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DYNAMIC INTERACTION OF SOIL AND COMPOSITE FOUNDATION

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ABSTRACT

A composite foundation has been employed for a high-rise building on a soft reclaimed soil. Composite foundations usually consist of a wall foundation with an internal pile group and an exterior pile group. The behavior of buildings built on such foundations is greatly influenced by soil-foundation interaction during earthquakes. In this study, a forced vibration test was performed on an actual composite foundation constructed in the Tokyo Bay area. The test results indicate that the basement vibrates as a rigid body and the wall foundation shows similar vibration modes to those of the internal piles. Analytical studies were carried out using an axisymmetric finite element method (Axi-FEM) to confirm changes in dynamic characteristics caused by the basement, internal piles and exterior piles. The results indicate that the basement and internal piles restrict the vibration of the internal soil. Analyses that take the exterior pile into account show a decreased foundation response, and represent well the test results. Correlation analyses were carried out to verify a simplified numerical model comprising a lumped-mass model. The proposed numerical model shows good agreement with the results by the Axi-FEM and the test results.

KEYWORDS

Soil-structure interaction; composite foundation; forced vibration test; axisymmetric FEM; lumped-mass model

INTRODUCTION

A large number of high-rise buildings are under construction or have been constructed in reclaimed coastal areas. Composite foundations have been employed for high-rise buildings constructed on reclaimed soil. They usually consist of a wall foundation with an internal pile group, and an exterior pile group which supports lower buildings. The behavior of high-rise buildings built on such foundations is greatly influenced by soil-foundation interaction during earthquakes. It is important for aseismic design of high-rise buildings on such foundations to clarify the dynamic interaction of the soil and the composite foundation. This paper investigates the dynamic characteristics of the composite foundation based on the results of a forced vibration test and analytical studies using an axisymmetric finite element method (Axi-FEM). A simplified lumped-mass numerical model with dynamic interaction springs is also verified by comparison with the Axi-FEM results and the test results.

FORCED VIBRATION TEST

Test Conditions

The forced vibration tests were performed for a basement supported on the composite foundation shown in Fig.1. The basement is 8m deep and the composite foundation comprises a 30m-square diaphragm wall with

20 piles inside and 65 piles outside. The wall is 1.2m thick and 18.3m long. The piles inside the wall are 18.3m long and 1.8m in diameter, while those outside the wall are 24.3m long and 0.6m in diameter. The wall and internal piles were constructed of cast-in-place reinforced concrete, while the exterior piles were precast. Table 1 shows the soil profile. Ground level is almost floor B1 level. The wall foundation and piles are supported on a Tokyo gravel layer about 23m deep. A high-rise building of 32 stories has been constructed on this foundation. After floor B1 was constructed, the forced vibration tests were conducted using one vibration generator (maximum excitation force of 3 ton) installed at the center of the diaphragm wall on floor B1. The test responses were measured using 5 accelerometers buried in the center of the wall flange, 3 accelerometers buried in an internal pile, and several displacement meters arranged on floors B1 and B2. The forced vibration was generated in the Y direction and the excited frequency range was from 1 to 8 Hz. The stress-strain relationship for the soil was in the linear range in this test because the vibration force was very small.

