Model loading tests in large soil tank on group behavior of piles

Essais de chargement modèle afin d'étudier le comportement de groupe de pieux dans un grand réservoir du sol

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ABSTRACT: Model pile loading tests in dry sand were conducted with applying confining pressure of 50-200kPa at the surface of the model ground to investigate the behavior of a group pile. The group pile consisted of 9 cylindrical model piles of 40mm in diameter, while two kinds of the pile spacing between pile centers were used; 2.5 times of the diameter of the pile and 5.0 times of the diameter. For comparison, a single pile with a large diameter was also tested under the same condition. The test results were discussed based from the following 4 points of view; the settlement at the yielding point of the total load, tip stress distribution by the pile location in the group pile, pressure distribution in the soil measured by the tactile sensors and ground deformation after the loading tests. All discussion suggested that the group pile of 2.5D spacing caused significant interactional effect between piles and behaved in one block. In contrast, each pile in the group pile of 5.0D spacing behaved more individually.

RÉSUMÉ : Des essais de chargement de modèle de pieu dans un sable sec ont été effectués en appliquant une pression de confinement de 50-200 kPa à la surface du sol modèle pour d'étudier le comportement d'un groupe de pieux. Le groupe de pieux comprend neuf pieux modèles cylindriques de 40 mm de diamètre. Deux types d'espacement entre les pieux ont été utilisés dans le groupe de pieux modèles : 2,5 fois le diamètre du pieu et 5,0 fois le diamètre entre les centres des pieux. Afin de comparer, un seul pieu à grand diamètre a également été testé dans les mêmes conditions. Les résultats sont examinés selon les quatre points de vue suivants : le tassement à la limite élastique du chargement total, la distribution de contraintes en fonction de la position du pieu au sein du groupe, la distribution de la pression au fond du réservoir contenant le sol, mesurée par des capteurs tactiles, la déformation du sol après les essais de chargement. L'analyse suggère que le groupe de pieux de 2,5D d'espacement a provoqué une forte intéraction entre les pieux qui se sont comportés en tant qu'un seul bloc. En revanche, chaque pieu appartenant au groupe de pieux de 5D d'espacement s'est comporté de manière individuelle.

KEYWORDS: group pile, model test, interaction

1 INTRODUCTION

Group pile is the foundation that supports a footing with several piles. The behavior of a group pile is totally different from that of a single pile if the pile spacing becomes narrow enough because of the pile-soil-pile interaction. To investigate the effects of the interaction in the group pile, model tests were conducted by previous researchers [Whitaker (1957), Vesic (1967), and Itoh and Yamagata (1998)]. However, the bearing mechanism of the group pile is not so clear yet as that of a single pile. As a result, it is not yet understood clearly whether or not the bearing capacity of the group pile is greater or less than that of a single pile

To understand the bearing mechanism of a group pile, the interaction should be studied more scientifically. It is thus necessary to observe precisely the behavior of piles and the surrounding ground in detail during group pile loading. Additionally, a large-scale model is also required to make clear the effects of interaction in a group pile.

Therefore, loading tests on a group pile and a single pile were conducted in a large soil tank with several sensors; strain gauges in the piles, colored sand layers and tactile sensors. To investigate the effect of pile spacing on the interaction, two kinds of models with different spacing were tested. A single pile with a large diameter was also tested for comparison based on the comparison between the group piles and the single pile, the bearing mechanism of group pile was discussed.

2 TEST APPARATUS & TEST PROCEDURE

Group pile loading tests and single pile loading tests were conducted in a large rigid soil tank as shown in Fig. 1. Its internal dimension was 1600mm×1600mm (width)×1650mm (height). At the top of soil tank, a loading actuator was installed. Loading tests were able to be conducted everywhere in the soil tank by moving the actuator. The maximum capacity of the actuator was 500 kN and the loading was performed in a displacement control manner. Details of the device were described by Goto et al. (2012). Air bags were placed on the surface of the model ground to generate confining pressure. Thus, the present tests reproduced the in-situ situation around and above pile tips.

