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NONLINEAR BEHAVIOR OF PILE GROUP IN DRY SAND BASED ON LATERAL CYCLIC LOADING TESTS WITH LARGE DISPLACEMENT AMPLITUDE

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ABSTRACT

Nonlinear effects of soil-structure interaction under strong ground motions should be considered in the seismic design. This paper presents the results of lateral cyclic loading test for pile groups in dry sand to investigate the nonlinear behavior of the soil-pile group interaction for large displacement range. The test parameters are the number of piles, the layout of pile groups, the relative density of soil and the loading rate. The major findings obtained from this study are summarized as follows: 1) the soil around piles deformed significantly even at small displacement amplitude, 2) load-displacement relationship at pile head shows strong nonlinearity even in very small displacement amplitude, 3) the shear forces carried by the leading piles are significantly larger than those carried by the trailing piles, 4) the ratio of the shear force carried by the individual pile to the total shear force carried by the entire pile group is affected by the yielding of piles and failure of the ground.

Keywords: Effect of pile group, Shear force at pile head, Dry sand, Large displacement amplitude, Cyclic loading

INTRODUCTION

To design pile group foundations for lateral loading, it is important to investigate the lateral load resistance of individual piles in the pile group. Therefore, many experiments have been conducted about the interaction between soil and pile groups. For instance, a large scale steel pipe pile group and a single steel pipe pile were tested subjected to bidirectional cyclic lateral loading by Brown et al. (1987) and pile group models in saturated sand was tested by Suzuki et al. (2003). On the other hand, the near-fault ground motions observed in Kobe and Niigata Chuetsu Earthquakes is far stronger than those commonly used for the Japanese seismic design practice. To predict the behavior of structures subjected to these strong ground motions, nonlinear effects of horizontal interaction between soil and pile groups should be accurately considered. Especially, nonlinearity of local soil around pile groups will significantly affect the behavior of structures. To comprehend the effects of nonlinearity of local soil on the interaction between soil and pile groups, it is important to investigate the behavior for not only small displacement of pile but also large displacement beyond the diameter of the piles. However, so far very few tests of pile groups have been conducted by lateral cyclic loading with the displacement beyond the diameter of the piles. Therefore, the tests of pile groups subjected extremely large lateral displacement are conducted. Dry sand which has the clear characteristic is used for soil

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model in the tests. The test parameters are the number of piles, the layout of pile groups, the relative density of soil and the loading rate. The obtained tests results are investigated about the deformation of soil, the load-displacement relationship at pile head and the shear force distribution ratio at the pile head.

TEST SETUP

As shown in Figure 1, the dimensions of the soil container are 3.0m in length, 1.2m in width, and 1.0m in height.

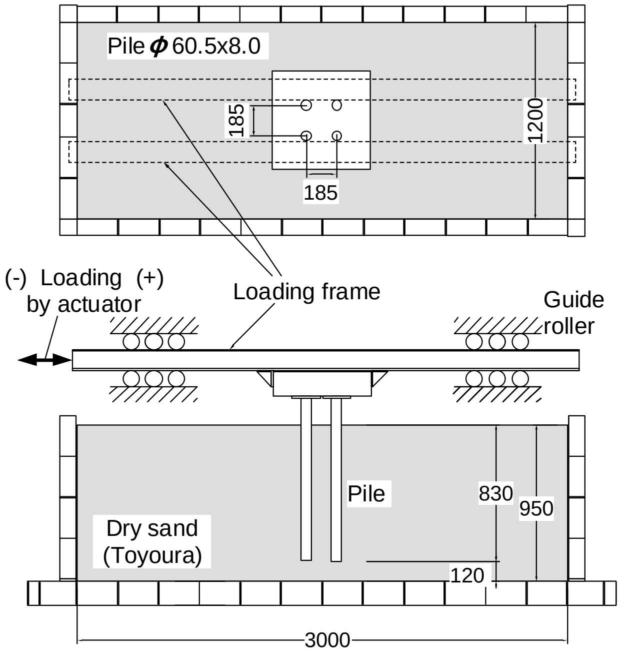
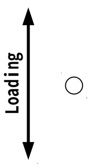
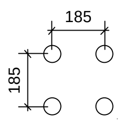
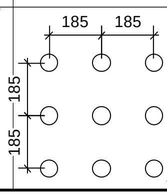
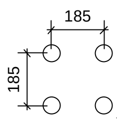
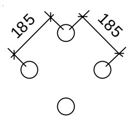
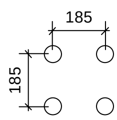


Figure 1. Layout of specimen (mm)

The test setup is designed to load the pile group through a rigid loading frame. The pile heads are tied on the rigid loading frame though a rigid connection, and the pile ends are free. The rigid loading frame is supported by the guide rollers, which have low friction, and the rigid loading frame is restricted so that it can only move in one direction.