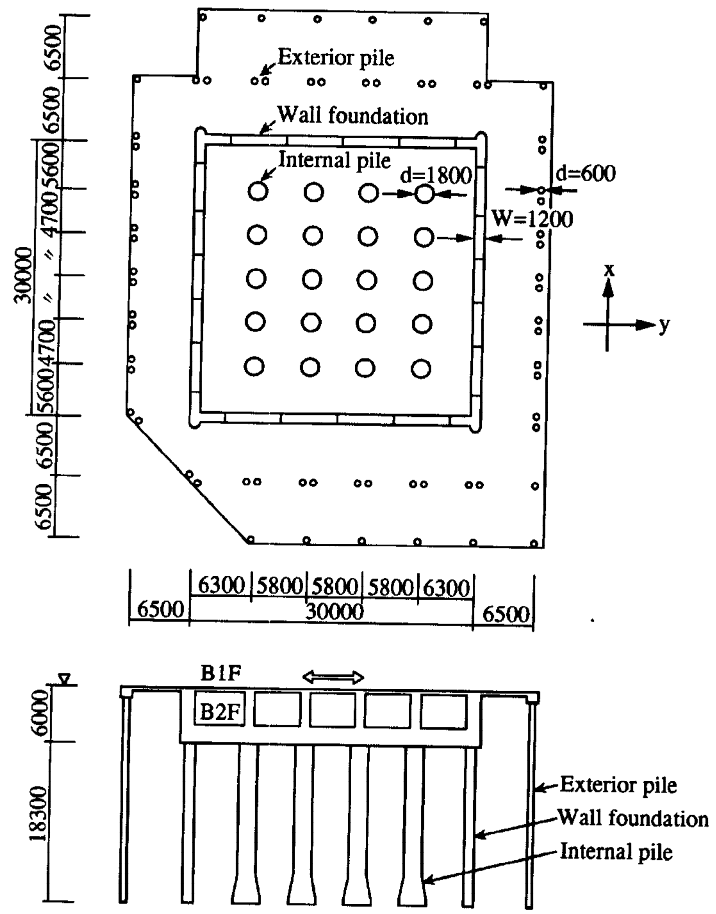


Fig.1. Plan and section of composite foundation

Table 1. Soil profile

Soil type	γ (t/m³)	Vs (m/sec)	ν	h (%)
sand	1.76	120	0.48	5
silt	1.68	105	0.48	5
sand	1.68	105	0.48	5
clay	1.65	125	0.48	5
sand	1.81	165	0.48	5
sand	1.81	360	0.48	2
clay	1.74	215	0.48	2
gravel	1.95	475	0.40	2
sand & clay	1.90	450	0.40	2
gravel	2.00	600	0.40	2

Depth(m): 0, -10, -20, -30, -60 (m)

γ : Unit weight　Vs : S wave Velocity
ν : Poisson's ratio　h : Damping factor

Test results

Fig.2 shows the resonance and phase lag curves of horizontal displacement at floors B1 and B2 in the Y direction and the rotational angle about the X direction. Fig.3 shows the vibration modes of floors B1 and B2, the wall foundation and an internal pile of 2.6, 3.8 and 6.0 Hz. The test results indicate that the horizontal displacements at each basement floor are almost the same and that the vertical ones are fairly small. The basement was confirmed to vibrate as a rigid body. The displacements shown in Fig.2 are averaged for each frequency using the least-squares method assuming that the basement is a rigid body. The resonance peak cannot be clearly confirmed and the phase lag curve rises gradually with radiation damping caused by dynamic interaction of soil and composite foundation. The horizontal amplitudes of floor B1 are larger than those of B2 in the excited frequency range, and the rotational angles of floors B1 and B2 are almost the same. These effects occurred because the basement rocked as a rigid body. As shown in Fig.3, the wall foundation and an internal pile show similar vibration modes in this frequency range. The phase differences between the upper and lower measuring points of the foundation increase with frequency.

