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REDUCTION OF SEISMIC RESPONSES DUE TO SPATIALLY INCOHERENT GROUND MOTIONS

Wen S. TSENG, Kiat LILHANAND, and Davian W. WING

Bechtel Power Corporation, San Francisco, California, USA

SUMMARY

This paper presents a newly-developed seismic soil-structure interaction analysis method for incorporating the spatial incoherence of ground motion in the analysis, and the application of this method for studying the effect of spatial incoherence on the seismic response of structures. The studies consider such parameters as different spatial incoherence characterization models, different sizes and shapes of foundation, and the effect relative to that of seismic wave passage.

INTRODUCTION

Studies of recorded eathquake motions at building foundations and in the free-field have indicated reductions of the foundation motions relative to the free-field motions, and such reductions cannot be attributed solely to the inertial soil-structure interaction (SSI) effect without taking into account the effect due to spatial variations of ground motions within the foundation footprint (e.g., Ref. 1). The studies on spatial variations of earthquake ground motions have only recently become possible with the availability of free-field recordings from strong motion arrays such as the El Centro differential array in California (Ref. 2) and SMART-1 array in Taiwan (Ref. 3).

Engineering studies of the effects of spatial variations of ground motions on the seismic response of structures, caused by the idealized plane seismic wave propagations, have been made for some time. The studies of the effects due to the more general variations characterized using the "spatial incoherence functions" have just recently started (e.g., Ref. 4). In this paper, a newly-developed SSI analysis method based on the theory of random vibration for incorporating the spatial incoherence of ground motions in the input, is presented. This method was developed as an extension of that proposed by Mita and Luco (Ref. 4). Using this method, a site-specific study of the effect on the seismic response of an actual nuclear power plant is described. The results and implications on the prediction of seismic responses of structures are presented and discussed.

CHARACTERIZATION OF SPATIAL INCOHERENCE OF GROUND MOTIONS

Many methods have been proposed for the characterization of spatial variations of ground motions for engineering applications. Some of the proposed methods such as the "response spectrum ratio method" in various forms are based on ad hoc considerations and, thus, are not suitable for rigorous applications. Those which are suitable for rigorous applications are generally based on the "cross-correlation method" which characterizes the spatial variations based on the measure of spatial coherency (or incoherency) between the Fourier components of ground motions at a pair of points on the free-field ground surface. The measure is usually made by estimating either the cross-correlation coefficients of the bandpass-filtered motions in the time domain (Ref. 2) or the normalized cross-power spectrum of the motions in the frequency domain (Ref. 5). The resulting estimates are usually represented by a set of smoothed "spatial incoherence functions," C, which are functions of both the Fourier frequency ω and the separation distance R between two points on the ground surface. The functions that have been proposed from analyses of instrument array data can generally be expressed in the following form:

$$C(a_o, R) = \exp[-(\alpha + \beta a_o + (\gamma a_o)^2)] \exp[-i\phi\bar{a}_o] \qquad (1)$$

where $a_o = \omega R/V_s$, and $\bar{a}_o = \omega\bar{R}/\bar{V}_s$, are the dimensionless frequencies; V_s and $\bar{V}_s$ are the shear and apparent wave velocities; $\bar{R}$ is the projection of R in the direction of $\bar{V}_s$. α, β, γ, and ϕ are site-specific constants to be determined from the analysis of ground motion data at the site. These constants may have different values for the horizontal and the vertical components of the ground motion.

SEISMIC RESPONSE ANALYSIS METHOD

In order to use the spatial incoherence functions as shown in Eq. (1) for seismic response analyses, it is necessary to represent the free-field ground motions at various points on the ground surface within a foundation region by a 3x3 ground motion covariance matrix in which the on-diagonal elements represent the auto-power spectral density and the off-diagonal elements represent the cross-power spectral density for the three components of the ground motion. To utilize the ground motion input in this form for seismic response analysis, an SSI analysis method was developed which utilizes the CLASSI method of SSI analysis (Ref. 4) and the random vibration method of seismic response prediction as implemented in the PROSPEC computer code (Ref. 6).

The step-by-step procedure of this analysis method, which includes applying the CLASSI computer code for calculating the scattered foundation motions and the SSI response transfer functions and the PROSPEC computer code for generating the probabilistic floor response spectra, is shown schematically in Fig. 1. This analysis methodology has been implemented in the computer code SIGMAS (Spatially Incoherent Ground Motion Analysis System) for engineering applications. As shown in Fig. 1, the spatial incoherence function is incorporated into the ground motion input at the step when the ground motion covariance matrices for various points on the ground surface covered by the CLASSI foundation model are calculated, and then integrated to generate the scattered foundation motions, using the foundation base contact traction vectors as the weighting functions. This method and the associated SIGMAS computer code have been benchmarked against the theoretical solutions for the scattered foundation motions and the structural response transfer functions obtained by Mita and Luco (Ref. 4) for a circular cylinder supported on the surface of a uniform elastic halfspace.

