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EFFECTS OF SOIL-STRUCTURE INTERACTION ON STRESS DISTRIBUTION WITHIN A PILE GROUP UNDER MULTI-DIMENSIONAL LOADING

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ABSTRACT

To investigate inertial and kinematic effects on stress distributions within a pile group, physical model tests were conducted at E-Defense, one of the largest shaking table facilities in the world. A 3x3 steel pile group supporting a foundation with a superstructure was set in a dry sand deposit prepared in a cylindrical laminar box with a height of 6.5 m and a diameter of 8.0 m. Natural periods of superstructures were variable in the tests. The tests were conducted under one-, two- or three-dimensional shaking. The test results have shown that pile stresses were mainly controlled by the inertial force when the natural period of superstructure was shorter than or close to that of the ground. In this case, the pile group effects were remarkable, in which pile stresses were the largest in the leading pile and the smallest in the following pile. In contrast, the pile stresses were mainly controlled by the ground displacement when the natural period of superstructure was longer than that of the ground. In this case, the pile group effects were insignificant in such a way that the pile stresses were almost the same within the pile group.

INTRODUCTION

Toward establishing reasonable seismic design of pile foundations, it is important to estimate effects of soil-structure interaction on pile behavior during earthquakes. In particular, if piles are closely spaced within a pile group, pile-soil-pile interaction effects, in which the stress zones induced by piles overlap with those of other piles, might have affected pile damage as well as pile behavior.

Previous studies on pile groups in non-liquefied sand (e.g., Rollins et al., 1998, 2006, Suzuki & Adachi, 2003) have indicated that load capacity of piles depends on its location within a pile group. Lateral load capacity in most of the previous studies was based on lateral loading tests but has seldom been discussed based on shaking table tests on pile groups, especially under multi-dimensional loading. Saito et al. (2002) conducted a soil-pile-structure interaction study using three-dimensional ground motions caused by mine blasting. The test using mine blasting was, however, insufficient to estimate inertial and kinematic effects on stress distributions within a pile group in detail due to ground motions without containing long period components and a limited number of sensors used.

To investigate inertial and kinematic effects on pile group during three-dimensional shaking, physical tests on soil-pile-structure models were conducted (Tabata and Sato, 2006, and Tokimatsu et al., 2007) using E-Defense at the Hyogo Earthquake Engineering Research Center of the National Research Institute for Earth Science and Disaster Prevention (NIED). E-Defense was one of the largest shaking table facilities in the world, opened in 2005, commemorating the tenth anniversary of the 1995 Kobe earthquake. About 900 channels of amplifiers and AD converters can be mounted under the shaking table platform for monitoring various outputs during shaking.

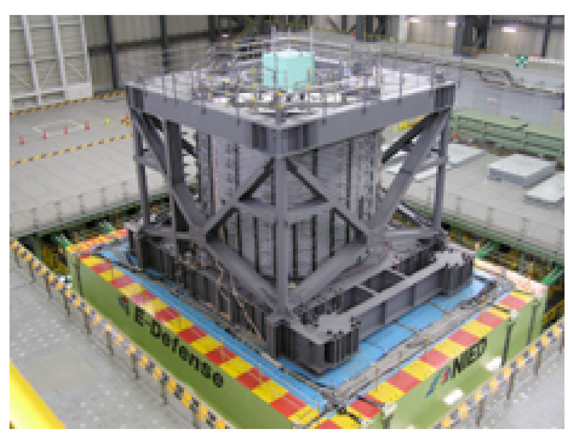

Photo 1. Laminar box on large shaking table

In the shaking table tests using E-Defense, superstructure models as well as input motion and maximum input acceleration were variable. The objective of this study is to investigate inertial and kinematic effects on stresses within a pile group based on shaking table tests conducted at E-Defense. Factors influencing pile stresses within a pile group are discussed through tests with different superstructure models.

SHAKING TABLE TESTS WITH SOIL-PILE-STRUCTURE MODELS AT E-DEFENSE

The E-Defense shaking table platform has a dimension of 15 m long and 20 m wide. It is supported on fourteen vertical hydraulic jacks and connected to five hydraulic jacks each in the two orthogonal horizontal directions. Fig. 1 and Photo 1 show a test model constructed in a cylindrical laminar box, with a height of 6.5 m and a diameter of 8.0 m, placed on the large shaking table. The cylindrical laminar box consists of forty-one stacked ring flames, enabling shear deformation of the inside soil during two-dimensional horizontal shaking.

