pile configurations (coupled piles with vertical and slanted piles) is shown in Fig. 8. It can be seen that, in the positively inclined piles, the shear strength does not differ so much from the vertical piles with two rows, even though the initial stiffness differs. For negatively inclined piles, the initial stiffness is same as the group pile with two vertical rows of piles, however, the decrease of shear strength is very significant. The reason can be attributed to the presence of slanted piles, which bear the load first, and that ultimately influences the initial stiffness. This is the reason why the coupled piles with positively inclined piles show improvement of the initial stiffness.

3 .2 *Earth pressure development and its relation to slope reinforcement*

Figures 9(a)-(d) show the relationship between the shear strength and the earth pressure developed in the piles due to shear deformation just above the shearing surface. In vertical piles with multiple rows (Fig. 9a), the earth pressures in the back side of piles (back side: the side that receives earth pressure) manifest well, and due to that the shear strength also mobilizes. However, the earth pressure in the front side of piles (front side: soil reaction side) does not manifest well.

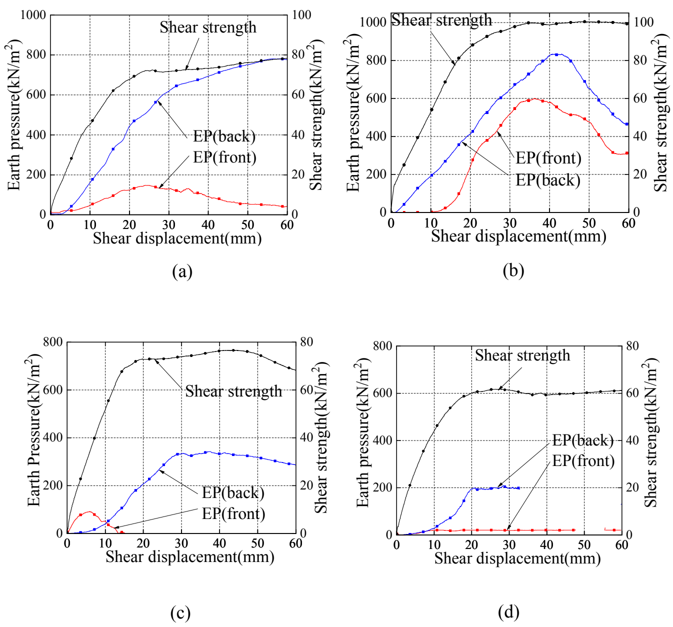

Figure 9. Earth pressure (EP) in the 3rd row and shear stress just above the sliding surface (a) Two rows head restrained (b) Slanted two rows head restrained (c) Coupled piles (inclination +20°) (d) Coupled piles (inclination -20°).

In the case of positively inclined piles with multiple rows (Fig. 9b), the earth pressure measured in the front side (shearing direction) of the pile is very high, and also that is maintained for quite a long as seen from this figure. The developed earth pressure in the front can exceed the reaction force that resists the shearing. Due to this increase in earth pressure on piles, pull out resistance and reaction force could be effectively mobilized, which ultimately could prevent failure, and this was the reason behind the increased maximum shear strength. It can be deduced from this figure that the soils did not yield and reinforcing effect could be mobilized well, and thus preventing any failure of the soils. This is one of the reasons why the shear strength is sustained for such a long period.

As compared to positively inclined coupled piles (Fig. 9c), negatively inclined coupled piles yield much smaller maximum shear strength (Fig. 9d). Therefore, to maximize the reinforcing effect of such piles, it is necessary that the earth pressure acting on piles is effectively mobilized since the maximum shear strength is dependent upon the earth pressure acting on the piles.

4 NUMERICAL SIMULATION

In order to make clear the preventive mechanism of small diameter steel piles in multiple rows, three dimensional elasto-plastic FEM analyses were performed. In the analyses, similar to the testing program, the upper shear box was kept fixed and lower shear box was forced to slide. Von Mises elasto-perfectly plastic model was used for modeling the piles. For the soils, Mohr-Coulomb model was used. The three dimensional view of the model for the three rows of piles is shown in Fig. 10.