Tactile sensors were installed on the bottom and sidewall of the tank to measure how the earth pressure propagated in the ground. The advantage of this filmy sensor is the ability to measure the distribution of normal (effective) stress. The sensor covered 440mm * 480mm area, containing 2016 sensing cells spaced at 10mm interval in each direction as shown in Fig. 2. In the experiments, stress distribution was measured in a wider area by combining several tactile sensors.

Model ground measured 1200mm in height and was made of air-dried Silica sand No.5; D_{50} = 0.523mm, e_{max} = 1.09 and e_{min} = 0.66. It was constructed by spreading dry sand and manual compaction at every 150 mm lift. The total amount of sand was measured and the average relative density was calculated to be around 90%. The several layers of colored sand were installed

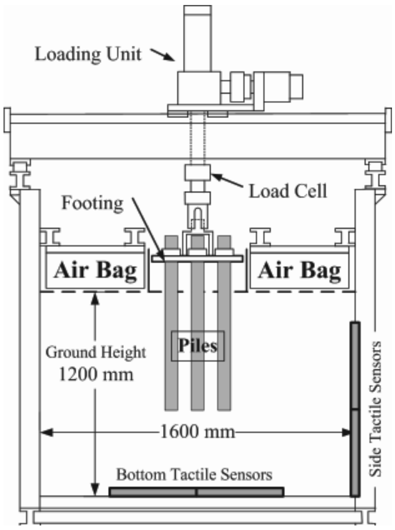


Figure 1. Cross section of the test equipment

Table 1. All conducted tests conditions

Case No.	Aim of the test	Number of piles	Pile Spacing	Pile length	Initial embeded depth
1	Loading test of the pile group	9	5.0 * D (200mm)	1000 mm	550mm
2			2.5 * D (100mm)		
3	Veritical pressure distribution under the pile group loading		5.0 * D	1300 mm	850mm
4			2.5 * D		
5	Loading test of the single pile	1		1000 mm	550mm

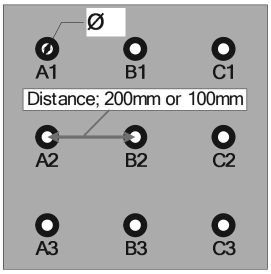


Figure 3. Pile layout in a pile group

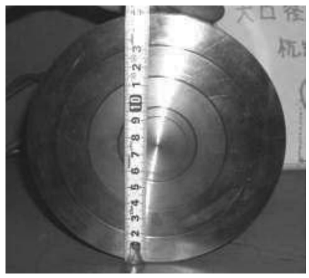


Figure 4. Annular load cells on the bottom

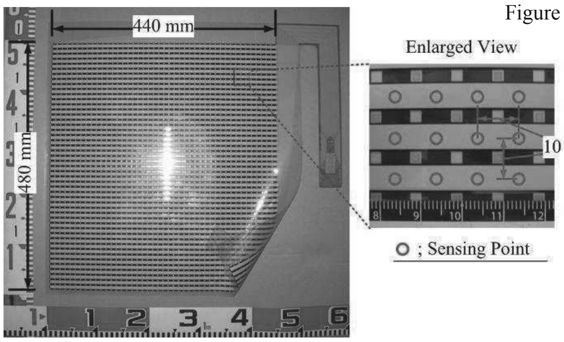


Figure 2. Tactile sensor sheet

in parallel below the initial height of the pile tips to observe the ground deformation after all loading tests were completed.

All conducted test conditions and main object of each test are shown in Table 1.

