SMiRT-12 / K. Kussmaul (Editor)

K04/1

SOIL-STRUCTURE INTERACTION ANALYSIS INCORPORATING THREE-DIMENSIONAL SPATIAL INCOHERENCY OF GROUND MOTIONS

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ABSTRACT

This paper presents a newly-developed soil-structure interaction analysis method which allows the incorporation of general three-dimensional spatial coherency of free-field motions in the seismic input, thus allowing it to be used for seismic response analysis of structures taking into account the effect of spatial incoherence of ground motions. The method has been developed using the conventional "deterministic" time-history analysis approach, as opposed to the "probabilistic" random vibrational analysis approach. The implementation and validation of this deterministic method are presented along with an example application to a prototypical nuclear containment structure to demonstrate the significance of the spatial incoherence effect on the seismic response of nuclear structures.

1 INTRODUCTION

Strong motion recordings show the earthquake response motions at building foundations to be less intense than the corresponding free-field motions. To fully explain this difference as soil-structure interaction (SSI) effects, it is necessary to consider the spatial variations in the free-field motions within the foundation footprint.

Due to complexities in the actual transmission of seismic wave energy from source to site, the spatial variation of free-field motions represented by idealized non-vertically propagating plane seismic waves cannot account for the randomness, or incoherency, observed in the spatial variations of actual recorded motions, especially those at the higher frequencies. In recent studies of strong motion array data, seismologists have characterized such randomness as "spatial incoherence" of ground motions which includes the effects of non-uniform finite sources, reflections and refractions along transmission paths, multiple scattering, and local site inhomogeneity. Methods for quantifying spatial incoherence in the free-field ground motions suitable for engineering applications have been developed. These generally follow the "cross-correlation" method which characterizes spatial incoherency (or coherency) in the frequency domain using the "coherency function," which is the normalized smoothed cross-power spectral density function (PSDF) of a pair of time histories in a single direction at two stations.

The spatial incoherency of strong ground motions can have significant effects on seismic response predictions for large engineered structures such as nuclear power plants. Such effects have only recently been considered rigorously in seismic analyses using the probabilistic (random vibrational) analysis approach (Luco and Mita, 1987; Tseng, et al., 1988). This approach, even though rigorous, suffers from the deficiency that its probabilistic PSDF-based seismic input and output are incompatible with the "deterministic" time-history-based seismic input and output normally used in the nuclear industry. Thus, the objective of this paper is to present a newly-developed deterministic SSI analysis method which allows the incorporation of spatial incoherence of free-field motions in the seismic input and the generation of seismic responses in terms of time-history responses. This method is applicable for structures with either surface-supported or embedded foundation configurations.

2 FORMULATION

The coherency function, denoted by $\gamma_{ij}(\omega)$, between the ground motions $x_i(t)$ and $x_j(t)$ in the same direction at two stations is a complex function of frequency ω defined as follows

$$\gamma_{ij}(\omega) = \frac{S_{ij}(\omega)}{\sqrt{S_{ii}(\omega)S_{jj}(\omega)}} \quad ; \; i, j = 1, 2, \ldots, n \text{ stations} \tag{1}$$

in which $S_{ij}(\omega)$ is the smoothed cross-PSDF between $x_i(t)$ and $x_j(t)$, and $S_{ii}(\omega)$ and $S_{jj}(\omega)$ are the smoothed PSDF of $x_i(t)$ and $x_j(t)$, respectively. Assuming that the ground motions at various points within a foundation region have a uniform PSDF equal to that of the reference station, i.e., $S_{ii}(\omega) = S_{jj}(\omega) = S_0(\omega)$, the covariance matrix of the incoherent ground motions, $[S_{U_g^I}(\omega)]$, can be related to the coherency matrix $[\gamma(\omega)]$ using the definition of Eq. (1) by

