Dynamic centrifuge model tests on plate-shape building's pile foundation in clayey ground

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ABSTRACT

Two dynamic centrifuge model tests were carried out to investigate the seismic behavior of a plate-shape building's pile foundation in the soft clayey ground. The first was a free-field model to explore procedures for producing soft clayey ground. The second was a model using a plate-shape building supported by four piles. It was observed that the rotation of a building remarkably increased when the uplift force on piles exceeded the pullout resistance, and that the inertia force generated in the superstructure was more dominant in the bending moment of piles than the ground deformation though the natural period of the ground (T_{g1}) was longer than that of the superstructure (T_{s1}).

Keywords: centrifuge model test; clayey ground; pile foundation; plate-shape building; seismic behavior

1 INTRODUCTION

The seismic behavior of pile foundations in the soft ground is extremely complicated since the soft ground is intensively nonlinear in mechanical properties and gives large relative displacements to the pile foundations during an earthquake. Plate-shape buildings cause large lateral force and varying axial force in their pile foundations, and also make their seismic behavior more complicated because they each have a high aspect ratio and a single span composed of two columns and several beams. This paper conducted dynamic centrifugal model tests to investigate the seismic behavior of a plate-shape building's pile foundation in the soft clayey ground. However, only a few model tests have been carried out on pile foundations in the clayey ground (Kohama & Sugano 2004, Zhang 2017) because it was troublesome and time-consuming to prepare model grounds from slurry clay. This paper also employs a new procedure using loam, where a wet tamping method was adopted to reproduce the soft clayey ground with a shear wave velocity from 100 m/s to 200 m/s.

This paper firstly reported the seismic response of a free-field model and compared the nonlinear properties obtained from undrained cyclic triaxial tests. Next, the interaction in a superstructure-pile-ground system was investigated in the model test using a plate-shape building and a pile foundation.

2 TEST PROGRAM

Figure 1 illustrates a schematic diagram of a plate-shape building and a pile foundation in the soft clayey ground. A 13-story superstructure with 40 m in height and a pile foundation using cast-in-concrete piles, the shaft and bell diameters of which were 1.5 m and 2.2 m respectively, were reproduced in a centrifuge field of 50 g (Kagawa 1978). The building model was made from steel parts to reproduce axial force on the piles (9330 kN) and natural periods of the superstructure (1st: 0.412 s, 2nd: 0.138 s, and 3rd: 0.084 s) in a prototype. Four piles made from an aluminum pipe with a thickness of 1.5 mm were connected to a slab plate through pile caps. There were openings between the pile caps and the soil to prevent the lateral force transmission from the pile caps to the ground.

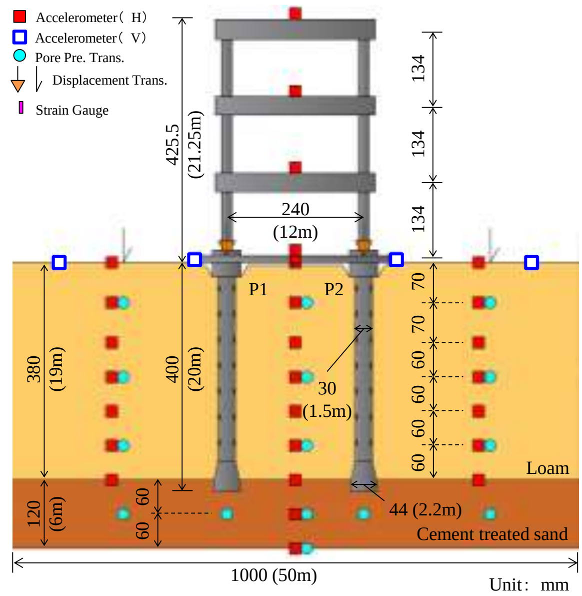


Fig. 1. Schematic diagram of centrifugal model using plate-shape building and pile foundation (Model 2).

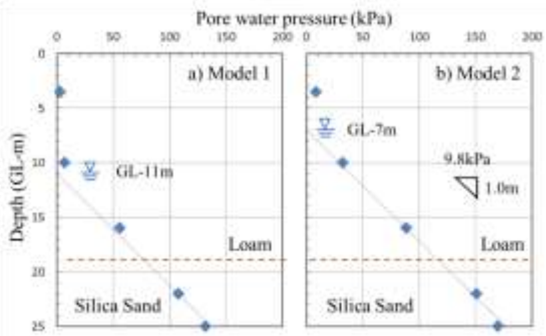
Cement-treated silica sand with an unconfined strength of about 1400 kN/m^2 was used as the bearing stratum for the pile tips. The soft clayey ground was made from loam, volcanic sandy silt and clay. The advantage of using loam was that it was easy to control shear stiffness and strength because it had a wide range of water content due to a wet tamping method. Table 1 shows the physical and mechanical properties of the loam for the centrifuge models. The velocities of the P and S waves in the specimens for cyclic triaxial tests were also measured under several stress conditions (Table 2). We used water as pore fluid, instead of viscous fluid with a viscosity of 50 cSt, for saving time in the consolidation process of a centrifuge field out of consideration that this substitution would not affect the permeability during shaking tests because of the loam's very low permeability (9.0E-07 m/s). Figure 2 shows the profiles of pore water pressure after the centrifuge consolidation. The water tables of the two models were observed to scatter according to the conditions of the models.

