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## FACTORS INFLUENCING SWAY-ROCKING MOTION OF PILE-STRUCTURE MODELS DURING LARGE SHAKING TABLE TESTS

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### ABSTRACT

To investigate soil-pile-structure interaction during earthquakes, factors influencing sway-rocking motion of pile-structure systems are estimated through large shaking table tests conducted at E-Defense facilities in which a structure supported by a 3x3 pile group 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. The presence of foundation embedment and input motions were variable in the tests. The test results have shown that foundation embedment restrains sway motion more than rocking motion. This is probably because the foundation embedment in these tests increases sway stiffness, but does not play an important role in rocking stiffness change. As a result, the foundation embedment increases ratios of rocking component in foundation displacements. This induces a unique bending strain distribution of piles in which it decreases toward the pile head. This contrasts well the bending strain distribution in the case without embedment in which it increases toward the pile head. The increase in sway stiffness induces a shorter natural period of the coupled vibration of a soil-pile-structure system and a larger amplitude ratio of the superstructure with foundation embedment than without foundation embedment. Sway and rocking stiffness becomes large if input motions dominate at a short period range. This trend is more significant in sway stiffness than rocking stiffness. As a result, ratios of rocking component in displacements are larger, thereby making a trend, in which bending strain decreases toward the pile head, more significant in the case, in which input motions dominate at a short period range than in the case in which input motions dominate a large period range.

Keywords: Large shaking table tests, soil-pile-structure interaction, sway-rocking motion

### INTRODUCTION

Toward establishing reasonable seismic design of pile foundations, it is important to estimate soil-pile-structure interaction during earthquakes. During earthquakes, kinematic force from the ground as well as inertial force from structures acts on piles. Such kinematic and inertial forces acting on piles vary depending on various factors, e.g. ground displacement and structure response. Tamura et al. (2010) have investigated response of structures based on centrifugal shaker tests conducted on spread foundation models, in which roughness of foundation surface and presence of foundation embedment were variable. In the study, when the foundation surface is smooth, the foundation embedment restrains sway motion of structures but encourages rocking motion and superstructure response. If this result is replaced with pile foundations, the foundation embedment might have increased inertial force of structures transmitted to pile heads. In addition, rocking motion might have affected pile stresses.

To investigate inertial and kinematic effects on pile groups during three-dimensional shaking, physical tests on soil-pile-structure models were conducted using E-Defense at the Hyogo Earthquake Engineering

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Research Center of the National Research Institute for Earth Science and Disaster Prevention (NIED) (Tabata and Sato, 2006, and Tokimatsu et al., 2007). 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. In the shaking table tests using E-Defense, structure models as well as input motion and maximum input acceleration were variable. The objective of this study is to investigate soil-pile-structure interaction during earthquakes based on shaking table tests conducted at E-Defense. Factors influencing sway-rocking motion are discussed through the shaking table tests.

**LARGE SHAKING TABLE TESTS AT E-DEFENSE**

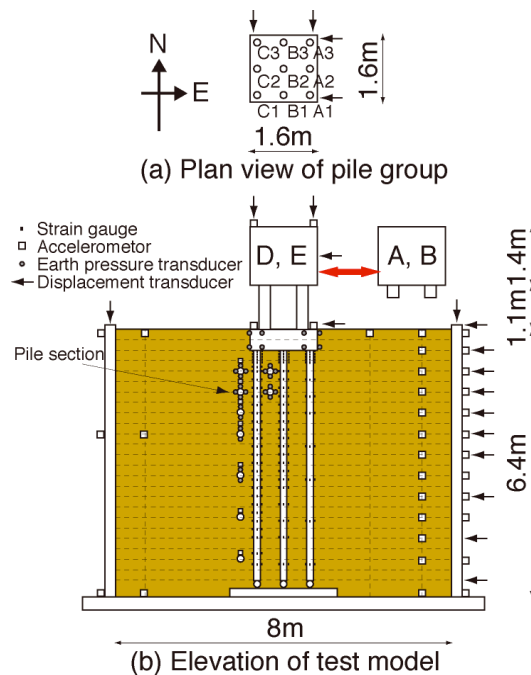
The E-Defense shaking table platform has a dimension of 15 m long and 20 m wide. It is supported on fourteen vertical hydraulic jacks and connected to five hydraulic jacks each in the two orthogonal horizontal directions. For tests with soil-pile-structure models, a cylindrical laminar box was constructed. The cylindrical laminar box with a height of 6.5 m and a diameter of 8.0 m consists of forty-one stacked ring flanges, enabling shear deformation of the inside soil during two-dimensional horizontal shaking. Figures 1 and 2 show the cylindrical laminar box placed on the shaking table and a test model constructed in the laminar box. In the test model, a 3x3 pile group with a structure penetrated a dry sand deposit, as shown in Figure 2.

