Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division III

APPLICATION OF SEISMIC GROUND MOTION INCOHERENCY EFFECTS IN SASSI ON SOIL SITES WITH MULTIPLE FOUNDATIONS

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ABSTRACT

Inclusion of incoherency effects in soil-structure interaction (SSI) analysis provides a more realistic determination of earthquake induced building structural responses than those obtained considering coherent ground motion. Separately, industry demand for high-fidelity, comprehensive coupled structural models that often directly include structure-soil-structure interaction (SSSI) effects continues to increase. Combining incoherency and SSSI effects has raised questions about whether the implementation of incoherency effects in the popular System for Analysis of Soil Structure Interaction (SASSI) software may cause incoherency effects to be inappropriately overemphasized for individual separate structures within a comprehensive, coupled SSSI model of multiple structures, due to the larger effective foundation area of the coupled structure model. If true, this could cause incoherent SSSI analysis to unintentionally predict un-conservative response in the high frequency range.

This paper provides a study example demonstrating that the spatial configuration of multiple foundations for a particular SSSI model has little influence on the magnitude of incoherent effects on building structural responses. Evaluation of foundation transfer function (TF) and incoherency transfer function (ITF) responses between a comprehensive, coupled SSSI model and analogous individual models shows little difference in magnitude of incoherency effects and demonstrates that the total effective coupled foundation area is not a driver of incoherent response. In addition, when the individual foundations of the SSSI model are integrated into a single, continuous foundation, incoherency effects are shown to be influenced by the dynamic foundation characteristics. It can therefore be concluded that for this study, incoherency effects appear to be mainly a function of the foundation area of each individual structure that comprise a coupled SSSI model. Derivation of the underlying mathematics associated with these observations needs further study.

INTRODUCTION

Inclusion of incoherency effects in soil-structure interaction (SSI) analysis provides a more realistic determination of earthquake induced building structural responses than those obtained considering coherent ground motion. Separately, there have been continued advances in the fields of structural, geotechnical, and computational engineering, and increased expectations for scope, detail, and refinements of analysis models for seismic evaluation of nuclear structures, which has led the industry to demand high-fidelity, comprehensive coupled structural models often directly including structure-soil-structure interaction (SSSI) effects. Put together, the analyst is faced with the potential to include both incoherency effects and SSSI effects with the same coupled SSI model. This paper describes a study performed to assess and compare the magnitude of incoherency effects evident on each foundation of a coupled SSSI model versus those from analogous stand-alone SSI models.

Previous studies have shown that foundation area is a key parameter on incoherency effects, noting that larger foundation footprints correspond to larger reductions in foundation response at high frequencies [EPRI 1013504 (2006)]. Furthermore, the Abrahamson coherency functions describe the incoherency effects as a function of separation distance between points [EPRI 1015110 (2007)] which translates to being a function of foundation area when implemented into frequency-domain SSI analysis such as SASSI [EPRI 1015111 (2007)]. Questions have been raised about whether this implementation in SASSI may cause incoherency effects to be inappropriately overemphasized for individual separate structures within a comprehensive, coupled SSSI model of multiple structures, due to the larger effective foundation area of the coupled structure. If true, incoherent SSSI analysis using SASSI may unintentionally, and un-conservatively, under-predict response in the high frequency range.

To address these questions, a study example is used to determine whether the spatial configuration of multiple foundations for a particular SSSI model has influence on the magnitude of incoherent effects on building structural responses. The study example features a coupled SSSI model, comprised of lumped mass stick models (LMSM) atop associated finite element (FE) foundation models. The LMSMs represent typical buildings found at a commercial nuclear power plant and are configured to represent a typical nuclear island arrangement. Real site-specific soil properties are considered for this study which is performed using SC-SASSI software [SC Solutions (2018)] a commercial derivative of SASSI, using plane-wave incoherency through the deterministic method using SASSI-SRSS approach for combining transfer functions of individual coherency modes [EPRI 1015111 (2007)].

