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Laboratory Tests on Embedded Reactor Building on Hard Ground

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Synopsis: In order to experimentally confirm the dynamic characteristics of embedded reactor building, shaking table tests and hammering tests were carried out, utilizing hard ground model made of hard silicone rubber and structural model made of aluminum which is embedded by soft silicone rubber. From the test results, it was confirmed that embedment increases system frequency of soil-structure interaction system, the ratio of elastic deformation of structure and radiation damping. Using the transient data of impulse responses, impedance function and foundation input motion could be identified in a smooth shape. Simulated results for non-embedded case by wave propagation theory and axi-symmetric FEM showed fairly good agreement with test results.

INTRODUCTION

Many reactor buildings are partially or mostly embedded in the ground in Japan. So, in seismic design of reactor buildings, it is very important to know the effects of embedment on seismic response. Laboratory model tests were planned to clarify the behavior of a reactor building with embedment during an earthquake and verify the reliability of the seismic analysis tools used for the design of nuclear power plants in Japan.

OUTLINE OF TESTS

Test Models

(1)Ground Specimens

The ground model used for this test is made of silicone rubber with rather high elastic modulus. The Young's modulus aimed is 18kg/cm^2, and the Poisson's ratio derived from measured velocities of P wave and S wave is 0.48. It is a cylindrical body, 70cm high, 3m in diameter, and has a pit of 76x76cm width at surface and 18cm depth at the center. To closely simulate the infinity of the actual ground at side boundary, vertical restraint bar made of brass (diameter: 3mm) was put in the periphery of the ground model. The sketch of ground model is shown in Fig. 1.

(2)Building model

The building model is mostly made of aluminum. The components of the model are rigid foundation, 2nd and roof floors, and columns made of phosphor bronze spring. It has a square foundation 30x30cm and a height 38cm (foundation height: 18cm). These parameters were selected by scale law considering actual reactor buildings in Japan. The sketch of the building model is shown in Fig. 2.

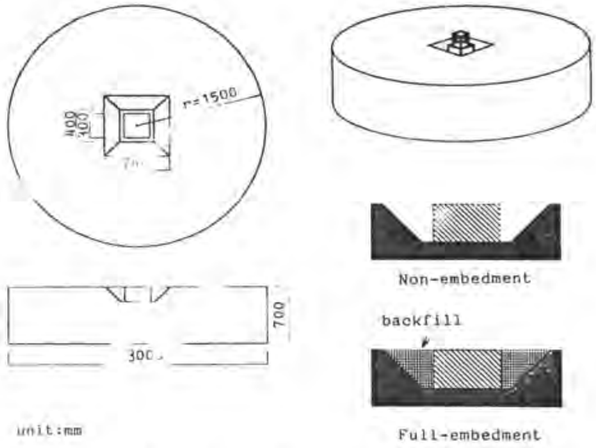


Fig.1 Ground and Foundation Model for Basic Characteristic Test

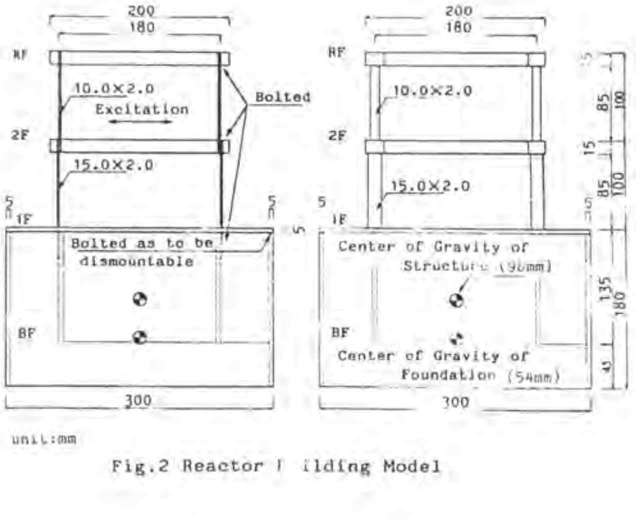


Fig.2 Reactor Building Model

Test Cases

(1)Basic Characteristics Tests

In these tests, the ground model was excited by the shaking table to know its vibration characteristics. In addition, ground-foundation interaction tests, setting the foundation model in the pit of the ground model, were conducted by shaking table and hammering with an impulse hummer.

(2)Building Characteristics Tests

In these tests, the building model was subjected to hammering excitation to know its vibration characteristics. In addition, ground-building interaction tests, setting the building model mounted on rigid foundation in the pit of the ground model, were conducted by shaking table and hammering.

Interaction tests mentioned above were carried out on both non-embedded case and embedded case to investigate embedment effect of the foundation. In the embedded cases, tests were carried out with back fill up to 18cm surrounding the foundation. Softer silicone rubber with a Young's modulus 3kg/cm^2 was used as the back fill material.

Test Methods

The following two tests were applied.

(1)Hammering test

Hammering test was carried out to obtain vibration characteristics of building model, and to evaluate vibration characteristics of ground-foundation and ground-building interaction systems. A impulse hammer equipped with a load-cell on contact surface was used for excitation.

In the hammering test, transfer function (acceleration/excitation force) of the vibrating system is derived. In order to remove the effect of the boundary, transient data analysis is also worked out using the excitation force and acceleration wave form.

In the basic characteristics tests, rigid foundation excitation was carried out at three levels of excitation positions; lower position of foundation (5.5cm high from the bottom of foundation), top of foundation (18cm high from the bottom of foundation) and top of excitation attachment above foundation (38cm high from the bottom of foundation).

