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EFFECT OF SEISMIC WAVE INCOHERENCE ON SSI RESPONSE OF US EPR EPGB

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ABSTRACT

Spatial incoherence of seismic waves has the effect of lowering responses of structural foundations. The effect is more significant at higher frequencies (generally exceeding 10 Hz) and larger building footprints.

The purpose of this paper is to present the results of a seismic SSI analysis of the US EPR Emergency Power Generating Building (EPGB), a surface-founded concrete structure, for a hard-rock soil case using both coherent and incoherent ground motion input. For this study both a detailed FE model of the building, and a corresponding tuned lumped-mass stick model on a rigid foundation were used. These models were subjected to horizontal and vertical components of input motion and incorporated the coherency model for hard rock. The hard rock reference motions consisted of high-frequency rock motions. The incoherent structural responses were obtained using the Response Simulation method in MTR/SASSI.

The SSI results were compared against each other to evaluate the effects of ground motion incoherency on the in-structure response spectra and to study the effects of model refinement (stick versus detailed FE model) on the calculated responses. This paper concludes with observations and recommendations regarding the treatment of incoherent input motions.

INTRODUCTION

The response of large and stiff foundations such as those of nuclear power plants are known to be significantly affected by the seismic wave scattering due to kinematic interaction as well as spatial incoherence of seismic waves. Both effects have the tendency to reduce the amplitudes of seismic response of the foundation mat to less than those in the free field. Although the effects of kinematic interaction on the response of structures to ground motions including wave passage effects have been investigated extensively in the past, the study of the effects due to spatial incoherence of ground motions has only gained popularity in the past decade or so as a result of licensing of the new reactors in the United States. This paper presents the results of seismic SSI analysis of the US EPR Emergency Power Generating Building (EPGB) on hard rock subjected to both coherent and incoherent ground motions.

Several procedures are currently available for analysis of ground motion incoherency in SASSI. Amongst these methods, the Response Simulation is shown to provide accurate and stable results and avoid the potential numerical issues observed in other procedures (Tabatabaie, 2015). For this study the Response Simulation procedure implemented in MTR/SASSI was used.

EPGB STRUCTURE MODEL

The EPGB is a concrete box type structure consisting of concrete shear walls, floor slabs and roofs. The structure has a medium size footprint and shallow embedment of 5 feet. The base slab incorporates 6-foot deep shear keys to improve the foundation stability against sliding. Figure 1 shows an overall configuration and dimensions of the building.