**Table 1. Test series**

	Embedment	Superstructure	Natural period (s)	Maximum input acceleration (m/s <sup>2</sup> )							
				Takatori				Taft and Tottori			
				X	Y	XY	XYZ	X	Y	XY	XYZ
A	Yes	Yes	0.1	0.3, 0.8				-		0.3, 0.8	
B	Yes	Yes	0.6								
C	Yes	No	-								
D	Yes	Yes	0.2	0.3, 0.8, 6.0, 8.0				0.3, 0.8			
E	No	Yes						-			



**Figure 1. Laminar shear box on shaking table platform**



**Figure 2. Soil-pile-structure model**

Albany sand, imported from Australia, was used for preparing of the dry 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 6.4 m. The natural period of the ground surface was about 0.2 s. A 3x3 stainless 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 Figure 2(a). 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 presence of foundation embedment of a height of 0.5 m and of superstructure of a weight of 28 tons and natural periods of superstructures varied. Each test series was named A to E, as listed in Table 1. In this study, factors influencing sway-rocking motion are discussed based on test series D and E, which had the same superstructure. Difference between two test series was the presence of foundation embedment. A superstructure had foundation embedment in test series D but did not have foundation embedment in test series E.

The tests were conducted under one-, two- or three-dimensional shaking with three different ground motions recorded at Takatori in the 1995 Kobe earthquake (Takatori), at Lincoln School in the 1952 Taft earthquake (Taft) and at Akasaki in the 2000 Tottori earthquake (Tottori). 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  $0.3\text{--}6\text{ m/s}^2$ . The NS and EW components of the ground motion were applied to the NS and EW directions as shown in Figure 2, with the UD component to the vertical direction. This paper describes effects of the presence of foundation embedment and input motions on sway-rocking motion based on test series D and E with Takatori (TK) or Tottori (TT) motions having maximum horizontal input accelerations of  $0.8\text{ m/s}^2$  under three dimensional loading. These are, hereafter, called D-TT, D-TK and E-TK, in which D or E means test series and TT or TK means input motions.

About 900 channels of amplifiers and AD converters can be mounted under the shaking table platform for monitoring various outputs during shaking. 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, as shown in Figure 2. Further details of the test apparatus and procedure have been described elsewhere (Tabata and Sato, 2006).

## DIFFERENCE IN SOIL-PILE-STRUCTURE RESPONSE BETWEEN MODELS

Figure 3 shows acceleration response spectra estimated from the observed accelerations of superstructures, foundations, the ground surface and the shaking table for Tests D-TT, D-TK and E-TK. The acceleration response spectra of the shaking table are related to predominant period range of the input motions. Namely, Tottori motion dominates only in short period range with a sharp spectral peak at less than 0.1 s, which is shorter than a natural period of the ground (D-TT, Figure 3(a)(b)). In contrast, Takatori motion dominates over wide period range covering from 0.1 s to 1.0 s including the natural period of the ground (D-TK, E-TK, Figure 3(c)-(f)). Depending on the predominant period range of input motions, the acceleration response spectra of the ground surface, the foundation and the superstructure take peaks at 0.1 s in D-TT (Figure 3(a)(b)). Such peaks in the acceleration response spectra are not shown in the tests with Takatori (D-TK, E-TK) (Figure 3(c)-(f)). Figure 4 shows amplitude ratios of the superstructure with respect to the shaking table acceleration for the three tests. Peak values of the amplitude ratios are the largest in D-TT and the smallest in E-TK among the three tests. It is interesting to note that the period, at

which the amplitude ratio takes a peak, is longer in E-TK than in D-TT and D-TK. This suggests that the presence of foundation embedment affects coupled vibration of soil-pile-structure systems.