$$[S_{U_g^I}(\omega)] = [\gamma(\omega)]S_0(\omega) \tag{2}$$

For an SSI analysis using the probabilistic approach, the covariance matrix for the incoherent ground motions defined by Eq. (2) is used directly as the input and the structural responses are obtained in the form of the response PSDF and associated probabilistic in-structure response spectra (Tseng, et al., 1988). For a deterministic SSI analysis, the incoherent ground motion input needs to be expressed in the form of time histories. This is accomplished by a complex decomposition of Eq. (2). Since, by definition, the coherency matrix $[\gamma(\omega)]$ is Hermitian and positive definite, it can be decomposed into its complex eigenvalues, $\lambda_i(\omega)$, and associated complex eigenvectors, $\{\phi_i(\omega)\}$, $i = 1, 2, \ldots, n$. Using the eigen properties of $[\gamma(\omega)]$, Eq. (2) can be expressed as

$$[S_{U_g^I}(\omega)] = [\phi(\omega)][\lambda^2(\omega)][\bar{\phi}(\omega)]^T S_0(\omega) \tag{3}$$

in which $[\bar{\phi}(\omega)]^T$ is the transpose of the conjugate of $[\phi(\omega)]$. Let $\{U_g^I(\omega)\}$ be the $n\times 1$ incoherent ground motion vector which is assumed to be of the form

$$\{U_g^I(\omega)\} = [\phi(\omega)][\lambda(\omega)]\{\eta_\theta(\omega)\}U_0(\omega) \equiv \{H^I(\omega)\}U_0(\omega) \tag{4}$$

where $U_0(\omega)$ is the ground motion at the reference station and $\{\eta_\theta(\omega)\}$ is the $n\times 1$ vector of random phase angles. Post-multiplying each side of Eq. (4) by the transpose of its own conjugate, and taking the expectation (ensemble average) of the resulting equation, it can be shown (Tseng, et al., 1992) that the incoherent ground motion vector $\{U_g^I(\omega)\}$ as defined by Eq. (4) satisfies the covariance matrix equation for incoherent ground motion defined in Eq. (3).

Let $\{H^C(\omega)\}$ denote the $n \times 1$ transfer function vector which relates the $n \times 1$ coherent ground motion vector, $\{U_g^C(\omega)\}$, to the control motion at the reference station, $U_0(\omega)$, based on a single plane-wave field assumption, i.e.,

$$\{U_g^C(\omega)\} = \{H^C(\omega)\}U_0(\omega) \tag{5}$$

For the general SSI analysis applications to structures with either surface-supported or embedded foundations, the incorporation of spatial incoherence of free-field motions for SSI analysis can be done by replacing the coherent ground motion vector $\{U_g^C(\omega)\}$ given in Eq. (5) by the incoherent ground motion vector $\{U_g^I(\omega)\}$ given in Eq. (4). In practical applications, only a few dominant eigenvalues and associated eigenvectors (mode shapes) of the coherency matrix $[\gamma(\omega)]$ are needed for capturing the effects of incoherent ground motions on the SSI response.

3 IMPLEMENTATION AND VALIDATION

For general applications, the incorporation of incoherent ground motions for SSI analysis as formulated previously has been implemented into a computer program module "INCOH" which works together with the general three-dimensional (3-D) finite element SSI analysis computer program SASSI. This module computes the matrix $[\gamma(\omega)]$ and its eigen properties, and calculates the incoherent ground motion vector, $\{U_g^I(\omega)\}$, which is then input to SASSI to enable it to carry out conventional time-history response analyses for the incoherent ground motion input in the same way as for the coherent ground motion input (Tseng, et al., 1992).

This newly-developed deterministic SSI analysis methodology and associated SASSI-INCOH computer program have been applied to solving two SSI problems subjected to incoherent ground motion inputs which also have been solved by Luco and Mita (1986; 1987) using a rigorous probabilistic SSI analysis methodology. These two problems are: (1) the scattering response of a rigid, massless circular foundation resting on the surface of a uniform elastic half-space; and (2) the seismic response of a flexible cylindrical structure supported on the surface of the same uniform elastic half-space as Problem (1) (see Fig. 1). The solutions in terms of the response transfer function amplitudes at selected locations obtained from the SASSI-INCOH analyses using 3 modes are compared with the corresponding solutions obtained by Luco and Mita in Figs. 2 and 3. It is seen that both results are in very close agreement.

