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SEISMIC SOIL-STRUCTURE INTERACTION ANALYSIS INCLUDING GROUND MOTION INCOHERENCY EFFECTS

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ABSTRACT :

During the past few years, significant progress has been made in developing ground motion incoherency models using the most recent data from dense arrays and in implementing these models into soil-structure interaction (SSI) analysis and its verification. In particular, the new incoherency models have been implemented in the well known SSI program SASSI2000. Both the incoherency models and its implementation have been reviewed by the US Nuclear Regulatory Commission (USNRC) and approved for design application.

In this paper a brief description of these recent developments and the regulatory perspective on the model and its implementation for soil-structure interaction methodology are presented. Sample results for two recent studies for nuclear facilities in Western and Eastern US, with their respective design motions are presented. Beneficial effects of SSI, particularly with modeling of ground motion incoherency, are illustrated and discussed.

KEYWORDS: Incoherency. SASSI2000. Soil-Structure Interaction. SSI.

INTRODUCTION

Spatial variation of ground motion, which has been confirmed from many field observations, has been recognized for many years. Using the recorded data from dense array sites, it can be shown the amplitudes and phase angles of ground motions at adjoining locations within the same site during the same event are different. The spatial variation is caused by many factors, including the seismic source-rupture characteristics, the wave passage effects, directional dependence, and scattering due to site inhomogenuity. 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 to model the spatial variation stochastically. The discussion of the spatial variation of ground motion and the various models used 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 one of the most recent ground motion incoherency models.

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

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

where $\gamma_{ij}(\omega)$ is the complex coherency function of ω (any given circular frequency), $S_{ii}(\omega)$ 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, depending on one's perspective) 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 recorded data, Abrahamson (1992) has developed several models over time and continually enhanced them using the most recent recorded data. The particular Abrahamson model (Abrahamson, 2007) adopted in SASSI2000 is based on the recorded motions collected at rock sites. This model has been reviewed by the USNRC and has been accepted for use in design (USNRC, May 2008). The amplitude of the associated coherency functions associated with horizontal and vertical motions are presented in Figures 1 and 2, respectively. As expected, 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 constrained, is expected to reduce. However, the foundation rocking and torsional motions tend to increase.

The sub-structuring formulation used in SASSI enables 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 (between soil and structure) in terms of a coherency matrix given the distance between the nodes for each frequency of analysis. The matrix is subsequently reduced to develop the free-field load vector for SSI analysis. The wave passage effects may be included as part of the model or can be specified using the inclined wave option in SASSI2000. The numerical method to develop the free-field vector is presented in the theoretical manual of the next version of the Computer Program SASSI and discussed in a report to USNRC (Ostadan et al, 2007). Verification and application of the SSI methodology have also been published previously (Ostadan, et al 2005, Mikami et. al, 2006). The USNRC acceptance of the SASSI2000 implementation of the model is reported in its Interim Staff Guidance (USNRC, 2008).