As shown in Table 1, totally six test cases, i.e. 1P, 4P, 9P, 4P-D, 4P-X, 4P-L, are considered with the number of piles, the relative density of soil, the loading velocity, the loading direction, and the layout of the pile group as parameters.

Table 1. Test case

Test Name	1P	4P	9P	4P-D	4P-X	4P-L
Number of pile	1	4	9	4	4	4
relative density	60%	61%	62%	62%	62%	45%
Loading	Static	Static	Static	Dynamic	Static	Static
Loading Direction	0°	0°	0°	0°	45°	0°
Layout of Pile Group						

1P represent the situation for a single pile. The piles were arranged in 2-by-2 for 4P and 3-by-3 for 9P with spacing of approximately 3 times the pile diameter. Without changing 2-by-2 arrangement, loading direction is turned 45 degree for 4P-X, relative density was decrease to 45 % for 4P-L, and the loading is switch to dynamic for 4P-D.

Dimensions and Material Properties of the piles are shown in Table 2. The piles are made of steel (STK400).These piles are regarded as relatively short piles according to the classification by Broms (1965).

Table 2. Dimensions and material properties of piles

Length	l=1000(mm)
Outer Diameter	B=60.23(mm)
Thickness	t=8.86(mm)
Yield Stress	s_y=288(N/mm^2)
Yield Moment	M_y=4.60(kN·m)
Full Plastic Moment	M_p=6.80(kN·m)

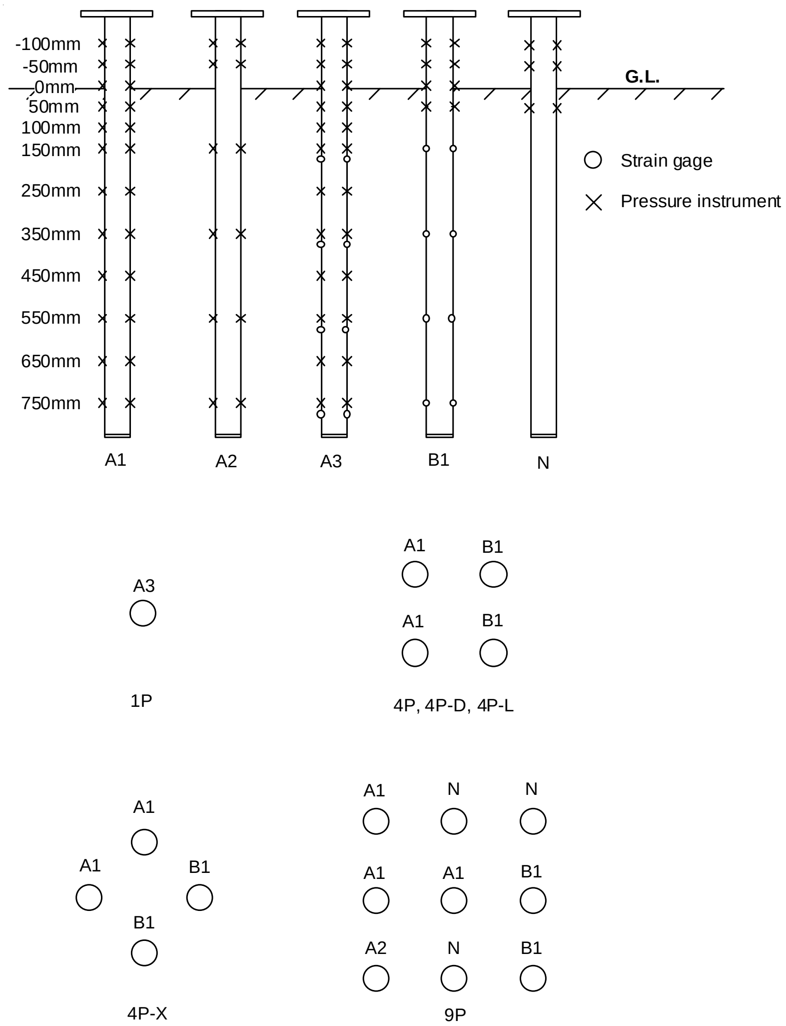


Figure 2. Layout of location of instrument (mm)

The model ground is made of Toyoura sand. The specific gravity, the maximum void ratio, and the minimum void ratio are 2.65, 0.95, and 0.58, respectively. When making the model ground, the sand is put one layer by one layer, and depth of each layer is 100mm. each layer is carefully leveled and compacted. Such a procedure is to achieve homogenous relative density.