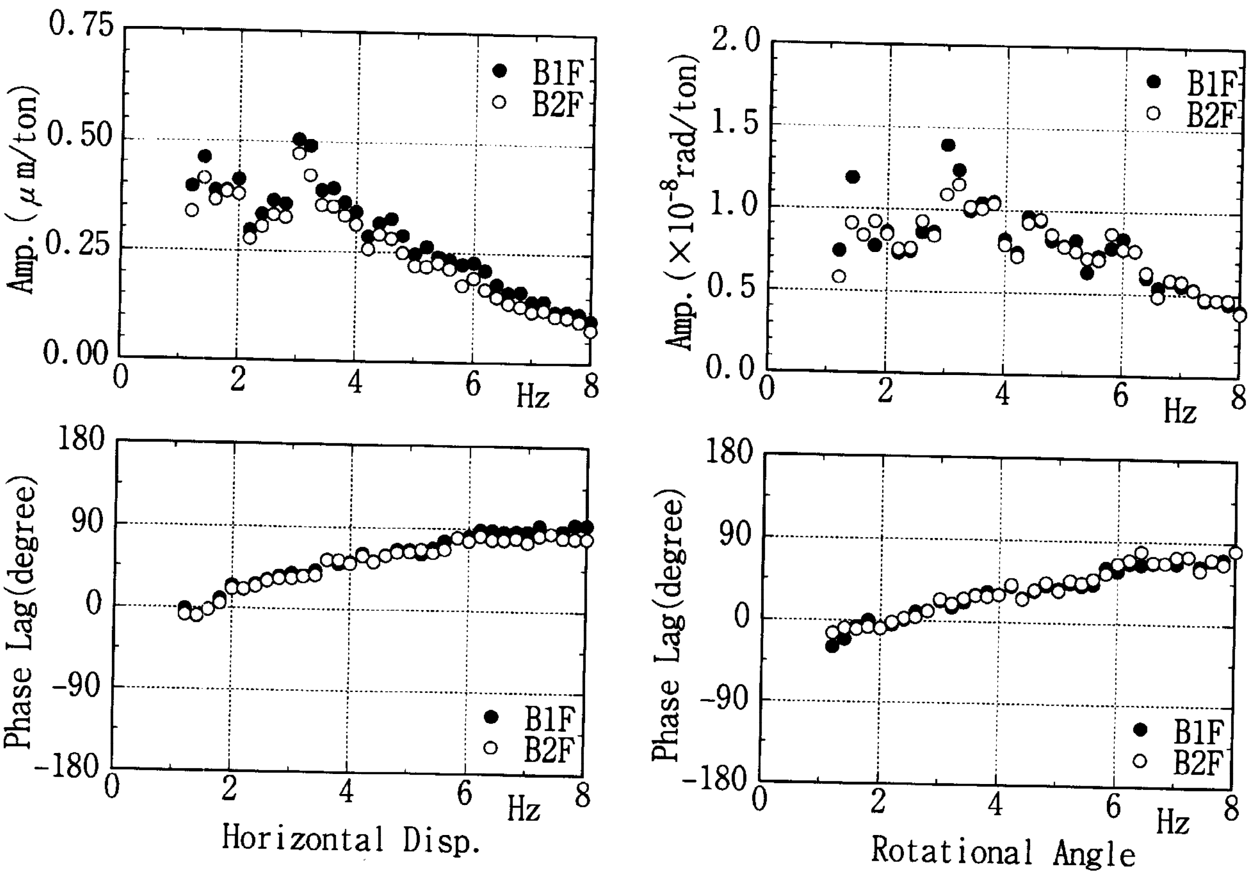


Fig.2. Resonance and phase lag curves at floor B1 and B2

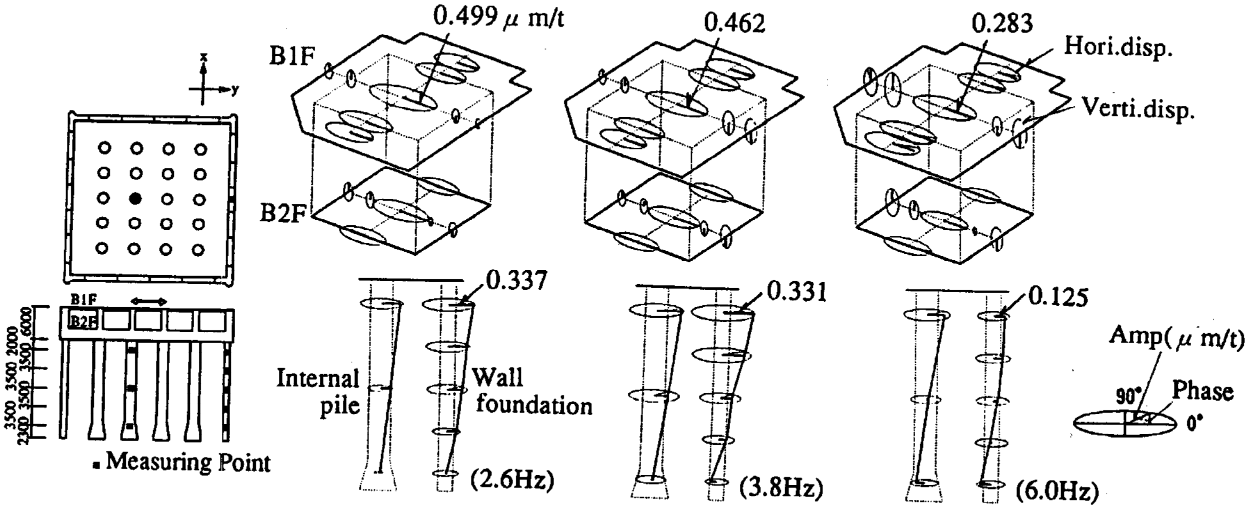


Fig.3. Vibration modes of composite foundation

CHARACTERISTICS OF COMPOSITE FOUNDATION

Analytical Model

Analytical studies were carried out to investigate the influence of the basement, the internal piles and the exterior piles on the dynamic characteristics of the composite foundation. The three models shown in Fig.4 were analyzed using an axisymmetirc finite element method (Axi-FEM). They are described as follows.

Model-1 comprises only a wall foundation.

Model-2 comprises a wall, a basement and an internal pile group.

Model-3 is the same as model-2, but with the addition of an exterior pile group.

Fig.5 shows the mesh layout of model-3. A wall foundation is modeled as a shell element with the same geometrical moment of inertia as the wall. The piles are rearranged in concentric arrangements. The internal piles were grouped in 2 rings and the exterior piles were grouped in one ring. A pile group is modeled as a ring pile element (Tyson *et al.*, 1983) with the same geometrical moment of inertia as the pile group. The side interface is adopted as the energy transmitting boundary, and the bottom is adopted as the viscous boundary. The basement is treated as a rigid body. The basement is mounted on ring pile elements and a shell element. The bottom of the basement was detached from the soil between ring pile elements, while the side of the basement was in contact with the soil.

