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Effects of lateral loading on shaft friction of piles based on centrifuge model tests

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ABSTRACT: The objective of this study is to investigate effects of lateral loading on the shaft friction of piles. Lateral and vertical loading tests were conducted on a 2 x 2 pile group under a centrifugal acceleration of 30 G. The pile group was set in a dry sand layer inside a rigid container. In the vertical loading tests, the pile group was pushed-in and pulled-out. In the lateral loading tests, the pile group was subjected to overturning moment as well as lateral loading. When the pile group was subjected to both vertical and horizontal loading, the shaft friction was different for different piles within the pile group. The shaft friction of piles on the front side increased at shallow depths, while on the rear side it significantly decreased at shallow depths. This difference is large when the pile spacing is small.

1 INTRODUCTION

During earthquakes, structure-supporting piles are subjected to lateral loads, as well as vertical loads due to the overturning moment of the structure. To counteract the vertical loads, the friction along the pile shafts increases. In previous studies, the generation of shaft friction on piles was investigated through vertical loading tests (e.g. Tsuha et al. 2012; White & Lehane 2004), but few studies have been conducted so far on the effects of lateral loading on shaft friction. When the spacing of piles is small, the pile group effects are significant. In this case, in the front pile the horizontal resistance is larger than in the rear pile due to shadowing effects (e.g. Danno et al. 2007; Rollins et al. 1998; Suzuki & Adachi 2003), whereby the stress state of the soil around piles is different for different piles within the pile group.

The lateral response of pile response under combined loads have been investigated in previous studies. Hussin et al. (2014) showed that the influence of vertical loading on lateral response of piles varied within a pile group based on finite elements analyses. Lu and Zhang (2018) investigated the influence of vertical-horizontal combined loads on response of a single pile based on centrifuge model tests. They reported that vertical load induced an increase in lateral resistance of piles due to the “soil densification effect”, in which the vertical load densified the soil near piles. Vertical and lateral response of piles might have interacted with each other when the piles are subjected to both vertical and lateral force.

The objective of this study is to investigate the effects of lateral loading on the shaft friction of piles. Lateral and vertical loading tests were conducted on a 2×2 pile group under a centrifugal acceleration of 30 G. The lateral load was applied on a tall plate, set on a pile group that thus was subjected to a vertical load due to the overturning moment as well as a lateral load. As a result, the piles on one side of the pile group were subjected to a compression load and those on the other side were subjected to a tension load. Based on test results, the difference in the shaft friction between lateral and vertical loading tests is estimated.

2 LOADING TESTS ON A 2×2 PILE GROUP

The loading tests were conducted under a centrifugal acceleration of 30 G and the length scale of the test models was 1:30. Figure 1 shows the test models constructed in a rigid container of 200 mm ×1000 mm ×500 mm. A 2×2 pile group was set with an embedment depth of approximately 300 mm in dry silica sand (e_{max} = 0.982, e_{min} = 0.604) that was air-pluviated with a relative density of approximately 70 % and a height of 392 mm. The pile models were made of stainless steel pipes with a diameter of 15.9 mm and a thickness of 0.3 mm.

In the vertical loading tests, the pile spacing within the pile group was 3.5 times the pile diameter (3.5 D). The pile group was pushed-in and pulled-out. In the lateral loading tests, the pile spacing was 3.5 D and 7.0 D. As shown in Figure 1(b), the pile group had a tall plate on its footing and the lateral load was applied on the plate 100 mm above the ground surface. Therefore, the pile group is subjected to vertical load due to overturning moment in addition to lateral load. The piles on the front side of the pile group are subjected to a compression load and those on the rear side are subjected to a tension load. Two piles within the pile group had strain gauges on their inner surface at nine depths and the other two had strain gauges installed at two depths. Displacement meters were set on the footing. To increase the shaft friction, dry silica sand was pasted on the surface of each pile.