Figure 2 shows the details of the instrumentation. Piles are instrumented with strain gages and pressure meter. Bending moment at the pile head is calculated based on the strain values obtained from the strain gages.

A hydraulic actuator is used for loading, and the target amplitudes are 1mm, 2mm, 4mm, 8mm, 10mm, 12mm, 15mm, 18mm, 24mm, 30mm, 45mm, and 60mm for all the cases. The tests are conducted with the gradually increasing displacement amplitudes. Each of amplitudes is repeated for two cycles. In addition, specimens are further loaded to extremely large displacement amplitudes, specifically, one cycle for 120mm and 180mm. A triangular load pattern is used for static loading, whereas sine wave is used for dynamic loading (4P-D). The period of sine wave is 0.5 second for the amplitude no greater than 30mm, and increase gradually for the amplitude larger than 30mm, and the period reaches 2.0 second for the amp1itude of 180mm. Such a change is due to the capacity limitation of the hydraulic actuator.

TEST RESULT

Ground deformation

Plan and section views of ground deformation for 1P, 4P, and 9P are shown in Figure 3.

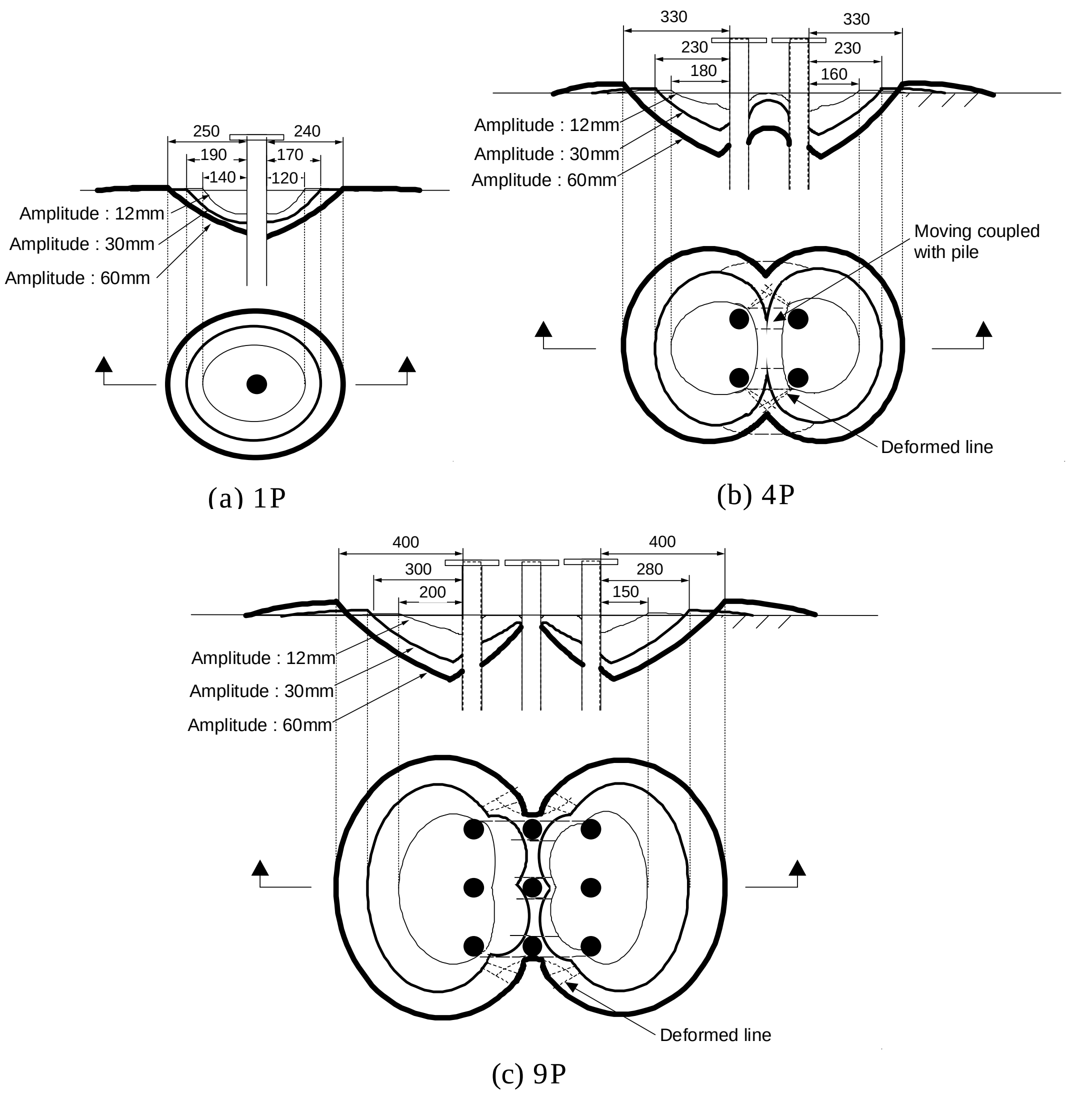
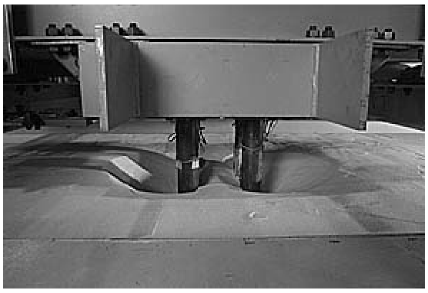


