

SOIL-STRUCTURE INTERACTION ANALYSIS INCLUDING GROUND MOTION INCOHERENCY EFFECTS

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ABSTRACT

For critical nuclear facilities located at soil sites, soil-structure interaction (SSI) analysis is required to develop seismic responses of the structures, systems and components. Such analyses are generally performed using the design motion by assuming a coherent wave field often consisting of vertically propagating shear and P-waves. The wave passage effects can also be considered depending on the seismic setting of the facility. Review of strong ground motion arrays from several dense arrays on soil and rock sites indicates that ground motion coherency reduces as frequency and separation distance of the monitoring points increase. These observations have resulted in several ground motion "incoherency" models to best represent the observed data. In this paper implementation of the most recent ground motion incoherency model in the Computer Program SASSI2000 is discussed. The results in terms of foundation scattered motion is compared with the fully coherent motion for a rock site and a typical 2000-year design motion for Western US (WUS). The incoherency model was also applied to a nuclear facility on a stiff soil site and the differences in the results are presented and discussed.

Keywords: Incoherency, SSI, Foundation Motion, SASSI2000.

1. INTRODUCTION

Spatial variation of ground motion from field observations has been recognized for many years. These effects are caused by many attributes changing both the amplitude and phase angles of recorded motions at the dense array locations of the same site. These effects are mainly caused by the seismic source-rupture characteristics, the wave passage effects and the directional dependence, and the scattering due to site inhomogeneity. A detailed description of the attributes to spatial variability of ground motion is discussed by Kausel et al. (2000). Many researchers have used the recorded field data and modeled the spatial variation stochastically (Kausel et al, 2000). The discussion of the spatial variation of ground motion and the current models to characterize the variation is beyond the scope of this paper. The emphasis of this paper is on the effects

of spatial variation of ground motion on seismic SSI responses using the most recent ground motion incoherency model.

2. GROUND MOTION INCOHERENCY MODEL AND ITS IMPLEMENTATION IN SASSI2000

The coherency function between the two ground motions at points “i” and “j” is defined as

$$\gamma_{ij}(\omega) = \frac{S_{ij}(\omega)}{\sqrt{S_{ii}(\omega)S_{jj}(\omega)}} \quad (1)$$

where $\gamma_{ij}(\omega)$ is the complex coherency function of omega, $S_{ii}(\omega)$ and $S_{jj}(\omega)$ are the power spectral density functions of the time histories at points “i” and “j”, respectively, and $S_{ij}(\omega)$ the cross-spectral density function of the same two motions.

There are several ways the coherency or incoherency can be described: lagged coherency, plane-wave coherency, and unlagged coherency. These three measures of coherency are described below.

The lagged coherency is the most commonly cited coherency measure. It is the coherency measured after aligning the time series using the time lag that leads to the largest modulus of the cross spectrum. There is no requirement that the time lags are consistent between frequencies. In general, the lagged coherency does not go to zero at large separations and high frequencies. The level depends on the number of frequencies smoothed.

The plane-wave coherency differs from the lagged coherency in that it uses a single time lag for all frequencies. That is, it measures the coherency relative to a single wave speed for each earthquake. As a result, the plane-wave coherency is smaller than the unlagged coherency. The plane-wave coherency is found by taking the real part of the smoothed cross-spectrum after aligning the ground motions on the best plane-wave speed. The plane-wave coherency will approach zero at high frequencies and large separations.

Finally, the unlagged coherency measures the coherency assuming no time lag between locations. It is the real part of the smoothed cross-spectrum. The unlagged coherency is smaller than the plane-wave coherency.

Using the recorded data, Abrahamson (1992) has developed several models over time and enhancing the models using the more recent recorded data. The most recent model (Abrahamson, 2005) is based on the data set from 12 different arrays and is considered the most updated ground motion incoherency model for design application. The amplitude of the coherency functions associated with horizontal and vertical motions are presented in Figs. 1 and 2, respectively. As shown, the coherency reduces significantly over distance and with increasing frequency. As a result of such spatial variation of ground motion, the foundation translational motion which is the constrained motion of the free-field motion, constrained by foundation rigidity, is expected to reduce. However, the rocking and torsional motions tend to increase. The effects of ground motion incoherency on the foundation and structural responses are discussed in a later section.

