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Effect of Seismic Wave Incoherence on Foundation and Building Response

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Technical Update Report, December 2005

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PRODUCT DESCRIPTION

Task S2.1 of the New Plant Seismic Issues Resolution Program—a joint effort of EPRI and the Department of Energy (DOE)—entails a research program into the effect of seismic wave incoherence on foundation and building response. The task's objective is to systematically study seismic wave incoherence effects on structures/foundations similar to those being considered for advanced reactor designs. Seismic wave incoherence occurs because of the horizontal spatial variation of both horizontal and vertical ground motion. The phenomenon of seismic wave incoherence has been recognized for many years, but the lack of extensive recorded data prevented its incorporation into the dynamic analysis of nuclear power plant (NPP) structures. Based on newly developed coherency functions, seismic response has been evaluated in this study using the soil-structure interaction (SSI) computer program CLASSI, combined with random vibration theory. Seismic response is evaluated for rigid, massless foundations and for example structural models on foundation mats that behave rigidly.

Results & Findings

Seismic analyses incorporating ground motion incoherence demonstrate a significant reduction in high-frequency seismic response as measured by in-structure response spectra. The computed incoherency transfer functions depend on the foundation area and are independent of site soil conditions. However, the resulting spectral reductions strongly depend on site soil conditions. The effect of seismic wave incoherence is primarily a high-frequency phenomenon. Hence, the observed reductions in foundation response spectra are much less for soil sites since the soil site-specific ground motion is deficient in the high-frequency portion of the spectra.

Challenges & Objective(s)

This task's objective is to systematically study seismic wave incoherence effects on structures/foundations similar to those being considered for advanced reactor designs. In EPRI NP-6041 (EPRI, 1991), American Society of Civil Engineers (ASCE) Standard 4 (ASCE, 2000), and DOE Standard-1020 (U.S. DOE, 2002), recommendations for response spectrum reduction factors were developed as a function of the foundation plan dimension and frequency. Since the original publication of these recommendations, several studies have indicated that these initial recommendations are likely conservative. Task S2.1 does demonstrate that the published spectral reductions may be overly conservative (too small) in certain cases. More importantly, the task demonstrates that spectral reduction is not the proper way to characterize seismic wave incoherence because spectral reductions are highly dependent on the shape of ground response spectra.

Applications, Values & Use

The basic effect of incoherence on seismic response of structures has been demonstrated in this project and validated through recorded ground motions and analyses of their effects with alternative methods. The phenomenon of incoherence is important for high-frequency ground motions and high-frequency response of structures (primarily greater than 10 Hz). Realistically accounting for ground motion incoherence on the seismic response of nuclear power plant structures is one of the most significant factors in treating high-frequency ground motion. For the realistic, but simplified, foundation shapes studied in this project, the most important parameter was foundation area. Foundation shape (square vs. rectangle) and site soil conditions had minimal to no effect on incoherency transfer functions (ITFs), which are equivalent to scattering functions in CLASSI nomenclature (frequency-dependent, complex-valued functions)

EPRI Perspective

Future potential research on the effect of seismic wave incoherence on foundation and building response will include sensitivity studies for differing foundation shapes, differing structures and their models, and increased complexity of foundations and structures. The following specific tasks have been identified as valuable research in support of Task S2.1:

- additional analyses for different and more complex foundation shapes,
- verification of the computed incoherency reductions based on studies of empirical data on foundation responses in real earthquakes,
- sensitivity study on coherency function uncertainty, and
- validation of the coherency function through peer review..

Approach

The project team developed the basic relationship between motion in the free-field and motion on rigid, massless foundations based on random vibration theory. The team described the relationship between free-field ground motion at the discretized points on the foundation by the cross power spectral density function, normalized by the power spectral density (PSD) function of the free-field ground motion. Using the resulting PSDs of the motion of the rigid, massless foundation, the team developed ITFs. The effects of incoherence on NPP structures/foundations are accounted for as a function of foundation area and other relevant parameters. The overall approach was validated during this study by an independent comparison with different methodology and software.

Keywords

Eastern U.S. earthquakes
Ground motions
High-frequency effects
Seismic wave incoherence
Random vibrations
Soil structure interactions

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ABSTRACT

Task S2.1 of the EPRI/Department of Energy (DOE) New Plant Seismic Issues Resolution Program has been conducted; project results are presented in this document. The objective of this task is to systematically study seismic wave incoherence effects on structures/foundations similar to those being considered for advanced reactor designs.

Current probabilistic seismic hazard assessments (PSHAs) for rock sites in the Central and Eastern United States (CEUS) result in site-specific uniform hazard spectra (UHS) that contain significant amplified response in the frequency range above 10 Hz. UHS are multi-parameter probabilistic descriptors of ground motion at the site of interest. They do not represent a single earthquake. There is no explicit relationship between the spectral ordinates at the various frequencies of the UHS. The only condition is that each spectral ordinate has the same probability of exceedance for a given return period. Earthquake records indicate that different earthquakes (for example, magnitudes and distances) govern responses in different frequency ranges; thus, UHS do not represent the recorded motion of a single earthquake. Nevertheless, UHS characteristics are representative of recorded earthquake ground motions on stiff rock sites and, therefore, form the ground motion basis for this study.

High-frequency ground motion is what would be measured at a rock site by a strong motion instrument on a small pad during an earthquake in the Central and Eastern United States. For nuclear power plant (NPP) structures that have large and stiff foundation mats, high-frequency amplified seismic response at the foundation mat is significantly reduced because of horizontal spatial variation of ground motion or incoherence. It has been observed that the effective input motion to structures is reduced from instrumental ground motion due to averaging or integrating effects of large, relatively rigid foundations.

The phenomenon of seismic wave incoherence has been recognized for many years, but the lack of extensive recorded data prevented the incorporation of the effect into the dynamic analysis of NPP structures. Abrahamson, in a separate study referenced in this report, presents a state-of-the-art representation of the coherency function based on the most applicable data available to date. Coherency functions define relationships between ground motion at separate locations as a function of the separation distance between the locations and the frequency of the ground motion. Generally, coherency of motion decreases significantly with increasing frequency and increasing distance between points of interest. For example, at a frequency of 20 Hz, the coherency of horizontal ground motion at two points 5 meters apart is about 0.35—on average, the motion at the two points are not in phase (they are not coherent). Hence, the foundation/structure introduced into this wave field is not significantly excited by the 20 Hz motion. Averaging or integrating over the foundation footprint accounts for this incoherence at all frequencies of interest and all discretized points on the foundation.

Based on these newly developed coherency functions, seismic response has been evaluated using the soil-structure interaction (SSI) computer program CLASSI, combined with random vibration theory. Seismic response is evaluated for rigid, massless foundations and, for example, structural models on foundation mats that effectively behave rigidly. The basic relationship between motion in the free-field and motion on the rigid, massless foundation is developed based on random vibration theory. The relationship between free-field ground motion at the discretized points on the foundation is described by the cross power spectral density function, normalized by the power spectral density (PSD) function of the free-field ground motion. Incoherency transfer

functions (ITFs) are directly developed from the resulting PSDs of the motion of the rigid, massless foundation. ITFs are equivalent to scattering functions in CLASSI nomenclature (frequency-dependent, complex-valued functions). ITFs, when applied to the free-field ground motion, take into account effects of incoherence on the foundation input motion. These scattering functions permit evaluation of structure and foundation seismic response directly using the CLASSI family of programs for SSI analysis. Similarly, ITFs may be applied to modify the seismologically-defined free-field ground motion. The modified ground motion is used in standard seismic response analyses as an alternate means of including effects of seismic wave incoherence. In either case, effects of incoherence on NPP structures/foundations are accounted for as a function of foundation area and other relevant parameters.

The overall approach was validated during this study by an independent comparison with different methodology and software. The random vibration approach used with CLASSI software produced excellent agreement with an eigen function decomposition approach with SASSI software.

The conclusions of this study include the following:

- The phenomenon of incoherence is important for high-frequency ground motions and high-frequency response of structures (primarily greater than 10 Hz). Realistically accounting for ground motion incoherence on the seismic response of nuclear power plant structures is one of the most significant factors in treating high-frequency ground motion. The averaging or integrating effects of high-frequency ground motions by stiff foundations in nuclear power plants reduces calculated in-structure response spectra significantly at frequencies greater than 10 Hz.
- Structure responses in frequency ranges below about 10 Hz are essentially unaffected by the phenomena.
- Horizontal and vertical ground motions are subject to the incoherence phenomena and the effects on both have been included in this study.
- Accounting for incoherency by applying ITFs may be accomplished in a direct and "exact" manner as in this study using CLASSI. An alternative approach to account for incoherency is to scale the Fourier amplitude spectra of the free-field ground motion by a modified ITF. This approach was validated for a rock site and a compatible site-specific high-frequency ground motion. This latter approach allows incorporation of the effect into standard seismic analysis programs.
- The cooperative benchmarking study by Bechtel on the effect of incoherency, using a different approach and a different computer program (SASSI), has confirmed the findings for the benchmark (rigid, massless foundation) on various site conditions.
- For realistic, but simplified, foundation shapes studied in this project, the most important parameter was found to be foundation area. Foundation shape (square vs. rectangle) and site soil conditions were found to have minimal to no effect on the ITFs.
- Potential enhancements to this study to broaden its applicability are in the areas of sensitivity studies for differing foundation shapes, differing structures and their models, and increased complexity of the foundations and structures. The assumption that mat foundations of typical nuclear power plant structures behave rigidly was made in this study. This assumption has been well justified by numerous previous studies and is caused by the stiffening effects of structural elements interconnected to the foundation.

- The basic effect of incoherence on seismic response of structures has been demonstrated and validated through recorded ground motions and analyses of their effects with alternative methods and programs.

The following tasks have been identified as valuable further research in support of this Task S2.1 effort. EPRI is committed to these additional tasks, subject to availability of appropriate funding, to broaden the application of these methods and to provide further verification of the procedures developed:

- additional analyses for different and more complex foundation shapes,
- verification of the computed incoherency reductions based on studies of empirical data on foundation responses in real earthquakes,
- sensitivity study on coherency function uncertainty, and
- validation of the coherency function through peer review.

In summary, seismic analyses incorporating ground motion incoherence demonstrate a significant reduction in high-frequency seismic response as measured by in-structure response spectra. The computed incoherency transfer functions depend on the foundation area and are independent of site soil conditions. However, the resulting spectral reductions strongly depend on the site soil conditions. The effect of seismic wave incoherence is primarily a high-frequency phenomenon. Hence, the observed reductions in foundation response spectra are much less for soil sites since the soil site-specific ground motion is deficient in the high-frequency portion of the spectra.

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1
INTRODUCTION AND BACKGROUND

Seismic Wave Incoherence

Task S2.1 of the EPRI/DOE New Plant Seismic Issues Resolution Program entails a research program into the effect of seismic wave incoherence on foundation and building response. The scope of work associated with Task S2.1 has been conducted with results presented herein. The objective of this task is to systematically study seismic wave incoherence effects on structures/ foundations similar to those being considered for Advanced Reactor designs. Seismic wave incoherence arises from the horizontal spatial variation of both horizontal and vertical ground motion. Two sources of incoherence or horizontal spatial variation of ground motion are:

1. Local wave scattering: Spatial variation from scattering of waves due to the heterogeneous nature of the soil or rock along the propagation paths of the incident wave fields.
2. Wave passage effects: Systematic spatial variation due to difference in arrival times of seismic waves across a foundation due to inclined waves.

This study considers both of these phenomena but the final results are based on local wave scattering. In general, ground motion is measured by an instrument located at a point on the ground surface. Studies of motion measured by instrument arrays have shown that there is a loss of coherence between the surface motion measured at two separated points. These measurements have indicated that the coherency of motion decreases with respect to both increasing separation distance and increasing frequency. The motion of a large rigid foundation results from the coherent portion of the ground motion. This phenomenon has been referred to as the base averaging effect by some authors. Thus, large foundations tend to have reduced motion which is characterized by lower motion amplitudes and by reduction of high frequency content when compared to the free-field surface motion at a single location.

In NUREG/CR-3805 (Chang, 1986), recommendations for response spectrum reduction factors were developed as a function of the foundation plan dimension and frequency. These recommendations were incorporated into EPRI NP-6041 (EPRI, 1991), ASCE Standard 4 (ASCE, 2000), and DOE Standard-1020 (U.S. DOE, 2002). Since the original publication of these recommendations, there have been several studies that have indicated that these initial recommendations are likely conservative. Task S2.1 demonstrates that the published spectral reductions may be overly conservative in certain cases but, most importantly, demonstrates that spectral reduction is not the proper way to characterize seismic wave incoherence because the spectral reductions are highly dependent on the shape of the ground response spectra. By this task, the effects of incoherency are treated directly in the soil-structure interaction analysis or by modifying the Fourier amplitude of the free-field ground motion instead of spectral modifications. Incoherency corrections in spectra are then evaluated after seismic wave incoherence is introduced into the seismic analysis.

The phenomenon of seismic wave incoherence has been recognized for many years, but the lack of extensive recorded data prevented the incorporation of the effect into the dynamic analysis of structures with large foundations, such as nuclear power plant (NPP) structures. Dr. Norm Abrahamson has developed a state-of-the-art representation of the coherency function based on the most applicable data available (Abrahamson, 2005). The coherency function is the relationship between ground motion at separate locations as a function of the separation distance between the locations and the frequency of the ground motion. The resulting coherency functions are employed in this task to demonstrate the effects of seismic wave incoherency on the seismic response of structures and their foundations.

Consideration of Incoherence at Diablo Canyon

Seismic wave incoherence was considered in support of the Long Term Seismic Program (LTSP) in the late 1980s. For this study site-specific spatial incoherence functions were developed from low amplitude motions. This site-specific representation of incoherence was determined by recordings from a dense array based on small earthquake motions, dynamite explosions in boreholes, and air gun shots fired at sea. The results of the analyses performed demonstrated that seismic wave incoherence generally results in reductions in the soil/structure seismic response. The Nuclear Regulatory Commission (NRC) addressed the LTSP soil-structure interaction (SSI) analyses including incoherency in Safety Evaluation Report, NUREG-0675, Supplement No. 34 (Rood, 1991). In this report, it is noted that the SSI analysis provides acceptable Diablo Canyon plant seismic responses (Dr. Carl Costantino and Professor A. Veletsos, acting as consultants to the NRC).

In the early 1990's, the LTSP seismic SSI analyses were performed again with a coherency representation based on data from the instrumentation array in Lotung, Taiwan. These data are more realistic than the Diablo Canyon data as they include ground motion from a range of significant earthquakes. The array provides much of the data used to evaluate seismic wave incoherence for the evaluations described in this report. The Lotung recorded data showed greater reductions in the free-field ground motion at the same distance and frequency parameters as previously recorded. When applying these new data to the Diablo Canyon structures, the re-analyses demonstrated greater reductions in foundation and structure response than previously predicted from the site-specific measurements.

Project Sub-Tasks

Based on the coherency functions developed recently (Abrahamson, 2005), seismic response has been evaluated using the soil-structure interaction computer program CLASSI (Wong, 1980), combined with random vibration theory. Seismic response is evaluated for rigid, massless foundations and for example structural models on rigid foundation mats. The basic relationship between motion in the free-field and motion on the rigid massless foundation is developed based on random vibration theory. The relationship between free-field ground motion at discretized points on the foundation is described by the cross power spectral density functions, normalized by the power spectral density (PSD) function of the free-field ground motion. Incoherency transfer functions (ITFs) are directly developed from the resulting PSDs of the motion of the rigid, massless foundation. ITFs are equivalent to scattering functions in CLASSI nomenclature, i.e., frequency-dependent, complex-valued functions when applied to the free-field ground motion take into account the effects of incoherence on the foundation input motion. These scattering functions permit the evaluation of structure and foundation seismic response directly using the CLASSI family of SSI analysis programs. Similarly, ITFs may be applied to modify the free-field ground motion. The modified ground motion is used in standard seismic response analyses as an alternate means of including the effects of seismic wave incoherence. In either case, the effects of incoherence on NPP structures/foundations are accounted for as a function of foundation area and other relevant parameters. An important sub-task is to benchmark the results by an independent comparison with different methodology and software.

Project sub-tasks to accomplish the work described above include:

1. Define cases to be analyzed including site conditions, foundation characteristics, and structural characteristics.
2. Develop the ground motion input to be considered including response spectra and time histories. Establish methods of computation of response spectra from PSD and PSD from response spectra.
3. Establish algorithms for expressing the coherency function for both horizontal and vertical ground motions as a function of separation distance and frequency including both local wave scattering and wave passage effect phenomena.
4. Incorporate the coherency function using CLASSI and determine the PSD of the response of a rigid, massless foundation of varying areas and shapes on a rock or soil site profile. Develop an incoherency transfer function from the PSD of foundation response that is normalized to the PSD of the free-field input motion.
5. Conduct parametric studies of the rigid, massless foundation to determine incoherency transfer functions and foundation response spectra. Comparison of foundation and free-field response spectra demonstrate spectral corrections due to seismic wave incoherence.
6. Benchmark the computed incoherency transfer functions and spectral corrections for a specific case by comparing CLASSI results to those obtained using SASSI (by others).
7. Conduct SSI analyses of an example structure incorporating seismic wave incoherence in two manners: 1) direct incorporation into CLASSI through scattering matrices, and 2) modification of the free-field ground motion time histories by scaling their Fourier amplitudes by the incoherency transfer functions. Compare and present these results.
8. Document all work in a final report.

Contents of the Report

The results of all analyses considering seismic wave incoherence for site conditions, input ground motion, and structure/foundation characteristics, typical of potential future advanced reactors, are presented in this report. This chapter provides introductory and background material. Parameters considered in the analyses for this study are described in Chapter 2. These parameters include: the basic coherency function developed by Dr. Abrahamson for horizontal and vertical ground motion, parameters describing the typical rock and soil site profiles as well as the simplified rock half-space considered for the benchmark comparison, foundation areas and shapes, and structure properties. The technical approach is described in Chapter 3. Chapter 4 is a presentation of the CLASSI-SASSI benchmark comparison. The incoherency transfer functions and foundation response spectra incoherency corrections for rigid, massless foundations are presented in Chapter 5. Incorporation of seismic wave incoherence into SSI and structure seismic response is described in Chapter 6. Chapter 7 provides a summary along with conclusions, and recommendations. Subsections of Chapter 7 cover: tasks performed and approach utilized, the benchmark comparisons, the incoherency transfer functions developed and the spectral corrections observed, along with observations on rocking and torsion response. Chapter 8 contains the list of references.

2
STUDY INPUT PARAMETERS

Coherency Function

For this project, Abrahamson developed a coherency function (Abrahamson, 2005) that describes the relationship between ground motion at separate locations as a function of the separation distance and the frequency of the ground motion. This coherency function is expressed by the following equation:

$$\gamma_{PW} = \left[1+\left(\frac{f\,Tanh(a_3\xi)}{a_1 f_c}\right)^{n1}\right]^{-\frac{1}{2}}\left[1+\left(\frac{f\,Tanh(a_3\xi)}{a_2 f_c}\right)^{n2}\right]^{-\frac{1}{2}} \quad \textbf{(Equation 2-1)}$$

$$\gamma = |\gamma_{PW}|[\cos(2\pi f\xi_R s)+i\sin(2\pi f\xi_R s)] = |\gamma_{PW}|e^{i2\pi f\xi_R s} \quad \textbf{(Equation 2-2)}$$

Where γ_{PW} is the plane wave coherency representing random horizontal spatial variation of ground motion and γ is coherency including both local wave scattering and wave passage effects. Eq. 2-2 can be used with vertically inclined waves to capture the systematic phase shifts due to an inclined wave (wave passage effects). The parameter f is ground motion frequency, ξ is the separation distance between locations in meters, and s is the slowness in seconds/meter. The reciprocal of s is the apparent wave velocity accounting for wave passage effects. Note that ξ_R is the separation distance in the radial direction in meters for which the median value is estimated as:

$$\xi_R = \frac{\xi}{\sqrt{2}} \quad \textbf{(Equation 2-3)}$$

Coefficients to be used in eq. 2-1 for horizontal and vertical ground motion are presented in Table 2-1.

Table 2-1
Coherency Function Coefficients

Coefficient	Horizontal Ground Motion	Vertical Ground Motion
a_1	1.647	3.15
a_2	1.01	1.0
a_3	0.4	0.4
$n1$	7.02	4.95
$n2$	5.1-0.51ln(ξ+10)	1.685
f_c	1.886+2.221ln(4000/(ξ+1)+1.5)	exp(2.43-0.025 ln(ξ+1)-0.048 (ln(ξ+1))2)

The coherency function is plotted as a function of frequency for a number of separation distances in Figures 2-1 and 2-2 for horizontal and vertical ground motion, respectively.

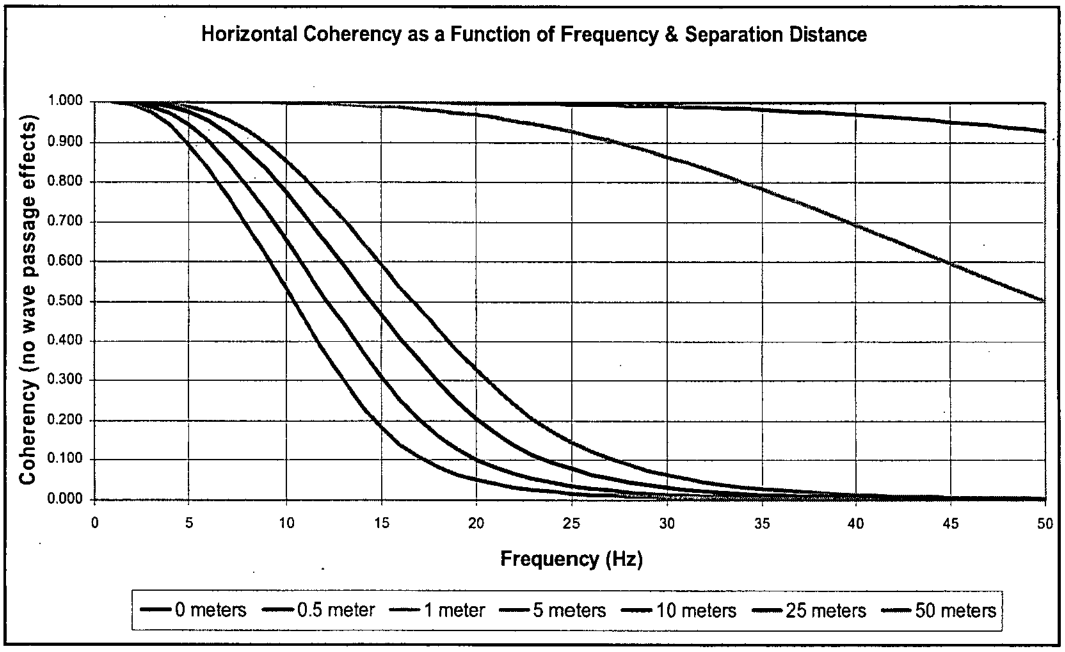

Figure 2-1
Coherency Function for Horizontal Ground Motion

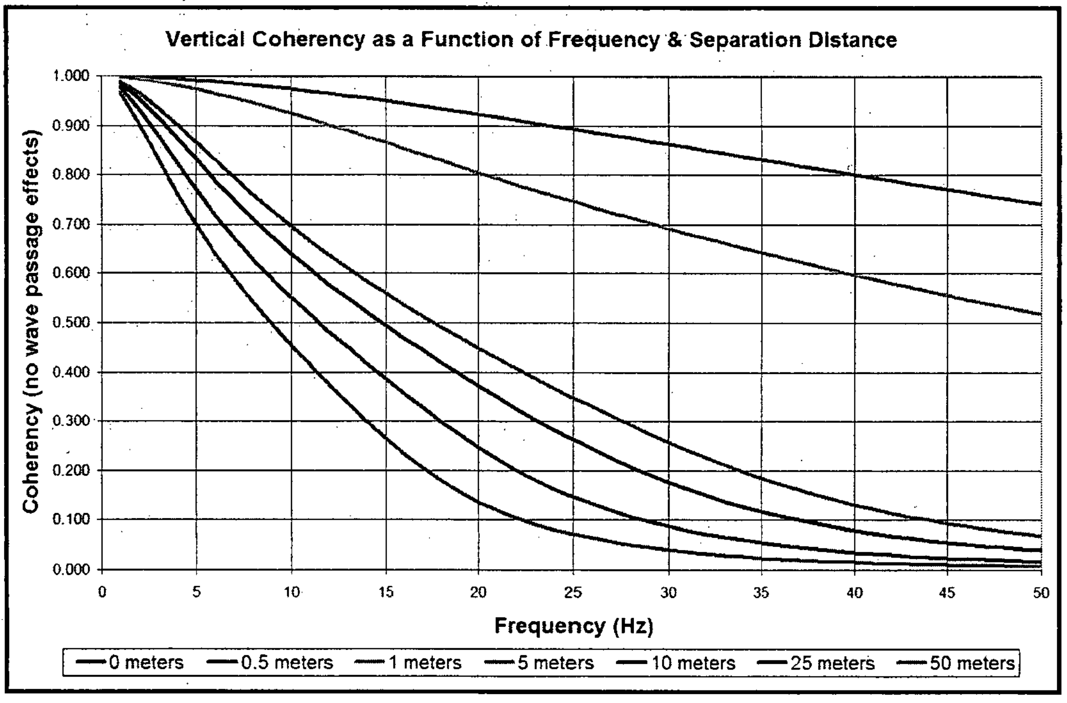

Figure 2-2
Coherency Function for Vertical Ground Motion

The coherency functions presented above have been developed from all available and applicable recorded ground motion from dense instrument arrays. Data is from a variety of site conditions and earthquake magnitudes. In the development of these functions, Dr. Abrahamson has reached the following conclusions (Abrahamson, 2005):

- Coherency functions are appropriate for all frequencies (including those above 20 Hz). Ground motion data analyzed to develop the coherency functions have frequency content of 20 Hz and less. It is logical that the trends observed should extrapolate to higher frequencies.
- Coherency does not vary as a function of site shear wave velocity, but is strongly affected by topography. Data with strong topographic effects were not included for development of the coherency function.
- Coherency does not vary as a function of earthquake magnitude. This is true for magnitudes of interest that are greater than magnitude 4.5 to 5.0.
- Each component of earthquake input can be treated as uncorrelated. The coherency of cross-components is near zero.

For the design of NPP structures, mean input ground motion is the goal. As a result, the goal is to use mean coherency. The functions of eqs. 2-1 and 2-2, and Table 2-1 model median coherency. Median coherency is slightly larger (only a few percent difference) than mean coherency.

Site Parameters and Input Ground Motion

Site soil profiles have been selected that are representative of sites in the Central and Eastern United States. Site-specific response spectra compatible with each of the sites have been developed and used in this study. Shear wave velocities as a function of depth beneath the free-field ground surface are shown in Figure 2-3. The site profiles shown in the figure extend down to the EPRI-defined bedrock that has shear wave velocity of about 9200 fps.

For the foundation areas considered for this incoherence study, it is sufficient to define the site profile to a depth of about 300 feet beneath the foundation. The soil and rock shear wave velocities to a depth of 500 feet are illustrated in Figure 2-4.

The soil layers and properties shown in Tables 2-2 and 2-3 have been used for the evaluation of coherency effects in this study. These properties were taken from information provided within the advanced reactor submittals. For the soil case, high strain properties were calculated as noted below, consistent with the approach outlined within the soil site submittals for advanced reactors.

For CLASSI modeling purposes, the rock site is represented by nine layers extending down to 130 ft below the surface, and then a half-space of bedrock at a shear wave velocity of 9200 fps. Rock is assumed to have the low strain shear modulus (shear wave velocity) and no variation of damping at earthquake strain levels (i.e., linear elastic behavior). A damping ratio of 0.02 is assumed, which corresponds to about 0.001% shear strain.