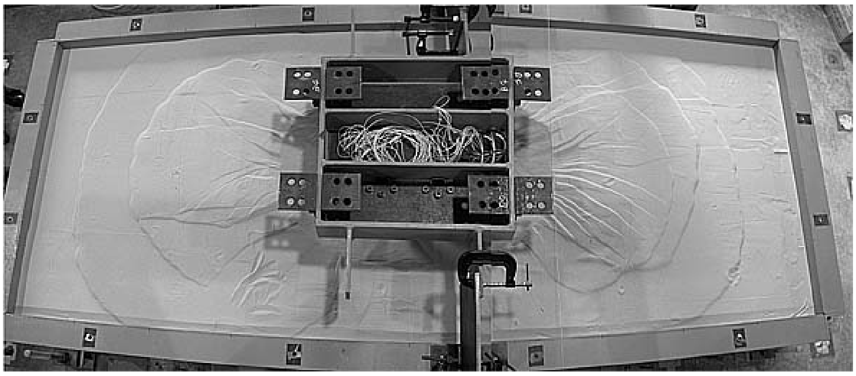
Figure 3. Plan and Section views of Ground

The solid lines in Figure 3 are the contours of the craters around the pile [refer to Figure 4 (a)], and broken lines are the traces of the ground slip [refer to Figure 4 (b)]. In 1P, it could be observed that the ground around the pile was settling down and the ground in front of the crater was raised. First, sand behind the pile filled into the gap which generated by the displacement of piles, and then formed an inclined plane. The diameter of this settlement was far larger than the displacement of pile. As displacement increased, the diameter and the depth of the crater got larger. The crater shapes are plotted in plan and section views for 4P and 9P in Figure 3 (b) and (c), respectively. In reference to Figure 4 (a), it is clear that the ground outside the pile groups deforms significantly, and formed large craters, whereas that between the piles arranged in loading direction did not deform much, and the ground left there and formed a small hill. This small hill decreased as displacement amplitude increases. When the amplitude reached 18mm, the deformed line, which was formed by the slip of the ground between the inside and outside of the pile group, could be clearly observed [refer to Figure 4 (b)]. The ground inside the deformed line moved together with the piles. When the amplitude reached the amplitudes 120mm, the ground around the crater rose in wide range and deformed like bump because of failure of the ground [refer to Figure 4 (c)]. This failure of the ground could not be observed in 1P.



(a) Crater

(b) Deformed line by slip



(c) Failure of the ground

Figure 4. Picture of ground around pile group

Load – displacement relationship at pile head

Figure 5 shows the force - displacement relationships at the pile head. The curve is in a satiated spindle-shape until the amplitude of 180mm for 1P and 60mm for 4P and 9P. In cases of 4P and 9P, the maximum force degrades after the amplitude of 60mm, and finally converges to a constant value. It is considered that this degradation of maximum force is caused by failure of the ground.