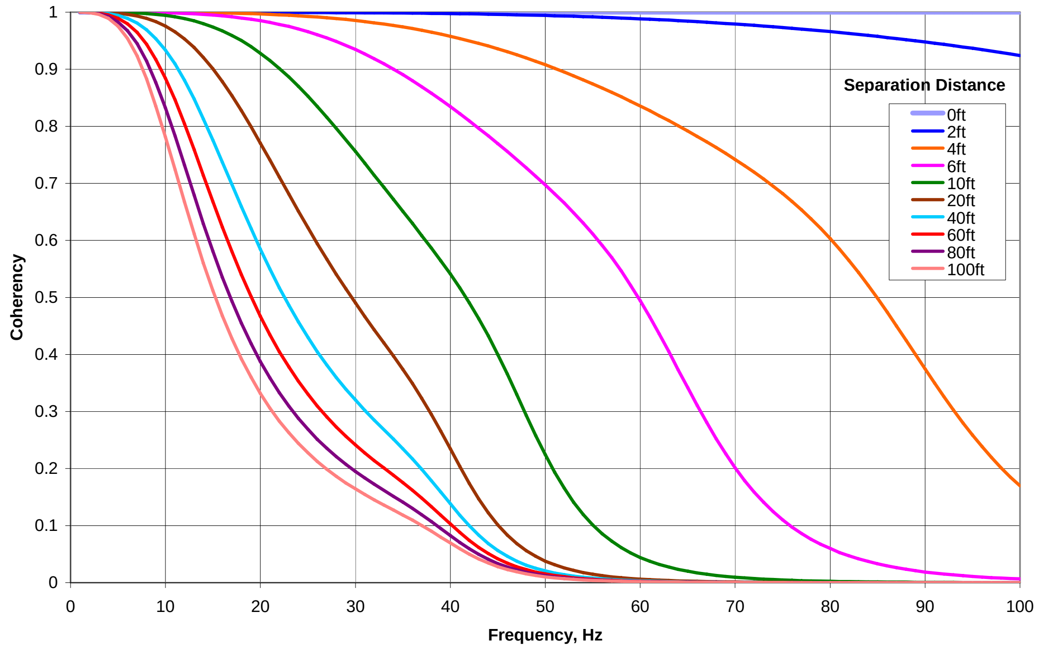


Figure 1 Amplitude of Horizontal Incoherency Function

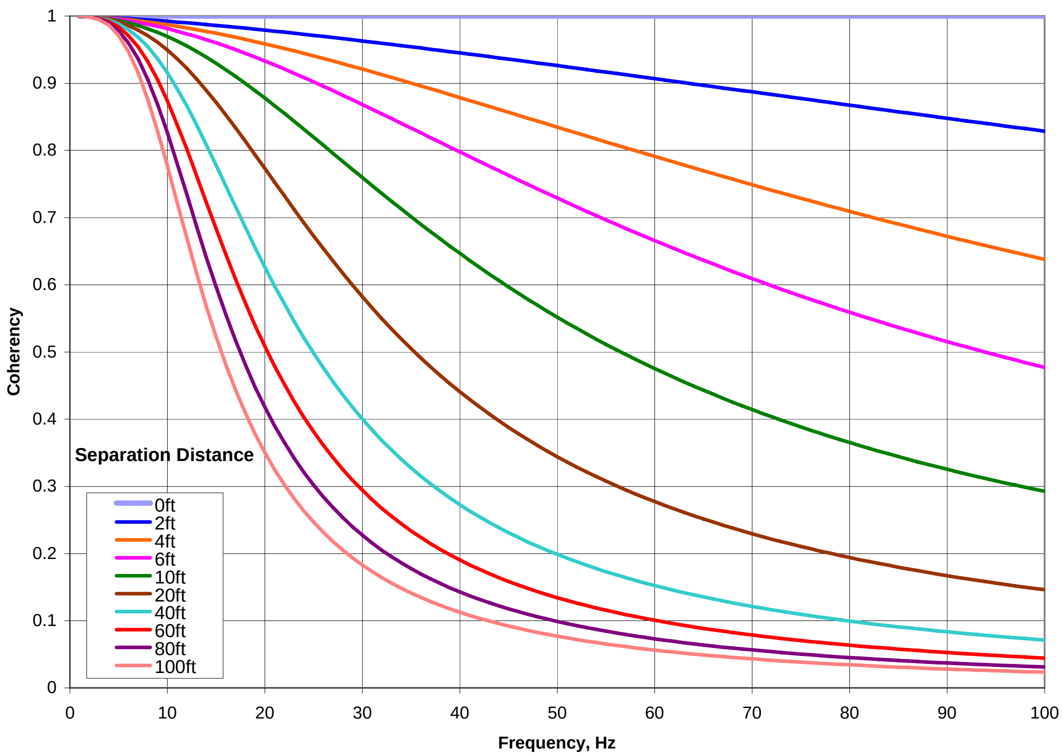


Figure 2. Amplitude of Vertical Incoherency Function

APPLICATION TO NUCLEAR STRUCTURES

a-Western US Site

The structure considered in the analysis is a large concrete structure for a vitrification facility at a site in Western US. The process areas in this structure consist of multiple cells and caves connected by transfer tunnels and shielded doors designed to meet confinement and shielding requirements. 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 the building is about 300 ft by 500 ft, rising above grade level to 120 ft. The embedment depth is up to about 50 ft, with the depth of embedment varying with plan location. The building has a steel structure all around and forming the roof. The large size of the structures and composite nature of the design result in a complex dynamic behavior of low frequency steel components interacting with the higher frequency concrete members causing local amplifications of motion. To capture the dynamic behavior of the structure, a detailed finite element model is constructed. The SASSI2000 model of the structure is shown in Figure 3. More detailed discussion of the structure and its modeling is presented by Ostadan et al, 2003.