The incoherency model (Abrahamson, 2005) is implemented in the Computer Program SASSI2000 (1999). The formulation of sub-structuring method in SASSI permits direct implementation of the incoherency model on a frequency by frequency basis. The coherency function is used to develop a functional relationship among all interaction nodes in terms of a coherency matrix given the distance among the nodes for each frequency of analysis. The matrix is subsequently reduced to develop the free-field load vector for SSI analysis. The numerical method to develop the free-field vector is presented in the theoretical manual of the next version of the Computer Program SASSI.

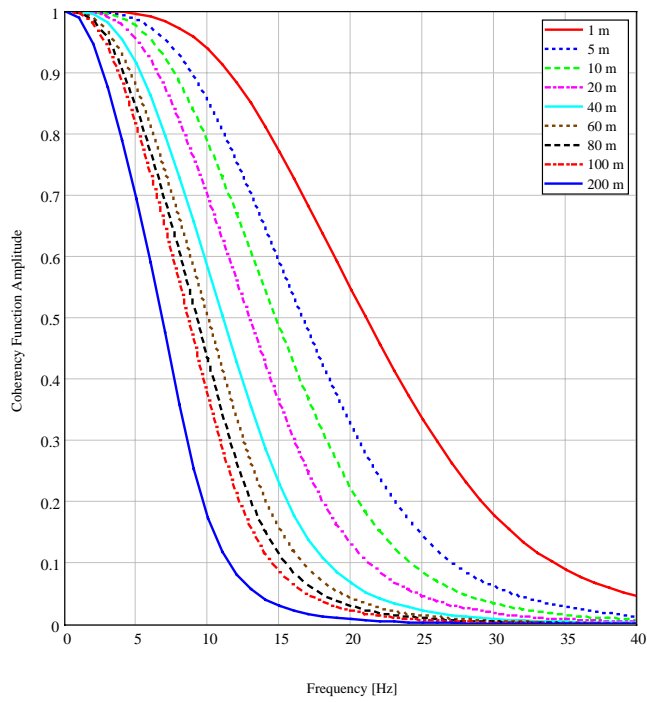


Figure 1 Amplitude of Horizontal Incoherency Function

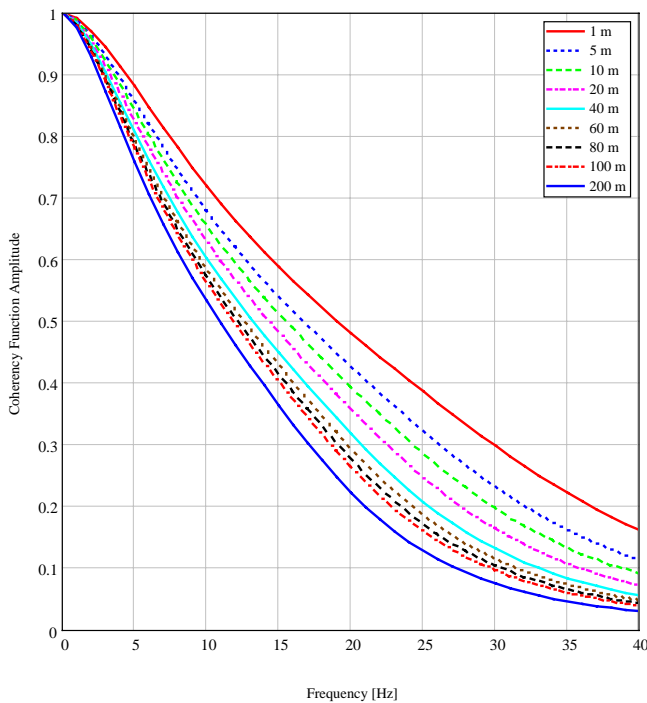


Figure 2. Amplitude of Vertical Incoherency Function

3. SSI CASES

3.1 Surface Rigid Square Foundation

To study the effects on foundation motion, a rigid 150-ft square, massless foundation on the surface of a uniform halfspace with a shear wave velocity of 6300 ft/sec (rock site) was analyzed. Results in terms of the transfer functions at the center of the foundation in the horizontal and vertical directions are shown in Fig. 3 indicating significant reduction of foundation motion at high frequency. It should be noted that for fully coherent motion, the transfer function for a surface rigid massless foundation is unity across the frequency range. The coupling responses of the foundation due to horizontal shaking reflecting the rocking in both directions and torsional motions are shown in Fig. 4. The increase in the coupling response is small. To evaluate the impact on the foundation motion in terms of acceleration response spectra, a typical WUS design motion was used in the analysis. The foundation motion in horizontal and vertical directions are shown in Figs. 5 and 6, respectively. The result for the coherent motion is the same as the input motion. As depicted in these two figures, the reduction of motion at high frequency, in the critical range important for equipment qualification and design, is significant.

3.2 SSI Analysis of a Vitrification Building

The construction of the vitrification facility of the River Protection Project (RPP), Waste Treatment Plant (WTP), in the Hanford Reservation in the State of Washington is progressing at this time. The facility is planned to vitrify nearly 205 million liters of radioactive and chemical wastes currently stored in 177 underground tanks at the Hanford site some of which date back to World War II. The vitrification process mixes waste into sturdy glass. The glass will be stored partly at the site and partly off-site.

The facility consists of several large complex structures that are categorized as Seismic Category I, following the US Department of Energy guidelines. The High Level Waste (HLW) is the main structure with a composite steel framing and concrete shear wall structural system inter-connected at multi-story levels. The shielding requirements stipulate concrete walls up to 4-ft thick and concrete slabs that range in thickness from 1 ft to 3 ft. The footprint of each of these buildings is about 240 ft by 320 ft, rising above grade level to Elevation 70 ft.

At the location of the facility, the site is a very deep soil site consisting primarily of dense to very dense sand and gravel layers. The shear wave velocity at the sites varies from 1200 ft/sec to over 2000 ft/sec at the depth of 150 ft. The details on the plant layout structural design and SSI analysis of the facility was published by Ostadan et. al (2003).

For the purpose of this study a simple beam stick model of the HLW structure was used. The structure was placed on the surface of soil profile to exclude the embedment effects for clear evaluation of the incoherency effects in this study. The SASSI beam stick model of the HLW building is shown in Fig. 7.

The results of analysis in terms of acceleration response spectra at the major floor of the building (Elevation 57 ft) in the horizontal and vertical directions are shown in Figs. 8 and 9, respectively. As shown in these figures, even at the soil sites with the design motion typical of WUS design motion, containing much less energy in the high frequency range as compared with the EUS design motions, the effect of ground motion incoherency is significant. The reduction results in less seismic demand for equipment analysis and qualification.

4. CONCLUSIONS

The observation of ground motion recorded data from dense arrays suggests strong incoherency effects in the free-field motion. Consideration for the ground motion incoherency effects in SSI analysis for structures on large foundations for stiff to rock sites shows significant reduction of the structural responses, particularly in the high frequency range. The study of the ground motion incoherency effects on structural responses will continue. The outcome of the study is scheduled to be implemented in the forthcoming version of the ASCE 4-98 in terms of foundation motion reduction factors to be used for design application.