Figure 5 shows time histories of bending strains at the heads of Pile A1, displacements of foundations and the ground surface and accelerations of superstructures, foundations, the ground surface and the shaking table. Figure 5 indicates that the difference in the predominant period range of the input motions induces difference in the magnitude of accelerations and displacements of superstructures, foundations and the ground as well as acceleration response spectra of them. The accelerations and displacements of the ground, the foundation and the superstructure are larger in the tests with Takatori (D-TK, E-TK) than in the test with Tottori (D-TT) (Figure 5(b)-(f)(i)-(m)(p)-(t)), confirming that the predominant period range of the input motion affects soil-structure behavior. The difference in the magnitude of values between tests is more significant in displacements than in accelerations. This confirms that long period range components in Takatori motion induce increases in displacements. A comparison between D-TK and E-

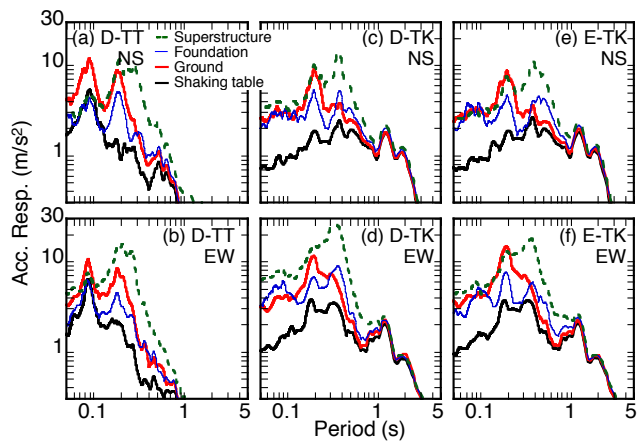


Figure 3. Acceleration response spectra

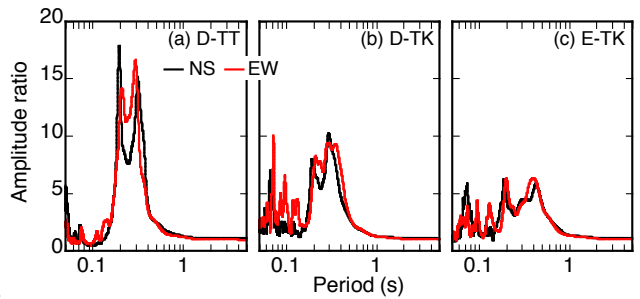


Figure 4. Amplitude ratios of superstructure with respect to input motion

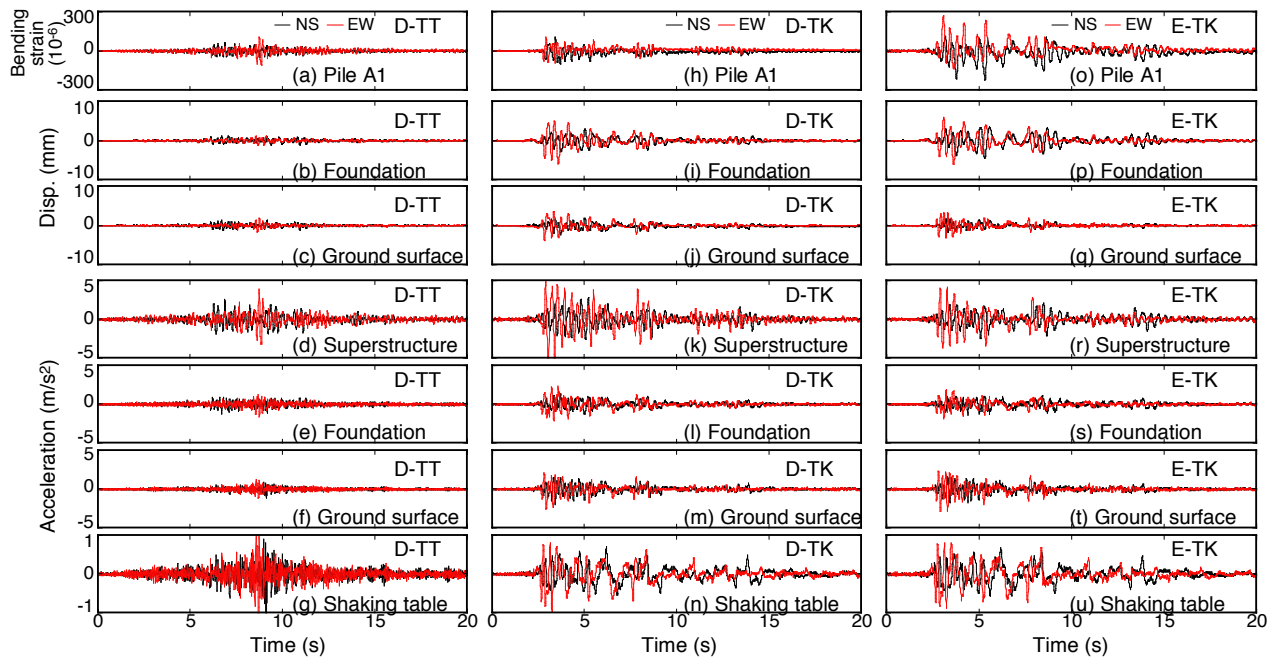


Figure 5. Time histories of major values

TK shows that the superstructure acceleration is larger in D-TK than in E-TK but the foundation displacement is smaller in D-TK than in E-TK (Figure 5(i)(k)(p)(r)). This indicates that the presence of the foundation embedment might have affected structure response similarly to the previous study by Tamura et al. (2010). The bending strain is the largest in E-TK among the three tests and is almost the same in other two tests (D-TT and D-TK) (Figure 5(a)(h)(o)). This trend does not correspond to the magnitude of superstructure acceleration.