Albany sand, imported from Australia, was used for preparing a sand deposit. The sand had a mean grain size D_{50} of 0.31 mm. After setting a pile group in the laminar box, the sand was air-pluviated and compacted to a relative density of about 70 % to form a uniform sand deposit with a thickness of 6.3 m. The natural period of the ground surface is about 0.2 s.

A 3x3 steel pile group was used for the test. The piles were labeled A1 to C3 according to their locations within the pile group, as shown in Fig. 1. Each pile had a diameter of 152.4 mm and a wall thickness of 2.0 mm. The piles were set up with a horizontal space of four-pile diameters center to center. Their tips were jointed to the laminar box base with pins and their heads were fixed to a foundation of a weight of 10 tons.

A total of five test series was conducted, in which the presence

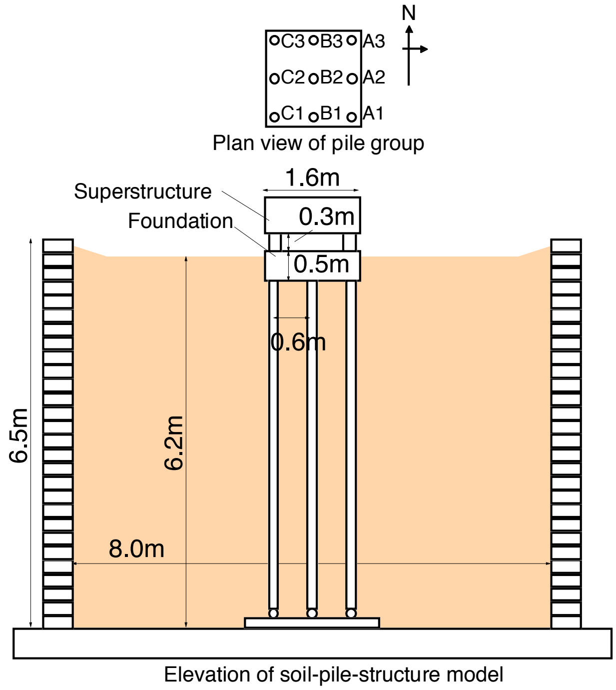

Fig. 1. Soil-pile-structure model

Table 1. Lists of test series

	Superstructure Natural period (s)	Maximum input acceleration (m/s^2)				
		JR Takatori				Taft and Tottori
		NS	EW	NS EW	NS EW UD	NS EW UD
S	0.1	0.3, 0.8				0.3, 0.8
M	0.2					
L	0.6					

Table 2. Number of sensor channels

	Strain gauge	Accelerometer	Velocity meter	Earth pressure transducer	Displacement meter	Settlement meter	Load cell
Superstructure	0	12	4	0	7	0	0
Column	48	0	0	0	0	0	0
Foundation	0	12	0	16	4	0	0
Pile	476	28	0	52	0	0	27
Ground	0	63	0	0	2	5	0
Laminar box	0	82	0	0	24	0	0
Total	524	197	4	68	37	5	27

of foundation embedment and superstructure and natural periods of superstructures were varied. In this study, stress distributions within a pile group will be discussed, based on three test series among the five test series, as listed in Table 1. In the three test series shown in Table 1, a foundation had embedment and carried a superstructure of a weight of 28 tons with four columns. A superstructure in series S was supported on four steel columns 0.3 m high, that in series M on four steel columns 1.0 m high, and that in series L on four rubber columns 0.3 m high. This achieved various natural periods of superstructures. The natural period of the superstructure was smaller than that of the ground in series S, but close to that of the ground in series M and larger than that of the ground in series L.

Table 2 shows the number of sensors used in the tests. Many strain gauges, accelerometers, velocity meters, earth pressure transducers, displacement transducers, settlement meters and load cells, about 900 sensors in total, were placed in the sand deposit as well as on the pile-structure model.

