Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Experimental study on the horizontal resistance of pile foundations adjacent to retaining walls and shallow ground improvements

K. Watanabe
Department of Civil Engineering, Aichi Institute of Technology, Aichi, Japan, k-watanabe_28@aitech.ac.jp

N. Kamogawa, M. Nakamura
Technical Research Institute, HASEKO Corporation, Tokyo, Japan, Naomasa_Kamogawa@haseko.co.jp, Mitsuo_Nakamura@haseko.co.jp

ABSTRACT: The functions required of foundation structures, including pile foundations, must satisfy the functions of the superstructure and safely support it, while also ensuring the stability and durability of the foundation structures themselves. In Japan, many large cities are located on soft alluvial plains, and pile foundations have come to be widely used to avoid functional deterioration of the superstructure due to factors such as the reliability of bearing capacity. The support performance of pile foundations supporting superstructures includes vertical support characteristics and horizontal resistance characteristics. In Japan, which is located in an earthquake-prone area, evaluating the horizontal resistance of pile foundations when subjected to horizontal forces caused by earthquakes is particularly important. It is desirable to establish a reasonable method for evaluating horizontal resistance while ensuring the functionality of pile foundations. Buildings with underground structures require excavation of the ground during construction of the underground structure. To prevent ground collapse or deformation of the surrounding ground during this process, retaining walls are constructed. In recent years, soil-cement mixing walls and shallow ground improvements have been widely adopted as retaining walls due to their performance and economic advantages. In this study, the objective is to evaluate the horizontal resistance characteristics of pile foundations installed near retaining walls through centrifugal model experiments, while ensuring the functionality of the pile foundations and establishing a reasonable method for evaluating horizontal resistance characteristics.

1 INTRODUCTION

Pile foundations and other types of foundation structures are required to safely support superstructures while satisfying their functional requirements, as well as to ensure the stability and durability of the foundation structures themselves. In Japan, many major cities are located on soft alluvial plains, and pile foundations have therefore been widely adopted to avoid deterioration of superstructure performance by ensuring reliable load-bearing capacity. The bearing performance of pile foundations supporting superstructures can be categorized into vertical bearing characteristics and lateral resistance characteristics.

In particular, because Japan is situated in a seismically active region, it is crucial to evaluate the lateral resistance of pile foundations subjected to horizontal forces induced by earthquakes. Therefore, in Japan, active research is being conducted on the horizontal resistance of pile foundations (e.g. Tominaga et al., 1980, Tokimatsu and Asaka, 1998, Shirato et al., 2008). Accordingly, it is desirable to establish a rational evaluation method for lateral resistance while maintaining the required functions of pile foundations.

Buildings with basements require excavation of the ground when constructing the underground structure. To prevent ground collapse and deformation of the surrounding ground during excavation, earth-retaining walls and shallow ground improvement bodies are constructed. In recent years, soil–cement column walls have been widely used as earth-retaining walls from the viewpoints of structural performance and economic efficiency. Soil–cement column walls are constructed by inserting core members, which act as stress-transmitting elements, into soil–cement formed in situ.

In this study, with the aim of ensuring the functional performance of pile foundations while rationally evaluating their lateral resistance characteristics, centrifuge model tests were conducted

Figure 1. The overview of the test equipment.

Table 1. The specifications of the test equipment.

Item	Specification
Effective radius	1,360mm
Maximum centrifuge acceleration	200G (75G)
Arm height	1.00m
Maximum centrifuge capacity	15G-t
Maximum loafing weight	0.2t (75G)
Maximum rpm	360rpm

to investigate the lateral resistance behaviour of pile foundations installed in close proximity to earth-retaining walls and shallow ground improvement.