The models of Case 1 to Case 4 were composed of 9 cylindrical piles as shown in Fig. 3. Each pile was made of aluminum, 40mm in outer diameter, 4mm in thickness and 1000mm (Case 1 and Case 2) or 1300mm (Case 3 and Case 4) in length. The bottom of the piles was closed by a flat plate. Strain gauges were attached inside the piles at 5 levels along the piles and each level had 4 strain gauges to measure both the axial force and bending moments in two directions. Two kinds of the center-to-center spacing between piles were adopted; 5.0 times the pile diameter (200mm) and 2.5 times (100mm).

The diameter of a single large pile in Case 5 was 150mm in the outer diameter, while the thickness being 10mm and 1,000mm in length. Area of the pile tip is 1.5 times the total area of 9 piles in group piles. The strain gauges were attached inside at the same elevation as in the case of group piles. Moreover, the bottom of the large pile was closed by a load cell that was divided into annular 4 rings as shown in Fig. 4 and the contact pressures were measured individually by each ring.

After the ground was built up to le level of the pile tips, pile models were set on the ground. The initial embedded depth is shown in Table.1. Each head of pile in a group pile was fixed to a steel plate that is called “footing” in Fig. 1. After setting the models, the ground was built again up to 1200mm in height.

Group-pile loading tests were conducted in a displacement-control manner; 0.1mm/min. The footing, to which each pile was connected, was pushed down so that all piles would move together into the ground. The confining pressure was increased from 50kPa to 200kPa at an interval of 50 kPa. The loading were performed till 30mm settlement under each confining pressure, the loading was suspended at every 10mm settlement to measure the pressure distribution by tactile sensors..

Additional loading tests were also performed on individual piles before the group pile loading under each confining pressure. The each head of 9 piles was pushed down without any connection to the footing in the individual loading.

The single pile loading tests in Case 5 was also conducted in a displacement-control manner but the loading rate was different from that of the group pile; 0.2mm/min. Other conditions were same as that of the group loading tests.

3 TEST RESULTS & DISUCUSSION

3.1 *Load settlement curve and yielding point*

Figure 5 shows the relationships between total bearing load measured by at the top by the load cell and the settlement of the footing. The pile spacing was 5.0D in Case 1 and 2.5D in Case 2. Irrespective of the pile spacing, the greater confining pressure induced the greater bearing load. Although this was partially caused by the increased stress level under higher confining pressure, it is important as well that the ground below pile tips had been compressed during the previous pile loading.

The inflection points of each curve, so called yielding points, were marked by arrows in Fig. 5. The settlement at yielding points when the pile spacing was 2.5D is greater than that of 5.0D spacing under each confining pressure. The settlement at yielding point became slightly greater at the same pile spacing when the confining pressure was increased.

Figure 6 shows the load-settlement curve until 20mm settlement under the confining pressure of 100 kPa with both pile spacing. The curve of the single pile loading tests with the large diameter in Case 5 and the individual loading tests in Case 1 under the same confining pressure are also shown in the figure. The yielding point of each curve was marked by the arrow. The settlement at the yielding point became greater as the pile diameter increased in case of the single or individual loading. This implies that the settlement of a single pile would increase if the diameter of pile becomes larger.

In comparison with the case of the single pile, the settlement at the yielding point in the group pile of 5.0D spacing was similar with that in the single pile of the small diameter; the individual loading result in Case 1. On the other hand, the settlement in the group pile of 2.5D spacing was similar with that in the single pile of the larger diameter. These suggest that the group pile of 2.5D spacing behaved as a unified group, while each pile in the group pile of 5.0D spacing behaved independently.