Table 1 lists the tests performed. The loads were applied until the piles strain reached 1000 μ or the applied load reached the capacity of the load cell. The maximum loads in the prototype scale are listed in Table 1. In V-3.5TC, the pile group was subjected to tension loads and then compression loads. In the other series, the pile group was subjected to loads twice in the same direction. Hereafter, the test results are referred to by their prototype scale.

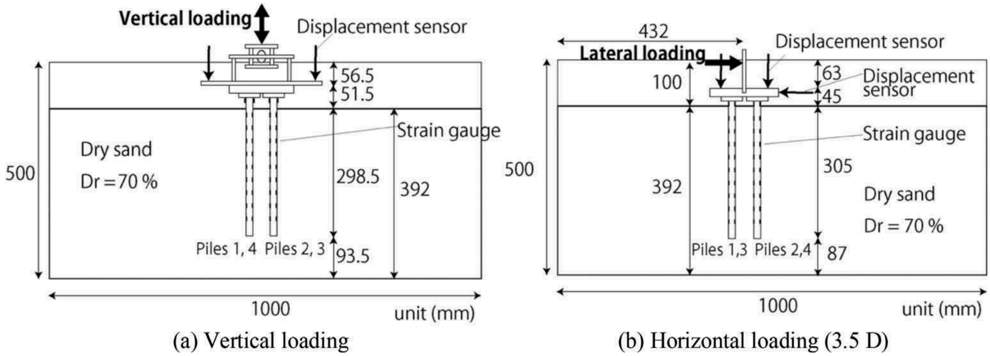

Figure 1. Loading test setup

Table 1. Test series

	Loading	Pile spacing	Maximum load (prototype scale)
V-3.5TC	Vertical loading (Tension (+), Compression (-))	3.5 D	+2700 kN -8800 kN
V-3.5C	Vertical loading (Compression (-))	3.5 D	-7700 kN
H-3.5	Horizontal loading	3.5 D	740 kN
H-7.0	Horizontal loading	7.0 D	1000 kN

*D: Pile diameter

3 TEST RESULTS

Figure 2 shows the relationship between the applied vertical loading and the vertical displacement of the footing for the vertical loading tests (V-3.5TC, V-3.5C). Positive and negative loads indicate tension and compression, respectively. In V-3.5TC, the pile group is pushed after being pulled. In V-3.5C, the pile group is pushed twice. The vertical displacement is 0.2 D (pile diameter) and 0.1 D when pushing and pulling, respectively. Figure 3 shows the relationship between the applied horizontal load and the horizontal displacement of the footing and between the overturning moment and the vertical displacement of the pile head, in the lateral loading tests (H-3.5, H-7.0). The overturning moment is computed under an assumption that the rotational center is located at the bottom of the footing. The vertical displacement at the pile head is estimated relative to four points of the footing, assuming that the footing is rigid. The compression force is applied on the front side of the pile group and the tension force is applied on the rear side by the overturning moment.

The horizontal displacement is larger in H-7.0 than in H-3.5 because the load applied in the former is larger (Figure 3a, b). Under the same loads, the horizontal displacement is larger in H-3.5 than in H-7.0, indicating that in H-3.5 the horizontal resistance is smaller. The vertical

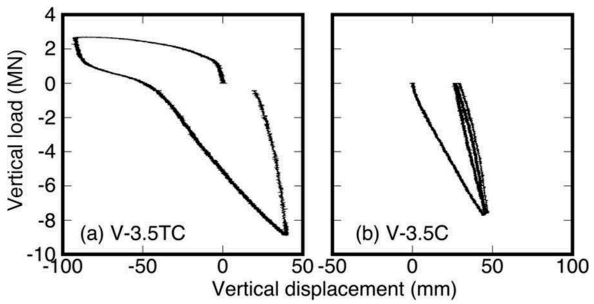

Figure 2. Relationship between vertical loading and vertical displacement for (a) V-3.5TC and (b) V-3.5C.

