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Horizontal loading tests of single piles with different diameters in a centrifugal field

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ABSTRACT: Large diameter cast-in-place concrete piles are frequently used in high-rise buildings. Evaluating the horizontal resistance of piles is one of the most important tasks in the design of pile foundations. However, the applicability of the design methods applied for small-diameter piles to large-diameter piles remains unclear. In this study, horizontal loading tests were conducted on five single piles with different diameters in centrifugal fields to obtain basic experimental data. The pile diameters ranged from 1 to 5m on the prototype scale. The experimental results showed that, as the pile diameter increased, the pile head load per pile diameter increased and the depth at which the maximum bending strain occurred increased. The results of these experiments provide valuable basic data for evaluating the horizontal resistance of large-diameter piles.

1 INTRODUCTION

In recent years, several high-rise buildings have been constructed in metropolitan areas. Large-diameter cast-in-place concrete piles are often used in high-rise buildings because of the heavy weight of their upper structures. The pile foundations of buildings are subjected to horizontal loads owing to earthquakes and winds. The evaluation of the horizontal resistance of piles is one of the most important tasks in the design of pile foundations. However, conducting full-scale horizontal load tests on large-diameter piles requires significant time and expense, and the applicability of design methods applied for small diameter-piles to large-diameter piles remains unclear.

Full-scale horizontal loading tests on piles with relatively large diameters piles have been reported (Yamamoto et al. 1979; Ebine et al. 1980; Ng et al., 2001). These tests were conducted on concrete piles with diameters up to 3 m. Mano et al., 2021 conducted lateral loading tests in a centrifugal field of rectangular piles with different pile widths ranging from 0.4 to 20.4 m on the prototype scale, and Odagiri et al., 2023 simulated these tests using 3D FEM analysis and discussed the effect of the pile width on the pile lateral resistance and soil deformation area caused by a lateral loaded pile.

Although some studies have focused on the lateral resistance of large-diameter piles, horizontal loading tests on piles are often conducted on piles with diameters of approximately 1 m or less. In this study, horizontal loading tests of five single piles with different pile diameters (1 to 5 m on the prototype scale) in centrifugal fields were conducted to obtain basic experimental data.

2 METHODOLOGY OF HORIZONTAL LOADING TEST

The experiments were conducted using a beam-type centrifuge at a centrifugal acceleration of 50*g* at the center depth of the ground (at the depth of 500 mm (prototype scale: 25 m) from surface). The experimental models are shown in Figure 1. Horizontal loading tests were conducted on five piles with different diameters. The experimental cases and pile sizes on the prototype scale are presented in Table 1. The pile diameters (D) ranged from 1 to 5 m. The pile sizes and stiffnesses on the model scale are listed in Table 2.

The model piles were aluminum pipes with diameters of 20 to 100 mm and thicknesses of 1 to 5 mm. The piles were designed assuming cast-in-place concrete piles. The pipe thickness was set so that the flexural rigidity of the pile was equivalent to that of a cast-in-place concrete pile with the same pile diameter. The target prototype pile flexural rigidity was the initial value and did not account for reduction of flexural rigidity due to pile deformation. All pile models were 983 mm in lengths (prototype scale: 49.15 m) and had embedded lengths (L) of 905 mm

(45.25 m). Because the models were designed as piles for building foundations, the pile lengths were sufficiently long to represent practical pile lengths. The pile length to diameter (L/D) ratio was 9.05 to 45.25. Pairs of strain gauges were affixed to 20 levels outside the piles. Lids were attached to the bottom of the piles, and the interiors of the piles were hollow. The pile caps were 30 mm high, and the planar shapes were square or hexagonal. Toyoura sand was bonded to the pile surfaces using an epoxy adhesive to account for the friction between the pile and ground.