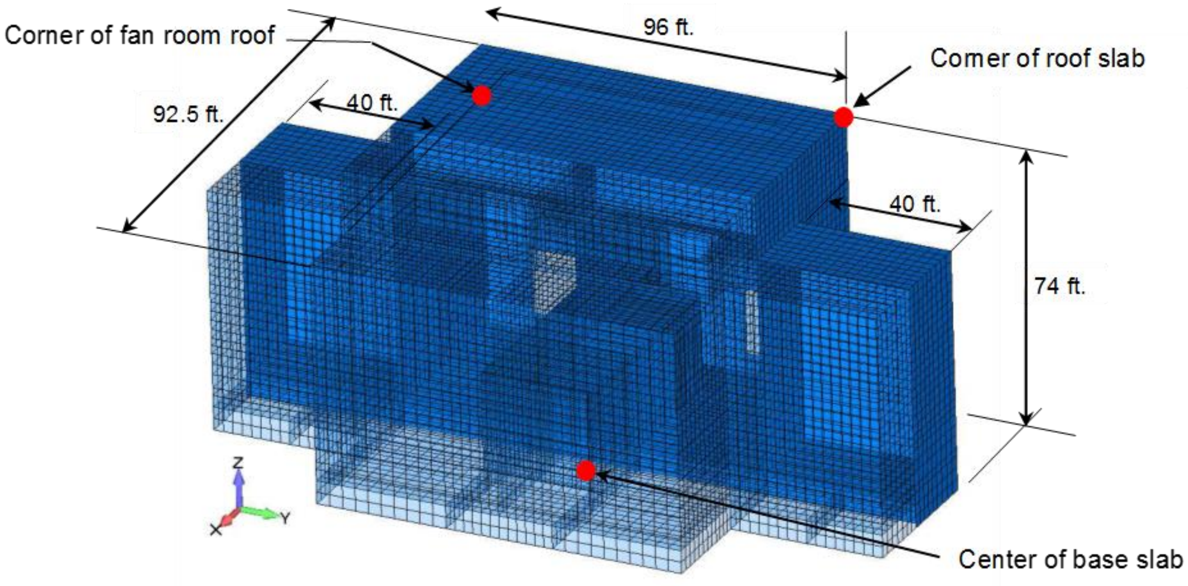

Figure 1. Detailed FE Model of EPGB

Both a stick and detailed finite element (FE) model of EPGB were used in this study. The idealization of EPGB as a stick model is shown in Figure 2. It represents the structure with three mass nodes that lump the mass of slabs and walls proportionally for each level. The mass of the shear keys is lumped with mass of the base slab node. Figure 3 shows the actual stick model of EPGB. Each story is modeled with two beams: one representing the axial stiffness of the corresponding story and is located at the center of mass, and the other representing the bending and shear stiffness of the story and is located at the center of stiffness. The two beams are then connected by rigid beams. The detailed FE model of EPGB is shown in Figure 1. The FE model incorporates all the major details of the EPGB structure. The FE model consists of plate/shell elements representing the concrete walls, roof and base slab - all of which are modeled as flexible members with appropriate section properties.