In the building characteristic tests, building excitation was applied horizontally at central part of building top (roof floor).

(2)Shaking table test

Shaking table test was carried out applying sinusoidal (stationary) seismic wave and pulse wave. The shaking table used here has a surface dimension of 4mx4m which is capable of tri-axial excitation.

In the sinusoidal excitation, acceleration was fixed at 20Gals and frequency was changed stepwisely from 1Hz to 50Hz with frequency intervals 0.1Hz.

In the seismic excitation, time axis was multiplied by 1/3 and excitation duration was set as 8.33 seconds considering the scaling factor of model. Figure 3 illustrates the time history of acceleration and its response spectra. Input wave to shaking table was multiplied by transfer function obtained in the hard ground test to generate wave shape and spectra illustrated in Fig.3 at ground surface.

In the pulse excitation, because of its flat characteristics in frequency range, similar transfer function as that of sinusoidal excitation can be obtained in short time. Half of a cycle of sinusoidal wave, whose period is 0.04 seconds was employed for pulse wave. Δt of input wave was set as 0.002 seconds and the duration 4.096 seconds. Excitation was carried out four times continuously.

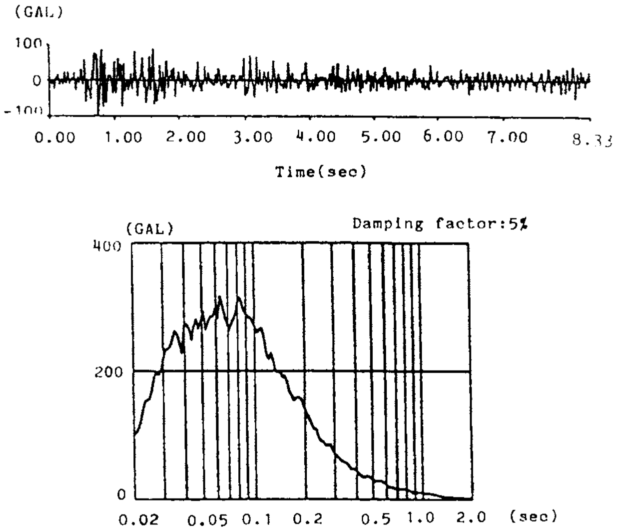


Fig.3 Time History of Acceleration and its Response Spectra of Seismic Excitation

TEST RESULTS

Ground Excitation Test

Figure 4 shows the transfer functions of the ground model obtained by sinusoidal excitation. In the figure, conspicuous peak are observed around 8Hz, 25Hz and 43Hz, which are considered corresponding to the first, second and third modes respectively. The measured data at the center have slightly larger number of peaks than those at the edge. This is considered owing to vibration modes other than the basic ones mentioned above. The phenomena can be explained that the effect of restraint bar is less effective at the center part of the ground model than at the edge, and the transfer function is affected by the modes due to the irregularity caused by the pit at the center of ground model. In the transfer function measured at the bottom of the pit, the first peak also exists near 8Hz. On the other hand, the peak amplitudes of second and third mode decrease to the same amplitude level as those of the modes caused by the irregularity of ground model.

Ground-Foundation Interaction Test

In order to obtain vibration characteristics of the ground-foundation interaction system, hammering and shaking table test were carried out.

(1)Hammering test

For the case of excitation at the top of excitation attachment, horizontal displacement transfer function at upper level (1F) and vertical displacement transfer function at the edge of foundation model is shown in Fig. 5. Both in X direction and Z direction, decrease of amplitude due to embedment effect is observed.

(2)Shaking table test

Pulse excitation results will be explained here. In Fig. 6, horizontal acceleration transfer function at upper level (1F) and vertical transfer function at the edge of foundation model are shown. Average motion of five points at the bottom of excavation in ground vibration test was employed as the reference. Decrease of amplitude is observed above 20Hz. Variation of transfer function shape caused by embedment is rather complex. This might be due to the fact that input to foundation changes by embedment, and average of five points at bottom of excavation in ground vibration test is no longer sufficient to express input to foundation with embedment effect.

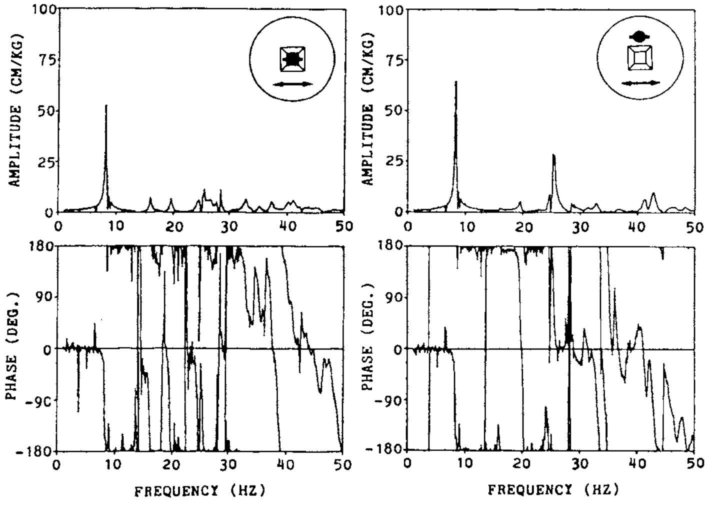
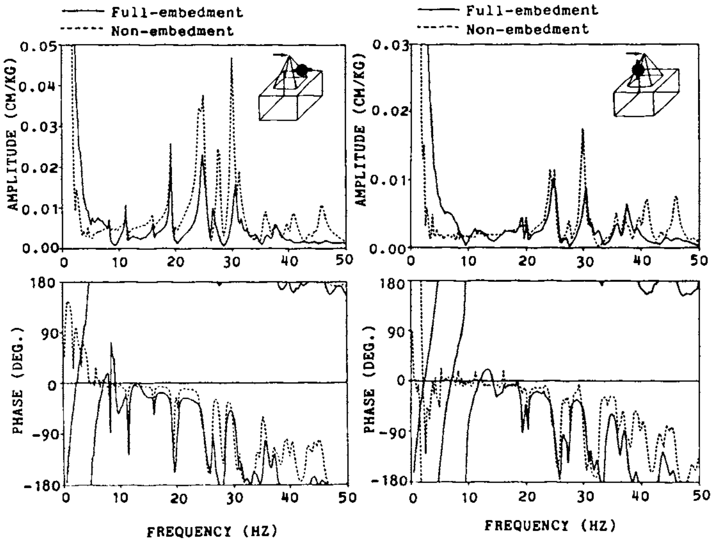