The internal dimensions of the rigid soil container were 840 mm long, 510 mm wide, and 1055 mm high. Maximum dimensions of the centrifuge table were 960 mm long, 650 mm wide, and 1350 mm high. The ground models were 1000 mm deep (50 m). Although the centrifugal acceleration was set at 50g at the center depth of the ground, the centrifugal acceleration

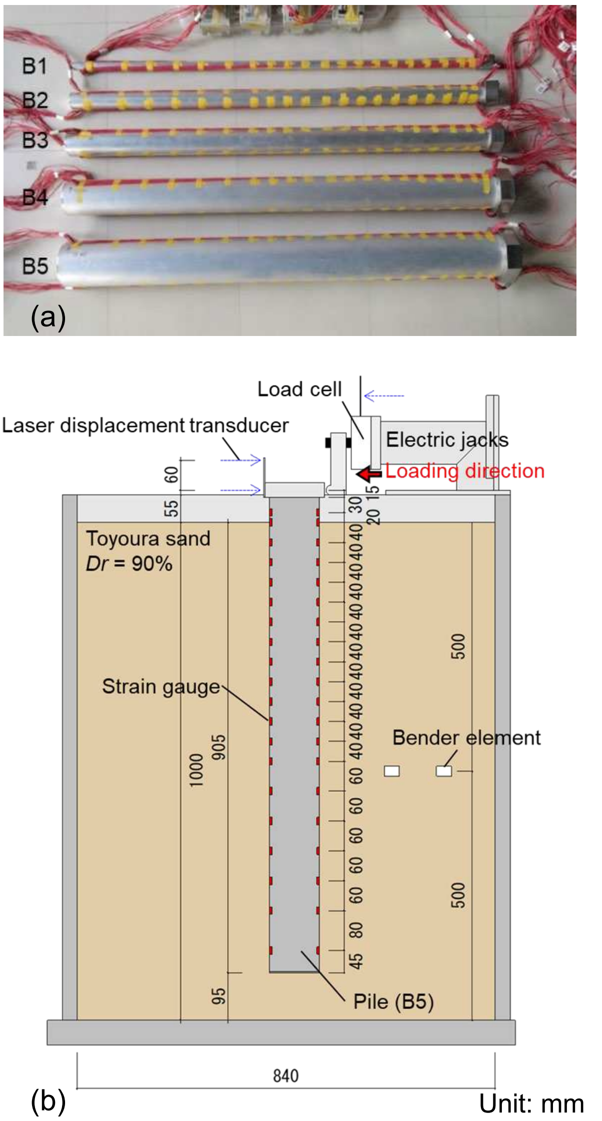

Figure 1. Experimental model: a) model piles and b) detail plan (B5).

measured at the bottom of the soil container was 59g and that measured at the surface level of the ground was 42g due to the height of the soil container. Dry Toyoura sand was used as the ground material. Figure 2 shows the grain size distribution curve. The average grain size (D_{50}) of the Toyoura sand was 0.196 mm and the relative density (D_r) of the ground was set to 90% using the air pluviation method. The model pile was set up when the ground was piled up to 95 mm from the bottom of the soil container. A surface layer was formed after the position of the pile head fixed. Bender elements were used to measure the shear wave velocity at the center depth of the ground.

Figure 3 shows the depth distributions of the shear wave velocity and shear modulus of the soil. The shear wave velocity was measured as centrifugal acceleration increased, with 5G increments. Depth represents the prototype-scale installation depth of the

Table 1. Experimental cases and sizes of the piles on the prototype scale.

Pile identifier	Diameter (D) (m)	Embedded length (L) (m)	L/D
B1	1	45.25	45.25
B2	2	45.25	22.63
B3	3	45.25	15.08
B4	4	45.25	11.31
B5	5	45.25	9.05

Table 2. Sizes and stiffnesses of the piles on the model scale.

Pile identifier	Diameter (mm)	Thickness (mm)	Flexural rigidity (Nm^2)
B1	20	1	183
B2	40	2	2930
B3	60	3	14800
B4	80	4	46900
B5	100	5	114000

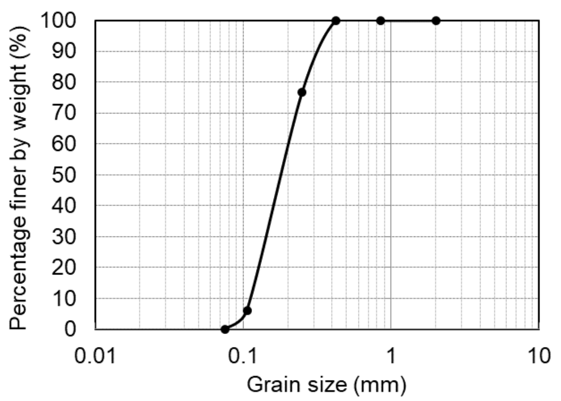

Figure 2. Grain size distribution curve of Toyoura sand.