Table 1. Physical and mechanical properties of loam used in centrifuge model.

Wet density, ρ_t (g/cm^3)	1.538
Void ratio, e	1.756
Water content, w (%)	63.1
Degree of saturation, Sr (%)	93.4
Cohesion, c' (kN/m^2)	23.5
Friction angle, ϕ' (deg.)	35.7

Table 2. Results of PS logging and undrained cyclic triaxial tests for measuring nonlinear property of loam.

	σ'_a kN/m^2	σ'_r kN/m^2	ρ_t g/cm^3	V_p m/s	V_s m/s	ν	G_d MN/m^2
1	25	25	1.577	461	99	0.476	15.5
2	50	50	1.592	474	102	0.476	16.6
3	100	100	1.594	608	152	0.467	36.8
4	200	200	1.593	833	174	0.477	48.2



(a) Model 1: free field model (b) Model 2: pile foundation model

Fig. 2. Profiles of pore water pressure after consolidation.

Figure 1 also shows the arrangement of transducers. Accelerometers and pore water pressure gauges with ceramic filters were used. Displacement transducers were installed to measure the vertical displacements at the footing and ground surface respectively. Several shaking tests were carried out with increasing the input motion step by step. Figure 3 shows an example of input motion defined as 2E. However, the input motion composed of the upward and downward waves (E+F) is necessary to control the shaking table. Therefore, one-dimensional seismic response analysis was executed using SHAKE. Table 3 shows the relationship between 2E and E+F.

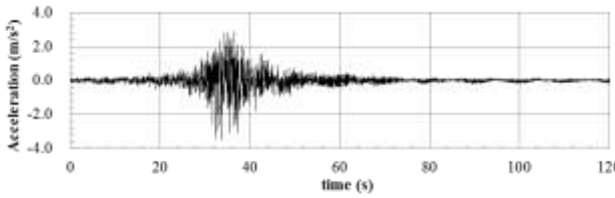


Fig. 3. Example of input motion with a peak acceleration of 3.5 m/s^2 defined as 2E.

Table 3. Peak acceleration used in shaking table tests.

Case No.	Peak acceleration (m/s^2)	
	Outcrop (2E)	Within (E+F)
1	0.50	0.35
2	1.50	0.89
3	2.00	1.23
4	3.50	2.14
5	4.50	2.96
6	6.00	3.85

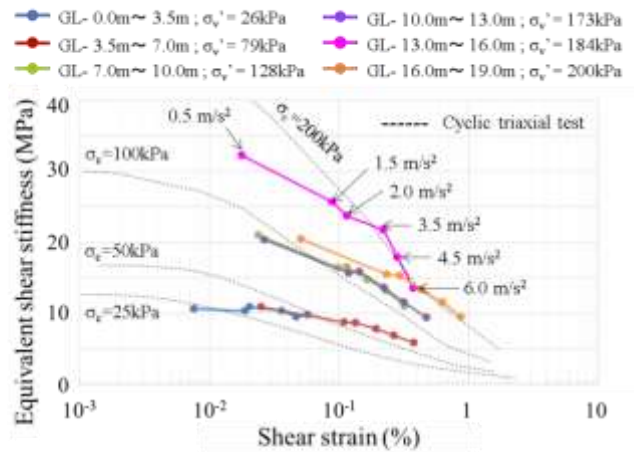


Fig. 4. Comparisons of nonlinear properties in undrained cyclic triaxial tests and centrifuge model test.

3 TEST RESULTS AND DISCUSSIONS

3.1 Seismic response of free-field model in Model 1

Model 1 using a free-field model was tested to explore procedures for producing soft clayey ground. In Fig. 4, the dotted lines show the nonlinear properties obtained from the undrained cyclic triaxial tests under several confining pressures. The solid lines show the relationship between shear strains and equivalent shear stiffness in the several shaking tests with increasing the input motion, where the shear strains were calculated from the measured accelerations, and the shear stresses were calculated using the inertia force at each depth to obtain the equivalent shear stiffness (Okumura et. al. 2017). It is clear from Fig. 4 that the nonlinear properties of the model ground corresponded with those of the undrained cyclic triaxial test results. This revealed that the soft ground was properly reproduced in a centrifuge field as we had expected.