2 CENTRIFUGE MODEL TEST

2.1 Centrifuge apparatus

The Aichi Institute of Technology Centrifuge (AIT Centrifuge) was used in the model test described in this paper. This centrifuge is a beam type with a pair of parallel arms that hold platforms on which the model container and a counterbalance weight are mounted as shown in Figure 1. Effective radius of rotation is 1.36m, which is the distance from the rotating shaft to the platform base. The surface of swinging platform is always normal to the resultant acceleration of the centrifuge acceleration, nG, and the earth's gravity. The specifications of AIT Centrifuge are summarized in Table 1.

2.2 Test condition

Centrifuge model tests were conducted for three cases: Case 1 (without an earth-retaining wall), Case 2 (with an earth-retaining wall at a separation distance of 1.0D), Case 3 (with an earth-retaining wall at a separation distance of 1.5D) , and Case 4 (with shallow ground improvement at a separation distance of 1.0D), where D denotes the diameter of the model pile. An overview of the test setup for the centrifuge model tests, as well as the locations of laser displacement transducers and strain gauges, are shown in Figure 2.

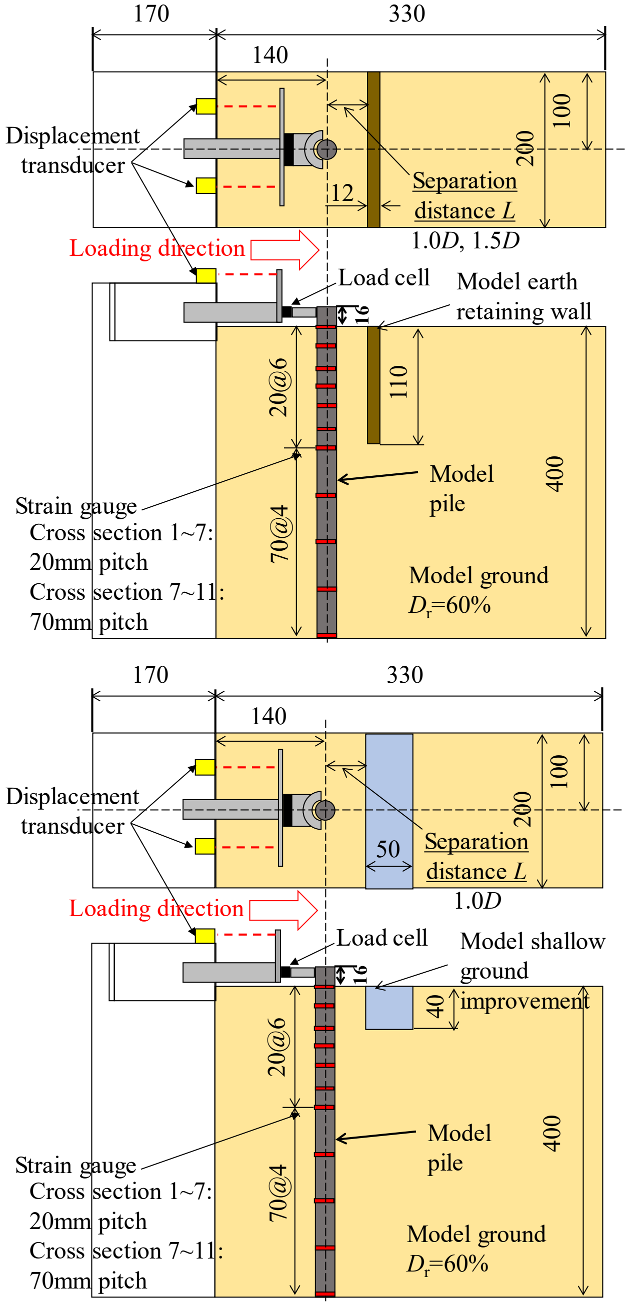


Figure 2. Overview of test setup for centrifuge model tests.

In the test setup, a model pile was installed in a rigid soil container, and model ground was prepared using the air-pluviation method to achieve the specified layer thickness and a relative density of D_r = 60%. The ground material used in the model tests was silica sand No. 7, and its physical properties are summarized in Table 2. In Cases 2 and 3, a model earth-retaining wall was installed at a prescribed depth.

