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AN EXPERIMENTAL STUDY ON NONLINEAR PILE-SOIL INTERACTION BASED ON FORCED VIBRATION TESTS OF A SINGLE PILE AND A PILE GROUP

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ABSTRACT

Forced vibration tests of both a single pile and a four-pile group constructed in the field are conducted with different shaking patterns in order to investigate the nonlinear behavior of pile foundations. The resonance curves of the response, the mode shapes of vibration, the distributions of flexural response and the impedance functions of the models are analyzed from the test results, and some discussions are made on the nonlinear pile-soil interaction effects for each model. It is remarked that the soil nonlinearity induced by a large strain has a great influence on the nonlinear response of single piles, and that a gap developed by the separation at the pile-soil interface strongly affects the nonlinear response of pile groups. As a consequence, the forced vibration tests presented here provide good data for investigating the nonlinear behavior of pile foundations.

KEYWORDS

Forced vibration tests; single pile; four-pile group; nonlinear pile-soil interaction; material nonlinearity of soil; gap and separation; resonance curves of response; mode shapes of vibration; impedance functions.

INTRODUCTION

In recent years, a number of vibration tests of field and model piles have been conducted, through which a remarkable progress has been made in theoretical studies on the dynamic behavior of pile foundations, especially the linear pile-soil-pile interaction in a large number of piles (Novak, 1991). Novak and Sharnouby (1984) continue to introduce the comprehensive comparison of test results and theoretical predictions performed by different approaches which are essentially based on the Green's function method for considering the pile-soil-pile interaction in a layered soil, and indicate a fairly good coincidence between tests and predictions. Currently, practical application of the interaction analysis for design purposes is also developed to compute the seismic response of a structure supported on pile groups (Hijikata *et al.*, 1994). However, most of the fruitful work is rather limited to studying linear elastic interaction effects and there are very few of both experimental and theoretical researches focused on the nonlinear behavior of pile foundations under a high intensity of dynamic loadings. Therefore, it is significant to investigate the nonlinear interaction effects that include both the material nonlinearity of the soil around the pile and the separation between the pile and its surrounding soil. More work will be necessary for the seismic design of pile foundations against strong ground motions.

In this paper, field shaker test results of both a single pile and a four-pile group with different levels of shaking forces are introduced to study the nonlinear behavior of pile foundations. The resonance curves of the response of the models, the mode shapes of vibration at the resonance frequency, the flexural deformation of the piles and the impedance functions at the pile head are investigated on the basis of measured data. The nonlinear pile-soil interaction effects for each model are discussed from the view point of both the local nonlinearity induced by a large strain of the soil around the pile and a gap developed by the separation at the pile-soil interface during the excitation of a high intensity.

OUTLINE OF FORCED VIBRATION TESTS

Test Yard and Soil Profile

The forced vibration tests of full scaled pile-foundation models are carried out at Kashiwazaki-Kariwa nuclear power plant located in Niigata Prefecture of central Japan. A layout of a single pile and a four-pile group models and a borehole for investigating the soil profile in the test yard is illustrated in Fig. 1. To examine the nonlinearity of the soil at the vicinity of the pile head, the area of 31.5 m x 18.0 m in the yard is excavated to the depth of 1.5m and then filled up with the clean and fine sand. The elastic wave exploration tested after back filling shows that the sand fill has the shear wave velocity of 90m/s and the poisson's ratio of 0.3. The soil profile in the yard, which is mainly obtained by the in-situ measurement from P-S seismic loggings conducted in the borehole, are depicted in Fig. 2. The site primarily consists of five layers including the back filling. The shear wave velocities of the layers gradually increase along the depth of the soil. The bottom of the piles is located at the depth of about 2.0 m from the surface of the third layer which consists of fine sand with N-values ranging from 30 to 40.

Test Models and Layout of Instruments

A single pile and a four-pile group models both with a reinforced concrete block at the top are chosen for the forced vibration tests. The plan and the section view of the models is illustrated in Fig. 3, where the location of the instruments is included. The piles are made of precast centrifugally compacted concrete with the diameter of 0.45 m and the length of 15.0 m. The distance between the piles in the four-pile group is 3.0 m in each direction. The dimension of the block for the single pile model is 2.0 m in both length and width, 1.0 m in height, and a weight of the block is about 10 ton. That for the pile group model is 4.5 m in both length and width, 2.0 m in height, and the block has a weight of about 100 ton. The block at the pile head is constructed with a gap of 0.25 m between the bottom surface of the block and the ground surface in order to remove friction. The length of 0.45 m from top of the pile is inserted into the block to obtain rigid connection, where the length is the same as the diameter of the pile.