This study first evaluates the incoherency effects of the comprehensive coupled model against the incoherency effects of the analogous individual models that comprise the comprehensive model to determine if the total effective foundation area of the coupled model has any significant influence on incoherency effects for the structures and soil site considered in this study. Second, this study evaluates how foundation area, a key parameter on incoherency effects, is considered in frequency-domain SSI analysis by comparing incoherency effects between coupled models with similar foundation areas, but that feature different connectivity conditions between the individual models comprising the comprehensive model.

STUDY MODEL DEVELOPMENT

The soil and structural models developed for this study are compatible with SC-SASSI software and represent actual site and typical structure conditions. The soil model is defined as a horizontally layered soil profile. The structure models are represented by LMSMs and FE shallow foundation models. Embedment effects are not considered.

Soil Model Development

The soil profile is developed based on input from the site response analyses of a probabilistic seismic hazard analysis (PSHA) for a specific Central and Eastern United States (CEUS) site. Soil properties are strain-compatible with the ground motion response spectra (GMRS) hazard level, which is between the 10^{-4} and 10^{-5} annual exceedance frequency (AEF) uniform hazard response spectra (UHRS). The resulting site profile used in this study is developed for best estimate (BE), or median, properties which are consistent with soft-rock properties and formatted into a horizontally layered soil profile with a minimum passing frequency of at least 50 Hz for input in SC-SASSI software. The shear and compression-wave velocities of the soil profile used in this study are shown in Figure *1*.