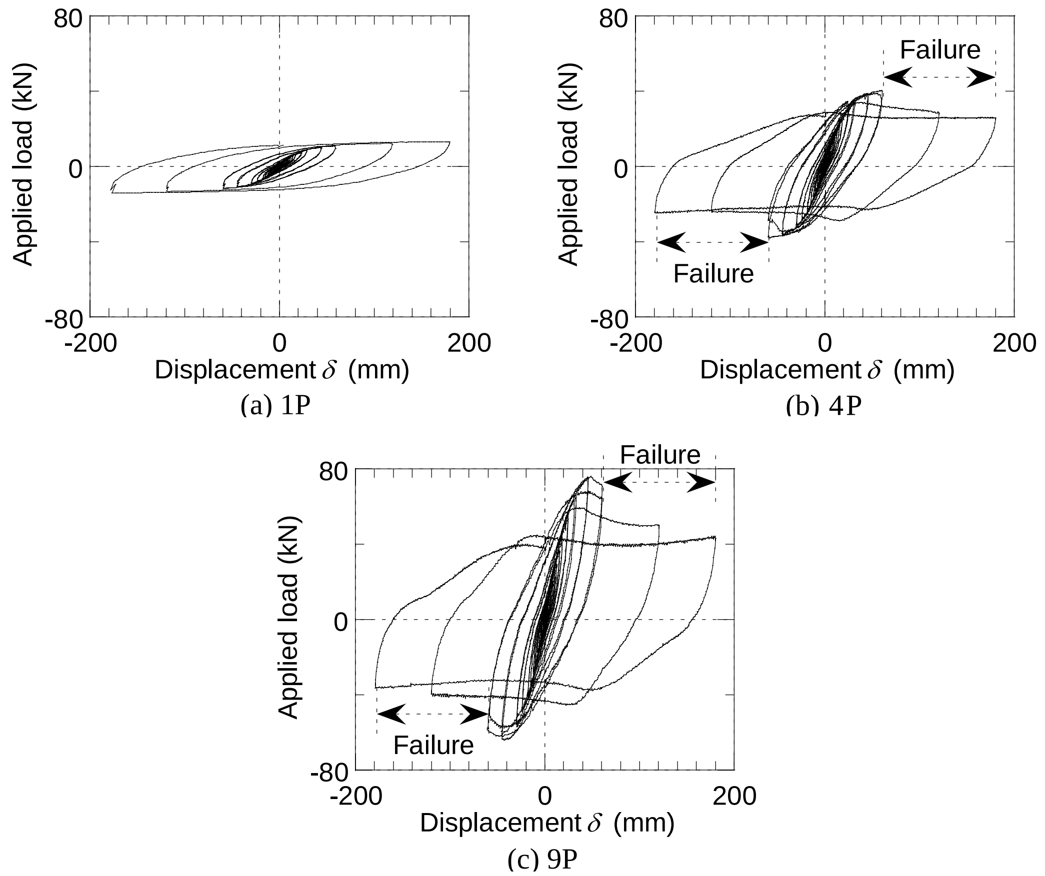
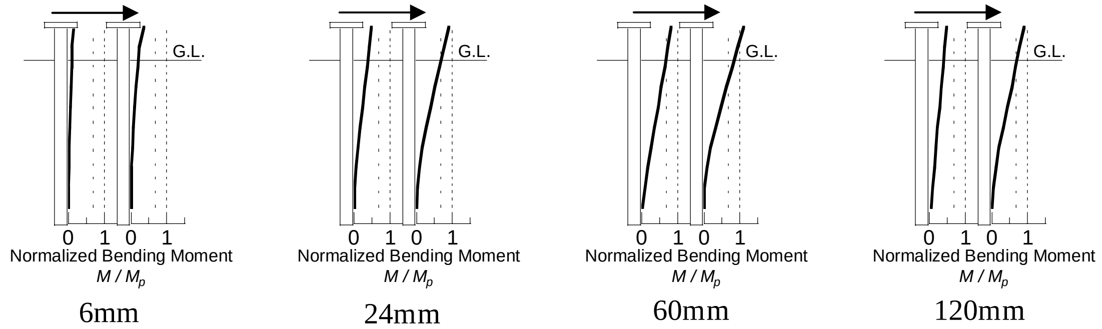


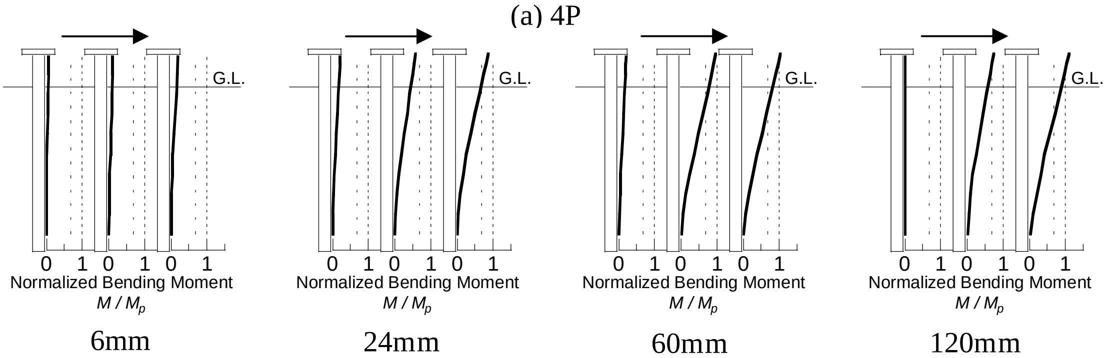
Figure 5. Force - displacement relationship at pile head