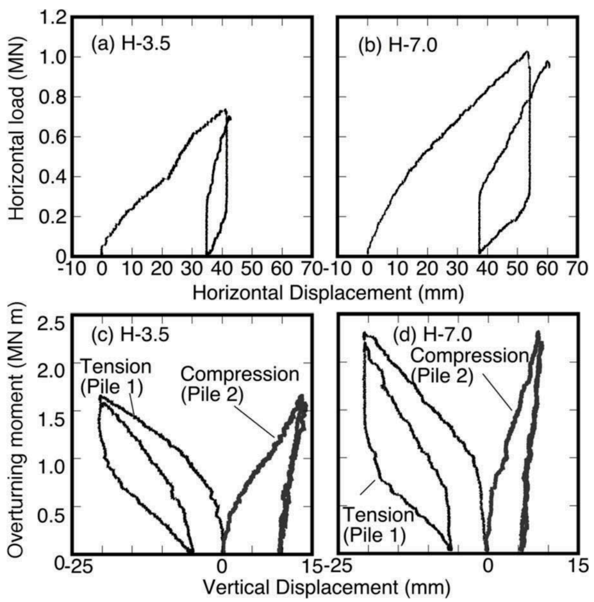

Figure 3. Relationship between horizontal load and horizontal displacement for (a) H-3.5 and (b) H-7.0 and between overturning moment and vertical displacement for (c) H-3.5 and (d) H-7.0.

displacement under the same overturning moment magnitudes is larger in H-3.5 than in H-7.0, indicating that the rotational resistance is also smaller in H-3.5 (Figure 3c, d). The vertical displacement is larger on the side under tension than the one under compression. Figures 2 and 3 show that the displacement is not zero during unloading. This study investigates the shaft friction during the virgin loading, but not during unloading and/or the second loading.

Figures 4 and 5 show the distribution of the axial forces with depth for the maximum loads in each test. The axial force is computed from the measured axial strain. In each test, the axial force is large at the pile head and decreases with depth. This indicates that the shaft friction acts against the external load. The inclination of the axial force with depth tends to be small in the tension direction. Furthermore, the axial force in the tension side appears constant near the ground surface in H-3.5 (Figure 5(a)).

Figure 6 shows the bending moment distributions with depth for the horizontal loading tests. A comparison between the bending moment of the piles shows that the difference in bending moment between the front and rear piles is bigger in H-3.5 than in H-7.0. This is attributed to the pile group effects being significant in groups with small pile spacing. It is interesting to note that the rotation of the footing is large in H-3.5, where the bending moment decreases towards the pile head. This is consistent with the observation that the vertical displacement is large in H-3.5 (Figure 3).

To investigate the difference between the axial forces, Figures 7 and 8 show the relationship between the vertical displacement and the shaft friction of the upper section (to a depth of approximately 4 m) and the lower section (to a depth of approximately 4 m to 8 m) for each test. Figure 7 indicates that the shaft friction in the vertical loading tests was larger in the lower section than in the upper section and was larger during compression than during tension. Figure 8 shows that in the lateral loading tests, the shaft friction at the compression side was larger in the upper section than in the lower section. In contrast, the shaft friction at the tension side was smaller in the upper section than in the lower section. This is likely caused by the piles subjected to horizontal loads as well as vertical loads. The lateral loading induced differences in the stress state of the soil between the front and rear sides of the pile group. The