SITE-SPECIFIC APPLICATIONS

In a recent site-specific study of the spatial variations of ground motions for a specific nuclear power plant site, four spatial incoherence characterization models (Models 1 through 4) were developed which have values of the coefficients in Eq. (1) as shown and compared to the Luco model (Ref. 4) with $\gamma = 0.1$ in Table 1. The eathquake source for this site-specific study was postulated to be a magnitude 7 earthquake caused by a predominately strike-slip fault located at a distance of 5 km from the rock site. The rock shear wave velocity is about 3000 ft/sec near the ground surface and 5000 ft/sec at the depth below 100 ft. The amplitude of the spatial incoherence function of Model 4 for the horizontal component of the ground motions is shown in Fig. 2.

Using the computer program SIGMAS described previously and the site-specific ground motion input with the spatial incoherence functions shown in Table 1, the seismic responses of the containment structure, auxiliary building, and turbine building having the foundation configurations with quite different sizes and shapes as shown in Fig. 3, were analyzed.

ANALYSIS RESULTS AND DISCUSSIONS

The results obtained from the site-specific analyses using the four spatial incoherence models of Table 1, expressed in terms of the amplitudes of the horizontal response transfer functions at the containment base center relative to the amplitude of the free-field input motion at the same point, are shown and compared with the corresponding result obtained using the Luco model with $\gamma = 0.1$, in Fig. 4. As shown, the response varies with the different characterization models used. The result of Model 4, which was considered to be most representative of the site-specific conditions, is shown to be equivalent to the result of Luco model with γ value equal to about 0.15.

The SSI response, in terms of the 5% damped floor response spectrum, for the horizontal translation at the top of auxiliary building resulting from the use of Model 4, is shown and compared in Fig. 5 with the corresponding spectrum obtained from the analyses with coherent ground motion input in which the spatial incoherence functions were set equal to unity. The ratio of the response spectra shown in Fig. 5 which represents the reduction of response as a function of frequency due to the effect of spatial incoherence applicable to the specific response location, is shown in Fig. 6. Due to the accompaning rocking and torsional response motions induced by the spatial incoherence, the response spectral ratio shown in Fig. 6 can be decomposed into contributions from different response modes, as shown in Fig. 7. As shown, the reduction of response is significantly affected by the induced rocking and torsional responses; thus, it is dependent on the location in the structure.

The 5% damped response spectral ratios for the horizontal response at the foundation base centers of all three structures which have different foundation sizes and shapes, are compared in Fig. 8. As shown, the reduction of response is proportional to the plan area of the foundation. The reduction of response at locations away from the base center is dependent on the foundation shape due to the effect of induced torsional motions. This is demonstrated by comparing the response spectral ratios in Figs. 9 and 10 for the translational responses in two horizontal directions of the turbine building basemat at point 0 (center) and point A (near one end) shown in Fig. 3. As can be seen, the reductions at these two locations are similar for the NS response (long direction) which is less sensitive to torsion; whereas they are different for the EW response (short direction) which is sensitive to torsion.

It can be shown that the reductions of response due to spatial incoherence at the foundation base centers as shown in Fig. 8, can be simulated by the effect of apparent horizontal plane wave passage, as suggested in Ref. 4.

However, such a simulation becomes impractical for the responses at other locations in the structure because it is difficult to simultaneously simulate the induced rocking and torsional motions at all frequencies by simple plane passage effects.

CONCLUSIONS

The results obtained from the site-specific study using the SSI analysis method as described herein indicated that the spatial incoherence of ground motions generally reduces the seismic response of the structures. This reduction was found to be dependent on the incoherence characterization models used and proportional to the plan area of the foundation. For structures with a large foundation, the reduction at the foundation base increases with frequency and can be as much as 15 to 20% over the frequency range above 10 cps. The reduction was also found to vary with the foundation shape and location within the structure. These variations are caused by the rocking and torsional response motions induced by the spatial incoherence of ground motions.

