Dynamic Stiffness of Pile Groups in a Multilayered Soil Part 1: Forced Vibration Tests for Pile Foundation Models

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ABSTRACT

For evaluating the dynamic stiffness of the pile group foundations, forced vibration tests are executed on pile group foundation models. Two types of test models are used, one is a single pile model and the other a four-pile model. Dividing the tests into 4 steps, the forced vibration tests are performed. Step 1 is for the single pile model, and steps 2 to 4 are for the four-pile model. In step 2 and step 3, the gap effects between the foundation bottom and the ground surface are examined. In step 4, the backfill effects are obtained. Based on the test results, the pile group effects, the gap effects and the backfill effects on the dynamic characteristics of the pile group foundations are described in this paper.

1 INTRODUCTION

In order to confirm the dynamic characteristics of structures supported by piles, it is important to evaluate accurately the dynamic interaction of the piles to piles through soil. However, only a few dynamic experiments have been reported in regard to the pile group foundations. It is the purpose of this research to execute the forced vibration tests for a single pile model and a four-pile model in multilayered soil, to evaluate experimentally the dynamic stiffness of the pile foundations, and to develop a rational analysis method for calculation of the dynamic stiffness of the pile groups. In this paper, the forced vibration tests for the pile foundation models and the test results are described. In Part 2, the rational analytical method for calculation of the dynamic stiffness of the pile groups and the comparisons of the analysis with the tests are described.

2 EXPERIMENTS

2.1 Test Models

The pile foundation models used for the tests are the two types shown in Fig. 1; a four-pile test model and a single pile test model. All piles are cast-in-place reinforced concrete (RC) piles of 0.6m in diameter and 7.5m in length. A 4.4m(W)x4.4m(L)x4.0m(H) solid RC block specimen is constructed on the four-pile model, while a 1.5m(W)x1.5m(L)x0.5m(H) solid RC block specimen is constructed on the single pile model. For determining the block dimensions on the single pile model, the size of the exciter to be installed on its top is taken into consideration, and the dimensions of the block on the four-pile model are designed so that resonant frequencies will be in the excitation frequency range.

2.2 Site and Soil Properties

The pile foundation models are constructed after excavating the ground to 3m depth as shown in Fig. 2. For the four-pile model, testing after backfilling of the excavated part is also executed. The physical characteristic values of the soil, obtained from the soil investigations, are shown in Table 1. The soil investigations are executed as for PS logging before excavation, ground surface seismic investigation after excavation, and PS logging for the backfilling soil after backfilling. The site has a clear 2-layer composition of sandy soil and mudstone. The model piles are constructed using this mudstone layer as the supported layer and the pile tip is embedded 50 cm in this layer.

2.3 Test Steps

The testing is divided into 4 steps, and a exciter installed on top of the block generates the harmonic excitation in the two directions of horizontal and vertical. Fig. 3 shows the test steps. The purposes of individual steps are shown below.

Step 1 (for the single pile model)
Confirmation of the dynamic characteristics of the single pile model and obtaining of basic information needed for examining the test results of the four-pile models obtained from the next step on.
Step 2 (for the four-pile model, before grouting and backfilling)
Measuring of the pile group foundation model in the case of gaps between the foundation bottom and the ground surface, and investigation of the pile group effects by comparison with step 1.
Step 3 (for the four-pile model, after grouting and before backfilling)
Measuring of the pile group foundation model in the case of contact between the foundation bottom and the ground surface and investigation of the gap effects by comparison with step 2.
Step 4 (for the four-pile model, after grouting and backfilling)
Investigation of the backfill effects.

As for the excitation force, small force levels are set for each step in order to keep the behavior of the piles and surrounding soil in the elastic range.

Measuring is executed by arranging displacement meters on the blocks and accelerometers embedded in a pile of the four-pile model. An example of the measuring points is shown in Fig. 4 for step 2.

3 TEST RESULTS

3.1 Dynamic Characteristics of the Four-Pile Models

The resonance curves and the phase lag curves are shown in Fig. 5 to Fig. 7 by superposing the results of the steps 2 to 4. These results are shown by coordinate conversion to the block bottom center for the response displacement of each measuring point after confirmation that the block is vibrating as rigid body. Table 2 shows a consolidation of the test results at the resonant frequency for horizontal excitation.