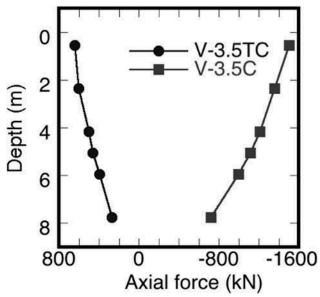

Figure 4. Distribution of axial forces for V3.5TC and V-3.5

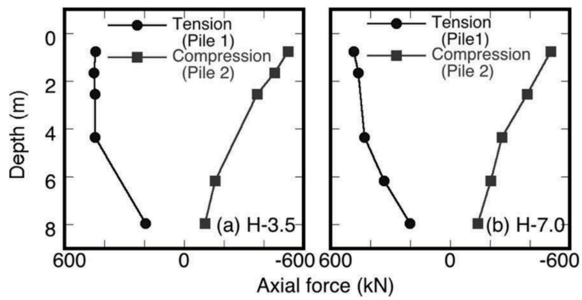

Figure 5. Distribution of axial forces for (a) H-3.5 and (b) H-7.0

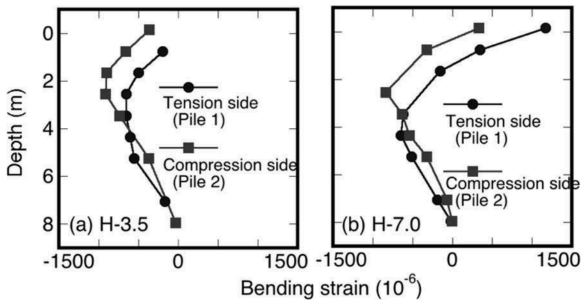

Figure 6. Distributions of bending strain for H-3.5 and H-7.0

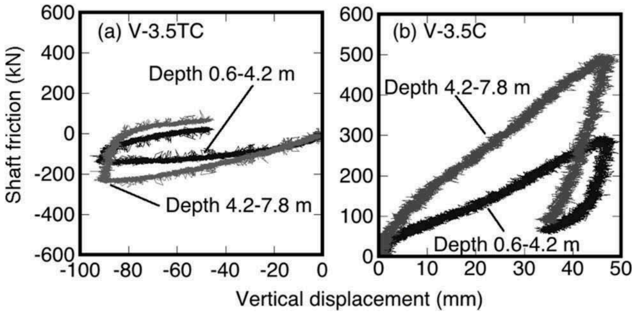

Figure 7. Relationship between shaft friction and vertical displacement for (a) V-3.5TC and (b) V-3.5C

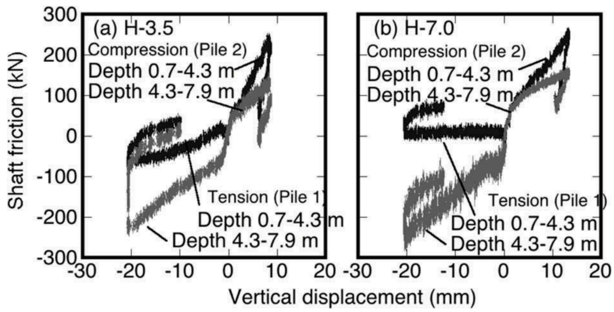

Figure 8. Relationship between shaft friction and vertical displacement for (a) H-3.5 and (b) H-7.0

horizontal stress was larger in the front pile than in the back pile due to pile group effects. As a result, near the ground surface, where the horizontal pile deformation was large, the shaft friction was larger in the front side (compression side). This trend is more significant in H-3.5, where the pile spacing was small.

4 CONCLUSIONS

To investigate effects of lateral loading on shaft friction of piles, lateral and vertical loading tests were conducted on a 2×2 pile group under a centrifugal acceleration of 30 G The following results were obtained:

1. The shaft friction of piles is larger in the compression direction than in the tension direction. When a pile group is subjected to only a vertical load, the shaft friction increases with increasing depth.

2. When a pile group is subjected to both vertical and horizontal loads, the shaft friction is different between piles on the compression and tension sides. The shaft friction of piles on the compression side increases at the upper depth. In contrast, the shaft friction of piles on the tension side significantly decreases at the upper depth. This is because lateral loading makes the front and rear sides of the pile group, so the horizontal stress of the soil around the piles is different on the two sides.
3. The difference in shaft friction between the piles on the two sides of the pile group is more significant when the pile spacing is smaller.

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