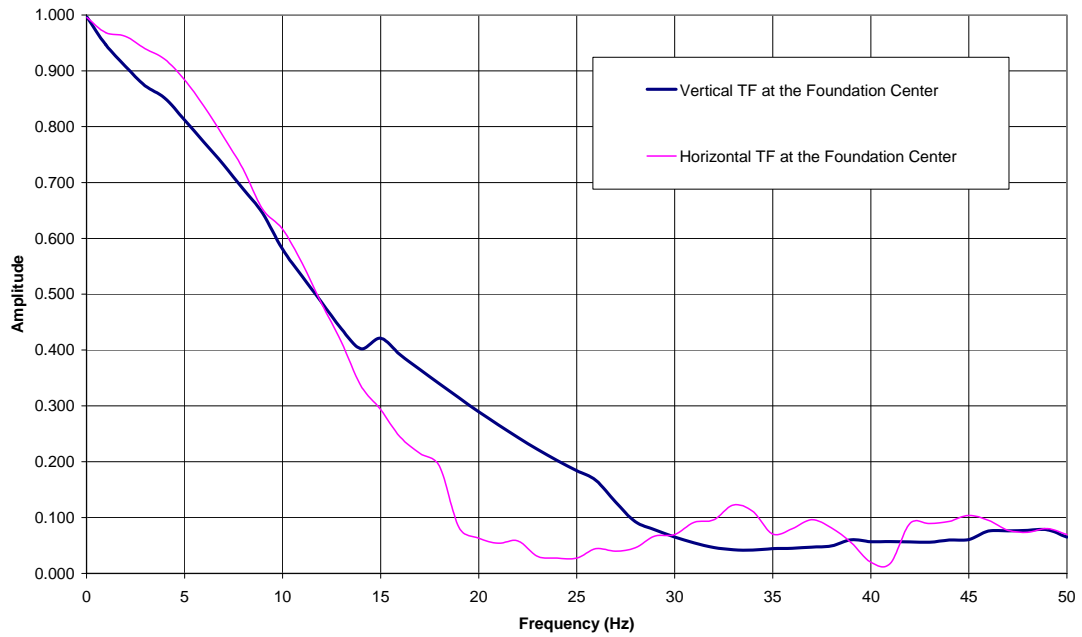


Figure 3. Horizontal and Vertical Response Transfer Functions of the Foundation Motion (Rigid Massless Square Foundation)

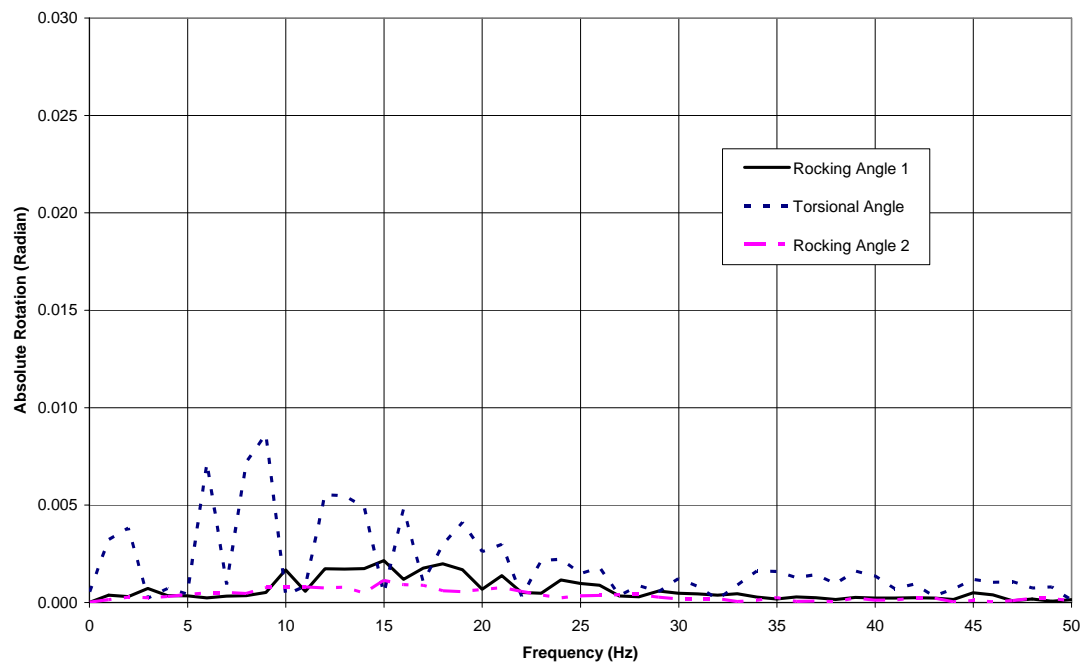


Figure 4. Coupling Response Transfer Functions of the Foundation Motion (Rigid Massless Square Foundation)

