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Case Study: Effect of SSI and Ground Motion Incoherency on NPP Structures

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ABSTRACT

It has been recognized that the soil-structure interaction (SSI) has significant impact on nuclear power plant (NPP) structures, especially for massive and rigid structures founded on soils such as containments. Requirement and acceptance criteria for incorporating the SSI effect in the seismic design and analyses of NPP structures are provided in the Nuclear Regulatory Commission (NRC) standard review plan (SRP), which the NRC staff uses 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 SRP, rev.3 also provided guidance foe use in 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. A typical containment structure is selected for the study. 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 and surface founded structure considered. The SSI model includes the foundation represented with brick elements and the superstructure represented using lumped mass and beams. Various soil conditions and ground motion coherency functions are considered to investigate the effect of the range of soil stiffness and ground motion incoherency effect on SSI in determining the seismic response of the structures.

This paper provides a description 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

It has been recognized that the soil-structure interaction (SSI) has 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 researched extensively on the SSI phenomenon and have developed requirements and analytical methods [1] for adequately incorporating the SSI effects into the seismic design and analysis of structures. Requirement and acceptance criteria for incorporating the SSI effect in the seismic design and analyses of NPP structures were specifically included in the Nuclear Regulatory Commission (NRC) Standard Review Plan (SRP) [2], which the NRC staff relies on 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 SRP, rev.3 and Interim Staff Guidance (ISG)[3] also included provisions which provide guidance foe use of ground motion spatial incoherency effect in the safety evaluation of seismic analyses associated with license applications.

A case study is performed 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 literature is available which offers

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diverse analytical methodologies and computational programs for SSI, SASSI [4] emerged to become the standard used for SSI analyses by the nuclear industry. The reason is that SASSI simplified the complex SSI phenomenon into several smaller subsystems whose solutions can readily be 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 allows for more realistic consideration of incoherent nature of seismic input motion in the SSI responses. This study will use ASC SASSI[5], which was developed by Ghiocel Predictive Technologies, Inc.

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

This paper describes 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 due to functional consideration of 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 uses lumped mass beams representation for the containment walls and floors and the foundation basemat is modeled with 3-D brick elements. Since the objective of this study focuses on the soil stiffness and ground motion incoherency effects, a rather simplified finite element model (FEM) for a typical PWR containment (Figure 1) is employed, 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.

Two site conditions are considered, rock and soil sites, respectively. For rock site, the shear wave velocity is varied in a range of 2000 ft/sec to 8000 ft/sec, encompassing soft to hard rocks. For soil site, the parameter for shear wave velocity varies between 600 ft/sec and 2000 ft/sec. The ground motion input for the rock site employs a ground motion response spectrum typical of Eastern US sites, which is characterized by rich energy in high frequencies (greater than 10 Hz). For the soil site, Regulatory Guide (RG) 1.60 [6] horizontal spectrum is used. Figure 3 depicts the input response spectra as input to SSI analyses. Both spectra are calculated at 5% damping. The rock spectrum is anchored to 0.5g peak ground acceleration (PGA), while RG 1.60 spectrum is anchored to 0.3g PGA. Since the frequency-domain time history analyses are performed, synthetic time histories compatible with the seismic input spectra are developed using PCARES [7].

The spatial variability of the ground motion is considered in ACS SASSI by means of either stochastical or deterministic approach. In this study, the deterministic approach is employed, 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 is employed for the SSI analyses for rock site. The Abrahamson's models were based on regression analyses of recorded data from dense arrays. The reason for the use of unlagged coherency function is due to the vertically propagating wave assumed in the study.

ANALYSIS RESULTS AND DISCUSSIONS

This section presents and discusses the analysis results which are presented in terms of 5% damped floor response spectra calculated at the basemat center and the containment top. As mentioned previously, two aspects are investigated: soil stiffness and ground motion incoherency effect. For soil stiffness, the soil shear wave velocity is varied between 600 ft/sec and 2000 ft/sec while for rock site, the range of shear wave velocity between 2000 ft/sec and 8000 ft/sec is considered. To simply the analysis, vertically propagating SV wave is included in the SSI analyses and the seismic input motion is specified at ground surface. The effect of soil stiffness is discussed first followed by a discussion of 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 are 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 become larger than 4000 ft/sec, the shift in energy content becomes significantly less pronounced. This is because 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 unlagged coherency function is used in the SSI analysis. The coherency function is a decreasing function of frequencies which higher frequency response tends to be more incoherent (or out of phases in the time space); thereby one would expect the decrease in response amplitudes for high frequency vibration modes. Let's first examine the calculated response spectra for soil site, which are shown in Figures 8 and 9. As depicted in this figure, the responses for coherent and incoherent seismic inputs are practically identical. Note that