The tests were conducted under one-, two- or three-dimensional shaking with three different ground motions recorded at Takatori in the 1995 Kobe earthquake, at Lincoln School in the 1952 Taft earthquake and at Akasaki in the 2000 Tottori earthquake. In each test series, either or both of the two horizontal or three-component motions were used as input to the shaking table with the largest horizontal acceleration being scaled to 0.3~6 m/s^2. The NS and EW components of the ground motion were applied to the NS and EW directions as shown in Fig. 1, with the UD component to the vertical direction. This paper describes inertial and kinematic effects on stress distribution within a pile group based on test series S, M and L with Takatori motion having maximum horizontal input accelerations of 0.8 m/s^2 under three dimensional loading. The three test series are, hereafter, called Tests S, M and L.

INERTIAL AND KINEMATIC EFFECTS ON BENDING STRESSES WITHIN PILE GROUP

Fig. 2 shows amplitude ratios of the superstructure with respect to the foundation and the ground surface with respect to the shaking table in Tests S, M and L, which are computed from the observed accelerations. This confirms the natural periods of the superstructures are slightly shorter in Test S, slightly longer in Test M and much longer in Test L than that of the ground. Fig. 3 shows acceleration responses of the superstructure, the ground surface and the shaking table in Tests S, M and L. The acceleration responses of the ground surface as well as the shaking table are almost the same among the three tests. In contrast, the acceleration response of the superstructure is different among the three tests. Namely, the periods at which the acceleration responses of the superstructure and the ground take peaks are close together in Tests S and M (Fig. 3(a)-(d)) but are different in Test L (Fig. 3(e)(f)).

Fig. 4 shows time histories of bending strains at the head of Pile A1, displacements of the foundation and the ground surface, accelerations of the superstructure and the shaking table of the NS and EW directions in Tests S, M and L. The maximum acceleration of shaking table is 0.8 m/s^2 (Fig. 4(e)(j)(o)). The accelerations of the superstructure are five times as large as that of the shaking table in Tests S and M but only twice as large as in Test L (Fig. 4(d)(i)(n)). The magnitude of ground surface displacement is slightly larger in Test S, which was conducted first, followed by Tests M and L. The bending strain is the smallest in Test L among the three tests (Fig. 4(a)(f)(k)), probably because the superstructure acceleration in Test L is the smallest among the three tests (Fig. 4(d)(i)(n)). It is interesting to note that the bending strain is larger in Test S than in Test M regardless of the almost the same superstructure acceleration (Fig. 4(a)(d)(f)(i)).

To estimate factors influencing bending strains, Fig. 5 shows relations of bending strains at the heads of Pile A1 with the inertial force and the ground displacement on the EW

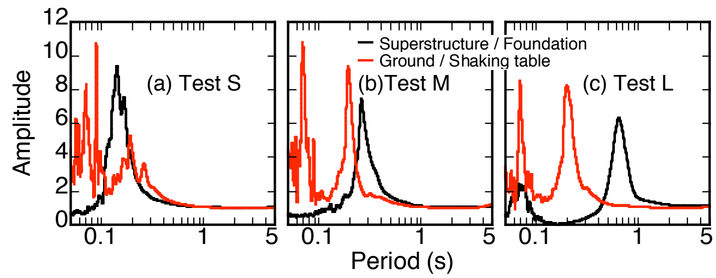

Fig. 2. Amplitude ratio in Tests S, M and L

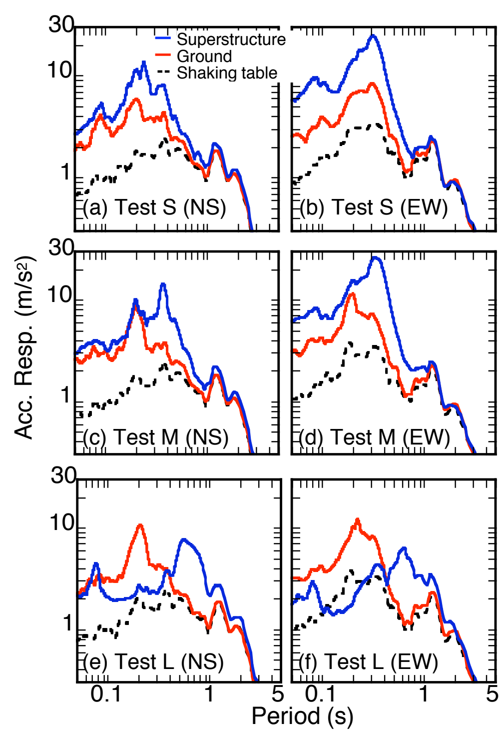

Fig. 3. Acceleration response in Tests S, M and L

direction in the three tests. The inertial force is estimated from the accelerations of the superstructure and the foundation. The bending strain increases with increasing both inertial force and ground displacement in Test S (Fig. 5(a)(b)). In contrast, the bending strain is correlated only with the inertial force in Test M and only with the ground surface in Test L (Fig. 5(c)-(f)).