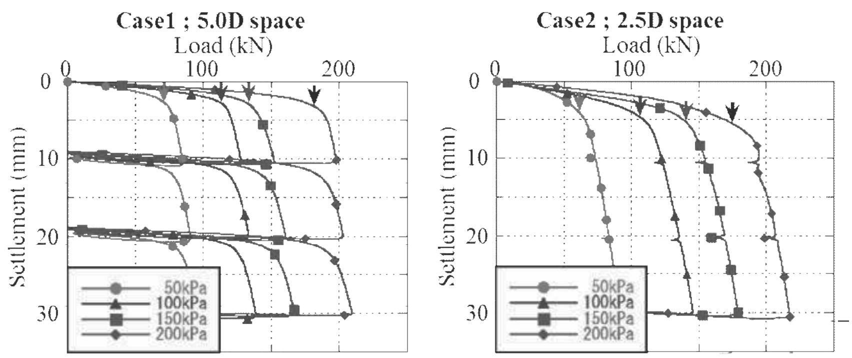


Figure 5. Total Load - settlement curve in the pile

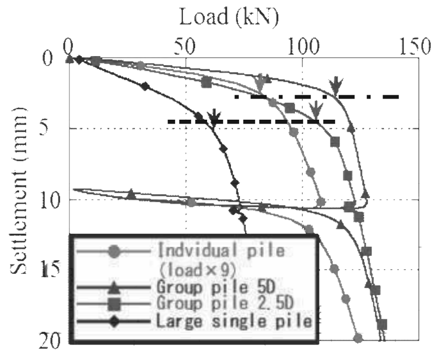


Figure 6. Total Load - settlement curve in both the single pile and the pile group

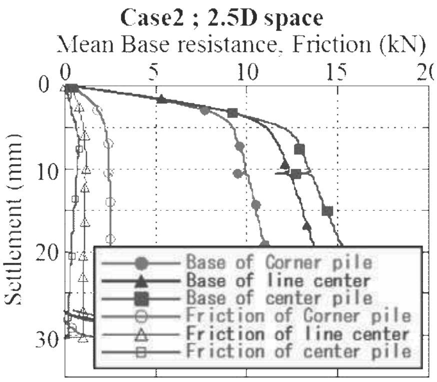


Figure 7. Mean base resistance and friction

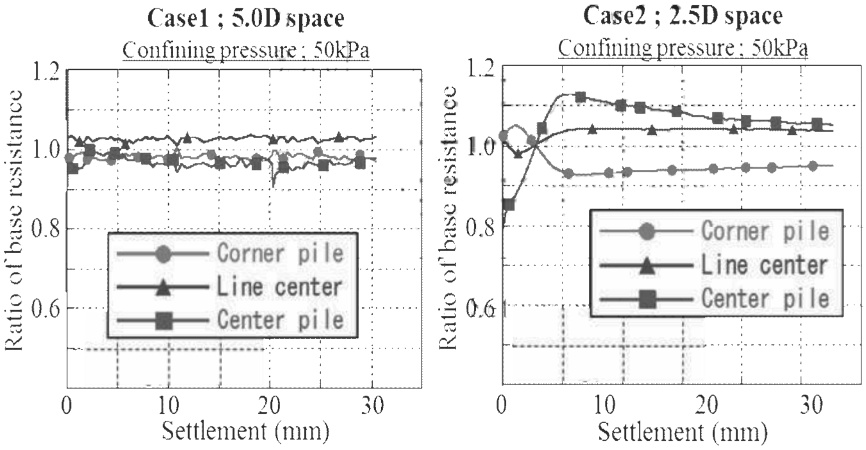


Figure 8. Ratio of base resistance

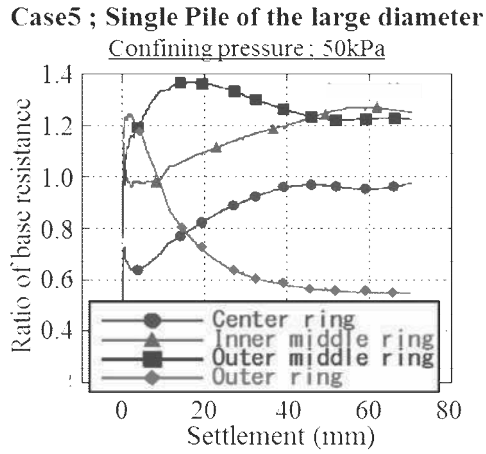


Figure 9. Distribution of contact pressure at base in a single pile with the large diameter

3.2 *Tip stress distribution by pile location in the group pile*

Figure 7 shows the mean pile tip resistance and skin friction changing with the location of piles – at the center (B2 pile in Fig.1), center of perimeter (A2, B1, B3 and C2), and corner (A1, A3, C1 and C3) in the group pile 2.5D spacing. The figure shows that the behavior of each pile in the group pile varies with the location if the spacing is small.

