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Load Bearing Mechanism of Piled Raft Foundation during Earthquake

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This paper deals with the dynamic characteristics of a structure supported by a piled raft foundation. A centrifuge model test and its simulation analysis are discussed first, followed by a parameter survey based on the finite element analysis. In the centrifuge models test, structures supported by a piled raft foundation and by a piled foundation were considered. A parameter survey was performed from the viewpoint of foundation types and types of connection conditions between the raft and the piles. It was found from this study that, although the effect of the pile head connection condition on the response characteristics of a superstructure is fairy small when compared to the type of the foundation, it does affect the load bearing characteristics of piles even when piles are not connected to the raft foundation.

INTRODUCTION

The piled foundation is normally used when constructing buildings on soft soils. The spread foundation, however, becomes an alternative when appropriate load bearing soil layers do not exist. In the latter case, from the viewpoint that the excessive settlement and differential settlement have to be avoided, the use of a composite foundation is becoming very popular in recent years. This composite foundation consists of a spread foundation, usually a raft foundation, and a comparatively few number of friction piles and is called a piled raft foundation. In the case of a piled raft foundation, the load bearing mechanism is fairly complex because a load is transmitted to the ground through a raft and piles.

The vertical load bearing mechanism has been extensively investigated by a number of researchers by applying the elasticity theory (Poulos 1994, Randolf 1994) and the finite

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element method (Yamashita 1998). Based on these results, piled raft foundations are becoming popular in practical use (Yamada et al. 1998).

The study on the load bearing mechanism under horizontal loading or during earthquakes, however, is very limited (Mano and Nakai 2000, Horikoshi et al. 2003). This is partially because piled raft foundations are considered as raft foundations in the current design practice. Since the behavior of a piled raft foundation during earthquakes is considered fairly complex due to dynamic interaction among a raft, piles and a soil, the design procedure should include the effect of this mechanism in an appropriate manner.

In the areas where the seismic activity is considered high, such as in Japan, load that piles have to carry during an earthquake is quite large. Especially, when the inertial force of a superstructure is large, which is often the case, stresses of a pile at its head become prohibitive since the connection condition between the foundation and the piles is usually a fixed condition. In order to avoid this situation, quite a few attempts have been made in this decade in Japan. In most cases the fixed condition is relaxed to some extent or completely by installing special devices at the pile head (Sugimura 2001, Wada et al. 2001). Another attempts include supplementary friction piles of very short length in addition to existing end bearing piles.

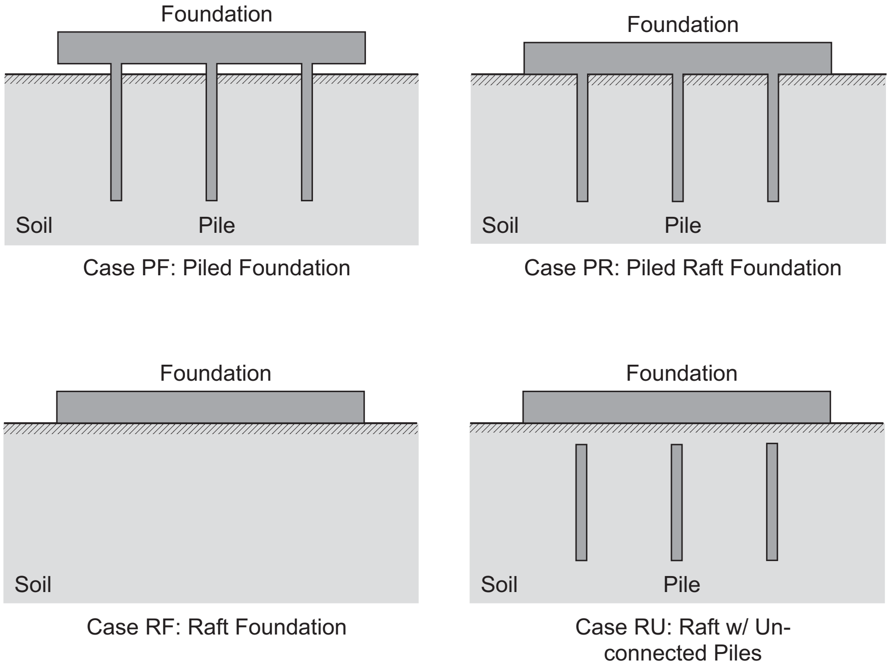
The objective of this paper is to investigate the effect of the connection condition between piles and a raft on the dynamic characteristics of a structure supported by a piled raft foundation. In this regard, a series of dynamic centrifuge model tests have been conducted, followed by a parameter survey based on the finite element analysis.

CENTRIFUGE MODEL TESTS

In order to examine the effect of the connection condition between a raft and piles on the dynamic behavior of a structure supported by a piled raft foundation, a series of centrifuge model tests have been conducted. As shown in Figure 1, four cases were considered in the model test: (1) a piled foundation consisting of a raft and free standing piles, called Case PR, (2) a piled raft foundation, called Case PR, (3) a raft foundation with unconnected piles installed in a soil under the raft, called Case RU, and (4) a raft foundation with no piles, called Case RF.

OUTLINE OF THE TESTS

Figure 2 shows a schematic illustration of the test apparatus for Case RU. The model consists of a soil and a structure supported by a raft foundation with unconnected piles installed in the soil under the raft. This model is the same as the one for Case PR, which is described elsewhere (Mano and Nakai 2004), except that there is a small gap of 5 mm (150 mm in the prototype scale) between the raft and the piles. In Case PF, the raft and the piles are firmly connected and there is a gap of 5 mm between the raft and the soil. In Case RU, there are no piles installed in the soil. A centrifuge acceleration of 30 G was applied in all four cases. Table 1 summarizes the properties of the model.



Case PF: Piled Foundation

Case PR: Piled Raft Foundation

Case RF: Raft Foundation

Case RU: Raft w/ Un-connected Piles

Figure 1. Foundation types considered in this study

The structure and the raft are made of aluminum and a total mass is 9.05 kg (244 t in the prototype scale). Piles are brass tubes of 12 mm diameter and 1 mm thickness. A total of nine piles with the embedment length of 180 mm and the center to center spacing of 72 mm were installed in Case PF, PR and RU. Four of the piles, called Pile-A, B, C and D, are instrumented to measure bending stresses during loading.