For horizontal excitation, the resonant frequency shows an increase of 1.2 Hz after grouting, and 1.6 Hz after backfilling, and the resonant amplitude decreases to 50% and 10% respectively. It can be seen from these results that the backfill effects are large in comparison with the gap effects. Meanwhile, the ratio of rocking displacement with the horizontal displacement on top of the block shows no large change; before and after grouting; and before and after backfilling, so the same vibration mode can be seen for all steps of horizontal excitation.

For vertical excitation, the resonant frequency shows practically no change with grouting. The amplitude is reduced slightly, but no difference can be recognized for the phase lag curve. Accordingly, it can be said that the gap effects between the block bottom and the ground surface are not large for changing the dynamic characteristics of the four-pile model in vertical direction. The test results after backfilling show the backfill effects clearly. The natural frequency (frequency where the phase lag becomes 90 degree) shifts from 18 Hz to 22 Hz, and the amplitude is reduced to 50%.

3.2 Displacement Distributions of the Pile

Fig. 8 shows the displacement distributions along a pile of the four-pile models at the resonant frequency with the accelerometers embedded in the pile. The horizontal displacements of the pile for horizontal excitation show a decreasing distribution in depth direction. This decrease rate declines in the order from step 2 to step 4. This result shows that the block inertia force flows into the ground through the block bottom in step 3 also through the sides in step 4, and that the soil around the pile is vibrated. The vertical displacements of the pile for vertical excitation show the same kind of tendency, but it is not as apparent as for horizontal excitation. And the phase lag values are almost the same in depth direction for each step. These results show that the pile deformation in the axis direction is small.

3.3 Dynamic Stiffness and Pile Group Effect

The dynamic stiffness of the four-pile model in horizontal, rotational, and vertical direction for the soil-piles system, calculated from the inertial force and the inertia moment of the block, and the excitation force, is shown in Fig. 9. The real part of horizontal and rotational dynamic stiffness increases by 50% after grouting, while the imaginary part shows practically no change. After backfilling, the real part and the imaginary part both become extremely large. The vertical dynamic stiffness shows only a small change from before to after grouting, but the real part and the imaginary part both increase after backfilling.

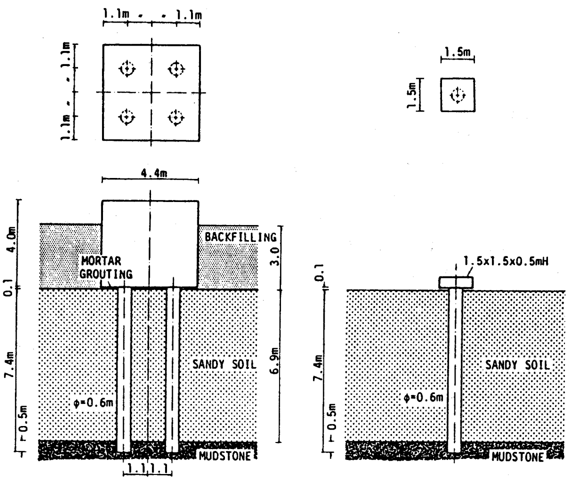
Fig. 10 shows a comparison of the dynamic stiffness of step 1 and step 2 in order to investigate the pile group effects. For the rotational stiffness of the single pile, the rotational component and the vertical component are taken into account. In regard to horizontal and rotational dynamic stiffness, the pile group effects can not be investigated directly from these results. The reason for this is the fact that the vibration mode of the block (ratio between horizontal displacement and rotation angle) is different for step 1 and step 2, so that the influence of the coupled component for horizontal direction and rotational direction differs. Fig. 11 shows the ratio between horizontal displacement and rotational angle for both steps. However, it can be confirmed for the horizontal and rotational dynamic stiffness of step 2 that the real part in the low frequency range decreases slightly and thus shows a pile group effect. The vertical dynamic stiffness is not influenced by the vibration mode, and the pile group effects appear distinctly. The pile group effects decrease the real part of the dynamic stiffness to 60% over the entire frequency range, but no significant difference is seen in the imaginary part.