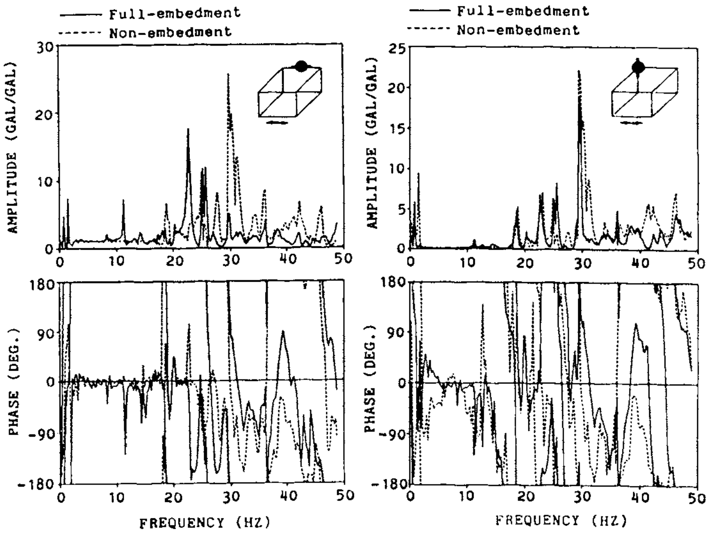
Fig.4 Acceleration Transfer Functions for Sinusoidal Shaking Table Test-X excitation, X component (Reference is the motion on the shaking table)



(a) X component on 1F

(b) Z component on 1F

Fig.5 Displacement Transfer Functions for X directional Hammering Test (Ground+Foundation with Attachment, Non-embedment, Full-embedment) (Reference is the excitation force)



(a) X component on 1F

(b) Z component on 1F

Fig.6 Transfer Functions for X directional Shaking Table Test(Pulse wave) (Ground+Foundation, Non-embedment, Full-embedment) (Reference is the averaged motion on the pit bottom)

(3)Impedance function

Since the ground had S wave velocity 25 m/s, approximately 0.04 seconds (=0.52x2/25) is required for the S wave generated by the foundation to come back to the foundation after being reflected at the surface of steel table. It takes about 0.08 seconds for the S wave to travel twice between the bottom of the foundation and the surface of the steel table. A transfer function, therefore, was obtained by the use of the wave forms of the following three durations:

1)T=0.04(sec):excluding all reflected waves
2)T=0.08(sec):including the first reflected wave
3)T=2.00(sec):including all reflected waves

Equation of motion of the foundation model can be written as follows:

$$\begin{bmatrix} m_i & m_i h_{Gi} \\ m_i h_{Gi} & I_i \end{bmatrix} \begin{Bmatrix} \ddot{u}_i \\ \ddot{\phi}_i \end{Bmatrix} + \begin{bmatrix} K_{HH} & K_{HR} \\ K_{RH} & K_{RR} \end{bmatrix} \begin{Bmatrix} u_i \\ \phi_i \end{Bmatrix} = \begin{Bmatrix} F_i \\ F_i h_{Fi} \end{Bmatrix} \quad i=B,T \qquad (1)$$

where, m_i: foundation mass
I_i: rocking inertia
h_{Gi}: height of center of gravity
h_{Fi}: excitation height
K_{HH}, $K_{HR}=K_{RH}$, K_{RR}: impedance function
u_i: horizontal displacement
ϕ_i: angle of rotation
F_i: excitation force
B,T: corresponds to excitation at bottom or top of the foundation

With respect to three unknown values K_{HH},K_{HR} and K_{RR}, Equation (1) is rewritten as follows:

$$\begin{bmatrix} \ddot{u}_B & \ddot{\phi}_B & 0 \\ 0 & \ddot{u}_B & \ddot{\phi}_B \\ \ddot{u}_T & \ddot{\phi}_T & 0 \\ 0 & \ddot{u}_T & \ddot{\phi}_T \end{bmatrix} \begin{Bmatrix} K_{HH} \\ K_{HR} \\ K_{RR} \end{Bmatrix} = -\omega^2 \begin{Bmatrix} F_B - m_B \ddot{u}_B - m_B h_{GB} \ddot{\phi}_B \\ F_B h_{FB} - m_B h_{GB} \ddot{u}_B - I_B \ddot{\phi}_B \\ F_T - m_T \ddot{u}_T - m_T h_{GT} \ddot{\phi}_T \\ F_T h_{FT} - m_T h_{GT} \ddot{u}_T - I_T \ddot{\phi}_T \end{Bmatrix} \qquad (2)$$

Concerning the three unknown parameters, Equation (2) contains four equations. Solving Equation (2) by the least square method, one can obtain dynamic impedance functions.

