3-Dimensional Earthquake Response Analysis of Embedded Reactor Building Using Hybrid Model of Boundary Elements and Finite Elements

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Abstract

In order to investigate the 3-dimensional earthquake response characteristics of an embedded structure with consideration for soil-structure interaction, the authors have developed an analytical method using 3-dimensional hybrid model of boundary elements (BEM) and finite elements (FEM) and have conducted a dynamic analysis of an actual nuclear reactor building.$^{1)}$

This paper describes a comparative study between two different embedment depths in soil as elastic half-space. As the results, it was found that the earthquake response intensity decreases with the increase of the embedment depth and that this method was confirmed to be effective for investigating the 3-D response characteristics of embedded structures such as deflection pattern of each floor level, floor response spectra in high frequency range.

1. Introduction

The soil-structure interaction plays an important role in the earthquake response of massive and large structures such as nuclear reactor buildings and many studies pertaining to this subject have been reported in the past. However, especially in cases of embedded structure in spite of a need of the precise analysis up to high frequency range, the past analytical methods are still insufficient to investigate the 3-dimensional dynamic response characteristics taking into account the complicated configuration of the structure, back-filled soil and the semi-infinity of the 3-D soil medium.

Therefore, the authors have developed an analytical method using a 3-dimensional hybrid model taking into account the advantage of BEM and FEM in order to evaluate the effect of soil-structure interaction of the case of an actual embedded reactor building and have investigated its dynamic response characteristics up to high frequency range.

This paper describes the dynamic response analysis of a typical BWR reactor building as a comparative study between two different embedment depths in elastic half space.

2. Outline of Analytical Method

The earthquake response analysis in this paper is based on substructure method where the soil-structure interaction system is divided into two domains as shown in Fig.1. One is the domain composed of the building and the back-filled soil which are modeled by finite elements, and the other is the half space soil domain by boundary elements.

In the domain modeled by finite elements (super suffix B), the relationship between nodal forces $\{P\}$ and displacements $\{U\}$ is expressed by the following equation, distinguishing adjacent nodal points to half space soil medium (under suffix S) from other nodal points (under suffix B).

$$\begin{Bmatrix} P_S^B \\ P_B^B \end{Bmatrix} e^{i\omega t} = \left(\begin{bmatrix} K_{SS}^B & K_{SB}^B \\ K_{BS}^B & K_{BB}^B \end{bmatrix} - \omega^2 \begin{bmatrix} M_{SS}^B & M_{SB}^B \\ M_{BS}^B & M_{BB}^B \end{bmatrix} \right) \begin{Bmatrix} U_S^B \\ U_B^B \end{Bmatrix} e^{i\omega t} \qquad (1)$$

While, in the half space soil medium (super suffix H), the following integral equation is satisfied on its boundary of the building and back-filled soil.

$$c_j^i u_j^i + \int_\Gamma q_{jk}^* u_k \, d\Gamma - \int_\Gamma u_{jk}^* q_k \, d\Gamma = u_{fj}^i \;^{2)} \qquad (j = x, y, z, \; k = x, y, z) \qquad (2)$$

where, u_k q_k : displacement and traction on boundary surface Γ respectively

u_{jk}^* q_{jk}^* : Green's function of elastic half-space concerning displacement and traction respectively

c_j^i : 1/2 (on the smooth boundary)

u_j^i : displacement in j direction at point i on boundary surface Γ

u_{fj}^i : free field displacement in j direction at point i on boundary surface Γ

Now, by dividing the boundary surface Γ into small elements (Boundary Element), by using an interpolation function for the displacement and tractions of each element and by discretizing integral Eq.(2), the following algebraic equation is obtained.3)

$$[\lceil C \rfloor]\{U_S^H\} + [H]\{U_S^H\} - [G]\{Q_S^H\} = \{U_f\} \qquad (3)$$

where, $[H]$: influence matrix obtained from integrating q_{jk}^* on each boundary element

$[G]$: influence matrix obtained from integrating u_{jk}^* on each boundary element

$[\lceil C \rfloor]$: diagonal matrix which consists of c_j^i

Then, in order to obtain the relation between displacement vector $\{U_S^H\}$ and nodal force vector $\{P_S^H\}$, by rewriting Eq.(3) in terms of vector $\{Q_S^H\}$ and premultiplying by transform matrix $[A]$ which transforms vector $\{Q_S^H\}$ to vector $\{P_S^H\}$, the following equation is obtained.