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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 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, rock sites, especially for the Eastern US rock sites, ground motions based on site-specific probabilistic seismic hazard analyses (PSHA) 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 thru. 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. It is also observed 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 presented a case study to investigate the soil stiffness and ground motion incoherency effects on seismic response of NPP structures. A typical PWR containment model was employed 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. The analysis results were presented and discussed in this paper. It was concluded that the response in terms of response spectra shows shifts in energy toward higher frequency as site becomes stiffer. It was also shown 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

This paper was prepared by staff of the U.S. Nuclear Regulatory Commission (NRC). 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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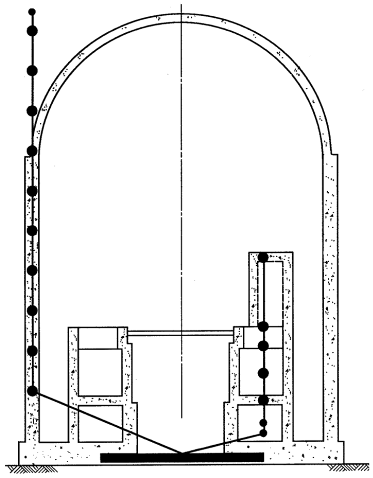

FIGURE 1 TYPICAL PWR CONTAINMENT.

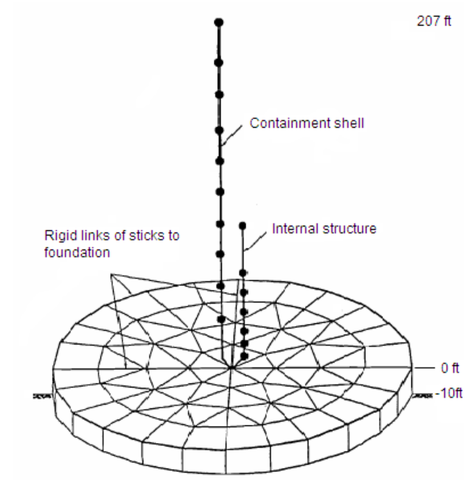

FIGURE 2 SIMPLE SURFACE FOUNDED LUMPED MASS BEAM MODEL.

