

## Seismic Response Analysis of BWR Buildings With Embedded Foundation

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### ABSTRACT

An investigation on the effect of various types of foundations embedded into soil deposit to the responses of BWR buildings is made. The frequency characteristics of massless rigid foundations such as impedance functions and input motions are first obtained, depending on the embedment depth, contact condition of side wall to soil and the thickness of surface layer in a two-layered soil. From the results it is found that the embedment depth and the thickness of surface layer have a distinct effect to the responses contributed by the impedance functions and the response values characterized by the input motions are obviously influenced by the embedment depth and the contact length of side wall to soil deposit.

### 1. Introduction

The embedment of the foundation influences the soil-foundation interaction effect, and consequently affects the responses of a structure. Therefore, the evaluation of interaction effect due to the embedment of foundations is essential for the seismic design of nuclear power plants, which are more or less embedded into a supporting soil medium. Because of the awareness of that importance, this paper presents the results of seismic response analyses of BWR buildings, taking into account of the interactive effect of embedded foundations.

In order to analyse the interactive phenomena, this paper adopts the boundary integration equations method, using the Green's functions. Hence the solutions for a point force inside the elastic multi-layered soil medium are already obtained<sup>1)</sup> by one of the authors. The frequency dependent impedance functions and effective input motions of massless rigid foundations are solved under the mixed boundary conditions. One of the conditions is given by the displacement restricted by the rigid behavior of a part of foundation at which the side wall is perfectly bonded to the soil, and other is given as the free boundary condition due to no contact.

Using the above method, this paper investigates the effects due to the embedment of foundation to the responses of BWR buildings with respect to the following parameters of foundation and soil deposit.

- 1) The embedment depth of foundation
- 2) The contact length of the interface between foundation and soil
- 3) The thickness of surface layer in the case of two-layered soil deposit

2. Mathematical formulation to analyse the behavior of massless rigid foundations

The total wave motions, i.e. displacement  $u$  and surface traction  $t$  at a point in the field subjected to the incident seismic wave, additional scattered by the foundation as is shown in Fig.1 might be written as

$$\begin{aligned} u(a) &= u^*(a) + \int_B g(a, b_0) \cdot p(b_0) \cdot dB \\ t(a) &= t^*(a) + \int_B h(a, b_0) \cdot p(b_0) \cdot dB \end{aligned} \quad (1)$$

in which the first term in Eq.(1) is the motion in the free field due to incident seismic wave and the second is the scattered wave motion. Then,  $B$  denotes the boundary between foundation and soil,  $b_0$  is a point on  $B$ ,  $p(b_0)$  is the unknown potentials distributed on  $B$ , and  $g(a, b_0)$  and  $h(a, b_0)$  are the Green's functions already obtained.<sup>1)</sup> Under the assumptions in which the tractions and potentials are constant in some small element on  $B$  and the displacement is represented by that at the center of an element, as  $a \rightarrow b$  on  $B$  in Eq.(1), the equations over the boundary can be obtained in the discretized form, expressed as

$$u = u^* + \underline{G} \cdot P, \quad T = T^* + \underline{H} \cdot P \quad (2)$$

Now consider the boundary conditions given by the displacement on  $B_1$  and the traction on  $B_2$  as shown in Fig.1. In this problem, Eq.(2) can be rewritten in the following, composed of the subelements in Eq.(2)

$$\begin{Bmatrix} u_1 \\ T_2 \end{Bmatrix} = \begin{Bmatrix} u_1^* \\ T_2^* \end{Bmatrix} + \begin{Bmatrix} \underline{G}_{11} & \underline{G}_{12} \\ \underline{H}_{21} & \underline{H}_{22} \end{Bmatrix} \cdot \begin{Bmatrix} P_1 \\ P_2 \end{Bmatrix} \quad (3)$$