Impedance functions for the embedded case are shown in Fig. 7 together with test results for the non embedded case. Impedance functions here were derived from transfer function of 2.00 seconds duration.

In each component of horizontal and rotation, real and imaginary part of impedance function exceed those of non-embedded case as frequency increases, and they show restriction effect and increase of radiation damping effect. However, at higher frequency, an abrupt decrease is observed.

(4)Foundation input motion

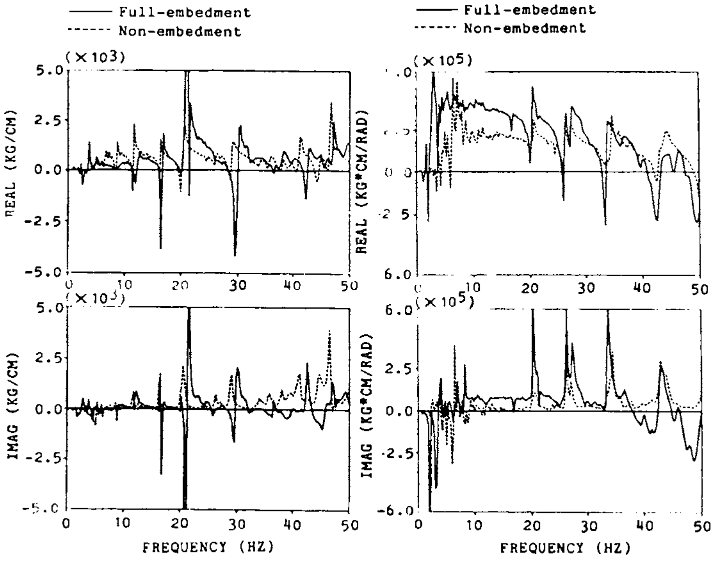
To obtain foundation input motion defined at the center of the bottom surface of foundation from the response displacement, it is necessary to remove the mass effect. The foundation input motion is obtained from the equation given as:

$$\{U^*(\omega)\}=\{U(\omega)\}-\omega^2[K(\omega)]^{-1}\{U(\omega)\} \qquad (3)$$

where $\{U(\omega)\}$: response displacement at the center of the foundation bottom
$[K(\omega)]$: impedance function matrix
$\{U^*\}$: foundation input motion

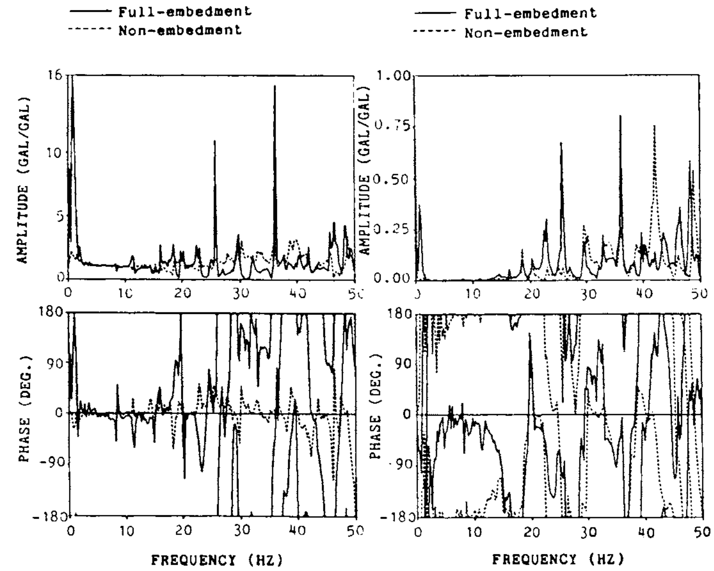
Foundation input motion for full embedded case is shown in Fig. 8 together with the test results for non-embedded case. Average motion of excavation bottom in ground tests is used as reference.

Although there is little difference in low frequency area, input motion of full embedded case tends to decrease above 20Hz.



(a) Horizontal impedance functions (b) Rocking impedance functions

Fig.7 Impedance Functions(T=2.00seconds)
(Non-embedment, Full-embedment)



(a) Horizontal component (b) Rocking component

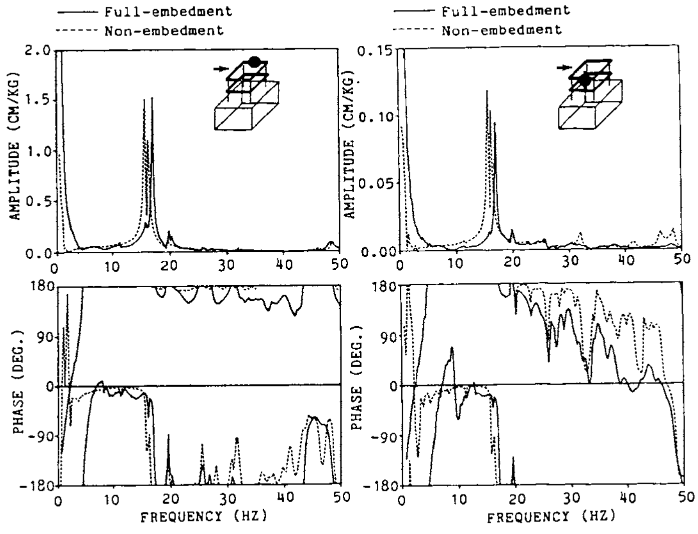
Fig.8 Foundation Input Motion(T=2.00seconds)
(Non-embedment, Full-embedment)
(Reference is the averaged motion on the pit bottom)

Ground-Building Interaction Test

In order to obtain vibration characteristics of ground-building interaction system, top vibration test by hammering and shaking table excitation were carried out.