Bending moment diagram

A bending moment distribution along the depth is plotted in Figure 6 for 4P and 9P. In the figure, horizontal axis is the bending moment normalized by the full plastic moment of the corresponding pile. The bending moment increases as the displacement amplitude increases until bending moment at pile head reaches the full plastic moment. After moment at pile head reaches full plastic moment, bending moment keeps constant approximately. The corresponding displacement amplitude is 30mm for both 4P and 9P. After the ground comes into failure at the amplitude of over 60mm, bending moment decreased especially for the trailing piles.



(a) 4P

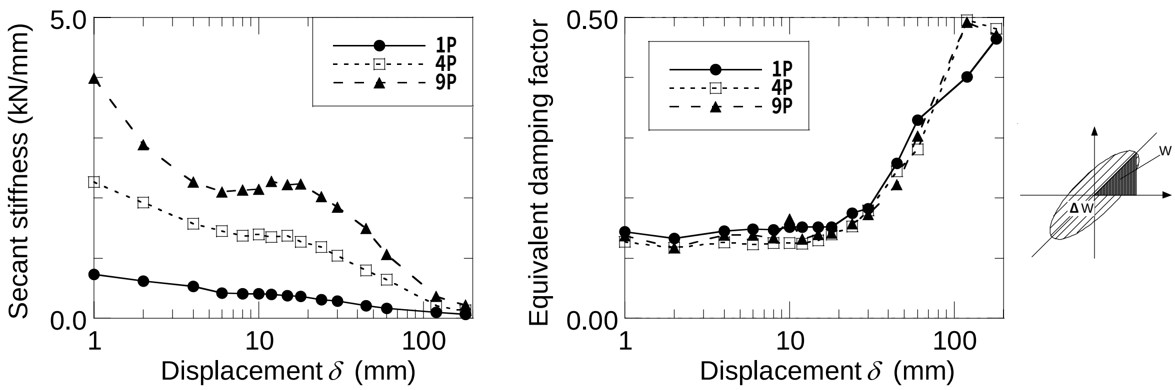


(b) 9P

Figure 6. Plots of bending moment vs. depth for 4P and 9P by row position

Nonlinearity of soil-pile system

As shown in Figure 5, the soil-pile interaction exhibits significant nonlinearity. In order to provide information on the nonlinearity of soil-pile systems, the Secant stiffness and the equivalent damping factor are plotted in Figure 7 with respect to the displacement amplitude. In the figure, the data plotted are the average of the two sets results obtained from plus and minus directions. The scant stiffness of decreases as the amplitude increases in all tests. Average scant stiffness increases as the number of piles in the pile group decreases. The equivalent damping factor is approximately 10% until the amplitude of 30mm and increases to about 30% until the amplitude of 60mm and the difference of equivalent damping factor among the test cases is very small. At the amplitude of 120mm, the equivalent damping factor at 4P and 9P is a little larger than 1P. It is believed that such deference is because of failure of the ground.

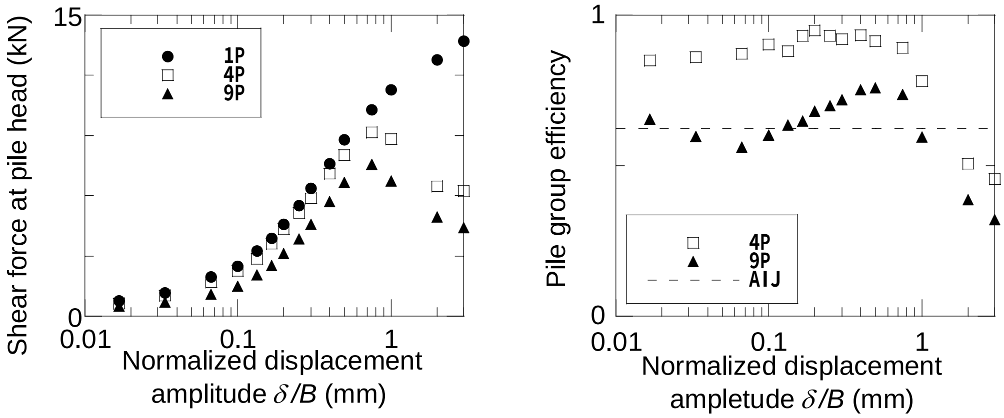


(a) Scant stiffness (b) Equivalent damping factor

Figure 7. Secant stiffness and equivalent damping factor vs. displacement relationship

