

LABORATORY TESTS ON THE EFFECTS OF PARTIAL EMBEDMENT ON SOIL-STRUCTURE INTERACTION (EMBEDMENT EFFECT TEST ON SOIL-STRUCTURE INTERACTION)

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1 INTRODUCTION

A series of Model Tests of Embedment Effect on Reactor Buildings has been carried out by the Nuclear Power Engineering Corporation (NUPEC), under the sponsorship of the Ministry of International Trade and Industry (MITI) of Japan.

Reactor buildings in Japan are partially embedded in general. Therefore, it is important to know how partial embedment affects the vibration characteristics of reactor buildings relating to seismic safety. Laboratory tests were conducted using a ground model made of silicone rubber

(Young's modulus 2.3×10^6 Pa, Poisson's ratio 0.484, Density 1.24×10^3 kg/m³, Damping ratio 0.01) and a foundation model made of aluminum shown in Fig.1 to study the effects of embedment on soil-structure interaction with different backfill types.

The ground model is a cylinder, 70cm high and 300cm in diameter, with pit where the parallelepiped foundation model with square plan of 30cm \times 30cm and 18cm high was placed. Four types of backfill of silicone rubber (Young's modulus 3.4×10^5 Pa, Poisson's ratio 0.490, Density 1.00×10^3 kg/m³, Damping ratio 0.03) softer than that of ground model filled the pit to realize non-embedment, full-embedment, one-side embedment, and two-sides embedment. Excitation types varied from hammering excitation at two different heights for acquiring impedance functions to shaking table excitation for foundation input motion.

The authors have discussed the effect of one-side embedment on soil-structure interaction¹⁾, and this paper follows focusing on two-sides embedment. Impedance functions and foundation input motion of two-sides embedded foundation are firstly compared with directions regarding to the backfill, i.e., perpendicular and parallel, then with other embedment types. 2-D FEM analysis is employed to simulate those functions for two-sides embedment.

2 IMPEDANCE FUNCTIONS

Equations of motion which governs the foundation is shown in Eq. (1).

$$-\omega^2 \begin{bmatrix} m_i & m_i h_{Gi} \\ m_i h_{Gi} & I_{0i} \end{bmatrix} \begin{Bmatrix} u_{xi} \\ \theta_{yi} \end{Bmatrix} + \begin{bmatrix} k_{HxHx} & k_{HxRy} \\ k_{RyHx} & k_{RyRy} \end{bmatrix} \begin{Bmatrix} u_{xi} \\ \theta_{yi} \end{Bmatrix} = \begin{Bmatrix} F_{xi} \\ F_{xi} h_{Fi} \end{Bmatrix} \quad (1)$$

where m_i : mass of the foundation, I_{0i} : rotational moment of inertia regarding to the foundation bottom, h_{Gi} : height of gravity center from the bottom, h_{Fi} : height of a force excitation from the bottom, F_{xi} : excitation force in x direction, k_{ij} : component of impedance function,

u_{xi} : displacement component in x direction at the bottom, θ_{yi} : rotational angle with y axis, ω : circular frequency. Suffix i represents L or U according to the excitation heights.

Rearranging Eq. (1), Eq. (2) is obtained for unknown variables of k_{ij} 's which can be determined by the least square fitting.

$$\begin{bmatrix} u_{xL}/F_{xL} & \theta_{yL}/F_{xL} & 0 \\ 0 & u_{xL}/F_{xL} & \theta_{yL}/F_{xL} \\ u_{xU}/F_{xU} & \theta_{yU}/F_{xU} & 0 \\ 0 & u_{xU}/F_{xU} & \theta_{yU}/F_{xU} \end{bmatrix} \begin{Bmatrix} k_{HxHx} \\ k_{HxRy} \\ k_{RyRy} \end{Bmatrix} = \begin{pmatrix} 1 + \omega^2 (m_L u_{xL}/F_{xL} + m_L h_{GL} \theta_{yL}/F_{xL}) \\ h_{FL} + \omega^2 (I_{0L} \theta_{yL}/F_{xL} + m_L h_{GL} u_{xL}/F_{xL}) \\ 1 + \omega^2 (m_U u_{xU}/F_{xU} + m_U h_{GU} \theta_{yU}/F_{xU}) \\ h_{FU} + \omega^2 (I_{0U} \theta_{yU}/F_{xU} + m_U h_{GU} u_{xU}/F_{xU}) \end{pmatrix} \quad (2)$$

In Fig.2, horizontal and rocking components are compared for different directions, i.e., in x direction perpendicular to the backfill and in y direction parallel to the backfill. Noisy portion below 10 Hz means lack of precision due to acceleration measurement and impulse loading. Rocking component in x direction exceeds the one in y direction to show higher resistance in perpendicular direction to the backfill.