Dry Toyoura sand with the relative density of over 90% was used for the model ground. Special equipment called bending elements was installed in the soil in order to measure the shear wave velocity of the soil during the application of centrifugal acceleration. According to the results measured by this equipment prior to vibration, the shear wave velocity, V_s, of the soil can be correlated with the overburden pressure, σ'_v, by:

Table 1. Properties of model and prototype

	Properties	Model	Prototype
Raft and Structure	Width × Length	204 mm × 204 mm	6.24 m × 6.24 m
	Mass	9.05 kg	244 t
	Weight	88.7 N	2395 kN
Pile	Diameter	12 mm	360 mm
	Length	180 mm	5.4 m
	Bending rigidity	3.01×10^{-5} kNm^2	24.4 kNm^2
Soil	Thickness	400 mm	12.0 m
	Density	1.63 t/m^3	1.63 t/m^3

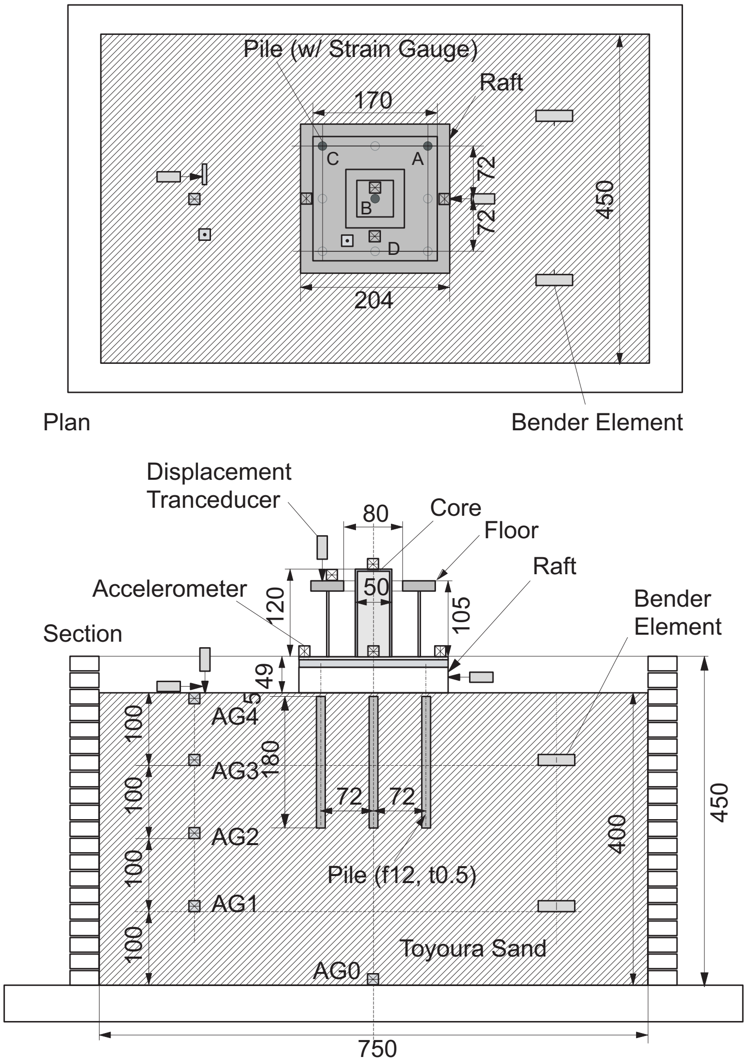
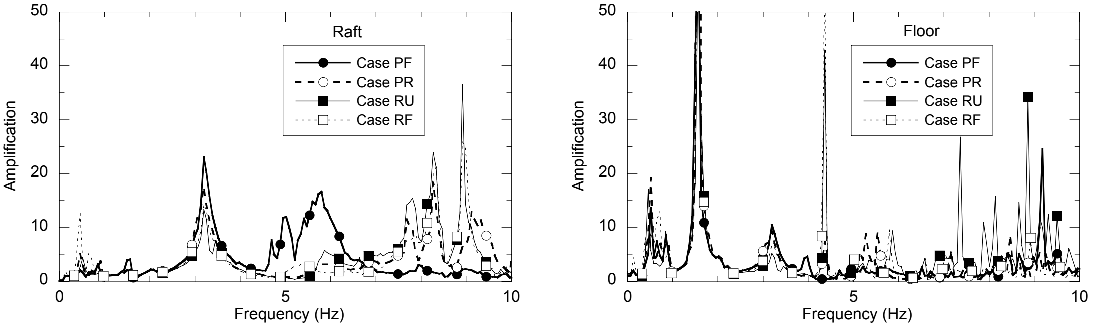


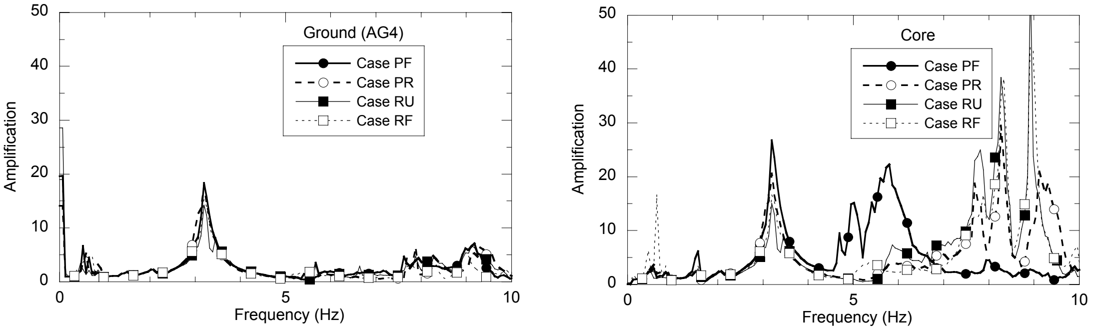
Figure 2. Schematic illustration of test apparatus for Case RU

$$V_s = 70 \cdot \left(\sigma'_v\right)^{0.25} \qquad (1)$$

The test apparatus shown in Figure 2 was placed on a shaking table that was set up in the centrifuge test package. An artificial earthquake wave with the amplitude of 180 cm/s2 in the prototype scale was used as an input to the shaking table. Maximum accelerations of actual input recorded at the shaking table were 178.7, 187.0, 215.8 and 223.5 cm/s^2 for Case PF, PR, RU and RF, respectively.