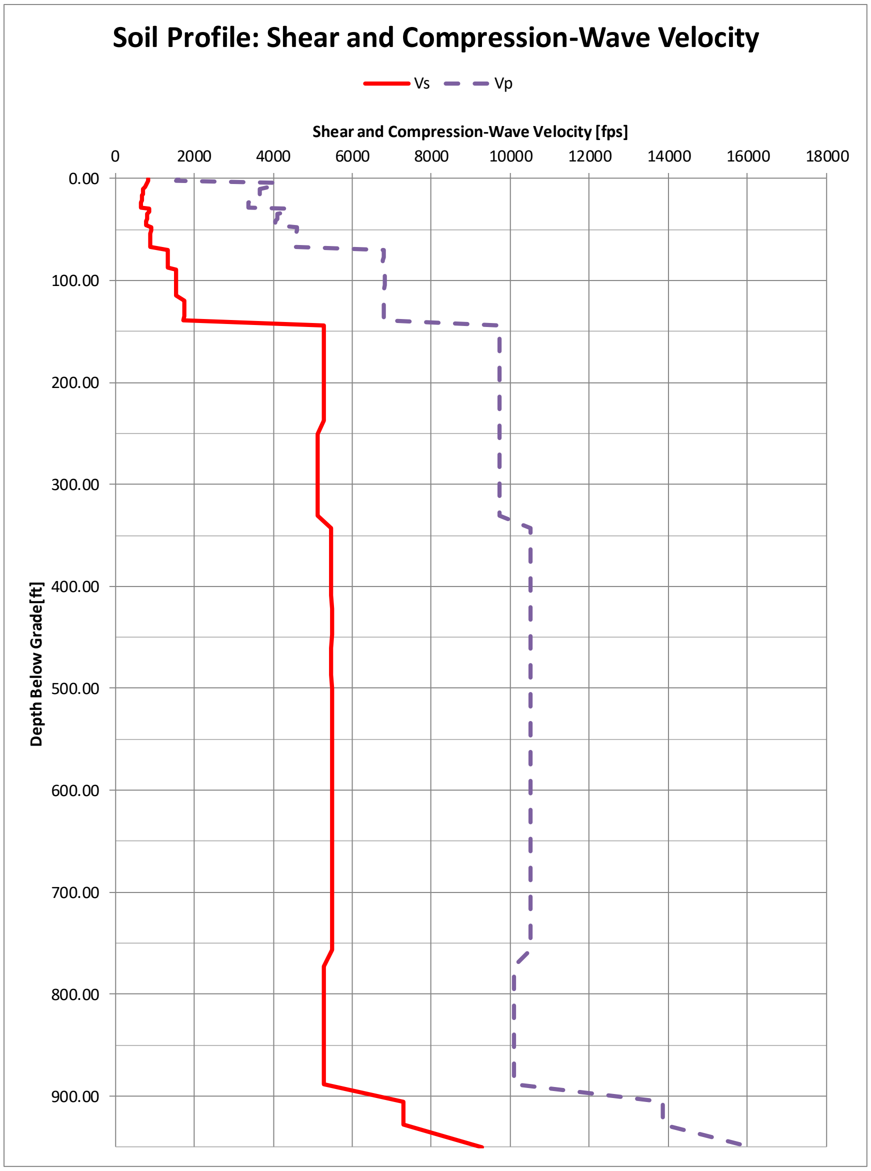

Figure 1. Shear and Compression Wave Soil Profile for Each Study Model.

Structure Model Development

A total of six (6) finite elements models are developed for this study; three (3) stand-alone structure models and three (3) coupled SSSI models.

The three stand-alone models are representative of typical buildings found at a commercial nuclear plant: A) Auxiliary Building (AB); B) Containment Building (CB); and C) Turbine Building (TB). The superstructure LMSMs are modelled with beam and lumped mass finite elements and the mass and stiffness properties are tuned to approximately represent typical AB, CB, and TB structures, as shown in Table 1. The foundations for each structure are simplified into rectangular shallow foundations with varying thickness and foundation area as shown in Table 2. The foundations are explicitly modelled with shell elements and the LMSMs are connected to the foundation models with rigid beams to approximate bearing wall locations to more realistically distribute the structure load.

Table 1: Lumped Mass Stick Model Properties

Model	**Structural Mass (Excl. foundation)**	**E**	**Ix/Iy**	**Cross-Sectional Area**	**Height**	**Fundamental Frequency**
	[kips-s^2/ft]	**[ksf]**	**[ft^4]**	**[ft^2]**	**[ft]**	**[Hz]**
AB (A)	1900	449600	55600	836	26.0	8.00
CB (B)	3100	449600	319000	2002	53.0	5.00
TB (C)	2000	449600	34900	662	24.0	7.00

Table 2: Foundation Model Properties

Model	**Thickness**	**Density**	**E**	**Length**	**Width**
	[ft]	**[kcf]**	**[ksf]**	**[ft]**	**[ft]**
AB (A)	3.00	0.006213	449570	132	104
CB (B)	12.00	0.005357	519119	96	104
TB (C)	1.00	0.007764	449600	108	204

The three coupled SSSI models are each comprised of the three stand-alone models developed for the representative AB, CB, and TB structures and differ only by the boundary conditions between each structure. The coupled SSSI models are modelled with: 1) AB, CB, and TB structures arranged with isolated foundations, i.e. arranged with physical space between the structure foundations; 2) AB, CB, and TB foundations directly adjacent, without sharing common nodes at the boundaries; and 3) AB, CB, and TB foundations are directly connected to form a single, integrated foundation slab. The three coupled SSSI models have nearly identical foundation areas and the arrangement is shown in Figure 2.

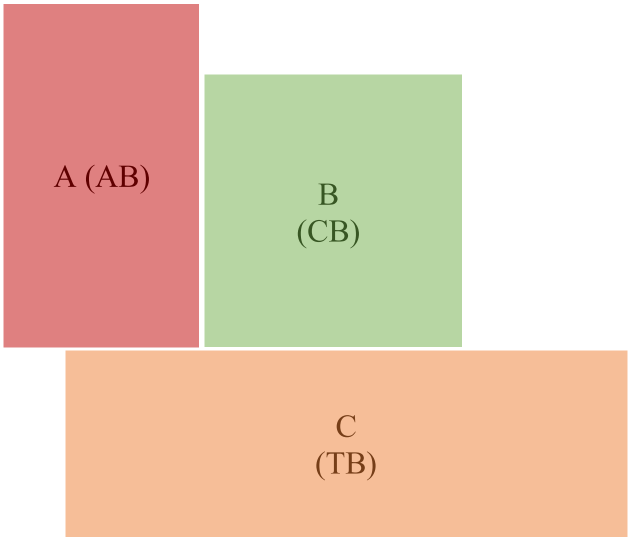

Figure 2. Foundation Layout for Coupled Models 1, 2, 3.