To investigate effects of the difference in soil-pile-structure interaction on pile stresses, Figure 6 shows distributions of bending strains with depth for Piles A1, B2 and C3 at instants, when the bending strain takes the largest peak in the three tests. The bending strain shown in Figure 6 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 a pile group. At this instant, the inertial force increases southeastward in all the three tests, making Pile A1 the leading piles and Pile C3 the following pile. The bending strain is larger in the leading pile than in the trailing pile. In addition, the depth at which the bending strain takes the maximum tends to be smaller in the leading pile, i.e., Pile A1 than in any other trailing piles. These trends confirm that the pile stresses vary within the pile group and that bearing load is the largest in the leading corner pile due to the shadowing effects. A comparison in bending strains between the three tests shows that the bending strain is the largest in the E-TK among the three (Figure 6(g)-(i)), regardless of a trend in which the superstructure acceleration is the largest in D-TK (Figure 5(k)). This is probably because foundation embedment affects bending strains in such a way the earth pressure acting on a foundation reduces the shear force transmitted to pile heads from a superstructure, as mentioned in the previous studies (e.g., Imaoka et al, 1998; Tamura et al, 2002). In addition, it is also interesting to note that the bending strain decreases toward pile heads. This trend is significant in D-TT and D-TK (Figure 6(a)-(f)).