Given the conditions of  $u_1 = \underline{\Delta} \cdot U_c$  on  $B_1$  restricted by the rigid-body motion of foundation and  $T_2 = 0$  on free surface  $B_2$ , the unknown potentials  $P$  in Eq.(3) can be determined. Hence  $U_c$  is the 6\*1 vector

$$U_c = \{ U_x, U_y, U_z, \phi_x \cdot L, \phi_y \cdot L, \phi_z \cdot L \}^T \quad (4)$$

where  $U_i$  and  $\phi_i$  indicate the components of translation and rotation of displacements at the center (0,0,D) respectively, as shown in Fig.1. Incidentally the total forces acting on the foundation are defined as

$$F_c = \{ F_x, F_y, F_z, M_x/L, M_y/L, M_z/L \}^T \quad (5)$$

Substituting the unknowns into Eq.(2), the total forces are obtained in the form as

$$F_c = \underline{\Delta}^T \cdot T_1 = 4\mathcal{R}\mathcal{M}_1 \cdot \underline{K} \cdot (U_c - \underline{I}n \cdot u_g) \quad (6)$$

in which  $\mathcal{M}_1$  is the shear modulus of surface soil,  $\underline{K}$  is the dimensionless 6\*6 impedance matrix and  $\underline{I}n$  is the input motion of foundation against the free field surface motion  $u_g$ .

### 3. Frequency contents of impedance functions and input motions

The impedance functions and input motions of massless rigid foundations are calculated for three kinds of foundations as illustrated in Fig.2. In these analyses, Poisson's ratio of 0.4 of soil deposit and the vertical incidence of SH-wave are assumed.

Fig.3 shows the results on the effect of embedment depth of foundation with the parameter of  $D/L$ . In these figures, the horizontal axis indicates dimensionless frequency  $LO = \omega D/V_s$ . From the results it is seen that the impedance  $K_{hh}$  linearly increases with  $D/L$  having the rate of nearly 1.0 in low  $LO$  for equivalent stiffness and 2.8 for damping, respectively and  $K_{rr}$  parabolically increases with  $D/L$ . As for the input motion,  $I_h$  decreases and  $I_r$  increases as the  $D/L$  and/or  $LO$  becomes large. It is noted here that in the case of foundation on ground surface  $I_h$  and  $I_r$  become 1 and 0, respectively independent to frequency and then the free field motion at the bottom is zero at dimensionless frequency  $\omega D/V_s = \pi/2$ .

The results for the foundations with respect to the contact length ratio  $C/D$  having the embedment depth  $D=L$  in Fig.2(b) are shown in Fig.4. These figures show that though the impedances in low frequency range are nearly same as those of foundation with the same side wall depth ( $D=C$ ) shown in Fig.3, the impedances in high frequency and the input motions are rather different from the results in Fig.3.

Fig.5 shows the results in terms of the parameter  $H/L$  on the effects of thickness  $H$  of surface layer overlying the harder base layer. The embedment depth of each foundation is  $0.5L$  and  $V_s$  of base layer is twice as much as that of surface layer. The results for impedance function indicate, that the stiffness becomes large as the surface layer is thinner. The damping decreases until the thickness becomes thin to be  $H=L$ , however, in the case of  $H=0.5L$  i.e., the bottom of foundation is contact to base layer, the damping is disposed to be large. On the other hand, the input motions resemble each other except the foundation in the case of  $H=0.5L$ , of which the input motion is smaller.

#### 4. Seismic response analyses of BWR buildings

The results of seismic response analyses BWR buildings having the rigid foundations as shown in Fig.2 are herein presented. The building illustrated in Fig.6 is supported by the soil with shear wave velocity of 600m/sec and is modelled into the lumped mass system. In this paper, the response analyses are performed by the use of the random vibration method<sup>2)</sup> and the free field surface motion is characterized by power spectra even in the case of two-layered soil deposit, given by

$$S(\omega) = |\omega^2 / (\omega^2 + \alpha^2) \cdot \exp(-q\omega)|^2 \cdot S_0 \quad (7)$$

with the duration time 9.33 sec as stationary wave. In Eq.(7) the predominant period of spectra  $T_p$  is 0.3 sec,  $(\alpha T_p / 2\pi)^2$  is 0.3 and  $S_0$  is 700 gal<sup>2</sup>.sec. The response spectra are shown in Fig.7, compared with the Ohsaki spectra corresponding to SI earthquake.

Using the results in Chapt.3, the response values of the maximum shear forces of members and the floor response spectra at base-mat are computed as presented in figures 8 through 10. The effects due to various types of foundations expressed by the impedance functions and input motions well appear to the variations of the amplitudes and peak frequencies of responses.