To further investigate pile stresses in the three tests, Fig. 6 shows distribution with depth of bending strains for three piles, i.e., Piles A1, B2 and C3 at instants, when the bending strain takes the largest peak as presented in circles in Fig. 5. The bending strain is computed by the sum of NS and EW components. Pile A1 is located on the southeast corner, Pile B2 on the middle and Pile C3 on the northwest corner within the pile group. At these instances in all the three tests, Pile A1 is the leading corner pile and Pile C3 is the trailing corner pile. In Tests S and M, the bending strains are larger in the leading pile (Pile A1) than in the trailing piles (Piles B2 and C3) (Fig. 6(a)-(f)). In addition, the depth at which the bending strain takes the maximum tends to be smaller in the leading pile, i.e., Pile A1 (Fig. 6(c)(f)) than in any other trailing pile (Fig. 6(a)(b)(d)(e)). These trends confirm that the pile stresses vary within the pile group and that bearing load is the largest in the leading corner pile. In contrast, the bending strains in Test L are almost the same among nine piles and the difference in inflection of the bending strains among the pile group is unclear (Fig. 6(g)-(i)).

Figs. 7 and 8 show shear force distributions at the pile heads and subgrade reaction distributions 0.3 m below the pile heads within the pile group in the three tests. The shear forces and the subgrade reaction are computed by the differentiation of bending moments with depth. The shear force and the subgrade reaction are the largest in the leading pile of Tests S and M but almost the same within the pile group in Test L. In addition, the subgrade reaction is significantly smaller in Test L than in Tests S and M (Fig.8 (a)-(c)). The difference in stress distributions within the pile groups might have related to difference in factors influencing pile stresses (Fig. 5). Namely, the shadowing effects within a pile group are significant if pile behavior is controlled by the inertial force such like that in Tests S and M but not significant if pile behavior is mainly controlled only by the ground displacement such like that in Test L.

Fig. 9 shows pile displacement distributions with depth for three piles (Piles A1, B2 and C3). Symbols of circles in the figure stand for the ground surface displacement. The pile displacement in Tests S and M is larger than the ground due to the inertial force acting on the pile heads (Fig. 9(a)(b)), inducing the relative displacement of the piles with the ground. In contrast, the pile displacement in Test L is almost the same as the ground displacement (Fig. 9(c)), creating a small relative displacement between piles and the ground. Since the shadowing effects of pile groups is insignificant in Test L, a small relative displacement between a pile and ground causes insignificant showing effects as well as a small subgrade