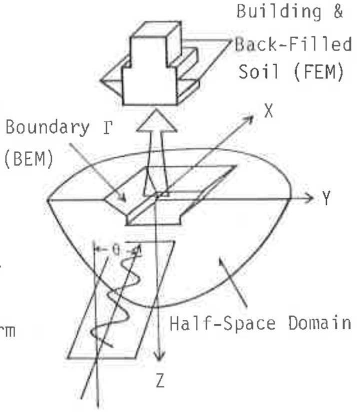

Fig.1 Substructure Model

$$\begin{aligned} \{P_S^H\} &= [A][G]^{-1}[\hat{H}]\{U_S^H\} - [A][G]^{-1}\{U_f\} \\ &= [K_S^H]\{U_S^H\} - \{D_S^H\} \end{aligned} \qquad (4)$$

where, $[\hat{H}] = [\lceil C \rfloor] + [H]$, $[K_S^H]$: impedance matrix, $\{D_S^H\}$: driving force vector which indicates the force vector not to move the boundary to incident wave.

Then, the boundary conditions are expressed as follows.

$$\{U_S^B\} = \{U_S^H\}, \quad \{P_S^B\} = -\{P_S^H\}, \quad \{P_B^B\} = \{0\} \qquad (5)$$

By substituting eq. (5) into eq.(1) and eq.(4), finally the following equation is obtained.

$$\left(\begin{bmatrix} K_{SS}^B + K_S^H & K_{SB}^B \\ K_{BS}^B & K_{BB}^B \end{bmatrix} - \omega^2 \begin{bmatrix} M_{SS}^B & M_{SB}^B \\ M_{BS}^B & M_{BB}^B \end{bmatrix} \right) \begin{Bmatrix} U_S^B \\ U_B^B \end{Bmatrix} e^{i\omega t} = \begin{Bmatrix} D_S^H \\ 0 \end{Bmatrix} e^{i\omega t} \qquad (6)$$

By solving eq.(6) to each frequency component, the transfer function of each point of the building to the control point is obtained. Then earthquake response analysis is carried out easily by using algorithm of Fast Fourier Transform.

3. 3-Dimensional Dynamic Response Characteristics of a Reactor Building[4)]

(1) The Subject of Analysis

Fig.2 shows the BWR (MARK-I) type reactor building of subject matter herein. The basemat is square shaped 75m x 75m with 5m depth and the building is 65m high from the bottom of the basemat to top. The main structural components are the shield wall, the inner wall and the outer wall.

And as an analytical case, two different embedement depths in elastic half-space soil medium with a shear wave velocity of 1000m/sec are taken into account. In Case 1, the building is embedded 20m deep with surrounding back-filled soil, and a 1/4 analytical model of the finite elements with 212 nodal points and about 270 elements, and the boundary elements with 40 elements are used. While, in Case 2 only the basemat of the building is embedded without any back-filled soil.

(2) Analytical Conditions

Damping factors of the building and back-filled soil are 5 % and 10 % as complex damping respectively.

The incident wave to the hybrid model is taken into account as a vertically propagating SH wave and controlled by the free field surface. The sinusoidal wave and EL CENTRO (1940 NS) earthquake wave with the maximum acceleration of 100 gal are used as the motion of the free field surface. (see Fig.6)

(3) Analytical Results

Acceleration Transfer Function: Fig.3 and Fig.4 show the acceleration transfer functions of main points at the operating floor and the basemat respectively.

From these figures, the following findings are pointed out.

1) Fundamental resonance frequency is almost the same in both cases but acceleration amplification factor decrease in all frequency ranges in Case 1 in comparison with Case 2.
2) At the operating floor, two points in the inner wall (15 & 22) indicate the same behaviors in all frequency ranges, but the other two points (17 & 23) show different behaviors from the aforementioned points in the inner wall, furthermore in high frequency range beyond 8 Hz, not only the shear deflection but also the axial deflection are generated. These behaviors are observed to be almost the same in both cases although the quantity is different.
3) At the basemat in Case 1, acceleration amplification factor to free field surface is less than 1.0 in all frequency ranges and the difference of each point is remarkable in frequency range beyond 8 Hz. While in Case 2 acceleration amplification factor is larger than that in Case 1 and behaviors of each point is almost the same up to about 12 Hz.

Maximum Earthquake Responses Acceleration: Fig.7 shows the maximum acceleration distribution in two vertical sections in view of comparison with both cases. Solid line and chained line show the results for Case 1 and Case 2 respectively.

From these figures, the following findings are pointed out.

1) Although little difference is found at the lower parts, there is a distinct difference at the upper part above the 3rd floor and the maximum acceleration in Case 1 is 25%-30% smaller than that of Case 2.

2) The maximum response acceleration of the shield wall is larger than those of the inner wall with regard to both horizontal and rotational motions.