ACKNOWLEDGEMENT

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REFERENCES

1. Crouse, C. B., "Engineering Studies of the San Fernando Earthquake," Report No. EERL 73-04, California Institute of Technology, (1973)
2. Smith, S. W., Ehrenberg, J. E., and Hernandez, E. W., "Analysis of the El Centro Differential Array for the 1979 Imperial Valley Earthquake," Bull. Seism. Soc. Am. 72, 237-258, (1982).
3. Loh, C. H., Penzien, J., and Tsai, Y. B., "Engineering Analysis of SMART-1 Array Accelerograms," Earthquake Eng. Struct. Dynamics, 10, 575-591, (1982).
4. Mita, A., and Luco, J. E., "Response of Structures to a Spatially Random Ground Motion," Third U.S. National Conference on Earthquake Eng., 907-918, (1986).
5. Harichandran, R. S., and Vanmarcke, E. H., "Stochastic Variation of Earthquake Ground Motion in Space and Time," ASCE, J. Eng. Mechanics 112, 154-174, (1986).
6. Lilhanand, K., Wing, D. W., and Tseng, W. S., "Systematic Evaluations of Probabilistic Floor Response Spectrum Generation," SMiRT-8, K12/2, Brussels, (1985).

Table 1 Site-Specific Spatial Incoherence Models

Incoherence Model No.	Horizontal Motion				Vertical Motion			
	α	β	γ	ϕ	α	β	γ	ϕ
Model 1	0.1	-	-	-	0.2	-	-	-
Model 2	0.05	0.04	-	-	0.06	0.03	-	-
Model 3	0.01	0.07	-	-	0.02	0.07	-	-
Model 4	0.01	0.07	-	1.25	0.02	0.07	-	1.0
Luco Model	-	-	0.1	-	-	-	0.1	-

$V_s = 800$ m/sec; $\bar{V}_s = 10$ km/sec

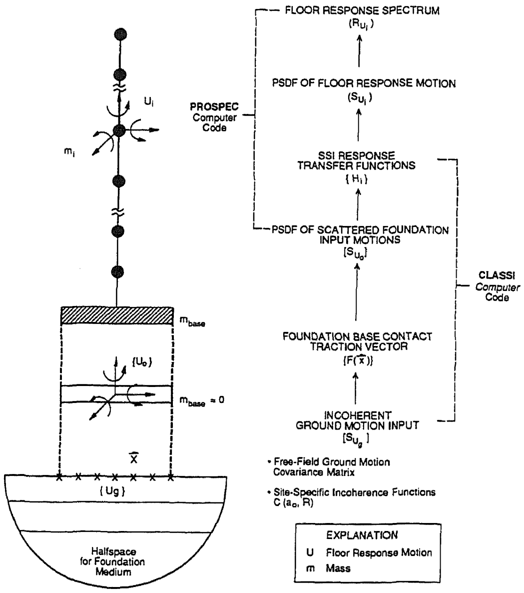

Fig. 1 Schematic Diagram of SSI Analysis Procedure for Spatially Incoherent Ground Motion Input

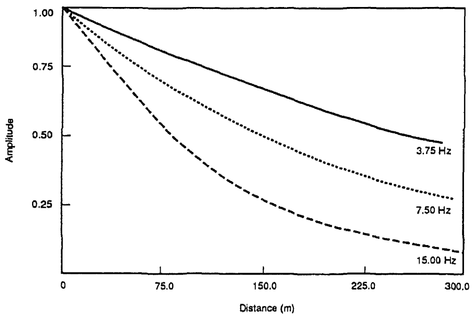

Fig. 2 Amplitudes of Horizontal Site-Specific Spatial Incoherence Functions

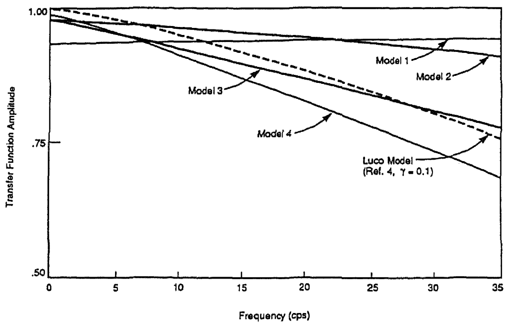

Fig. 4 Transfer Function Amplitude of DCPP Containment Foundation Response Motions to Free-Field Input Motions