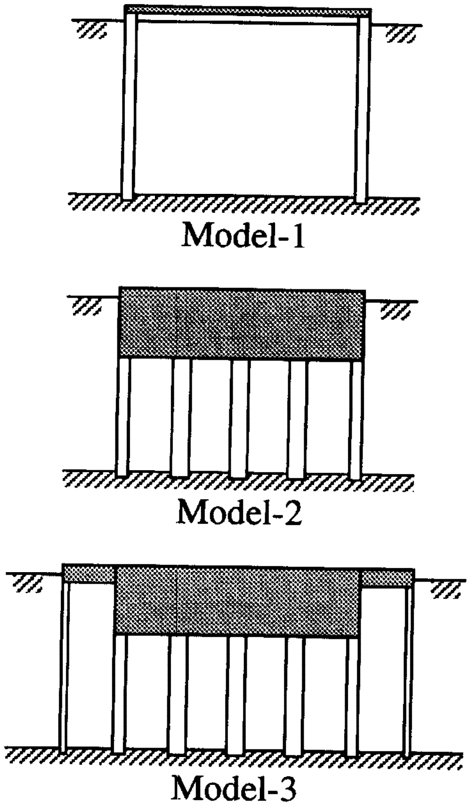


Fig.4. Analytical models

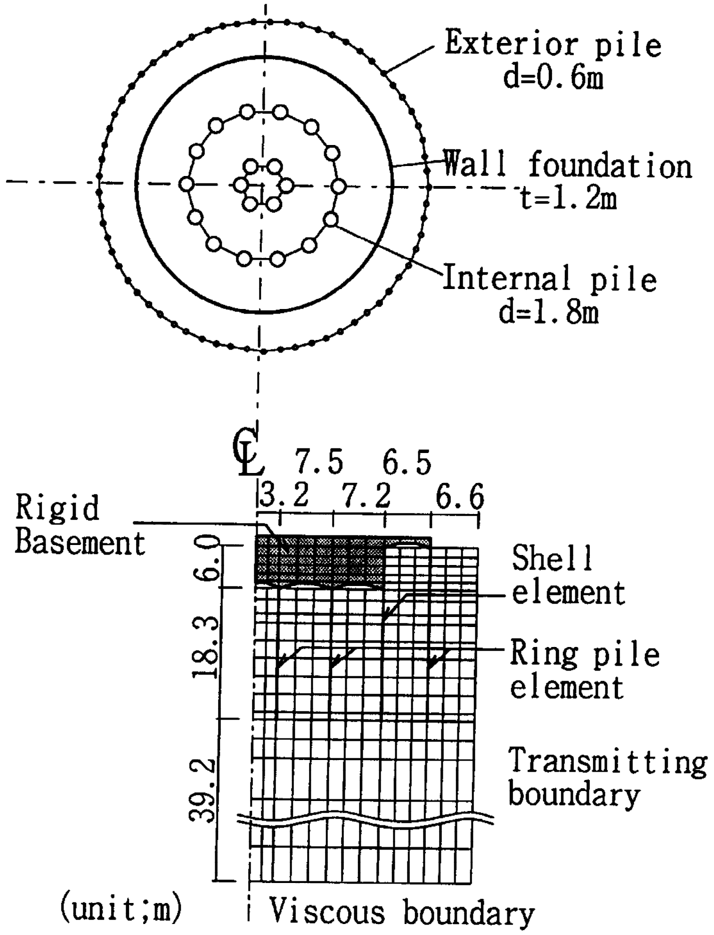


Fig.5. Mesh layout of Axi-FEM model (Model-3)

Analytical Results

Fig.6 shows the resonance and phase lag curves of horizontal displacement and rotational angle at floor B1 obtained from the Axi-FEM. The horizontal displacements and rotational angles for model-1 and model-2 have almost the same amplitudes in the lower frequency range 1 to 3 Hz. However, the resonance curves of model-1 have frequency characteristics in the high frequency range, and vary greatly from those of model-2. Fig.7 shows the vibration modes of model-1 and model-2 at 2.0 and 4.8 Hz. The wall foundation and internal soil of model-1 show similar vibration modes to those of model-2 at 2.0 Hz. It is confirmed that the existence of the basement and internal piles have little influence on the vibration mode in the lower frequency range. The vibration mode of model-1 shows a small displacement amplitude for the wall foundation at 4.8 Hz because the natural vibration of the internal soil is excited. The wall foundation of model-2 shows a similar vibration mode to the soil because the basement and the internal piles restrict the natural vibration of the internal soil in the higher frequency range.

As shown in Fig.6, the horizontal displacement and rotational angle of model-3, which take the exterior piles into account, decrease in the frequency range 1 to 8 Hz. Compared with model-2, the resistance of the exterior piles influences the rotational angle of the foundation more than the horizontal displacement. The results of model-3 represent well the test results.

These analytical studies indicate that the existence of the basement and internal pile group effectively restrict the natural vibration of the internal soil, and the exterior pile group decreases the response of the composite foundation.