(1)Hammering test

Horizontal displacement transfer functions of each position against excitation force are compared in Fig. 9. Fundamental natural frequency of the ground-building interaction system is shifted from around 15.5Hz to around 17Hz by embedment, reflecting the restraining effect of the embedment. Peak is split around 16Hz in both cases, which is due to the existence of a natural mode of the ground model at this point.



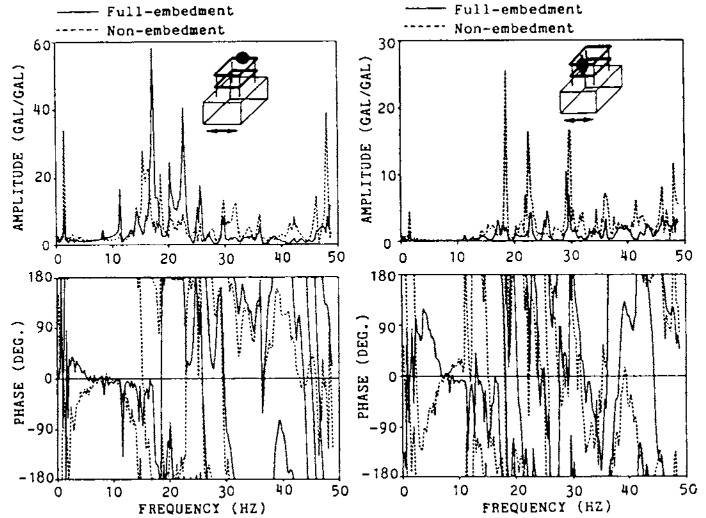
(a) X component on RF (b) Z component on 1F

Fig.9 Displacement Transfer Functions for X directional Hammering Test
(Ground+Building, Non-embedment, Full-embedment)

(2)Shaking table test

Acceleration transfer function and bottom soil pressure transfer function obtained by shaking table pulse excitation are compared in Fig. 10 and Fig. 11. The peak around 16Hz, which must be the fundamental natural frequency of the ground-building interaction system, is decreased by embedment and the frequency is shifted to higher side. Several peaks observed in the region above 20Hz in non-embedded case, which are considered to be due to the excavation, are not visible in embedded case. This tendency is more prominent at Z direction observation points.

Figure 12 compares acceleration response spectra by seismic excitation. The figures were calculated with damping factor 5%. It is obvious that, at each floor of the building, the peak shifts to shorter period side and the peak amplitude decreases to about 1/2 by embedment.



(a) X component on RF (b) Z component on 1F

Fig.10 Transfer Functions for X directional Shaking Table Test (Pulse excitation)
(Ground+Building, Non-embedment, Full-embedment)
(Reference is the averaged motion on the pit bottom)

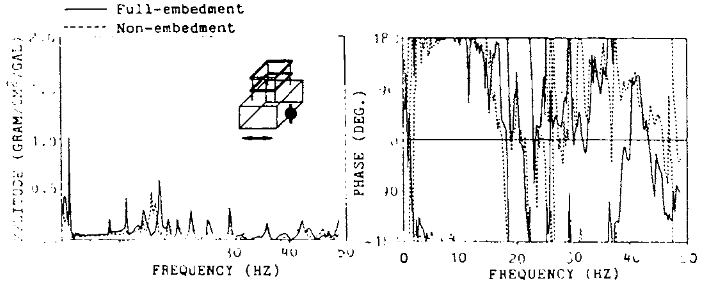
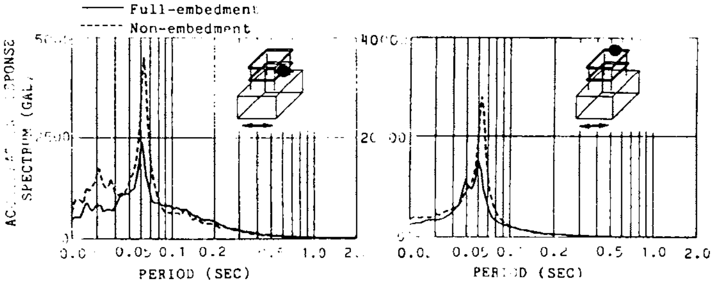


Fig.11 Transfer Functions of Soil Pressure for X directional Shaking Table Test (Pulse excitation)
(Ground+Foundation, Non-embedment, Full-embedment)



(a) 1F (b) RF

Damping Factor 5%

Fig.12 Acceleration Response Spectra for Artificial Earthquake Excitation
(Ground+Building, Non-embedment, Full-embedment)

(3)Natural frequency and displacement mode ratio

In Table 1, fundamental natural frequency in X direction and displacement mode ratio obtained by hammering test are compared. The system identification was carried out by spectrum fitting of multi-degree-of-freedom system. Displacement mode ratio was derived from amplitudes of each point when the phase lag is $-\pi/2$ at the top of the building model.

The fundamental natural frequency of ground-building interaction system increases from 15.6Hz to 17.1Hz due to the restraining effect of embedment. The elastic deformation ratio of the building tends to increase by embedment.