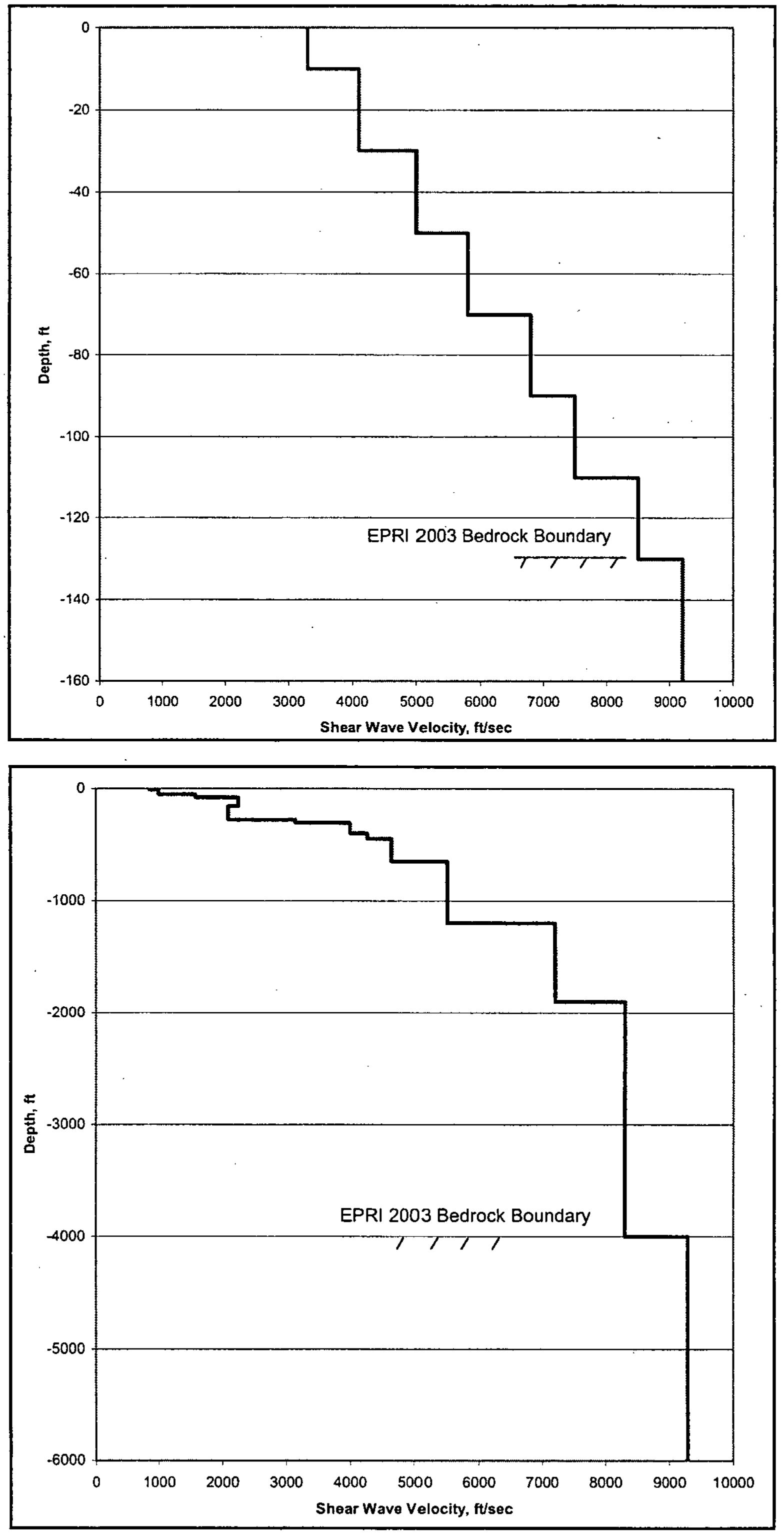

Figure 2-3
Rock and Soil Site Profile Shear Wave Velocities vs. Depth

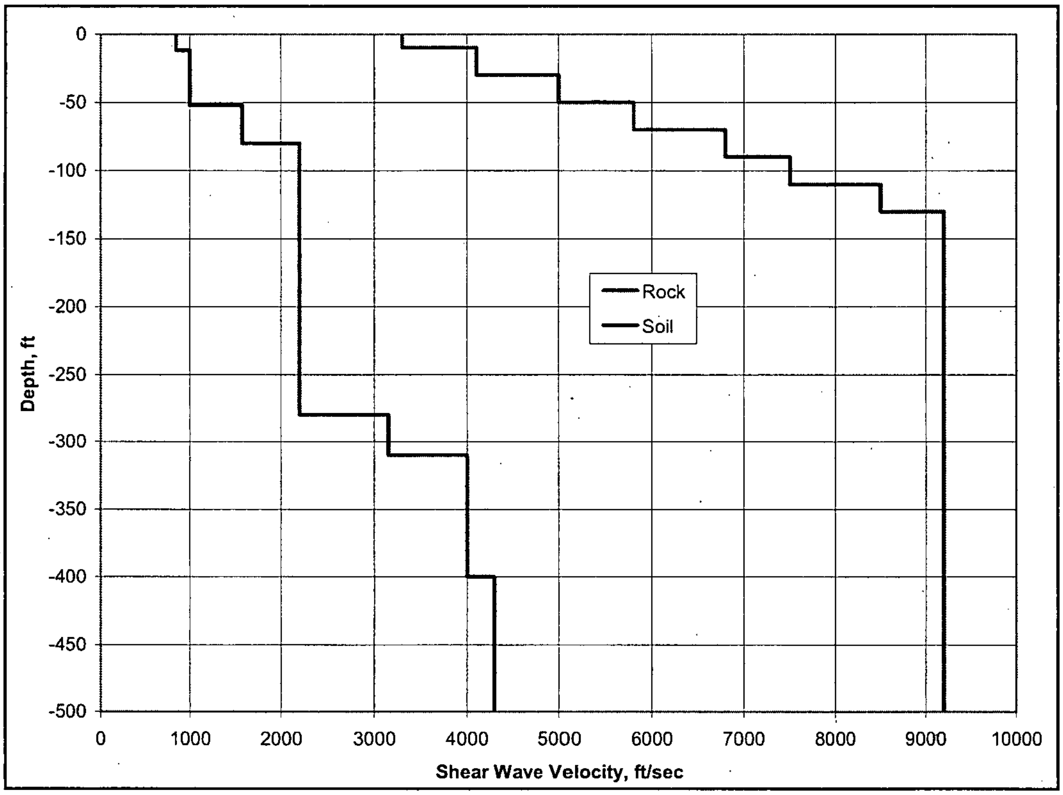

Figure 2-4
Rock and Soil Site Profiles Within 500 Feet of the Ground Surface

Table 2-2
Layers and Properties for the Rock Site (EQ Strain)

Layer	Shear Wave Velocity (fps)	Weight Density (pcf)	Poisson's Ratio	Damping (fraction)	Thickness (ft)	Layer Top Depth (ft)
1	3300	160	0.33	0.02	5	0
2	3300	160	0.33	0.02	5	5
3	4100	160	0.33	0.02	10	10
4	4100	160	0.33	0.02	10	20
5	5000	160	0.33	0.02	20	30
6	5800	160	0.33	0.02	20	50
7	6800	160	0.33	0.02	20	70
8	7500	160	0.33	0.02	20	90
9	8500	160	0.33	0.02	20	110
10	9200	160	0.33	0.02	Half-space	130

The soil site is represented by 11 layers extending down to 400 ft below the surface, and then a half-space of bedrock at a shear wave velocity of 4300 fps. Soil shear modulus (shear wave velocity) and damping have been determined using EPRI degradation and damping curves (EPRI

1993 Guidelines for Determining Design Basis Ground Motion) as a function of earthquake strain level and depth. Earthquake strain level of 10^{-2}% has been assumed.

Table 2-3
Layers and Properties for the Soil Site (EQ Strain)

Layer	Shear Wave Velocity (fps)	Weight Density (pcf)	Poisson's Ratio	Damping (fraction)	Thickness (ft)	Layer Top Depth (ft)
1	730	131	0.46	0.05	6	0
2	730	131	0.46	0.05	6	6
3	860	131	0.46	0.05	12	12
4	910	131	0.46	0.034	12	24
5	910	131	0.46	0.034	16	36
6	1470	116	0.46	0.028	28	52
7	2040	148	0.46	0.028	50	80
8	2090	148	0.46	0.022	50	130
9	2090	138	0.46	0.022	100	180
10	3040	150	0.38	0.02	30	280
11	3860	160	0.33	0.02	90	310
12	4150	160	0.33	0.02	Half-space	400

Site-specific ground response spectra appropriate at the free ground surface at Elevation 0 for each site profile, as shown in Figure 2-4, were used for this coherency study. Five percent damped site-specific response spectra are illustrated in Figures 2-5 and 2-6 for rock and soil sites, respectively. Also, plotted on the figures are the US NRC Regulatory Guide 1.60 design ground response spectra anchored to 0.3 g peak ground acceleration (PGA) for comparison purposes.

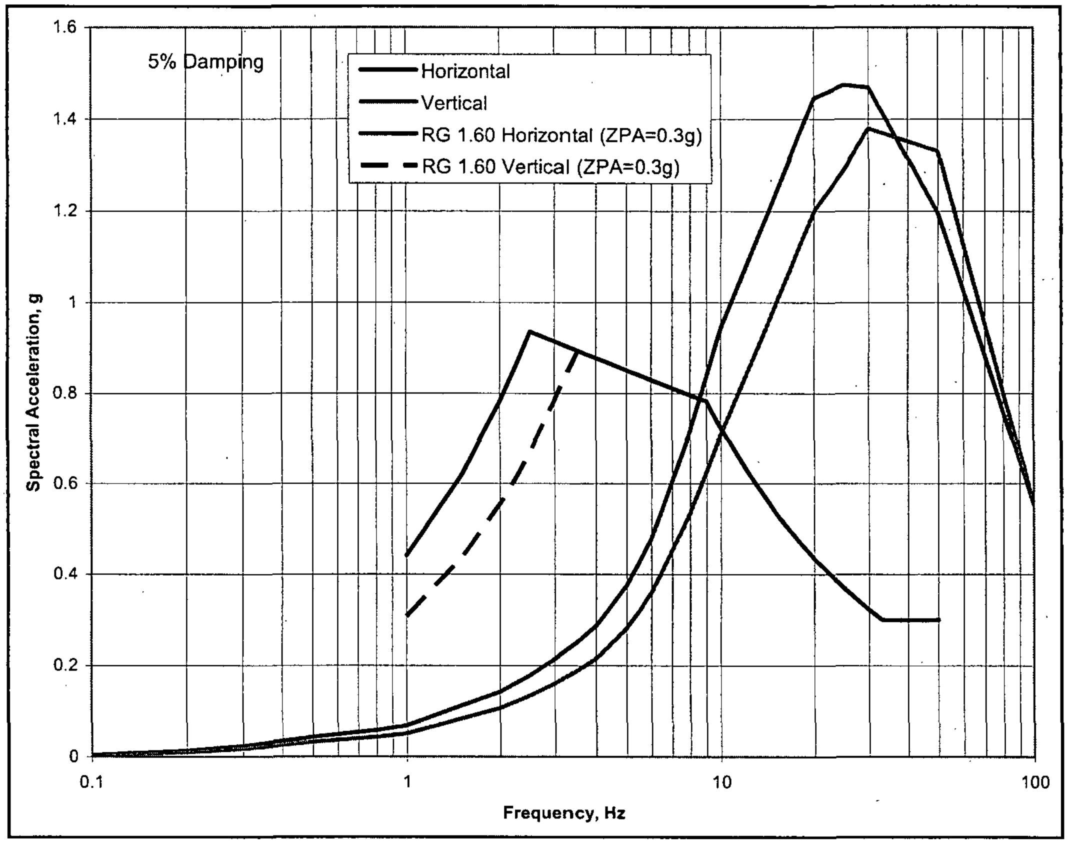

Figure 2-5
Site-Specific Response Spectra for Rock Site at Ground Surface (Depth 0 ft)

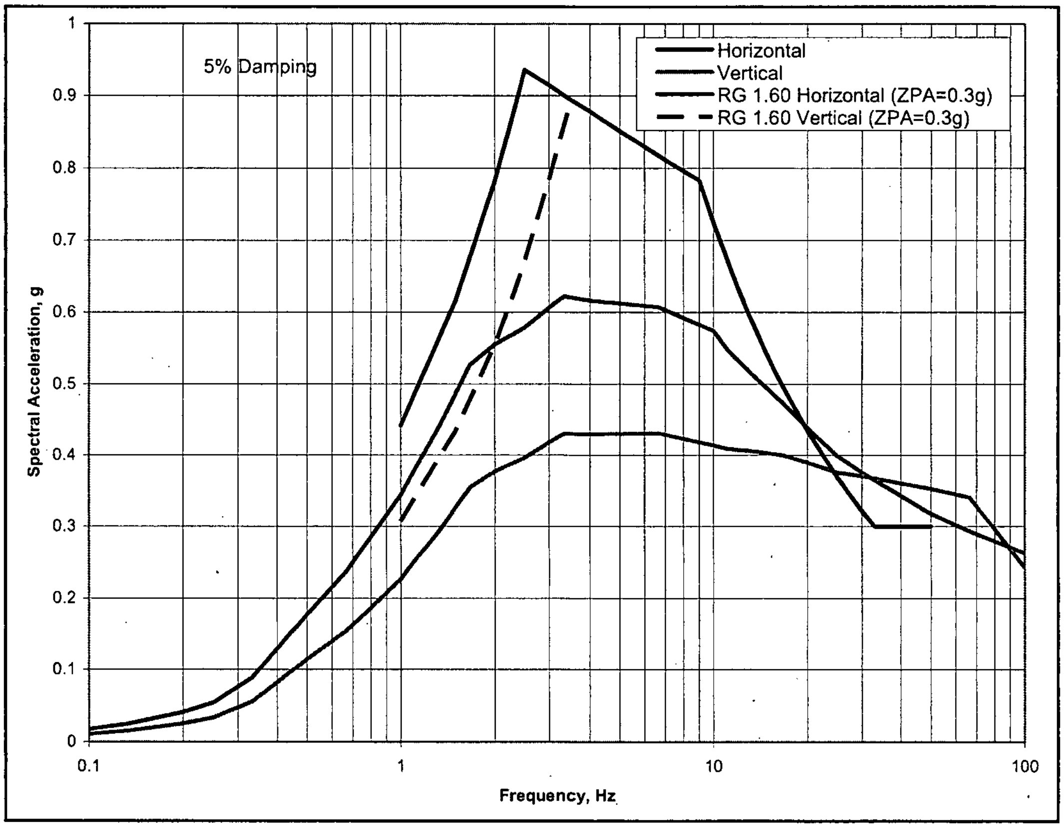

Figure 2-6
Site-Specific Response Spectra for Soil Site at Ground Surface (Depth 0 ft)

The rock site-specific ground response spectra have peak amplification in the 20 to 30 Hz range. The soil site-specific ground response spectra have peak amplification in the 3 to 8 Hz range.

For soil-structure interaction analyses and the evaluation of structure response including the effects of seismic wave incoherence, spectrum compatible time histories for the rock site were required. These were developed by Dr. Abrahamson. The computed spectra and the target spectra (Figure 2-5) are shown in Figure 2-7. Three uncorrelated components were generated for two horizontal directions and the vertical direction.

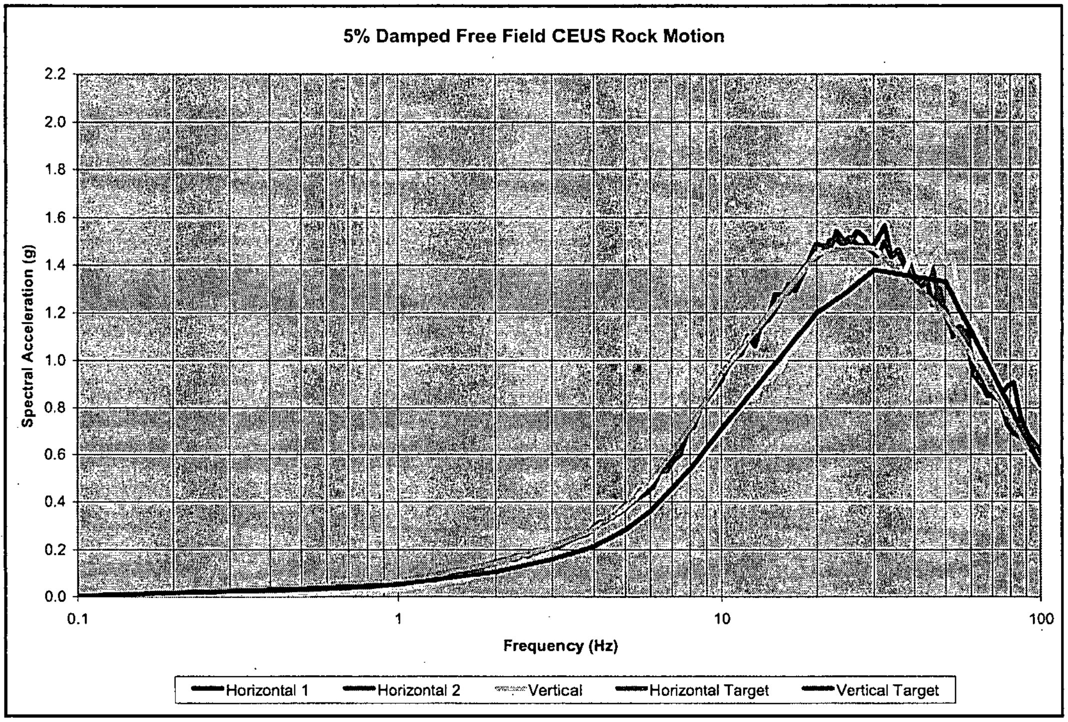

Figure 2-7
Computed and Target Response Spectra for Rock Site

Foundation Parameters

Descriptions of two advanced reactor designs (AP 1000 and ESBWR) were reviewed in order to understand the foundation and building configurations. Based on the foundation configurations presented for these two new plant designs, a rectangular foundation that is 225 x 100-ft in plan, and a square foundation that is 150 x 150-ft in plan were selected for this study. These foundations have the same plan area such that analyses will be able to demonstrate the effect of foundation shape on seismic wave incoherence effects. The benchmark comparison case between CLASSI and SASSI analyses utilized the 150-ft square foundation plan. To address the effect of foundation area, two additional square foundation footprints were considered, a 75-ft square foundation footprint, and a 300-ft square foundation footprint. The basic foundation area is 22,500 sq ft. The small foundation has one-fourth of this area and the large foundation has four times this area.

The SSI seismic analyses, by CLASSI and SASSI, were performed for the 150-ft square foundation footprint. For these analyses the foundation was assumed to be 15-ft thick. The resulting diagonal mass matrix terms are 1572 kip-sec^2/ft in the horizontal and vertical directions, 2.98 x 10^6 kip-ft-sec^2 about the horizontal axes, and 5.90 x 10^6 kip-ft-sec^2 about the vertical axes.

Structure Properties

Soil-structure interaction seismic analyses for the purpose of evaluating structure and foundation response including the effects of seismic wave incoherence has been performed using a very simple stick model of the main containment/auxiliary building based on the AP 1000 advanced reactor design (Orr, 2003). This model is illustrated in Figure 2-8 with model properties presented in Tables 2-4 and 2-5. The model consists of three concentric sticks representing the Coupled Auxiliary & Shield Building (ASB), the Steel Containment Vessel (SCV), and the Containment Internal Structure (CIS). The model has not been checked in detail against the AP 1000 model provided by R. Orr and he has commented that the fundamental frequencies differ slightly from those of the AP 1000 models. However, the model is considered to be adequate for the purposes of this study.

For CLASSI SSI seismic analyses, the structure properties input are described by the fixed base dynamic modal properties including frequencies, mode shapes and participation factors. These dynamic properties were developed using the finite element program, SAP2000 (CSI, 2004). One hundred and sixty (160) modes were included with total mass participation in each direction of about 95 percent. Fundamental frequencies for each of the three structure concentric sticks are:

- Coupled Auxiliary & Shield Building (ASB)
  - X- Horizontal – 3.2 Hz
  - Y- Horizontal – 3.0 Hz
  - Z- Vertical – 9.9 Hz
- Steel Containment Vessel (SCV)
  - X- Horizontal – 5.5 Hz, 9.5 Hz, 9.9 Hz
  - Y- Horizontal – 6.10 Hz
  - Z- Vertical – 16.0 Hz
- Containment Internal Structure (CIS)
  - X- Horizontal – 13.3 Hz, 20.1 Hz, 28.9 Hz
  - Y- Horizontal – 12.0 Hz, 14.9 Hz
  - Z- Vertical – 41.4 Hz

The mode shapes for the fundamental modes of the Coupled Auxiliary & Shield Building (ASB), the Steel Containment Vessel (SCV), and the Containment Internal Structure (CIS) in the Y-horizontal direction are shown in Figures 2-9, 2-10, and 2-11, respectively.

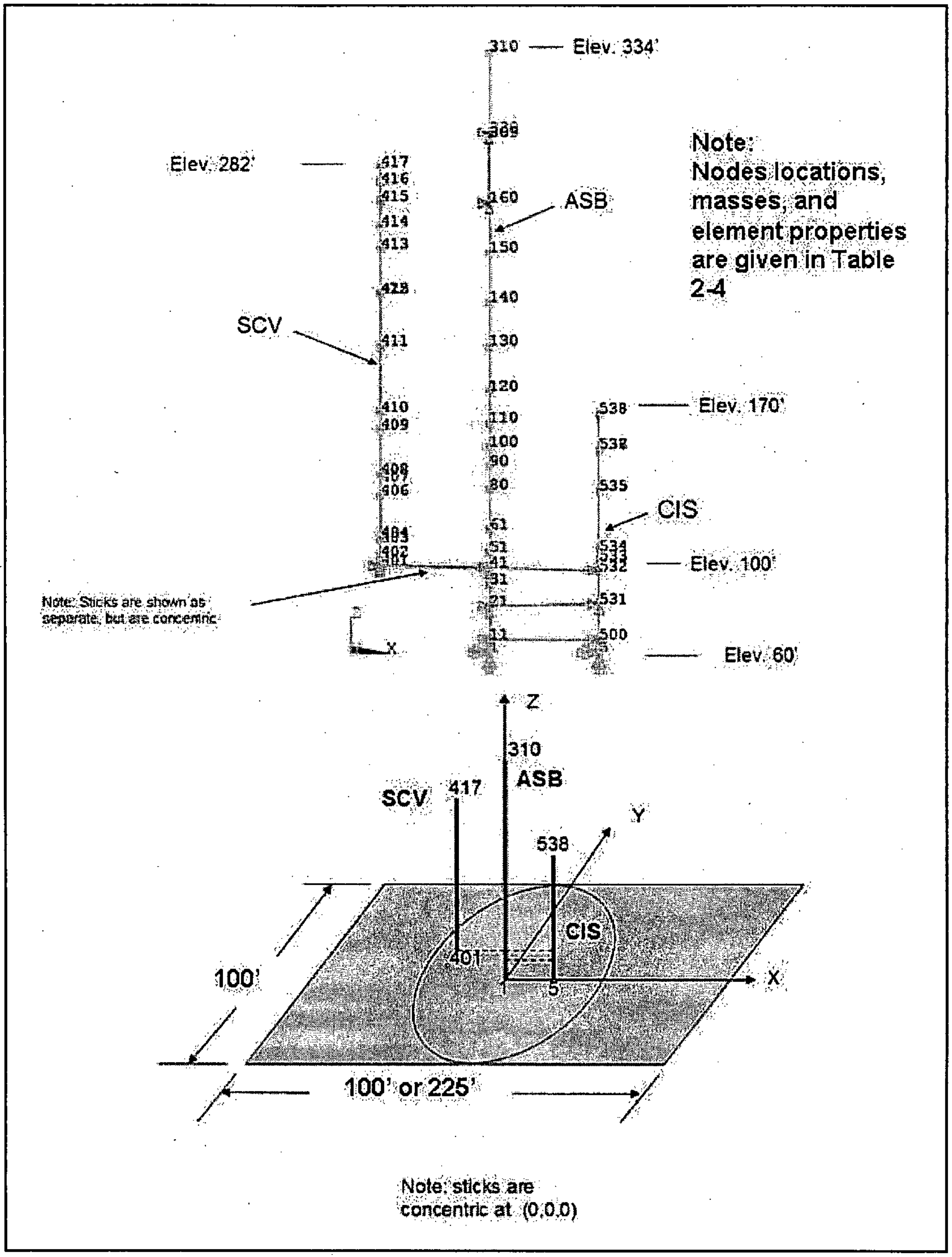

Figure 2-8
Advanced Reactor Structure Stick Model

Table 2-4
Nodes and Mass Properties for Structural Model

				North-south model			East-west model		
NODE	**X**	**Y**	**Z**	**MX**	**MZ**	**Iy**	**MY**	**MZ**	**Ix**
ASB									
1	0	0	60.50	536.980	536.980	4356000	536.980	536.980	474600
11	0	0	66.50	236.400	236.400	1641500	236.400	236.400	466740
21	0	0	81.50	494.260	494.260	3612000	494.260	494.260	847820
31	0	0	91.50	307.080	439.280	1938300	307.080	439.280	456250
41	0	0	99.00	330.460	330.460	2619900	330.460	330.460	484190
51	0	0	106.17	210.100	210.100	1287500	210.100	210.100	390700
61	0	0	116.50	597.740	465.540	2526200	597.740	465.540	764330
80	0	0	134.87	441.849	441.849	3448492	441.849	441.849	710952
90	0	0	145.37	165.406	165.406	933560	165.406	165.406	293100
100	0	0	153.98	190.099	190.099	1022510	190.099	190.099	316650
110	0	0	164.51	164.371	164.371	422680	164.371	164.371	271344
120	0	0	179.56	200.431	200.431	323582	200.431	200.431	349825
130	0	0	200.00	126.050	126.050	317710	126.050	126.050	317710
140	0	0	220.00	132.470	132.470	333900	132.470	132.470	333900
150	0	0	242.50	140.260	140.260	353540	140.260	140.260	353540
160	0	0	265.00	231.223	231.223	529020	231.223	231.223	529020
309	0	0	295.23	263.980	433.530	276470	263.980	433.530	276470
310	0	0	333.13	135.590	91.320	63050	135.590	91.320	63050
320	0	0	296.77	0.000	0.000	0	0.000	0.000	0
CIS									
5	0	0	60.5	424.2	424.2	518000	424.2	424.2	518000
500	0	0	66.5	595.3	593.4	568000	595.3	595.3	568000
531	0	0	82.5	927.6	927.6	1422000	927.6	927.6	1371000
532	0	0	98	468.7	468.7	708000	468.7	468.7	680000
533	0	0	103	146.3	286.2	185000	146.3	286.2	177000
534	0	0	107.17	319.1	238.7	358900	319.1	238.7	319130
535	0	0	134.25	298.2	238.6	282150	298.2	238.6	255550
536	0	0	153	14.6	14.6	2019	14.6	14.6	2504
537	0	0	153	30.8	30.8	6065	30.8	30.8	4321
538	0	0	169	9.4	9.4	748	9.4	9.4	696

Table 2-4 (cont.)
Nodes and Mass Properties for Structural Model

				North-south model			East-west model		
NODE	X	Y	Z	MX	MZ	Iy	MY	MZ	Ix
SCV									
401	0	0	100.000	1.739	1.739	3636	1.739	1.739	3636
402	0	0	104.125	5.541	5.541	11732	5.541	5.541	11732
403	0	0	110.500						
404	0	0	112.500	15.388	15.388	33362	15.388	15.388	33362
406	0	0	131.677	17.907	17.907	37914	17.907	17.907	37914
407	0	0	138.583						
408	0	0	141.500	17.904	17.904	38689	17.904	17.904	38689
409	0	0	162.000	18.349	18.349	38850	18.349	18.349	38850
410	0	0	169.927	28.994	28.994	61388	28.994	28.994	61388
411	0	0	200.000	28.340	28.340	60003	28.340	28.340	60003
412	0	0	224.000	40.251	51.739	81602	51.522	51.739	81602
413	0	0	224.208	15.746	15.746	33338	15.746	15.746	33338
414	0	0	255.021	11.271	11.271	21897	11.271	11.271	21897
415	0	0	265.833	10.288	10.288	14610	10.288	10.288	14610
416	0	0	273.833	10.070	10.070	8149	10.070	10.070	8149
417	0	0	281.901	5.618	5.618	0	5.618	5.618	0
425	0	0	224.000	28.439	16.951		17.168	16.951	

Note: All values are in kip, seconds, feet units

Assume:
Iz = Ix + Iy

Table 2-5
Element Properties for Structural Model

			North-south model			East-west model			
ELEM	NODES		A	IYY	AshearY	A	IZZ	AshearZ	Material	Modal damping
ASB										
1	1	11	15484.00	97176000	10322.67	15484.00	11236800	10322.67	Concrete	4 %
2	11	21	3462.50	6266240	1366.35	3462.50	4061440	1011.30	Concrete	4 %
3	21	31	3462.50	6266240	1366.35	3462.50	4061440	1011.30	Concrete	4 %
4	31	41	3462.50	6266240	1366.35	3462.50	4061440	1011.30	Concrete	4 %
5	41	51	3293.30	5744880	1214.35	3293.30	3562800	1008.14	Concrete	4 %
6	51	61	3293.30	5744880	1214.35	3293.30	3562800	1008.14	Concrete	4 %
7	61	80	3293.30	5744880	1214.35	3293.30	3562800	1008.14	Concrete	4 %
31	80	90	3197.52	4196560	1185.61	3197.52	4412370	1360.04	Concrete	4 %
32	90	100	3197.52	4196560	1185.61	3197.52	4412370	1360.04	Concrete	4 %
33	100	110	2501.52	3676560	874.54	2501.52	3311570	1121.07	Concrete	4 %
34	110	120	1954.00	3083632	810.51	1954.00	3290960	746.70	Concrete	4 %
35	120	130	1338.00	2700000	535.20	1338.00	2700000	535.20	Concrete	4 %
36	130	140	1338.00	2700000	535.20	1338.00	2700000	535.20	Concrete	4 %
37	140	150	1338.00	2700000	535.20	1338.00	2700000	535.20	Concrete	4 %
38	150	160	1338.00	2700000	535.20	1338.00	2700000	535.20	Concrete	4 %
301	160	309	50.45	1	0.000	50.45	1	0.000	Concrete	4 %
302	320	309	13.59	2680	10.872	13.59	2681.6	10.872	Concrete	4 %
303	309	310	704.50	431720	281.800	704.50	431720	281.800	Concrete	4 %
	160	320	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid		
CIS										
500	5	500	15175	1.24E+07	9228.29	15175	1.11E+07	8311.88	Concrete	4 %
501	500	531	15175	1.24E+07	9228.29	15175	1.11E+07	8311.88	Concrete	4 %
502	531	532	6732	4.50E+06	2976.99	6732	3.33E+-6	2965.86	Concrete	4 %
503	532	533	7944	6.74E+06	4411.70	7944	5.95E+06	3948.04	Concrete	4 %
504	533	534	5160	4.60E+06	3026.91	5160	2.93E+06	2702.19	Concrete	4 %
505	534	535	1705	7.83E+05	613.65	1705	5.75E+05	405.33	Concrete	4 %
506	535	536	326	3.15E+03	13.10	326	1.77E+04	67.36	Concrete	4 %
507	535	537	484	3.89E+04	93.98	484	1.58E+04	64.30	Concrete	4 %
508	537	538	164	2.11E+03	29.24	164	2.47E+03	17.16	Concrete	4 %
506	535	536	326	3.15E+03	13.10	326	1.77E+04	67.36	Concrete	4 %
507	535	537	484	3.89E+04	93.98	484	1.58E+04	64.30	Concrete	4 %
508	537	538	164	2.11E+03	29.24	164	2.47E+03	17.16	Concrete	4 %

Table 2-5 (cont.)
Element Properties for Structural Model

			North-south model			East-west model				
ELEM	**NODES**		**A**	**IYY**	**AshearY**	**A**	**IZZ**	**AshearZ**	**Material**	**Modal damping**
SCV										
401	401	402	14.49	29,107	27.6	14.49	29,107	27.6	Steel	4 %
402	402	403	59.63	126,243	29.81	59.63	126,243	29.81	Steel	4 %
403	403	404	59.63	126,243	29.81	59.63	126,243	29.81	Steel	4 %
405	404	406	59.63	126,243	29.81	59.63	126,243	29.81	Steel	4 %
406	406	407	59.63	126,243	29.81	59.63	126,243	29.81	Steel	4 %
407	407	408	59.63	126,243	29.81	59.63	126,243	29.81	Steel	4 %
408	408	409	59.63	126,243	29.81	59.63	126,243	29.81	Steel	4 %
409	409	410	59.63	126,243	29.81	59.63	126,243	29.81	Steel	4 %
410	410	411	59.63	126,243	29.81	59.63	126,243	29.81	Steel	4 %
411	411	412	59.63	126,243	29.81	59.63	126,243	29.81	Steel	4 %
412	412	413	59.63	126,243	29.81	59.63	126,243	29.81	Steel	4 %
413	413	414	13.15	110,115	27.1	13.15	110,115	27.1	Steel	4 %
414	414	415	4.58	83,714	24.6	4.58	83,714	24.6	Steel	4 %
415	415	416	1.74	46,047	19.89	1.74	46,047	19.89	Steel	4 %
416	416	417	0.55	13,850	8.56	0.55	13,850	8.56	Steel	4 %
	Spring		Kz	Kx		Kz	Ky			
	412	425	27630	80439		27630	9467			4 %