To measure the swaying and rocking response of the block, velocity meters are placed on the block. The meters are designated by AH1-6 and AV1-4 in the single pile model and BH1-6 and BV1-4 in the pile group model, respectively. Herein, AH1-6 and BH1-6 are the meters for recording the horizontal response of the block, and AV1-4 and BV1-4 are for the vertical one. In order to detect the flexural response of the pile at different depths, the instrumented piles are equipped with ten strain gauges denoted by AS1-10 in the single pile and BS1-10 in the pile group, as shown in Fig. 3. The Accelerometers are also included and designated as AH7-13 and BH7-13 for the horizontal response, and AV5-11 and BV5-6 for the vertical one. To observe the separation at the pile-soil interface during heavy shaking, earth pressure cells are installed on the pile surface at the ground level. The cells are indicated by AP1 and AP2 in the single pile, and BP1 and BP2 in the pile group model, respectively.

Test Condition and Excitation Cases

The test models are excited in the horizontal E-W direction with a harmonic wave which is generated by a rotating mass type shaker placed on the block. Two shakers of the same type are used and tuned for the pile group model. The shaker used here has the following specification: a maximum exciting force is 5 ton and a maximum eccentric moment is 100 kgm. To investigate the nonlinear behavior of the models, four different excitation patterns are considered for each test as follows:

(1) First, as the excitation step 1 (S1), a shaking test is conducted with a low level excitation to obtain principal data for the linear elastic response.
(2) Second, as the excitation step 2 (S2), a shaking test is carried out with a middle level excitation to grasp the response slightly affected by the soil nonlinearity when compared with the step 1.
(3) Third, as the excitation step 3 (S3), a strong shaker test is performed by a high level excitation to obtain data which show the nonlinear behavior.
(4) Finally, as the excitation step 4 (S4), a shaking test with the same level excitation as the step 1 is made to

investigate the elastic behavior after presenting the soil nonlinearity.

The excitation force is assumed to be constant and the frequency range from 1 to 20 Hz is considered for each case mentioned above. Furthermore, two different excitation patterns are taken into consideration for the respective cases. One is the case that the excitation frequencies gradually increase from 1 to 20 Hz, refered to as a UP-case. The other is that the frequencies gradually decrease from 20 to 1 Hz, refered to as a DN-case.

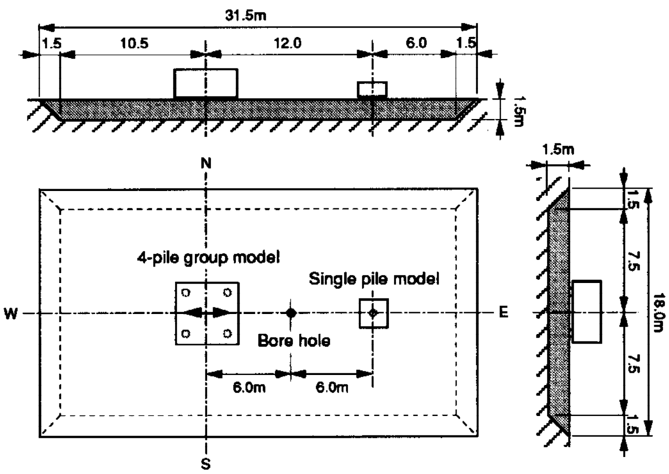


Fig. 1. Test yard and layout of test models.