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. A comprehensive geotechnical investigation program with emphasis on multiple geophysical testing techniques was executed to develop the best estimate as well as the range of dynamic soil properties needed for seismic soil-structure interaction (SSI) analysis. The initial and strain-compatible shear wave velocity profile used in the analysis is shown in Figure 4.

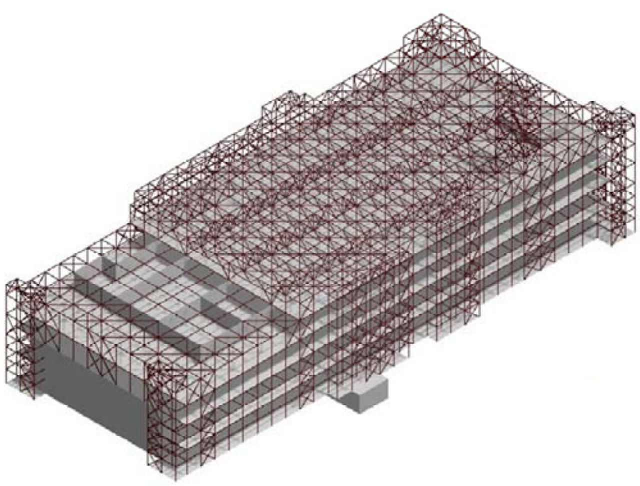


Figure 3 SASSI2000 Model of the Vitrification Building

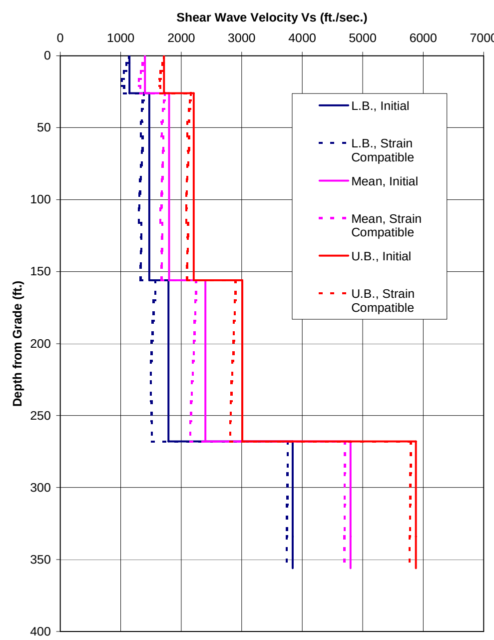
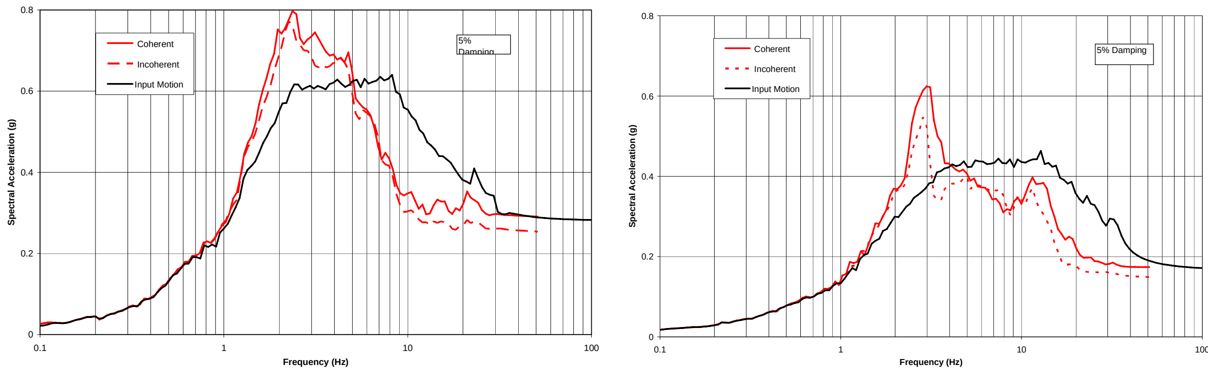


