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Case Study: Effect of Soil-Structure Interaction and Ground Motion Incoherency on Nuclear Power Plant Structures

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ABSTRACT

The soil-structure interaction (SSI) has a significant impact on nuclear power plant (NPP) structures, especially for massive and rigid structures founded on soils, such as containments. The U.S. Nuclear Regulatory Commission's (NRC) Standard Review Plan (SRP) provides the requirement and acceptance criteria for incorporating the SSI effect in the seismic design and analyses of NPP structures. The NRC staff uses the SRP for safety review of license applications. Recent studies have indicated that ground motions in recorded real earthquake events have exhibited spatial incoherency in high-frequency contents. Several techniques have been developed to incorporate the incoherency effect in the seismic response analyses. Section 3.7.2 of Revision 3 of the SRP also provided guidance for use in the safety evaluation of seismic analyses considering ground motion spatial incoherency effect.

This paper describes a case study of the SSI and incoherency effects on seismic response analyses of NPP structures. The study selected a typical containment structure. The SSI model is generated based on the typical industry practice for SSI computation of containment structures. Specifically, a commercial version of SASSI was used for the study, which considered a surface-founded structure. The SSI model includes the foundation, represented with brick elements, and the superstructure, represented using lumped mass and beams. The study considered various soil conditions and ground motion coherency functions to investigate the effect of the range of soil stiffness and the ground motion incoherency effect on SSI in determining the seismic response of the structures.

This paper describes the SSI model development and presents the analysis results as well as insights into the manner in which the SSI and incoherency effects are related to different soil conditions.

INTRODUCTION

Soil-structure interaction (SSI) has a significant impact on nuclear power plant (NPP) structures, especially for massive and rigid structures founded on soils, such as containments. Over the past several decades, both the scientific and engineering community have conducted extensive research on the SSI phenomenon and developed requirements and analytical methods [1] for adequately incorporating the SSI effects into the seismic design and analysis of structures. The U.S. Nuclear Regulatory Commission's (NRC) Standard Review Plan (SRP) [2] specifically includes requirement and acceptance criteria for incorporating the SSI effect in the seismic design and analyses of NPP structures. The NRC staff relies on the SRP for safety review of license applications. Recent studies have indicated that ground motions in recorded real earthquake events have exhibited spatial incoherency in high-frequency contents. Several techniques have been developed to incorporate the incoherency effect in the seismic response analyses. Section 3.7.2 of Revision 3 of the SRP and interim staff guidance [3] also include provisions which provide guidance for use of ground motion spatial incoherency effect in the safety evaluation of seismic analyses associated with license applications.

The NRC performed a case study based on parametric analysis to investigate the effect of soil stiffness and ground motion incoherency on SSI response analyses of NPP structures. Although an abundant body of literature is available which offers diverse analytical methodologies and computational programs for SSI, SASSI [4] emerged to become the standard used for SSI analyses by the nuclear industry. SASSI simplified the complex SSI phenomenon into several smaller subsystems for which solutions can be readily formulated. The subsystems are then assembled to obtain the solution for the SSI response based on the principle of superposition. Recently, several commercial versions of SASSI also incorporated the ground motion incoherency effects, which allow for more realistic consideration of the incoherent nature of seismic input motion in the SSI responses. This study used ASC SASSI [5], developed by Ghiocel Predictive Technologies, Inc.

The study selected a typical pressurized-water reactor (PWR) containment structure (Figure 1). The SSI model is generated based on the typical industry practice for SSI computation of containment structures. The study considered several soil profiles to investigate the effect of the range of soil stiffness on SSI. The study also addressed the ground motion incoherency effects in determining the seismic response of the structures.

This paper describes the SSI model and presents the analysis results as well as insights into the manner in which the SSI and incoherency effects are related to different soil conditions.

SSI MODEL AND ANALYSIS PARAMETERS

NPP containment structures are typically designed to be massive and rigid because of the functional consideration of the nuclear systems housed by them. When founded on soils, the seismic response of NPP structures is typically controlled by coupled soil-structure modes. The SSI model using SASSI in this study employed a lumped mass beams representation for the containment walls and floors, and the foundation basemat was modeled with three-dimensional brick elements. Since the objective of this study focuses on the soil stiffness and ground motion incoherency effects, the analysis employed a rather simplified finite element model for a typical PWR containment, which is shown in Figure 2. The containment sticks are rigidly linked to the foundation basemat at nodal point to maintain the rigid basemat. The structure is considered surface founded, and the media below is modeled as a uniform half-space.