(a) Raft (b) Floor

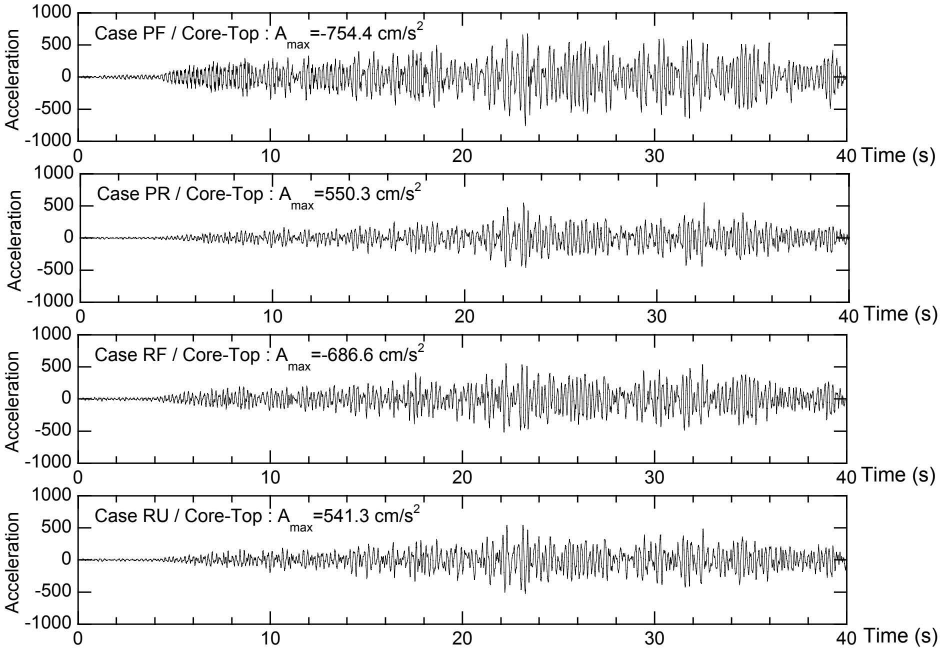


(c) Ground Surface (AG4) (d) Core

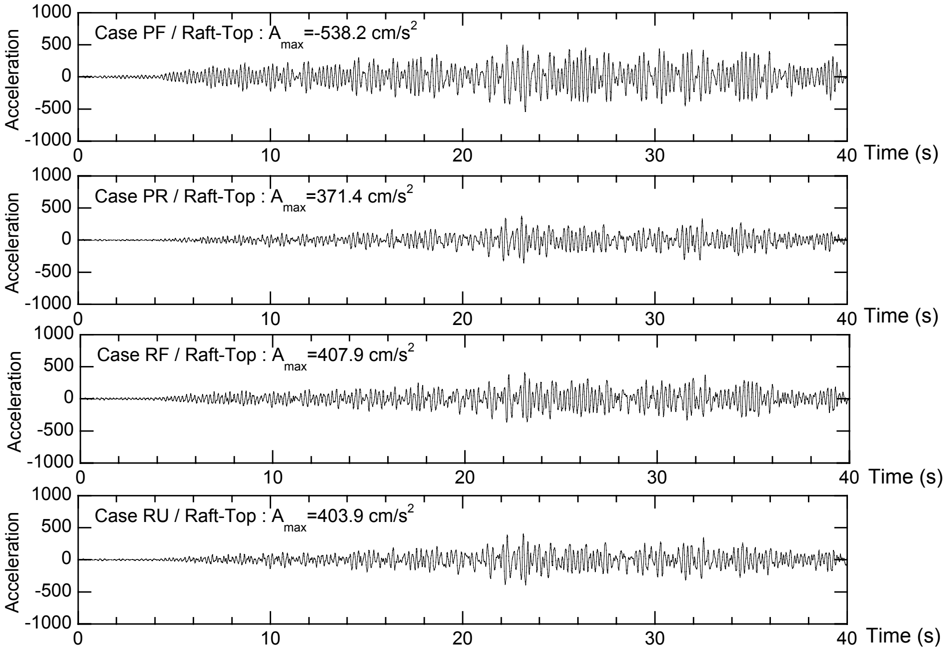
Figure 3. Transfer functions at various points with respect to the bottom of the soil, AG0

TEST RESULTS

Figure 3 shows the transfer function at various points with respect to the bottom of the soil, obtained from the so-called sweep test which is basically a small amplitude steady-state vibration but its frequency changes gradually. As can be seen in Figure 3 (c), the first natural frequency of the soil is about 3.2 Hz and the second is about 9.2 Hz. The natural frequencies of the raft and the floor are 5.8 Hz and 2.6 Hz, respectively. That of the core seems much higher and is not seen in Figure 3. The figure also indicates that test results are a little noisy in the higher frequency range. Comparison among all four cases indicates that the response of the structure is reduced considerably by introducing the contact between the raft and the soil.