bender element at that centrifugal acceleration. In the case of B3, shear wave velocity was not measured at 5G (depth of 2.5 m). In all of the experimental cases, the shear wave velocity of the soil was confirmed to be generally proportional to the 1/4 power of the depth, and the ground conditions for all experiments were approximately the same. The shear modulus of the soil was calculated using the shear wave velocity (Figure 3 (a)) and the soil density (ρ: 1.60 g/cm³) determined from the minimum dry density (ρ_{min}: 1.353 g/cm³) and maximum dry density (ρ_{max}: 1.638 g/cm³) of Toyoura sand. It was confirmed that the shear modulus of the ground was generally proportional to the 1/2 power of the depth (Figure 3 (b)).

Horizontal loading was applied to the pile cap (65 mm above the ground surface) using an electric jack. The electric jack was fixed to the soil container. The loading system was designed to allow the loading level to be as close as possible to the ground surface level to simulate the external forces acting on the actual piles of buildings. The pile head was free. A load cell was used to measure the load on the pile head, and laser displacement transducers were used to measure the horizontal displacement of the jack, pile head at the loading level and the upper part of the pile 60 mm above the loading point (Figure 1 (b)).

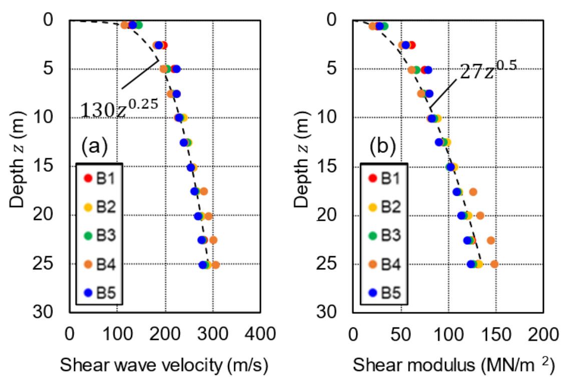

Figure 3. Depth distribution: (a) shear wave velocity and (b) shear modulus.

3 EXPERIMENTAL RESULTS

The experimental results are presented on the prototype scale. Figure 4 shows the relationships between the pile head displacement (loading point height) and horizontal load of the pile head. Owing to the capacity of the loading system, the pile head displacements for B4 and B5 were small. As the pile diameter increased, the pile head load also increased. When the pile head displacements were 1000 mm, the pile head loads of B1 and B2 were almost in the ultimate state, and the pile head load of B2 was 5.6 times that of B1.

Figure 5 shows the relationships between the pile head displacement and pile head load per pile diameter D. As the pile diameter increased, the pile head load per pile diameter also increased. Mano et al., 2021 conducted lateral loading tests on rectangular piles with equal pile thicknesses but different pile widths and reported that the pile head load per pile width decreased, as the pile width increased. Although this report by Mano et al., 2021 contradicted the results of these experiments in this paper, the flexural rigidity of the rectangular piles used by Mano et al., 2021 was constant, regardless of the pile width, whereas the flexural rigidity of piles in this study increased as the

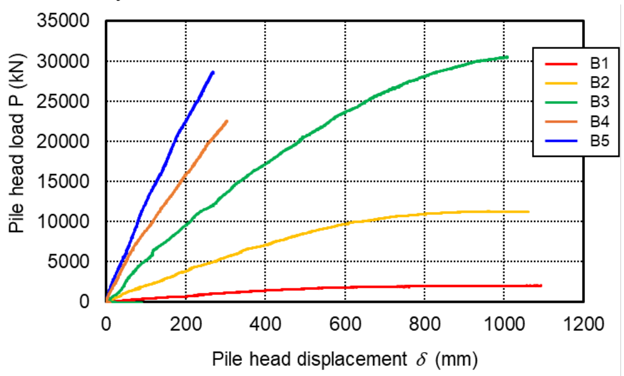

Figure 4. Relationships between pile head displacement and pile head load.