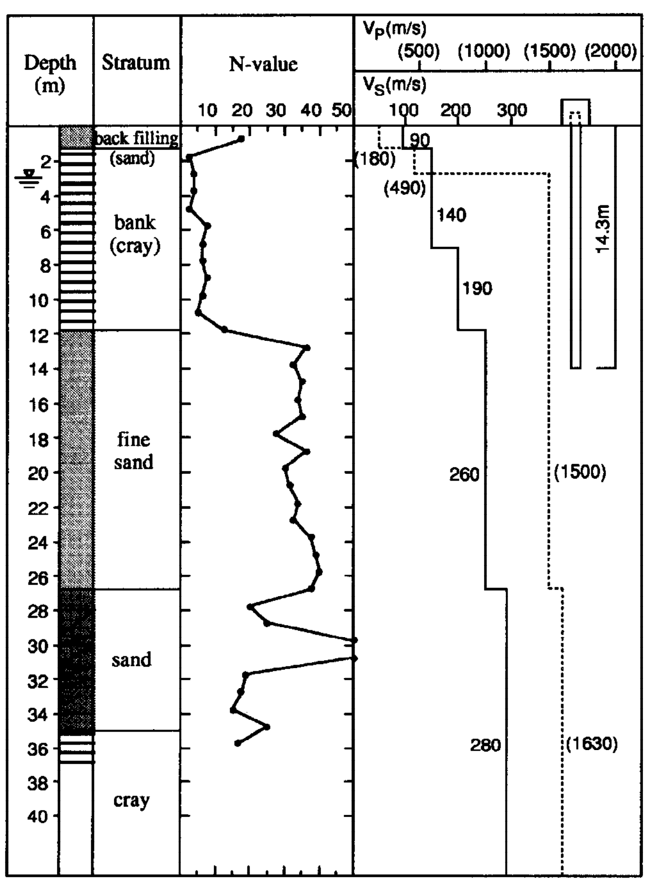
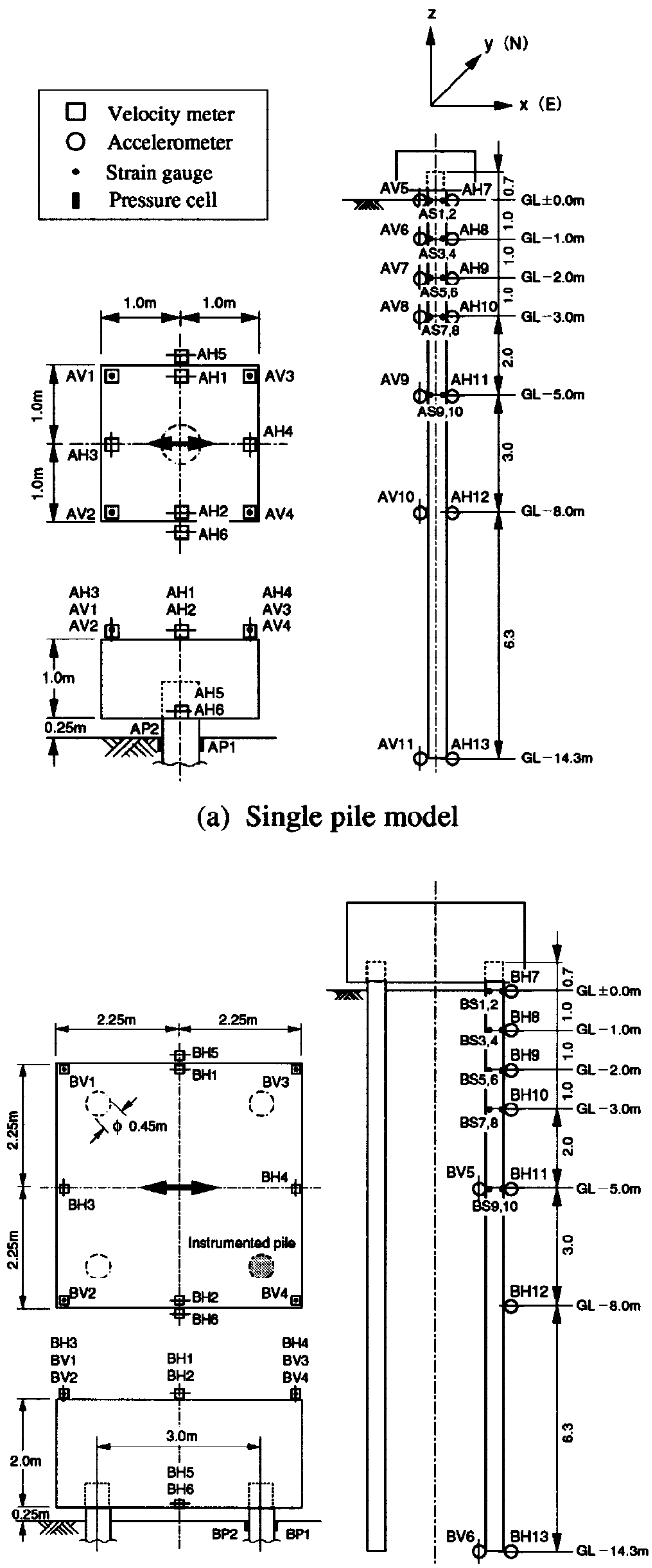


Fig. 2. Soil profile in test yard.



(a) Single pile model

(b) 4-pile group model

Fig. 3. Test models and location of instruments.

TEST RESULTS AND DISCUSSION

Swaying and Rocking Response of Block

Test results of several cases for the single pile model are briefly listed in Table 1, where the results of both S1 and S4 cases with low level excitations are not shown since these are still under examination. Results of all cases for the pile group model are listed in Table 2. In these tables, the resonance frequency, the damping factor, and the swaying and rocking displacement ratios at the top of the block, which are obtained from the resonance curves of the horizontal response measured at the top of the block, are summarized.

Figures 4 (a) and (b) show the horizontal displacement, U_T at the top of the block for both models. The displacement amplitude is normalized by the excitation force described in Tables 1 and 2. In these figures, the curves are compared among different excitation cases to discuss the response affected by the soil nonlinearity. From Fig. 4 (a), it is noted that the resonance frequency decreases and its amplitude decreases when the excitation force becomes large. The reason seems to be due to the increase of hysteresis damping induced by a large strain of the soil around the pile, as suggested from Table 1. On the other hand, one can find from Fig. 4 (b) for the pile group model that the resonance frequency decreases and its amplitude increases when the excitation force becomes large. It seems that the radiation damping decreases because of the separation at the interface between the pile and the soil, as indicated in Table 2. To make the effect clear, the distribution of the earth pressure at the pile head is drawn in Fig. 5, where the amplitude of the pressure is schematically illustrated as a circle in the phase plain. As understood from viewing the distribution after developing the resonance frequency, it is recognized that the separation is clearly occurred in the pile group model due to the high intensity of shaking.