Notes:
1. All values are in kip, seconds, feet units
2. Material properties:
   Concrete:
      Elastic modulus = 519120 ksf
      Poisson's ratio = 0.17
   Steel:
      Elastic modulus = 4248000 ksf
      Poisson's ratio = 0.30

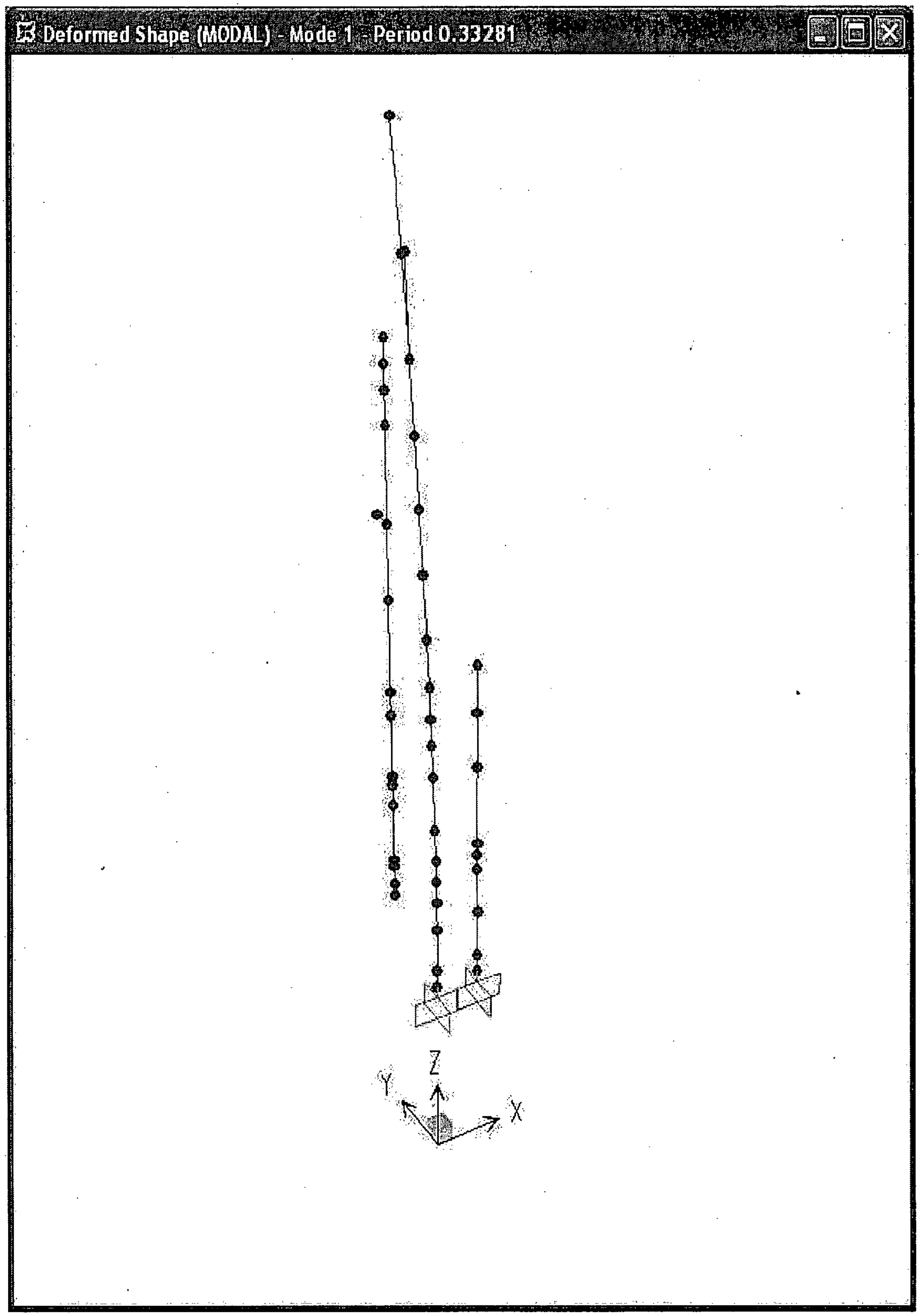

Figure 2-9
Mode 1–ASB Fundamental Mode, Y-Direction, f = 3.0 Hz

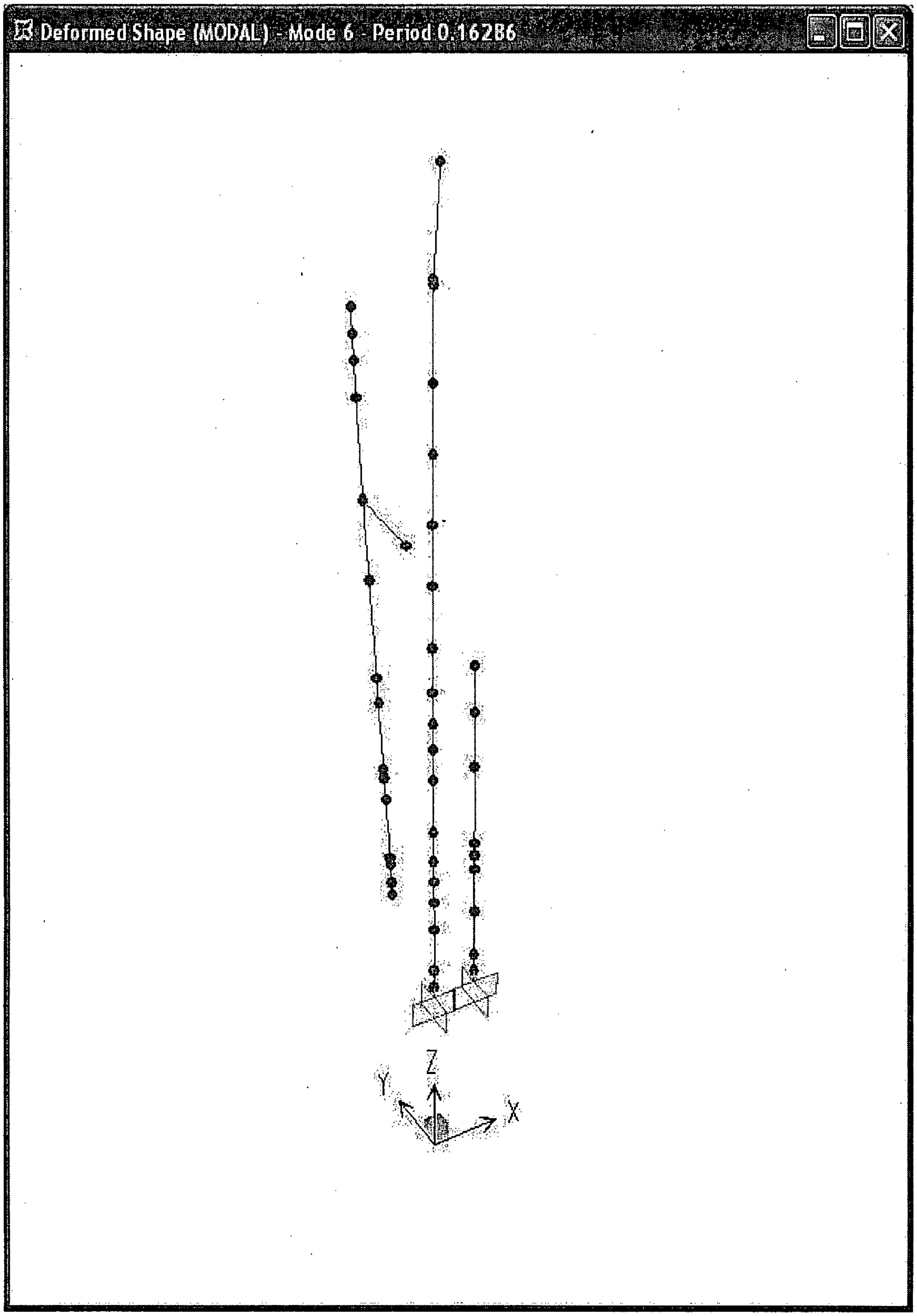

Figure 2-10
Mode 6–SCV Fundamental Mode, Y-Direction, f = 6.1 Hz

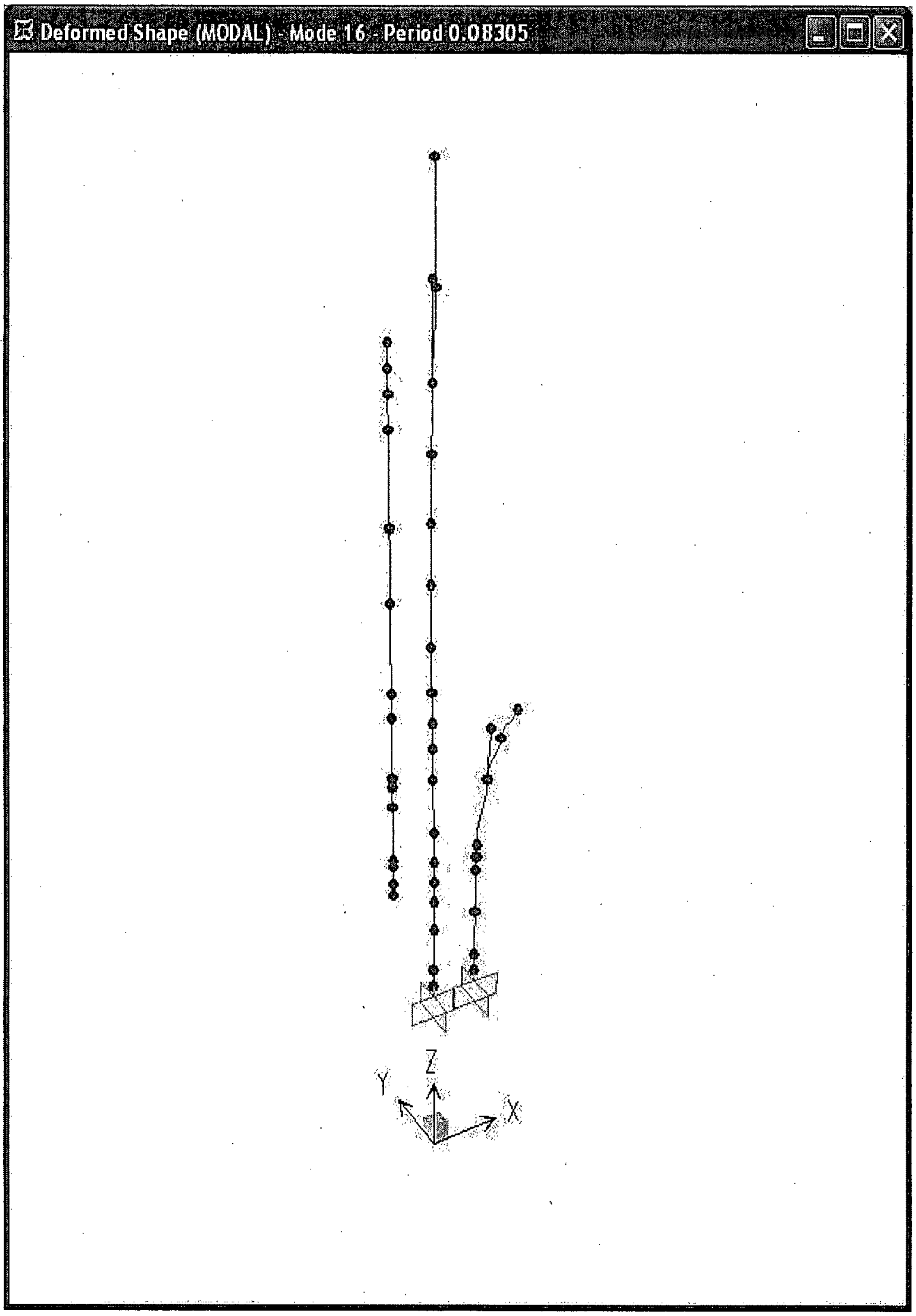

Figure 2-11
Mode 1–CIS Fundamental Mode, Y-Direction, f = 12.0 Hz

3
TECHNICAL APPROACH

General

In order to incorporate seismic wave incoherence into seismic analyses a stochastic approach has been employed as described in this chapter. This approach is described in detail in EPRI Report TR-102631 2225 (EPRI, 1997) and briefly summarized in this chapter. By this approach, incoherency transfer functions have been developed for the rigid massless foundation and validated to be appropriate by evaluating structure response for a typical NPP structure. Random vibration theory (RVT) has been employed to convert response spectra to power spectral density (PSD) functions and PSD to response spectra in order to determine spectra incoherency corrections on the rigid, massless foundation. As described in Chapter 2, coherency functions as a function of separation distance, frequency, apparent wave velocity, and direction of motion from Abrahamson, 2005 are used as the basic input for all evaluations. The incoherency transfer functions and spectra corrections have been generated for the rigid, massless foundation using the computer program, CLASSI. The ultimate goal is to be able to apply the incoherency transfer function to reduce the Fourier amplitude spectra in the free-field. The reduced Fourier amplitude spectra and the unmodified Fourier phase spectra are then processed by an inverse Fast Fourier Transform resulting in an engineering-modified input ground motion accounting for incoherency effects. This engineering-modified ground motion time history can be used in conventional SSI analyses to generate structure response that includes the effects of seismic wave incoherence. The incoherency transfer function and spectra corrections have been validated for complete SSI using CLASSI. For these latter analyses the site, foundation, and structure properties described in Chapter 2 have been used.

Procedure to Evaluate the Incoherency Transfer Function, ITF

The incoherency transfer function is determined using the computer program, CLASSI. To run CLASSI (Wong, 1980), we must first define the foundation footprint plan dimensions, underlying soil layers with properties of density, shear wave velocity, Poisson's ratio, material damping, and layer thickness, and frequencies for analysis. The foundation footprint is divided into n sub-regions for input to CLASSI. The coherency function is evaluated at the mid-point of each of these sub-regions with the separation distance being the distance between all of the combinations of sub-region mid-points.

Based on the assumption that ground motions can be represented by a stationary random process, the coherency function between ground motions $x_i(t)$ and $x_j(t)$, denoted by $\gamma(f)$, is a complex function of frequency, f, defined by:

$$\gamma(f) = \frac{S_{ij}(f)}{\sqrt{S_{ii}(f)S_{jj}(f)}} \qquad \textbf{(Equation 3-1)}$$

In which S_{ij} is the cross power spectral density function between motions $x_i(t)$ and $x_j(t)$ and S_{ii} and S_{jj} are the power spectral density functions for motions $x_i(t)$ and $x_j(t)$, respectively.

[γ] is evaluated as a 3n by 3n matrix of the Abrahamson coherency function based on the separation distances between sub-regions for each selected frequency and for input apparent wave velocity or slowness.

The incoherency transfer function, ITF(f) is equal to the amplitude of the square root of the diagonal terms of $[S_{UoI}]$ where $[S_{UoI}]$ is the 6 by 6 cross PSD matrix of rigid massless foundation motion subjected to unit PSD input.

$$[S_{UoI}] = [F]\,[S_{UGI}]\,[FC]^T \quad \textbf{(Equation 3-2)}$$

Where [F] is a 6 by 3n scattering transfer function matrix relating sub-region displacements to rigid body displacements and [FC] is the complex conjugate of [F] and $[S_{UGI}]$ is a 3n by 3n covariance matrix of incoherent ground motions for unit PSD input given by [I] [γ] [I] where [I] is an identity matrix. [F] is determined by:

$$[F] = [C]\,[T]^T \quad \textbf{(Equation 3-3)}$$

Where [C] is the 6 by 6 compliance matrix (equal to the inverse of the impedance matrix $[K]^{-1}$); and [T] is a 3n by 6 traction matrix representing contact tractions on all n sub-regions subjected to unit rigid body motions

$$[T] = [G]^{-1}\,[\alpha_b] \quad \textbf{(Equation 3-4)}$$

[G] is the 3n by 3n Green's function matrix containing responses of the foundation to unit harmonic point loads and $[\alpha_b]$ is a 3n by 6 rigid foundation mode shape matrix. One of the program modules to CLASSI uses soil profile properties to determine the Green's function. $[\alpha_b]$ is a rigid foundation mode shape matrix.

CLASSI is used to evaluate the impedance matrix [K] and the traction matrix [T] at each selected frequency. Normal outputs are impedance and scattering matrices. Also, [T], a Green's function matrix [G], and $[\alpha_b]$ are generated internally by the program. Input is the foundation footprint and the definition of sub-regions. For this study, the foundation foot print was divided into 10-ft square sub-regions. Around the periphery of the foundation, the outside 10-ft was further divided into 5-ft square sub-regions.

Based on CLASSI determined [K], [T], [G], and $[\alpha_b]$ the 6 by 6 cross PSD, $[S_{UoI}]$ of the rigid massless foundation to unit PSD input due to incoherent input motion is generated. For this purpose, the coherency matrix, [γ], the covariance matrix for unit PSD input, $[S_{UGI}]$ and the scattering transfer function, [F] are evaluated. Also, incoherency transfer function, ITF, which is equal to the amplitude of the square root of the diagonal terms of $[S_{UoI}]$ is calculated.

Procedure to Evaluate the Rigid Massless Foundation Incoherent Response Spectra

In order to evaluate the foundation response spectra for the rigid massless foundation, it is necessary to input ground motion response spectra for CEUS rock sites, [RS_o] as described in Chapter 2. These response spectra are converted to power spectral density (PSD) functions and procedures similar to that described in the previous sub-section are employed to evaluate the PSD of the foundation response. This output PSDs are then converted to response spectra.

The PSD for a component of ground response spectrum, $S_o(f)$, is evaluated by random vibration theory using computer program, PSD-RVT. Standard relationships of stationary random vibration theory are used to convert response spectra (RS) into power spectral density (PSD) functions and vice versa. To calculate a PSD from a RS, an iterative process is used. A starting PSD uniform function (white noise) is used and iterations performed until the RS calculated from the new PSD matches the target RS. To calculate a RS from a PSD, a direct integral relationship exists. Numerical integration is performed to calculate the moments of the PSD and the peak factors relating the standard deviation of the maximum response to the mean of the maximum peak response (RS). Der Kiureghian, A., "Structural Response to Stationary Excitation," Journal of the Engineering Mechanics Division, American Society of Civil Engineers, December 1980 is the basic reference followed (Der Kiureghian, 1980).

The PSD of the rigid massless foundation to actual incoherent input motion is determined using [S_{UG}], a 3n by 3n covariance matrix of actual incoherent ground motions as determined by eq. 3-5.

$$[S_{UG}] = [S_o^{1/2}]\,[\gamma]\,[S_o^{1/2}] \qquad \textbf{(Equation 3-5)}$$

where [$S_o^{1/2}$] is a 3n by 3n on-diagonal PSDF matrix on the input ground motion and $S_o(f)$ is the power spectral density of the input ground motion. The difference between [S_{UG}] and [S_{UGI}] is that [$S_o^{1/2}$] is used instead of identity matrix, [I].

[S_{Uo}], the 6 by 6 cross PSD of rigid massless foundation motion is determined from:

$$[S_{Uo}] = [F]\,[S_{UG}]\,[FC]^T \qquad \textbf{(Equation 3-6)}$$

[F] the 6 by 3n scattering transfer function matrix relating sub-region displacements to rigid body displacements and its complex conjugate [FC] are determined in exactly the same manner as described in the previous sub-section.

The response spectrum for the foundation response, [RS_{Uo}] is then determined from the PSD defined by the diagonal terms of the [S_{Uo}] matrix using the PSD to RS option of the program, PSD-RVT.

Procedure to Evaluate the Foundation and Structure Incoherent Response Spectra by Random Vibration Theory

The 6 by 6 cross PSD of foundation response motion, $[S_{UF}]$ is determined by pre-multiplying $[S_{Uo}]$, the 6 by 6 cross PSD of rigid massless foundation motion by $[H_F]$ a 6 by 6 transfer function matrix between foundation response and the scattered foundation input motions and post-multiplying by $[H_FC]$, the complex conjugate of $[H_F]$:

$$[S_{UF}] = [H_F]\,[S_{Uo}]\,[H_FC]^T \qquad \textbf{(Equation 3-7)}$$

The foundation transfer matrix is given by:

$$[H_F] = ([I]-\omega^2\,[C]\,([M_b] + [M_s(f)]))^{-1} \qquad \textbf{(Equation 3-8)}$$

In the above equation, [I] is an identity matrix, ω is the frequency of interest in radians per second, [C] is the compliance matrix previously defined, $[M_b]$ is the 6 by 6 diagonal mass matrix containing the foundation mass and mass moment of inertia, and $[M_s(f)]$ is the 6 by 6 equivalent mass matrix of the structure about its base computed by:

$$[M_s] = [\alpha_s]^T\,[M]\,[\alpha_s] + [\Gamma_s]^T\,[D(f)]\,[\Gamma_s] \qquad \textbf{(Equation 3-9)}$$

Where [D(f)] is the k by k diagonal modal amplification matrix (k is the number of fixed base structure modes) given by:

$$[D] = \left[\frac{(\omega/\omega_r)^2}{\left(1-\dfrac{\omega^2}{\omega_r^2}\right)+2i\beta_r(\omega/\omega_r)}\right] \quad \text{where r goes from 1 to k} \qquad \textbf{(Equation 3-10)}$$

$[\alpha_s]$ is a q by 6 rigid body transformation matrix of the structure about its base where q is the number of structure dynamic degrees of freedom above its base. $[\alpha_s]$ is given by:

$$[\alpha_s] = \begin{bmatrix} \cdots\cdots & & & & & \\ \cdots\cdots & & & & & \\ 1 & 0 & 0 & 0 & z^j & -y^j \\ 0 & 1 & 0 & -z^j & 0 & x^j \\ 0 & 0 & 1 & y^j & -x^j & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad \textbf{(Equation 3-11)}$$

where j goes from 1 to q, the number of structure nodes with coordinates x, y, and z. $[\Gamma_s]$ is a k by 6 matrix of modal participation factors given by:

$$[\Gamma_s] = [\phi_s]^T [M] [\alpha_s] \quad \textbf{(Equation 3-12)}$$

In which $[\phi_s]$ is the q by k fixed base mode shape matrix of the structure and [M] is the q by q structure mass matrix.

The response spectrum for the foundation response, $[RS_{UF}]$ is then determined from the PSD defined by the diagonal terms of the $[S_{UF}]$ matrix using the PSD to RS option of the program, PSD-RVT.

The q by q cross PSD of structural response motion, $[S_{Us}]$ is determined by pre-multiplying $[S_{Uo}]$, the 6 by 6 cross PSD of rigid massless foundation motion by $[H_T]$ (a q by 6 transfer function matrix between structural response and the scattered foundation input motions) and post-multiplying by $[H_TC]$, the complex conjugate of $[H_T]$:

$$[S_{Us}] = [H_T] [S_{Uo}] [H_TC]^T \quad \textbf{(Equation 3-13)}$$

The structure transfer matrix is given by:

$$[H_T] = ([\alpha_s] / [\phi_s]^T [D] [\Gamma_s]) [H_F] \quad \textbf{(Equation 3-14)}$$

Where all matrices and terms have been previously defined.

The response spectrum for the foundation response, $[RS_{Us}]$ is then determined from the PSD defined by the diagonal terms of the $[S_{Us}]$ matrix using the PSD to RS option of the program, PSD-RVT.

Procedure to Evaluate the Foundation and Structure Incoherent Response Spectra by CLASSI

The complete random vibration approach described above could have been employed herein. However, the formulation of CLASSI and its ease of use permitted implementation of a more direct approach to the SSI analysis of structure/foundation. In addition, an alternate approach by which the Fourier amplitude of the input motion is scaled by the incoherency transfer function frequency by frequency has been employed. It will be shown in a later chapter that these two approaches give the same results in terms of in-structure response spectra including seismic wave incoherence effects.

CLASSI program modules generate the complex impedance and scattering matrices at each frequency considered. The impedance matrix represents the stiffness and energy dissipation of the underlying soil medium. The foundation input motion is related to the free-field ground motion by means of a transformation defined by a scattering matrix. The term "foundation input motion" refers to the result of kinematic interaction of the foundation with the free-field ground motion. In general, the foundation input motion differs from the free-field ground motion in all cases, except for surface foundations subjected to vertically incident waves. The soil-foundation interface scatters waves because points on the foundation are constrained to move according to its geometry and stiffness. Modeling of incoherent ground motions is one aspect of this phenomena and the focus of this study.

In essence, the incoherency transfer function is the scattering matrix accounting for the effects of seismic wave incoherency over the dimensions of the foundation. For this application, a 6 by 6 complex incoherency transfer function matrix [ITF] is evaluated by taking the square root of [S_{UoI}], the 6 by 6 complex cross PSD matrix of rigid massless foundation motion to unit PSD input. The scattering matrix for vertically propagating waves is replaced by the columns of the incoherency transfer function matrix at each frequency of interest that correspond to the directions of input excitation. CLASSI SSI analyses are then performed in a conventional manner to evaluate the structure and foundation in-structure response spectra. CLASSI solves the SSI problem in the frequency domain. Ground motion time histories are transformed into the frequency domain, SSI parameters (impedances and scattering matrices) are complex-valued, frequency-dependent, and the structure is modeled using it fixed base eigensystems. SSI analyses are performed–output are time histories of response of interest from which in-structure response spectra are computed. The resulting in-structure response spectra at structure and foundation locations of interest include the effects of soil-structure interaction and seismic wave incoherence.

4
BENCHMARK PROBLEM COMPARISON

The development of incoherency transfer functions and spectral corrections for an example rigid, massless foundation has been validated by independent benchmark comparisons of results. For this purpose, the effect of incoherent ground motion has been evaluated by:

- Two different SSI computer programs; CLASSI and SASSI
- Two different algorithms; CLASSI-stochastic method and SASSI eigen decomposition method
- Two different analytical approaches; random vibration theory (RVT) by CLASSI and time history dynamic analyses by SASSI
- Two different organizations conducting the analyses; CLASSI by ARES and SASSI by Bechtel

Bechtel-SASSI results are from Ostadan, 2005. The problem considered for the benchmark comparison of the two approaches was to determine the incoherency transfer function and the response spectra for motion of a rigid, massless foundation founded on a rock half-space. Input earthquake excitation was the rock input motion for which the response spectra are shown in Figure 2-5. Other problem parameters included:

- 150 x 150-ft square foundation footprint
- 6300 fps rock shear wave velocity half-space
- Soil material damping of 1 percent

The comparison of incoherency transfer functions for both horizontal and vertical ground motion is presented in Figure 4-1. CLASSI and SASSI generated incoherency transfer functions agree within 10 percent at all frequencies.

Horizontal foundation response spectra by CLASSI and SASSI are presented in Figure 4-2 and vertical foundation response spectra by CLASSI and SASSI are presented in Figure 4-3. These spectra also agree within 10 percent at all frequencies. Both computer programs and analytical approaches demonstrate significant reductions in the foundation motion as compared to the high frequency free-field input response spectra.

The CLASSI and SASSI computer programs have been validated in accordance with the quality assurance program of each respective company. Software verification and validation have been performed by solving of example problems that exercise the features of the programs that are utilized in this study. Results are compared with results from alternative methods.

Excellent agreement is obtained for both incoherency transfer functions and spectra corrections on the foundation. The benchmark comparison is convincing validation of the technical approach being employed in Task S2.1.