Analyses were performed in several steps. First analysis was performed under gravity loading, followed by applying the confining stress of 25 kN/m^2, and then providing forced displacement to the lower box. Joint elements were introduced to simulate the discontinuities in the sliding surface and around the piles.

Figs. 11(a) and 11(b) show the stress distribution (in the x direction) on the siliding surface at the shear deformation of 30 mm. Here compressive stress is represented as negative and tensile stress is represented as positive within the range of -500 kN/m^2 (shown in blue) to 500 kN/m^2 (shown in red). From these results, we can see that a compression zone in the form of an arch develops around the pile, and mobilization of reinforcing effect is possible due to development of those archs. It could also be confirmed that the formation of this compression zone corresponds to the displacement at the maximum mobilized shear strength in the unreinforced case. The compressive arch around the piles prevents any flow of soils between the piles and that ultimately prevents the sliding.

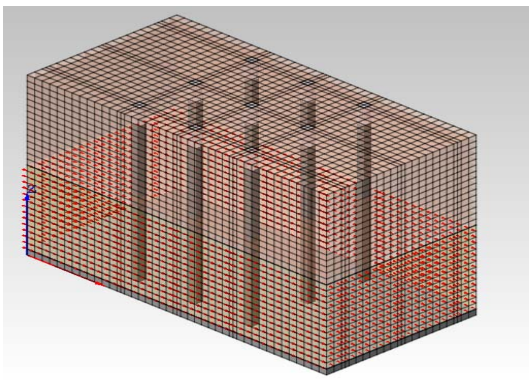

Figure 10. Three dimensional FEM model of the testing program (Three rows of vertical piles).

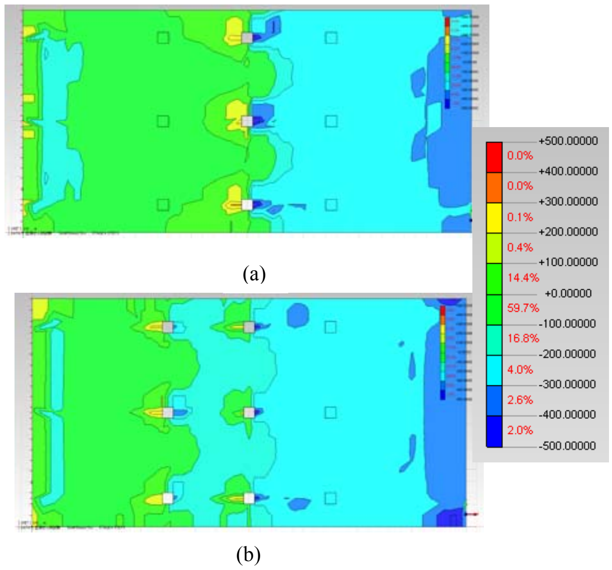

Figure 11. Shear stress distribution just above the sliding surface (x-direction stress). (a) One row of pile (b) Two rows of pile.

5 CONCLUDING REMARKS

The following are some important conclusions based on this research.

(1) The reinforcing effect by small diamater steel pipe piles is realized below the point, where the yield stress is reached in the unreinforced case.
(2) Due to formation of arch around the piles, the flow of soils between the piles could be prevented, and this ultimately menifests as the mechanism behind reinforcing the slope.
(3) In case of coupled piles, the confining effect dominates during the initial shear due to increase of the pull out resistance of slanted piles and the increase of soil resisting force.

Based on the conclusions above, it can be inferred that the coupled piles is the most effective placement and configuration of piles, when small diameter steel pipe piles are installed in multiple rows. However, further studies with prototype scale are required to arrive at definite configurations and dimension of the piles.

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