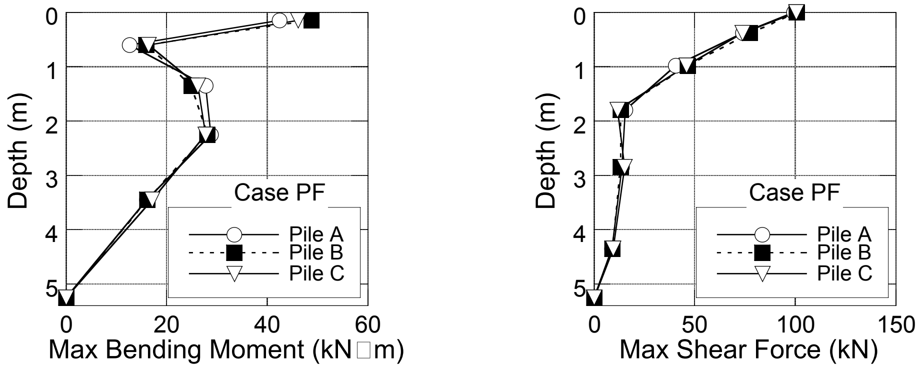


(a) Acceleration at the top of Core

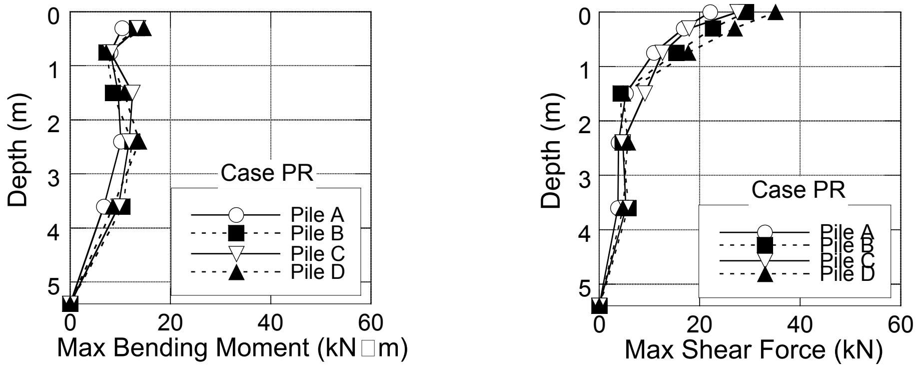


(b) Acceleration at the top of Raft

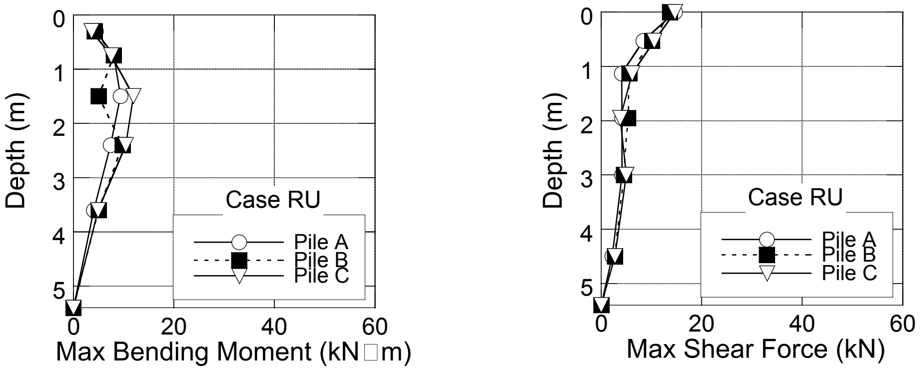
Figure 4. Comparison of acceleration time history



(a) Case PF



(b) Case PR



(c) Case RU

Figure 5. Comparison of bending moments and shear forces

Figure 4 shows the accelerograms at the top of the core and on the raft. Note that actual input waves slightly differ from case to case in terms of the maximum amplitude, as mentioned earlier. It is found from the figure that the acceleration of the raft of Case PF is significantly larger than that of other three cases. This tendency corresponds to the result of the transfer function and the reduction of the response is due to the contact between the raft and the soil. The fact that the response at the top of the core of Case RF is larger than Case PR and RU, however, indicates a dominant rocking motion for Case RF, hence the vibration mode is slightly different. It is worthy of note that piles are not connected to the raft in Case RU but that they have significant contribution to the dynamic soil-structure interaction.

Figure 5 shows the distribution of maximum bending moments and shear forces along the piles. Since a structure is supported only by piles in the case of a piled raft foundation, Case PF gives the largest response. It is again worthy of note that piles of Case RU that are not connected to the raft carry a fairly large amount of load. This is considered to reduce the input to the structure.

SIMULATION ANALYSIS OF MODEL TESTS

Before going on to a numerical analysis-based parameter survey, a simulation analysis of the centrifuge model tests has been performed for Case PR and RU. The analysis is basically a three dimensional finite element analysis in which a dynamic substructure method is effectively utilized. A computer code ACS SASSI was used and the analysis was made in the frequency domain.

ANALYSIS MODEL

Figure 6 shows the finite element mesh layout used in the analysis for Case PR. The mesh layout for Case RU is the same as Figure 6 except that topmost elements of the piles are replaced with soil elements in order to simulate a gap between the raft and the piles. The shear wave velocity of the soil was determined by reducing the value computed from Eq. 1 by one third, in order to account for soil nonlinearity during loading.

Piles are often modeled as beams in the finite element analysis due to their flexural characteristics. However, since beams do not occupy any volume in the three dimensional space, the direct use of beam as a pile in conjunction with solid elements as soils is not appropriate in the dynamic soil-structure interaction analysis. The reason is because a pile modeled by a beam has very small diameter hence it tends to have small resistance. According to the authors' experience, it is confirmed that the beam element modeling underestimates impedance functions and overestimates foundation input motions. Based on this, piles are modeled by solid elements in this paper, as shown in Figure 6. The bending moment and shear force of the pile can be obtained by superposing very soft beam elements on the center of each pile and extracting resulting stresses.