In Fig.3, rocking components are compared with non-embedment, one-side embedment, two-sides embedment, and full-embedment in x direction. The rocking component of two-sides embedment exceed that of one-side embedment in lower frequency range, which ascertains that two-sides embedment gives larger resistance to the foundation than one-side embedment. The rocking component of two-sides embedment lies between non-embedment and full-embedment especially in lower frequency range, and the characteristics in frequency vary little.

3 FOUNDATION INPUT MOTION

Foundation input motion is defined as response of a massless rigid foundation due to traveling waves and calculated as shown in Eq. (3).

$$U_x^* = -\omega^2 k_x^{-1} M U_x + U_x \quad (3)$$

$$U_x^* = \begin{Bmatrix} u_x^* \\ \theta_y^* \end{Bmatrix}, \quad U_x = \begin{Bmatrix} u_x \\ \theta_y \end{Bmatrix}$$

where u and θ represent displacement at the bottom and rocking angle due to shaking table excitation, and the quantities with asterisk are related to the foundation input motion. Other symbols are the same as those explained for Eq. (1).

In Fig.4, horizontal and rocking input motion divided by ground motion are compared in x direction perpendicular to the backfill and in y direction parallel to the backfill. Ground motion is defined as an average horizontal motion at the excavated horizontal plane without the foundation and backfill. Slight change between directions is observed, and horizontal component is basically unity and rocking component is small in lower range of frequency. At frequencies larger than 20Hz, significant rocking input is obtained to show the effects of excavation and embedment.

In Fig.5, horizontal components are compared with non-embedment, one-side embedment, two-sides embedment, and full-embedment in x direction. The horizontal input motion of two-sides embedment is almost the same as that of one-side embedment in lower frequency range. The horizontal component of these three cases are similar, however, in higher frequency range the component of two-sides embedment resembles that of full-embedment more.

4 2-D FEM ANALYSIS

In Fig. 6, 2-D FEM in-plane model is depicted, which involves the ground, backfill, and foundation in x direction. Model parameters are explained in the introduction, and vertical brass bars constraining vertical deformation along the outermost circumference of the soil are modeled as vertical constraints.

In Fig.7, rocking impedance functions are compared to show good agreement in the middle range of frequency, however, components obtained by FEM show more fluctuations than experimental ones. In Fig.7, input motion is compared well and 2-D FEM is considered effective for the cases relevant to in-plane modeling.

5 CONCLUSIONS

Laboratory test was performed to study the effects of partial embedment on impedance functions and foundation input motion. The ground model is made of silicone rubber with pit, where the aluminum box foundation sits and it is surrounded by backfill with various types of soft silicone rubber.

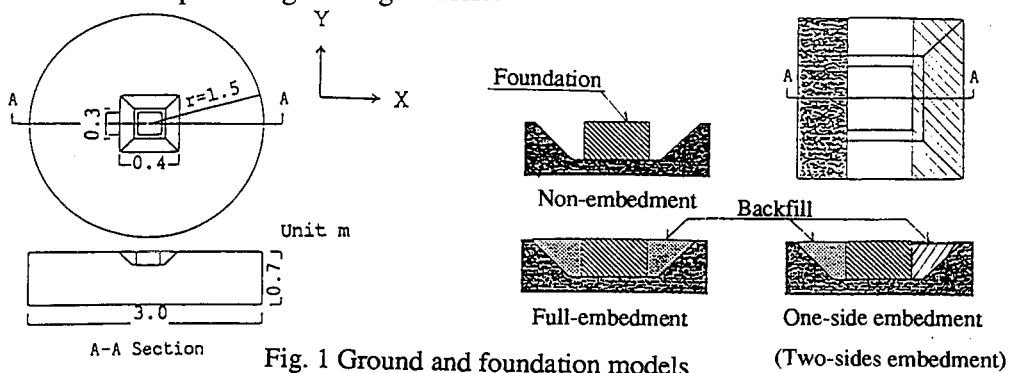
Firstly, impedance functions are acquired by hammering excitation at two different heights with the least square fitting, which shows; 1) Rocking impedance of two-sides embedment in the direction perpendicular to the backfill is greater than that in the direction parallel to it, 2) Impedance functions for two-sides embedment are larger than those for one-side embedment in low frequency range. Then, input motion is acquired by eliminating the foundation mass effect, which shows; 3) Input motion of two-sides embedment resembles that of full-embedment more than that of non-embedment. Finally, 2-D FEM in-plane analysis was carried out to show 4) Impedance functions and foundation input motion are simulated well by 2-D FEM in the direction perpendicular to the backfill.