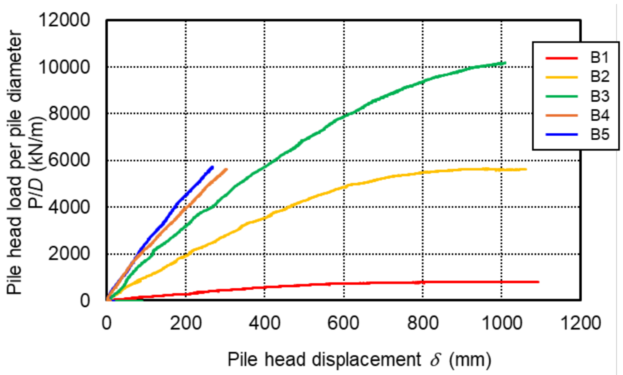

Figure 5. Relationships between pile head displacement and pile head load per pile diameter.

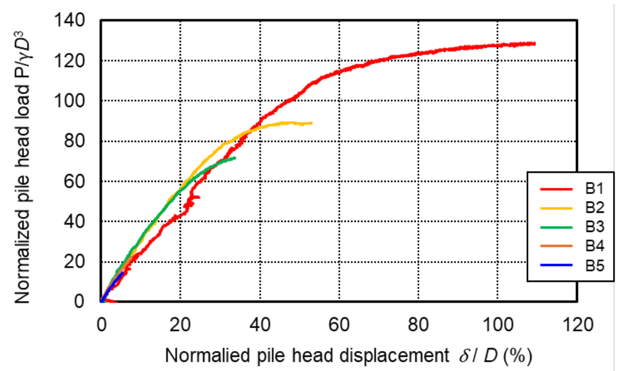

Figure 6. Relationships between the normalized pile head displacement and normalized pile head load.

pile diameter increased. Therefore, in this study, it is considered that the pile head load per pile width increases as pile diameter increases.

Figure 6 shows the relationships between the normalized pile head displacement and normalized pile head load. The pile head displacement δ wasnormalized by the pile diameter D, and the pile head load P was normalized as P/γD^3, where P is the pile head load, γ is the unit weight of the soil, and D is the pile diameter. The initial stiffness of all piles became almost identical through normalization. At B1, the pile head load increased almost linearly until the pile head displacement was approximately 40% of the pile diameter, and the increase in the pile head load became smaller when the pile head displacement exceeded 50% of the pile diameter. In the last phases of the tests, B1 and B2 reached almost the ultimate state with the increase in the pile head load being less than one-tenth of the initial increase. Comparing B1 and B2 the normalized maximum pile head load was greater for B1.

Odagiri et al., 2024 reported that pile displacement formed a 3D resistance zone in the soil. Figure 7 shows the contour charts of the total displacement of ground surface and ground section at the pile head horizontal displacement of 40% of the pile diameter. The displacement distribution in front of the pile on the ground surface exhibited a nearly circular pattern, whereas that on the ground section exhibited a quadrangular. The result that the normalized ultimate load on B1 was larger than that of B2 suggests that the size of this resistance zone was not scaled by the pile diameter in each direction.

Figure 8 shows the depth distribution of the bending strain at pile head displacements of 20, 40, 60, 80, and 100 mm. The bending strain was calculated using a pair of strain gauges affixed at the same level. The bending strains of B3 at a depth of 8 m and B5 at a depth of 12 m were not measured. The maximum bending strain was larger for smaller pile diameters at the same pile head displacement. The depth at which the maximum bending strain occurred increased with the pile diameter. This is because the flexural rigidity of the piles increased as the pile diameter increased.

The bending strain was maximized at a depth of approximately 3 m for B1 and at a depth of approximately 15 m depth for B5. The bending strainoccurred at depths of approximately 10 times the pile diameters. As the pile diameter increased, the flexural rigidity of the piles also increased, and the stresses were transmitted to the deeper parts of the piles.

Figure 9 shows the pile models after loading. B1 exhibited apparent plastic deformation. Both the depth at which deformation occurred and that at which the maximum bending strain occurred for B1 were 3 m. B5 did not show obvious deformation, which was owing to the effect of the strain occurring even in the deeper part (Figure 8 (e)).