#### 5. Conclusions

The results are summarized as follows:

- 1) As the embedment depth of the foundation becomes large, both the equivalent stiffness and the radiation damping increase with the feature of sudden increase in a little embedment.
- 2) The input motions of translation of embedded foundations subjected to seismic wave decrease with the increase of frequency. The tendency of decrease becomes large, as the embedment depth increase. In the embedded foundation, however, the rotational input motions are added, even in the case of vertical incidence investigated herein.
- 3) When the side wall of foundation is not contact to the soil deposit, the impedances are similar to the results of foundation on the ground surface, however, the input motions are much different.
- 4) In the case of two-layered soil, as the thickness of surface layer decreases, the stiffness increases and the damping decreases. Then, when the bottom of foundation is near to the base layer, the stiffness becomes quite large and the damping tends to increase on

account of the direct effect of stiff base layer.

5) The shear forces and the peak values of floor response spectra of BWR buildings have the tendency to decrease with increase of embedment depth or the thickness of surface layer.

REFERENCES

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- 2) Watabe, M., Chiba, O. and Tohdo, M., 1979, "Generation of simulated 3-dimensional earthquake ground motions", 5th SMIRT, K1/2

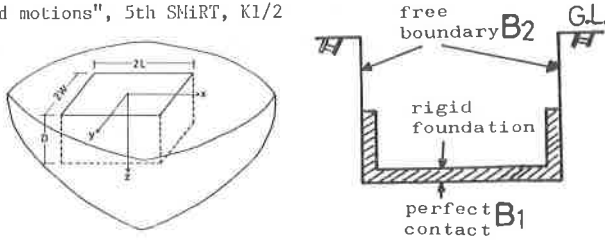


Fig.1 Analytical model of rigid massless foundation

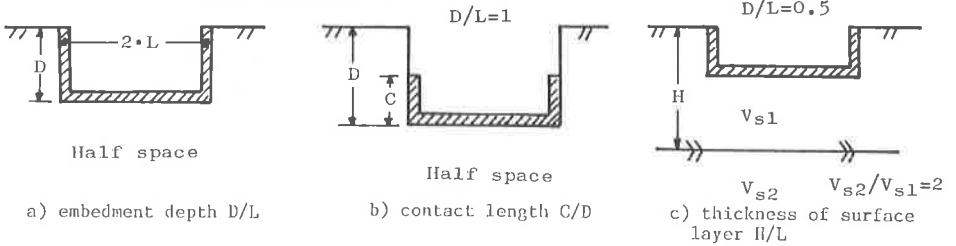


Fig.2 Computational model for parametric study

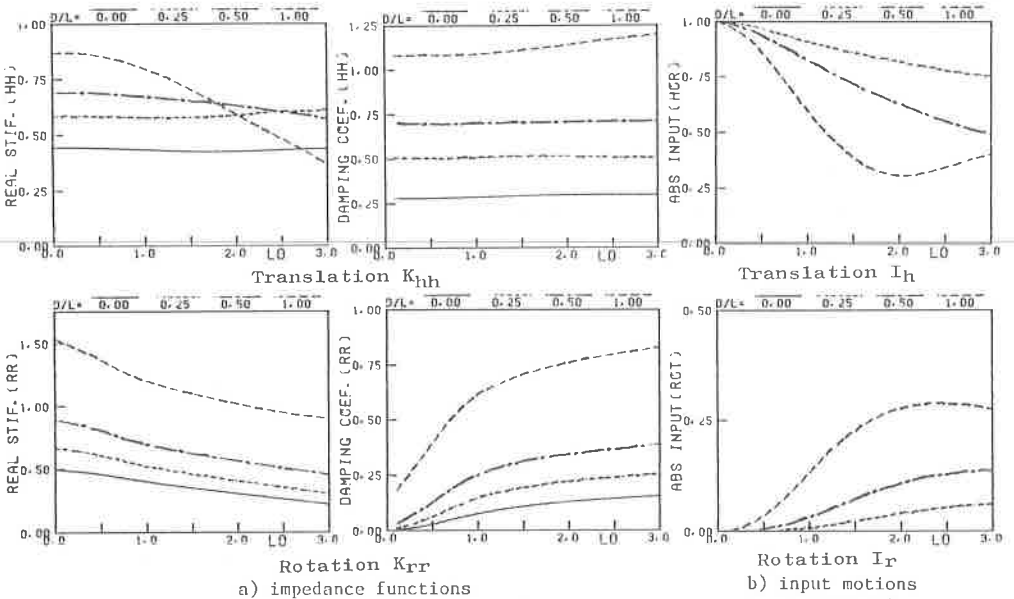


Fig.3 Impedance functions and input motions in terms of embedment depth  $D/L$

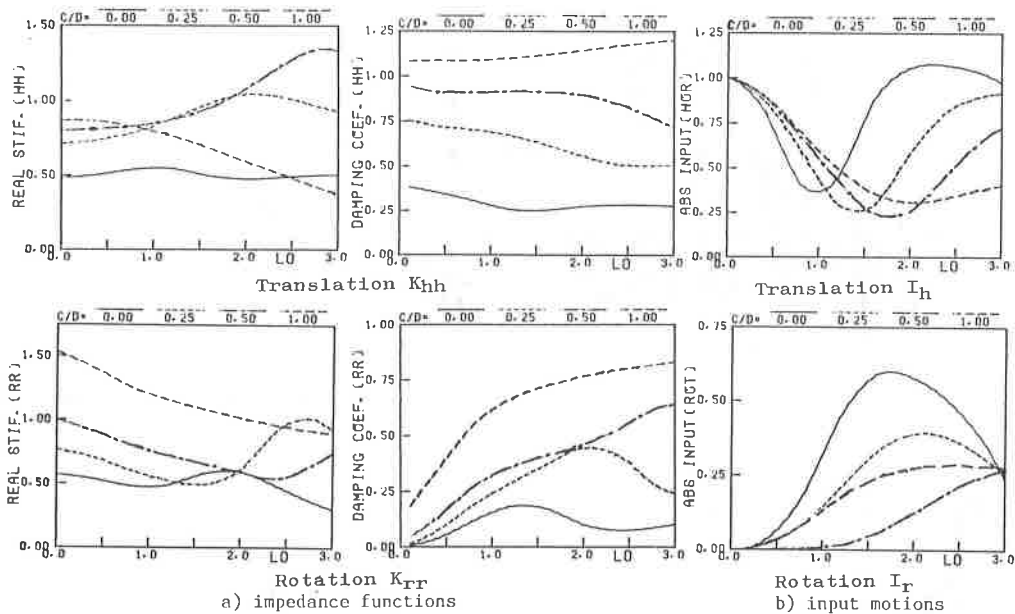


Fig.4 Impedance functions and input motions in terms of contact length of side wall  $C/D$

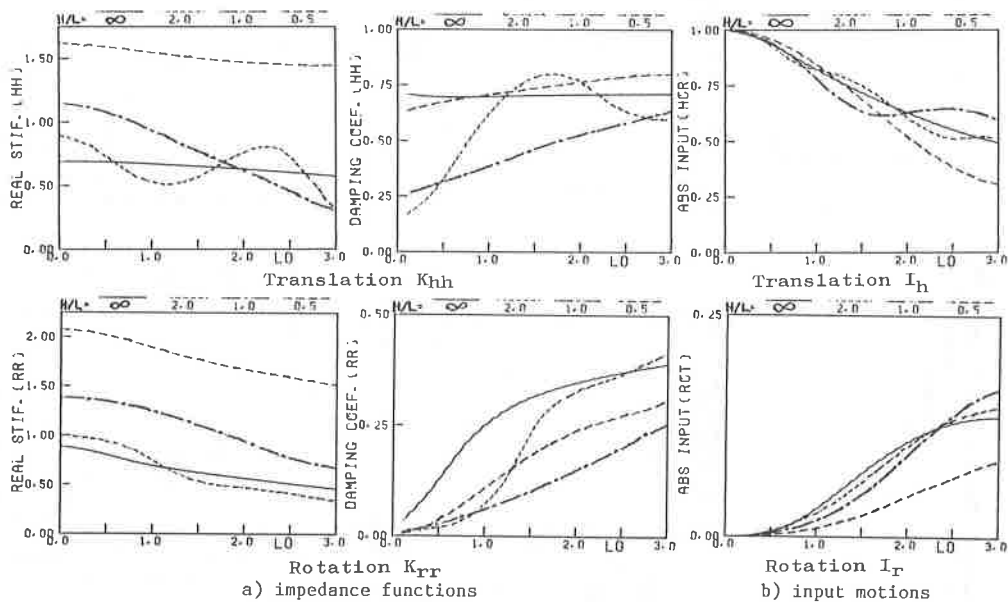
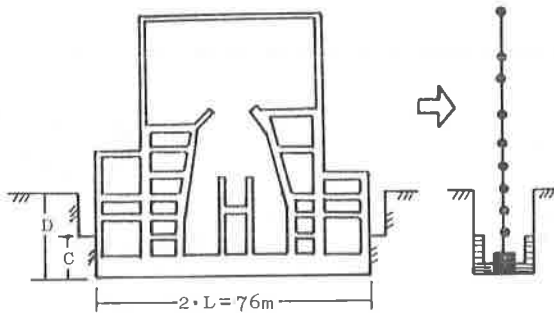