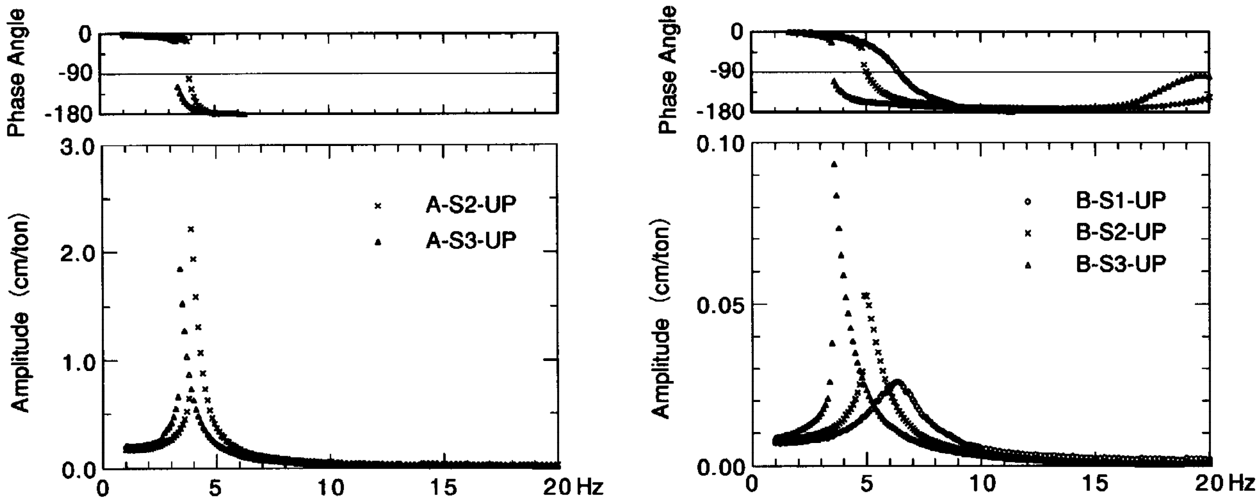
Figure 6 shows the amplitude ratio and the phase lag of the rocking displacement, U_R at the top of the block against the swaying displacement, U_S. As the excitation force becomes large, the ratio of U_R/U_S gets smaller in the lower frequency range in which the first mode is predominant. It is followed that the swaying mode of the block grows due to the development of the separation at the pile-soil interface, especially in the pile group model. On the contrary, when the shaking force is large, the ratio gets larger in the higher frequency range, and the out-of-phase vibration in the response of U_R and U_S becomes significant. This phenomenon suggests that the second mode of the block is developed in the high frequency range.

Table 1. Summary of forced vibration test results for single pile model

Excitation Case	Excitation Frequencies	Excitation Force	Resonance Frequency f(Hz)	Damping Factor h(%)	Swaying Ratio Us/Ut(%)	Rocking Ratio Ur/Ut(%)
A-S2-UP	1~20Hz	40kgf	3.9	4.1	60	40
A-S2-DN	20~1Hz		3.9	4.1	60	40
A-S3-UP	1~20Hz	150kgf	3.4	5.6	65	35
A-S3-DN	20~1Hz		3.2	6.5	65	35

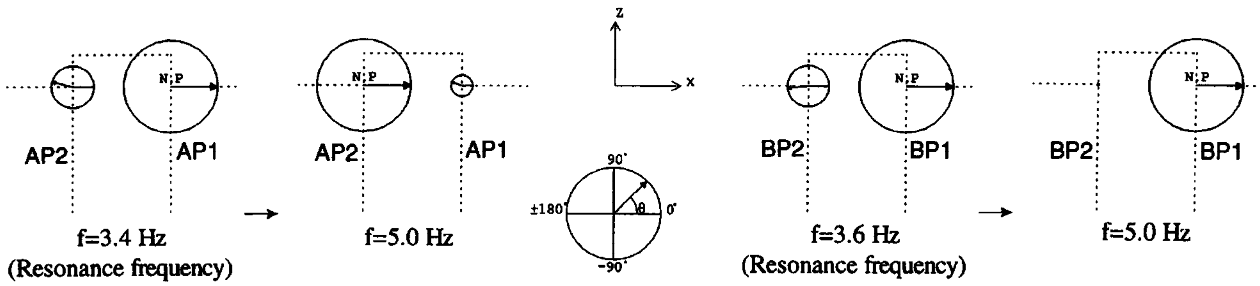
Table 2. Summary of forced vibration test results for 4-pile group model