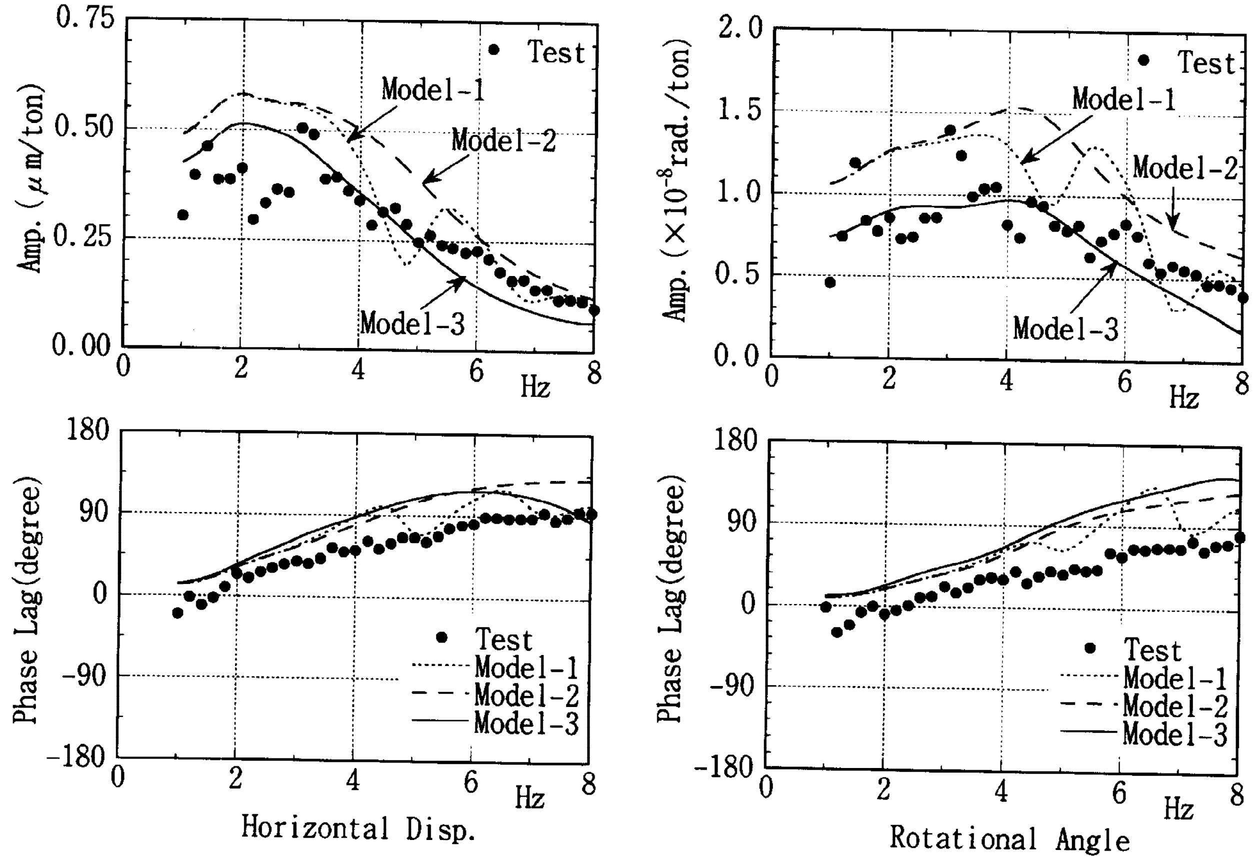


Fig.6. Comparisons of responses at floor B1 by Axi-FEM

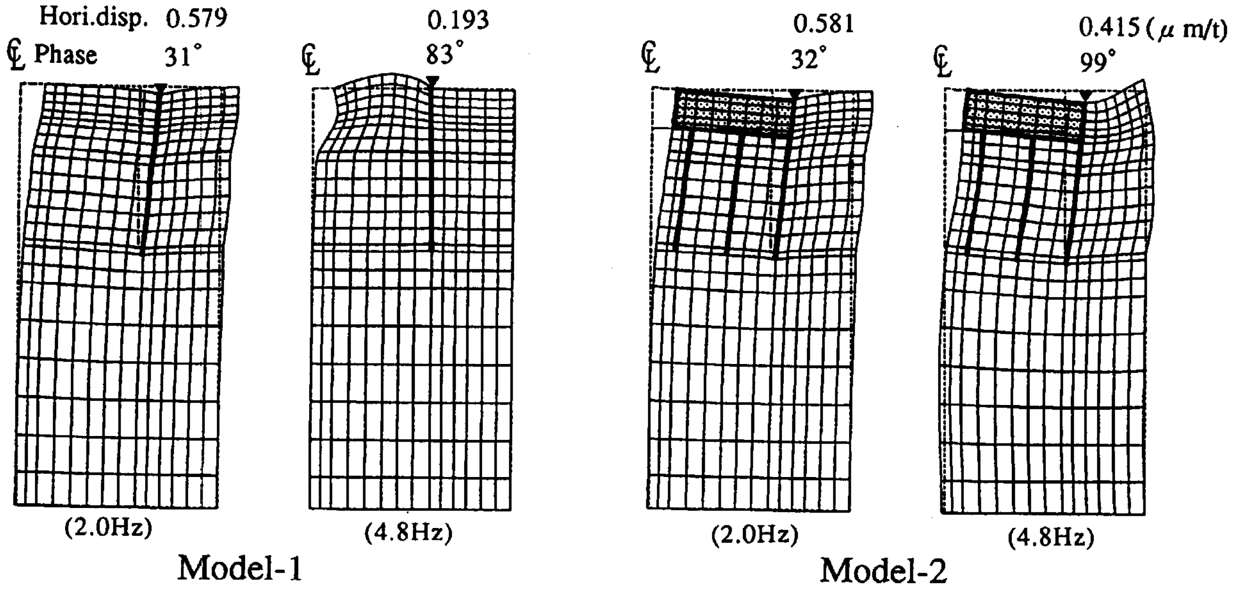


Fig.7. Vibration modes of Model-1 and Model-2

CORRELATION ANALYSIS BY LUMPED-MASS NUMERICAL MODEL

Analytical model

Correlation analyses of models 1 to 3 were carried out using a simplified lumped-mass numerical model connected by beam elements taking interaction springs into account. Fig.8 shows the lumped-mass model for model-3. The forced vibration test indicates that the wall foundation and internal piles vibrate in almost the same mode, so they are modeled as one beam with frequency-dependent dynamic interaction springs. The beam elements between the adjoining lumped masses have shearing and flexural rigidity. The shearing rigidity of the beam is evaluated using only the web part of the wall foundation, and the flexural rigidity is evaluated using both web and flange parts. The stiffness of the internal piles is neglected. The each lumped mass is estimated by summing up the mass of the wall foundation and the internal piles at each level, and the rotational inertia is estimated using only that of the wall foundation.

The dynamic interaction springs are evaluated independently by separating them into 3 parts as shown in Fig.8. The interaction springs for the wall foundation and the internal piles are estimated by neglecting the internal and exterior pile group. Then, the soil surface is assumed to be at the top of the wall. The interaction springs are evaluated by the