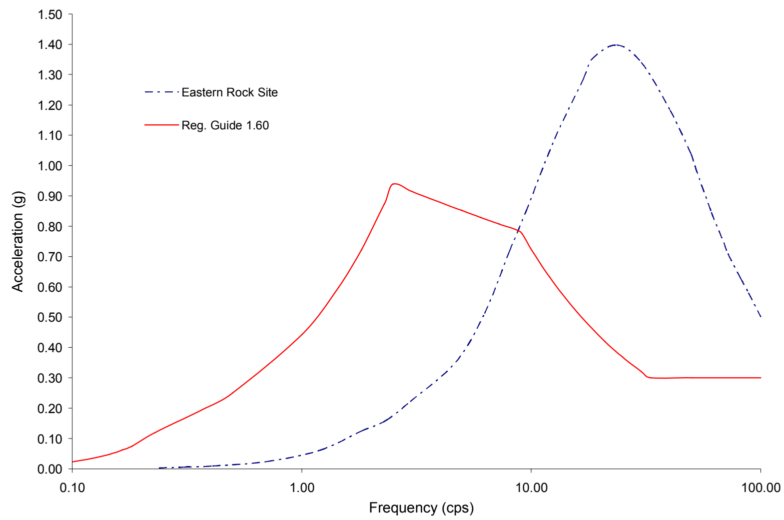

FIGURE 3 GROUND MOTION INPUT SPECTRA

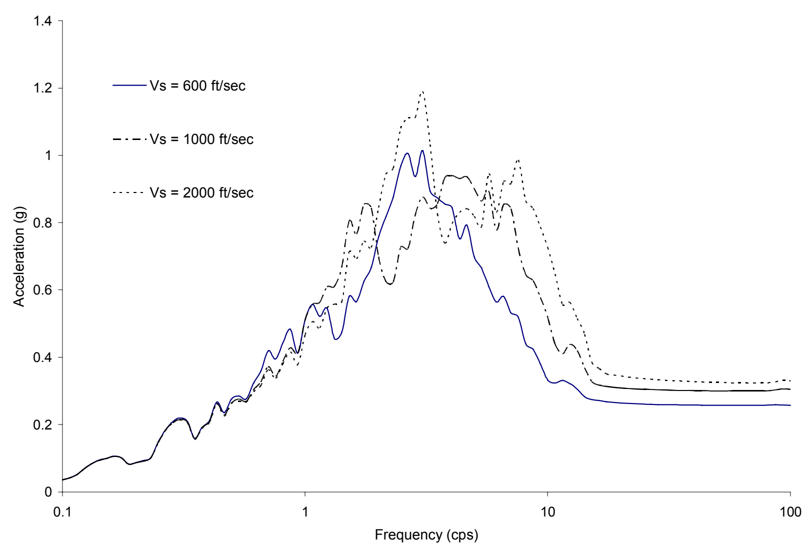

FIGURE 4 BASEMAT RESPONSE SPECTRA WITH RG1.60 COHERENT INPUT

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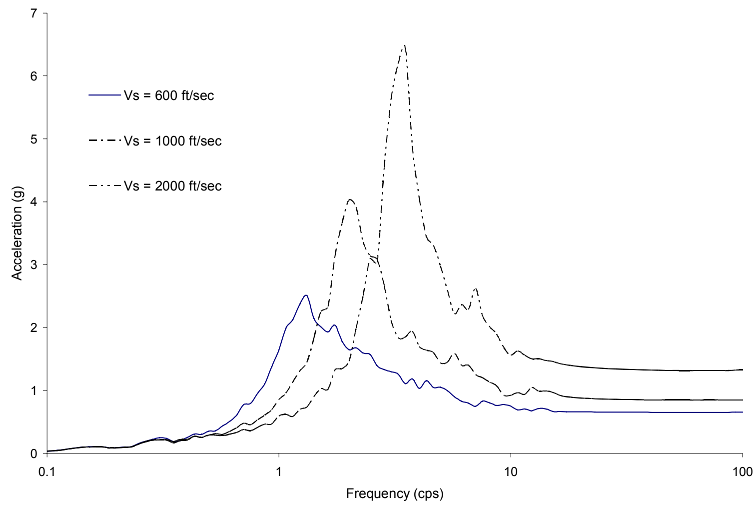