Excitation Case	Excitation Frequencies	Excitation Force	Resonance Frequency f(Hz)	Damping Factor h(%)	Swaying Ratio Us/Ut(%)	Rocking Ratio Ur/Ut(%)
B-S1-UP	1~20Hz	100kgf	6.3	12.8	82	18
B-S1-DN	20~1Hz		6.3	13.1	82	18
B-S2-UP	1~20Hz	2,000kgf	4.9	7.5	87	13
B-S2-DN	20~1Hz		4.9	9.7	87	13
B-S3-UP	1~20Hz	8,000kgf	3.6	5.0	92	8
B-S3-DN	20~1Hz		3.4	8.7	92	8
B-S4-UP	1~20Hz	100kgf	5.1	8.5	87	13
B-S4-DN	20~1Hz		5.1	8.8	87	13



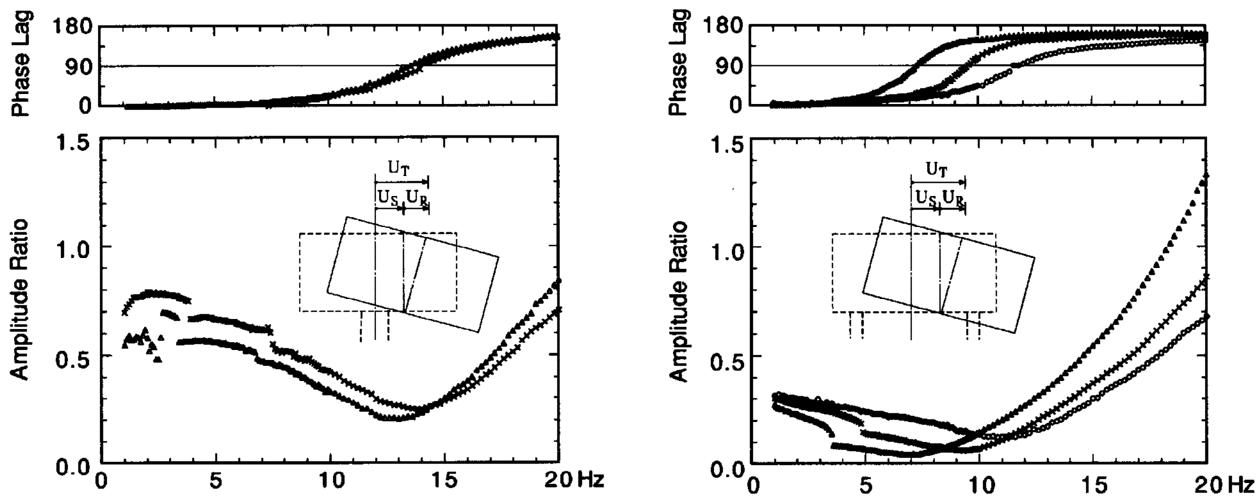
(a) Single pile model (b) 4-pile group model

Fig. 4. Resonance curves of horizontal displacement at top of block, U_T.



(a) Single pile model (b) 4-pile group model

Fig. 5. Distribution of earth pressure at resonance frequencies in the case of S3-UP.



(a) Single pile model (b) 4-pile group model

Fig. 6. Amplitude ratio and phase lag of rocking displacement against swaying one, U_R/U_S.

<u>Mode Shapes of Vibration at Resonance Frequency</u>

To discuss the flexural deformation of the block-pile system, the mode shapes of vibration at the resonance frequency are illustrated in Fig. 7. The figure is plotted by the same manner as Fig. 5. The deformation view in accordance with the harmonic response of the system is also added in the figure. The mode shapes are considerably different between the single pile and the pile group models. It is recognized from the view of the single pile model that bending deformation of the pile is remarkable as the pile cap condition looks nearly free.

This seems to be the cause for the growth of a large strain of the soil around the pile head. On the other hand, from the view of the pile group model, the swaying mode of the block is dominant because of the fixity condition at the pile cap, and the flexural deformation of the pile is larger in the deeper position compared with that of the single pile model. This seems to be caused by the development of a gap due to the separation at the pile-soil interface.

Flexural Response of Pile

Figure 8 shows the distributions of both the displacement and the bending moment of the pile. In the figure, the resulting curves at the resonance frequency are compared among different excitation cases. The bending moment is obtained from the strain measured in the instrumented piles. It is indicated that the characteristics of the mode shapes shown in Fig. 7 are reflected in the flexural response of the piles: from Fig. 8 (a) for the single pile model, the displacement amplitude near the pile head is extremely large and the amplitude decays sharply along the depth of the pile because of the free condition at the pile cap. From the figure (b) for the pile group, it is found that the curvature in the vicinity of the top of the pile is smaller than that of the single pile and the deformation declines not so rapidly along the depth, and that the bending moment at the pile head is remarkably large because of the fixity condition.