Thin Layered Element Method (TLM) as follows. The soil corresponding to the wall is discretized both horizontally and vertically as shown in Fig.9(a). The soil flexibility matrix for each direction is obtained by applying Green's functions to the horizontal and vertical directions of all the nodes (Kausel *et al.,* 1982). Then the soil stiffness matrices are also obtained as inverse of the flexibility matrices. These stiffness matrices in the horizontal and vertical directions are reduced to horizontal and rotational matrices which have dimension associated with the number of lumped masses by applying the rigid body mode assumption at each depth. Thus the horizontal matrix is obtained by applying the same displacement (Ui) to all nodes at each depth, as shown in Fig.9(b). The rotational matrix is also obtained by applying the rotational displacement (Vi) of the rigid body around the center of the wall as shown in Fig.9(c).

The dynamic interaction springs of the basement are evaluated by adapting the TLM for the external surface soil neglecting the exterior piles. The springs are estimated by the method of Tajimi *et al.,* 1986.

The interaction springs of the exterior pile group are evaluated by neglecting the basement, wall foundation and internal piles. The horizontal and rotational springs at the head of the exterior pile group are evaluated by the method of Masuda *et al.,* 1993. The springs are fixed to the floor B1 level.

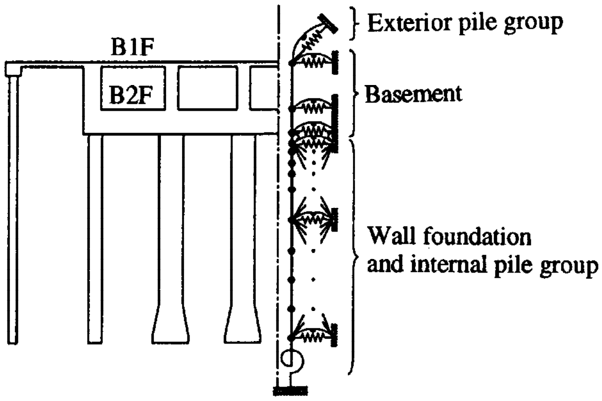
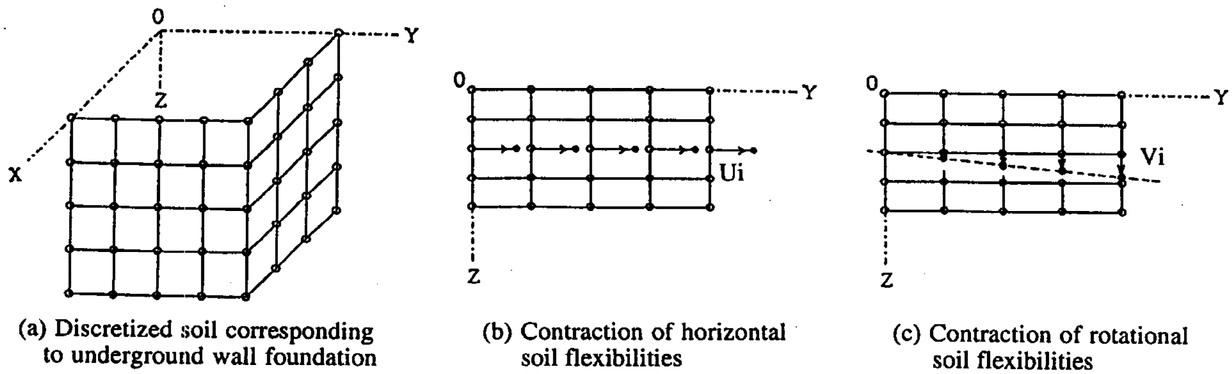