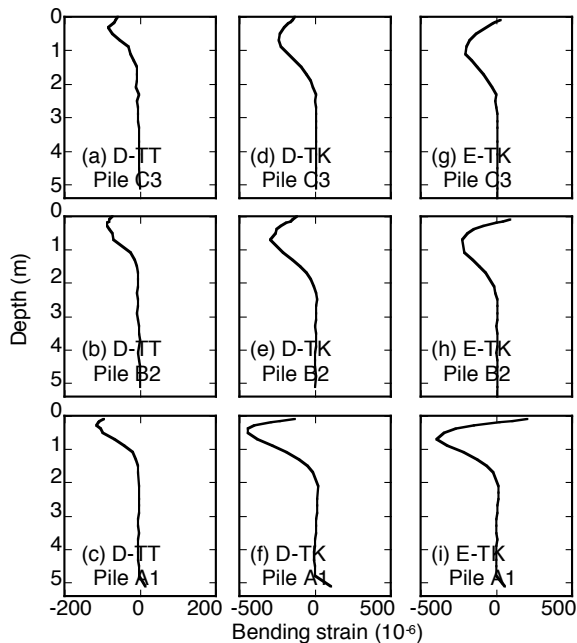


Figure 6. Distributions of bending strains

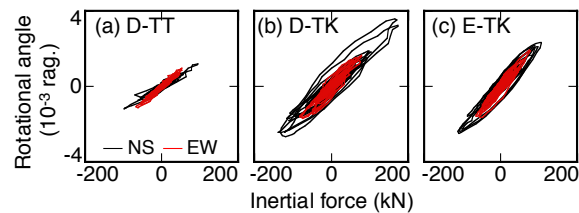


Figure 7. Relations of inertial force and rotational angle

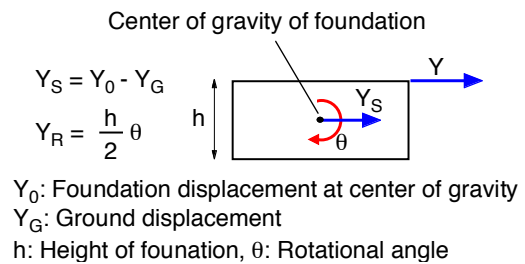


Figure 8. Sway and rocking motion

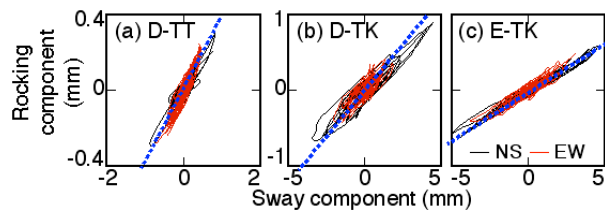


Figure 9. Relations of sway and rocking components

## SWAY-ROCKING MOTION OF FOUNDATION

To investigate factors influencing soil-pile-structure interaction, sway-rocking motion of foundations is estimated. Vertical as well as horizontal components of accelerations were measured at the top four edges of the foundation, which gives vertical and horizontal components of displacements by the integration. Rotational angles of a foundation are computed from relative vertical displacements at the opposite edges of the foundation. Figure 7 shows relations between the inertial force and the rotational angle of the foundation. The inertial force is computed from the accelerations of a superstructure and a foundation. The rotational angle of the foundation as well as the inertial force is the largest in D-TK and the smallest in D-TT among the three tests. This suggests that the rotational angle of the foundation is related to structure response.

To further investigate foundation behavior, sway and rocking components of displacements at the foundation top are defined by the following equation:

$$Y = Y_S + Y_R \quad (1)$$

in which  $Y$  or  $Y_S$  is the relative displacement with respect to the ground at the top of or at the center of the gravity of a foundation and  $Y_R$  is the displacement at the foundation top, which is induced by rotational motion, as shown in Figure 8. Namely, the relative displacement at the foundation top,  $Y$  consists of sway and rocking components,  $Y_S$  and  $Y_R$ .  $Y$  and  $Y_R$  could be computed from the observed accelerations of a foundation and the ground and  $Y_S$  is given by Equation (1).

Figure 9 shows relations between sway and rocking components of foundations in the three tests. Ratios of the rocking components to the sway components are 0.4 in D-TT, 0.2 in D-TK and 0.1 in E-TK. This indicates that the foundation embedment restrains sway motion but does not restrain rocking motion. In addition, ratios of the rocking components are larger in D-TT than in D-TK, suggesting that input motion might have affected the sway-rocking motion of a foundation. These findings suggest that ratios of sway and rocking components vary depending on presence of foundation embedment and input motion. A comparison with bending strain distributions presented in Figure 6, such a trend, in which the bending strain decreases toward pile heads, is probably induced by the increase in ratios of the rocking components.

To investigate stiffness of sway and rocking motions, equilibrium of force acting on a foundation is discussed. Figure 10(a) illustrates horizontal force,  $P_Y$  and rotational moment,  $M_X$ , which are induced by inertial effects from structure accelerations. The equations of motion are given by the following (Architecture Institute of Japan, 1996):

$$[M]\{\ddot{u}(t)\} + [C]\{\dot{u}(t)\} + [K]\{u(t)\} = \{f(t)\} \quad (2)$$

$$\{u(t)\} = \{Y_1, Y_0, \Phi_0\}^T \quad (3)$$

$$\{f(t)\} = \{0, P_Y, M_X\}^T \quad (4)$$

in which  $[M]$ ,  $[K]$  and  $[C]$  are matrices of mass, stiffness and damping.  $\{u(t)\}$  and  $\{f(t)\}$  are vector of displacement and force. The displacement vector consists of displacements of a superstructure and a foundation,  $Y_1$  and  $Y_0$ , and rotational angles of a foundation,  $\Phi_0$ . The force vector consists of  $P_Y$  and  $M_X$ , which act on a foundation. By Equations (2)-(4),  $P_Y$  and  $M_X$  are computed from the observed