The skin friction of the corner pile was most significant and that of the center pile was the least for 2.5D spacing. The soil immediately below the tip of the central pile was affected by the other piles and moved down with piles as Fig.12 shows. That is why the skin friction of the center pile became smaller. In contrast, the corner piles were in contact with the outer ground that was less affected by pile displacement. Hence the skin friction on the corner pile was largest.

The tip resistance of the center pile was the largest and that of the corner pile was the smallest. This would be because the ground below the center pile was compacted by other piles.

To discuss the tip resistance more in detail, the resistance ratio was plotted in Fig. 8. This figure shows the tip resistance changing with the location of piles, normalized by the total tip resistance under the confining pressure of 50kPa. With 5.0D spacing, the ratio of each pile was almost equal to unity throughout the loading. It suggests that each pile behaved independently. In contrast, for 2.5D spacing, the ratio changed with the penetration of the group pile. The load concentration shifted from the corner piles to the center pile.

Figure 9 shows the tip resistance changing with the location within the bottom of the large pile that was measured by annular load cells as shown Fig.4. The stress concentration also shifted from the edge to the center of the pile. The tendency of the stress concentration changing in the bottom of one pile was similar to that of the 2.5D spacing group pile. This suggests that the significant interaction occurred in the 2.5D spacing group pile and all 9 piles behaved as a block.

3.3 *Response of tactile sensor*

Figure 10 shows the normal pressure distribution at the bottom of the soil tank, measured by tactile sensors. The lighter color means higher pressure. The distance between the bottom of piles and the sensors was 290 mm. In both pile spacings, the highest pressure occurred below the center pile and the pressure decreased in an annular manner.

In contrast, the stress distribution near the tip of the piles varied with the spacing of piles. Fig. 11 shows the stress distribution when the distance between the pile tip and the sensor was 110 mm. For 5.0D spacing, the higher pressure occurred individually below the bottom of each pile. On the other hand, in case of 2.5D spacing, the pressure distribution looks like one block and the maximum pressure occurred in the zone between piles and formed a circular shape. This also suggests the strong interaction near the pile tip incase of 2.5D spacing.

3.4 *Observed ground deformation*

Figures 12 and 13 show the ground deformation after the completion of loading tests. The colored sand layers were installed in the horizontal direction with the equal interval prior to model construction. The dotted lines show the initial location of each colored sand layer. After the pile penetration of 240 mm, the distance of colored sand layers decreased to 5% of the original distance at the maximum below the pile bottom. This means that the ground just below the pile bottom was compressed severely. In the compressed core, heavy particle crushing was observed. These features occurred in both cases of pile spacing.

In contrast, the shape of ground deformation between or below piles was different according to the spacing. For 5.0D spacing, the ground below each pile moved down separately. On the other hand, in case of 2.5D space the ground under the group pile deformed in a continuous convex way. Furthermore, the ground between piles also moved down. This suggests that the ground not only below the pile but also between piles was compressed downward together in the case of 2.5D spacing.

4 CONCLUSIONS

The vertical loading tests of the group pile and the single pile were conducted. By comparing the bearing load, stress concentration by the pile location, pressure distribution and the ground deformation, the following conclusions may be drawn.