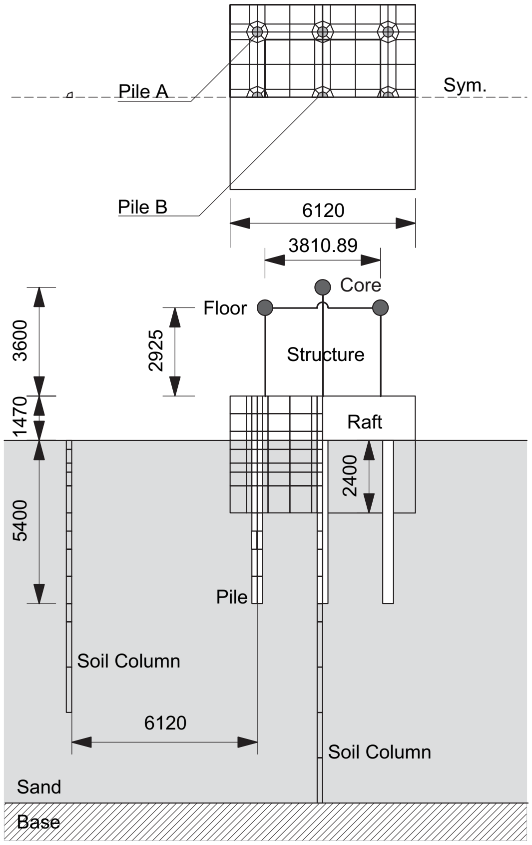
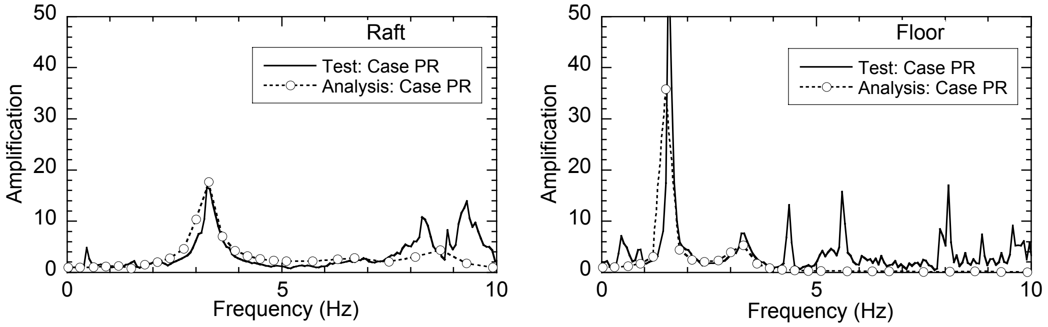


Figure 6. Finite element mesh layout

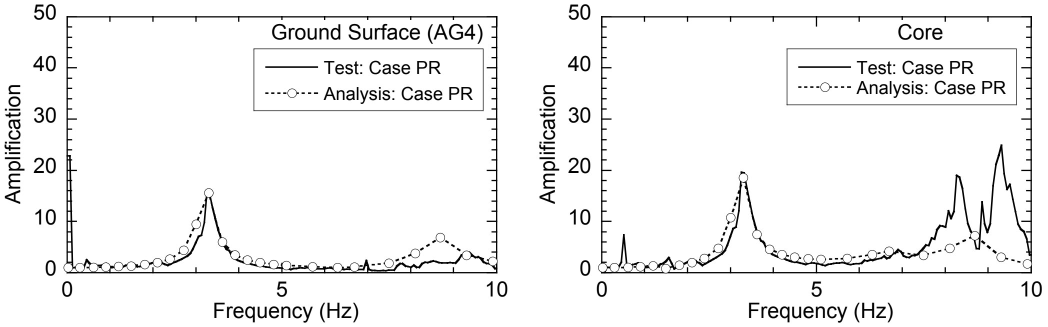
COMPARISON BETWEEN ANALYSIS AND MODEL TEST

Figure 7 demonstrates a comparison of transfer functions between analysis and sweep test results of Case PR. From the figure, it can be seen that the natural frequencies of the soil (3.2 Hz) and the floor (2.6 Hz) are well predicted by the analysis although the computed peaks are a little higher than the test results. Computed transfer functions in the higher frequency range give larger amplification for the soil and smaller amplification for the structure when compared with test results. This suggests that the variation of the soil stiffness along the depth assumed in the analysis may differ from the actual one.

Figure 8 shows acceleration time histories for Case PR and RU observed at various locations during earthquake excitation. The fact that computed values are significantly smaller than measured values is resulted from low amplification of the computed transfer function in the high frequency range.

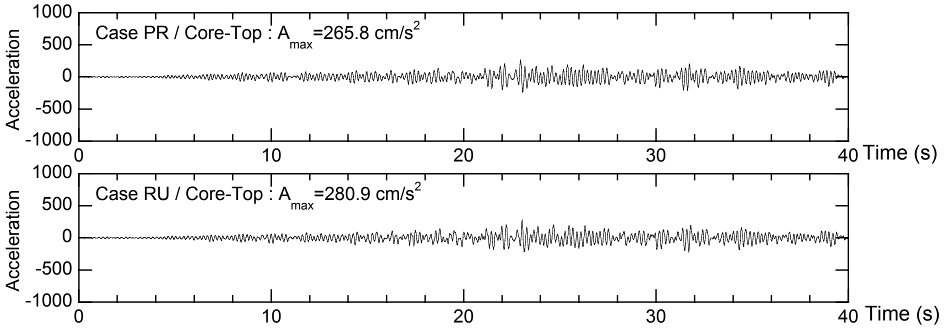


(a) Raft (b) Floor

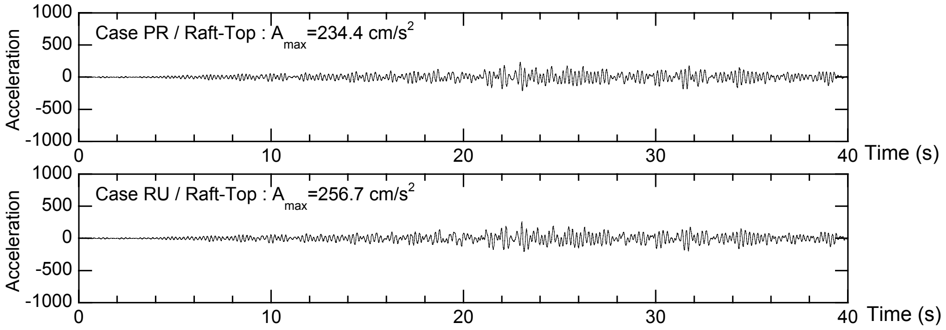


(c) Ground Surface (AG4) (d) Core

Figure 7. Comparison of transfer functions between analysis and centrifuge model test (Case PR)