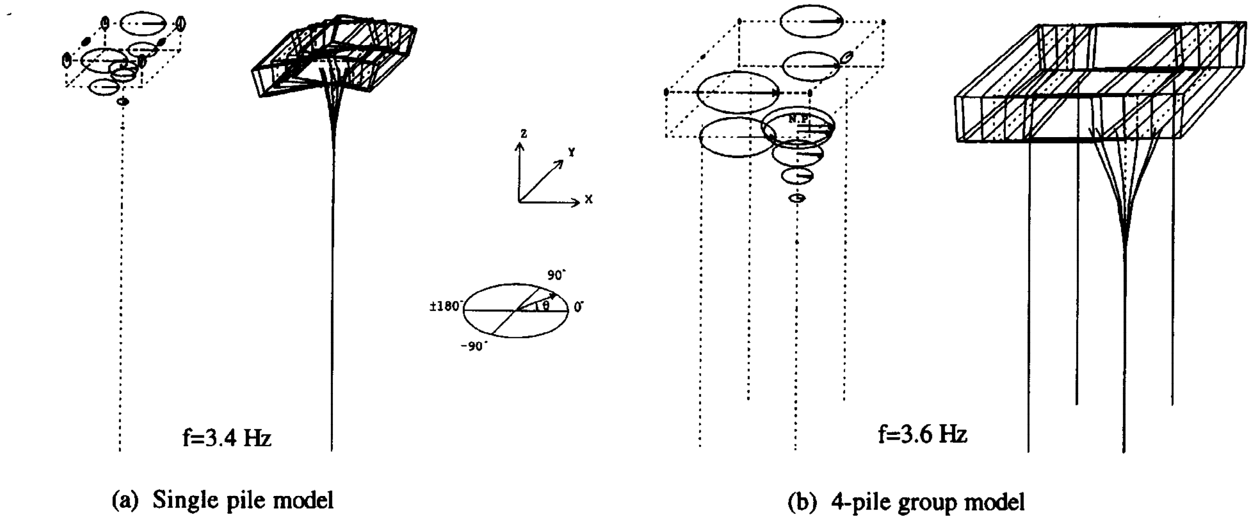


Fig. 7. Mode shapes of vibration at resonance frequencies in the case of S3-UP.

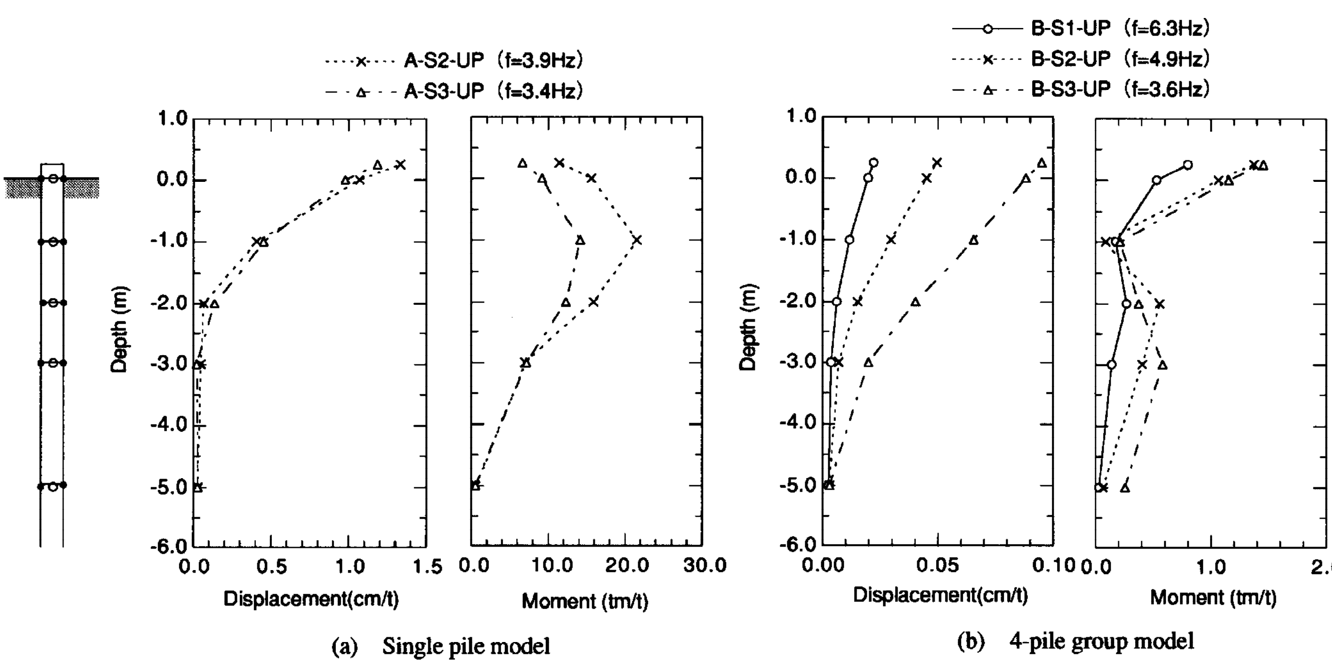


Fig. 8. Distributions of displacement and bending moment compared among different excitation cases.