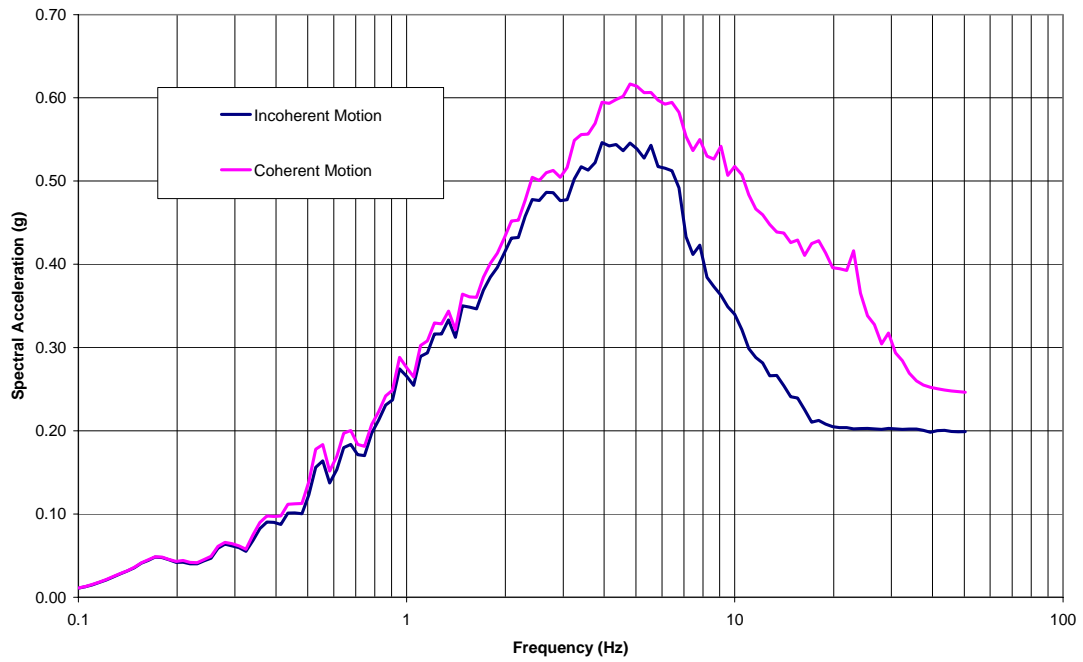


Figure 5. Foundation Motion in the Horizontal Direction (5% Damping)
(Rigid Massless Square Foundation)