The analysis considered two site conditions: rock and soil sites. For rock site, the shear wave velocity was varied between 2,000 feet per second (ft/s) and 8,000 ft/ s, encompassing soft to hard rocks. For soil site, the parameter for shear wave velocity varied between 600 ft/s and 2,000 ft/s. The ground motion input for the rock site employed a ground motion response spectrum typical of Eastern United States sites, which is characterized by rich energy in high frequencies (greater than 10 hertz (Hz)). For the soil site, the analysis used the Regulatory Guide (RG) 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants" [6] horizontal spectrum. Figure 3 depicts the input response spectra as input to SSI analyses. Both spectra are calculated at 5-percent damping. The rock spectrum is anchored to 0.5g peak ground acceleration (PGA), while the RG 1.60 spectrum is anchored to 0.3g PGA. Since the frequency-domain time history analyses were performed, synthetic time histories compatible with the seismic input spectra were developed using PCARES [7].

ACS SASSI considers the spatial variability of the ground motion by means of either a stochastical or deterministic approach. This study employs the deterministic approach, which is based on specifying coherency functions that are empirically obtained. The unlagged coherency function developed by Abrahamson [8] in 2005 for soil sites was applied to the SSI analyses for soil site, while the unlagged coherency function also developed by Abrahamson [9] in 2007 was employed for the SSI analyses for rock site. The Abrahamson models were based on regression analyses of recorded data from dense arrays. The unlagged coherency function is used because of the vertically propagating wave assumed in the study.

ANALYSIS RESULTS AND DISCUSSIONS

This section discusses the analysis results which are presented in terms of the 5-percent damped floor response spectra calculated at the basemat center and the containment top. As mentioned previously, the study investigated two aspects—soil stiffness and ground motion incoherency effect. For soil stiffness, the soil shear wave velocity varied between 600 ft/s and 2,000 ft/s, while for rock site, the range of shear wave velocity varied between 2,000 ft/s and 8,000 ft/s. To simply the analysis, the SSI analyses include a vertically propagating SV wave, and specified the seismic input motion at ground surface. The following sections discuss both the effect of soil stiffness and the ground motion incoherency effect.

Foundation Media Stiffness Effect

Figures 4 and 7 present the response spectra calculated at basemat center and containment top, respectively. To investigate the soil stiffness effect, coherent input motions were applied for the SSI analyses. As shown in Figures 4 and 5 for soil site, the energy content in the response spectra tends to shift to higher frequencies as the site becomes stiffer. A similar tendency is also observed for rock site responses, as shown Figures 6 and 7, except that, for rock site, as the site stiffness becomes greater than 4,000 ft/s, the shift in energy content becomes significantly less pronounced. The higher stiffness associated with rock site essentially converges to the fixed-based boundary condition for the structure.

Incoherency Effect of Ground Motion

To investigate the incoherency effect on SSI response, the SSI analysis used the unlagged coherency functions. The coherency function is a decreasing function of frequencies, with higher frequency response tending to be more incoherent (or out of phases in the time space). Thus, one would expect a decrease in response amplitudes for high-frequency vibration modes. Let us first examine the calculated response spectra for soil site, which are shown in Figures 8 and 9. As depicted in these figures, the responses for coherent and incoherent seismic inputs are practically identical. Note that the RG 1.60 spectrum has the seismic energy concentrated between 1 and 10 Hz. As discussed in the previous section, typical empirically developed coherency function affects the vibration modes at 10 Hz and above. Therefore, SSI analyses for soil sites remain valid based on coherent seismic inputs which have the practice for soil sites in the past.