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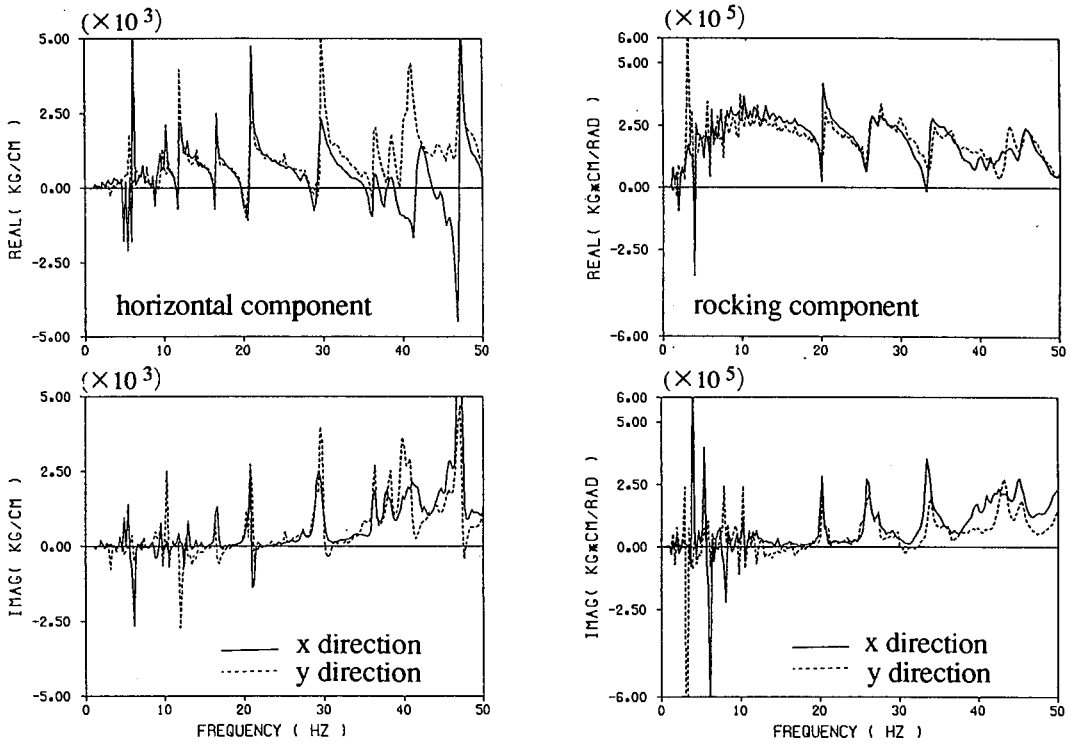


