Dynamic Soil-Structure Interaction Analysis Based on Discretized Green Function

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SUMMARY

In the seismic design of massive and rigid structure such as a nuclear reactor building, it is important to evaluate the dynamic interaction effect between soil and structure. The authors developed an advanced and practical method to evaluate, by the use of the discretized Green Function method, the interaction effect between the soil which is considered to be semi-infinite elastic medium, and the structure in which flexibility is considered.

In this report, this method is applied to a seismic analysis of the full size BWR Mark I type reactor building.

For horizontal input earthquake, the vibrational degrees of freedom shall be considered both horizontal and vertical as the rocking response occurs because of the overturning moment caused by the building's horizontal response.

The results of earthquake response analysis show that the floors deform in-place and the response acceleration at the center of the floor is larger than that of at the side wall.

The response spectra also differ each other even if on the same floor because of the in-place deformation of the floor slab. It means that in analytical modeling of the reactor building, multi-stick model considering deformation of floor slab is required instead of single-stick model.

The ratio of the peak acceleration response of the roof floor to the input earthquake is about 2.5.
1. INTRODUCTION

In the seismic response analysis of massive and rigid structures such as a nuclear reactor building, it is important to evaluate the dynamic interaction effect between soil and structure adequately.

Some studies on dynamic soil-structure interaction treat the soil as a semi-infinite elastic medium. In those studies, the vibrational admittance theory and the dynamic ground compliance theory are used frequently.

In these theories, the stress or displacement pattern of the soil surface area alone, is assumed. Then, the dynamic characteristics of both soil and structure are combined.

However, the stress or displacement distribution pattern of the soil surface depends on both soil stiffness and mass distribution of the building. So, it is easy to anticipate that these stress and/or displacement pattern are very complicated for a reactor building which has a large base mat foundation area.

In this report, building and base mat foundation are evaluated by FEM, and the stress distribution pattern and displacement are treated as functions which depend on the soil-structure interaction effect. The seismic response analysis is conducted to obtain the dynamic characteristics of the reactor building during the earthquake.

2. OUTLINE OF ANALYSIS

2.1 ANALYTICAL THEORY

The dynamic characteristics of soil are obtained in the form of a frequency dependent stiffness matrix, corresponding to the each node of the base mat foundation. The matrix is based on the discretized Green function method, where soil is considered as a semi-infinite elastic medium.

The response displacement $W(x, y)e^{i\omega t}$ for the sinusoidal distributed stress excitation $\sigma(x, y) e^{i\omega t}$ on the soil surface of the base contact region $S$ is expressed by using a Green function $G(x, y; \xi, \eta)$ as in the following integral form:

$$W(x, y)e^{i\omega t} = \int_S G(x, y; \xi, \eta) \sigma(\xi, \eta) e^{i\omega t} dS$$  \hspace{1cm} (1)

Considering the region $S$ as the sum of finite sub-regions $dS$, this integral form can be transformed to matrix form as

$$\begin{pmatrix} W_j \end{pmatrix} e^{i\omega t} = \left[ G_{ij} \right] \begin{pmatrix} P_i \end{pmatrix} e^{i\omega t}$$  \hspace{1cm} (2)

In this matrix form, the complex matrix $\left[ G_{ij} \right]$ represents dynamic flexibility matrix which combines the force vector $\{P_i\}$ and displacement vector $\{W_j\}$.

The inversion of dynamic flexibility matrix gives dynamic stiffness matrix $\left[ K_{ij} \right]$. By this procedure, the dynamic characteristics of soil is expressed by the following complex form using the stiffness matrix corresponding to the points on the surface.

$$\begin{pmatrix} P_i \end{pmatrix} = \left[ K_{ij} \right] \begin{pmatrix} W_j \end{pmatrix}$$  \hspace{1cm} (3)

The dynamic characteristics of the structure is expressed by mass matrix $M$ and stiffness matrix $K$ as follows:

$$\begin{bmatrix} M \end{bmatrix} \begin{bmatrix} \ddot{X} \\ \dot{W} \end{bmatrix} + \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{bmatrix} X \\ W \end{bmatrix} = \{F\}$$  \hspace{1cm} (4)
where $W$ is the displacements of the nodes on the contact plane between the structure and the rock foundation, and $X$ is the portion of the displacement of the upper part of the structure. Refined method such as Finite Element Method will be applied for estimating $M$ and $K$.