(a) Acceleration at the top of Core

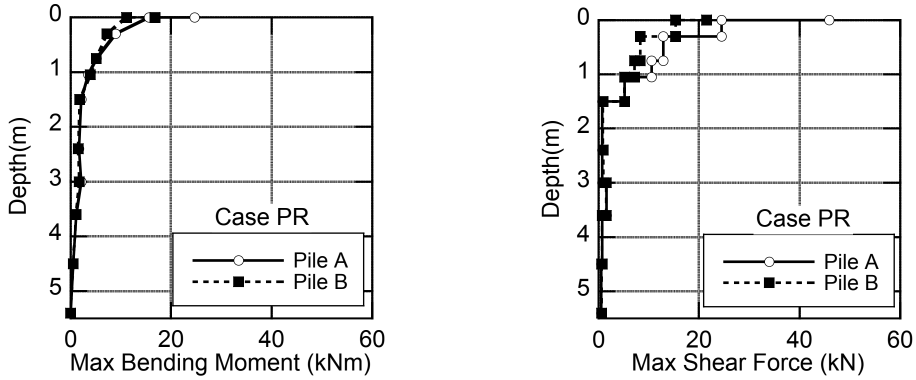


(b) Acceleration at the top of Raft

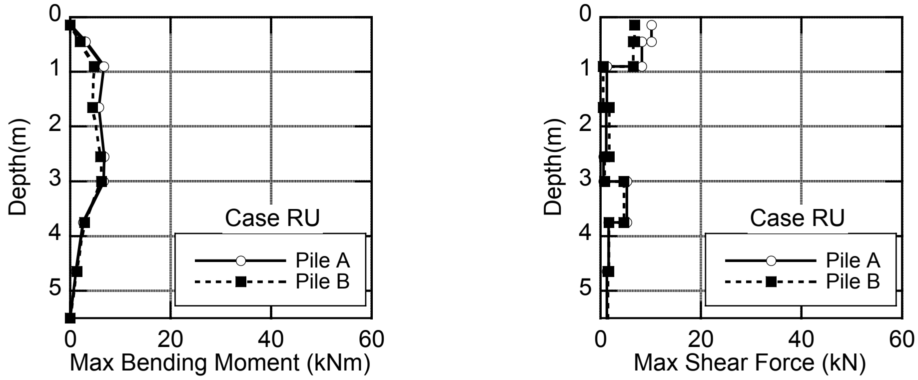
Figure 8. Comparison of acceleration time history

Figure 9 gives a comparison of maximum bending moments and shear forces along the piles during earthquake excitation. A similar discussion to the above can be made on this comparison, i.e. computed stresses of the piles are smaller than measured ones especially in their deeper portion.

The above mentioned discussion suggests that further reduction of the soil stiffness and increase of the damping corresponding to the strain level of the soil during earthquake excitation, may improve the agreement between analysis and test results.



(a) Case PR



(b) Case RU

Figure 9. Comparison of bending moments and shear forces

EFFECT OF PILE-RAFT CONNECTION CONDITION AND SUPLEMENTARY SHORT PILES

In this section, the effect of pile-raft connection conditions on the behavior of a structure during an earthquake is studied first based on the three dimensional finite element analysis.

The effect of supplementary short piles is then examined from the viewpoint of the load bearing characteristics, i.e. how much of the inertial force of a structure is transferred to the soil either from the base of the raft or from the piles.

ANALYSIS MODEL

The analysis method is the same as the one used in the previous section. In the analysis, the soil is assumed to be an elastic half space. The foundation including a raft and piles are modeled by solid elements while a superstructure which is a five storey building is modeled by beam elements.

Analysis parameters considered in the study include:

- Piled foundation (PF) and piled raft foundation (PR)
- Fixed condition (CF) and hinged condition (CH)
- Supplementary short piles (Yes) and no short piles (No)

In addition, the following cases have been considered for comparison:

- Raft foundation with unconnected piles (RU) and raft foundation with no piles (RF).

Figure 10 summarizes the cases that were considered in the analysis.

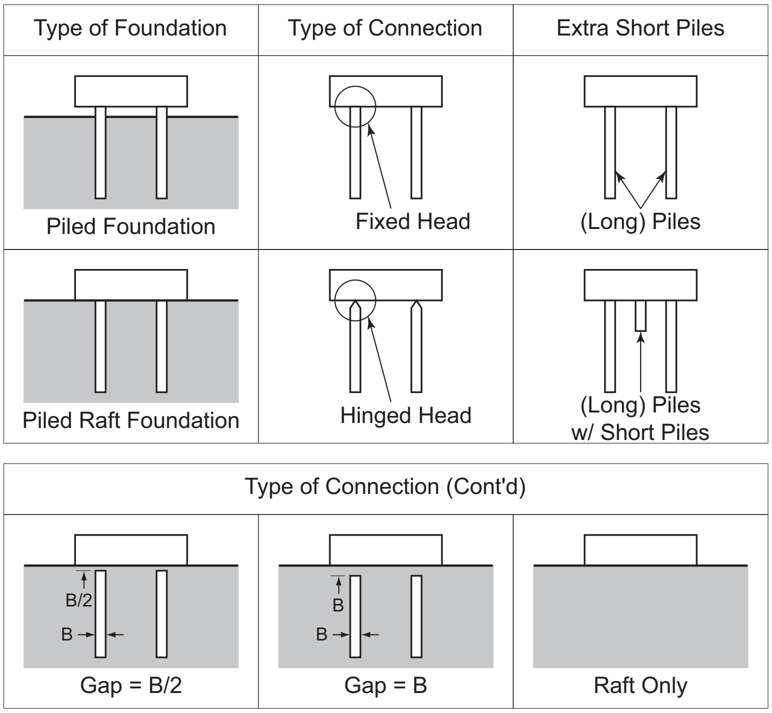


Figure 10. Analysis cases

Figure 11 shows a finite element mesh layout for Case PR-CF. The hinged condition between a raft and a pile is implemented by placing a small gap between them and by connecting both with a beam. A superstructure with a natural frequency of 2 Hz was considered. El Centro 1940 NS accelerogram with the amplitude of 342 cm/s^2 was used as an input wave defined at the ground surface.