Figure 4 Shear Wave velocity profile at Location of the Virification Facility

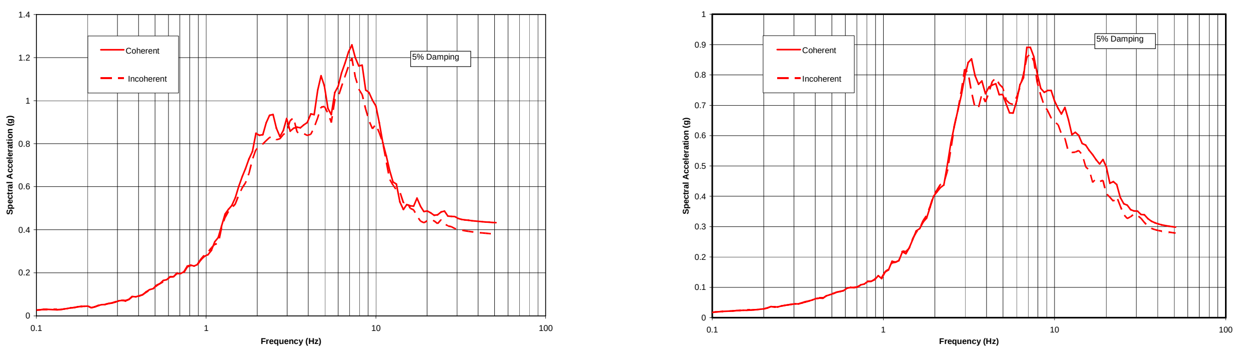
The SSI analyses of the structure were performed using the incoherency model as well as a conventional analysis using fully coherent vertically propagating body waves. Both analyses use the same design motion as the input motion. The acceleration response spectra of the input motion in horizontal and vertical directions are shown in

Figures 5. As depicted in these Figures, the motion is a typical Western US design motion rich in low frequency. The SSI response of the structure at the foundation level and at main floor at 98 ft above ground surface level for fully coherent and incoherent analysis in horizontal and vertical directions are compared in Figures 5 and 6.



(a) (b)

Figure 5 Comparison of the (a) Horizontal and (b) Vertical Response Spectra of Input Motion and Foundation Response Motion at the Grade Level



(a) (b)

Figure 6 Comparison of the (a) Horizontal and (b) Vertical Response Motions at Elevation 98 ft

b-Eastern US Site

For the Eastern US site, a surface-founded diesel generator building for a nuclear power plant located on a hard rock site is considered. This building has a footprint of 100 ft by 170 ft and elevates to elevation 70 ft above the grade level. The building has a small footprint but has a high fundamental frequency of about 12 Hz in the horizontal direction. The SASSI2000 model of the structure is shown in Figure 7. The input motion and foundation response motion at the grade level in the horizontal and vertical directions are shown in Figure 8. The response motions at the roof level are compared in Figure 9.