Table 1 Displacement Mode Ratio at the Top of Test Model (Ground+building)

Embedment	Frequency (Hz)*	Sway (%)	Rocking (%)	Elastic Deformation (%)
Non-Embedment	15.6	6	20	74
Full-Embedment	17.1	2	17	81

*Frequency when the phase reaches -π/2 for the first time

ANALYSIS AND EVALUATION FOR NON-EMBEDDED CASE

Outline of analysis

Simulation analysis of test results for non-embedded case was carried out. First, the model constants of ground model and building model were defined by results of ground tests and building tests. Next, by using these model constants, impedance function was calculated by wave-propagation theory (point-load solution of a thin layered medium) and axi-symmetric FEM. Foundation input motion, transfer function of building and ground and earth pressure were also calculated by axi-symmetric FEM.

Impedance function

(1) Study by wave-propagation theory

Impedance functions for half space ground were obtained by point-load solution of a thin layered medium. They are compared with the test results in Fig. 13. Although the excavation cannot be taken into consideration in this method, fairly good agreement can be seen. The point-load solution of a thin layered medium evaluates the imaginary part of the horizontal and rotational impedance function slightly larger. It can be seen that their agreement are not so good in the lower frequency range under 10Hz. It is considered because of the low value of S/N ratio of accelerometer.

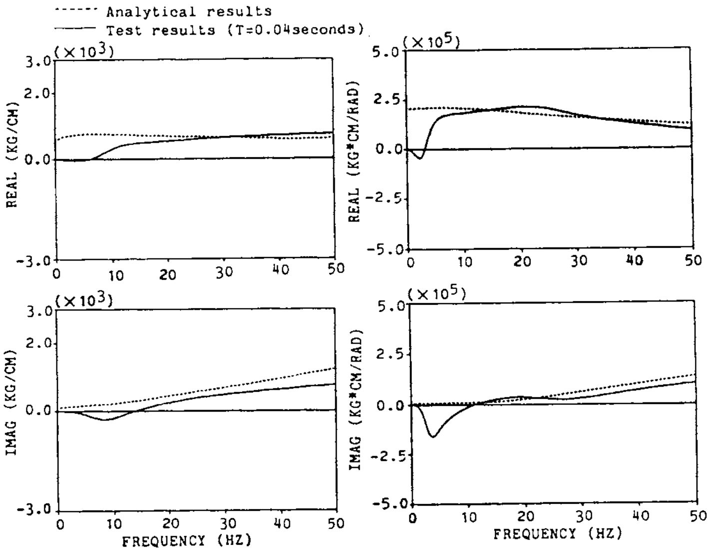
(2) Study by axi-symmetric FEM

Half space axi-symmetric FEM model is shown in Fig. 14. Calculated impedance functions are compared with the test results in Fig. 15. Both the real part and imaginary part are quite in good agreement with the test results.

In this case, axi-symmetric FEM showed better results in imaginary part compared to the point-load solution of a thin layered medium.

Foundation input motion

Foundation input motion was studied by axi-symmetric FEM model shown in Fig. 14, where average motion at pit of the ground model was taken as the reference. Calculated results are compared with the test results in Fig. 16. There are dips near 50Hz both in horizontal



(a) Horizontal impedance function (b) Rocking impedance function

Fig.13 Impedance functions(Uniform half space, point-load solution in a thin layered medium)

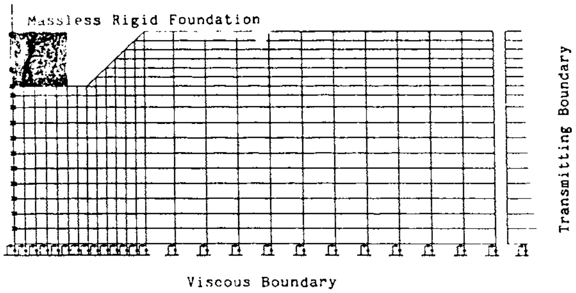
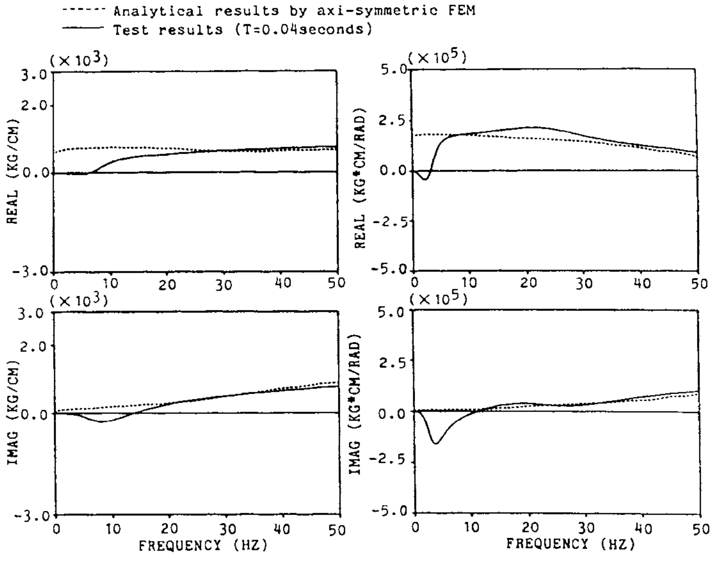


Fig.14 Model for Axi-symmetric FEM (Ground+Foundation, Non-embedment, Uniform half space)



(a) Horizontal impedance function (b) Rocking impedance function

Fig.15 Impedance functions (Uniform half space, Axi-symmetric FEM) components and rotational components of test results, while they are not visible in analytical results. Horizontal components are in good agreement except for low frequency range and around 50Hz. As for the real part of rotational component, test result has dips near 20Hz and 50Hz, but analytical results has only slight undulation.