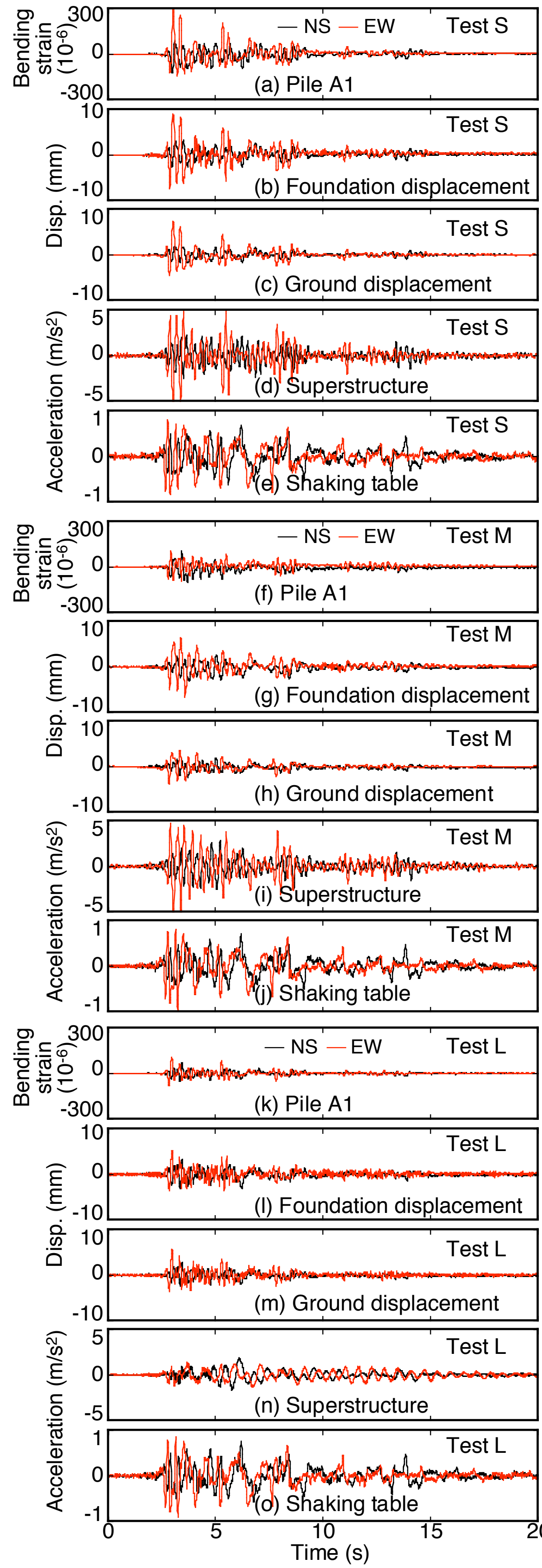

Fig. 4. Time histories of major values in Tests S, M and L

reaction (Fig. 8(c)).

A comparison in stresses between Tests S and M shows that the bending strain, the shear force and the subgrade reaction are larger in Test S than in Test M and that the difference in pile stresses between the leading and following piles is more remarkable in Test M than in Test S (Figs. 6-8). It is also interesting to note that the bending strain in Test M is small at the pile heads. In contrast, the bending strain in Test S does not show such a trend.

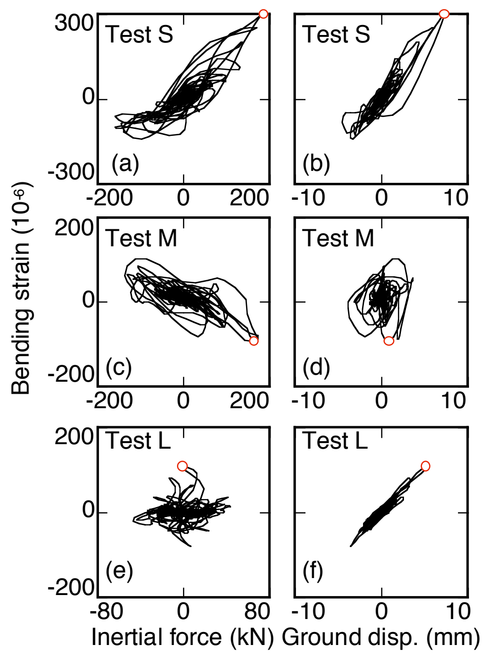

Fig. 5. Relation of bending strain with inertial force and ground displacement in Tests S, M and L