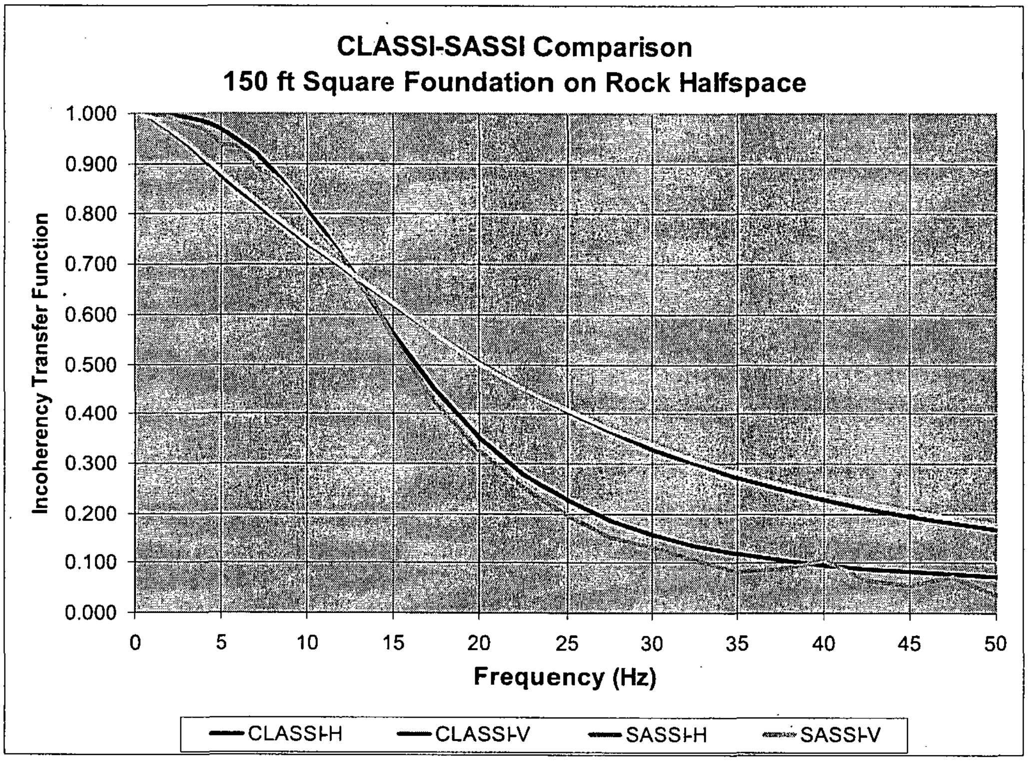

Figure 4-1
CLASSI-SASSI Comparison of Incoherency Transfer Functions

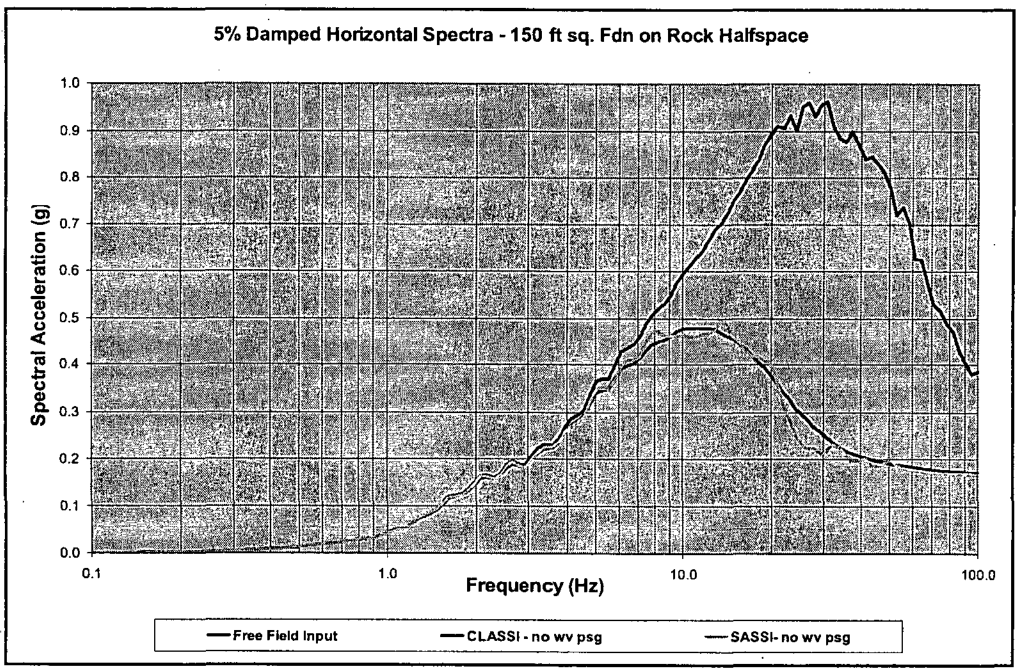

Figure 4-2
CLASSI-SASSI Comparison of Horizontal Foundation Response Spectra

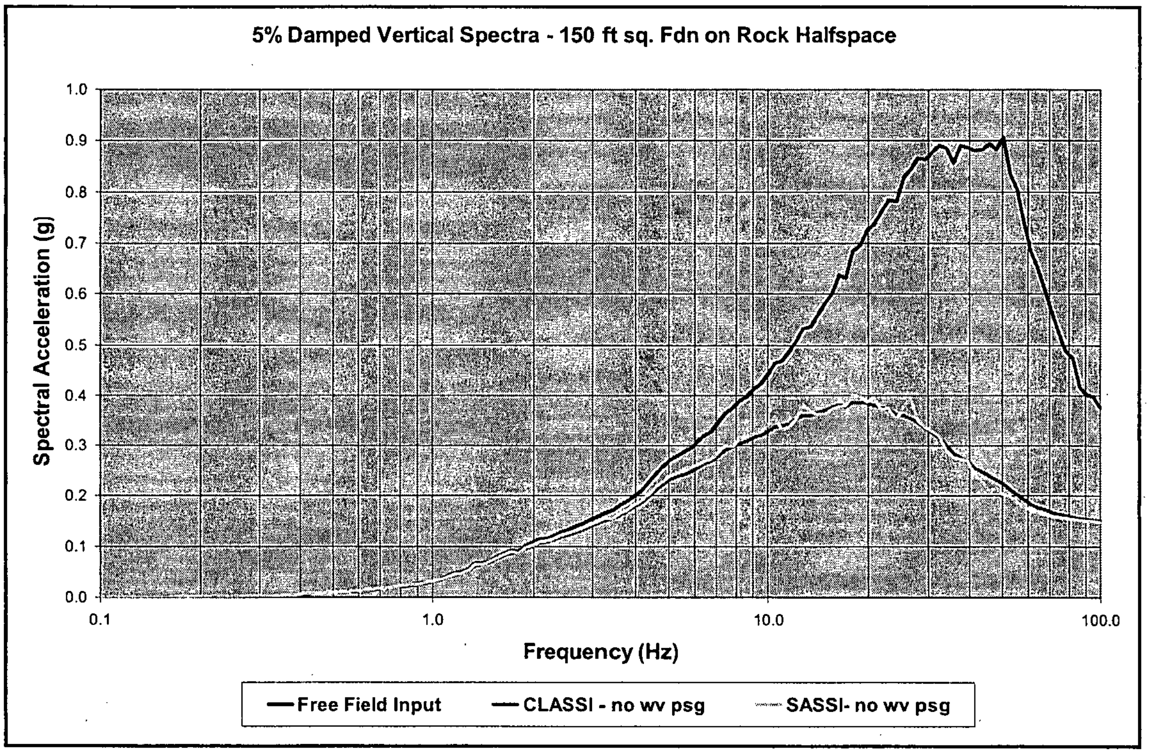

Figure 4-3
CLASSI-SASSI Comparison of Vertical Foundation Response Spectra

5
RIGID, MASSLESS FOUNDATION RESPONSE

General

The effect of seismic wave incoherence is demonstrated in this chapter for the seismic response of a rigid massless foundation. Analyses reported in this chapter represent the essence of Task 2.1 developing the incoherency transfer functions that enable the effects of incoherence to be implemented into seismic analyses.

For most analyses the soil properties and foundation areas presented in Chapter 2 are used. These properties include the rock and soil profiles along with the corresponding high and low frequency content site-specific ground response spectra. A study of the effects of wave passage phenomena was performed to separate the effects of wave passage and local wave scattering. The wave passage study was performed for the same foundation footprint and rock site condition used in the benchmark comparison analyses.

Wave Passage Effects

The Abrahamson coherency function accounts for horizontal spatial variation of ground motion from both wave passage effects and local wave scattering.

- Wave passage effects: Systematic spatial variation due to difference in arrival times of seismic waves across a foundation due to inclined waves.
- Local wave scattering: Spatial variation from scattering of waves due to the heterogeneous nature of the soil or rock along the propagation paths of the incident wave fields.

For this project, only local wave scattering of ground motion will be considered. Local wave scattering results in large reductions in foundation motion and wave passage effects produce minimal further reductions. However, to take advantage of these further reductions in foundation motion due to wave passage, an apparent wave velocity must be assigned to the site. Assigning an appropriate and defensible apparent wave velocity for wave passage effects may be controversial.

The effects of wave passage are demonstrated in terms of incoherency transfer functions and spectral corrections as shown in Figures 5-1, 5-2, 5-3, and 5-4. These results were generated for the 150-ft square foundation on a rock half-space. Wave passage analyses considered are:

- Apparent wave velocity of 2000 m/s (Slowness of 0.00050 s/m)
- Apparent wave velocity of 4000 m/s (Slowness of 0.00025 s/m)
- No wave passage effects (Apparent wave velocity = infinity - Slowness of 0 s/m)

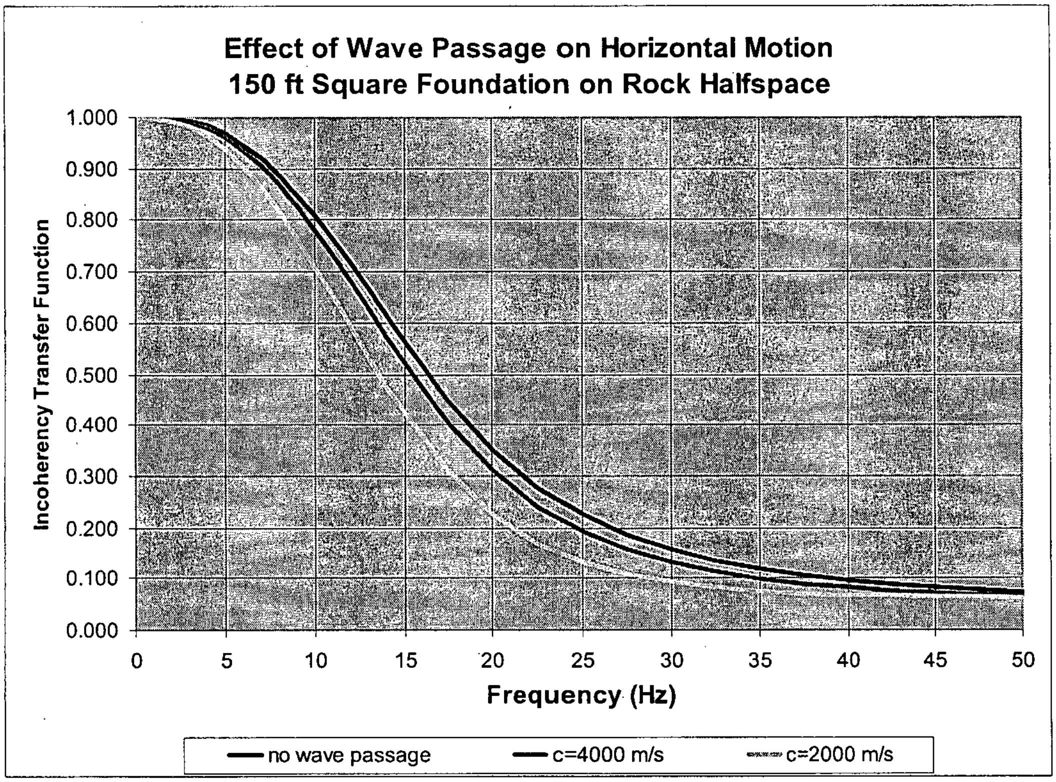

Figure 5-1
Effect of Wave Passage on Incoherency Transfer Function for Horizontal Motion

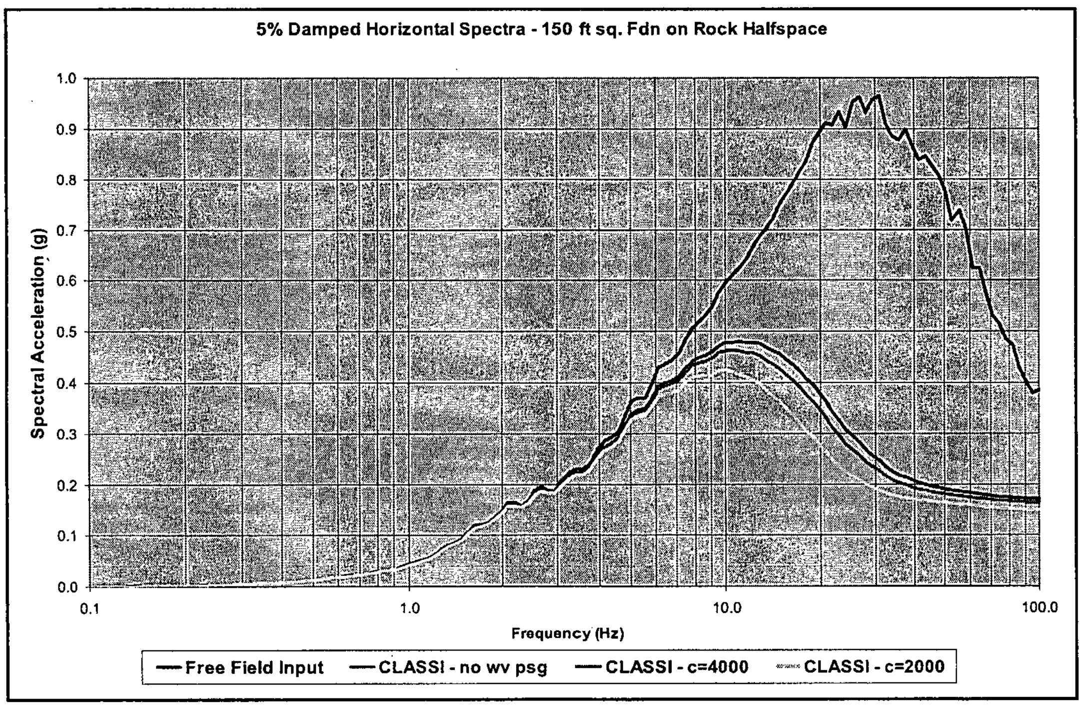

Figure 5-2
Effect of Wave Passage on Foundation Horizontal Response Spectra

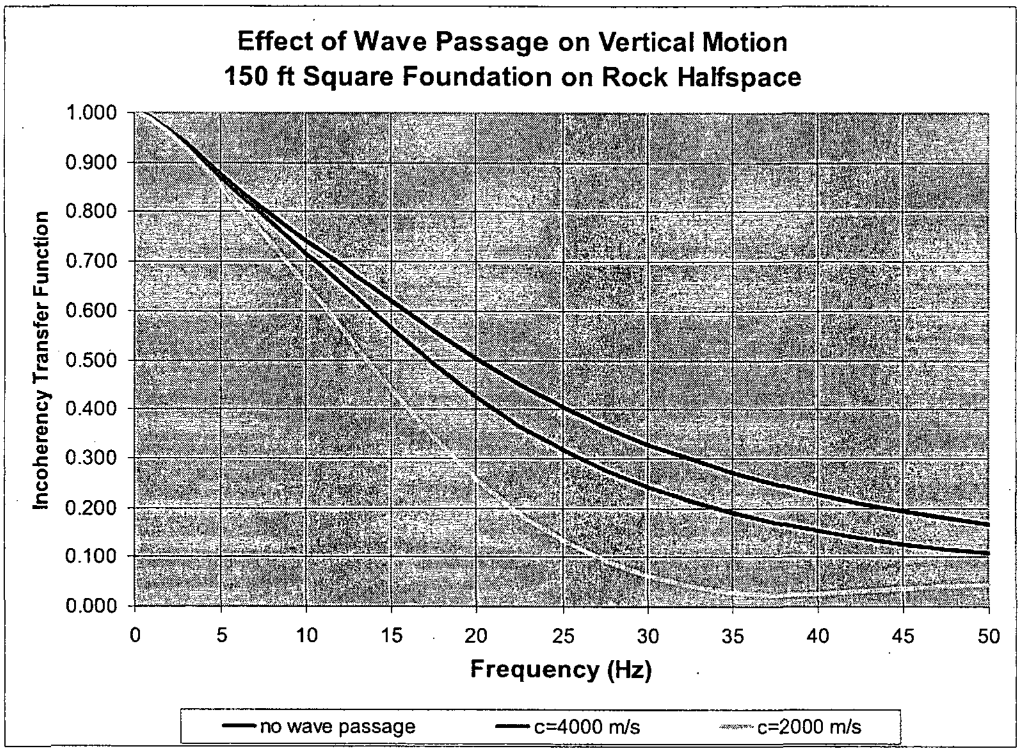

Figure 5-3
Effect of Wave Passage on Incoherency Transfer Function for Vertical Motion

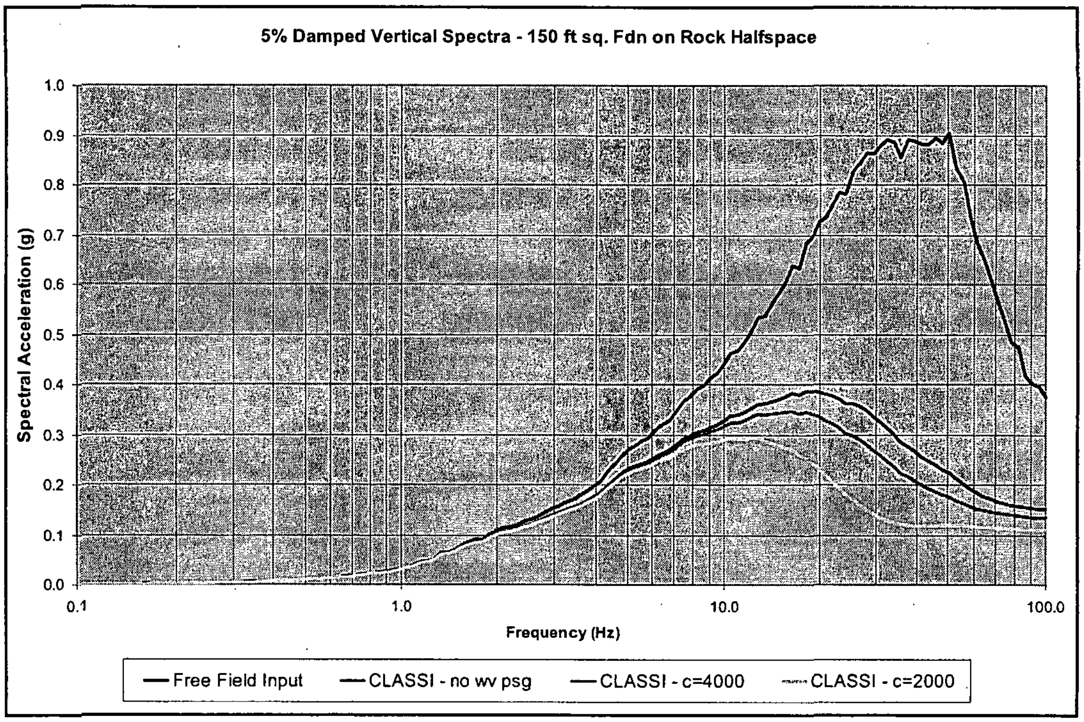

Figure 5-4
Effect of Wave Passage on Foundation Vertical Response Spectra

Incoherency Transfer Function

Incoherency transfer functions or wave scattering due to seismic wave incoherence have been computed in the manner described in Chapter 3. The incoherency transfer function demonstrates the effects of seismic wave incoherence as a function of frequency for the foundation footprint considered. Incoherency transfer functions have been developed for both the rock and soil site profiles described in Chapter 2. Parametric studies have been performed for:

- Foundation Shape, (Constant Area)
  - 150-ft square footprint
  - 100 by 225-ft rectangle footprint
- Foundation Area (Constant Shape)
  - 75-ft square footprint
  - 150-ft square footprint
  - 300-ft square footprint

Calculations have been performed for local wave scattering effects only; wave passage effects have not been considered.

Foundation shape. For the rock site, the effects of foundation shape on the incoherency transfer functions are shown in Figures 5-5 and 5-6 for the horizontal and vertical directions, respectively. For the soil site, the same comparisons are shown in Figures 5-7 and 5-8. On these figures, the lines of different colors lie on top of each other so only one color is visible. The conclusion is that for these variations in foundation shape, i.e., square vs. rectangular (with reasonable aspect ratio of 2:1), the incoherency transfer function is independent of foundation shape. This conclusion applies only to the foundation shapes considered in this study and may change when foundations of different shapes (e.g., L shape) or larger aspect ratios are considered.

Foundation area. The effect of foundation area on the incoherency transfer function is presented in Figures 5-9 and 5-10 for the rock site, and Figures 5-11 and 5-12 for the soil site. Square foundation footprints with area varying by a factor of 4 are considered. Although the variation on the plots appears small, the actual difference amounts to about 30 to 45 percent for an area difference of a factor of 4. Going from the 75-ft square foundation footprint to the 300-ft square foundation footprint results in an increased reduction from about 0.45 at 20 Hz and 0.23 at 30 Hz to about 0.27 at 20 Hz and 0.12 at 30 Hz.

Soil profile. The effect of soil profile on the incoherency transfer function is illustrated in Figures 5-13 and 5-14 for horizontal and vertical ground motion, respectively. From these figures, it may be seen that the incoherency transfer function and hence the effect of seismic wave incoherence are independent of the site profile. The incoherency transfer functions are essentially identical at all frequencies for soil and rock.

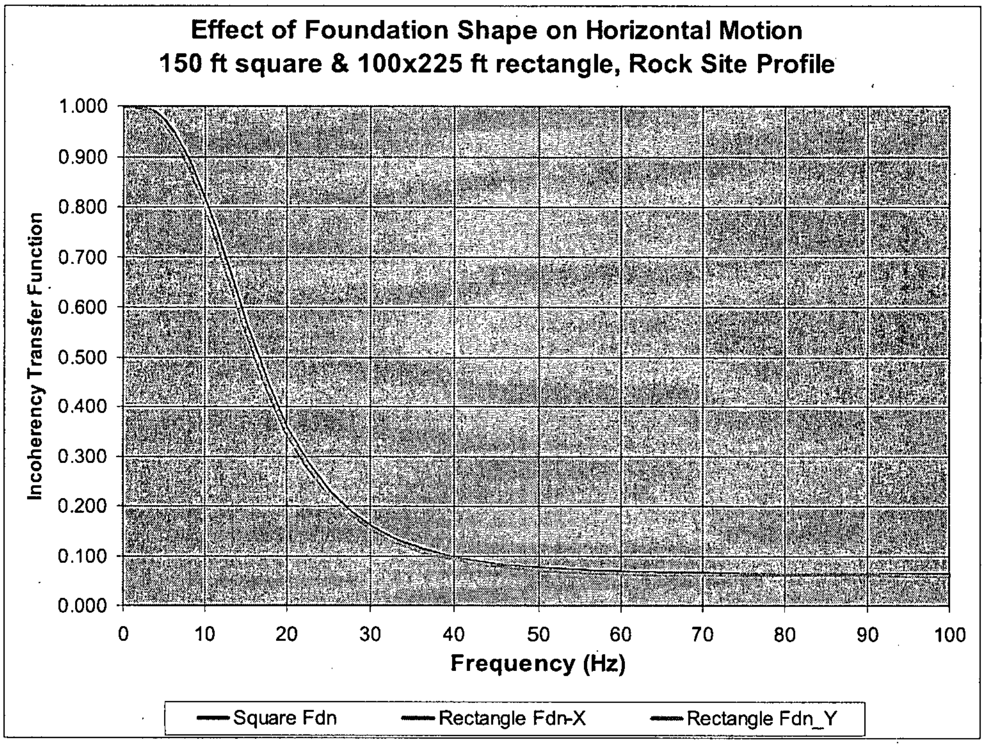

Figure 5-5
Horizontal Motion Incoherency Transfer Function, Rock Site–Effect of Foundation Shape

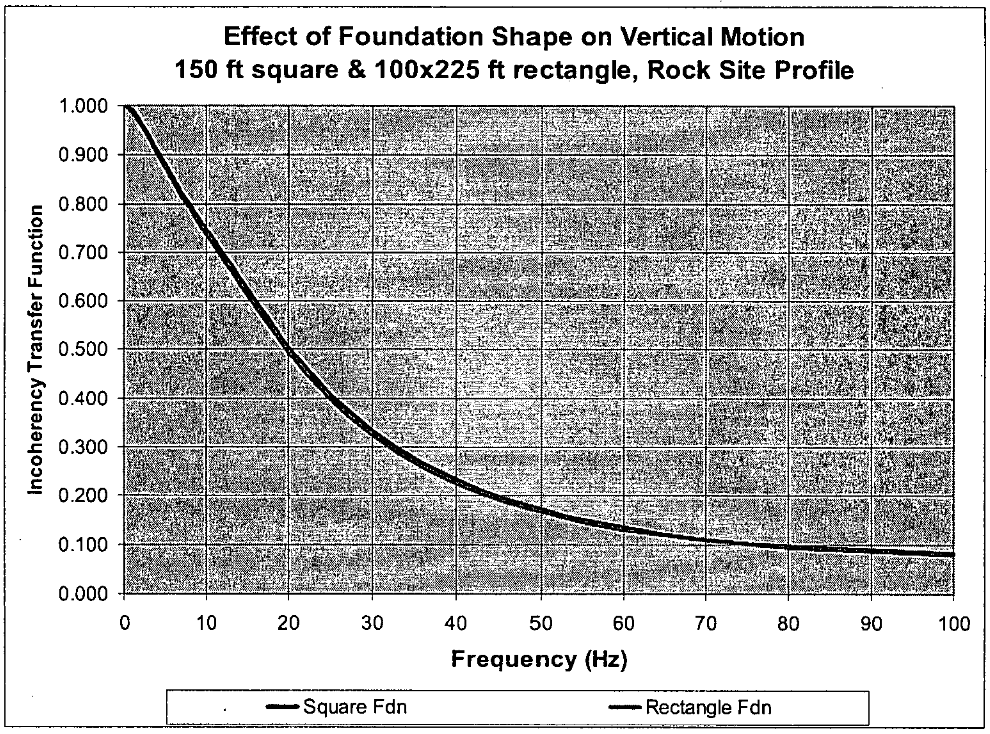

Figure 5-6
Vertical Motion Incoherency Transfer Function, Rock Site–Effect of Foundation Shape

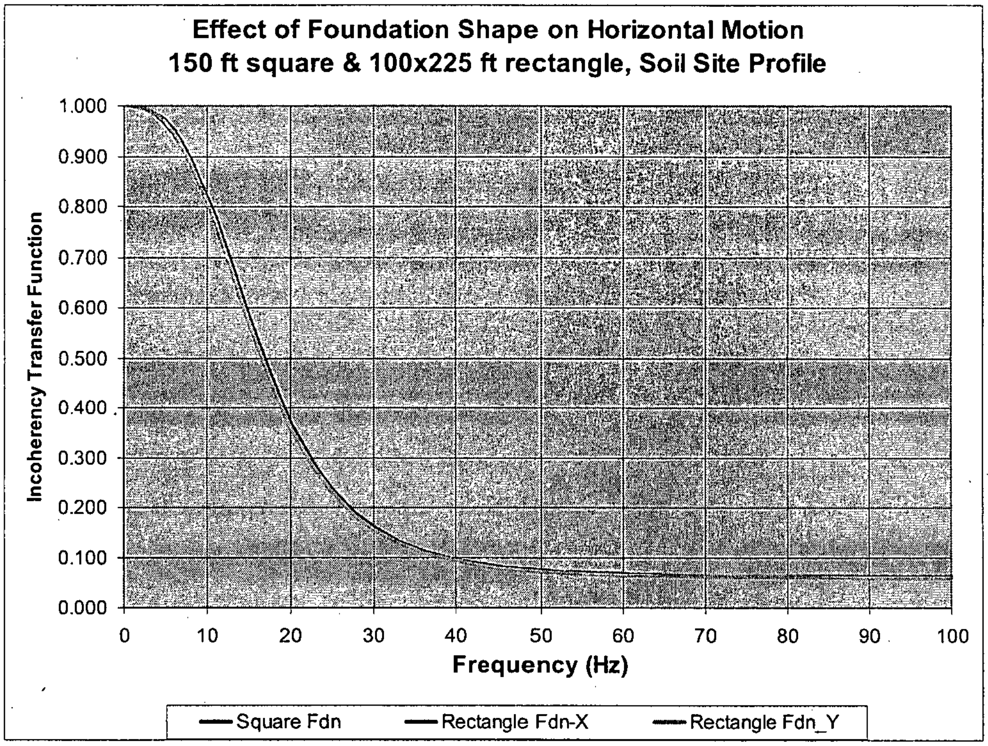

Figure 5-7
Horizontal Motion Incoherency Transfer Function, Soil Site–Effect of Foundation Shape

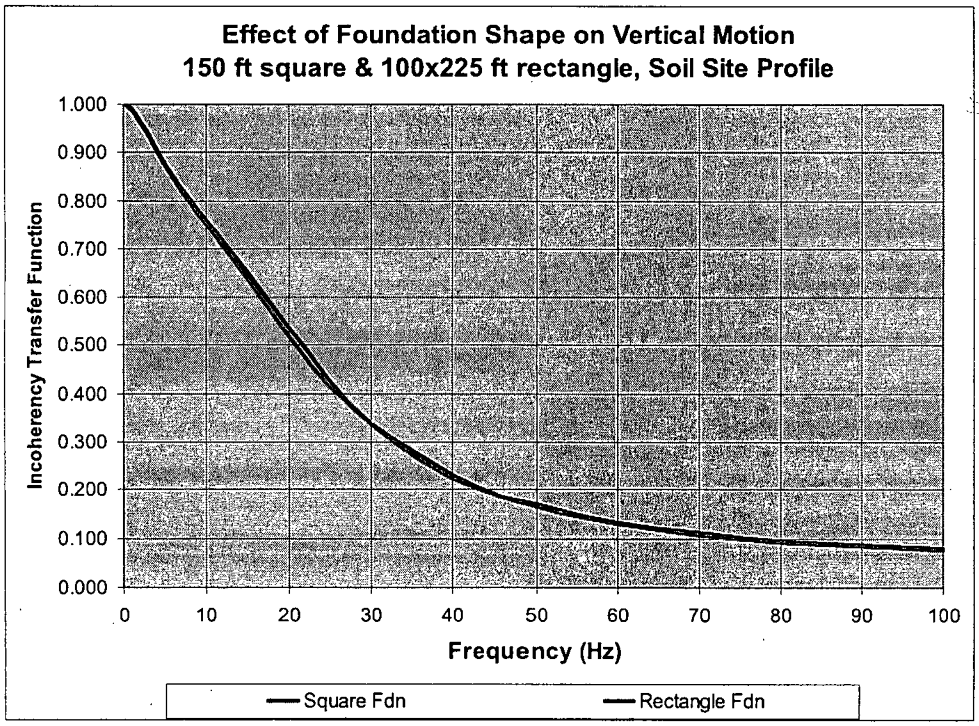

Figure 5-8
Vertical Motion Incoherency Transfer Function, Soil Site–Effect of Foundation Shape

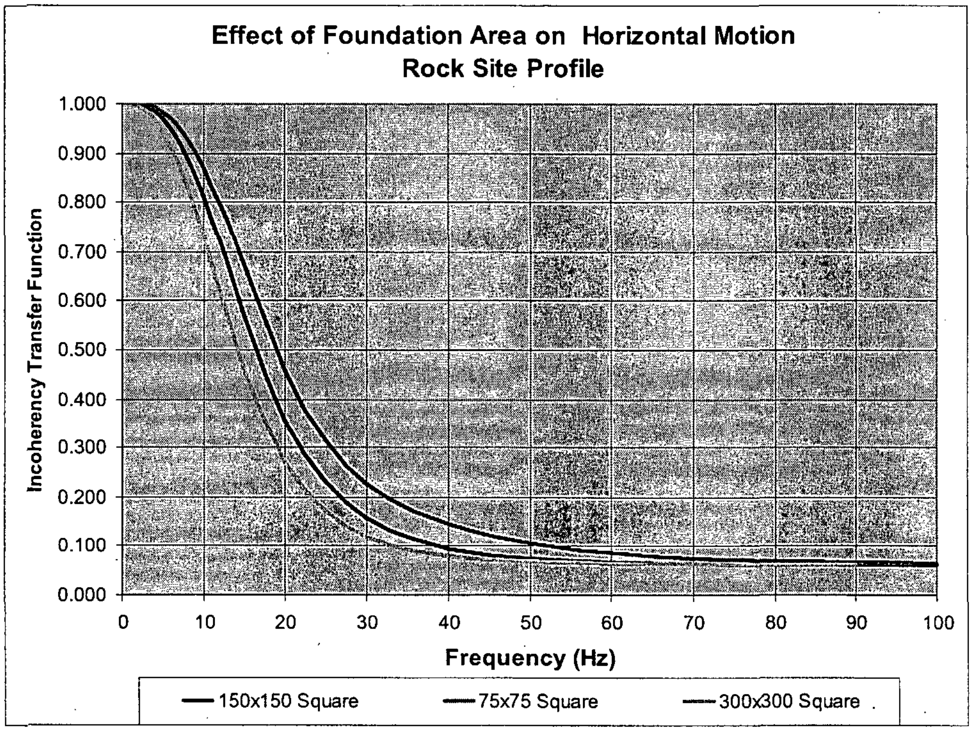

Figure 5-9
Horizontal Motion Incoherency Transfer Function, Rock Site–Effect of Foundation Area