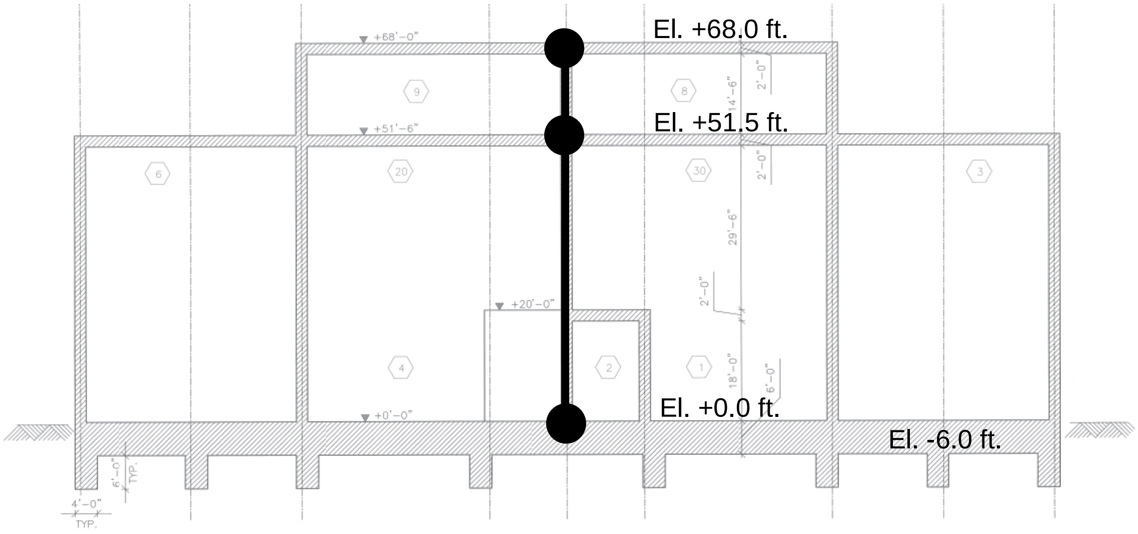

Figure 2. Building Cross Section showing Building Idealization as Stick Model

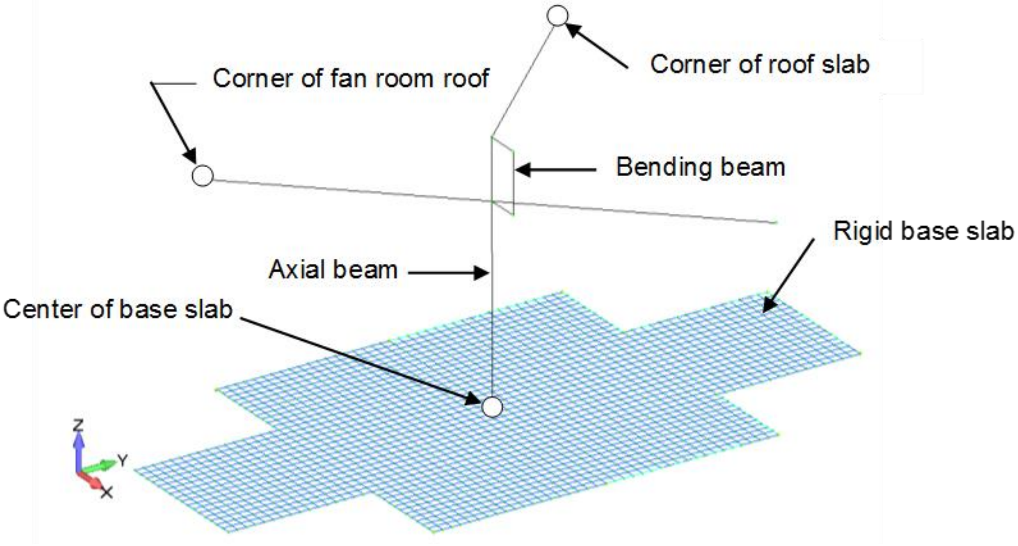

Figure 3. Stick Model of EPGB

TUNING OF STICK MODEL

The stick model was tuned against the detailed FE model to provide proper alignment of major global modes of the structure. This included some adjustment to the stiffness of the sticks to account for the effects of openings, recesses and partition walls as well as flexibility of the plane sections that were not accounted for in development of the stick model. In order to tune the stick model both the FE and stick models were first fixed at the fan room elevation +50.5 ft. (see Figure 2) so that the roof slab can be tuned. Following this the FE and partially tuned stick model were fixed at the base slab elevation -6.0 ft. (see Figure 2) so that the fan room slab can be tuned. The final results of tuning in terms of the fixed-base transfer functions of the building roof slab from the initial stick (no tuning), tuned initial stick and detailed FE model in the x- (and typical for y-) and z-directions are shown in Figure 4a and 4b, respectively. Based on the results of model tuning, the dominant mode of the structure has a frequency of about 10 Hz in the x- and y-directions and 40 Hz in the vertical direction.

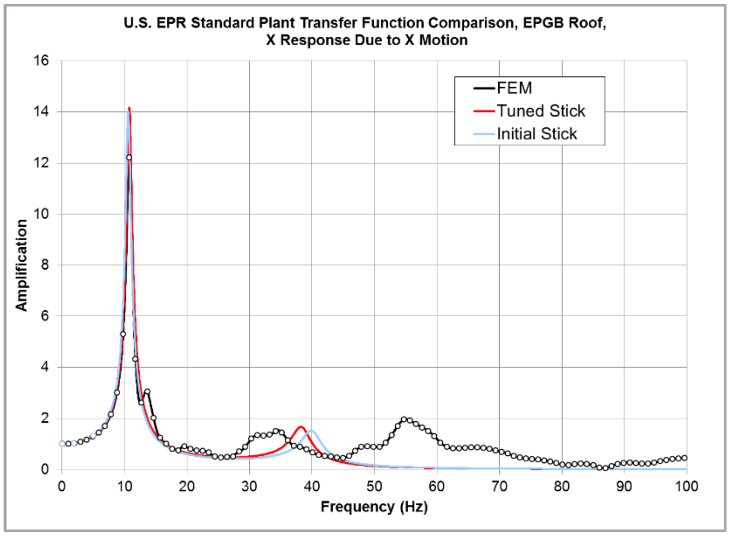

Figure 4a. Tuning of Stick Model, Roof Slab, X-Dir.

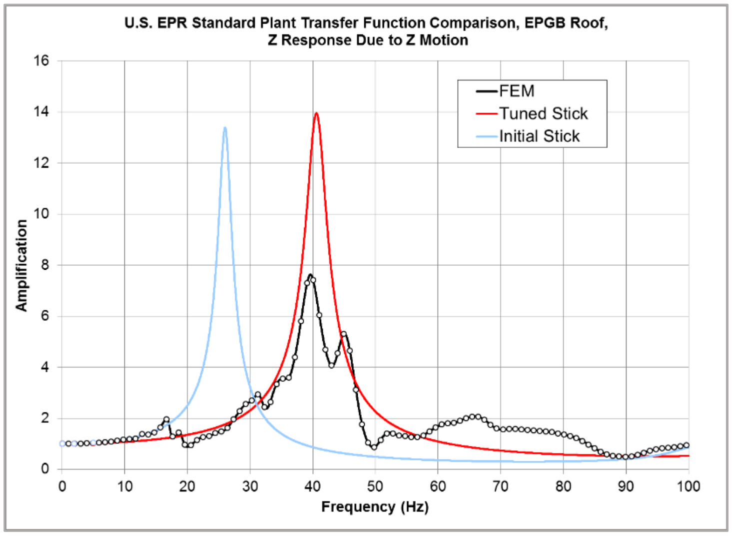

Figure 4b. Tuning of Stick Model, Roof Slab, Z-Dir.

It is noted that the EPGB is an ideal structure to be represented by a stick model because a) it is a regular building where lateral and vertical force resisting systems are the primary structural components, b) the main shear walls are directed towards the principal building axes and are relatively undisturbed by openings or discontinuities and c) floor slabs can be considered rigid in the in-plane direction because of only minor openings and no difference in elevation.