Fig.8. Lumped-mass model (Model-3)



(a) Discretized soil corresponding to underground wall foundation

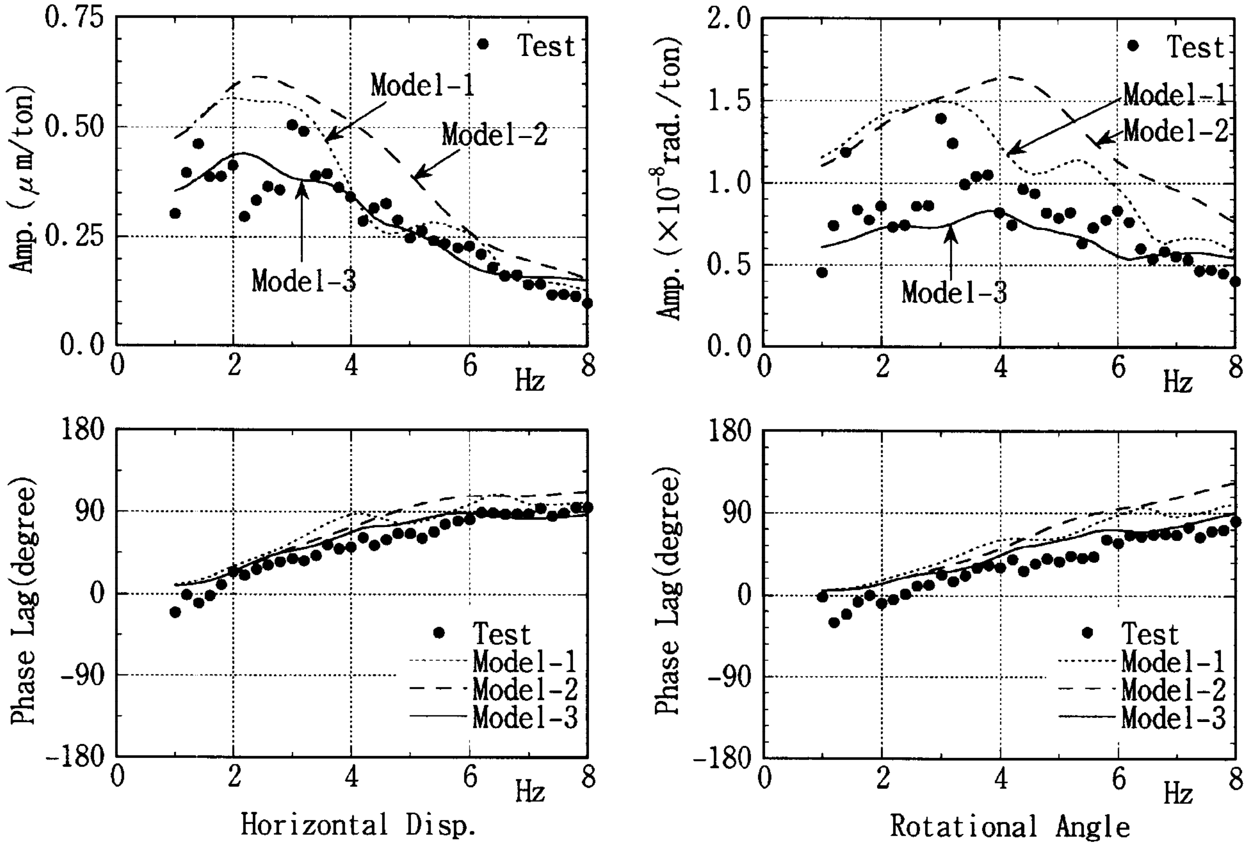
(b) Contraction of horizontal soil flexibilities