4 CONCLUDING REMARKS

The following concluding remarks are derived from the forced vibration tests results on pile foundation models.

(1) As for the four-pile model, the gap effects appear for the real part of horizontal and rotational dynamic stiffness, but not for the imaginary part. The gap effects are small to the vertical dynamic stiffness. The backfill effects appear distinctly for real and imaginary part in horizontal, rotational, and vertical direction.

(2) The pile group effects can be confirmed clearly in the vertical dynamic stiffness which is calculated without the influence by the vibration mode of the block. As for horizontal and rotational dynamic stiffness, the effects are confirmed in the low frequency range. As the results, the pile group effects are notable for the real part of the dynamic stiffness, while they hardly appear for the imaginary part.



(a) Four-Pile Model (b) Single Pile Model

Fig. 1 Test Models.

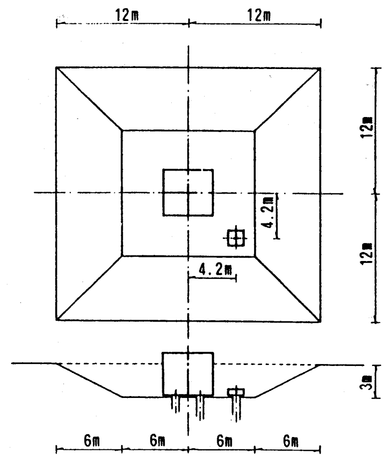


Fig. 2 Layout of Test Models.

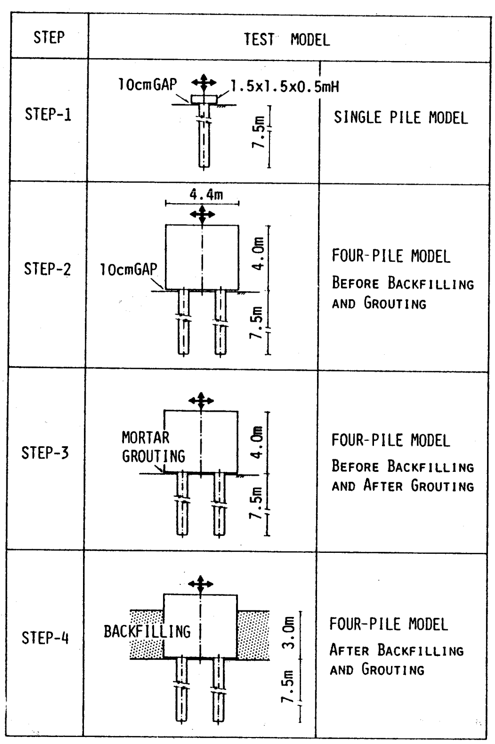


Fig. 3 Test Steps.

Table 1 Soil Properties.

Depth(m)	Soil Profile	Mass Density (t/m^3)	S-Wave Velocity (m/s)	Poisson's Ratio
	Backfilling Soil	1.85	95	0.199
			145	0.341
			180	0.219
5	Fine Sand	1.80	250	0.179
			320	0.292
			320	0.429
10	Mudstone	1.75	510	0.459
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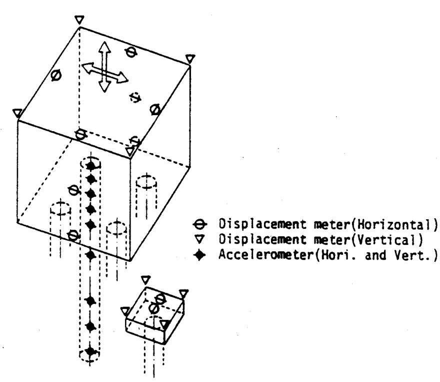


Fig. 4 Measuring Points Arrangement for Test Step 2.