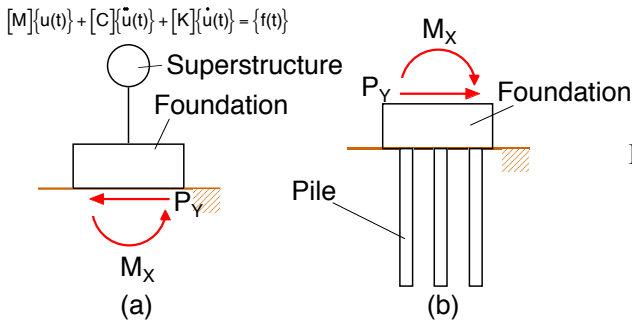


Figure 10. Forces acting on foundation

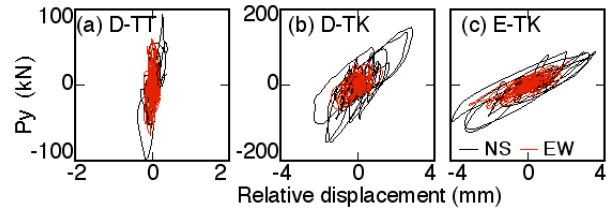


Figure 11. Relations of relative displacement and horizontal force

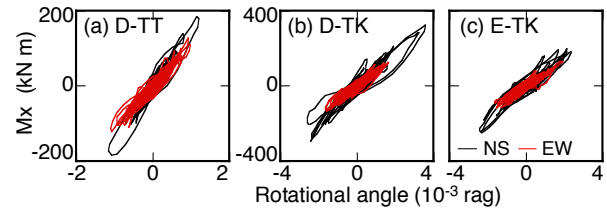


Figure 12. Relations of rotational angle and rotational moment

accelerations and displacements of a superstructure and a foundation. In contrast to Figure 10(a), Figure 10(b) illustrates forces acting on a foundation-pile system, which are induced due to kinematic effects from the ground. If forces due to the kinematic effects are equal to those due to the inertial effects, they are defined by Equations (2)-(4).

Figures 11 and 12 show relations between horizontal force,  $P_Y$  and relative displacements of the gravity center of foundations with the ground and rotational moment,  $M_X$  and rotation angles of foundations. Slopes of these relations correspond to stiffness of sway and rocking motion. A comparison between D-TK and E-TK shows that the stiffness of rocking motion is almost the same but the stiffness of sway motion is larger in D-TK than in E-TK (Figures 11 and 12(b)(c)). This suggests that foundation embedment increases sway motion stiffness but does not play an important role in change in rocking motion stiffness. The presence of foundation embedment also induces an increase in structure response, making the soil around the foundation stiff, in addition to the sway motion stiffness. This corresponds to trends shown in Figure 4, in which a natural period of the coupled vibration of a soil-pile-structure system is shorter in D-TK than in E-TK and the peak value of amplitude ratios of superstructures is larger in D-TK than in E-TK. As a result, the superstructure acceleration is larger in D-TK than in E-TK.

A comparison between trends in D-TT and D-TK, sway and rocking motion stiffness is larger in D-TT than in D-TK (Figures 11 and 12(a)(b)). This trend is more significant in sway motion than in rocking motion. As a result, the ratio of rocking components to sway components in D-TT is large relatively (Figure 9(a)). This confirms that sway and rocking motion is affected by input motions and suggests that sway and rocking stiffness might have depended on the predominant period range of input motion.

## CONCLUSIONS

To investigate soil-pile-structure interaction during earthquakes, factors influencing sway-rocking motion of a foundation are discussed through physical model tests on soil-pile-structure systems with using the large shaking table at E-Defense, NIED. The test results and discussions have led to the following:

- 1) Foundation embedment restrains sway motion more than rocking motion. This is probably because the foundation embedment in these tests increases sway stiffness, but does not play an important role in rocking stiffness change. As a result, the foundation embedment increases ratios of rocking component

in foundation displacements. This induces a unique bending strain distribution of piles in which it decreases toward the pile head. This contrasts well the bending strain distribution in the case without embedment in which it increases toward the pile head.

- 2) The presence of foundation embedment increases sway motion stiffness. This in turn induces a shorter natural period of the coupled vibration of a soil-pile-structure system and a larger amplitude ratio of the superstructure with foundation embedment than without foundation embedment.
- 3) Sway and rocking stiffness is larger in the case, in which input motions dominate at a short period range, than in the case, in which input motions dominate at a large period range. This trend is more significant in sway stiffness than rocking stiffness. As a result, ratios of rocking component in displacements are larger, thereby making a trend, in which bending strain decreases toward the pile head, more significant in the case, in which input motions dominate at a short period range than in the case in which input motions dominate a large period range.

### ACKNOWLEDGEMENTS

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