(c) Contraction of rotational soil flexibilities

Fig.9. Evaluation of soil springs of wall foundation

Analytical Results

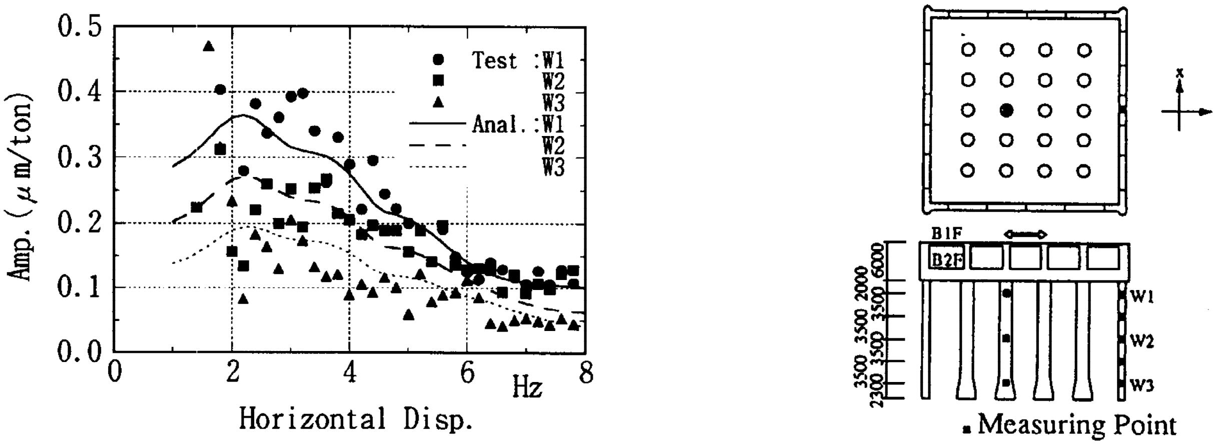
Fig.10 compares the resonance and phase lag curves of the horizontal displacement and rotational angle at floor B1 for 3 models with the test results. The results for model-1 and model-2 show almost the same characteristics as the Axi-FEM. This shows that the basement and internal piles restrict the natural vibration of the internal soil like the verification by the Axi-FEM studies. The resonance curves for model-3 show smaller amplitude than the Axi-FEM. This is because the interaction of exterior pile group and wall foundation is neglected. However, the results for model-3 by this proposed method show good agreement with the test results. Fig.11 compares the horizontal displacement responses for the test results of the wall foundation at each depth with the analytical results for model-3. The test results indicate that the responses of the wall foundation decrease with depth. The analytical results for model-3 show good agreement with the test results. It is thus confirmed that the lumped-mass model effectively simulates the response of the composite foundation including the wall foundation.



Horizontal Disp.

Rotational Angle

Fig.10. Comparisons of responses at floor B1 by lumped-mass model



Horizontal Disp.

Fig.11. Comparisons of displacement responses of wall foundation by Model-3

Fig.12 compares the horizontal and rotational dynamic impedances at the bottom of the basement for model-3 with the test results. The dynamic impedance was obtained from test results by using the excitation force and the horizontal and rotational inertia forces and displacements of the basement. The real parts of the horizontal and rotational impedances of the test results are almost constant, while the imaginary parts rise due to radiation damping. The analytical results for model-3 show good agreement with the test results.

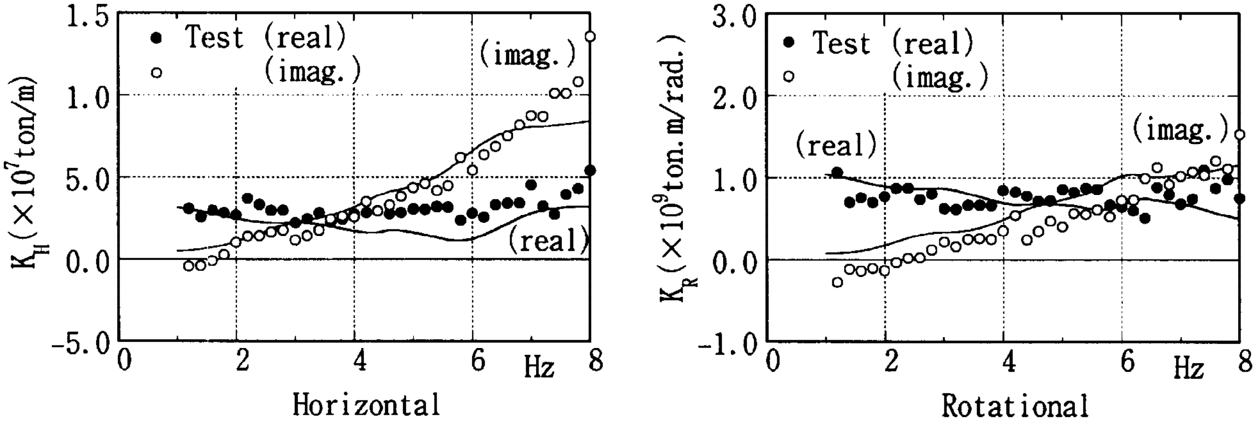


Fig.12. Comparisons of dynamic impedance by Model-3

CONCLUSION

The concluding remarks of this study are as follows:

1. The forced vibration test shows that the basement vibrates in the horizontal and rotational mode of a rigid body and that the wall foundation and the internal pile have similar vibration modes. The resonance peak at each floor cannot be clearly confirmed by the embedment effect.
2. The analytical studies by the Axi-FEM indicate that the existence of the basement and internal piles restrict the natural vibration of the internal soil. It is confirmed that the exterior piles decrease the horizontal and rotational responses of the basement. Taking the exterior piles into account, the analytical results show good agreement with the test results.
3. The simplified numerical model comprising a lumped-mass model with dynamic interaction springs simulates well those of the Axi-FEM and the test. It is thus effective in predicting the composite foundation response.

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