In contrast to soil sites, for rock sites, especially for the Eastern United States rock sites, ground motions based on site-specific probabilistic seismic hazard analyses are generally characterized with high-energy content in frequencies 10 Hz and above. When the high-frequency ground motion is applied to the SSI model, it is expected that out-of-phase high-frequency modes will be randomly distributed across the foundation footprint in accordance with the specified coherency function. Such incoherency effect should therefore reduce the high-frequency response. Figures 10 through 15 show the calculated response spectra using high-frequency seismic input in conjunction with the incoherency function and their comparisons with respective responses based on coherent seismic input. It is readily seen from these figures that the high-frequency responses are reduced significantly and in some cases are practically eliminated. These figures also show that, for frequencies below 10 Hz, the spectral amplitudes are practically identical between incoherent and coherent ground inputs further substantiating the analysis results for the soil site.

CONCLUSIONS

This paper presents a case study to investigate the soil stiffness and ground motion incoherency effects on seismic response of NPP structures. The study used a typical PWR containment model with two site conditions: rock and soil sites. SSI analyses were performed for rock and soil sites with seismic motions and coherency functions pertinent to the particular site conditions. This paper presented and discussed the results of the analysis. The NRC staff concluded that the response in terms of response spectra showed shifts in energy toward higher frequency as a site becomes stiffer. The study also showed that considering the incoherency effect on ground input motion reduces the high-frequency response of 10 Hz and above; however, the incoherency effect showed practically no impact on the soil site.

DISCLAIMER NOTICE

The NRC staff prepared this paper. It may present information that does not currently represent an agreed upon NRC staff position. The findings and opinions expressed in this paper are those of the authors and do not necessarily reflect the views of the NRC.

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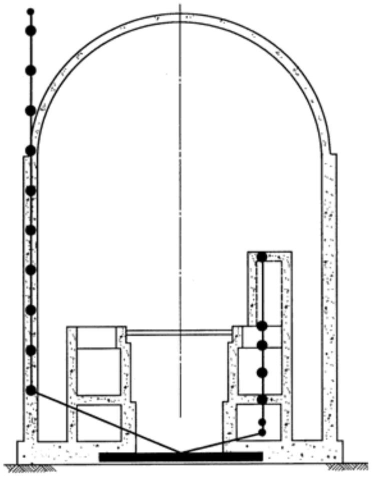