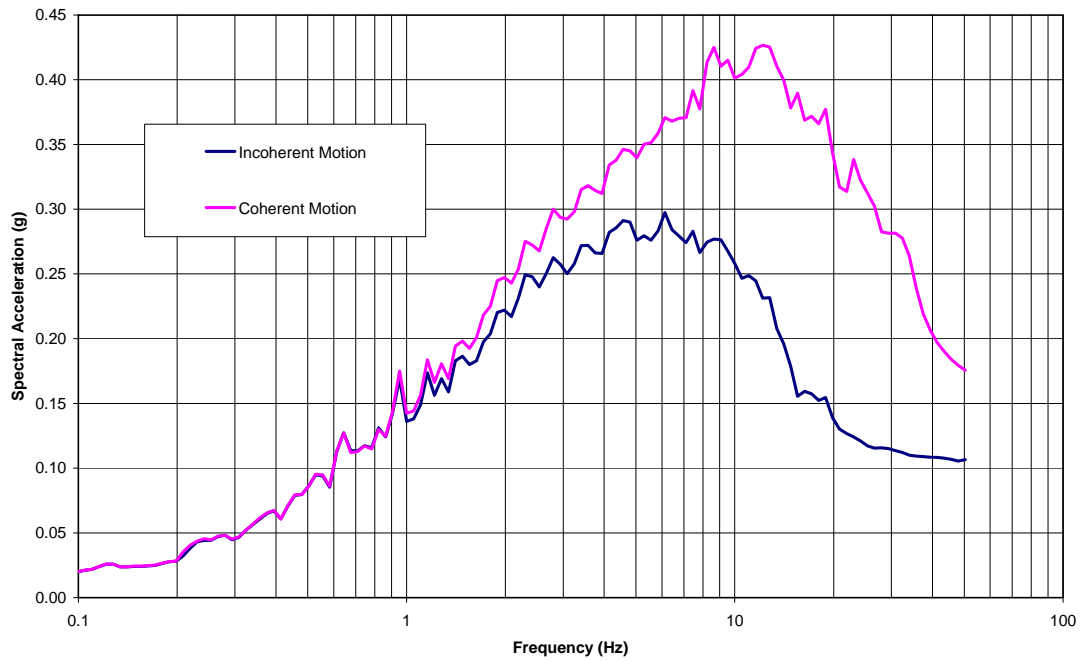


Figure 6. Foundation Motion in the Vertical Direction (5% Damping)
(Rigid Massless Square Foundation)