The model pile was designed to represent a concrete pile, and a stainless steel (SUS) pile was used as the model pile in consideration of similitude laws.

Table 2. Physical properties of silica sand No. 7.

Parameter	Value
Density of soil particle ρ_s	2.626g/cm^3
Minimum void ratio e_{min}	0.621
Maximum void ratio e_{max}	1.156
Mean particle diameter D_{50}	0.192mm
Uniformity coefficient U_c	2.442
Coefficient of curvature U_c'	1.085

Figure 3. Model earth retaining wall.

Table 3. Mix proportions of soil–cement column wall.

Material	Mixing quantity per unit volume (kg/m^3)
Water	448.6
Cement	231.5
Sand (Silica sand No. 7)	1178.0
Bentonite	28.1
Dispersing agent	20.0

The model pile had a diameter of 30 mm, a length of 416 mm, and a wall thickness of 0.4 mm, with the pile tip fixed.

The earth-retaining wall was assumed to be a soil–cement column wall, with a height of 110 mm, a depth of 200 mm, and a thickness of 12 mm. A miniature H-shaped steel section (H-8 × 4 × 0.16 × 0.26 mm) as shown in Figure 3 was inserted into the wall body as a core member. The distance between the tip of the soil–cement and the core member was set to 10 mm. The mix proportions of the soil–cement column wall are shown in Table 3. The strength of the soil–cement column wall was confirmed by unconfined compression tests using test specimens prepared at the time of casting, and the centrifuge tests were conducted after the target strength had been achieved.

To simulate actual construction conditions, No. 7 silica sand was applied to the side and bottom surfaces of the soil–cement column wall model. In this study, a 1/50-scale model was adopted, and centrifuge acceleration of 50G was applied to perform static lateral loading tests. Loading was applied at the pile head using an electric jack installed within the model soil container, with a displacement-controlled loading rate of 1.0 mm/min. The measured parameters

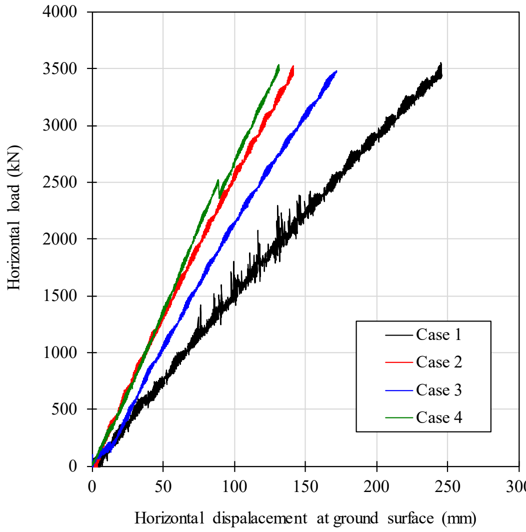


Figure 4. Relationships between horizontal load and displacement at ground surface.

included the horizontal load and displacement at the loading point, as well as strains along the pile shaft.

3 EXPIERIMENT RESULTS

The experimental results presented in this chapter were all converted to prototype scale based on the similitude laws of centrifuge model testing. Figure 4 shows the relationship between horizontal load and ground surface displacement obtained from each test. The ground surface displacement was calculated using Eqs. (1) and (2), based on Chang's elastic beam-on-Winkler-foundation theory for piles in a homogeneous ground. (The Japanese Geotechnical Society, 2002)