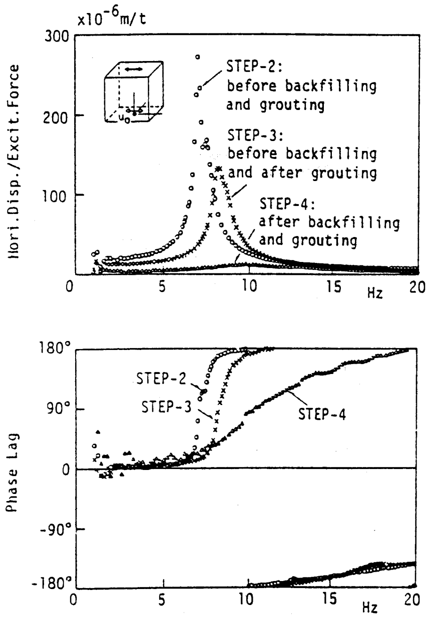


Fig. 5 Resonance Curves and Phase Lag Curves of Four-Pile Models. (Horizontal Displacement for Horizontal Excitation)

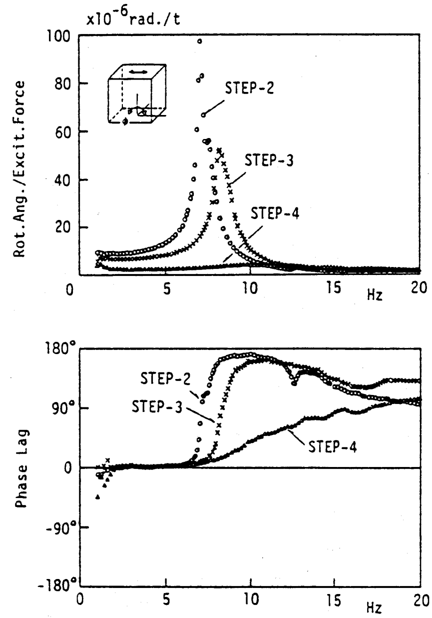


Fig. 6 Resonance Curves and Phase Lag Curves of Four-Pile Models. (Rotation Angle for Horizontal Excitation)

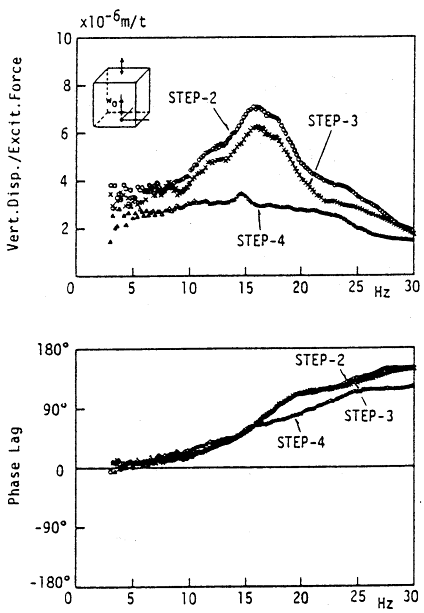
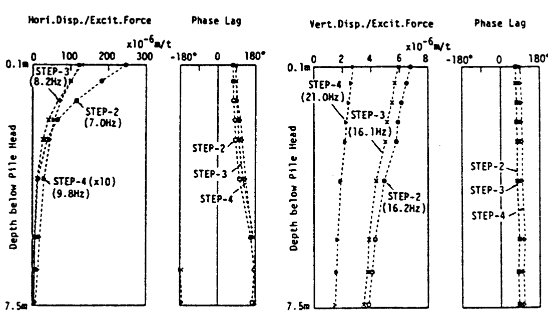


Fig. 7 Resonance Curves and Phase Lag Curves of Four-Pile Models. (Vertical Displacement for Vertical Excitation)

Table 2 Test Results of Four-Pile Models for Horizontal Excitation.

Test	Peak Freq. (Hz)	Hori. DISP. ($x10^{-6}$ m/t)	Rot. Ang. ($x10^{-6}$ rad./t)	Rocking Disp. Ratio at Top of Block (%)
STEP-2	7.0	271.75	97.36	59
STEP-3	8.2	132.41	52.08	61
STEP-4	9.8	13.58	4.50	57



(a) Horizontal Excitation

(b) Vertical Excitation

Fig. 8 Pile Displacement Distribution of Four-Pile Models at Resonance Frequency of Each Step.