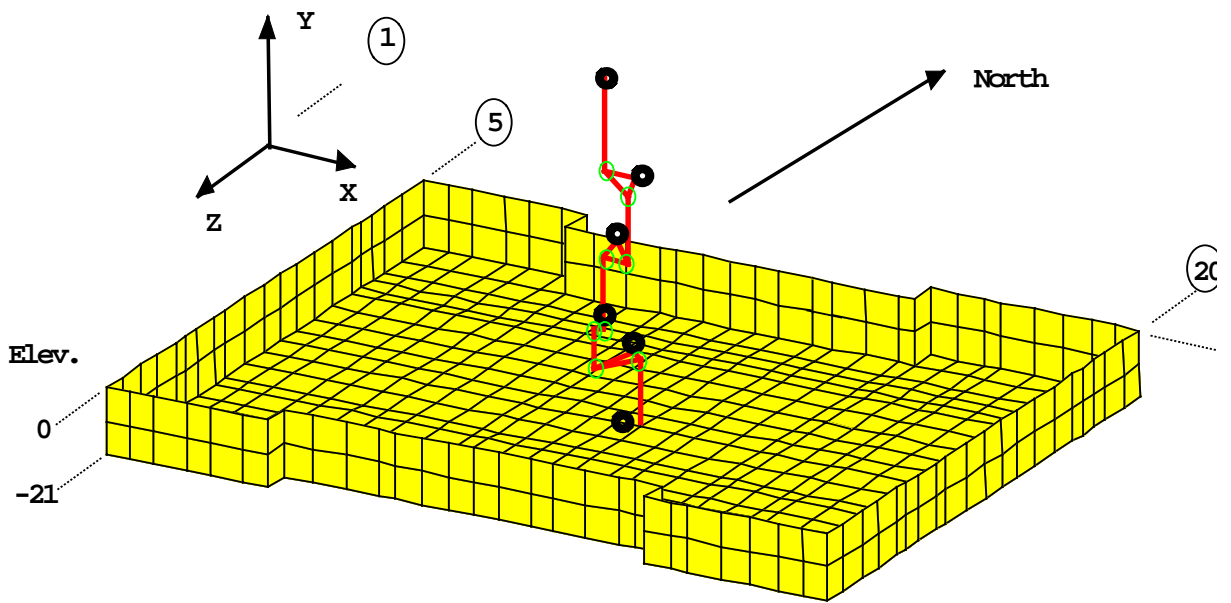


Figure 7. SASSI Beam Stick Model of the HLW Building

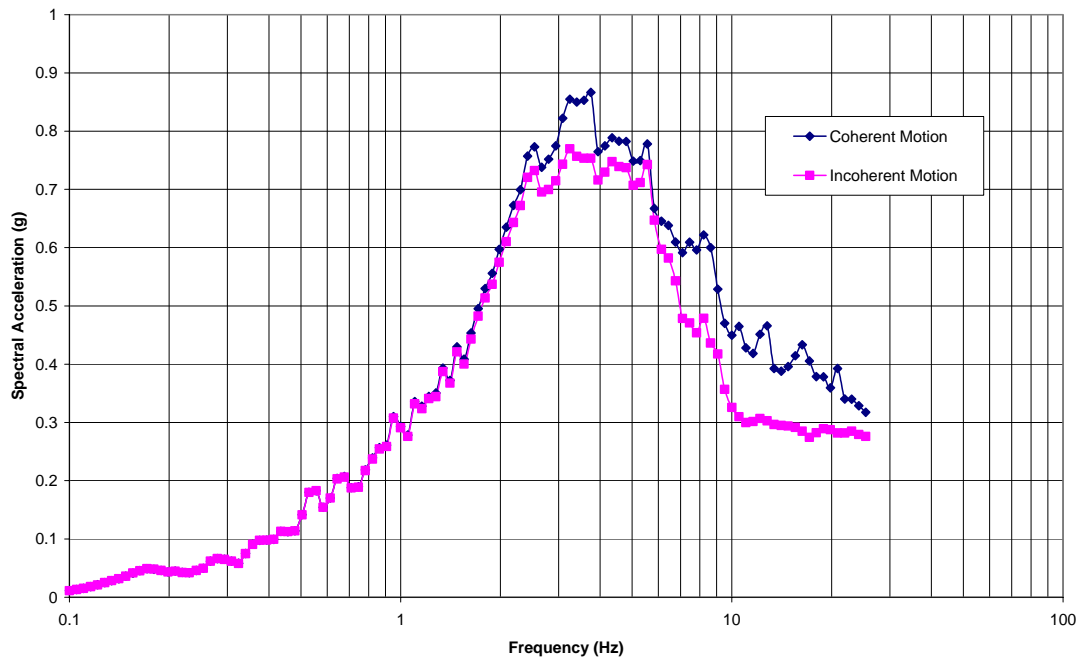


Figure 8. Comparison of Horizontal Response Motion (5% Damping) at Elevation 57 ft