Distribution of shear force at pile head

Figure8 (a) shows the comparison of the average load per pile for 1P, 4P and 9P at maximum displacement in each amplitude. In Figure 8, the average load is plotted as a function of normalized displacement amplitude δ / B, in which δ is displacement amplitude and B is diameter of pile. The average load for pile groups is smaller than the load for the single pile. According to Recommendations for Design of Building Foundations (2001), the pile group efficiency is defined as the average load per pile carried by the pile groups to the load carried the single pile. Figure 8 (b) shows the pile group efficiency with normalized displacement amplitude. For the normalized displacement amplitude up to 1, the pile group efficiency is increased but the rate of the increase is little. For the normalized displacement amplitude over 1, the pile group efficiency is decreased because of failure of the ground except for 1P and the average load carried by piles at 4P and 9P is decreased.



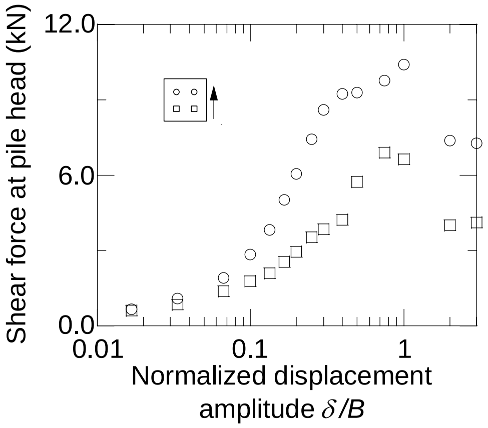
(a) Average load per pile (b) Pile group efficiency

Figure 8. Comparison of average load per number of pile and of pile group efficiency

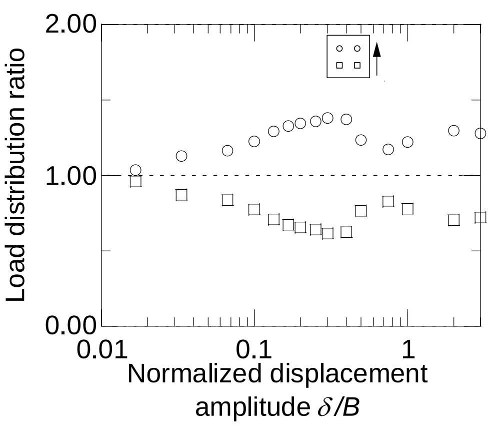
As shown in Figure 8, the average load carried by pile groups is smaller than the load of the single pile. One of the reasons of difference between the average load of pile groups and the load of the single pile is the loss in soil resistance relative to that of an isolated single pile for group piles in various row positions. In this test, to investigate the load distribution to the individual piles in pile groups, shear force at the pile head carried by the individual piles in the same pile group but at different positions are compared. Load distribution ratio is defined as the shear force carried by the individual pile to average load carried per pile. In Figure 9, 10 and 11, the data plotted are the average values of the two sets obtained from the plus and minus directions.

As shown in Figure 9 (a), the shear force carried by the leading pile is larger than that at trailing pile for the normalized displacement amplitude up to 0.4, and it is about twice at the normalized displacement amplitude of 0.4. As shown in Figure 9 (b), load distribution ratio for leading pile increases but that for the trailing pile decreases, as displacement amplitude increases.

In Figure 9 (a), the increase of shear force at leading pile gets smaller for the normalized displacement amplitude over 0.4 because the pile head of leading pile sustains significant plastic, whereas the increase of the shear force at trailing pile does not change much. Therefore in Figure 9 (b), load distribution ratio at leading pile decreases for the normalized displacement amplitude over 0.4. For the normalized displacement amplitude over 1, shear force decreases drastically and finally shear force and the load distribution ratio converged to constant values because of failure of the ground.



(a) Shear force



(b) Load distribution ratio

Figure 9. Comparison of load at pile head for group by row position at 4P until 180mm

Load distribution ratio between the piles in the same pile group but at different positions for 9P is shown in Figure 10. The distribution ratio of the leading piles increases for the normalized displacement amplitude up to 0.4, and decreases thereafter. At the amplitude of 0.4, load distribution ratio for leading pile is about three times as large as for trailing pile. Note that the pile head sustains full plastic moment at about 0.4. For the normalized displacement amplitude over 0.4, load distribution ratio at the trailing pile does not increase, whereas that of the middle piles increases.