FIGURE 5 TOP RESPONSE SPECTRA WITH RG1.60 COHERENT INPUT

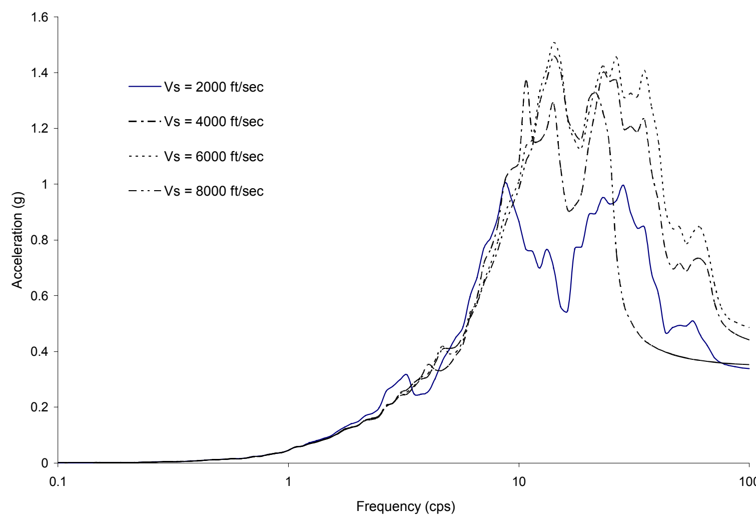

FIGURE 6 BASEMAT RESPONSE SPECTRA WITH HIGH FREQUENCY COHERENT INPUT

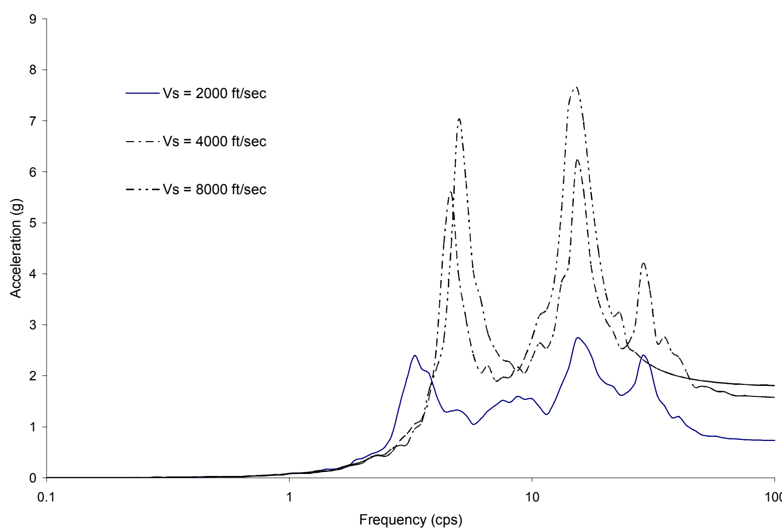

FIGURE 7 TOP RESPONSE SPECTRA WITH HIGH FREQUENCY COHERENT INPUT

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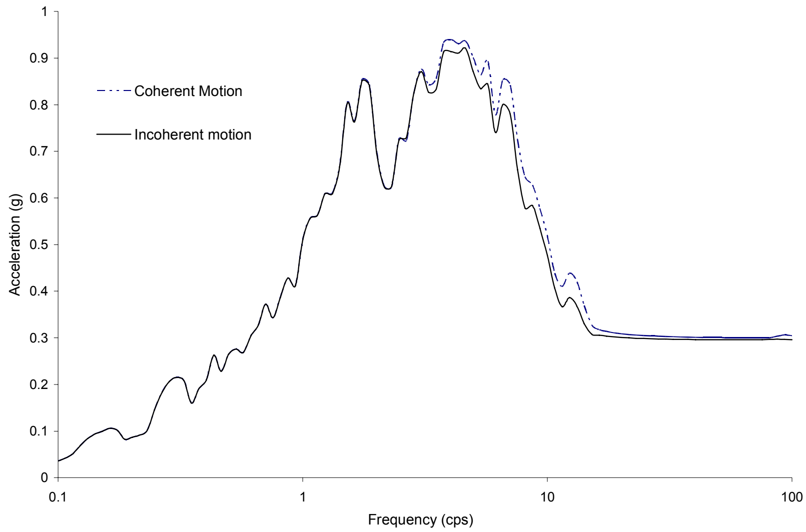