CHARACTERIZATION OF INPUT MOTIONS

The foundation media consists of rock halfspace having a shear wave velocity of 4000 m/s. For incoherent ground motion analyses, the hard rock coherency functions provided in EPRI (2007a) were used. Figure 5a and 5b show the horizontal and vertical components of the coherency functions, respectively. For coherent ground motion analyses, the coherency function is 1 at all frequencies (i.e. fully coherent). Both coherent and incoherent analyses assume vertically propagating plane waves (i.e. no wave passage effect) with control motion specified at the free-field ground surface.

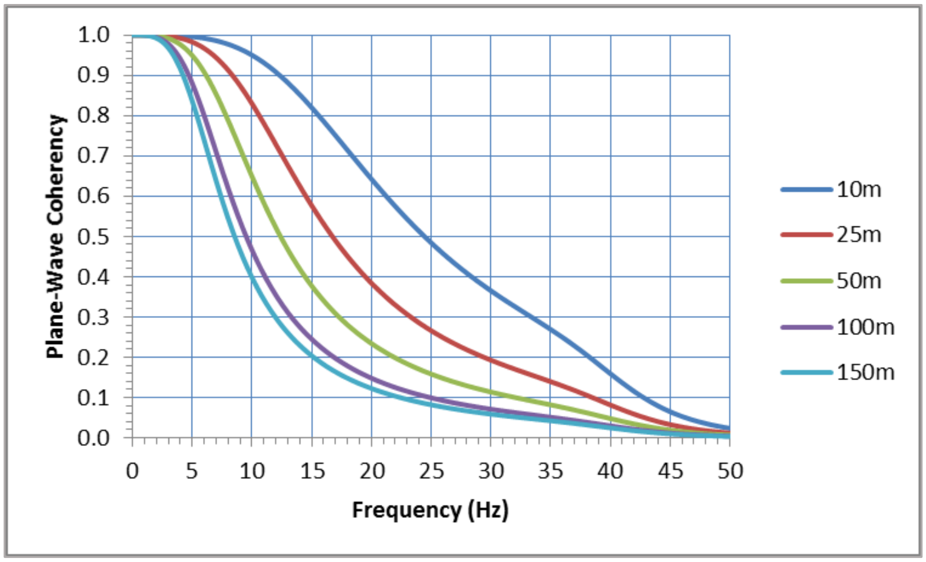

Figure 5a. Plane-Wave Coherency Functions, Hard Rock, Horizontal Component

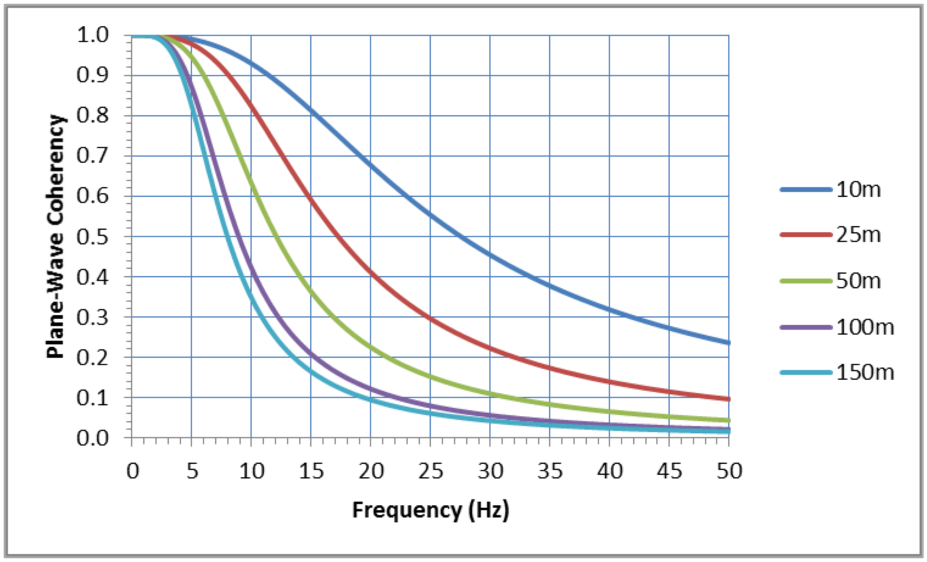

Figure 5b. Plane-Wave Coherency Functions, Hard Rock, Vertical Component

The control motion consists of three orthogonal components (two horizontal and vertical) of acceleration time histories spectrally matched to the high-frequency (HF) hard rock uniform hazard spectra (UHS) typical for the Central and Eastern United States (CEUS). Figure 6 shows 5%-damped acceleration response spectra of the control motions.