3.2 Seismic behavior of pile foundation in Model 2

The peak accelerations and displacements of the superstructure and ground are summarized in Fig. 5, where the displacements were calculated from the second-order integration of the acceleration records. The charts indicate that the story shear force coefficient obtained from the peak acceleration did not reach 1.0 though the intensive input motion with the maximum acceleration of 6.0 m/s^2 was used, and that the displacement at the footing was larger than that at the ground surface. Figure 6 shows the transition of the 1st natural periods of the superstructure (T_{s1}) and the ground (T_{g1}) with the increase of input motion. We found that the natural period of the ground gradually increased because the nonlinearity of the ground intensified, while the natural period of the superstructure hardly changed.

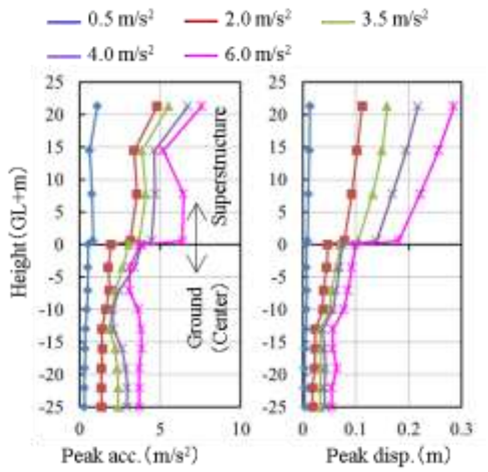


Fig. 5. The peak accelerations and displacements of superstructure and ground in Model 2.

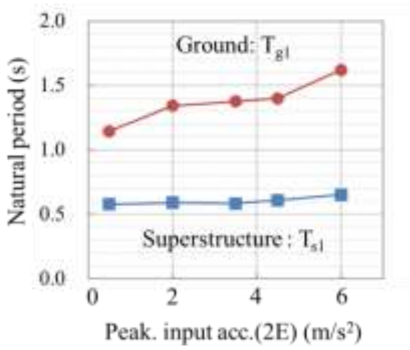


Fig. 6. Transition of the 1st natural periods of superstructure and ground in Model 2.

Figure 7 shows the relationship between the rotation of the superstructure and the overturning moment at the footing level, where the loops were observed in a cycle when the peak acceleration was induced. The rotation was proportional to the overturning moment until the input motion of 3.5 m/s^2. At the levels of 4.5 m/s^2 and 6.0 m/s^2, the rotation suddenly increased, while the overturning moments were restricted to certain values. We consider the reason for this is that the uplift force on the piles pulled out the piles.

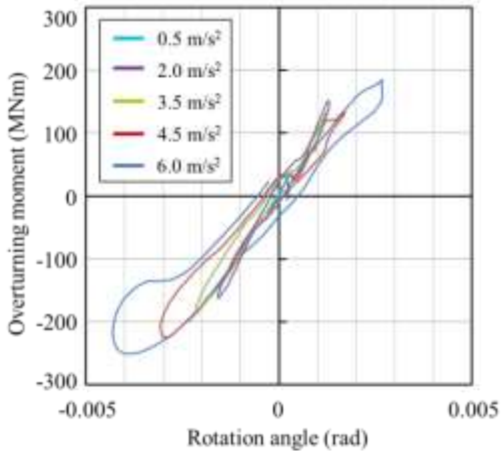


Fig. 7. Relationship between rotation and overturning moment.

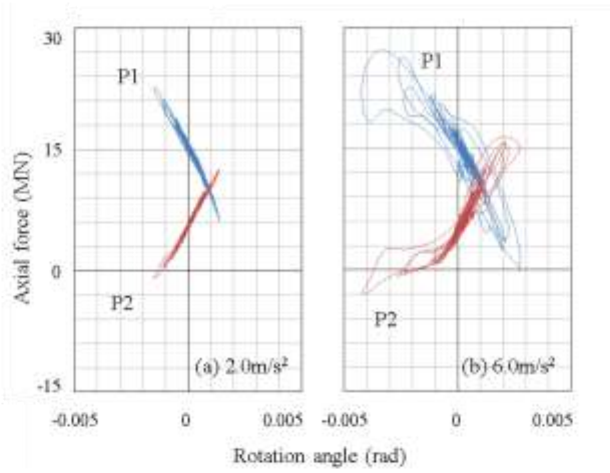


Fig. 8. Relationship between rotation and axial force.