(1) For the narrower 2.5D pile spacing, the group pile yields at a larger settlement and the settlement was almost same as that in the loading of a pile of a large diameter. In contrast the settlement in the 5.0D pile spacing was similar to that in the loading of a single pile of the same diameter.
(2) For 2.5D pile spacing, tip resistance concentrated to the corner piles in the early state of loading. The concentrated load shifted to the center pile after the settlement increased. The same shift of the concentration occurred in the bottom of the single pile with the larger diameter as well.
(3) The higher ground pressure occurred below the bottom of each pile individually in 5.0D spacing group pile near the pile bottom. In contrast, the higher pressure was observed in a block manner and the highest pressure showed a ring distribution in 2.5D spacing group pile.
(4) The ground only below the bottom of each pile deformed downward individually in case of 5.0D spacing. Conversely, the ground under the group pile deformed in a contiguous convex curve for 2.5D spacing.

From these observations, it was concluded that individual piles in the group pile with 5.0D spacing behaved independently. In contrast, the group pile of 2.5D spacing behaved in a block, similar to one large single pile.

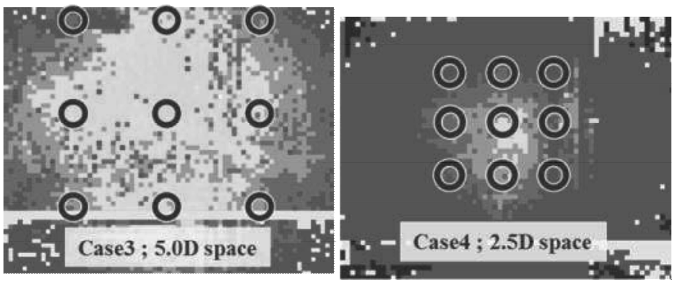


Figure 10. Pressure distribution at 290mm distance

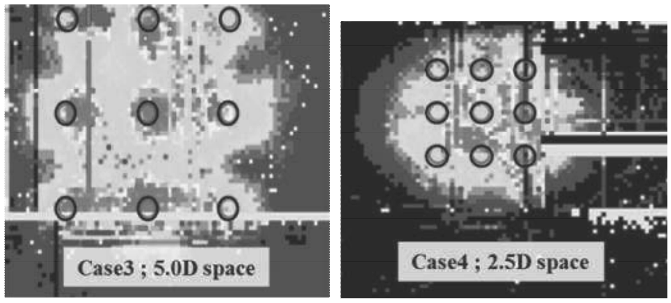
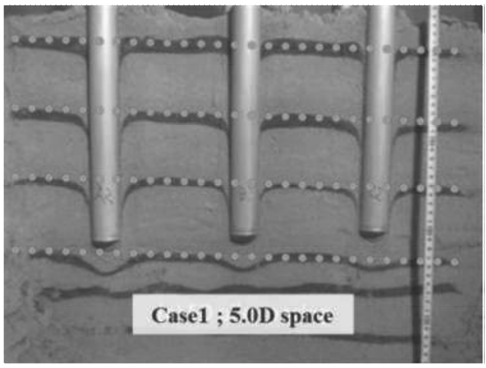


Figure 11. Pressure distribution at 110mm distance



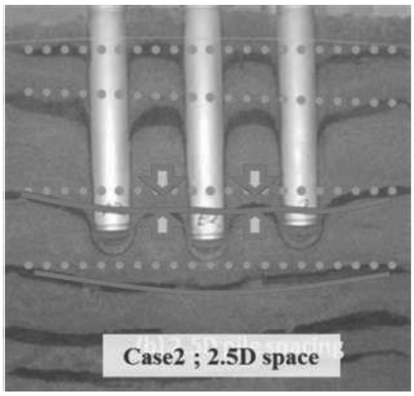


Figure 12. Ground deformation after all loading tests

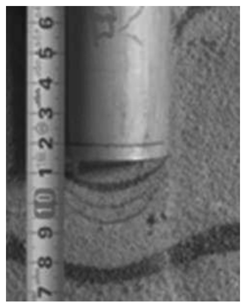


Figure 13. Ground deform. near the pile bottom

5 ACKOWREDGEMENT

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