For all six study models, interaction nodes (up to 2976) are defined consistent with the direct method of analysis in SC-SASSI. For the coupled SSSI model with directly adjacent but separate foundations (i.e. Model 2), the interaction nodes at the foundation boundaries are defined in an alternating manner so that each foundation model contains an equal number of interaction nodes at the foundation boundaries.

ANALYSIS STUDY CASES

The study is performed using SC-SASSI software, a commercial derivative of SASSI to perform SSI analysis using the direct method of analysis with inclusion of incoherency effects. Incoherency effects are considered using plane-wave incoherency through the deterministic method using SASSI-SRSS approach for combining transfer functions of individual coherency modes. The 2007 Abrahamson incoherency model for hard rock is selected and deemed appropriate for use on sites with the BE soft-rock properties used in this study [EPRI 1015110 (2007)]. All the incoherent modes are retained for each analysis, i.e. for the surface-founded structures in this study, the number of incoherent modes is set equal to the number of interaction nodes defined for each problem. A total of 85 frequencies of analysis are selected between 0-50 Hz. Foundation response in the form of TF and ITF response are obtained to evaluate SSSI and incoherency effects, where the ITF is defined [EPRI 1013504 (2006)] as the ratio of the incoherent TF response over the coherent TF response.

Analysis cases are first defined to evaluate foundation response of stand-alone models A), B) and C), against the response of the same structures as part of the coupled SSSI model 1). Coherent response is first evaluated to establish baseline response and identify SSSI effects, followed by comparison of incoherent response to evaluate incoherency effects.

Following evaluation of incoherency effects for the stand-alone structures vs. coupled SSSI model, the foundation response between coupled SSSI models 1), 2) and 3) are evaluated to assess how effective foundation area, defined through the different connectivity conditions between the individual models that comprise the comprehensive coupled models, captures incoherency effects. The foundation layout configurations for the coupled analysis cases are shown in Figure 3 and Figure 4.

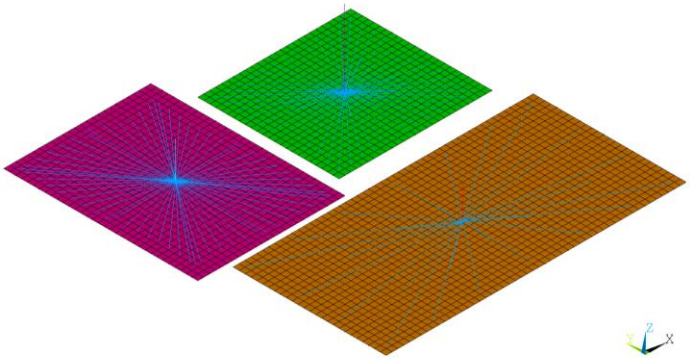

Figure 3. Isometric View of Coupled SSSI Model 1 – Isolated Foundations

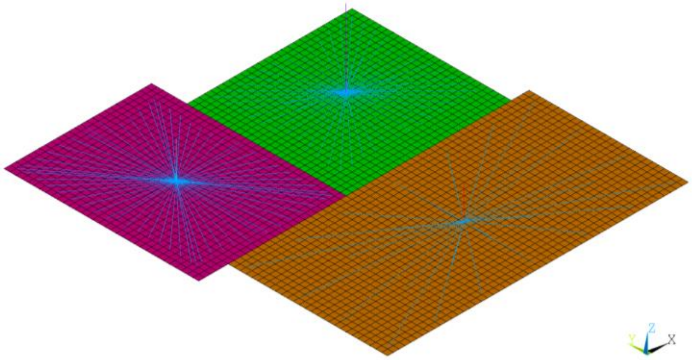

Figure 4. Isometric View of Coupled SSSI Model 2 – Adjacent Foundations, and Model 3 – Integrated Foundations