Impedance Functions at Pile Head

One of the aims of conducting shaker tests of a rigid block is to obtain the measured values of the impedance functions for several modes, and to compare the experimental functions with the theoretical ones given by a numerical method which is reliable and useful for the application to a design analysis of actual foundations. In this section, the experimental impedance functions obtained from the procedure noted below are compared with the theoretical functions in order to investigate the nonlinear pile-soil interaction effects related to the gap. Generally, the relationship between the impedance functions of K_{HH}, K_{RR} and K_{HR} coupled with the horizontal and rotational modes and the functions of K_H and K_R with uncoupled those modes is given by

$$K_{HH} + K_{HR}(\theta_0/u_0) = K_H \tag{1}$$

$$K_{RR} + K_{HR}(u_0/\theta_0) = K_R \tag{2}$$

where, K_H and K_R are derived from equilibrium of the forces acting at the pile head in the following form:

$$K_H = \left(P + \omega^2 m_G u_G\right)/u_0 \tag{3}$$

$$K_R = \left(Ph_P + \omega^2 m_G u_G h_G + I_G\theta_0\right)/\theta_0 \tag{4}$$

where, P and ω are the excitation force and the frequency of a shaker. m_G and I_G are the mass of the block and the inertia moment at the center of gravity of the block. h_G is the height from the center of gravity of the block to the pile head. h_P is the height from the position of the rotating mass of the shaker to the pile head. u_G and u_0 are the horizontal displacement at the center of gravity of the block and at the bottom surface of the block, respectively. θ_0 is the rotational displacement of the block. As understood from Eqs. (1) and (2), the coupled functions of K_{HH}, K_{RR} and K_{HR} can not be definitely determined. Here, the impedance ratio of α=K_{HR}/K_{HH} which is computed by using the theoretical impedance functions is effectively utilized for this purpose. Substituting from K_{HR}=αK_{HH} into Eqs. (1) and (2), one can obtain

$$K_{HH} = K_H/\{1 + \alpha(\theta_0/u_0)\} \tag{5}$$

$$K_{RR} = K_R - \alpha K_{HH}(u_0/\theta_0) \tag{6}$$

Figure 9 shows the comparison of the theoretical and experimental impedance functions in the case of S2-DN for the pile group model with the middle level excitation. Other cases are omitted here owing to paper limitation. The theoretical functions are predicted by the thin layer method in which the gap to the depth of 0.75 m from the ground surface along the pile is considered for including the nonlinear interaction effects. Both results are in comparatively good agreements, except for the rotational mode of K_{RR} for the frequencies of around 9 Hz. To investigate the inaccuracy of K_{RR}, the displacement ratio of θ_0/u_0, which is employed to compute the measured value of the impedance functions as denoted in Eqs. (5) and (6), is plotted in Fig. 10. As found from this figure, both the real and imaginary parts of θ_0/u_0 become almost 0 at about 9 Hz. Therefore, it seems that the so-called ill condition is occurred in the range around the reference frequency when the experimental impedance function of K_{RR} is calculated from Eq. (6). The reference frequency of 9 Hz corresponds to the frequency where the motion of the block changes from the first mode to the second one, as indicated in Fig. 6 (b).

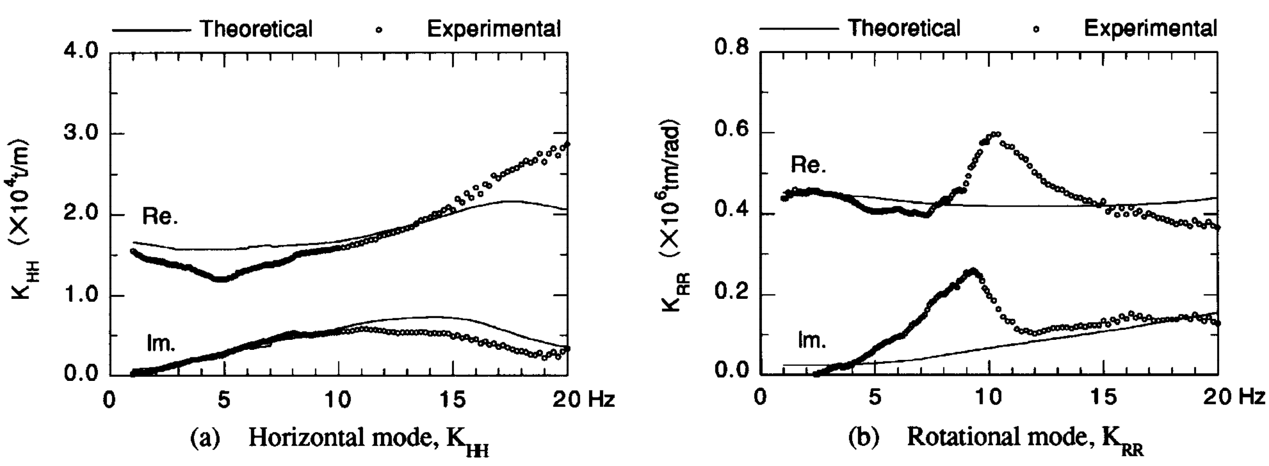


Fig. 9. Comparison of theoretical and experimental impedance functions in case of B-S2-DN.