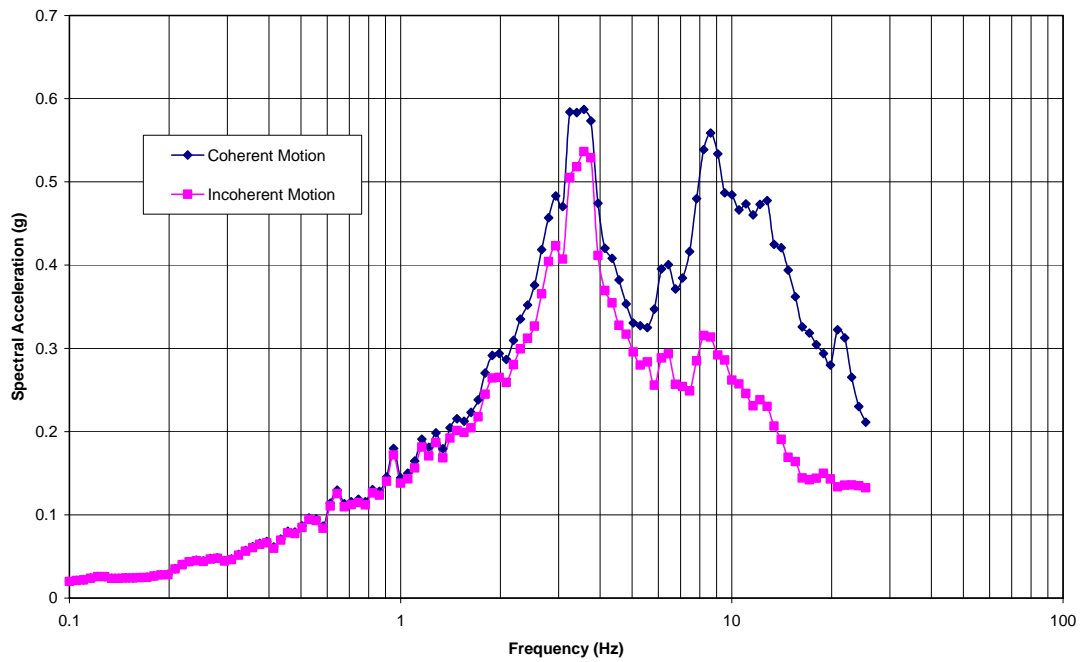


Figure 9. Comparison of Vertical Response Motion (5% Damping) at Elevation 57 ft

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