STUDY RESULTS SUMMARY

Evaluation of foundation transfer function and incoherency transfer function (ITF) responses between the comprehensive coupled model (Model 1) and the analogous individual models (A, B, and C) shows little difference in magnitude of incoherency effects, as demonstrated by selected TF comparison in the horizontal X-Direction at the centre of foundation of Model A, B, and C, which is representative of response compared at other foundation locations and output directions. Coherent TF response comparison between SSSI model 1 and standalone Models A, B and C, illustrates the SSSI effects acting on Model A, B and C as part of the coupled model against the response of the standalone Model A, B and C, as shown in the top figures in Figure 5 through Figure 7. The middle figures in Figure 5 through Figure 7 illustrate the incoherent TF response comparison between coupled SSSI Model 1 and standalone Models A, B and C respectively, and show that; (i) the SSSI effects are consistent with coherent response observed in the top figures and; (ii) the amplitude and frequency content above 10 Hz (where incoherency effects are typically observed) of the incoherent TF response is similar between the combined SSSI model and the standalone models. To assess the relative differences in incoherency effects, the ITF is generated and shown in the bottom figures of Figure 5 through Figure 7, which illustrates that incoherency effects between the coupled SSSI model and standalone Model A, B, and C are nearly identical. Based on evaluation of all model foundations, which are represented by the TF and ITF for Model A, B, and C, it can be concluded that the total, coupled foundation area is not a driver of incoherent response and that incoherency effects appear to be mainly a function of the foundation area of each individual structure that comprise the comprehensive model for the representative soil and structure characteristics selected for this study.

Furthermore, the differences in foundation connectivity between Models 1, 2, and 3 are assessed by comparing ITF to observe how effective foundation area, defined through the different connectivity conditions between the individual models that comprise the comprehensive coupled models, captures incoherency effects. For representative response at the center of foundation slab for Model A, B, and C, the ITF in Figure 8 through Figure 10 respectively shows that the incoherent response between Model 1 and Model 2 are nearly identical, while for Model 3 featuring integrated foundations slabs, the incoherent response deviates. Because the comparisons show that the Model 1 isolated foundation response is comparable to Model 2 with adjacent foundations, it is observed that the incoherency effects are driven by the individual structure foundations rather than the total effective area, despite adjacent foundations being in contact, similar to the preceding study case. However, differences in incoherency effects are observed for Model 3, resulting from the integrated foundations having different dynamic characteristics than those of Model 1 and Model 2 due to having continuous stiffness at the structure boundaries, but even this case does not show grossly exaggerated incoherency effects that one might expect from artificially increasing foundation.

The underlying mathematics supporting these observations have not been thoroughly investigated. This study provides compelling empirical evidence that the effect of incoherence is driven by the foundation characteristics of an individual structure and is independent of the total foundation size of a coupled SSSI model with the presence of neighbouring (but separate) structures, which is consistent with expectations and observations elsewhere. The derivation of the underlying mathematics, to explain the reason for the findings of this study, needs further investigation.