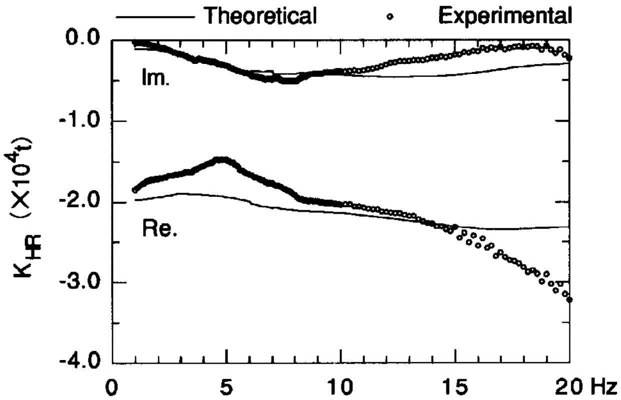


Fig. 9 (c) Coupling Mode, K_{HR}

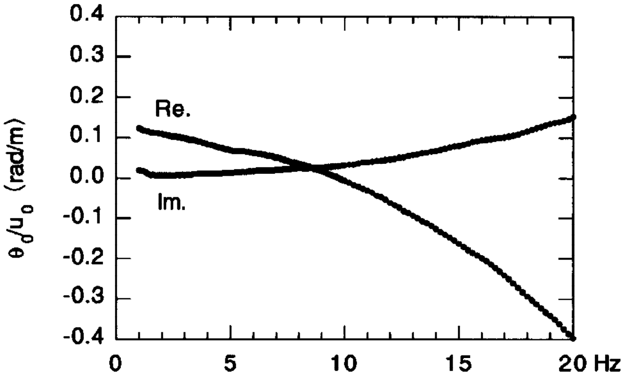
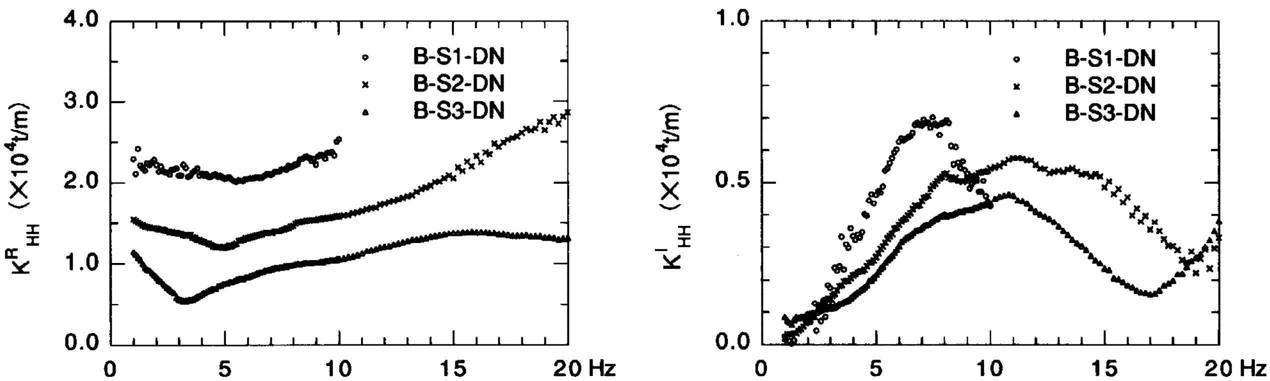


Fig. 10. Displacement ratio, θ_0/u_0 in case of B-S2-DN.



(a) Real part of K_{HH} (b) Imaginary part of K_{HH}

Fig. 11. Comparison of horizontal impedance, K_{HH} among three different excitation cases for 4-pile group.

Figure 11 shows the comparison of the measured values of the horizontal impedance, K_{HH} among three different cases of the excitation force for the pile group model. From this figure, both the real part of the functions associated with the resistance effect of the soil and the imaginary part related to the radiation damping decrease in the wide frequency range when the excitation force is larger. It is concluded that an influence due to the separation between the pile and the soil is rather dominant when considering the nonlinear interaction effects of the pile group model with a high intensity of shaking.

CONCLUSION

The forced vibration tests presented here provide reliable and useful data for the nonlinear behavior of pile foundations. The nonlinear behavior of pile foundations is mainly caused by both the material nonlinearity of the soil and the separation at the pile-soil interface. It is remarked that the local nonlinearity induced from a large strain of the soil around the pile has a great influence on the nonlinear response of single piles, and that a gap developed by the separation at the interface strongly affects the nonlinear response of pile groups.

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