FIGURE 8 BASEMAT RESPONSE SPECTRA WITH RG 160 AND SOIL VS = 1000 FT/SEC

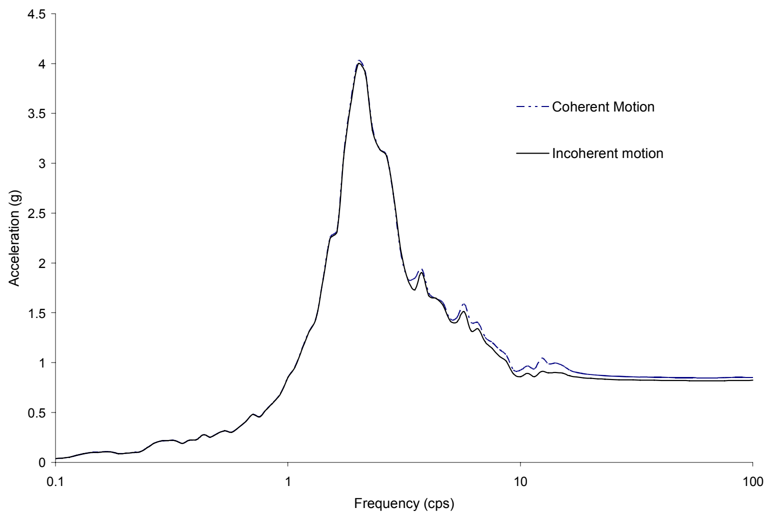

FIGURE 9 TOP RESPONSE SPECTRA WITH RG 160 AND SOIL VS = 1000 FT/SEC

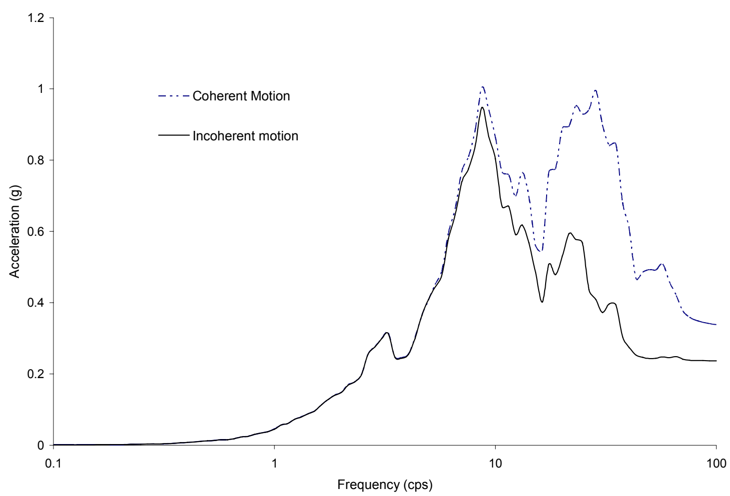

FIGURE 1 BASEMAT RESPONSE SPECTRA WITH HIGH FREQUENCY INPUT AND SOIL VS = 2000 FT/SEC

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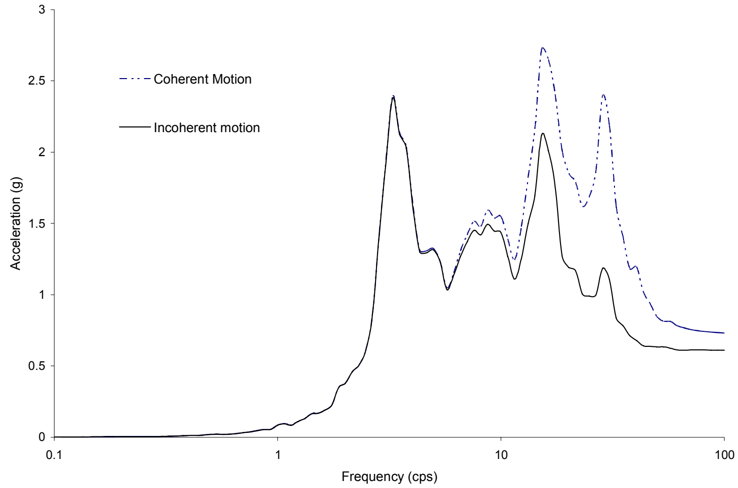