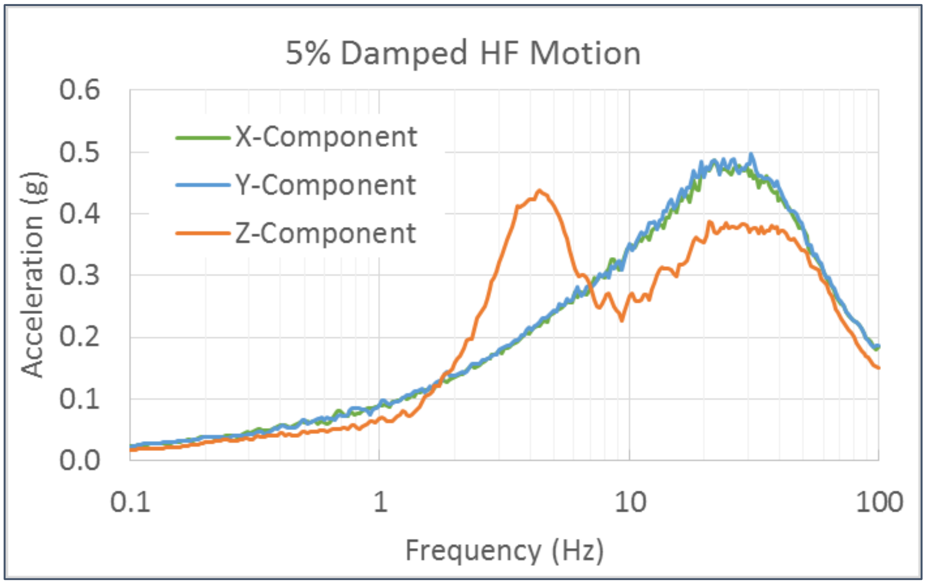

Figure 6. 5% Damped Response Spectra of Reference Hard Rock Motion

SSI ANALYSIS OF EPGB STRUCTURE MODEL

The stick and detailed FE models of EPGB supported on hard rock were analyzed with both coherent and incoherent ground motions for two sets of control motions to study:

1) The effect of spatial incoherence of ground motions on the structural response
2) The effect of model refinement (detailed FE versus stick) on the incoherent structural response

The SSI analysis was performed using the MTR/SASSI program. The Response Simulation procedure was used to calculate the incoherent structural response. The results for both the stick and detailed FE model included 10 significant spectral modes of the coherency functions and represent the mean of 20 simulations with random phase angle. Both the number of spectral modes and simulations were selected to ensure convergent results. The cut-off frequency for both coherent and incoherent analyses is 70 Hz.

DISCUSSION OF RESULTS

The response of EPGB in terms of 5%-damped acceleration response spectra at the center of base slab, corner of building roof and corner of fan room roof (see Figure 1 and 3) are calculated and compared. These locations represent typical building response characteristics. The spectra are calculated from acceleration time history responses in a given direction obtained by algebraically summing the co-directional acceleration time history output from separate analysis of the three directions of input motion.

Effect of Incoherent Ground Motions on Structural Response

Figure 7 shows the calculated response at the center of base slab from coherent and incoherent ground motions for both the stick and FE model. As shown in Figure 7 in the absence of incoherency, the response of the base slab is very similar to the free field motion. This was expected because of the hard rock foundation support which essentially represents fixed-base condition with no SSI or foundation kinematic effects. It is noted that the coherent response of the structure is generally higher at the dominant mode and lower at the secondary modes of the structure for the stick model as compared to detailed FE model. This is due to the fact that the stick model represents only few global modes of the structure with full mass participation in those modes as compared to the FE model that distributes the mass to all modes in the structure.

With respect to the incoherent response, the results show moderate to significant reduction in the base slab motion relative to the free field motion at frequencies above 10 Hz (see Figure 7). The reduction in base slab response due to incoherency of ground motions appears to be larger in the x- and y-directions as compared to the z-direction for both models and larger from the stick as compared to the detailed FE model. In the structure however, as seen in Figure 8 and 9, this above trend is reversed, which means the reduction in response due to incoherency is larger in the z-direction as compared to the x- and y-direction and larger from the detailed FE model as compared to the stick model. This reverse in trend perhaps has to do with how the structural modes respond to the spatial variation of base motions due to ground motion incoherency.