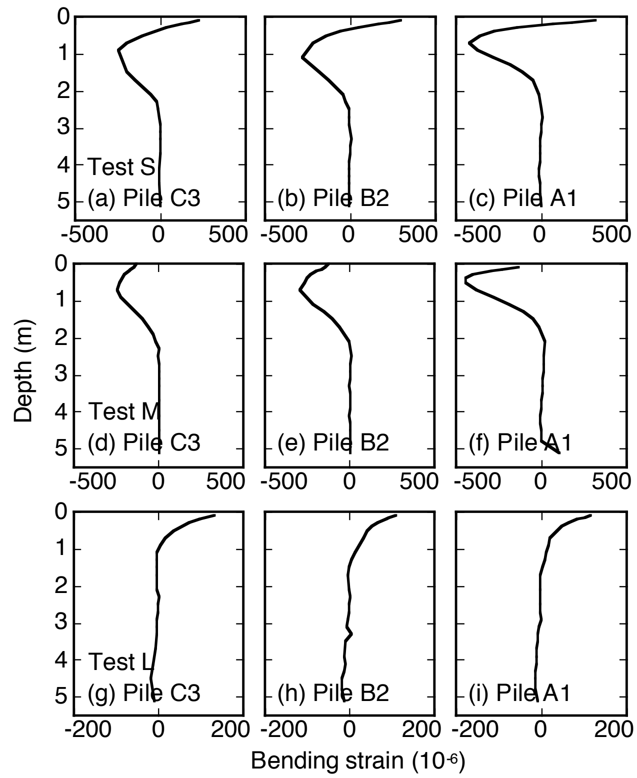

Fig. 6. Distributions of bending strains in Tests S, M and L

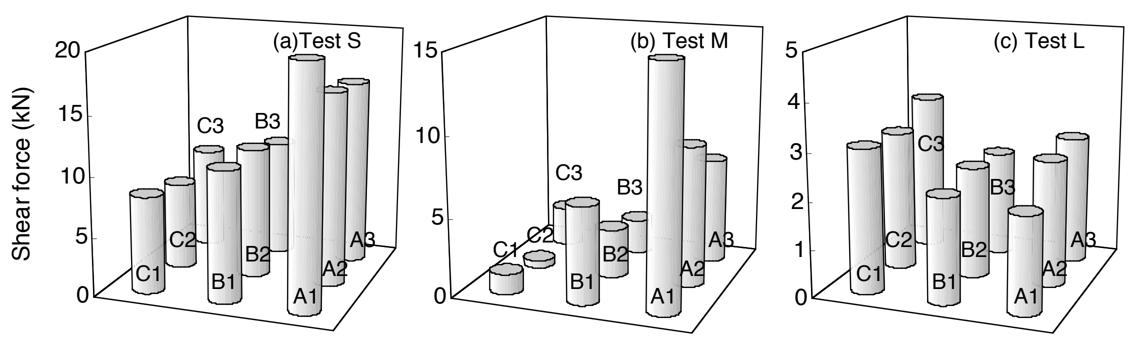

Fig. 7. Distributions of shear forces within pile group in Tests S, M and L

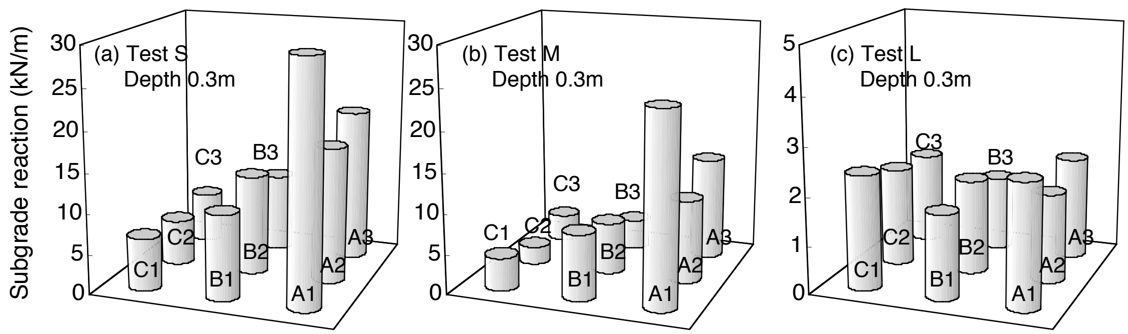

Fig. 8. Distributions of subgrade reactions within pile group in Tests S, M and L

To estimate the difference in pile stresses between Tests M and L, earth pressures are computed by the difference between the inertial force and the shear force at the pile heads (Tamura et al., 2002). Fig. 10 shows relations of the shear force with the inertial force as well as those of the earth pressure with the inertial force and relative displacement between the ground and the foundation in the EW direction. In all the tests, the earth pressure acts against the inertial force, reducing the shear force transmitted to the pile heads (Fig. 10(a)(b)(d)(e)(g)(h)). The shear force is the smallest in Test L among the three tests (Fig. 10(a)(d)(g)). This confirms that the inertial force transmitted to the pile is small and thus the pile stress is mainly controlled by the ground displacement (Fig. 5(e)(f)). A comparison between Tests S and M shows that the earth pressure is larger and the shear force is smaller in Test M than in Test S (Fig. 10(a)(b)(d)(e)). This is probably because the relative displacement between pile and soil is larger in Test M than in Test S (Fig. 10(c)(f)). In addition to the difference in the relative displacement, the ground and the superstructure responses in Test M are out of phase with each other as shown in Fig. 5(c)(d), leading to the large earth pressure (Tokimatsu et al., 2005).