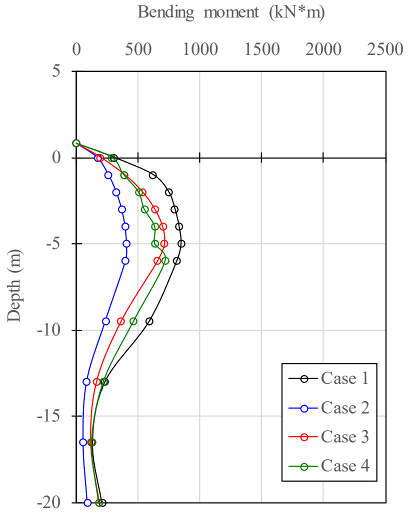
$$y_{top} = \frac{(1+\beta h)^3 + 1/2}{3EI\beta^3} H \tag{1}$$

$$y_0 = \frac{1+\beta h}{2EI\beta^2} H \tag{2}$$

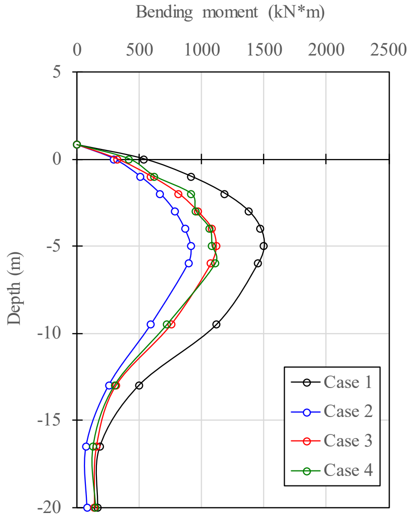
where y_{top} (m) is the displacement at pile head, β is the characteristic values of the pile, h (m) is the Load application height, E (kN/m^2) is the Young's modulus of the pile, I (m^4) is the second moment of area of the pile, and H (kN) is the horizontal load.

As shown in Figure 4, a comparison of the ground surface displacement at a horizontal load of 3000 kN indicates values of 210 mm for Case 1, 120 mm for Case 2, 150 mm for Case 3, and 110mm for Case 4. These results demonstrate that the presence of an earth-retaining wall in close proximity to the pile reduces the ground surface displacement under the same applied load. Moreover, this tendency becomes more pronounced as the separation distance between the pile and the earth-retaining wall decreases. This indicates that the lateral resistance of the pile is enhanced by the presence of the earth-retaining wall, and that a smaller separation distance contributes more significantly to the increase in lateral resistance. In addition, with increasing horizontal load, the difference in ground surface displacement under the same load becomes more evident.

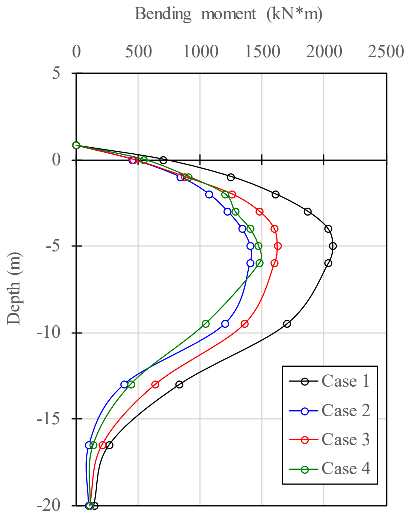
Figure 5 shows the depth distributions of bending moment along the pile at horizontal loads of 400, 800, and 1200 kN. As illustrated in Figure 5, in all cases, relatively large bending moments are generated in the pile within a depth range of up to 10 m from the ground surface. Furthermore, the maximum bending moment tends to decrease when the pile is located closer to the earth-retaining wall. It is also evident that the



(a). Horizontal load H = 400kN.

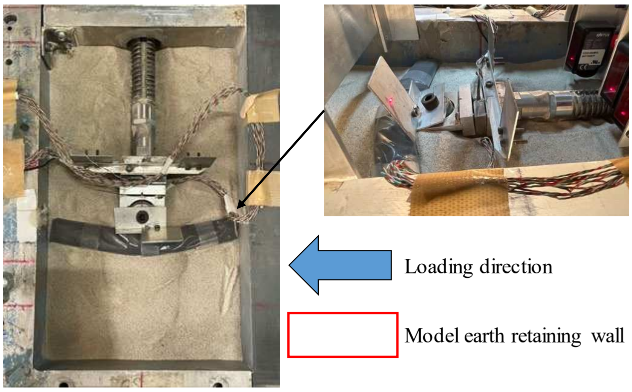


(b). Horizontal load H = 800kN.