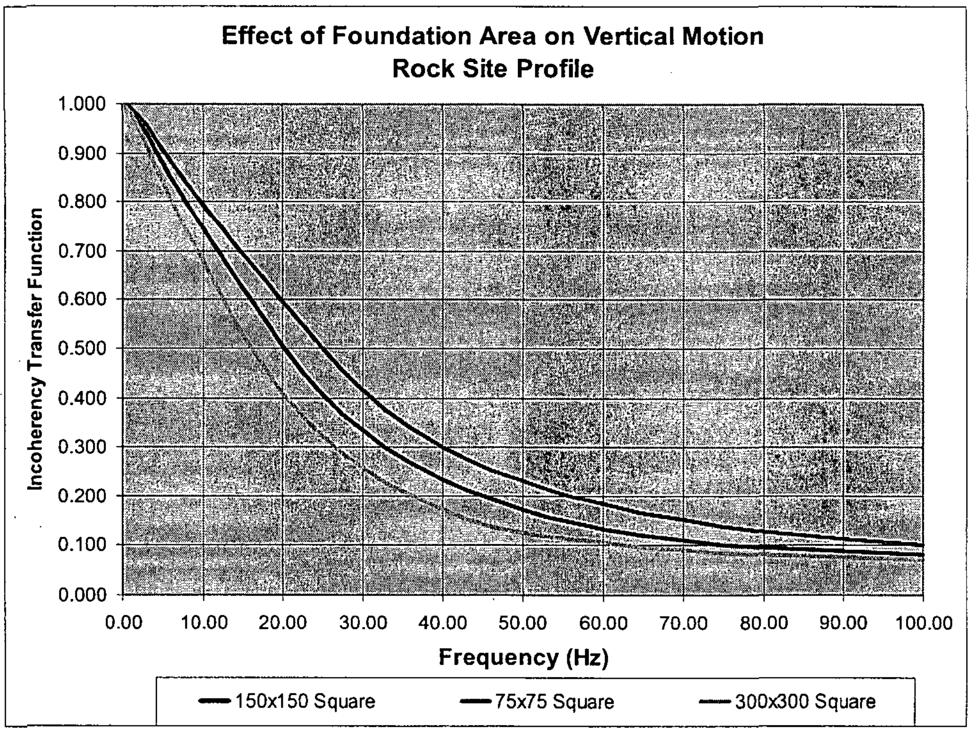

Figure 5-10
Vertical Motion Incoherency Transfer Function, Rock Site–Effect of Foundation Area

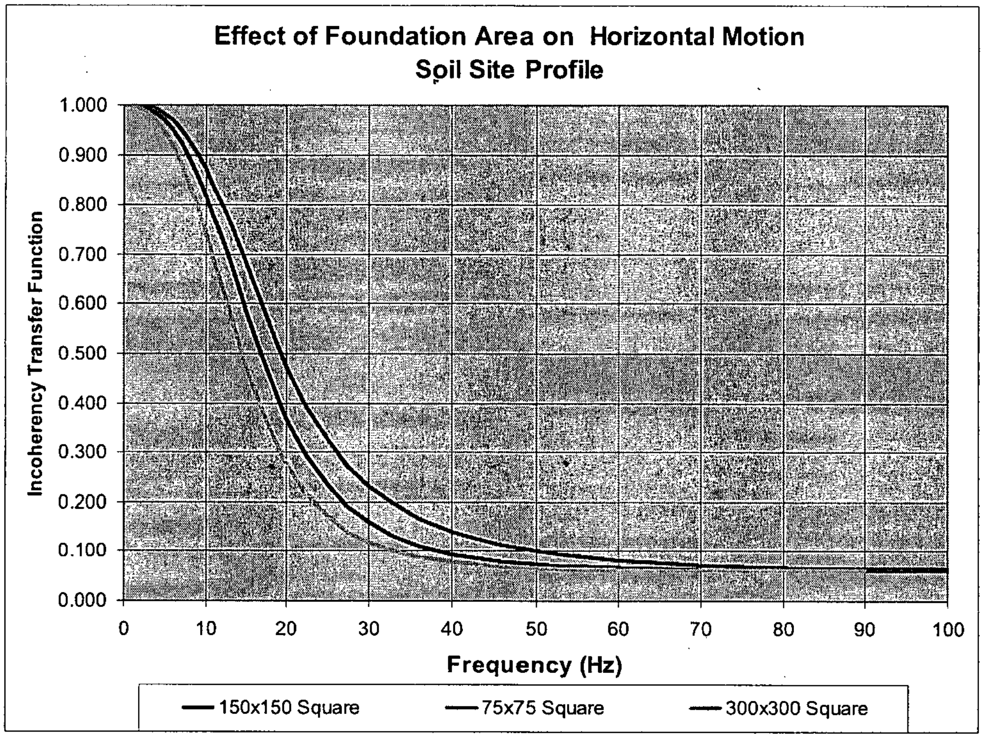

Figure 5-11
Horizontal Motion Incoherency Transfer Function, Soil Site–Effect of Foundation Area

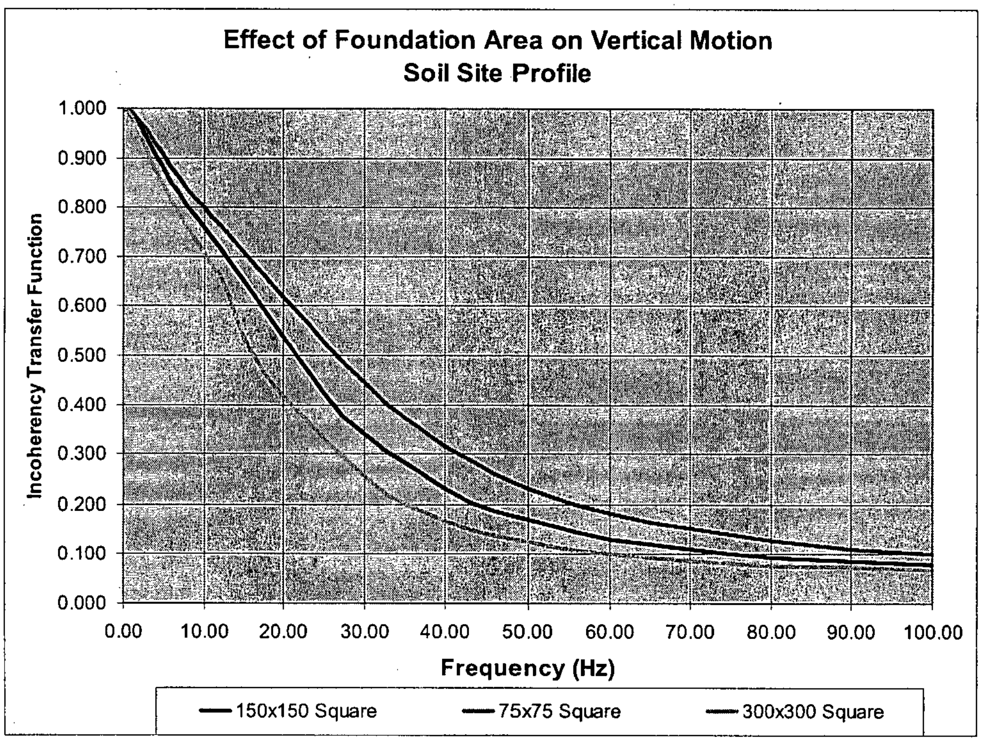

Figure 5-12
Vertical Motion Incoherency Transfer Function, Soil Site–Effect of Foundation Area

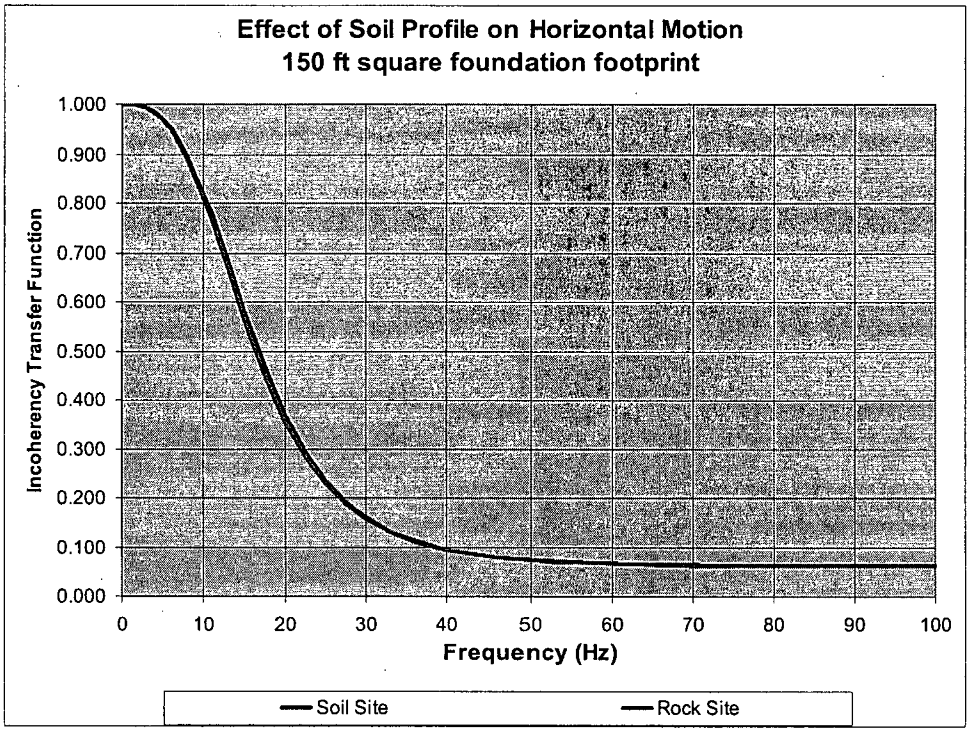

Figure 5-13
Horizontal Motion Incoherency Transfer Function–Effect of Soil Profile

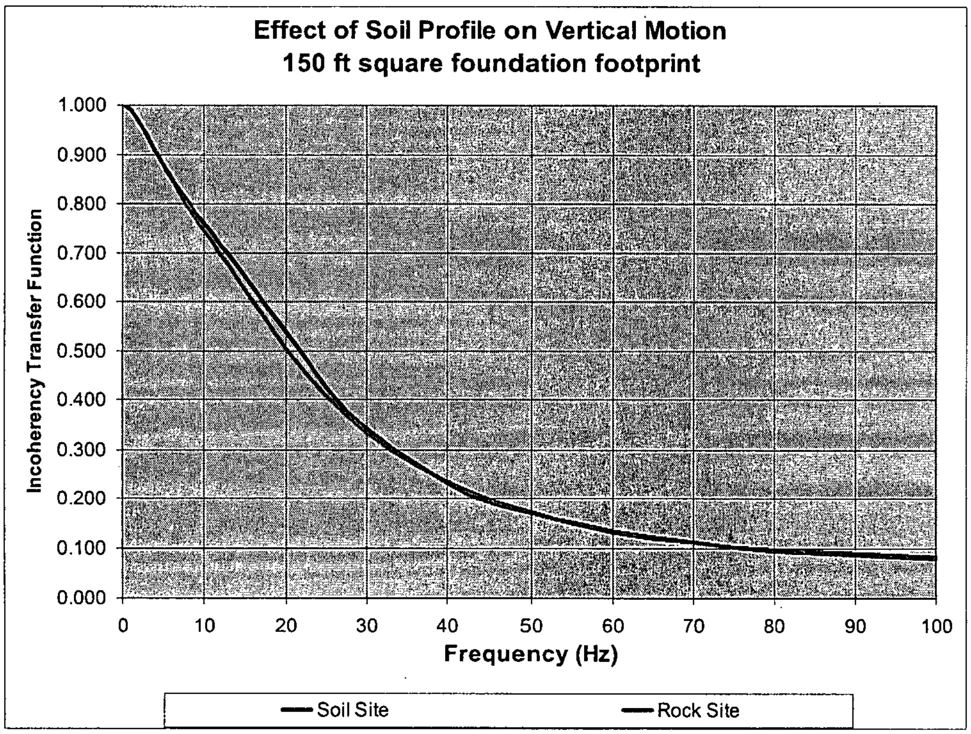

Figure 5-14
Vertical Motion Incoherency Transfer Function–Effect of Soil Profile

Spectral Corrections

Foundation response spectra accounting for seismic wave incoherence have been computed in the manner described in Chapter 3. By this approach, the PSD is computed from the response spectra of the free-field input motion and input to CLASSI. The program then evaluates the PSD of the foundation motion including the effects of seismic wave incoherence. The resulting response PSD is then converted to foundation response spectra by random vibration theory. Foundation response spectra have been developed for both the rock and soil site profiles described in Chapter 2 using the compatible free-field high frequency rock and lower frequency soil ground response spectra, respectively. Parametric studies have been performed for:

- Foundation Shape, (Constant Area)
  - 150-ft square footprint
  - 100 by 225-ft rectangle footprint
- Foundation Area (Constant Shape)
  - 75-ft square footprint
  - 150-ft square footprint
  - 300-ft square footprint

Results are shown in Figures 5-15 through 5-18.

Rock site. Figures 5-15 and 5-16 display response spectra for free-field ground motion and foundation response for the rock site. Figure 5-15 shows horizontal motion; Figure 5-16 shows vertical motion. Two free-field ground motion response spectra are plotted: the site-specific ground response spectra for the rock site and for reference, the US NRC Regulatory Guide 1.60 design response spectra (modified in the high frequency region) anchored to a Peak Ground Acceleration of 0.3g (call the AP 1000 SSE in the figures). Foundation response spectra for the four cases listed above are super-imposed on the free-field ground motion. It may be seen from these figures that the foundation spectra for the 150-ft square footprint and the 100 by 225-ft rectangle footprint are the same as would be expected since the incoherency transfer functions are the same. These figures also show the effects of foundation area on response spectra for the 75-ft, 150-ft, and 300-ft square foundation footprint.

Soil site. Figures 5-17 and 5-18 display response spectra for the soil site in a similar manner to the data shown in Figures 5-15 and 5-16 for the rock site. Note, however that the site-specific free-field ground motion is significantly different than the site-specific rock motion. The same comparisons of foundation response spectra for the soil site are made. Note, there are reductions in response spectral values due to incoherence, but the most significant of those occurs in the frequency range above 10 Hz. The response spectra reductions as a function of foundation area are much more significant for the rock site than for the soil site. The effect of seismic wave incoherence is primarily a high frequency phenomenon. Hence, the observed reductions in foundation response spectra are much less for the soil site since the soil site-specific ground motion is deficient in high frequencies. For the rock site, the peak of the horizontal spectra is reduced from 0.85g for the 75-ft square foundation to 0.76g for the 150-ft square foundation to 0.67g for the 300-ft square foundation. All of these peak spectra values are much less than the 1.48g peak of the free-field input spectra in the horizontal direction. Similar behavior is observed for the vertical ground motion.

Approximate Treatment of Incoherency of Ground Motions. Spectral corrections taken from the figures are shown in Tables 5-1 and 5-2 for horizontal and vertical motion, respectively, along with the spectral corrections that are given in ASCE 4. Reductions are shown for the foundation dimension of 75, 150, or 300 feet. It may be seen that spectral reductions are significantly greater than the ASCE 4 values for the rock site but are actually somewhat similar for the soil site. This demonstrates that spectral reductions are not a proper way to account for seismic wave incoherence as they strongly depend on the frequency content of the free-field input ground response spectra. An approach based on the incoherency transfer function (ITF) as proposed in this report is appropriate because the function is independent of the input motion.

Table 5-1
Spectral Corrections for Horizontal Motion

Frequency	ASCE 4		Rock-H			Soil-H		
	150	300	75	150	300	75	150	300
5.00	1.00	1.00	0.95	0.93	0.89	0.98	0.97	0.95
10.00	0.90	0.80	0.84	0.78	0.71	0.90	0.85	0.79
15.00	0.86	0.71	0.68	0.59	0.49	0.78	0.71	0.63
20.00	0.82	0.65	0.50	0.41	0.33	0.68	0.62	0.56
25.00	0.80	0.60	0.38	0.30	0.24	0.64	0.60	0.55
30.00	0.80	0.60	0.32	0.25	0.20	0.64	0.60	0.56
40.00	0.80	0.60	0.27	0.22	0.19	0.65	0.62	0.59
50.00	0.80	0.60	0.26	0.22	0.19	0.68	0.66	0.63

Table 5-2
Spectral Corrections for Vertical Motion

Frequency	ASCE 4		Rock-V			Soil-V		
	150	300	75	150	300	75	150	300
5.00	1.00	1.00	0.88	0.85	0.80	0.91	0.89	0.86
10.00	0.90	0.80	0.78	0.73	0.66	0.83	0.79	0.74
15.00	0.86	0.71	0.69	0.62	0.54	0.76	0.71	0.62
20.00	0.82	0.65	0.61	0.52	0.43	0.69	0.63	0.54
25.00	0.80	0.60	0.53	0.44	0.36	0.64	0.57	0.50
30.00	0.80	0.60	0.46	0.38	0.30	0.59	0.52	0.46
40.00	0.80	0.60	0.36	0.29	0.23	0.53	0.48	0.43
50.00	0.80	0.60	0.31	0.25	0.20	0.50	0.46	0.42

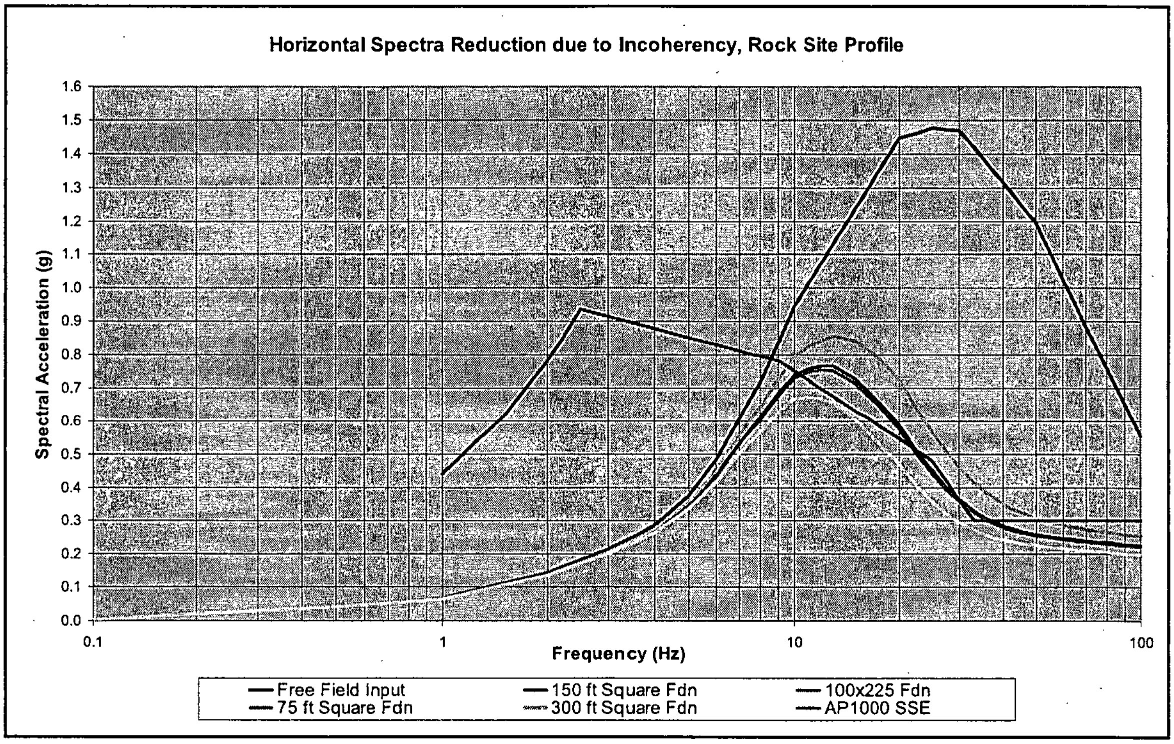

Figure 5-15
Horizontal Motion Foundation Response Spectra, Rock Site

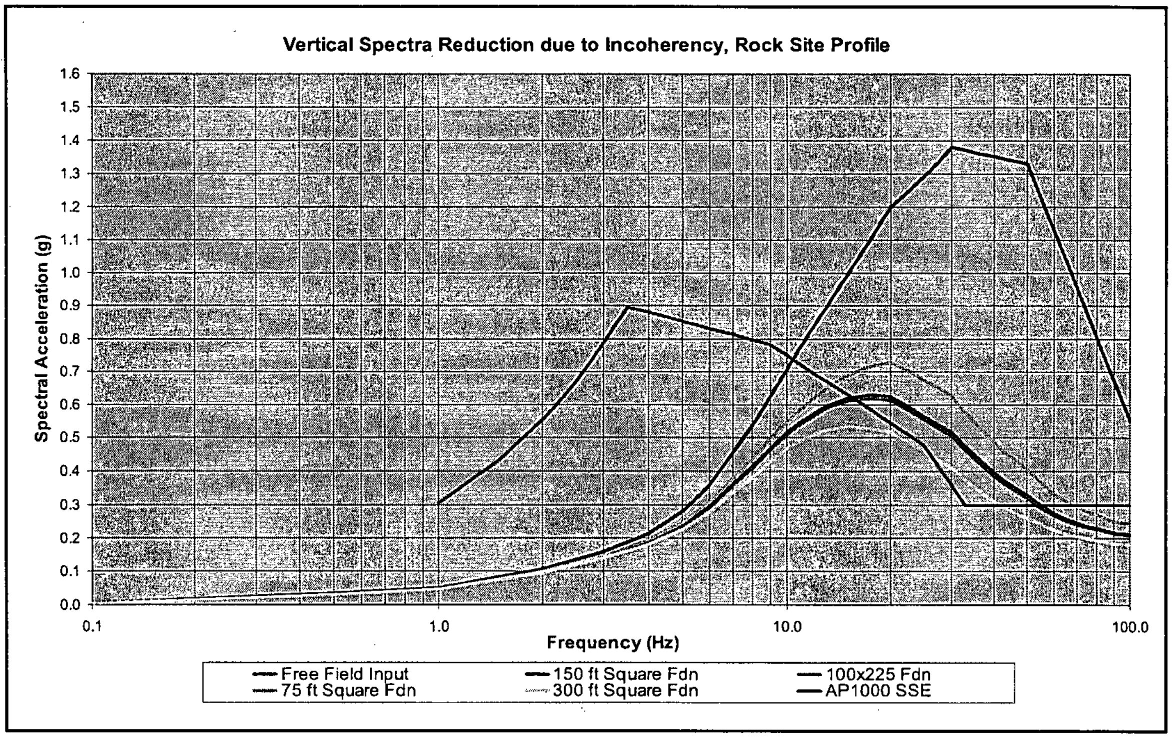

Figure 5-16
Vertical Motion Foundation Response Spectra, Rock Site

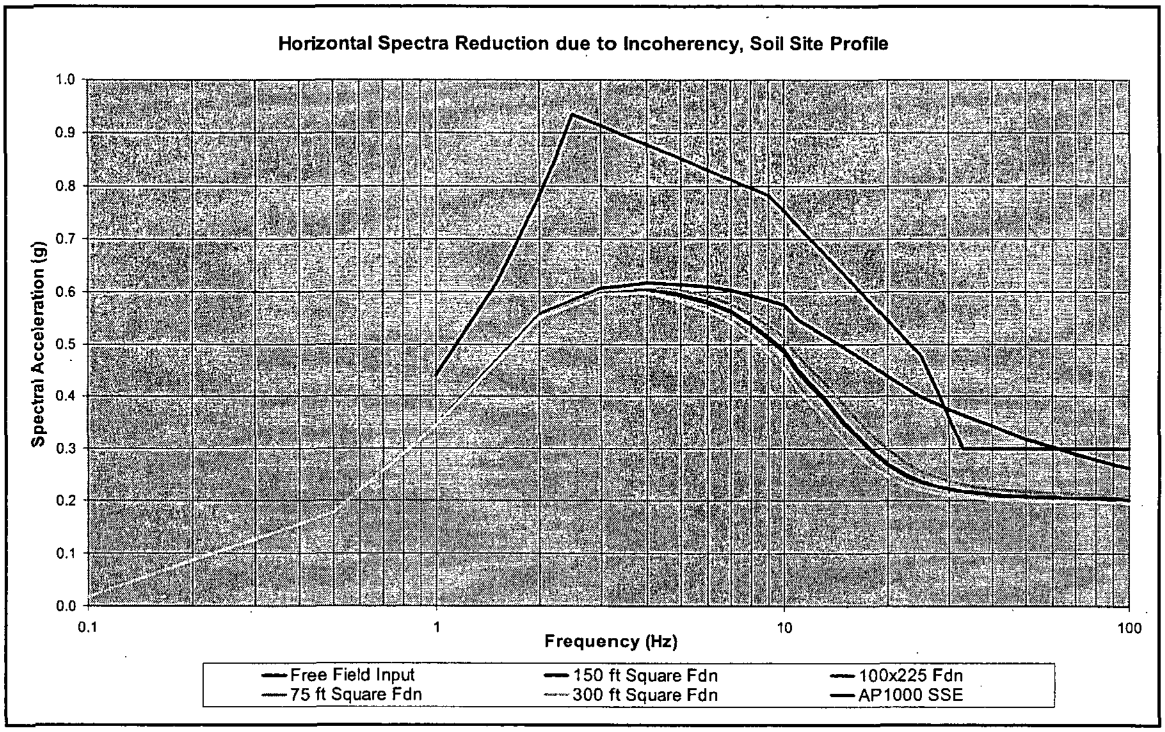

Figure 5-17
Horizontal Motion Foundation Response Spectra, Soil Site

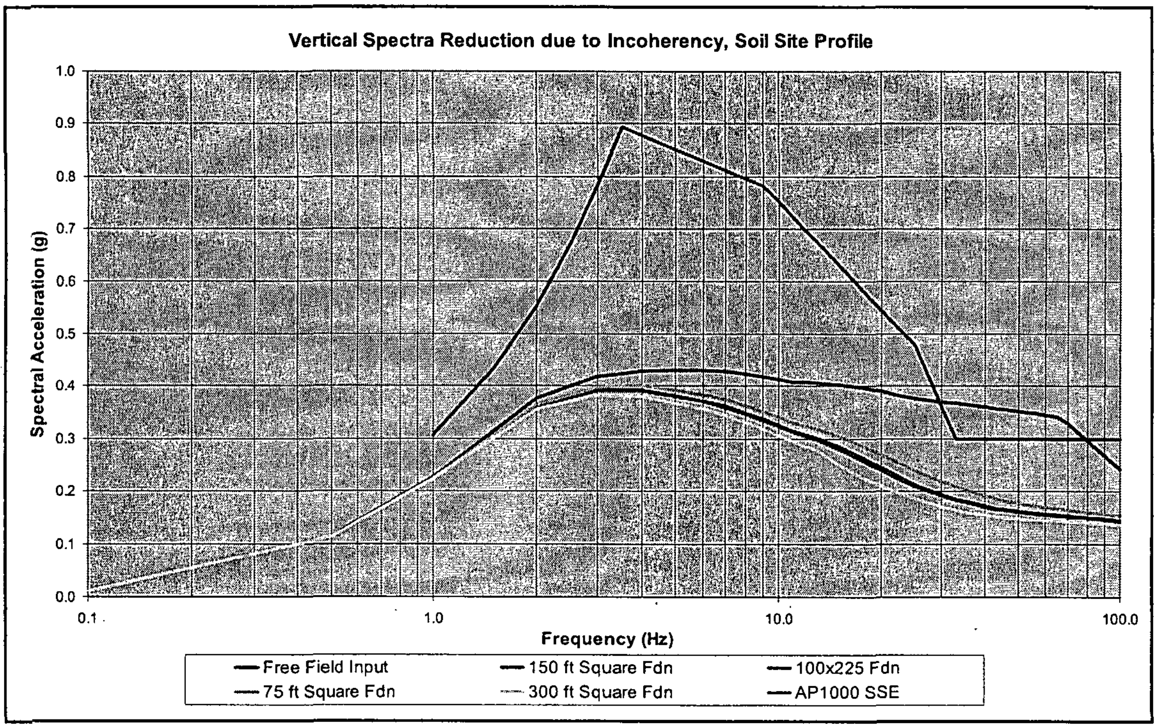

Figure 5-18
Vertical Motion Foundation Response Spectra, Soil Site

6
SSI & STRUCTURE RESPONSE

General

The purpose of this project is to develop a simplified method to incorporate seismic wave incoherence into seismic analysis of NPP structures including soil-structure interaction (SSI). Analyses described in this chapter are performed to demonstrate that the approach of multiplying the Fourier amplitude of the input ground motion by the incoherency transfer function (ITF) to form an engineering modified input motion gives accurate seismic response including incoherency effects. For this purpose, four analyses have been performed using the AP 1000 structural model described in Chapter 2:

1. Fixed base analysis
2. SSI analysis with coherent input motion
3. SSI analysis with incoherent input motion
4. SSI analysis with input motion modified by incoherency transfer function

All four analyses were performed using the computer program CLASSI. The rock site profile described in Chapter 2 was used for Analyses 2, 3, and 4. For all analyses, the spectrum compatible time history for the high frequency rock site response spectra was used. This time history and a comparison of calculated and target response spectra are described in Chapter 2. For Analyses 2, 3, and 4, the very simplified AP 1000 structural model was supported by a 15-ft thick concrete foundation mat with 150-ft square plan dimensions.

SSI and Incoherence – Direct Method

The results of Analyses 1, 2, and 3 are presented here including fixed base, SSI coherent, and SSI incoherent. The SSI incoherent analyses incorporate seismic wave incoherency through the scattering matrix populated by the incoherency transfer functions generated for the rock site and for the rigid massless foundation of 150-ft square. In this manner, incoherence is directly incorporated into the seismic analysis.

As presented in Chapter 2, fundamental frequencies for each of the three structure concentric sticks modeled as fixed base are:

- Coupled Auxiliary & Shield Building (ASB)
  - X- Horizontal – 3.2 Hz
  - Y- Horizontal – 3.0 Hz
  - Z- Vertical – 9.9 Hz
- Steel Containment Vessel (SCV)
  - X- Horizontal – 5.5 Hz, 9.5 Hz, 9.9 Hz
  - Y- Horizontal – 6.10 Hz

- Z- Vertical – 16.0 Hz

- Containment Internal Structure (CIS)
    - X- Horizontal – 13.3 Hz, 20.1 Hz, 28.9 Hz
    - Y- Horizontal – 12.0 Hz, 14.9 Hz
    - Z- Vertical – 41.4 Hz

Results presented are in-structure response spectra at the foundation and at the top of each of the three models, ASB, SCV, and CIS. In-structure response spectra at these four locations for two horizontal, X and Y, and the vertical direction, Z of ground motion are presented in Figures 6-1 through 6-12.