FIGURE 1 TYPICAL PWR CONTAINMENT

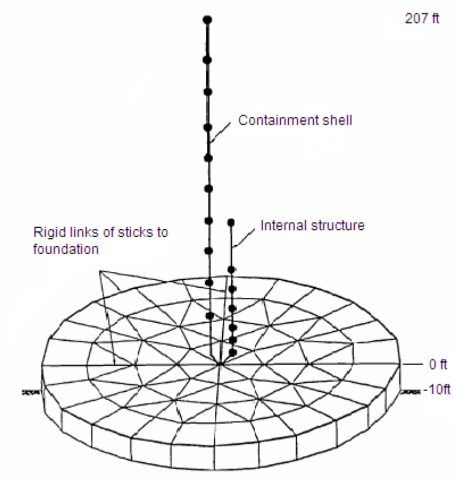

FIGURE 2 SIMPLE SURFACE-FOUNDED LUMPED MASS BEAM MODEL

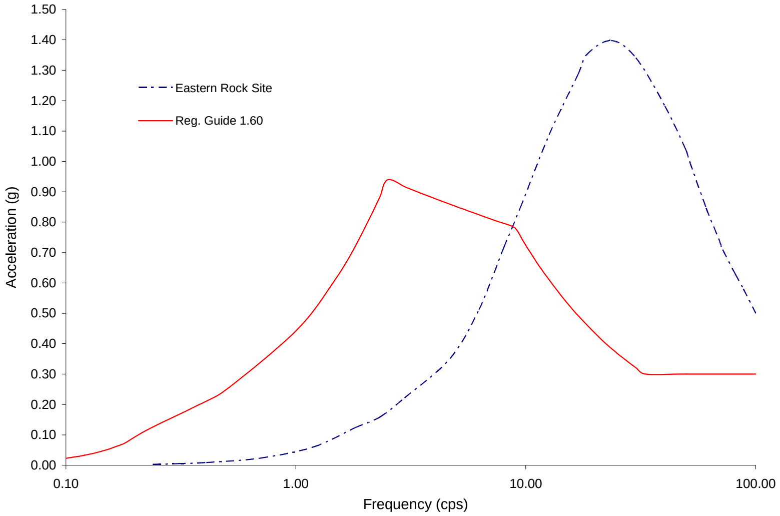

FIGURE 3 GROUND MOTION INPUT SPECTRA

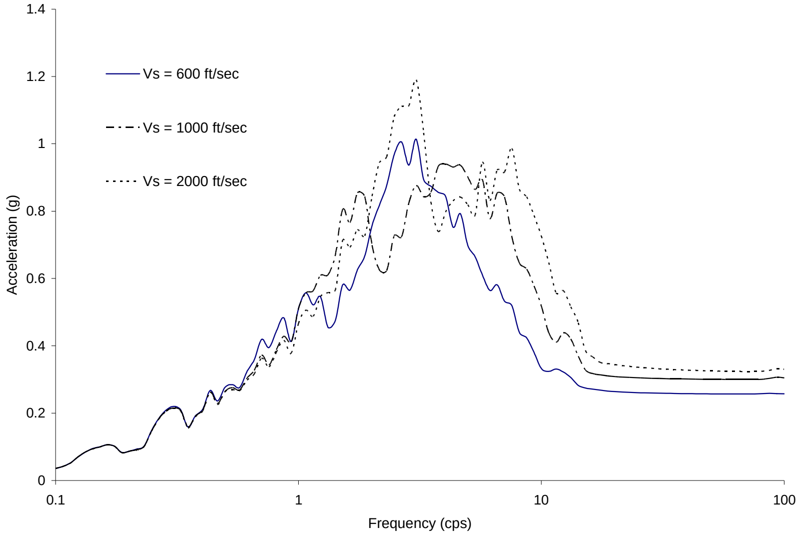

FIGURE 4 BASEMAT RESPONSE SPECTRA WITH RG 1.60 COHERENT INPUT

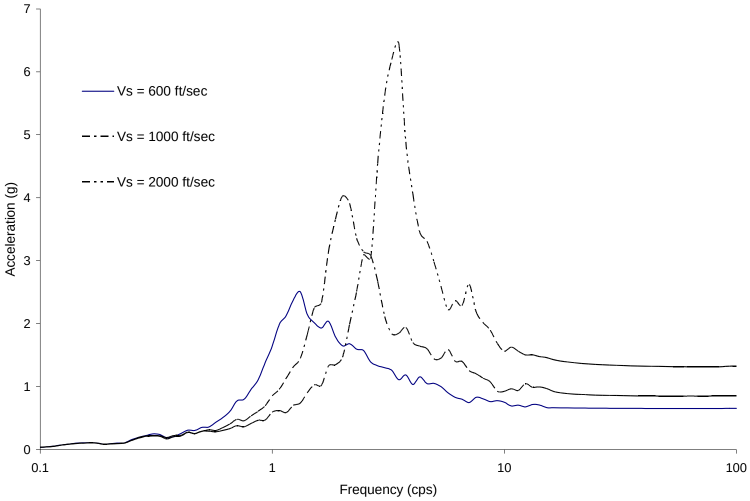