3) At the upper parts above the operating floor such as the roof slab and the perpendicular inner wall, the amplification factor shows increase due to local vibration effect.

Floor Response Spectra: Figs.8(a) and (b) show acceleration response spectra at shown points of the 5th floor in comparison with both cases.

From these figures, it is found that spectral values decrease with the increase of embedment depth and that the floor response spectra are different, especially remarkable in the short period range even at the same floor level.

4. Concluding Remarks

Concluding remarks in this study are as follows;

(1) As the results of comparative study, it was comfirmed that the earthquake response intensity such as maximum acceleration and floor response response spectra up to high frequency range decrease with the increase of embedment depth when 3-dimensional soil-structure interaction effects are taken into account.

(2) It was confirmed that difference of behavior due to the position is significant even at the same floor level, especially in high frequency range, therefore it is necessary to take into account the shear and axial deflections of the slab in the modeling of the building up to high frequency range.

Finally, the authers hope that the aforementioned findings will contribute to the rationalization of aseismic design of reactor buildings and that the analytical method described here will make it effective to conduct the dynamic analysis for embedded structures, where the precise analysis is required, such as nuclear power plant facilities.

Acknowledgement

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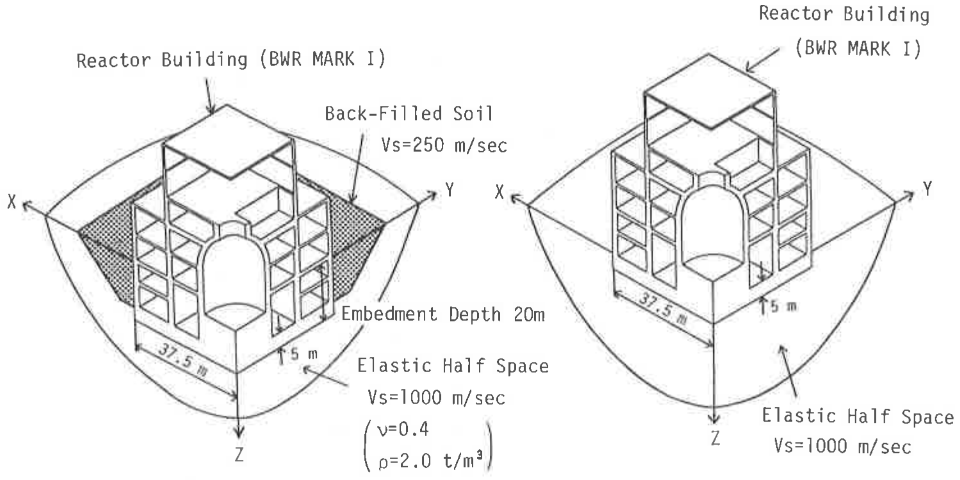
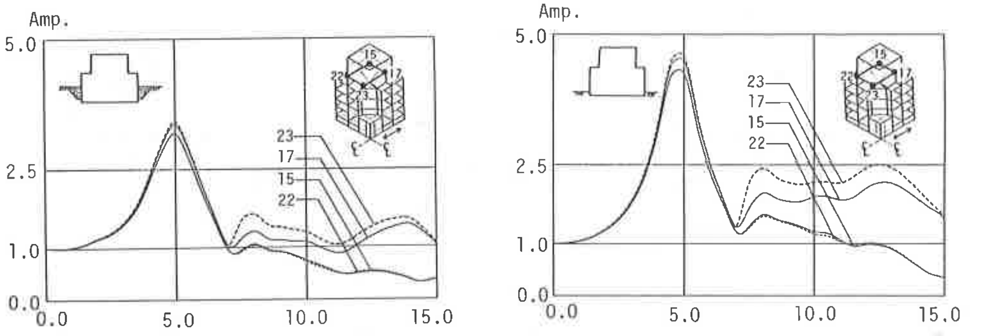