Foundation response is presented in Figures 6-1, 6-2, and 6-3. SSI analyses with coherent input produced reduced motions at frequencies above about 12 Hz in the horizontal directions. In the vertical direction, there is increased response in the 10 to 20 Hz region, but reduced response above 20 Hz due to SSI with coherent input motion. Incoherency results in significant reductions of the response spectra (comparing those for the coherent ground motions with those including the effects of incoherency) at frequencies above 10 Hz for all directions. Spectral accelerations are reduced by a factor of as much as 2 over a significant frequency range.

Response at the top of the coupled auxiliary & shield building (ASB) is presented in Figures 6-4, 6-5, and 6-6. SSI analyses with coherent input produced increased motions at peaks of 3 and about 6 Hz and reduced motions at frequencies above about 10 Hz in the horizontal directions. In the vertical direction, there is increased response in the 10 to 15 Hz region, but reduced response above 15 Hz due to SSI with coherent input motion. Incoherency results in reductions of the response spectra on the order of about 30 percent at frequencies in the range of 10 to 30 Hz for all directions. There are significant reductions due to incoherency for vertical ground motion at frequencies beyond 30 Hz.

Response at the top of the steel containment vessel (SCV) is presented in Figures 6-7, 6-8, and 6-9. SSI analyses with coherent input produced increased motions at peaks of 5.5 to 6 Hz and reduced motions at frequencies above about 12 Hz in the horizontal directions. In the vertical direction, there is reduced response above about 15 Hz due to SSI with coherent input motion. Incoherency results in reductions of the response spectra on the order of about 30 to 50 percent at frequencies in the range of 15 to 40 Hz for all directions. In addition to these reductions in response spectra in the range of 15 to 40 Hz, there are significant reductions due to incoherency for vertical ground motion at frequencies beyond 40 Hz.

Response at the top of the containment internal structure (CIS) is presented in Figures 6-10, 6-11, and 6-12. SSI analyses with coherent input produced reduced motions at frequencies above about 12 Hz in the horizontal directions for this stiff part of the structure. In the vertical direction, there is reduced response above about 18 Hz due to SSI with coherent input motion. The reductions in the high frequency fixed base spectra due to SSI are dramatic. Incoherency results in reductions of the response spectra on the order of about 50 to 90 percent at frequencies in the range of 15 to 100 Hz for all directions.

Figures 6-1 through 6-12 demonstrate the corrections to fixed base and free field response spectra due to both soil-structure interaction and seismic wave incoherence. The figures show significant high frequency reductions to in-structure response spectra due to soil-structure interaction for this rock site. The high frequency content of the spectra makes it necessary to conduct SSI analyses even for a rock site. Significant further reductions to high frequency response are demonstrated due to seismic wave incoherence.

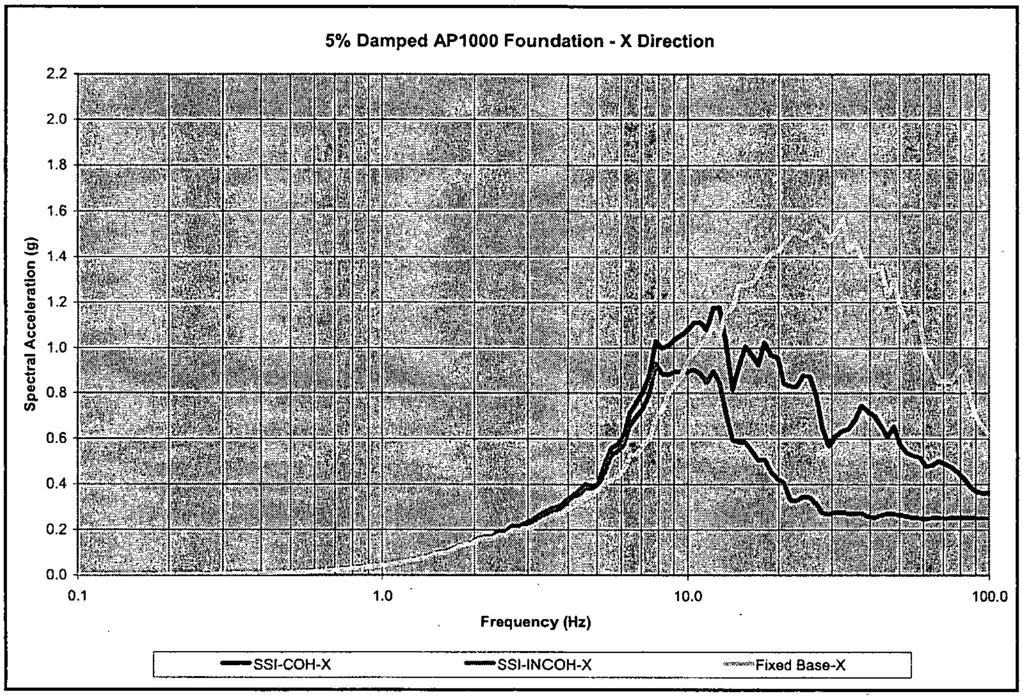

Figure 6-1
Foundation Response Spectra–X Direction–Free Field (Fixed Based), SSI Coherent, SSI Incoherent

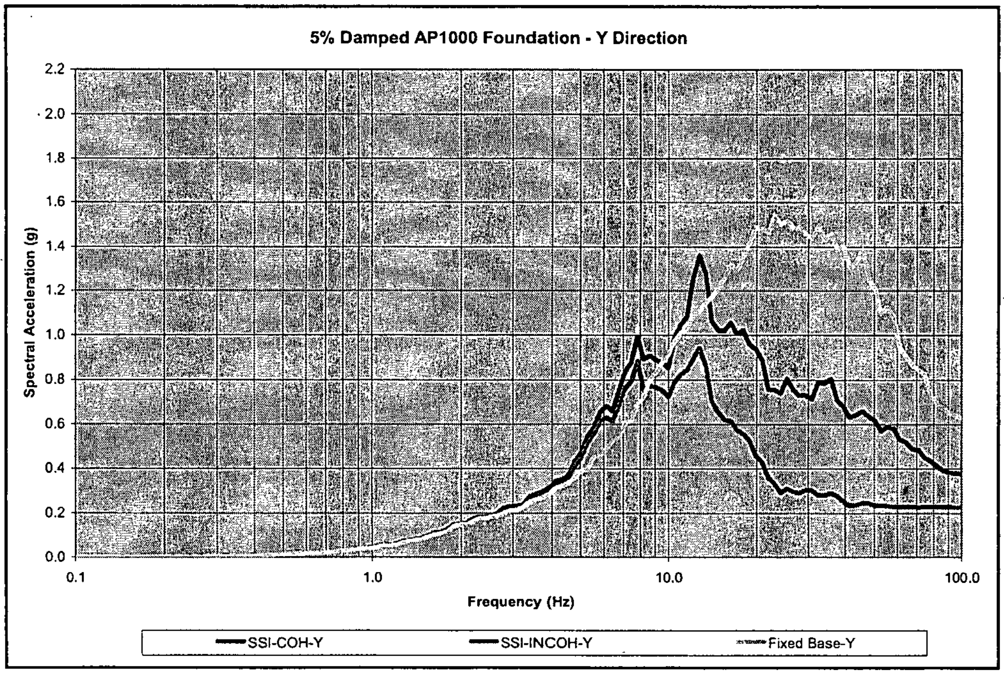

Figure 6-2
Foundation Response Spectra–Y Direction–Free Field (Fixed Based), SSI Coherent, SSI Incoherent

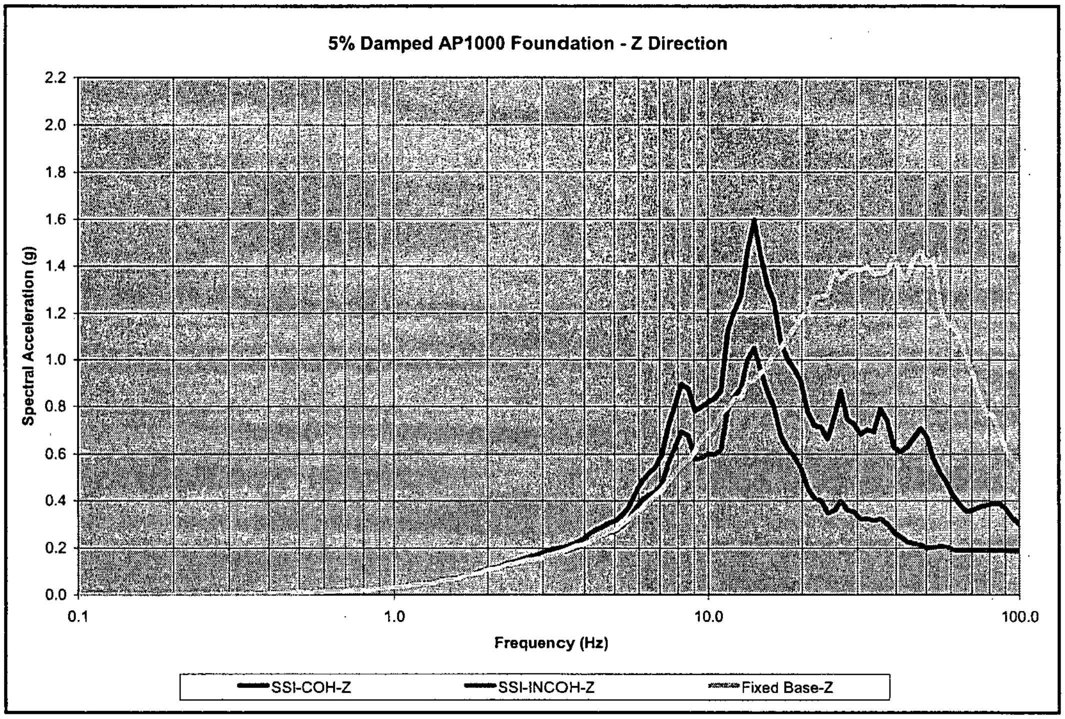

Figure 6-3
Foundation Response Spectra–Z Direction–Free Field (Fixed Based), SSI Coherent, SSI Incoherent

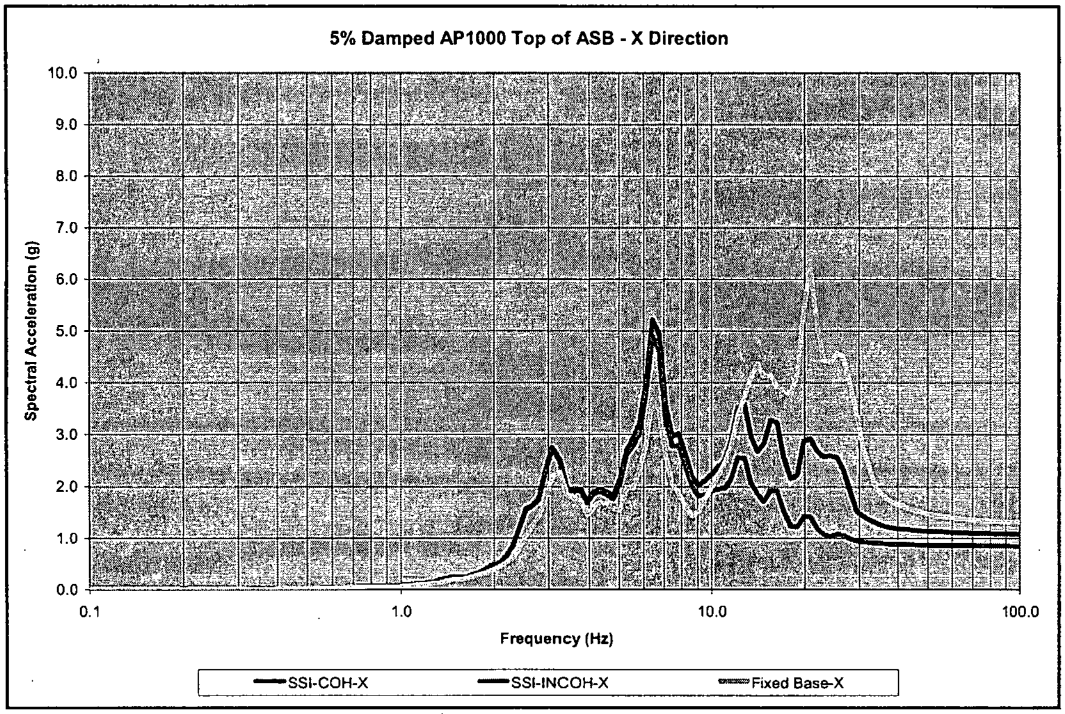

Figure 6-4
Top of ASB Response Spectra–X Direction–Fixed Base, SSI Coherent, SSI Incoherent

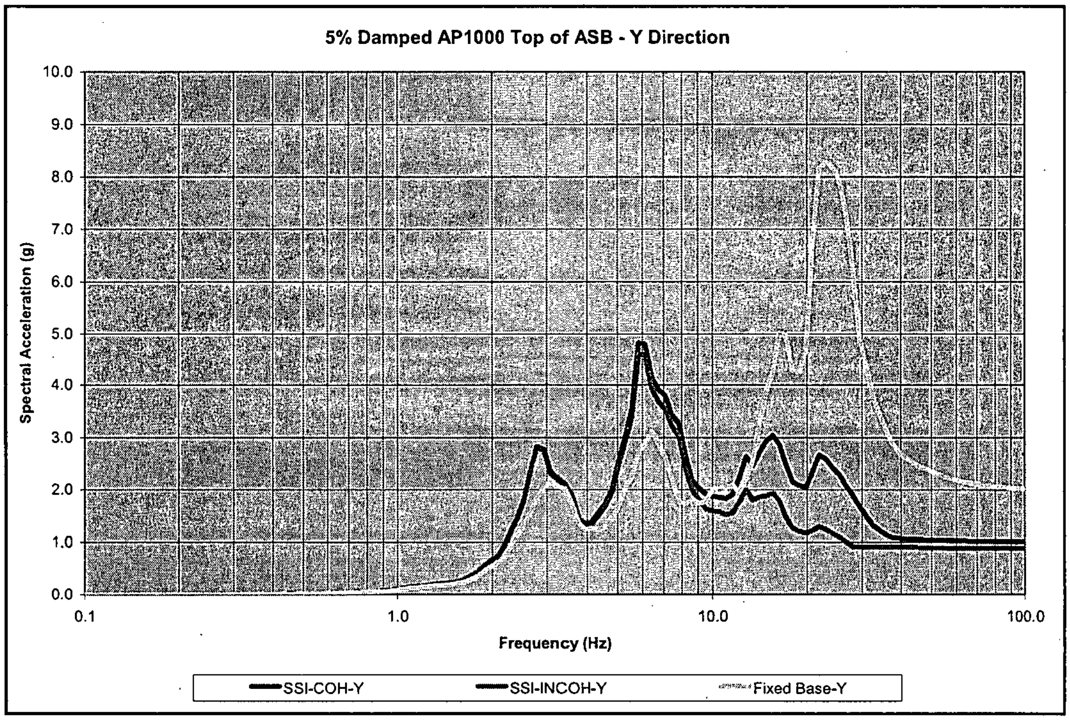

Figure 6-5
Top of ASB Response Spectra–Y Direction–Fixed Base, SSI Coherent, SSI Incoherent

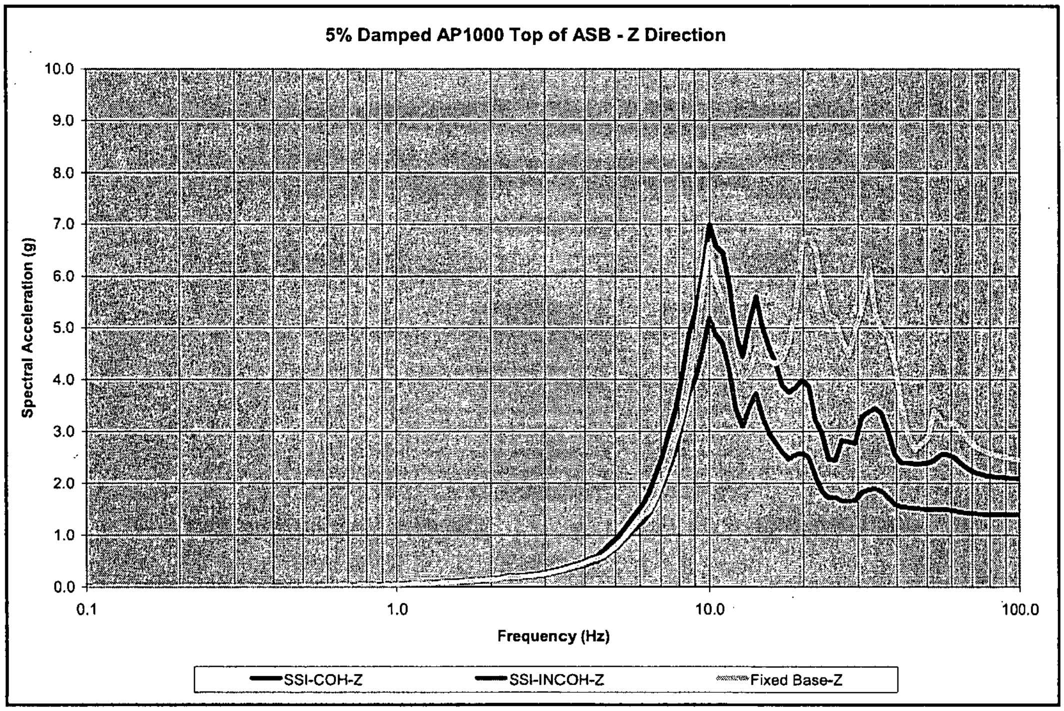

Figure 6-6
Top of ASB Response Spectra–Z Direction–Fixed Base, SSI Coherent, SSI Incoherent

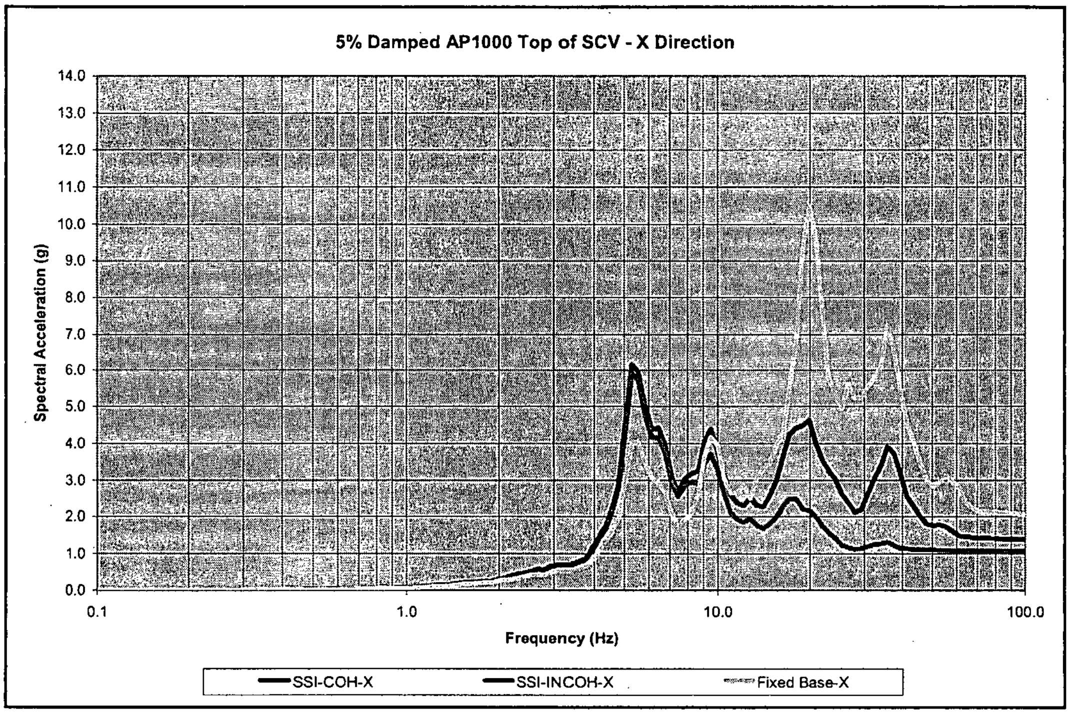

Figure 6-7
Top of SCV Response Spectra–X Direction–Fixed Base, SSI Coherent, SSI Incoherent

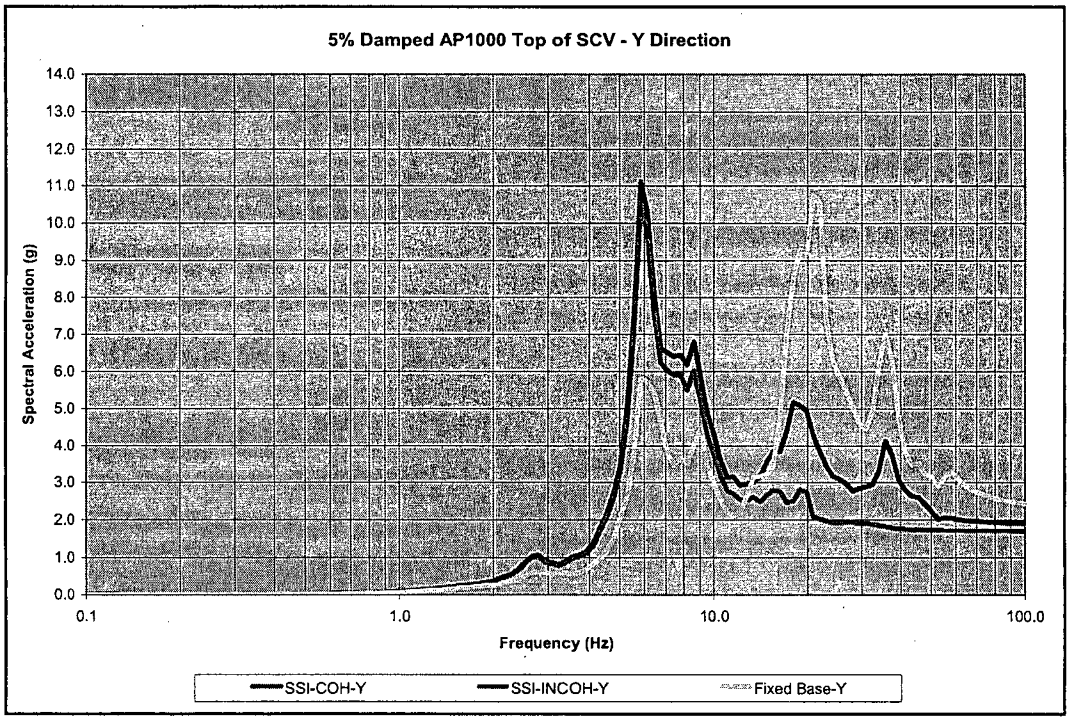

Figure 6-8
Top of SCV Response Spectra–Y Direction–Fixed Base, SSI Coherent, SSI Incoherent

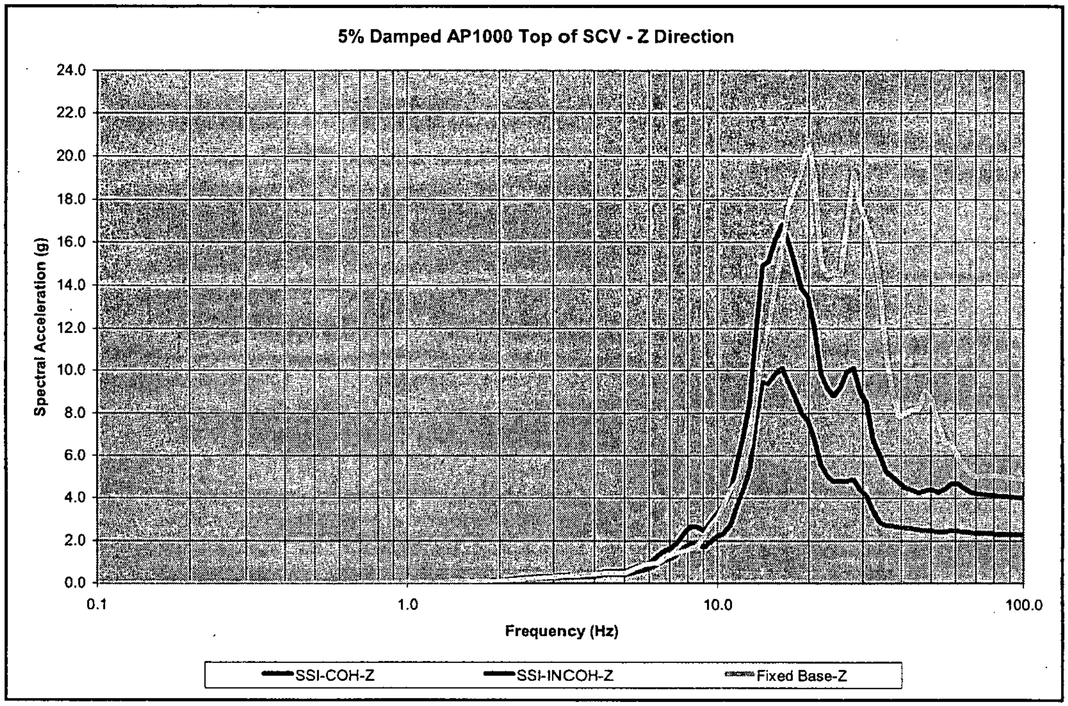

Figure 6-9
Top of SCV Response Spectra–Z Direction–Fixed Base, SSI Coherent, SSI Incoherent

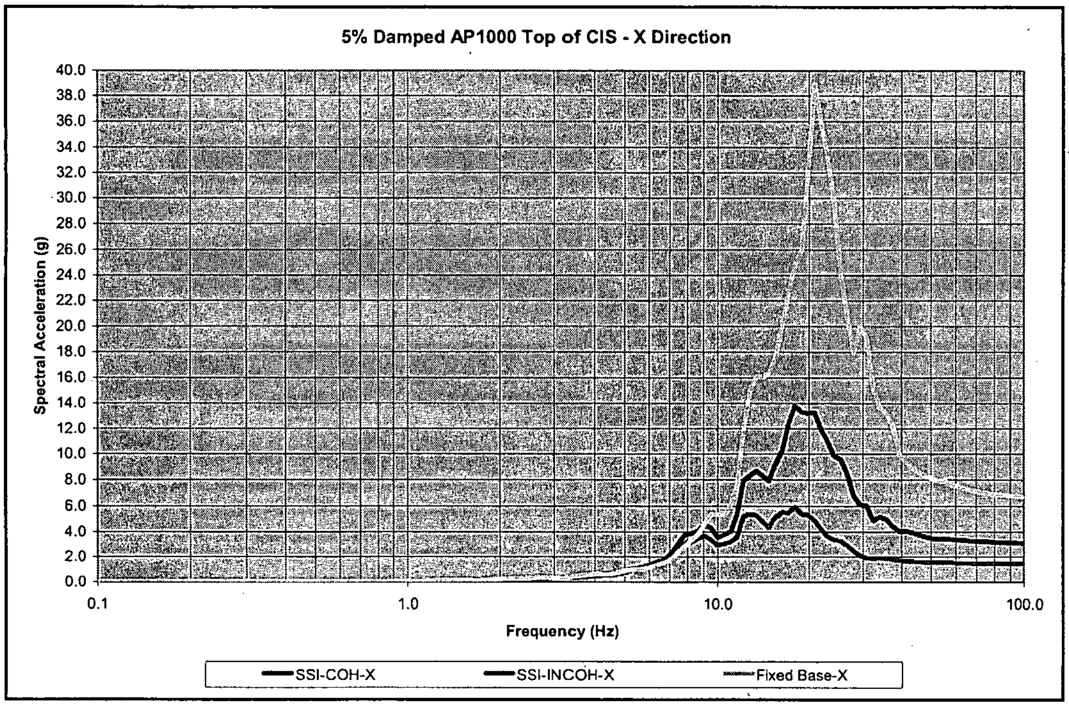

Figure 6-10

Top of CIS Response Spectra–X Direction–Fixed Base, SSI Coherent, SSI Incoherent

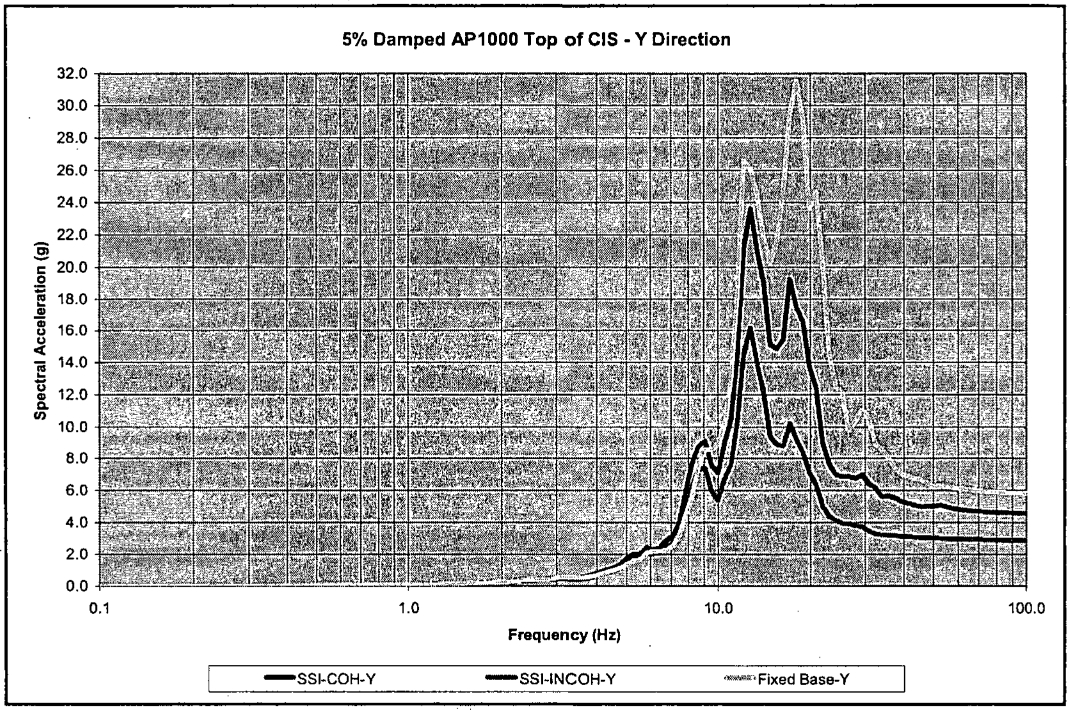

Figure 6-11
Top of CIS Response Spectra–Y Direction–Fixed Base, SSI Coherent, SSI Incoherent

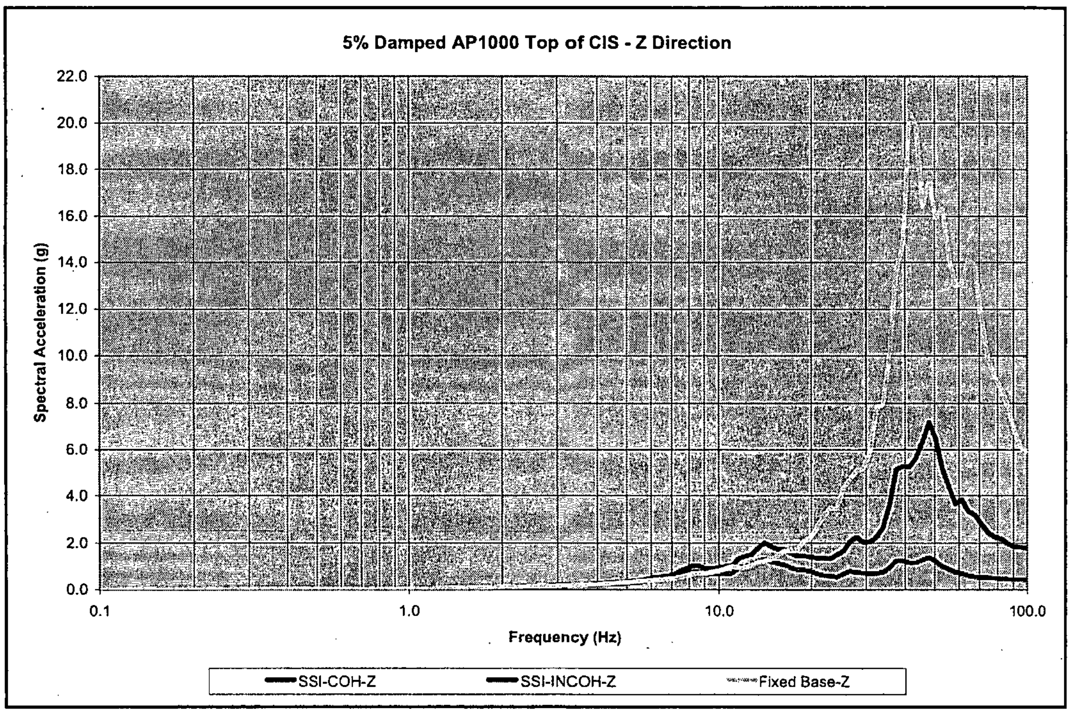

Figure 6-12
Top of CIS Response Spectra–Z Direction–Fixed Base, SSI Coherent, SSI Incoherent

SSI and Incoherence – Scaling Input Fourier Amplitude

An alternate means of incorporating seismic wave incoherence into seismic analyses is investigated in this chapter and compared with the results generated by the direct or "exact" implementation. The alternative approach is to scale the Fourier amplitude spectrum of the free-field input motion by the Incoherency Transfer Function (ITF). The Fourier phase spectrum is unaffected.