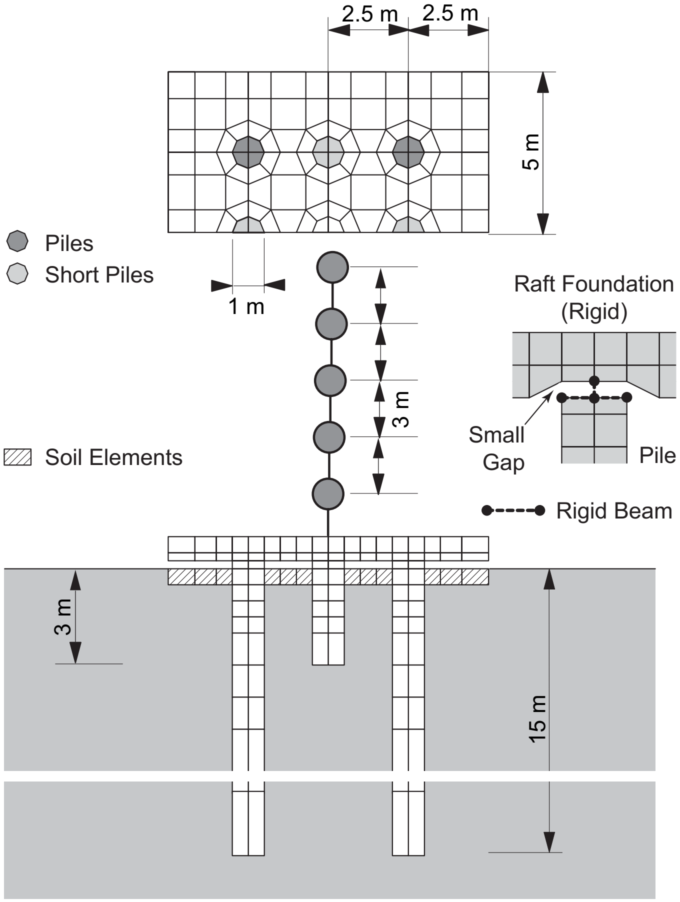


Figure 11. Finite element mesh layout (Case PR-CF)

EFFECT OF PILE-RAFT CONNECTION CONDITION

Table 2 summarizes maximum accelerations, maximum shear forces and maximum overturning moments of the superstructure. From this table, it is seen that differences of the response among the analysis cases is not very large.

If we further look into the results, however, the following discussions can be made:

- The difference between fixed (CF) and hinged (CH) conditions is very small for both piled (PF) and piled raft (PR) foundations.

- Piled rafts (PR) give about 5 % smaller base shears, 12 % smaller over-turning moments and 20 % smaller accelerations over piled foundations (PF). This can be resulted from larger soil-structure interaction in piled rafts over piled foundations.
- If piles are not connected to the raft (RU), then the response becomes slightly larger compared with piled rafts (PR). The response is also larger than that of raft foundations (RF) except the maximum accelerations that are slightly smaller than those of raft foundations.
- From the viewpoint of adding piles to a raft foundation, it increases base shears, slightly increases over turning moments and decreases maximum accelerations.

Table 2. Maximum response

Type of Foundation	Connection Condition	Short Piles	Maximum Response			
			Base Shear [kN]	Over-turning Moment [kNm]	Acceleration [m/s^2]	Inertial Force [kN]
Piled Foundation (PF)	Fixed (CF)	No	1000	10981	13.62	1092
		Yes	1025	11130	13.60	1130
	Hinged (CH)	No	989	10846	13.82	1180
		Yes	998	10873	13.65	1160
Piled Raft Foundation (PR)	Fixed (CF)	No	960	9769	11.03	1212
		Yes	958	9748	11.01	1203
	Hinged (CH)	No	960	9660	10.84	1230
		Yes	960	9654	10.86	1228
Raft w/ Un-connected Piles (RU)	Gap = 0.5*B* (*B*: width)	No	1009	10602	12.79	1215
		Yes	1011	10622	12.78	1219
	Gap = 1.0*B* (*B*: width)	No	1002	10704	13.24	1172
		Yes	1005	10724	13.23	1176
Raft Found.	-	-	825	9627	13.49	1003

EFFECT OF SUPPLEMENTARY SHORT PILES

An additional study was made on the effect of supplementary short piles added to the piled and piled raft foundations. A short pile of 3 m length with the same width as the existing pile of 15 m length (called a bearing pile, hereafter) is taken as a standard short pile. Half and double lengths were considered and half and double cross sectional areas were also considered.

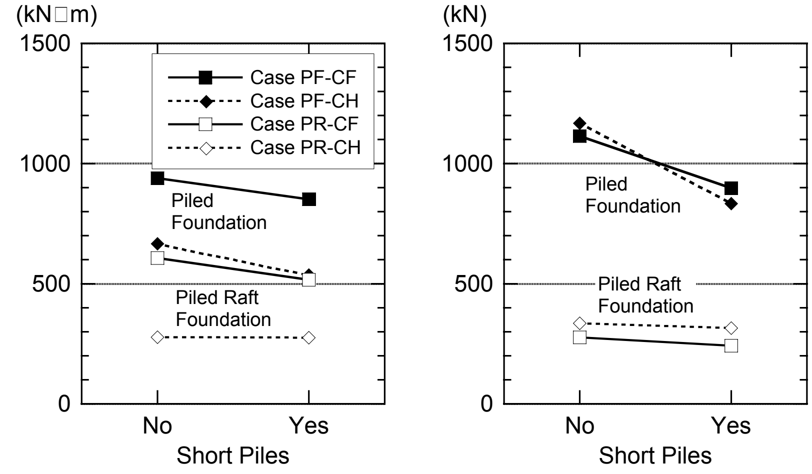
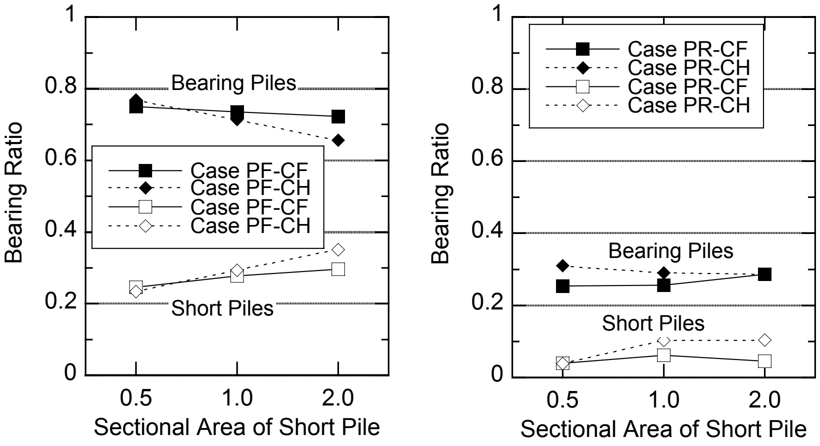
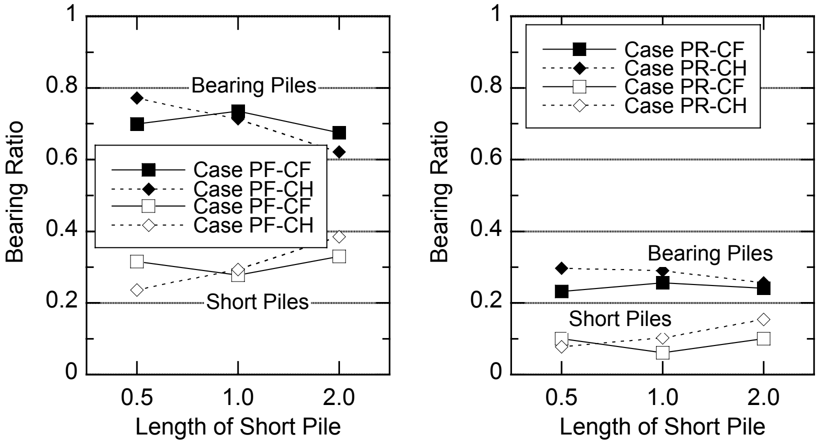