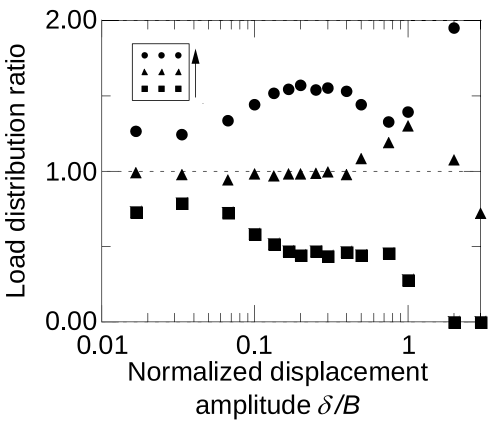
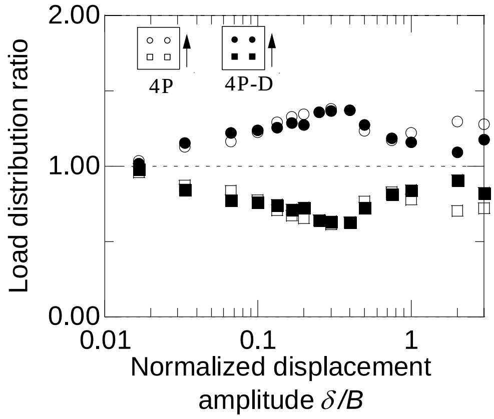
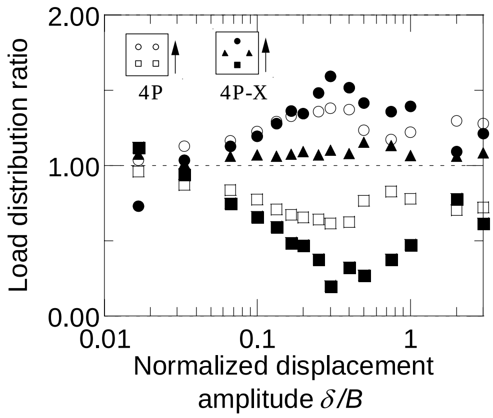


Figure 10. Comparison of load distribution ratio for group by row position at 9P

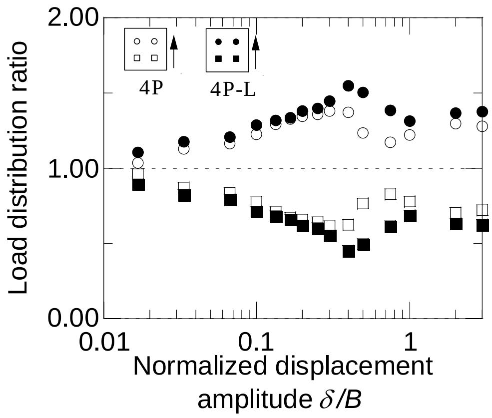
Figure 11 shows the load distribution ratio for the piles in the same pile group but at different positions for 4P-D, 4P-X, and 4P-L. It can be observed that the load distribution ratio significantly depends on the soil density, and loading direction. However, for the normalized displacement amplitude over 1, test results of 4P-D, 4P-X, and 4P-L converge to similar values.



(a) 4P and 4P-D



(b) 4P and 4P-X



(b) 4P and 4P-L

Figure 11. Comparison of load distribution ratio for group by row position at 4P-D, 4P-X, and 4P-L

These results in this section indicated that the load distribution ratio was significantly influenced by displacement amplitude at pile head. It is important to investigate the effects of the displacement amplitude on the variation of the load distribution ratio. Further experimental study will be conducted focusing on the different diameter of piles.

CONCLUSION

This paper presents the results of lateral cyclic loading test for pile groups in dry sand to investigate the nonlinear behavior of the soil-pile group interaction for large displacement range. The findings obtained from this study are summarized as follows: 1) the ground around piles deformed significantly even at small displacement amplitude and the settlement was deformed by the loss of sand around the pile, 2) load-displacement relationship at pile head shows strong nonlinearity even in very small displacement amplitude, and except for 1P the maximum force degrades after the amplitude of diameter of pile, and finally converges to a constant value, 3) the shear forces carried by the leading piles are sometimes over twice as large as those carried by the trailing piles, 4) the ratio of the shear force carried by the individual pile to the total shear force carried by the entire pile group is changed by increasing displacement amplitude and is affected the yielding of piles and failure of the ground as well as the number of piles, the pile location, the soil density, and the loading direction.

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