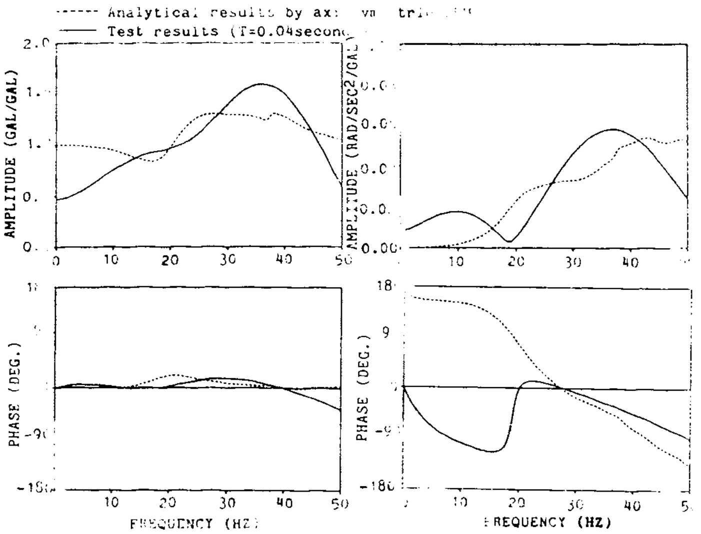
Transfer function

Figure 17 shows an axi-symmetric FEM model of finite ground with building. Transfer functions of building on finite ground by hammering test are compared in Fig. 18. Though analytical result has a higher primary peak and a little difference can be seen in phase, fairly good agreement could be obtained. These difference are related to that of impedance functions of test and analysis.

Transfer function of building by shaking table test is shown in Fig. 19. Comparing tests and analysis, it can be said that simulation is reasonably good, though there are some difference in peaks around 16Hz and around 25Hz. These are due to the difference of foundation input motion around 16Hz and 25Hz.

Analytical transfer functions of building on half infinite ground are compared with test results in Fig. 20 for top hammering and in Fig. 21 for shaking table test. The test results in the figures were derived by using impedance function and foundation input motion for half infinite ground. Comparing analytical results by axi-symmetric FEM with test results, transfer functions by hammering test are in good agreement since impedance function values of test and analysis are almost identical.

Transfer functions by shaking table test have some difference in 1F vertical vibration above 40Hz, since there is difference in foundation input motion between test and analysis. Frequencies of coupled primary, and coupled secondary vibrations are in good agreement.



(a) Horizontal component (b) Rocking component

Fig.16 Foundation Input Motion
(Uniform half space, Axi-symmetric FEM)
(Reference is the averaged motion on the pit bottom)

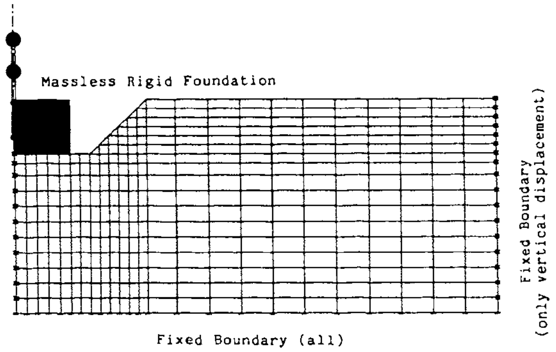
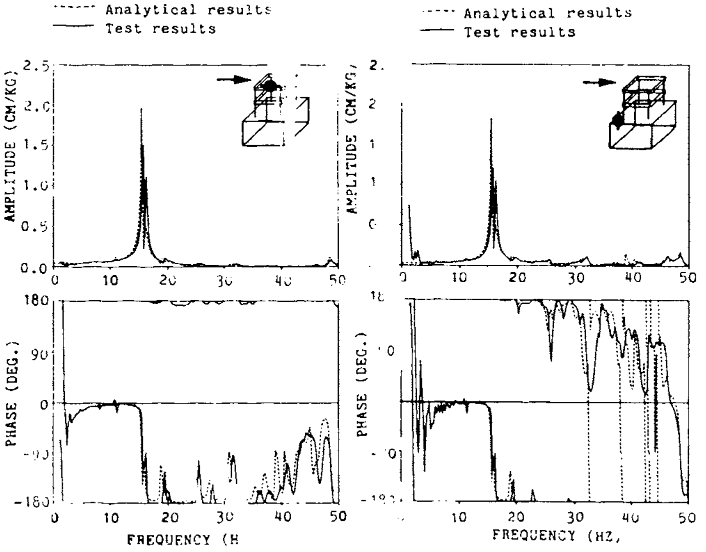
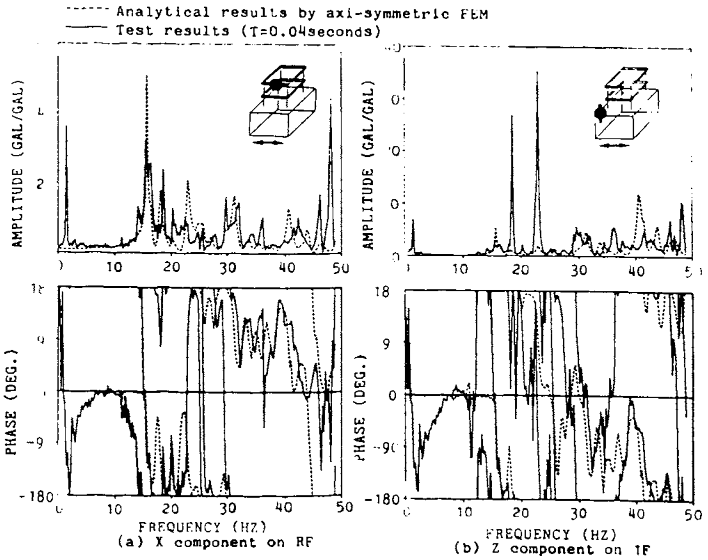