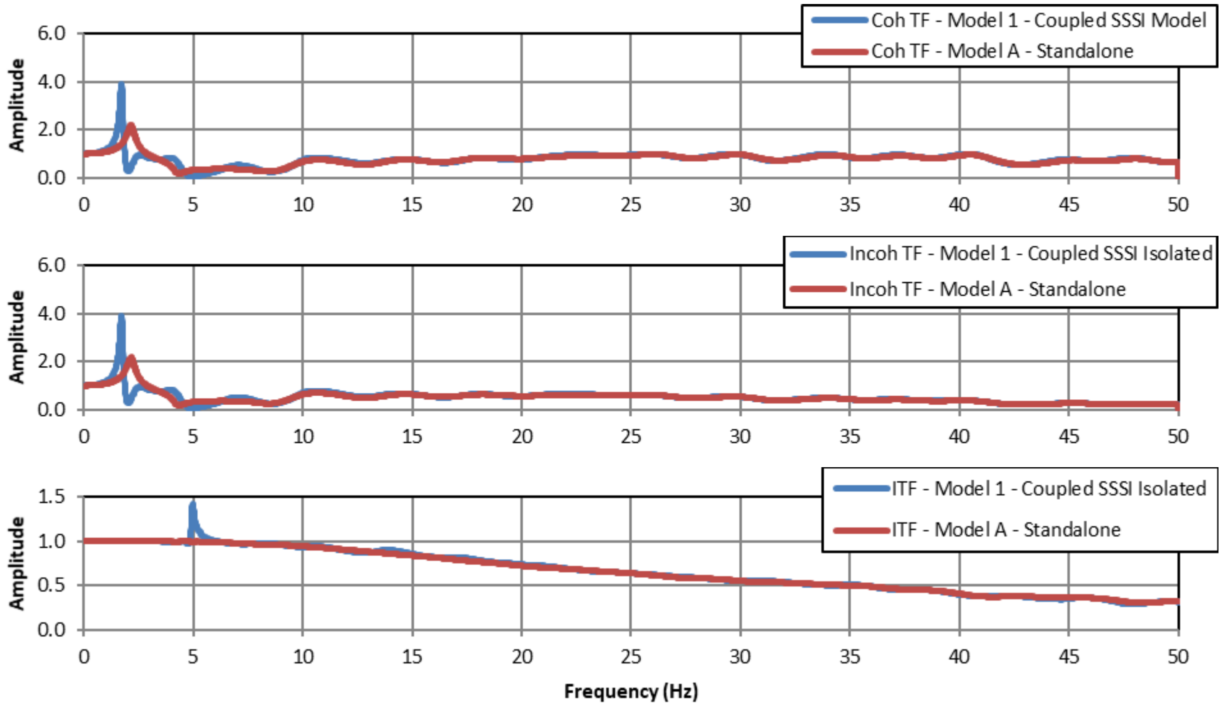

Figure 5. Coherent TF (top), Incoherent TF (middle), ITF (bottom) – Horizontal X-Direction – Model 1 Coupled SSSI Isolated vs Model C (TB) Standalone – Centre of Slab, Model A (AB)