FIGURE 5 TOP RESPONSE SPECTRA WITH RG 1.60 COHERENT INPUT

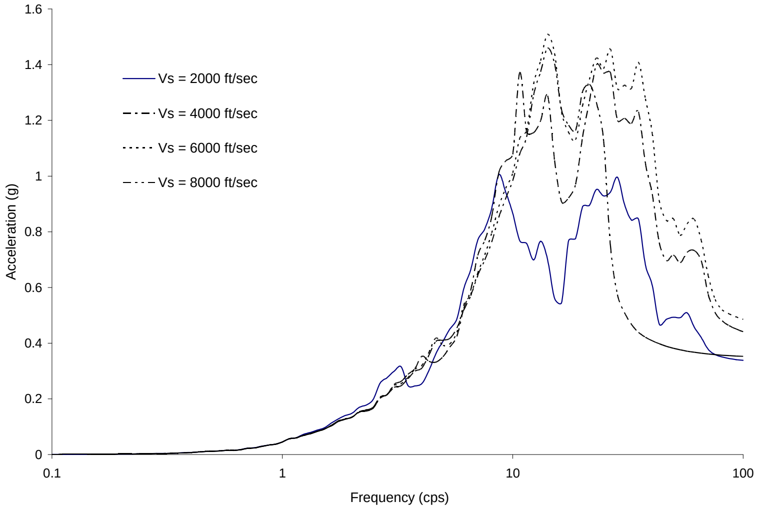

FIGURE 6 BASEMAT RESPONSE SPECTRA WITH HIGH-FREQUENCY COHERENT INPUT

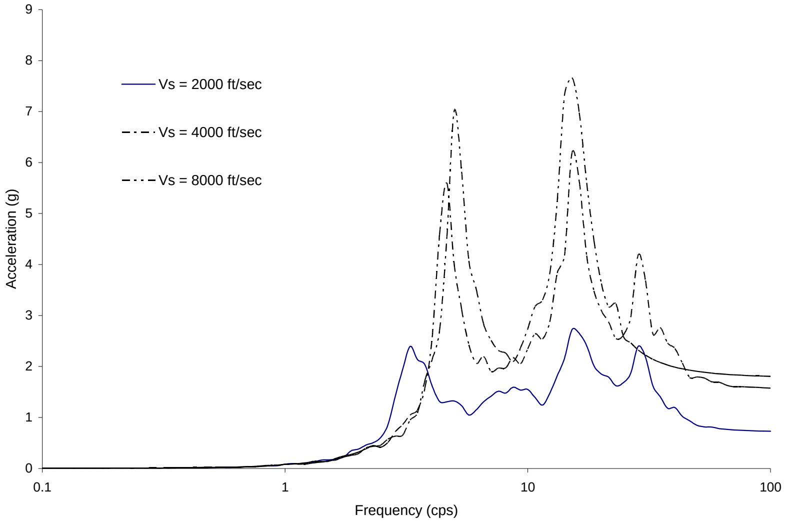

FIGURE 7 TOP RESPONSE SPECTRA WITH HIGH-FREQUENCY COHERENT INPUT

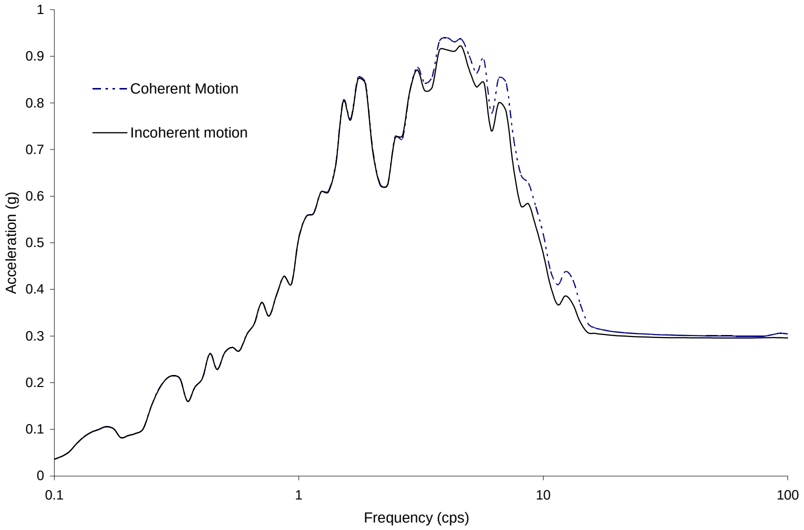

FIGURE 8 BASEMAT RESPONSE SPECTRA WITH RG 1.60 AND SOIL VS = 1,000 FT/S