Fig.2 Impedance functions of two-sides embedment in x and y directions

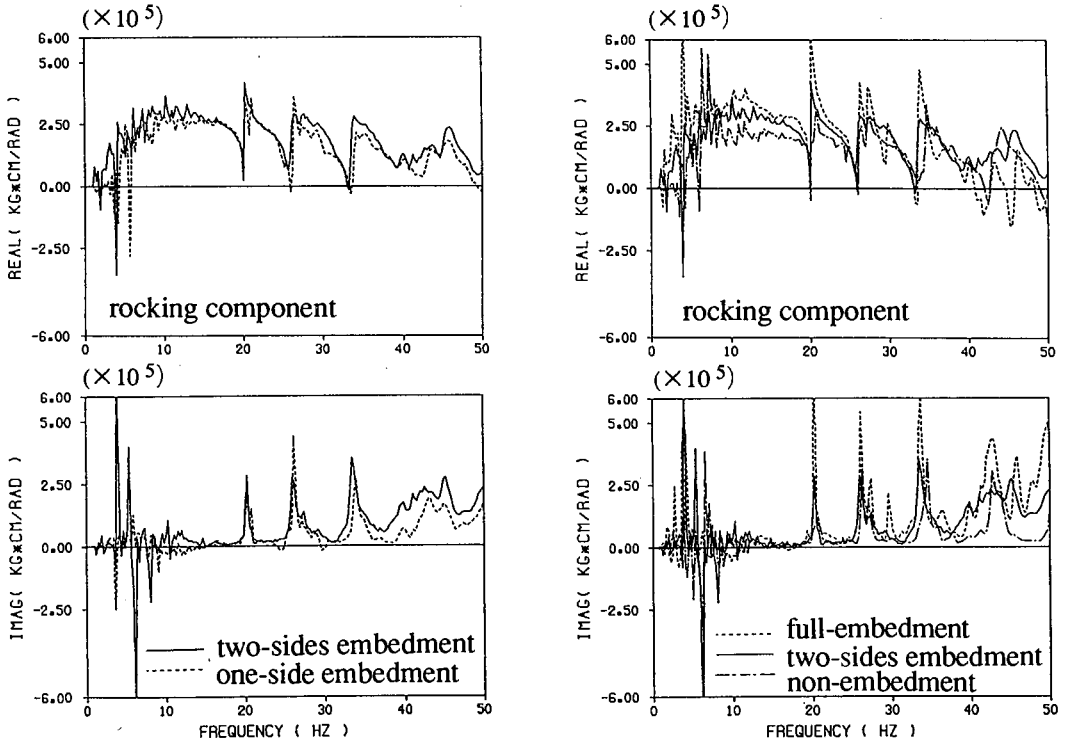


Fig.3 Comparison of rocking impedance functions in x direction for various embedment types