FIGURE 11 TOP RESPONSE SPECTRA WITH HIGH FREQUENCY INPUT AND SOIL VS = 2000 FT/SEC

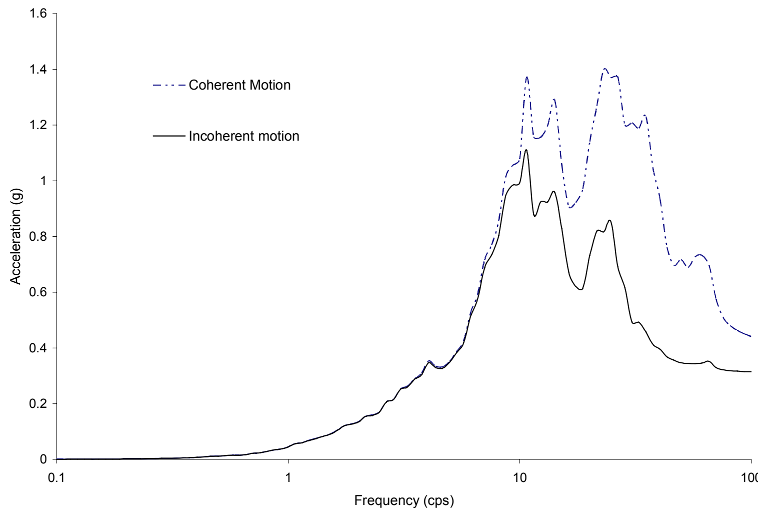

FIGURE 12 BASE RESPONSE SPECTRA WITH HIGH FREQUENCY INPUT AND SOIL VS = 4000 FT/SEC

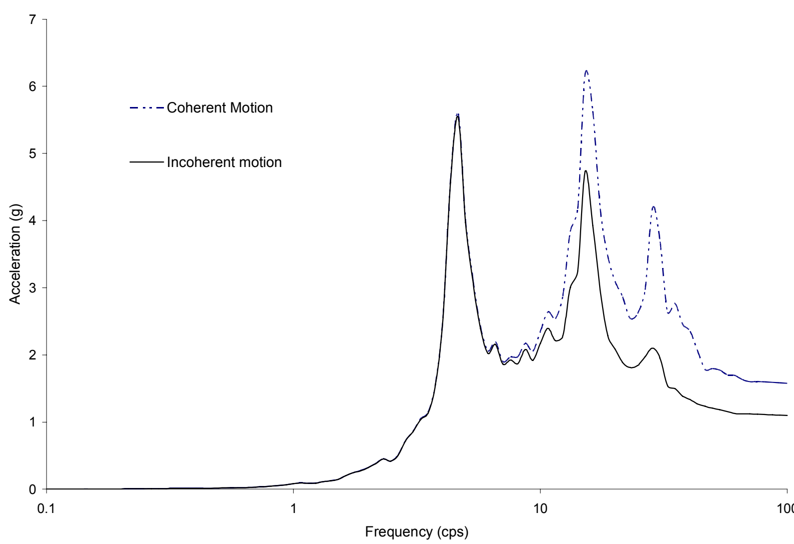

FIGURE 13 TOP RESPONSE SPECTRA WITH HIGH FREQUENCY INPUT AND SOIL VS = 4000 FT/SEC

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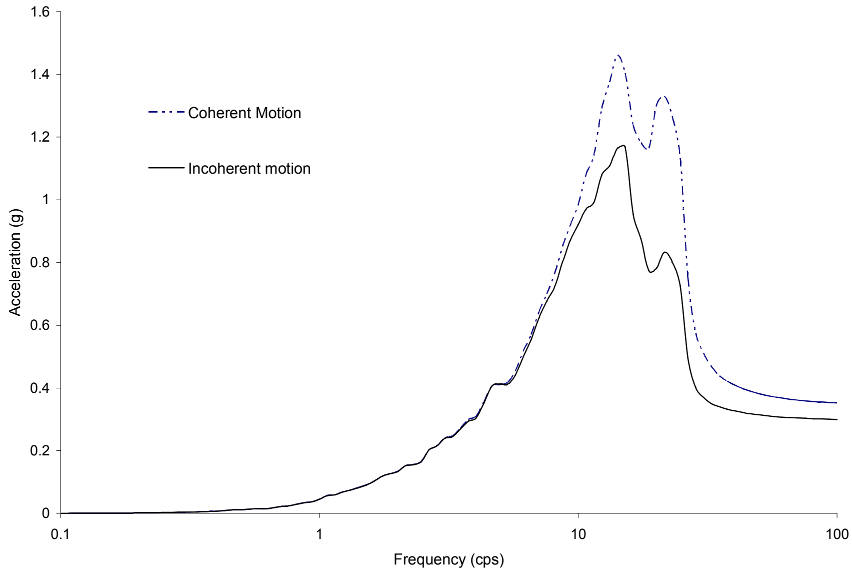

FIGURE 14 BASE RESPONSE SPECTRA WITH HIGH FREQUENCY INPUT AND SOIL VS = 8000 FT/SEC

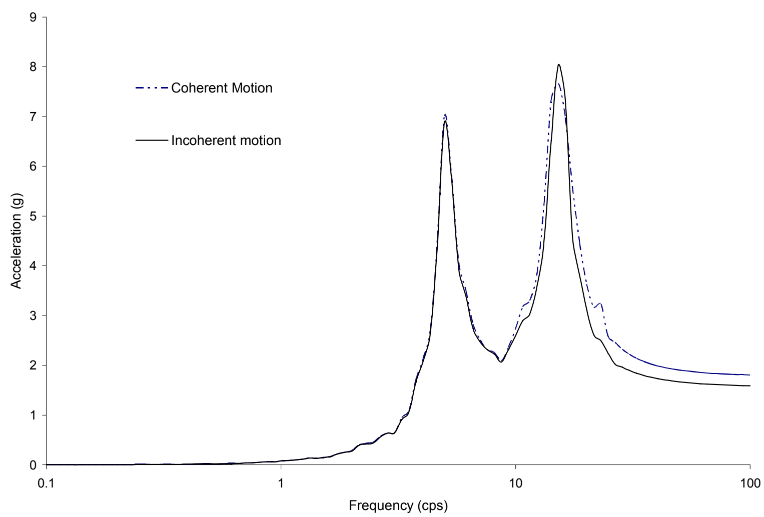

FIGURE 15 TOP RESPONSE SPECTRA WITH HIGH FREQUENCY INPUT AND SOIL VS = 8000 FT/SEC

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