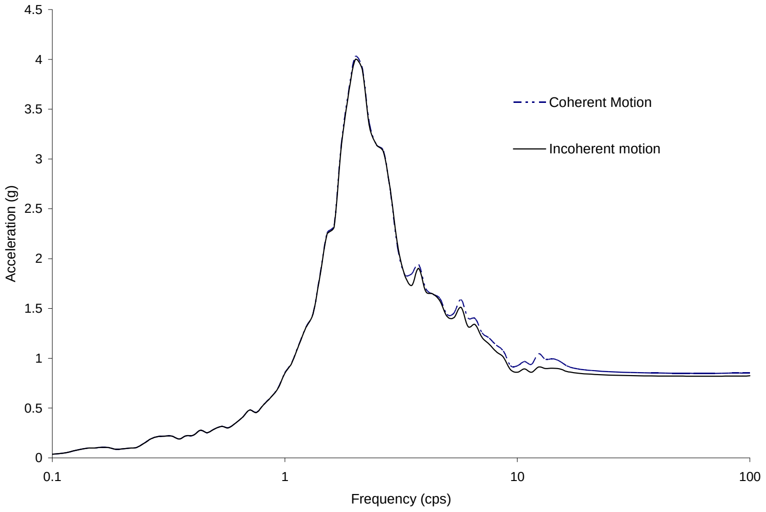

FIGURE 9 TOP RESPONSE SPECTRA WITH RG 1.60 AND SOIL VS = 1,000 FT/S

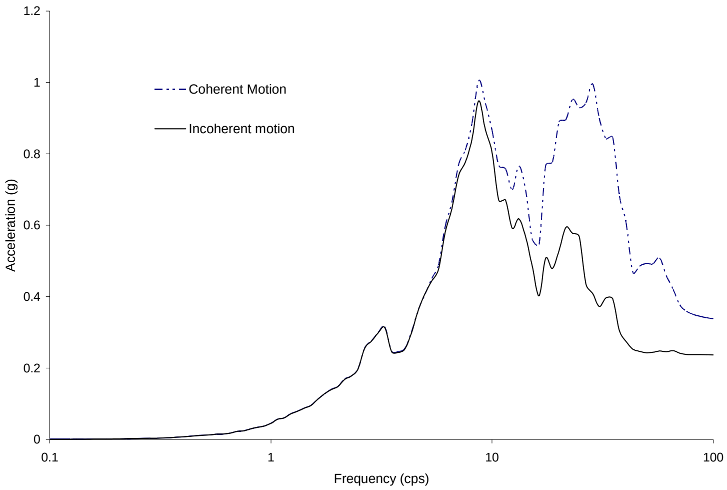

FIGURE 10 BASEMAT RESPONSE SPECTRA WITH HIGH-FREQUENCY INPUT AND SOIL VS = 2,000 FT/S

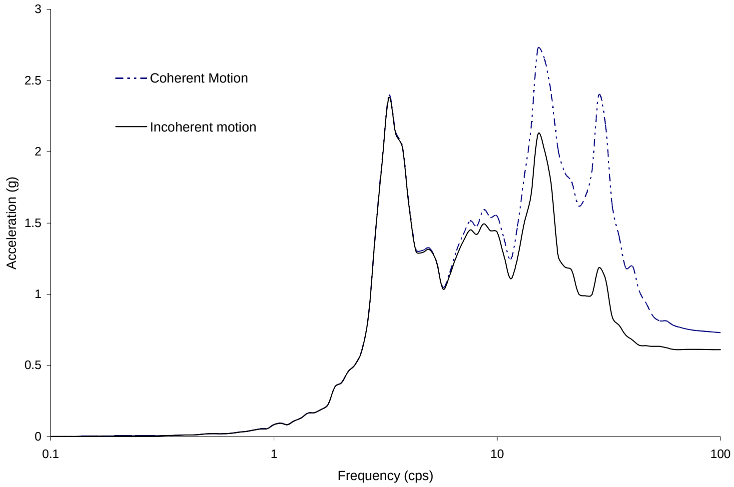

FIGURE 11 TOP RESPONSE SPECTRA WITH HIGH-FREQUENCY INPUT AND SOIL VS = 2,000 FT/S