4 APPLICATION

To illustrate the application and to demonstrate the effect of spatial incoherence of ground motions on the response of a prototypical nuclear plant structure, an example analysis using SASSI-INCOH is presented for a typical containment structure of a PWR plant (Fig. 4) supported on a rock site of an actual plant (shear wave velocity 3000 to 4000 fps) subjected to spatially incoherent ground motion inputs characterized by a coherency function developed for the site. The horizontal and vertical control motions used for the inputs are the U.S. NRC Regulatory Guide 1.60 horizontal and vertical response-spectrum-compatible synthetic acceleration time histories scaled to 0.20 and 0.18 g, respectively. To separately demonstrate the effect of embedment and the effect of spatial incoherence of input motion on the structural response, three cases have been analyzed: (1) the entire structure including the basemat is supported on the rock surface and is subjected to coherent vertically propagating plane wave inputs; (2) the basemat of the structure is fully embedded into the rock and the structure is subjected to the same coherent motion input as for Case (1); and (3) the structure with the embedded basemat of Case (2) is subjected to the site-specific incoherent motion inputs.

The results of the SASSI-INCOH analyses for the above three cases, expressed in the form of 5%-damped in-structure response spectra for the response motions at the shell springline location (El. 143.8′), the top of interior concrete (I/C, El. 61′), and the top of basemat (El. 0.0′) are shown in Fig. 5. As can be seen, both the foundation embedment and the spatial incoherence of input motions result in reductions in the in-structure response spectral amplitudes in the high frequency range (> 7 cps), and such reductions increase as the spectral frequency increases which can be as much as 50% at the high-frequency spectral peaks. The fact that substantial reduction in the response can be realized by considering incoherence of input motions for a containment structure which has a relatively small foundation, one can expect even larger reductions for the prototypical auxiliary and turbine buildings which have foundation sizes much bigger than the containment structure. Furthermore, since the spatial incoherence effect is more significant in the high frequency range, it is expected that this effect would be larger for structures on rock sites than those on soil sites. This is because the structures on rock sites generally have higher frequencies than those on soil sites; and ground motions on rock sites generally contain higher frequency motions than on soil sites.

5 CONCLUSION

A deterministic (time-history-based) methodology for incorporating spatial incoherence of ground motions in the seismic input has been developed for SSI analysis applications to structures with either surface-supported or embedded foundations. For practical applications, this methodology has been implemented into a computer program module "INCOH" which works together with the 3-D SSI analysis computer program, SASSI. Using this newly-developed methodology and its associated SASSI-INCOH program, it is now possible to realistically assess the effect of spatial incoherence of ground motions on the seismic response of nuclear power plants. Results of a practical example analysis show that spatial incoherence of ground motions can result in substantial reductions in structural response motions in the high frequency range.

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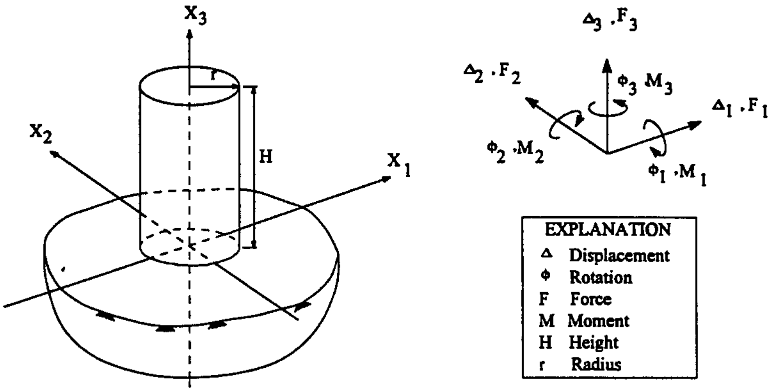