Next, the axial force calculated from the strain gauges at G.L.-15.75 m was plotted against the rotation of the superstructure (Fig. 8). In the stage of 2.0 m/s^2, the uplift force was hardly induced in the piles of P1 and P2. In contrast, the rotation in the stage of 6.0 m/s^2 remarkably increased when the axial force of P2 reached zero. In other words, the rotation became larger because the piles were pulled out due to the large overturning moment. Figure 9 shows the relationship between the inertial force from the superstructure and the bending moment at the pile head, where we found that the bending moment had a distinct correlation with the inertial force of superstructure, and that the bending moment in the stage of 6.0 m/s^2 was restricted to a certain value since the piles were pulled out. In other words, the inertia force generated in the superstructure was more dominant in the bending moment of piles than the ground deformation, though the natural period of the ground was longer than that of the superstructure.

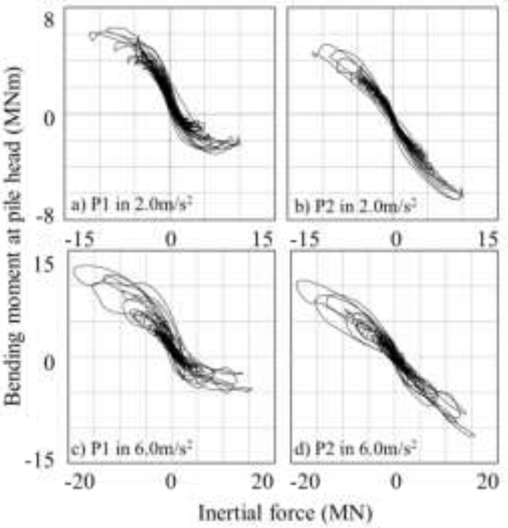


Fig. 9. Relationship between inertial force and bending moment.

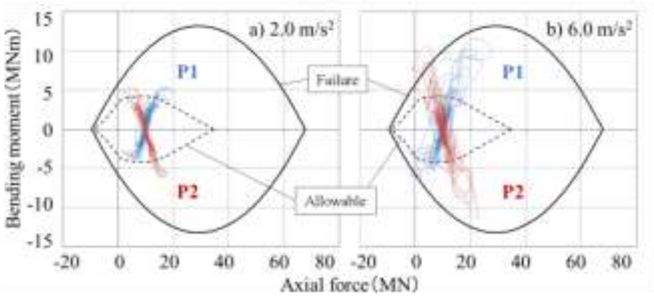


Fig. 10. Relationship between axial force and bending moment at the pile head in M-N interaction curves.

Table 4. Sectional properties of prototype pile.

Diameter, D	1.5 m
Compression strength of concrete, Fc	33 N/mm^2
Sectional area ratio of longitudinal bar, p_g	1.246 %
Tension strength of steel bar, ft	390 N/mm^2

Finally, the relationship of the axial force and the bending moment at the pile head was plotted in the M-N interaction curve in Fig. 10, where the rupture and solid lines indicate the limit strength curves determined by the allowable stress for temporary load and failure stress respectively. These the limit strength curves were calculated based on the *Recommendations for Design of Building Foundations 2001* (Architectural Institute of Japan) and the sectional properties of the piles shown in Table 4. It was observed that the relationship between the axial force and the bending moment in the stage with an input motion of 2.0 m/s^2 exceeded the rupture lines. That was because the peak acceleration at the footing was larger than that at the ground surface, and reached about 3.0 m/s^2. In a stage with an input motion of 6.0 m/s^2, the relationship between the axial force and the bending moment is mostly inside the solid lines. We consider the reasons for this to be the axial force determined by the uplift resistance of piles restricted the overturning moment to a certain upper limit.

4 CONCLUSIONS

Dynamic centrifuge model tests were carried out to investigate the seismic behavior of a plate-shape building's pile foundation in soft clayey ground. The following conclusions were obtained,

1) Use of loam and a wet tamping method made it possible to produce soft clayey ground with a range of shear wave velocity from 100 m/s to 200 m/s in a short time.
2) We have found that the peak acceleration at the foundation may exceed that at the ground surface. However, the story shear force coefficient obtained from the peak acceleration did not reach 1.0 though the intensive input motion with the maximum acceleration of 6.0 m/s^2 was used.
3) As a seismic behavior during a large earthquake, the rotation of the superstructure suddenly increased because the piles were pulled out with the increase of overturning moment.
4) In the bending moment of piles, the effect of the inertia force generated in the superstructure was more dominant than that of the ground deformation though the natural period of the ground was longer than that of the superstructure.

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