As the last step, the interaction analysis can be conducted by combining the matrix of the structure and soil.

$$
[M] \{X\} + [K] \{X\} = \{F\} \quad \text{(5)}
$$

where external force vector $\{F\}$ is the excitor force of a vibration test and/or inertia force by an earthquake acceleration.

$$
\{F\} = (m\omega^2) e^{i\omega t} \quad \text{(excitor force)}
$$

$$
\{F\} = -[M] \{I\} A(\omega) e^{i\omega t} \quad \text{(inertia force)}
$$

where $\{I\}$: influence vector

$A(\omega)$: Fourier coefficient of earthquake acceleration

2.2 ANALYTICAL MODEL

As an example, a response analysis of a BWR-Mark I 1100 MW reactor building is conducted.

Main structural parts consist of concrete outer, inner and shield walls with a base mat foundation of 5 m thick. Each wall is connected by floor slats. This structure is 80 m x 80 m in plan and 65 m in height with a total weight of about 300,000 tons. Figures 1 show cross-sections.

In the analysis, assuming symmetry about axes 6 and 7, only a quadrant of the building is evaluated its mass matrix and stiffness of walls, base mat foundation, floors and pool wall by applying the FEM.

Figures 2, 3 show the mesh layout and node and/or element number of the FEM model.

2.3 ANALYTICAL CONDITION

a) Earthquake analysis

The 1940 EL CENTRO (NS) earthquake is considered with regard to its horizontal acceleration. Maximum acceleration occurs at 100 gal. The earthquake's duration is 5.12 seconds with a time increment of 0.02 seconds.

b) Damping

Damping value of the reactor building is assumed 5% and dissipation damping of the soil is already evaluated in its stiffness matrix.

c) Response analysis method

Response analysis of the earthquake is conducted in the frequency domain.

The earthquake can be transformed from its time domain to its frequency domain by application of Fourier transformation. Then, multiplying this transformed function by a frequency transfer function of the soil-structure interaction system, the response of the earthquake is obtained in its frequency domain. Next, by inverse Fourier transformation, the response is transformed back into its time domain.

d) Soil constants

The soil is considered a semi-infinite elastic medium with constants as follows:
Shear velocity \( V_s = 700 \text{ m/s} \)
Shear modulus \( G = 9 \text{ t/cm}^2 \)
Density \( \rho = 1.8 \text{ t/m}^3 \)
Poisson's ratio \( \nu = 0.4 \)

3. RESULTS OF ANALYSIS

3.1 FREQUENCY TRANSFER FUNCTION
Transfer functions of the third floor of the frame A, which is perpendicular to the direction of input acceleration, are shown in Figure 4.

3.2 RESULTS OF SEISMIC RESPONSE ANALYSIS
Maximum response acceleration distribution of frame C is shown in Figure 5.
Horizontal and vertical acceleration response spectra on the third floor of frame A are shown in Figure 6.

4. CONCLUSION
In this seismic response analysis of a reactor building, the dynamic characteristics of the building structure, the base mat foundation and soil, which is considered as a semi-infinite elastic medium, are evaluated separately. Afterwards, these are combined by compatible condition of stress and displacement on the contact plane, and an interaction analysis is conducted.

A response analysis of a BWR 1100 MW reactor building on rock foundation with a 700 m/s shear wave velocity, leads to the following conclusions:

1) The ratio of the peak acceleration response of the roof floor to the input earthquake is about 2.5.
2) Each floor has deformation of both in- and out-of-plane.
3) There is a great difference in response spectrum among node points, even if they are on the same floor. The maximum difference is about 2 times.

(REFERENCE)

FIG. 1 STRUCTURAL CROSS SECTION

a) B2 (FL-15.0M)

b) 1F (FL 0.0M)

c) 2F (FL 9.0M)

d) 3F (FL 18.0M)

FIG. 2 FEM MESH LAYOUT (PLAN)
FIG. 3  FEM MESH LAYOUT (SECTION)
FIG. 4 Acceleration Transfer Function
a) HORIZONTAL EL CENTRO 1940(NS) 100gal max. b) VERTICAL
FIG. 5 MAXIMUM RESPONSE ACCELERATION (FRAME ©)

FIG. 6 FLOOR RESPONSE SPECTRA (h=5%) (3rd FLOOR OF FRAME A)