Fig. 1 SSI System Considered in Validation

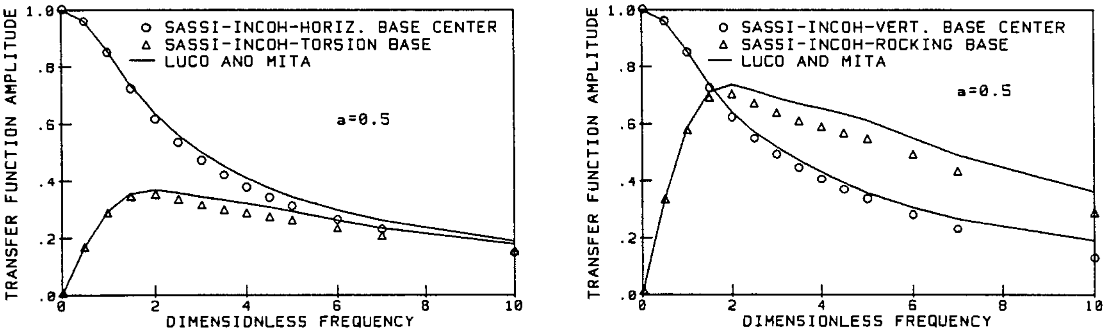

Fig. 2 Scattering Responses of a Rigid Massless Circular Foundation

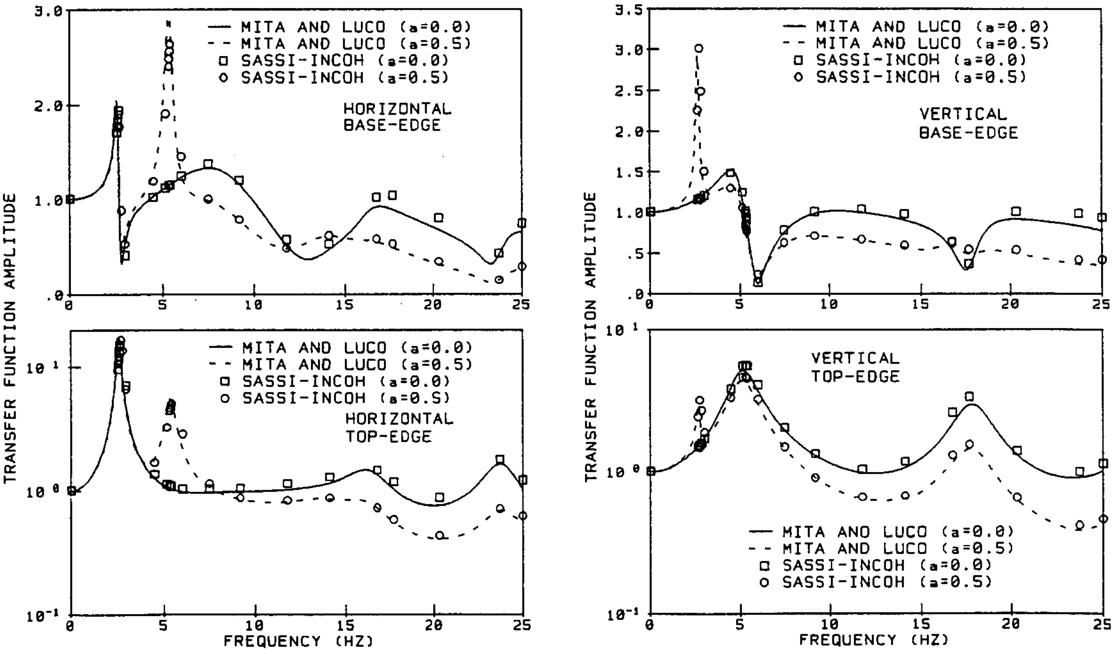

Fig. 3 Seismic Responses of the SSI System Shown in Fig. 1