Effect of Model Refinement on Incoherent Structural Response

One of the objectives of this study was to investigate whether the use of stick model in lieu of more detailed FE model of the structure may miss some aspects of the incoherent response that could be beneficial or critical in evaluation of the equipment that are sensitive to high frequency components of in-structure response spectra. To that extent the current results show that the spectral accelerations in the base slab in the x- and y-directions at frequencies above 10 Hz are significantly underestimated from the stick model as compared to the FE model (see Figure 7). In the structure, the stick model tends to overestimate the spectral response due to incoherency at the dominant mode and underestimate at secondary modes of the structure as compared to the FE model. This effect is more pronounced in the z-direction (see Figures 8 and 9).

CONCLUSION

The following observations and conclusions are noted from this study.

- The ground motion incoherency reduces the response of EPGB at frequencies above 10 Hz as compared to the coherent response. The amount of reduction in spectral accelerations can range from small (few percent) to moderate (30-35%) depending on the frequency and direction of motion.
- The stick model tends to underestimate the response of the base slab at all frequencies above 10 Hz as compared to the detailed FE model. The under prediction of the base slab spectral accelerations from stick model is significant in the x- and y-direction, and moderate in the z-direction.
- For the structural response, the stick model overestimates the spectral accelerations at the dominant mode and underestimates at the secondary modes of the structure. The over prediction of the spectral accelerations in the structure from the stick is more significant in the z-direction.

It is noted that the above findings do not consider the effects of torsion in the response due to mass eccentricity and/or significant stiffness discontinuity in the structure, soil-structure interaction, foundation embedment and ground motions with energetic lower frequency content.

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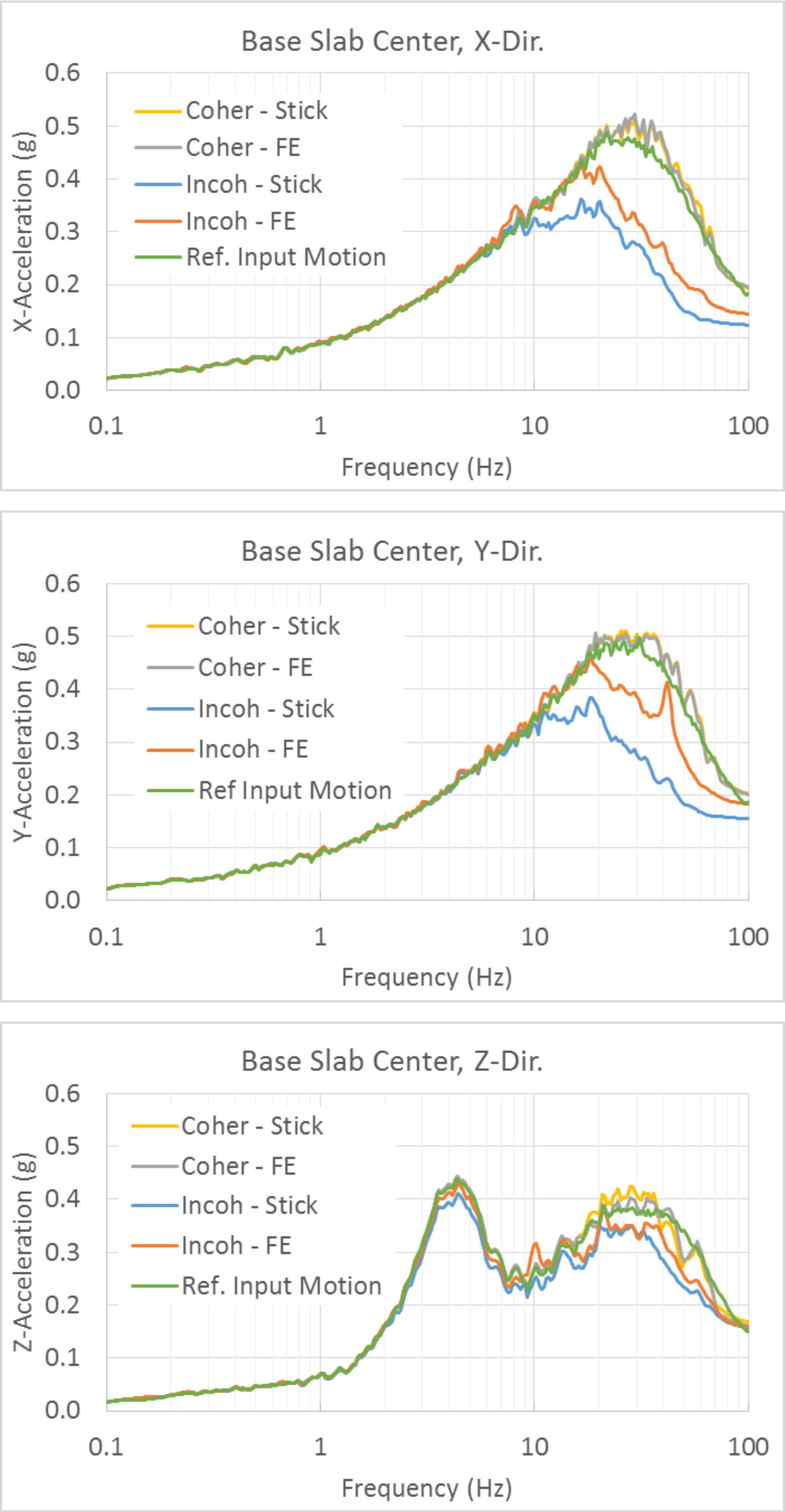