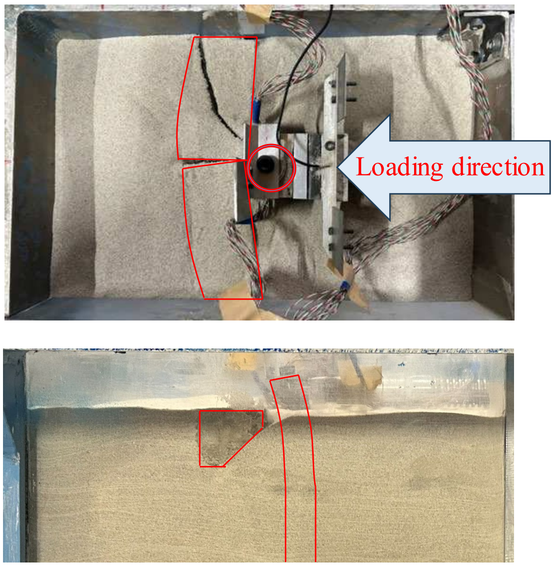


(c). Horizontal load H = 1200kN.

Figure 5. Depth distributions of bending moment.



(a). Case 3.



(b). Case 4.

Figure 6. Test specimen observed after the experiment.

maximum bending moment becomes smaller as the separation distance decreases. As shown in Figure 5, the location of the maximum bending moment is only slightly affected by the presence or absence of the earth-retaining wall, and little difference is observed among the cases.

Figure 6 shows the condition of the test specimen observed after the experiment; the results for Case 3 and Case 4 are presented. After the test, settlement was observed in the ground on the loading rear side of the pile, while ground heave occurred on the loading front side. This tendency was also observed in Cases 1 and 2. This behavior is considered to be caused by the progressive development of passive failure in the ground on the loading front side as loading proceeded. In addition, because loading was continued until the pile experienced large deformation, deformation and damage were observed in the central portion of the earth-retaining wall and the shallow ground improvement.

4 CONCLUSIONS

In this study, centrifuge model tests were conducted to evaluate the lateral resistance characteristics of piles installed in close proximity to earth-retaining walls and shallow ground improvement, with the separation distance between the pile and the earth-retaining wall and the shallow ground improvement adopted as a key parameter. The main findings obtained in this study are summarized as follows:

1) It was confirmed that the lateral resistance of the pile increases due to the presence of the earth-retaining wall and the shallow ground improvement.

2) The lateral resistance of the pile tends to improve as the separation distance between the pile and the earth-retaining wall and the shallow ground improvement decreases.

3) As loading progressed, passive failure developed on the loading front side, resulting in observable deformation on both the loading rear side and the loading front side of the pile.

4) In future work, numerical simulation analyses will be conducted to reproduce the experimental results and to perform more detailed investigations.

REFERENCES

Shirato, M., Nonomura, Y., Fukui, J. and Nakatani, M. (2008). Large-scale shake table experiment and numerical simulation on the nonlinear behavior of pile-groups subjected to large-scale earthquakes. Soils and Foundations, 48 (3): 375-396.

The Japanese Geotechnical Society (2002). Standard for Lateral Load Test of Piles and Its Commentary.

Tokimatsu, K. and Asaka, Y. (1998). Effects of liquefaction-induced ground displacements on pile performance in the 1995 Hyogoken-nambu earthquake. *Special Issue of Soils and Foundations*: 163-177.

Tominaga, K., Yamagata, K. and Kishida, H. (1983). Horizontal displacement of soil in front of laterally loaded piles. *Soils and Foundations*, 23(3): 80-90.