The incoherency transfer function is generated as presented previously for a discrete number of frequencies. The Fourier transformed free-field ground motion time histories are then scaled by ITF frequency-by-frequency. For these analyses, the incoherency transfer function as presented in Chapter 5 for the rock site profile and for the 150-ft square foundation footprint is used to be compatible with the analyses performed. Eq. 6-1 matches the incoherency transfer function with sufficient accuracy as shown in Figure 6-13.

$$ITF = \left[1 + \left(\frac{f * \tanh(\mathrm{k1})}{\mathrm{k2}}\right)^{\mathrm{k3}}\right]^{-\mathrm{k4}} \qquad \textbf{(Equation 6-1)}$$

Coefficient	Horizontal Motion	Vertical Motion
k1	0.006	0.04
k2	0.08	0.5
k3	2.4	2.5
k4	0.75	0.5

The analyses described in this section are a proof of concept such that an equation that matches the incoherency transfer function as closely as possible was sought and used. For actual applications to NPP structures a different design equation might be used. For example, the incoherency transfer function amplitude might be held to unity out to 10 Hz and then reduced according to a functional relationship for high frequencies.

The results of the analyses where the Fourier amplitude of the free-field input motion is scaled by the incoherency transfer function (ITF) are shown in Figures 6-14 through 6-25. Results presented are in-structure response spectra at the foundation and at the top of each of three structure models, ASB, SCV, and CIS. Also shown on these figures are the SSI Incoherent results previously presented in Figures 6-1 through 6-12–the direct or "exact" representation.

Comparing results from the direct incoherency implementation with the ITF-Fourier Amplitude scaling in Figures 6-14 through 6-25 demonstrates very close agreement in the computed in-structure response spectra by both approaches. Hence, it is shown that the ITF-Fourier Amplitude multiplication method is a reasonable and accurate approach for incorporating seismic wave incoherence.

Rotational effects (torsion and rocking) of the foundation were investigated to determine what factors, if any, may need to be applied to the ITFs to account for potential rotational effects. Two analyses were performed and/or evaluated to determine whether special treatment of the ITFs is required.

- First, comparison of the "exact" results with those determined by ITF scaling of input Fourier amplitudes illustrates that significant additional rocking does not result from consideration of seismic wave incoherence. The exact solution includes rocking induced by consideration of incoherence but the ITF scaled solution only includes translational input motion. The close agreement shown in Figures 6-14 through 6-25 demonstrates little rocking is induced due to seismic wave incoherence for this site.
- Second, as an additional check on the potential effects of rotations (rocking or torsion) on the in-structure response, a sensitivity study was performed by analyzing the structure for only the rotational portion of the scattered foundation input motion. The result being that translational foundation responses after SSI when subjected to rotations only were less than 0.01g. In-structure response was similarly low.

For the rock site condition, no additional consideration of rotations due to ground motion incoherence appears to be warranted.

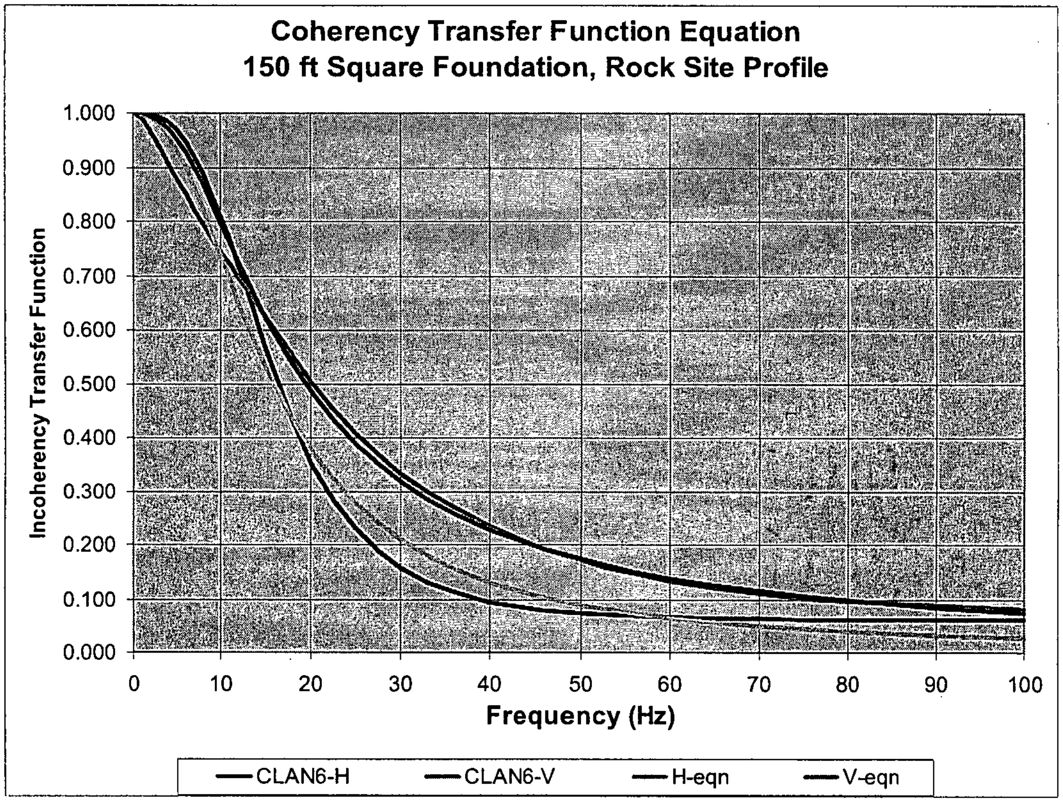

Figure 6-13
Foundation Response Spectra–X Direction–Fixed Base, SSI Coherent, SSI Incoherent

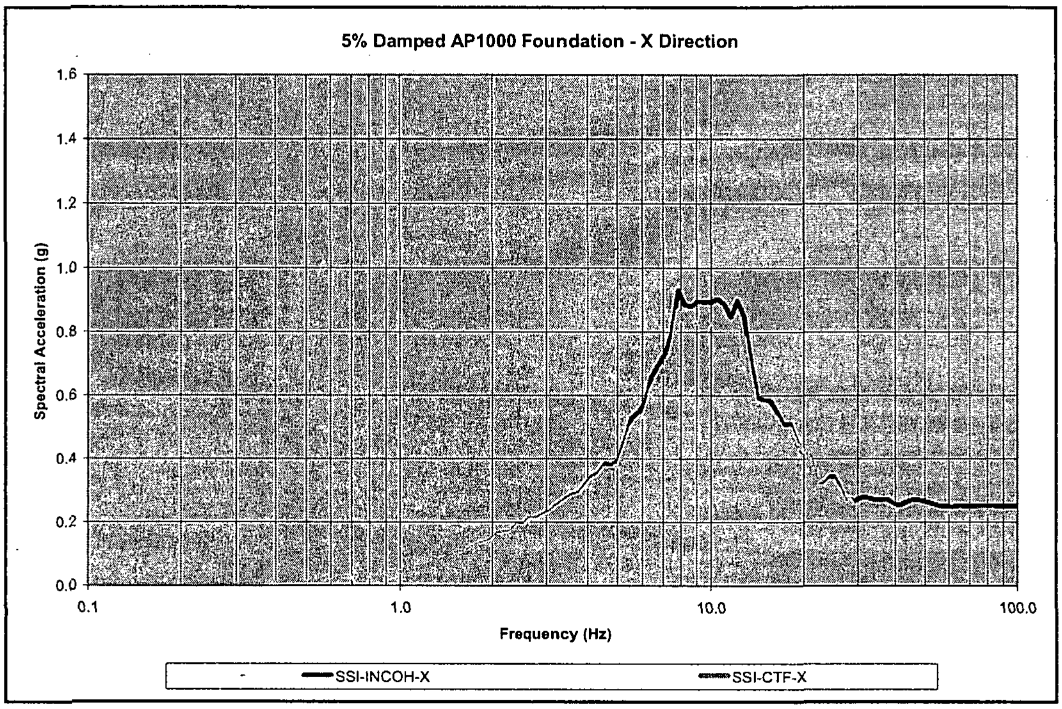

Figure 6-14
Foundation Response Spectra–X Direction–Exact Incoherency vs. ITF x Fourier Amplitude

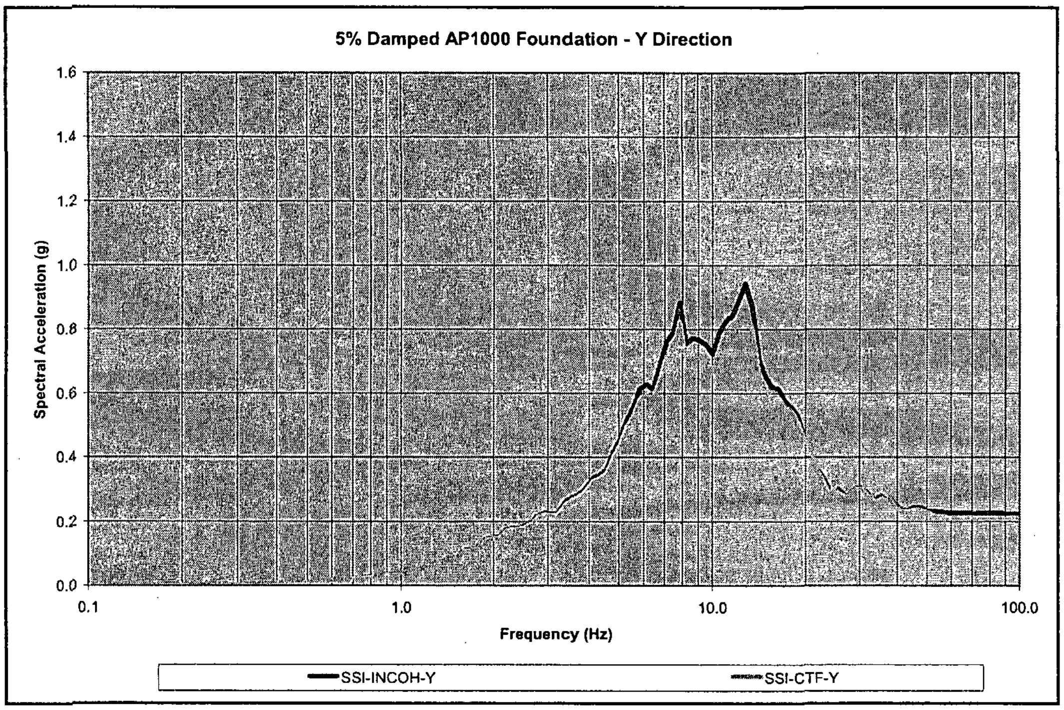

Figure 6-15
Foundation Response Spectra–Y Direction–Exact Incoherency vs. ITF x Fourier Amplitude

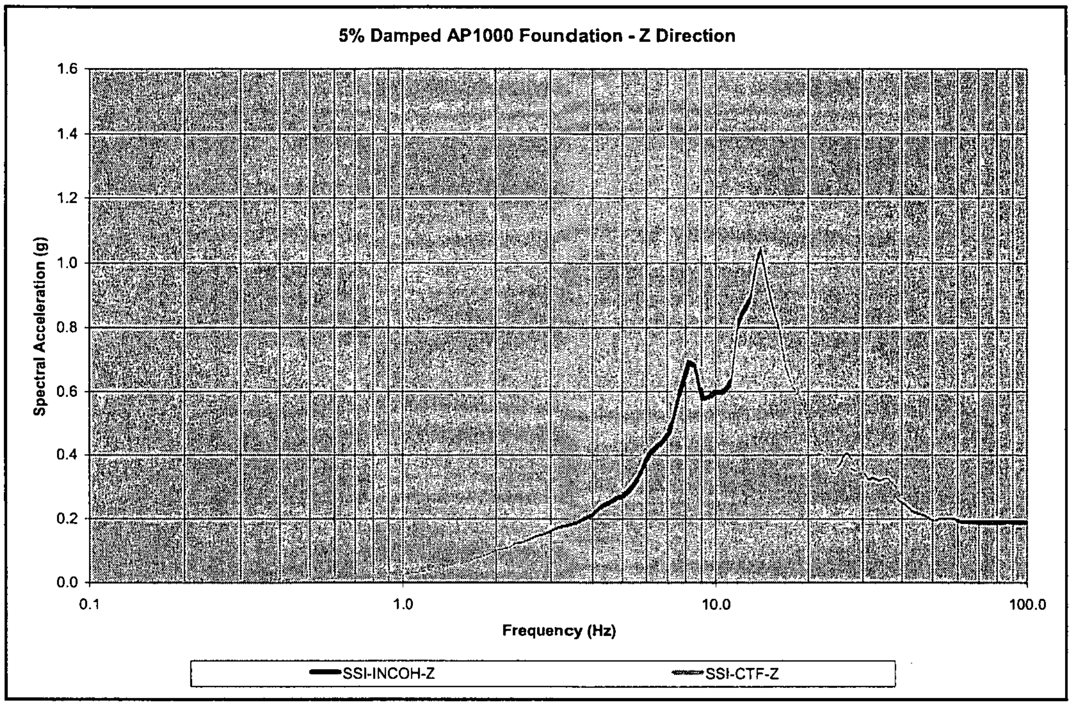

Figure 6-16
Foundation Response Spectra–Z Direction–Exact Incoherency vs. ITF x Fourier Amplitude

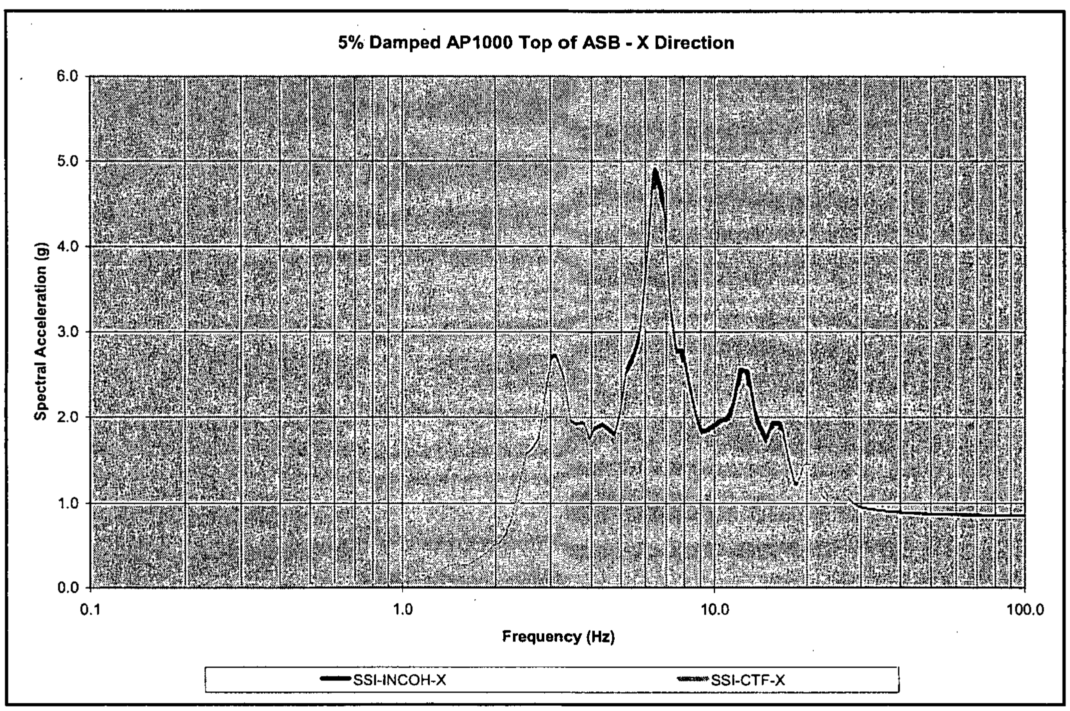

Figure 6-17
Top of ASB Response Spectra–X Direction–Exact Incoherency vs. ITF x Fourier Amplitude

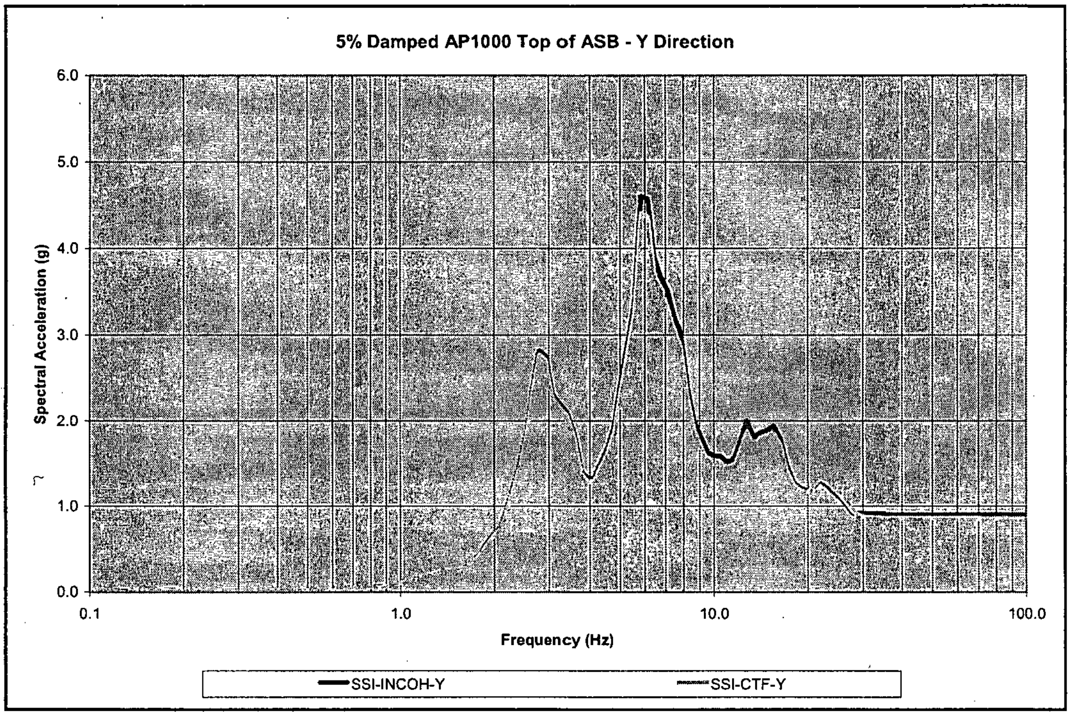

Figure 6-18
Top of ASB Response Spectra–Y Direction–Exact Incoherency vs. ITF x Fourier Amplitude

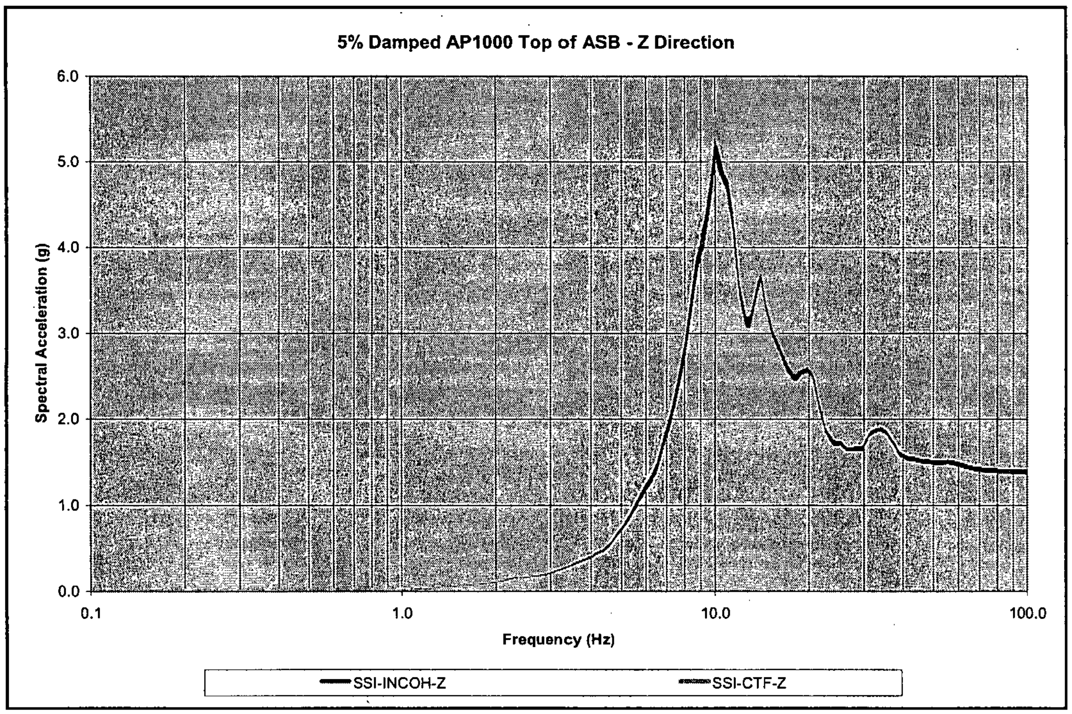

Figure 6-19
Top of ASB Response Spectra–Z Direction–Exact Incoherency vs. ITF x Fourier Amplitude

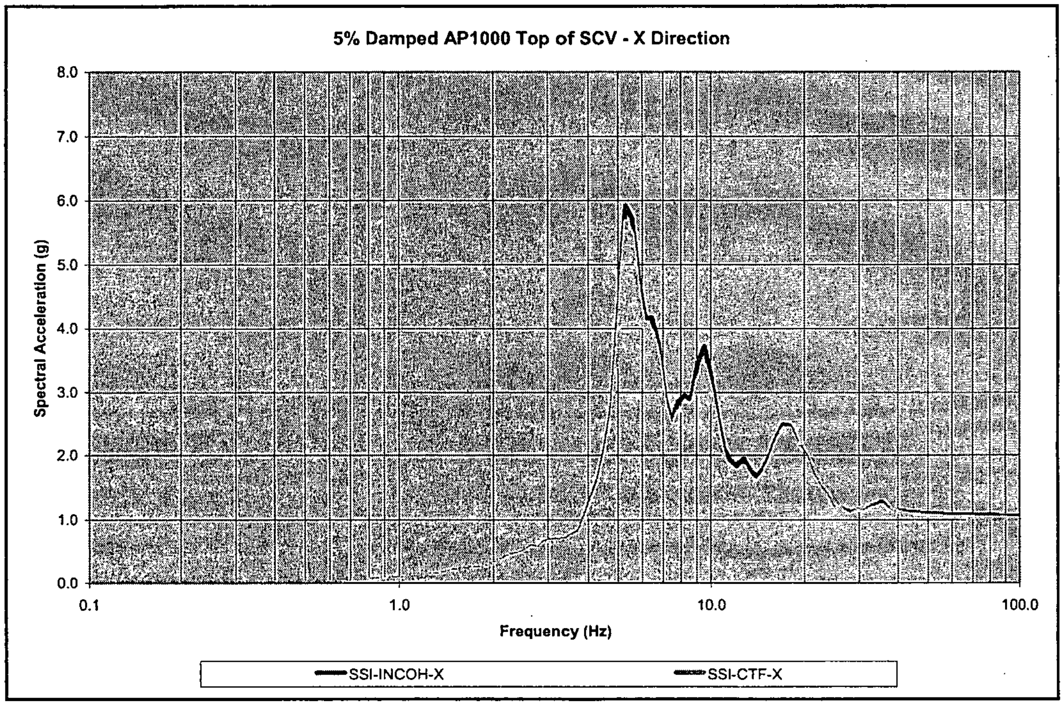

Figure 6-20
Top of SCV Response Spectra–X Direction–Exact Incoherency vs. ITF x Fourier Amplitude

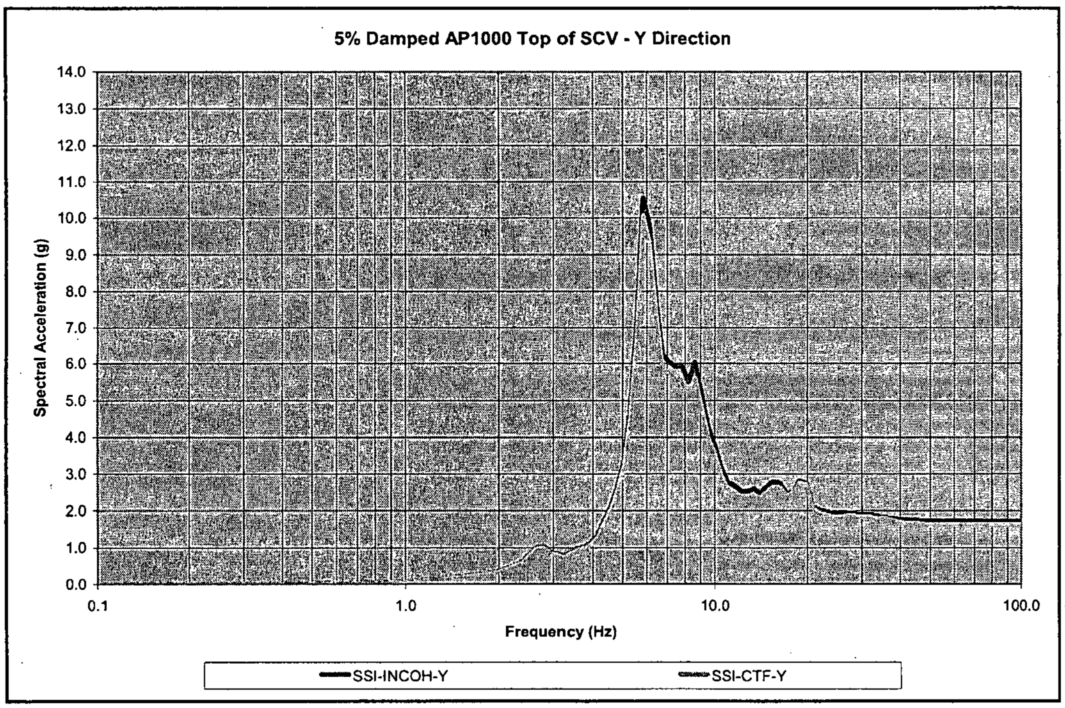

Figure 6-21
Top of SCV Response Spectra–Y Direction–Exact Incoherency vs. ITF x Fourier Amplitude

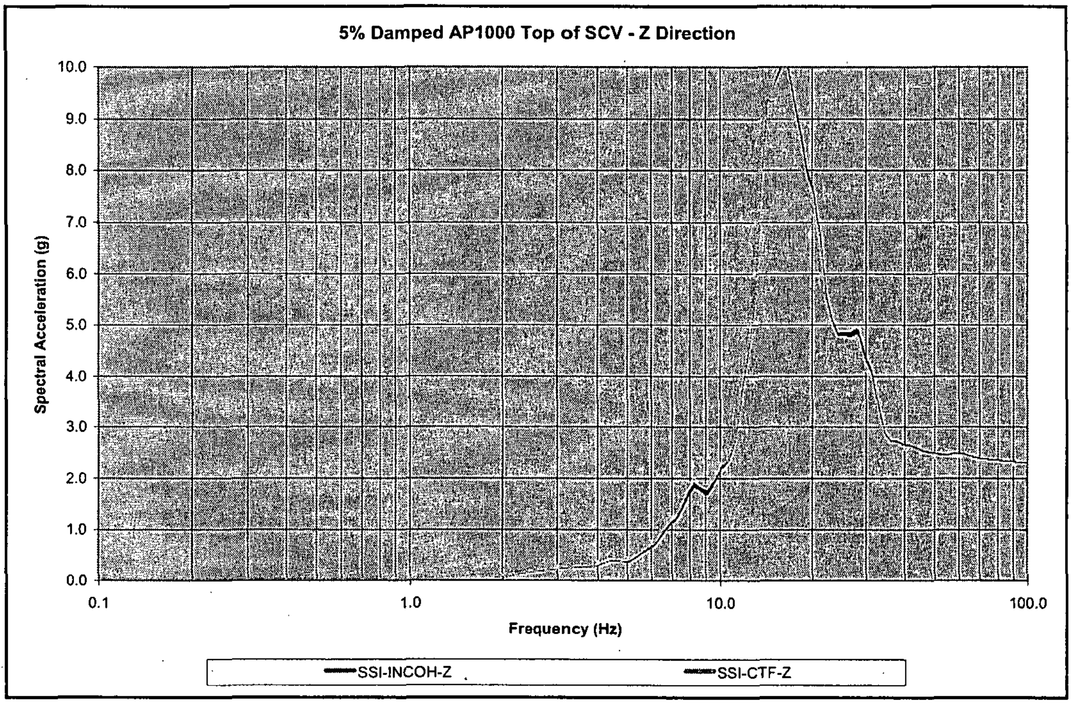

Figure 6-22
Top of SCV Response Spectra–Z Direction–Exact Incoherency vs. ITF x Fourier Amplitude