Fig. 11 shows relation between the inertial force and rotation of the foundation in the EW direction. The rotation of the foundation is computed from the relative vertical displacement between the opposite ends of the foundation. The rotation of the foundation is the largest in Test M among the three tests. Considering that the height of columns supporting the superstructure is the largest in Test M, the overturning moment inducing the rotation of the foundation might have been the largest in Test M. As shown in Figs. 6(d)-(f) and 7-9(b), the large rotation of the foundation induces the difference in pile stresses and displacements between the leading and following piles in Test M.

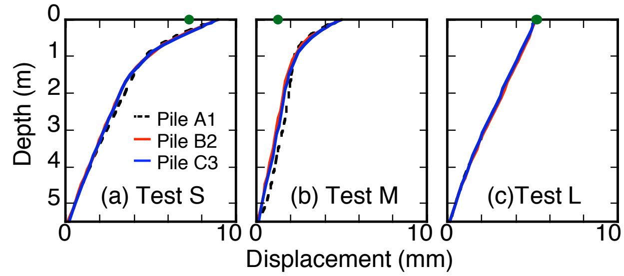

Fig. 9. Distributions of pile displacements in Tests S, M and L

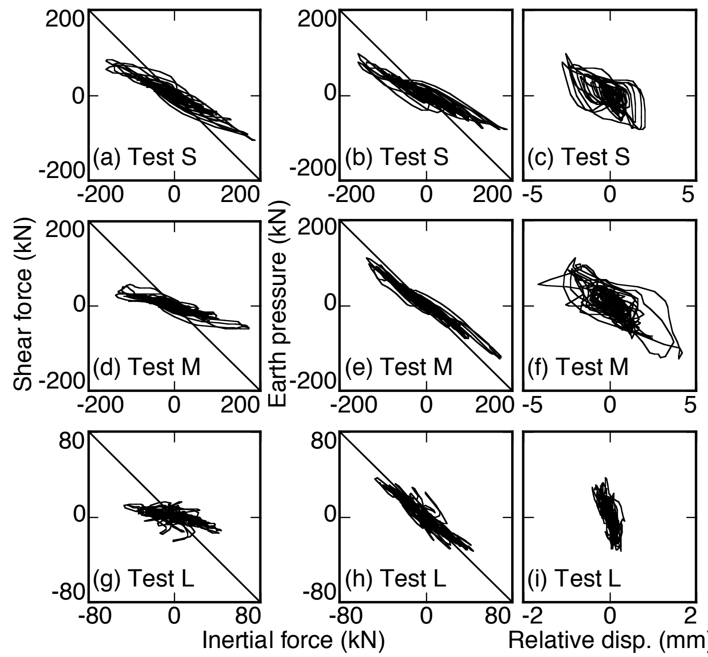

Fig. 10. Relations of shear force with inertial force and of earth pressure with inertial force and relative displacement between ground and foundation in Tests S, M and L

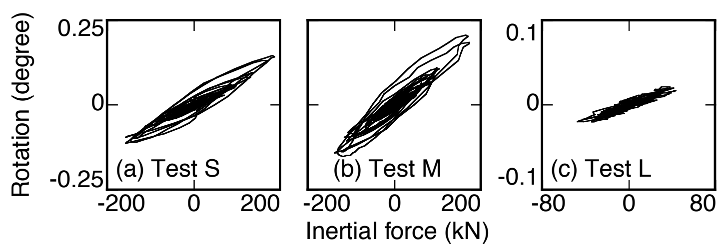

Fig. 11. Relations of foundation rotation with inertial force in Tests S, M and L

CONCLUSIONS

To investigate inertial and kinematic effects on stress distribution with in a pile group, physical model tests on soil-pile-structure systems were conducted using the large shaking table at E-Defense, NIED. The test results and discussions have led to the following:

1) When the natural period of superstructure was shorter than or close to that of the ground, the inertial force mainly controls pile stresses. In this case, the pile group effects were remarkable, in which pile stresses were the largest in the leading pile but the smallest in the following pile. The difference in pile stresses within a pile group is more remarkable when the rotation of a foundation is large.

2) When the natural period of superstructure was much longer than that of the ground, the ground displacement controls pile stresses. In this case, the pile group effects were insignificant in such a way that the pile stresses were almost the same within the pile group. This is because the relative displacement of piles with respect to the ground is significantly small.

ACKNOWLEDGEMENTS

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