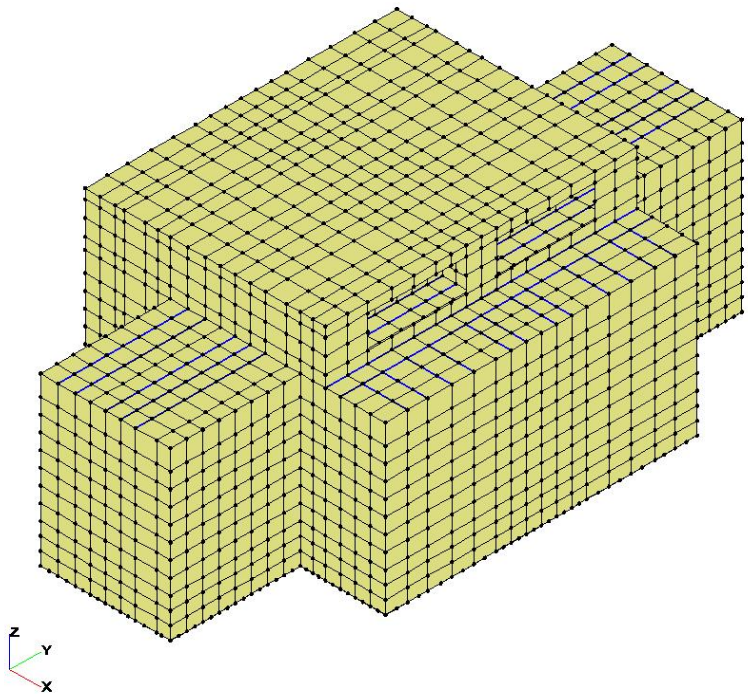
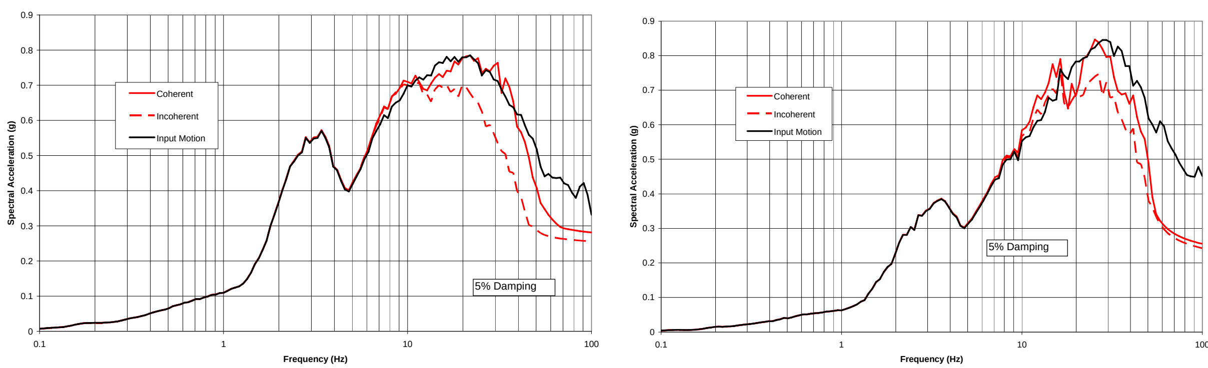
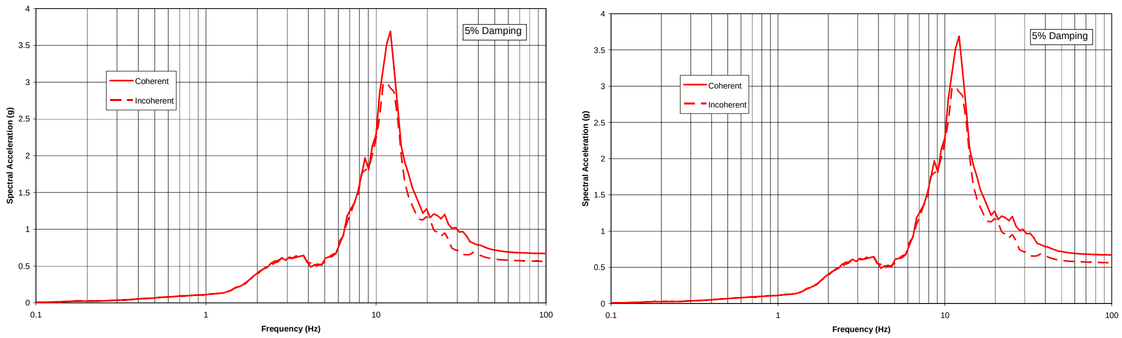


Figure 7 SASSI2000 Model of the Diesel Generator Building



(a) (b)

Figure 8 Comparison of the (a) Horizontal and (b) Vertical Response Spectra of Input Motion and Foundation Response Motion at Grade Level



(a) (b)

Figure 9 Comparison of the (a) Horizontal and (b) Vertical Response Spectra at the Elevation 68 ft

DISCUSSION OF THE RESULTS

As noted above, a typical Western US design motion is rich in low frequency such that the amplified response spectral range reduces from its peak values beyond 10 Hz frequency. The site considered in this evaluation is a very dense soil sites. The SSI effects are significant. Nevertheless, the effect of ground motion incoherency on structural responses is small. This is due to the fact the input motion has limited energy in the high frequency range and the incoherence effects mainly reduces the motion in high frequency range. In the case of the Eastern US study, the design motion is for a rock site with peak of spectral acceleration at about 25 Hz. The site is a rock site and the SSI effects do not reduce the fundamental structural frequencies. As a result, the incoherency effects are significant. The reduction due to wave incoherency is expected to increase for larger foundation sizes such as those for a typical standard nuclear power plant (i.e., the nuclear island structure). This reduction is particularly important for equipment design/qualification and anchorage design.

Additional studies are being performed to evaluate the structural responses up to the new high frequency requirement of 50 Hz (USNRC, 2008). While the higher modes of structural vibrations are expected to influence the floor/wall response spectra in the high frequency range, the reduction due to ground motion incoherency effects is also expected to be significant in this range. Systematic evaluations of the high frequency modes along with ground motion incoherency effects will be performed to develop guidelines for structural modeling.

CONCLUSION

This paper presents an update to the recent development of the ground motion incoherency model, its implementation in the SASSI2000 computer program and its application to nuclear structures in Eastern and Western US. The incoherency model and its implementation in SASSI2000 have already been approved by the USNRC for nuclear power plant design applications. Work is in progress to include these developments in the next version of ASCE 4-98 for general use.

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