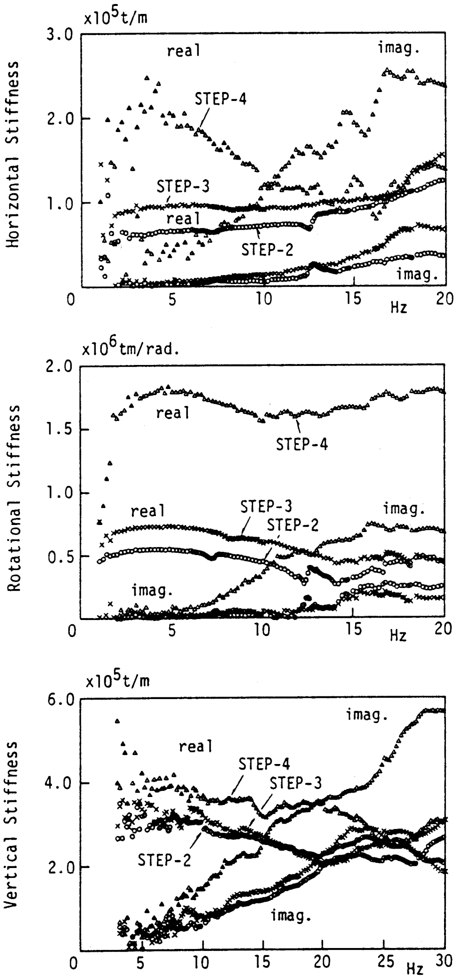


Fig. 9 Dynamic Stiffness of Four-Pile Models.

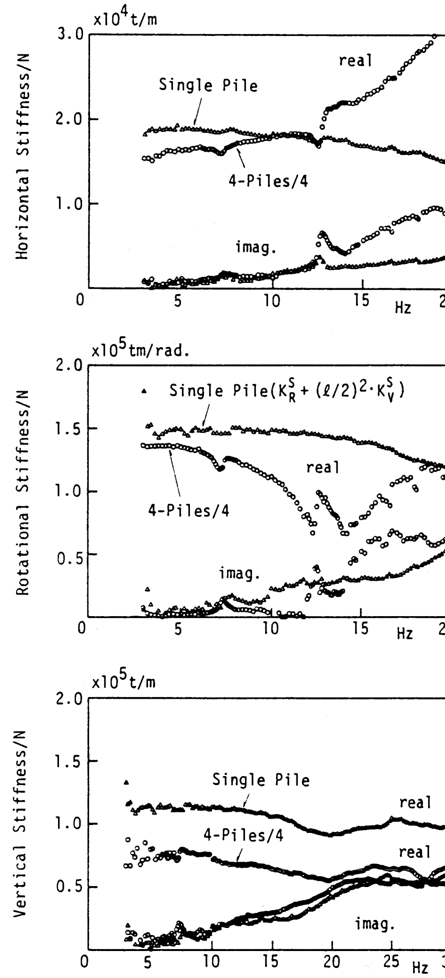


Fig. 10 Comparisons of Dynamic Stiffness of Single Pile Model (Step 1) and Four-Pile Model (Step 2).

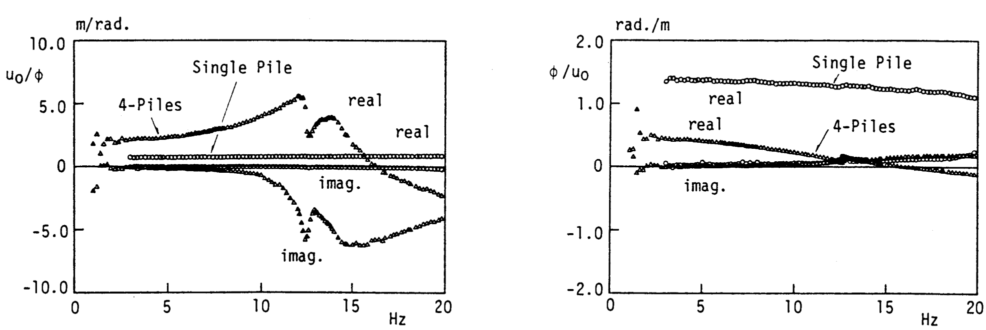


Fig. 11 Comparison of Block Vibration Mode of Step 1 and Step 2. (Ratio between Horizontal Displacement and Rotation Angle)