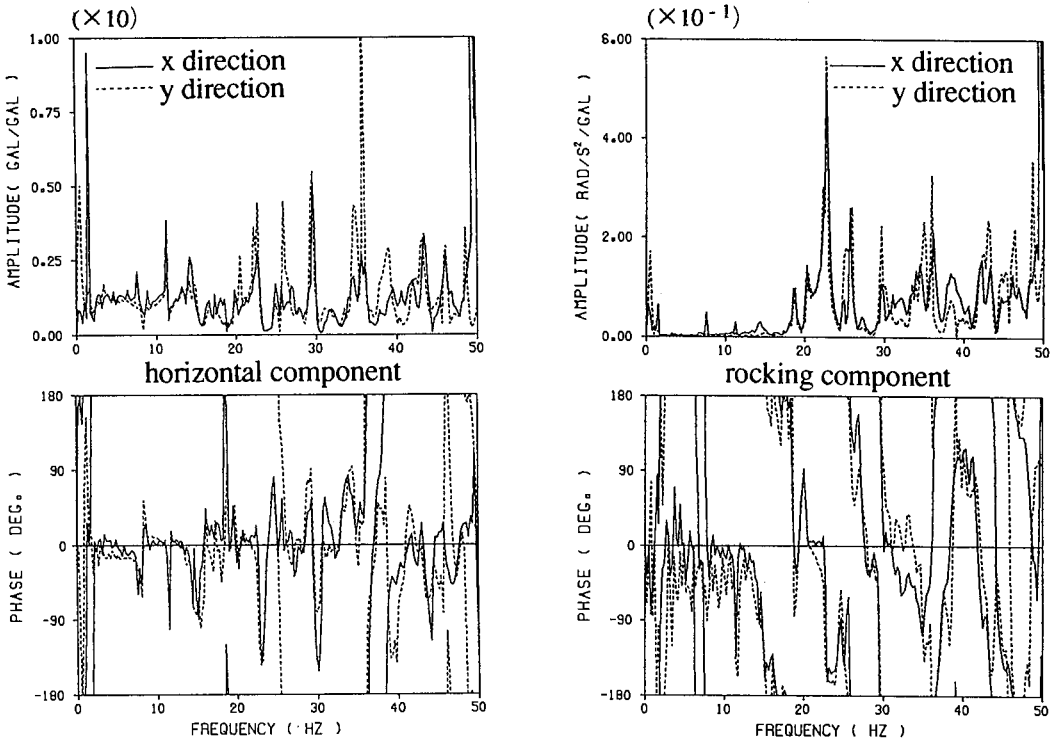


Fig.4 Input motion of two-sides embedment in x and y directions

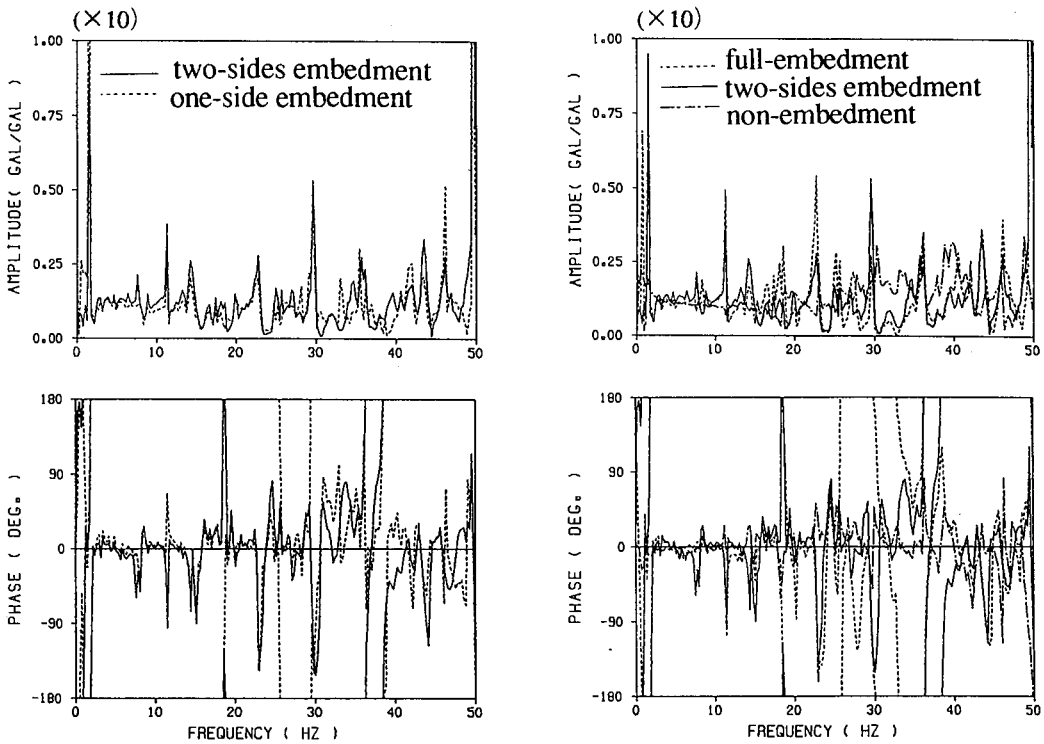


Fig.5 Comparison of horizontal component of input motion in x direction for various embedment types