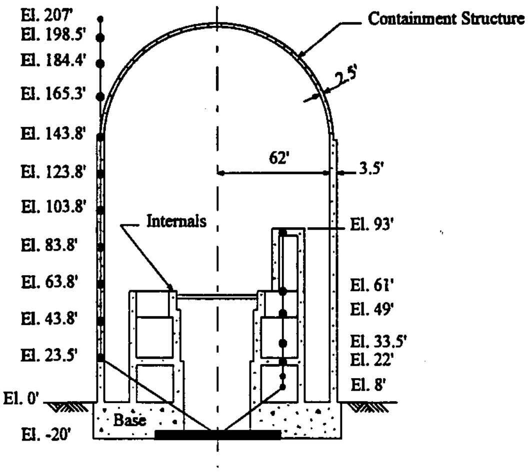

Fig. 4 Configuration of a Containment Structure of a PWR Plant

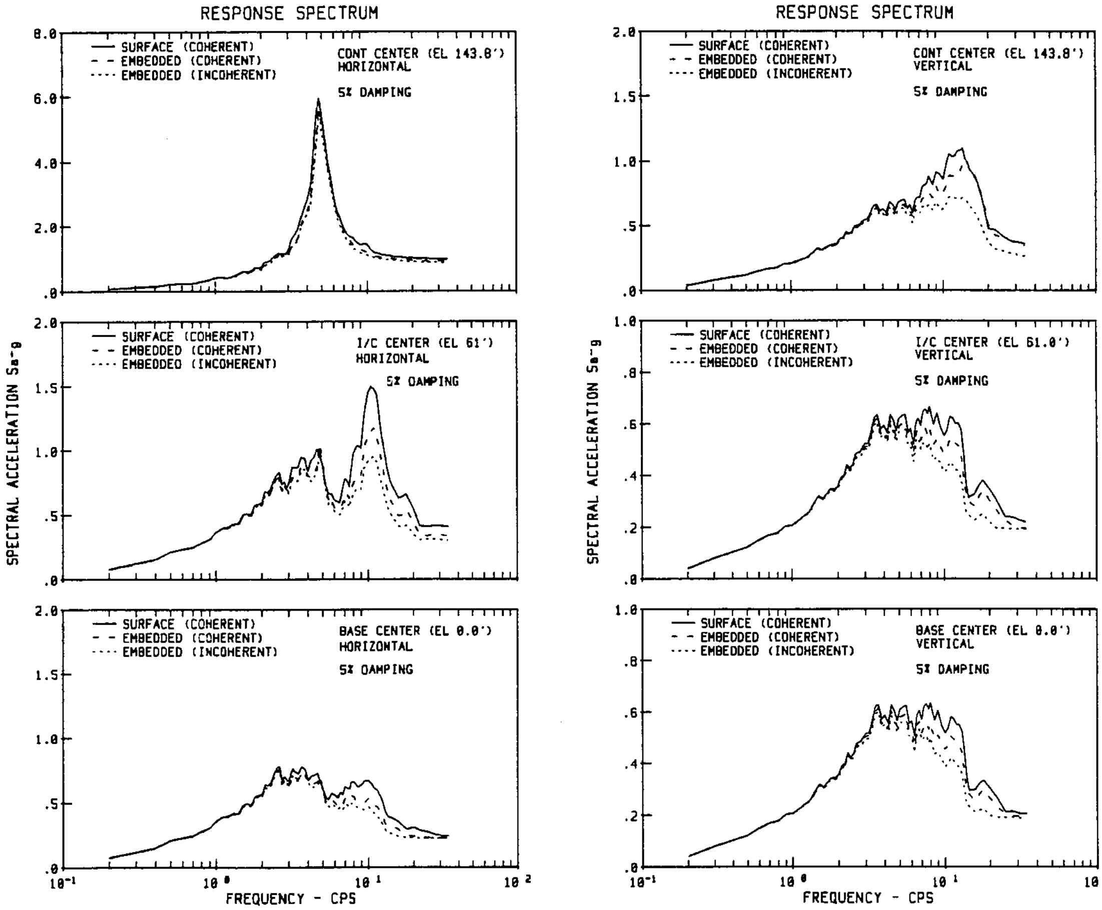

Fig. 5 Comparisons of In-Structure Response Spectra Computed by SASSI-INCOH