Fig.17 Model for Axi-symmetric FEM
(Ground+Building, Finite ground)



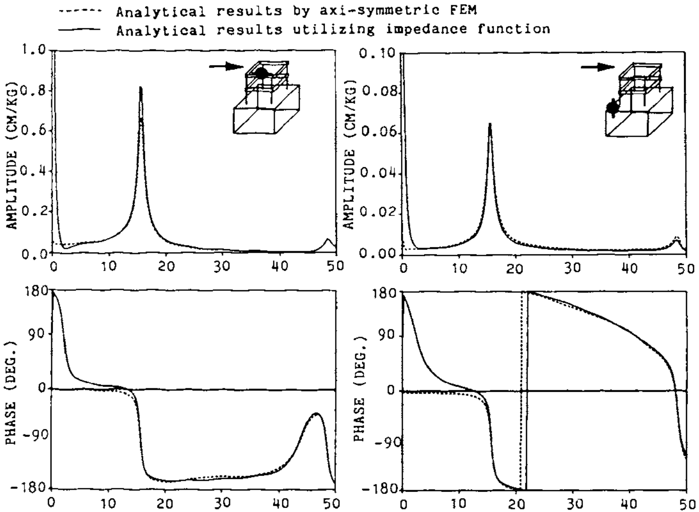
(a) X component on RF (b) Z component on 1F

Fig.18 Transfer Functions of the Building in Hammering Test
(Finite ground, Axi-symmetric FEM)



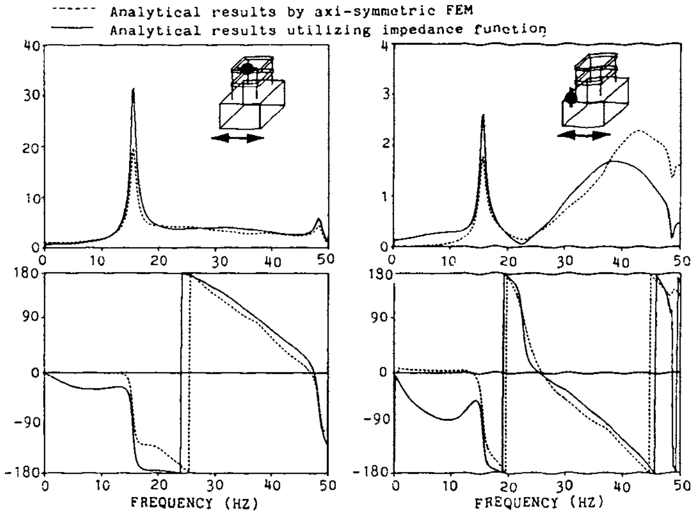
(a) X component on RF (b) Z component on 1F

Fig.19 Transfer Functions of the Building in Shaking Table test
(Finite ground, Axi-symmetric FEM)
(Reference is the averaged motion on the pit bottom)



(a) X component on RF (b) Z component on 1F

Fig.20 Transfer Functions of the Building for Hammering Test (Uniform half space, Axi-symmetric FEM)



(a) X component on RF (b) Z component on 1F

Fig.21 Transfer Functions of the Building for Shaking Table test (Uniform half spaoe, Axi-symmetric FEM) (Reference is the averaged motion on the pit bottom)

Natural frequency, displacement ratio and damping factor derived from transfer function by hammering test are shown in Table 2. Tests and analyses are in fairly good agreement, and it can be seen that displacement at the top of building includes large elastic deformation and the damping factor is small. As the damping factor of building is 0.3% and that of ground model is 1.0%, the damping factor obtained by hammering test is considered to include radiation damping.

CONCLUSIONS

Vibration tests were carried out on embedment effect, utilizing hard ground model made of hard silicone rubber and structural model made of aluminum which is embedded by soft silicone rubber. And simulation analysis of tests in non-embedded case were carried out by method based on wave propagation theory and axi-symmetric FEM.

From the transfer functions obtained by shaking table tests and hammering tests, impedance function and foundation input motion were calculated. In the case of full embedment of foundation, increase of the stiffness and radiation damping were observed. And processing the data using impulse response was proven to allow us to obtain a smooth impedance function and foundation input motion. And from ground-building interaction tests, it turned out that embedment increases natural frequencies, the ratio of elastic deformation of the building and radiation damping, and decreases sway component at foundation bottom.

In the analysis of axi-symmetric FEM, rectangular excavation is replaced by a circular cut-out, but is in fairly good agreement with test results. Change of impedance functions obtained by two methods of analysis is not visible for uniform half space, and it was found that the excavation in this ground model has little effect on impedance function.

Table 2 The First Natural Frequency of an Interaction System, Displacement Ratio at the Top of Building Model and Damping Factor

Embedment	Frequency (Hz)	Damping factor (%)	Sway (%)	Rocking (%)	Elastic Deformation (%)
Analytical Results Utilizing Impedance Function	15.7	2.4	9	10	81
Analytical Results by Axi-symmetric FEM	15.6	3.0	5	12	83

ACKNOWLEDGEMENTS

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