Fig.5 Impedance functions and input motions in terms of thickness of surface layer  $H/L$



$$V_{S1} = 600 \text{m/sec}$$

Fig.6 Modelling of BWR reactor buildings

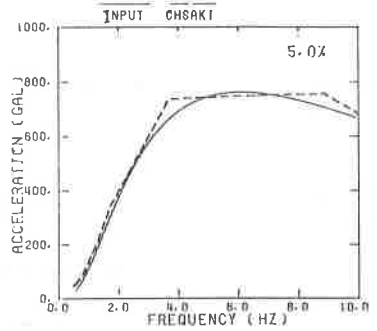


Fig.7 Comparison between response spectra of free field motion and Japanese design response spectra

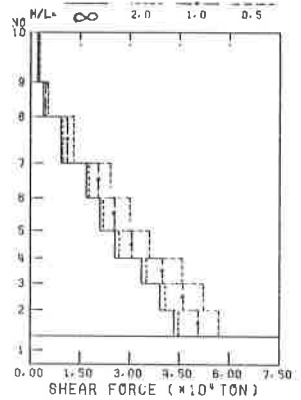
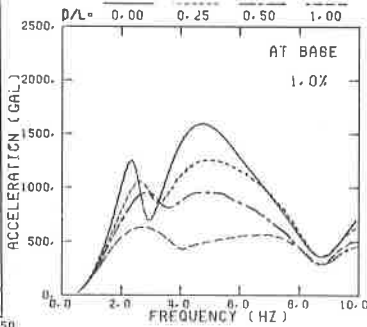
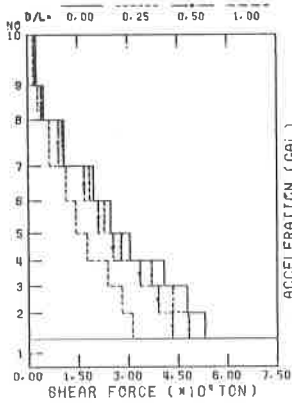


Fig.8 Shear forces and floor response spectra in terms of D/L

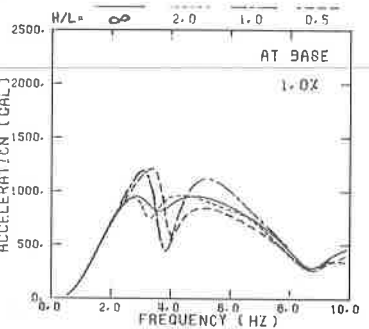
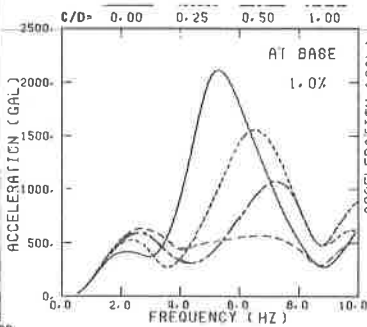
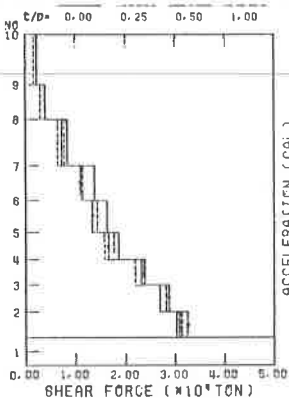


Fig.9 Shear forces and floor response spectra in terms of C/D

Fig.10 Shear forces and floor response spectra in terms of H/L