Figure 7. Comparison of 5%-Damped Response Spectra at Center of Base Slab,
Stick vs. Detailed FE Model

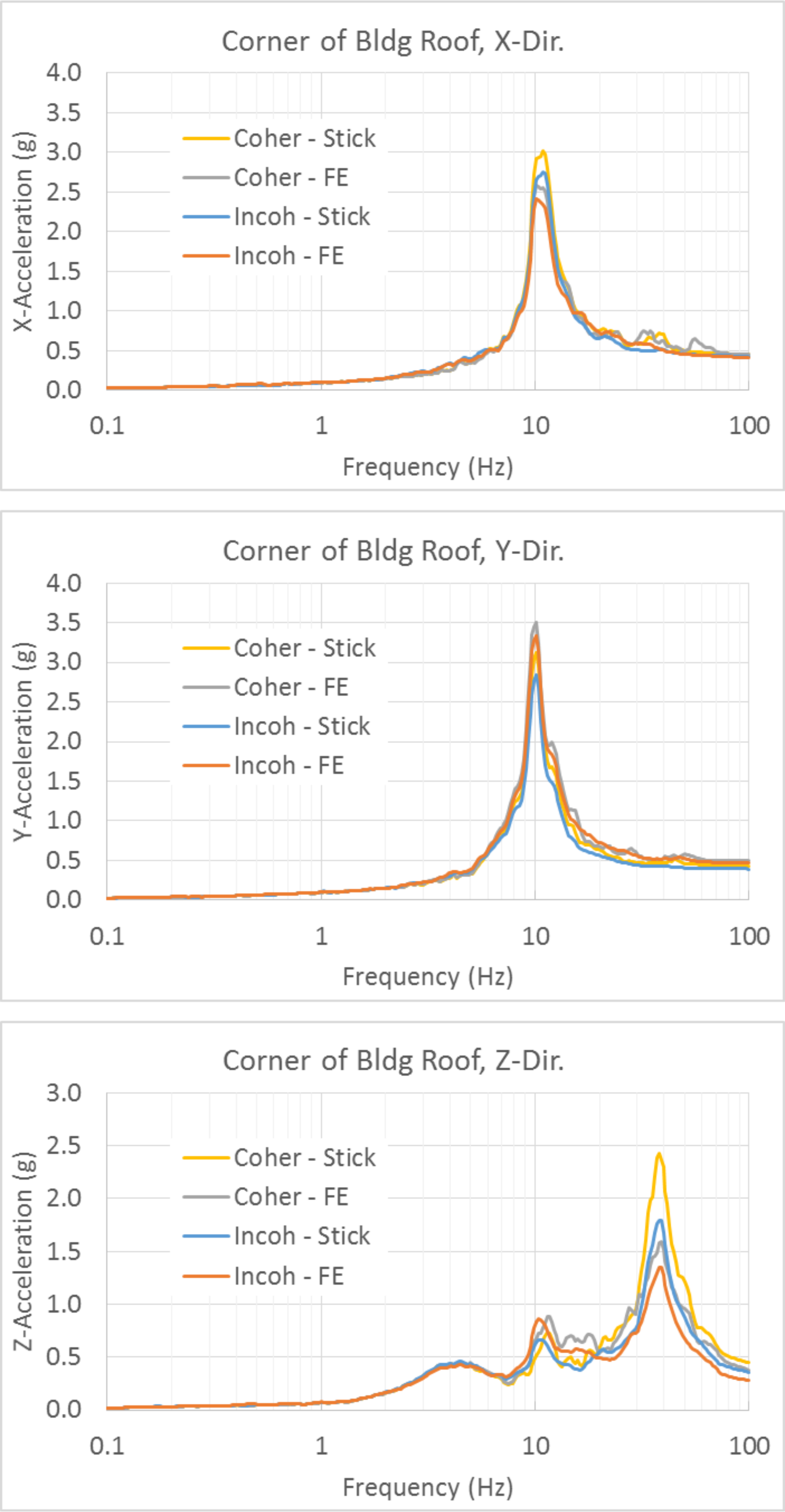

Figure 8. Comparison of 5%-damped Response Spectra at Corner of Building Roof, Stick vs. Detailed FE Model