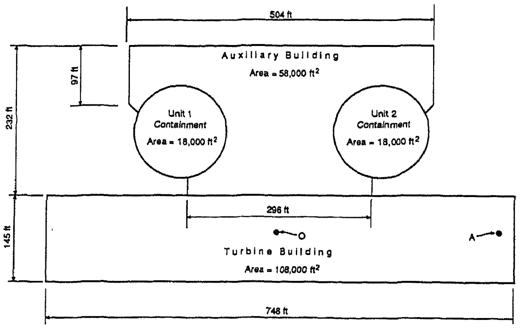

Fig. 3 General Configuration of Power Block Structures

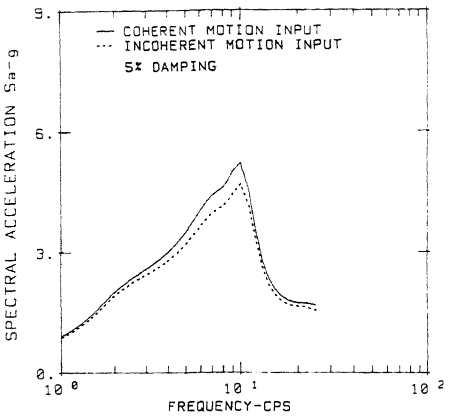

Fig. 5 Horizontal Floor Response Spectra at the Top of Auxiliary Building

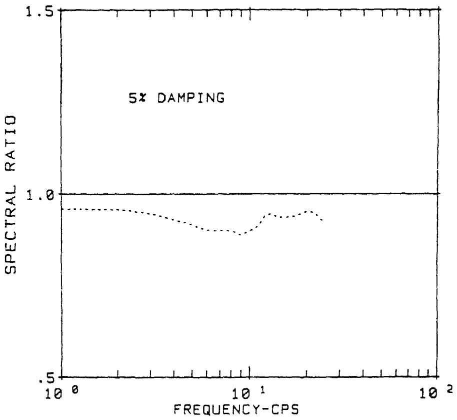

Fig. 6 Response Spectral Ratio of the Spectra in Fig. 5

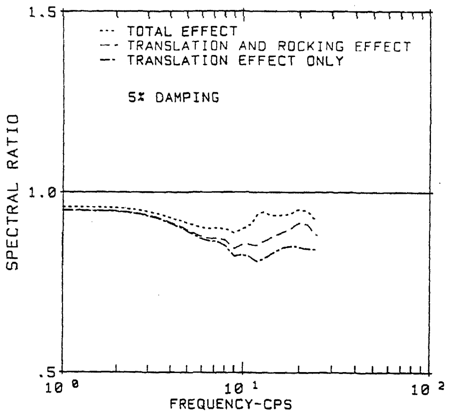

Fig. 7 Decomposition of the Spectral Ratio in Fig. 6

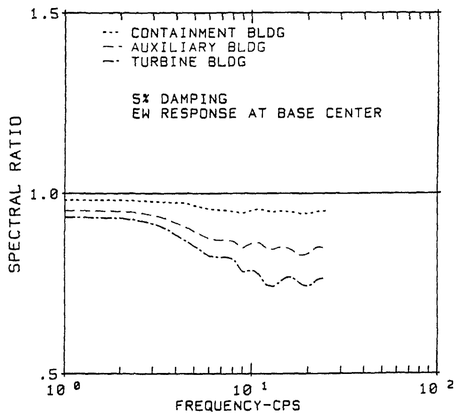

Fig. 8 Spectral Ratios at Base Centers of All Three Structures

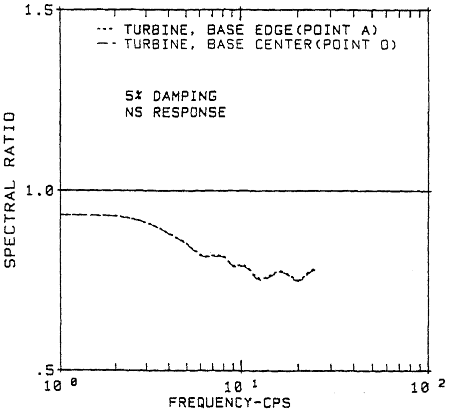

Fig. 9 NS Response Spectral Ratios at Turbine building Base

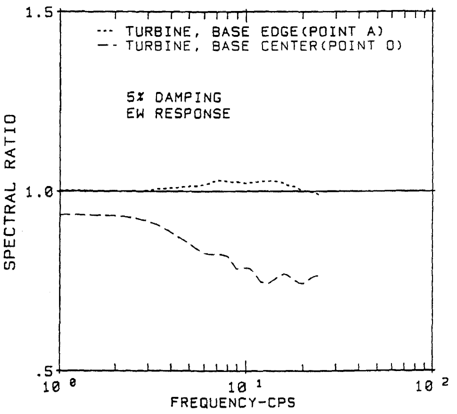

Fig. 10 EW Response Spectral Ratios at Turbine building Base