(a) Case 1

(b) Case 2

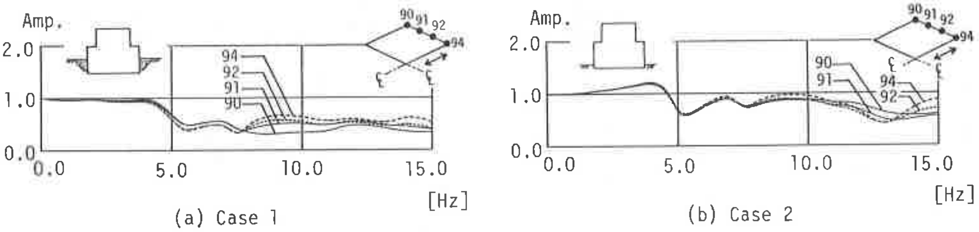
Fig.2 Reactor Building for Analysis



(a) Case 1

(b) Case 2

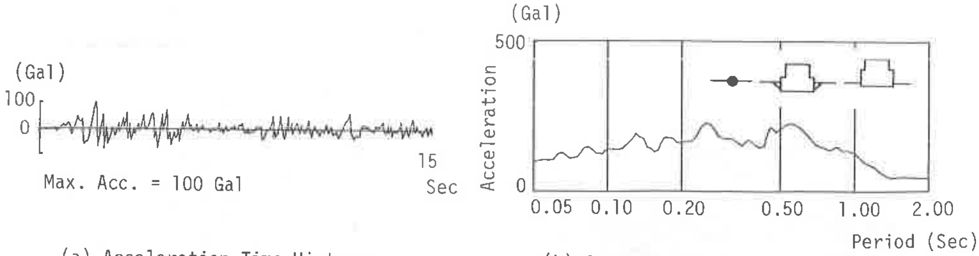
Fig.3 Acceleration Transfer Function of Main Points at the Operating Floor to Free Field Surface



(a) Case 1

(b) Case 2

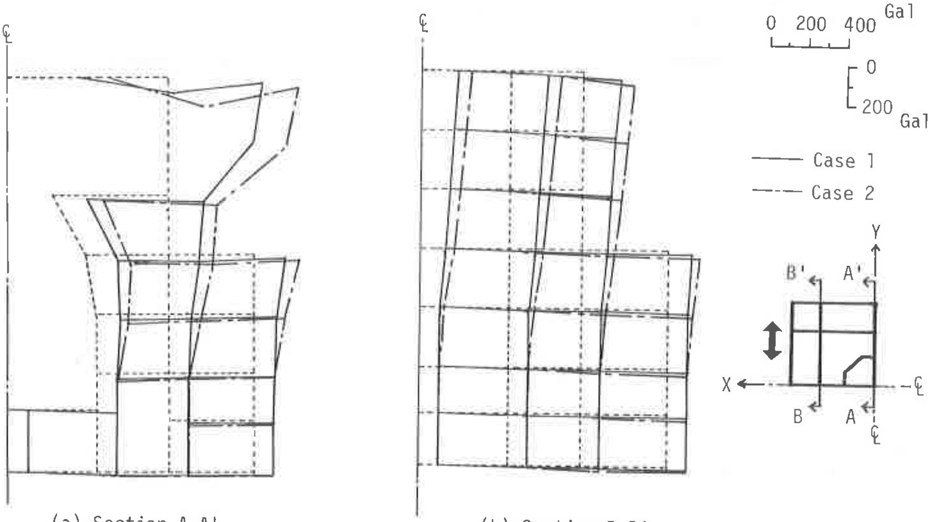
Fig.4 Acceleration Transfer Function of Main Points at the Basemat to Free Field Surface



(a) Acceleration Time History

(b) Acceleration Response Spectrum

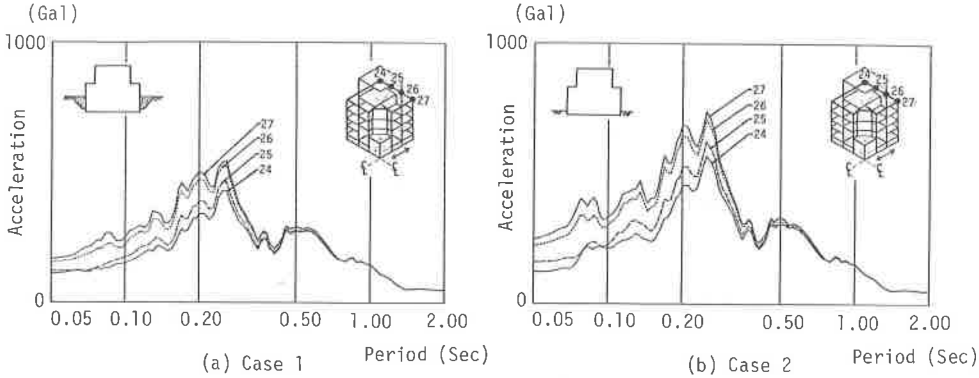
Fig.6 Time History and Acceleration Response Spectrum (Damping=0.05) of Free-Field Surface Motion (El Centro 1940 NS)



(a) Section A-A'

(b) Section B-B'

Fig.7 Maximum Acceleration Distribution in Vertical Section



(a) Case 1

(b) Case 2

Fig.8 Acceleration Response Spectra at Some Points of the 5th Floor (FL.33m, Damping=0.05)