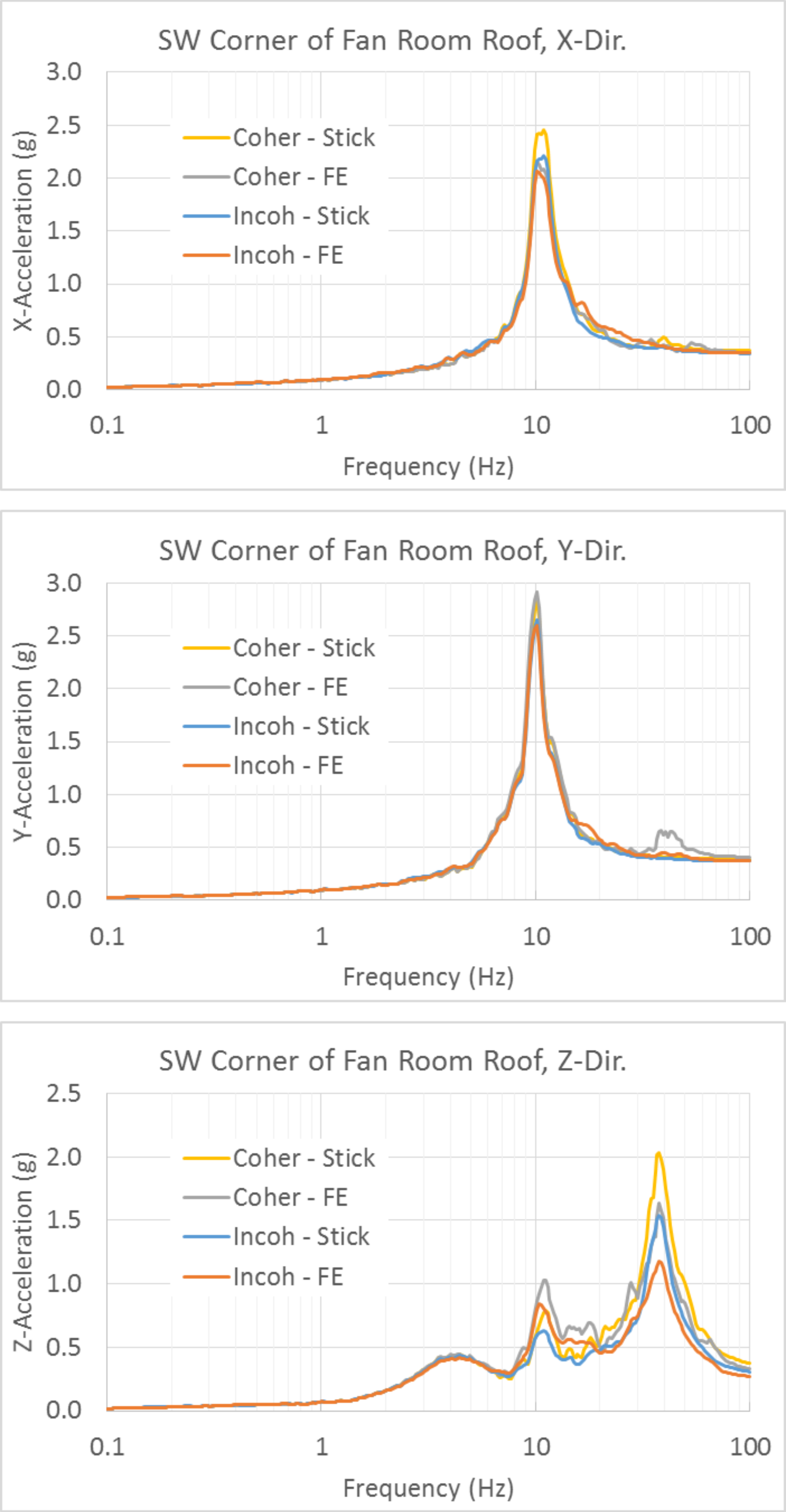

Figure 9. Comparison of 5%-damped Response Spectra at Corner of Fan Room Roof, Stick vs. Detailed FE Model