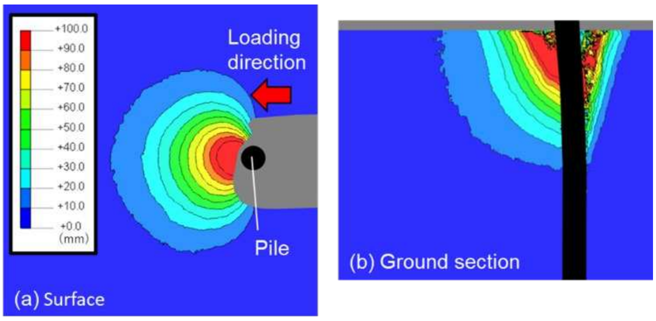

Figure 7. Total displacement of the ground surface and ground section during pile horizontal loading (revised to Odagiri et al., 2024).

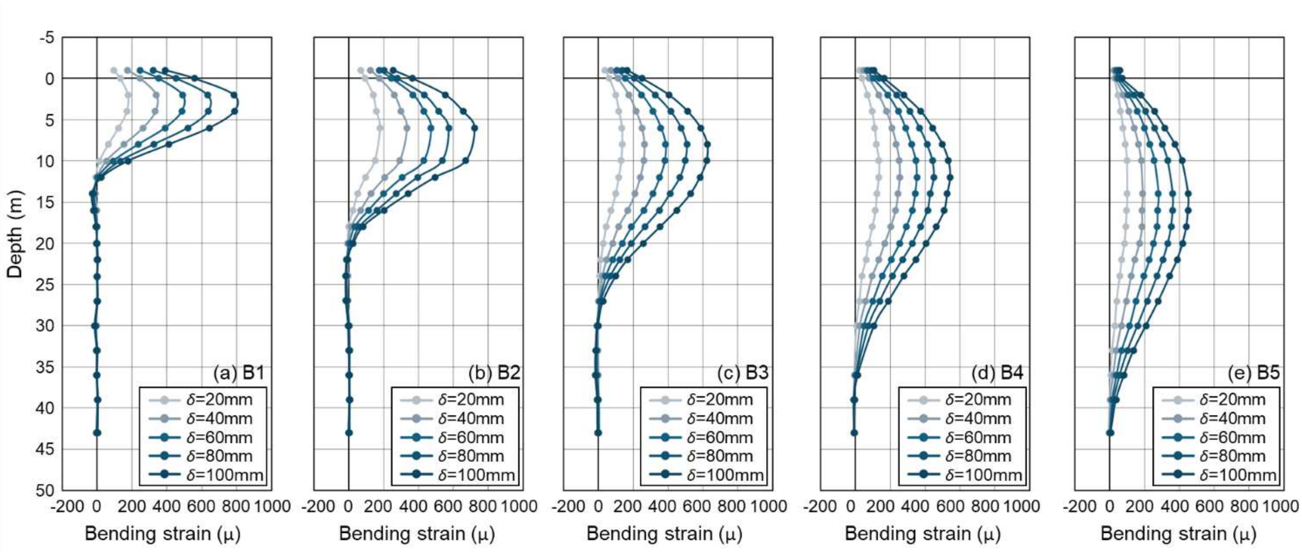

Figure 8. Depth distribution of bending strain at pile head displacements of 20, 40, 60, 80, and 100 mm: (a) B1, (b) B2, (c) B3, (d) B4, and (e) B5.

Figure 9. Pile model after loading.

4 CONCLUSIONS

Horizontal loading tests were conducted on five piles with diameters ranging from 1 to 5 m. The piles were designed assuming cast-in-place concrete piles. The experimental results showed that as the pile diameter increased, the pile head load per pile diameter increased and the depth at which the maximum bending strain occurred increased. This is because the flexural rigidity of the piles increased as the pile diameter increased. The initial stiffness of pile head load and pile head displacement relationships became almost identical regardless of pile diameters through normalization.

Further analyses will be conducted based on these experimental results to evaluate the effects of the pile diameter on the horizontal subgrade reaction.

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