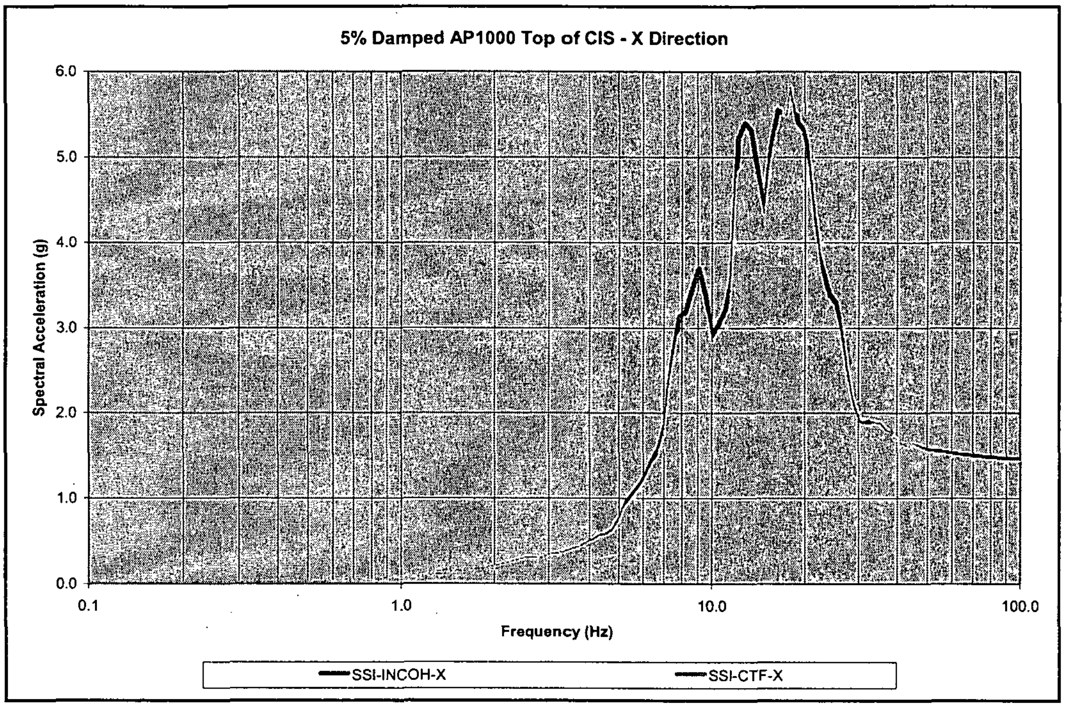

Figure 6-23
Top of CIS Response Spectra–X Direction–Exact Incoherency vs. ITF x Fourier Amplitude

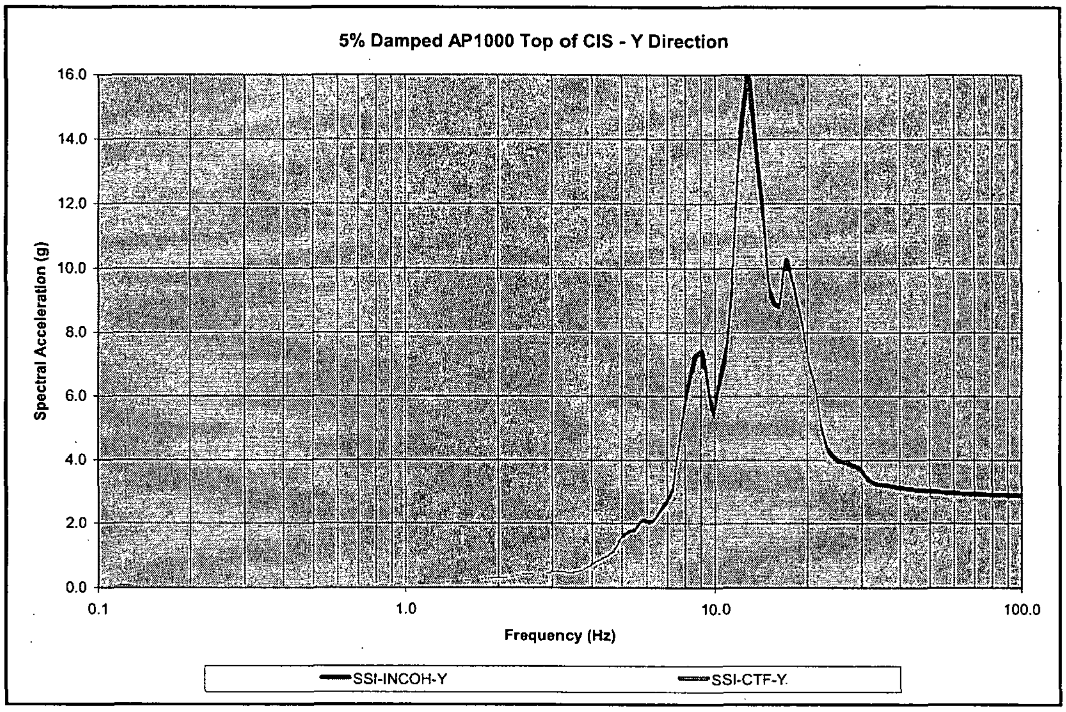

Figure 6-24
Top of CIS Response Spectra–Y Direction–Exact Incoherency vs. ITF x Fourier Amplitude

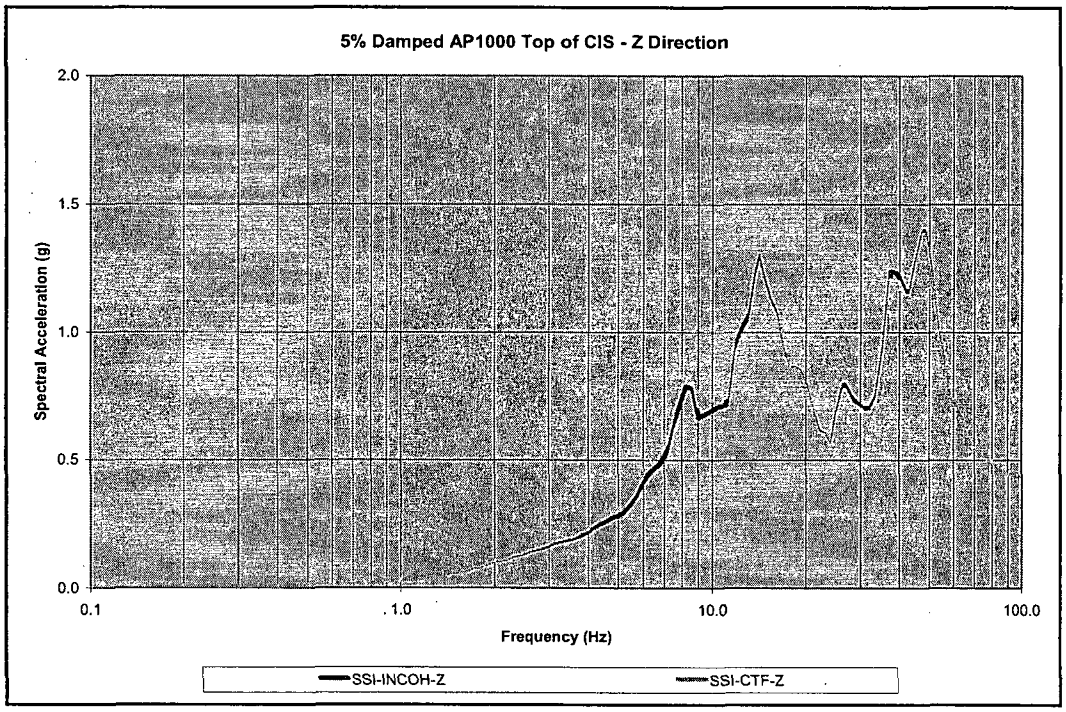

Figure 6-25
Top of CIS Response Spectra–Z Direction–Exact Incoherency vs. ITF x Fourier Amplitude

Effect of Embedment and Incoherence

All of these analyses conducted for this project have considered surface foundations. However, many NPP structures have embedded foundations and partially embedded structures. It is anticipated that the effects of embedment and the effects of seismic wave incoherence are independent of each other. However, analyses to demonstrate this relationship have not been performed.

Evidence does exist for investigating the effects of embedment in the analyses of the High Level Waste Building at Hanford for which the effects of embedment and incoherency were evaluated by Bechtel (Ostadan, 2005). This structure had shallow embedment. The spectral reduction ratios comparing in-structure response spectra for coherent motion to in-structure response spectra for incoherent motion showed similar levels indicating the independency of embedment and incoherency. In-structure spectra for one horizontal direction and for a surface founded and embedded model are shown in Figures 6-26 and 6-27, respectively.

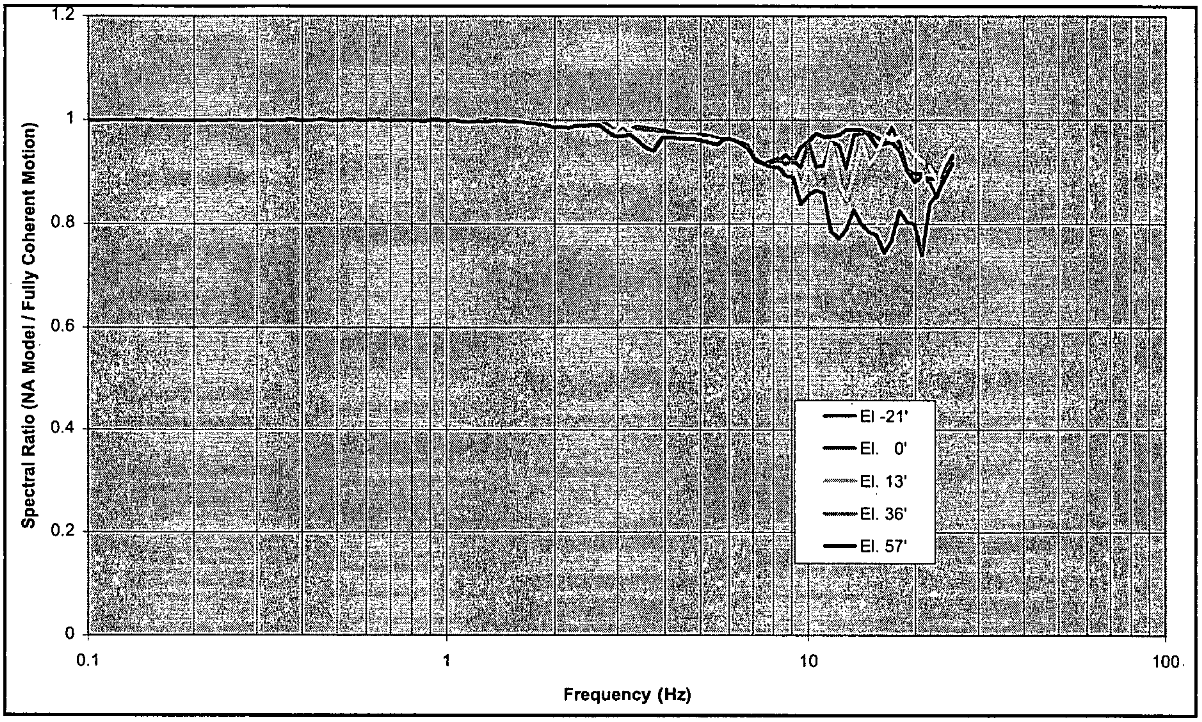

Figure 6-26
Spectral Correction Due to Incoherency–Surface Founded Model

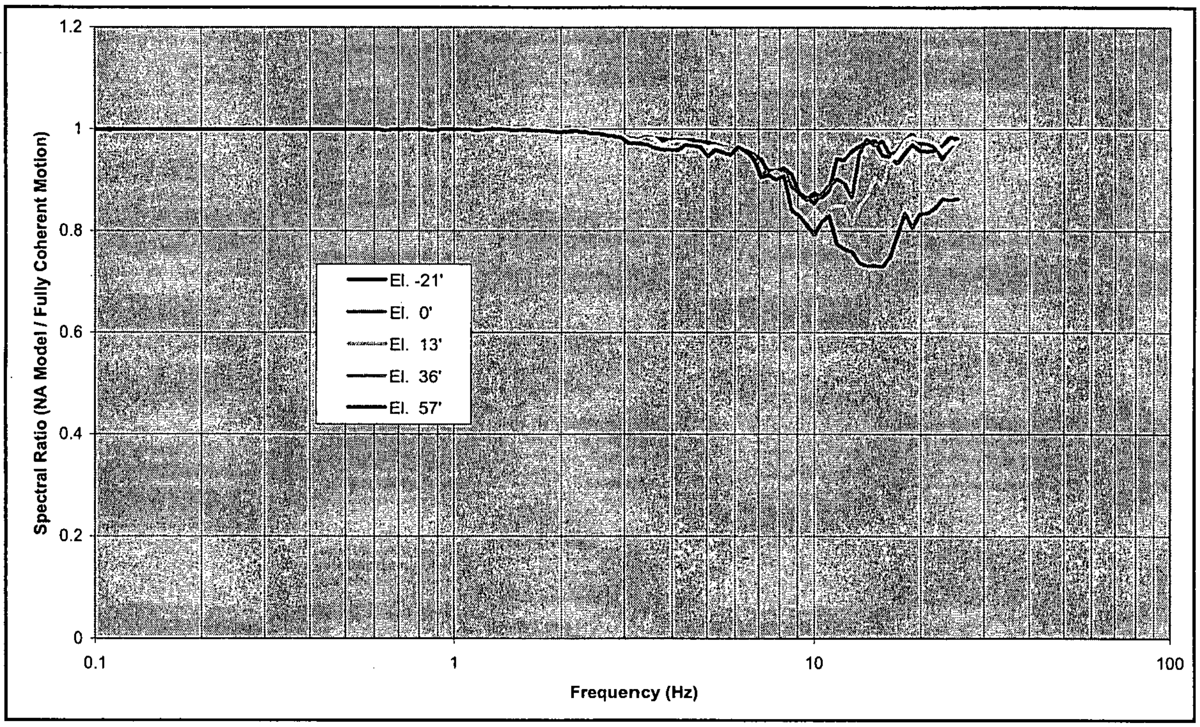

Figure 6-27
Spectral Correction Due to Incoherency–Embedded Model

7
SUMMARY, CONCLUSIONS, & RECOMENDATIONS

Tasks Performed & Approach

Task S2.1 of the EPRI/DOE New Plant Seismic Issues Resolution Program has been conducted with results presented herein. The objective of this task is to systematically study seismic wave incoherence effects on structures/foundations similar to those being considered for Advanced Reactor designs. Seismic wave incoherence arises from the horizontal spatial variation of earthquake ground motion. Horizontal spatial variation of both horizontal and vertical ground motion can occur and are considered in this task. Two sources of incoherence or horizontal spatial variation of ground motion are:

1. Local wave scattering: Spatial variation from scattering of waves due to the heterogeneous nature of the soil or rock along the propagation paths of the incident wave fields.
2. Wave passage effects: Systematic spatial variation due to difference in arrival times of seismic waves across a foundation due to inclined waves.

This study considers both of these phenomena but the final results are based only on local wave scattering.

Based on the coherency functions developed by Dr. Abrahamson (Abrahamson, 2005), seismic response has been evaluated using the soil-structure interaction computer program CLASSI, combined with random vibration theory. Seismic response was evaluated for rigid, massless foundations and for example structural models on rigid foundation mats. The basic relationship between motion in the free-field and motion on the rigid massless foundation is developed based on random vibration theory. The relationship between free-field ground motion at discretized points on the foundation is described by the cross power spectral density functions, normalized by the power spectral density (PSD) function of the free-field ground motion. The resulting PSDs of the motion of the rigid, massless foundation are used to define incoherency transfer functions (ITFs). ITFs are equivalent to scattering functions in CLASSI nomenclature (i.e., frequency-dependent, complex-valued functions). ITFs when applied to the free- field ground motion take into account the effects of incoherence on the foundation input motion. These scattering functions permit the evaluation of structure and foundation seismic response directly using the CLASSI family of SSI analysis programs. Similarly, ITFs may be applied to modify the seismologically defined free-field ground motion. The modified ground motion is used in standard seismic response analyses as an alternate means of including the effects of seismic wave incoherence. In either case, the effects of incoherence on NPP structures/foundations is accounted for as a function of foundation area and other relevant parameters. An important sub-task was to benchmark the results by an independent comparison with different methodology and software.

Benchmark Comparison

The development of incoherency transfer functions and spectral corrections for an example rigid, massless foundation has been validated by independent benchmark comparisons of results. For this purpose, the effect of incoherent ground motion has been evaluated by:

- Two different SSI computer programs; CLASSI and SASSI
- Two different algorithms; CLASSI-stochastic method and SASSI eigen decomposition method
- Two different analytical approaches; random vibration theory (RVT) by CLASSI and time history dynamic analyses by SASSI
- Two different organizations conducting the analyses; CLASSI by the ARES team and SASSI by Bechtel Corp.

Excellent agreement is obtained for both incoherency transfer functions and spectra corrections on the foundation. The benchmark comparison is convincing validation of the technical approach being employed in Task S2.1.

Incoherency Transfer Function

Incoherency transfer functions associated with local wave scattering due to seismic wave incoherence have been computed. The incoherency transfer function provides an indication of the reduction in foundation motion as a function of frequency due to seismic wave incoherence. Incoherency transfer functions have been developed for both the high frequency content rock and lower frequency content soil site profiles. Parametric studies have been performed for:

- Foundation Shape, (Constant Area)
  - 150-ft square footprint
  - 100 by 225 ft rectangle footprint
- Foundation Area, (Constant Shape)
  - 75-ft square footprint
  - 150-ft square footprint
  - 300-ft square footprint

Extensive calculations have been performed only for local wave scattering effects. The additional effect of wave passage was studied initially. It was found to provide additional reductions in foundation input motion. However, these additional reductions were small compared to those of local wave scattering and dependent on apparent wave velocity, which is an unknown parameter. Therefore, it was judged to be slightly conservative to not include wave passage effects.

Foundation shape. Foundation response computed for a rectangle and square of equal area were determined to be essentially identical. This result indicates that for these shapes, the incoherency transfer function is independent of foundation shape considering a square and a rectangle with about a 2 to 1 aspect ratio.

Foundation area. To investigate the effect of foundation area on the incoherency transfer function, square foundation footprints with area varying by a factor of 4 were considered. Larger foundation footprints lead to much larger reductions in foundation response at high frequencies. Increasing foundation area from a 75-ft square foundation to a 300-ft square foundation, a factor of 16 on area, results in an increased reduction at 20 Hz from about 0.45 to 0.27, and at 30 Hz from 0.23 to 0.12. Foundation area is a most important parameter.

Site conditions. The effect of soil profile on the incoherency transfer function was also investigated. From these analyses, it is demonstrated that the incoherency transfer function and hence the effect of seismic wave incoherence are independent of the site profile. The incoherency transfer functions are essentially identical at all frequencies for soil and rock.

Spectral Corrections

Foundation response

For a rigid, massless foundation, foundation response spectra accounting for seismic wave incoherence were computed. By this approach, the PSD is computed from the response spectra of the free-field input motion and input to CLASSI. The program then evaluates the PSD of the foundation motion including the effects of seismic wave incoherence. The resulting response PSD is then converted to foundation response spectra by random vibration theory. Foundation response spectra have been developed for both the rock and soil site using the compatible free-field high frequency rock and lower frequency soil ground response spectra, respectively. Parametric studies have been performed for:

- Foundation Shape, (Constant Area)
  - 150-ft square footprint
  - 100 by 225-ft rectangle footprint
- Foundation Area (Constant Shape)
  - 75-ft square footprint
  - 150-ft square footprint
  - 300-ft square footprint

Comparison of results demonstrate that the foundation spectra for the 150-ft square footprint and the 100 by 225-ft rectangle footprint are the same, as would be expected because the incoherency transfer functions are essentially the same. The effects of foundation area on foundation spectra were evaluated for the 75-ft, 150-ft, and 300-ft square foundation footprints. The spectra corrections as a function of foundation area are much more significant for the rock site than for the soil site. Again, this is expected because the site-specific free-field ground motion for the soil site is significantly different than the site-specific rock motion. The effect of seismic wave incoherence is primarily a high frequency phenomenon. Hence, the observed reductions in foundation response spectra are much less for the soil site since the soil site-specific ground motion is deficient in high frequencies. For the rock site, the peak of the horizontal spectra is reduced from 0.85g for the 75-ft square foundation to 0.76g for the 150-ft square foundation to 0.67g for the 300-ft square foundation. All of these peak spectra values are much less than the 1.48g peak of the horizontal free-field ground motion spectra. Similar behavior is observed for the vertical ground motion.

Spectral corrections from these analyses were also compared to the spectral corrections that are recommended to account for incoherence of ground motion in ASCE 4 (ASCE, 2000). Comparing the recommendations of ASCE 4 with the results generated here, the following points are apparent. The methodology of treating the phenomena should be as described herein, i.e., the free-field ground motion should be modified as a function of the foundation characteristics to take into account the phenomena rather than applying a scale factor to the end result in-structure response spectra. This is clearly demonstrated by comparing the correction factors of ASCE 4 with the calculated reductions from the current study. For the rock site, the reductions calculated here are significantly greater than those recommended in ASCE 4. For the soil site, the calculated reductions are comparable to those of ASCE 4. This demonstrated the need to perform SSI analyses accounting properly for the effects of incoherence or to apply incoherency transfer functions to the free-field ground motion, either approach has been shown acceptable. Simply applying correction factors, such as those recommended by ASCE, are expected to be conservative and possibly very conservative. The approach based on the incoherency transfer function as proposed in this study is appropriate because the functions are independent of the input motion.

Structure response

Spectra corrections due to seismic wave incoherence are also computed for a structural model accounting for soil-structure interaction effects. For this purpose, four analyses have been performed using a simplified structural model approximating the AP 1000 that is supported by a 15-ft thick concrete foundation mat with 150-ft square plan dimensions:

1. Fixed base analysis
2. SSI analysis with coherent input motion
3. SSI analysis with incoherent input motion
4. SSI analysis with input motion modified by the incoherency transfer function

Results presented are in-structure response spectra at the foundation and at the top of each of three structure models, Auxiliary Shield Building (ASB), Steel Containment Vessel (SCV), and Containment Internal Structure (CIS) for two horizontal, X and Y, and the vertical direction, Z of ground motion. All four analyses were performed using the computer program CLASSI. The rock site profile was used for Analyses 2, 3, and 4 and the spectrum compatible time history for the high frequency rock site response spectra was used for all analyses.

Analysis 2 was performed with CLASSI assuming the free-field ground motion was comprised of vertically propagating waves and with no incoherence effects. In CLASSI nomenclature, the scattering functions were frequency independent and equal to 1.0, i.e., the foundation input motion was identical to the free-field ground motion.

Analysis 3 was performed with CLASSI accounting for the incoherency of the ground motion through the Incoherency Transfer Functions (ITFs). The ITFs were defined from the PSDs of the motion of the rigid, massless foundation described above. The Incoherency Transfer Functions (ITFs) are equivalent to scattering functions in CLASSI nomenclature, i.e., frequency-dependent, complex-valued functions. ITFs when applied to the free-field ground motion take into account the effects of incoherence on the foundation input motion. These scattering functions permit the evaluation of structure and foundation seismic response directly using the CLASSI family of SSI analysis programs. This approach is direct and "exact".

Analysis 4 was performed with CLASSI implementing an alternative means of incorporating seismic wave incoherence into seismic analyses. The approach is to modify the free-field ground motion as a function of foundation parameters, site conditions, and frequency of the ground motion to incorporate the effects of incoherence. This alternative approach has numerous benefits if validated. Standard seismic analysis programs and methods could then be employed directly without special routines or programs written. The proposed methodology is to scale the Fourier amplitude spectra of the free-field ground motion by the ITFs. The Fourier phase spectrum is unaffected. Comparing results from the direct or "exact" incoherency implementation (Analysis 3) with the ITF-Fourier Amplitude scaling (Analysis 4) demonstrates very close agreement in the computed in-structure response spectra by both approaches. Hence, it is shown that the ITF-Fourier Amplitude scaling method is a reasonable and accurate approach for incorporating seismic wave incoherence.

Conclusions

The conclusions of this study are:

- The phenomena of incoherence are important for high frequency ground motions (primarily greater than 10 Hz) and high frequency response of structures. Realistically accounting for ground motion incoherence on the seismic response of nuclear power plant structures is significant and should be properly incorporated into seismic design analyses.
- Consideration of coherent earthquake ground motion that results from the assumption of vertically propagating plane waves produces overly conservative foundation motion. Seismic wave incoherence or spatial variation from scattering of waves due to the heterogeneous nature of the soil or rock along the propagation paths of the incident wave fields results in averaging or integrating effects of high frequency ground motions by stiff nuclear power plant structures' foundations. For the rock site and corresponding high frequency free field ground motion considered in this study, incoherent earthquake ground motion results in calculated in-structure response spectra reduced by factors of two or greater at frequencies greater than 10 Hz.
- Structure responses in frequency ranges below about 10 Hz are essentially unaffected by the phenomena. Horizontal and vertical ground motions are subject to the incoherency phenomena and have been included in this study.
- Accounting for incoherency by application of the Incoherency Transfer Functions (ITFs) may be accomplished in a direct and "exact" manner as in this study using CLASSI. An alternative approach to account for incoherency is to scale the Fourier amplitude spectra of the free-field ground motion by a modified ITF. This approach was validated herein for a rock site and a compatible site-specific high frequency ground motion. This latter approach allows incorporation of the effect into standard seismic analysis programs.
- For realistic, but simplified, foundation shapes studied herein, the most important parameter was found to be foundation area. Foundation shape (square vs. rectangle) and site soil conditions were found to have minimal to no effect on the ITFs.
- Significant rocking is not induced by consideration of seismic wave incoherence for this rock site. There is close agreement between the "exact" results that includes rocking induced by incoherence with results by the ITF scaling of input Fourier amplitudes that

only includes translational input motion. Hence, there is no significant rocking of the foundation due to incoherence as it would be observed in seismic response at the top of each structural model.

- Potential enhancements to this study to broaden its applicability are in the areas of sensitivity studies for differing foundation shapes, differing structures and their models, and increased complexity of the foundations and structures. The assumption that mat foundations of typical nuclear power plant structures behave rigidly was made in this study. This assumption has been well justified by numerous previous studies and is due to the stiffening of structural elements interconnected to the foundation. The assumption that the effect of incoherence of ground motion is equally applicable to surface-founded and embedded foundations was studied for one example configuration. The case cited in the study validates this assumption, but its specific configuration minimizes the effect of embedment due to its large foundation area and minimal relative embedment depth. Judgment dictates that the phenomenon of incoherence applies at depth in the soil or rock as on the surface.
- The basic effect of incoherence on seismic response of structures has been demonstrated and validated through recorded ground motions and analyses of their effects with alternative methods and programs.
- The following tasks have been identified as valuable further research in support of this Task S2.1 effort. EPRI is committed to the performance of these additional tasks, subject to availability of appropriate funding, in order to broaden the application of these methods and to provide further verification of the procedures developed:
  - Additional analyses for different and more complex foundation shapes
  - Verification of the computed incoherency reductions based on studies of empirical data on foundation responses in real earthquakes
  - Sensitivity study on coherency function uncertainty
  - Validation of the coherency function through peer review

  These future analyses should be structured to further validate the direct "exact" approach of treating incoherence and the approximate method applied to the Fourier amplitude spectra of the free-field motion.

Seismic analyses incorporating ground motion incoherence demonstrate a significant reduction in high frequency seismic response as measured by in-structure response spectra. The computed incoherency transfer functions depend on the foundation area and are independent of site soil conditions. However, the resulting spectral reductions strongly depend on the site soil conditions. The effect of seismic wave incoherence is primarily a high frequency phenomenon. Hence, the observed reductions in foundation response spectra are much less for soil sites since the soil site-specific ground motion is deficient in the high frequency portion of the spectra.

8 REFERENCES

Abrahamson, N. (2005). *Spatial Coherency for Soil Structure Interaction*, Electric Power Research Institute, Technical Update Report 1012968, Palo Alto, CA. Dec.

ASCE (2000). *Seismic Analysis of Safety-Related Nuclear Structures and Commentary*, American Society Civil Engineers, Report. ASCE 4-98.

Chang, C.-Y., M.S. Power, I.M. Idriss, P. Sommerville, W. Silva, and P.C. Chen, *Engineering Characterization of Ground Motion, Task II: Observational Data on Spatial Variations of Earthquake Ground Motion*, NUREG/CR-3805, Vol. 3, 1986.

CSI, Computers and Structures Incorporated, SAP2000, Integrated Software for Structural Analysis and Design, Version 9, 2004.

Der Kiureghian, A., *Structural Response to Stationary Excitation*, Journal of the Engineering Mechanics Division, American Society Civil Engineers, December, 1980.

EPRI (1991). *A Methodology for Assessment of Nuclear Power Plant Seismic Margin (Rev 1)*, Electric Power Research Institute, Report NP-6041-SL, Palo Alto, CA. Aug.

EPRI (1997). *Soil-Structure Interaction Analysis Incorporating Spatial Incoherence of Ground Motions*, Elec. Power Res. Inst., Report TR-102631 2225, Palo Alto, CA. Nov.

Orr, R., *APP1000 Inputs for 2D SASSI Analyses*, Calculation No. APP-1000-S2C-052, Rev. 0, Westinghouse, 2003.

Ostadan, F., Bechtel Corporation, personal communication to S. Short, ARES Corporation, June 2005.

Rood, H., et al, *Safety Evaluation Report Related to the Operation of Diablo Canyon Nuclear Power Plant 2*, NUREG-0675, Supplement No. 34, USNRC, June 1991.

U.S. Department of Energy, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, DOE-STD-1020-2002, January 2002.

Wong, H.L. and J.E. Luco, "Soil-Structure Interaction: A Linear Continuum Mechanics Approach (CLASSI)," Report CE, Department of Civil Engineering, University of Southern California, Los Angeles, California, 1980.

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