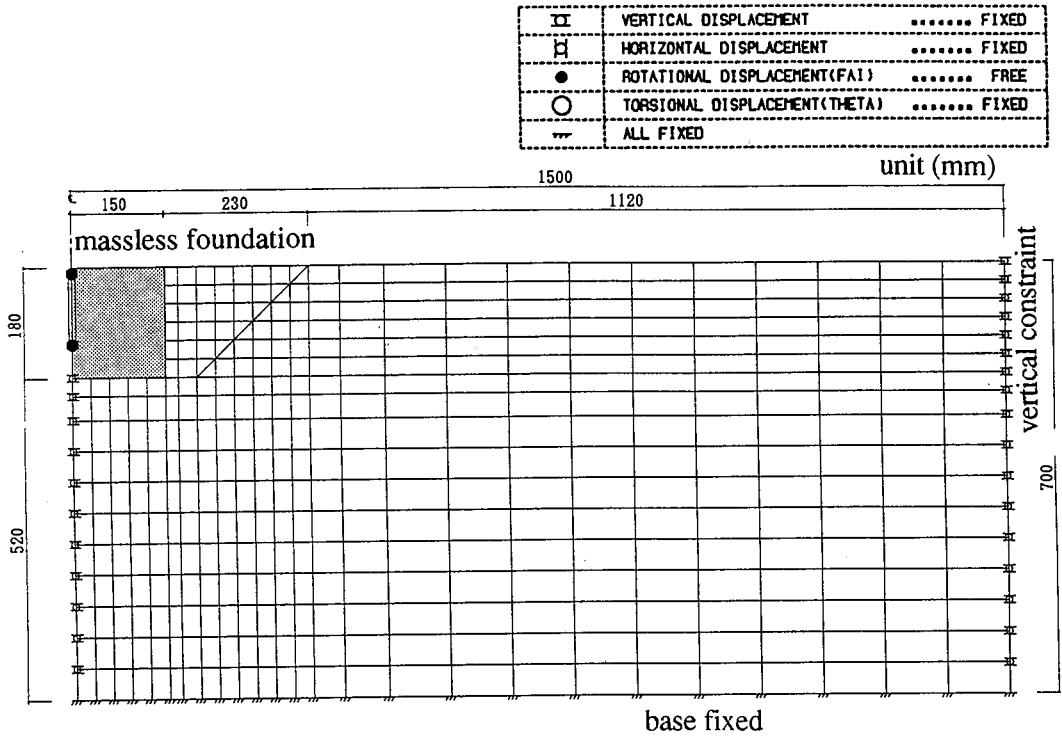


Fig.6 2-D FEM in-plane model

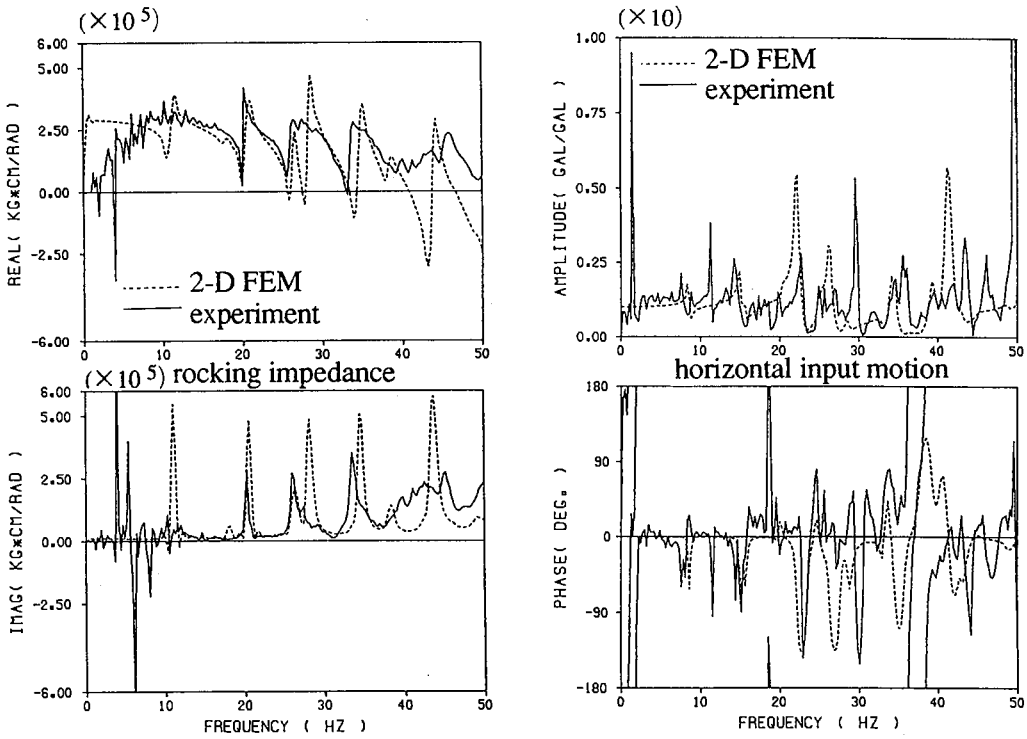


Fig.7 Rocking impedance function and horizontal input motion obtained by 2-D FEM and experiment