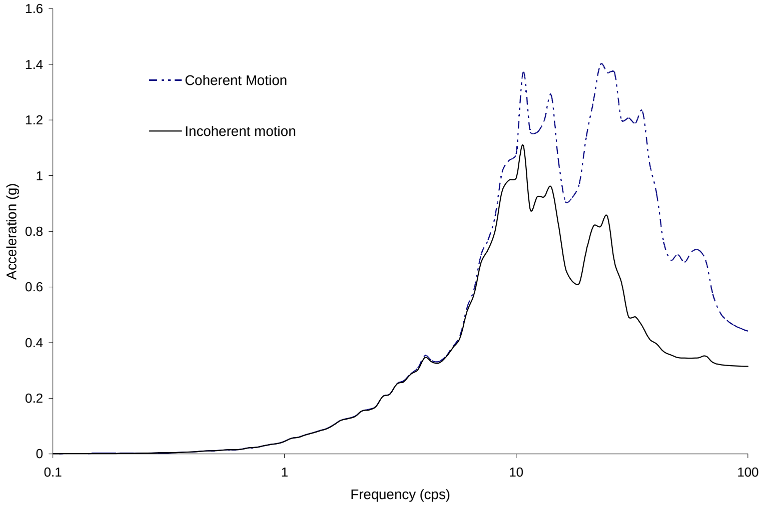

FIGURE 12 BASE RESPONSE SPECTRA WITH HIGH-FREQUENCY INPUT AND SOIL VS = 4,000 FT/S

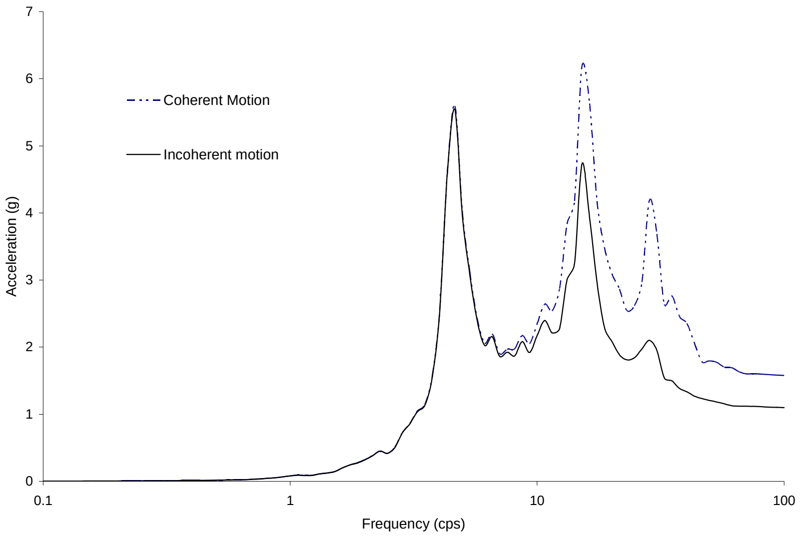

FIGURE 13 TOP RESPONSE SPECTRA WITH HIGH-FREQUENCY INPUT AND SOIL VS = 4,000 FT/S

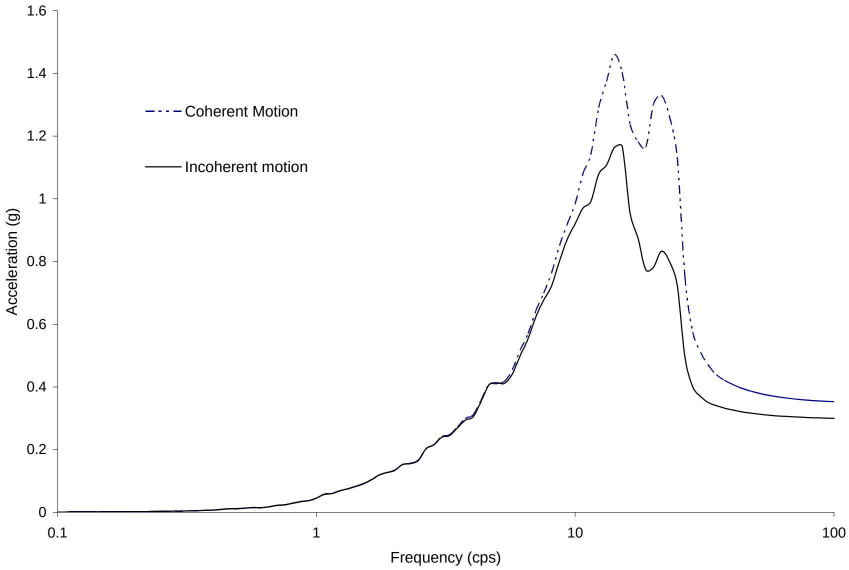

FIGURE 14 BASE RESPONSE SPECTRA WITH HIGH-FREQUENCY INPUT AND SOIL VS = 8,000 FT/S