Figure 12. Change of the stress of bearing piles due to the addition of short piles

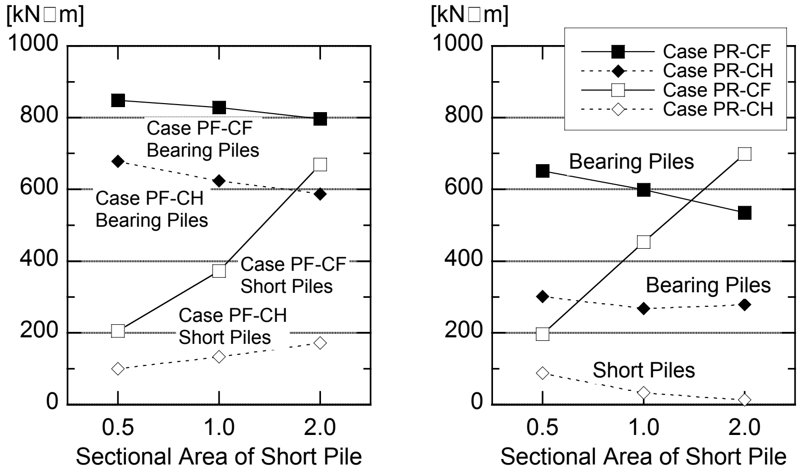


(a) Effect of Sectional Area of Short Pile

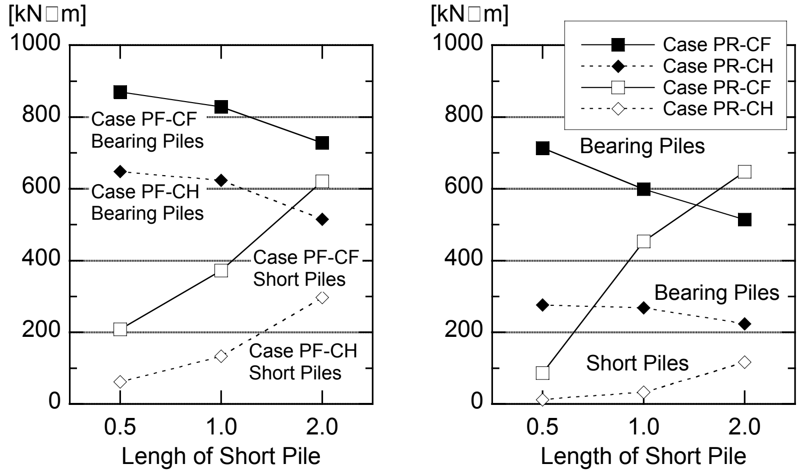


(b) Efect of Length of Short Pile

Figure 13. Effect of the size of short piles on the load bearing ratio



(a) Efect of Sectional Area of Short Pile



(b) Efect of Length of Short Pile

Figure 14. Effect of the size of short piles on maximum bending moments

Figure 12 shows the change of maximum bending moments and shear forces due to the addition of short piles. Figures 13 and 14 show the effect of the size of short piles on the load bearing ratio and the maximum stresses of piles. Here, the load bearing ratio was computed by averaging over the duration time the ratio between the shear force at the pile head and the inertial force of the structure. The inertial force of the structure means the sum of a base shear at 1st floor and the mass of the foundation multiplied by its acceleration.

From these figures, the following points are made:

- Supplementary short piles reduce shear forces and bending moments of bearing piles, especially in the case of piled foundations (PF).

- The change of the size of short piles has a relatively small influence on the load bearing ratio.
- However, forces and moments acting on the piles are greatly changed by the size of the short piles.

The above discussion suggests the effectiveness of supplementary short piles for the seismic resistance of a structure.

CONCLUSIONS

In this paper, the effect of the connection condition between piles and a raft on the dynamic characteristics of a structure supported by a piled raft foundation has been studied extensively by conducting a series of dynamic centrifuge model tests and simulation analyses. It was found from the study that:

(1) The dynamic response of a structure is reduced considerably by introducing the contact between the raft and the soil.

(2) The effect of pile head connection conditions on the response characteristics of a superstructure is fairy small when compared to the type of foundation.

(3) However, the connection condition affects the load bearing characteristics of piles.

(4) The existence of piles installed in the ground below the raft has a significant influence on the response characteristics of a superstructure.

The last conclusion suggests the possibility of using piles as ground improvement even for seismic design.

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