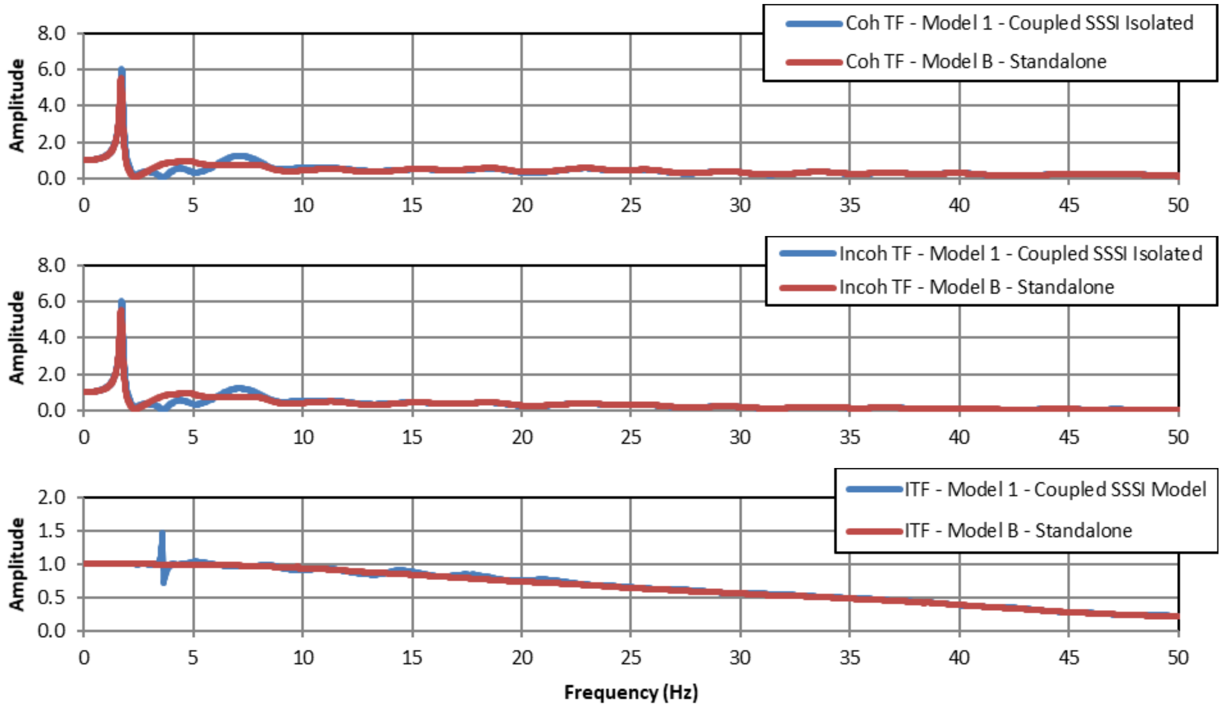

Figure 6. Coherent TF (top), Incoherent TF (middle), ITF (bottom) – Horizontal X-Direction – Model 1 Coupled SSSI Isolated vs Model C (TB) Standalone – Centre of Slab, Model B (CB)

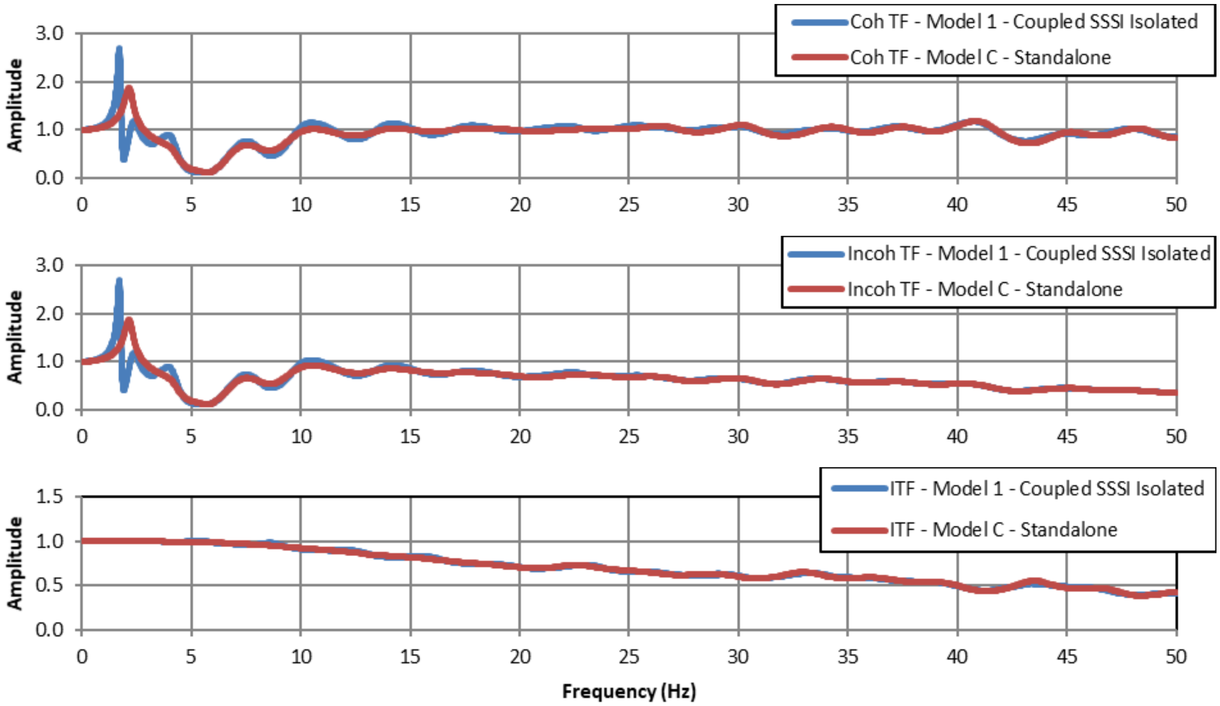

Figure 7. Coherent TF (top), Incoherent TF (middle), ITF (bottom) – Horizontal X-Direction – Model 1 Coupled SSSI Isolated vs Model C (TB) Standalone – Centre of Slab, Model C (TB)

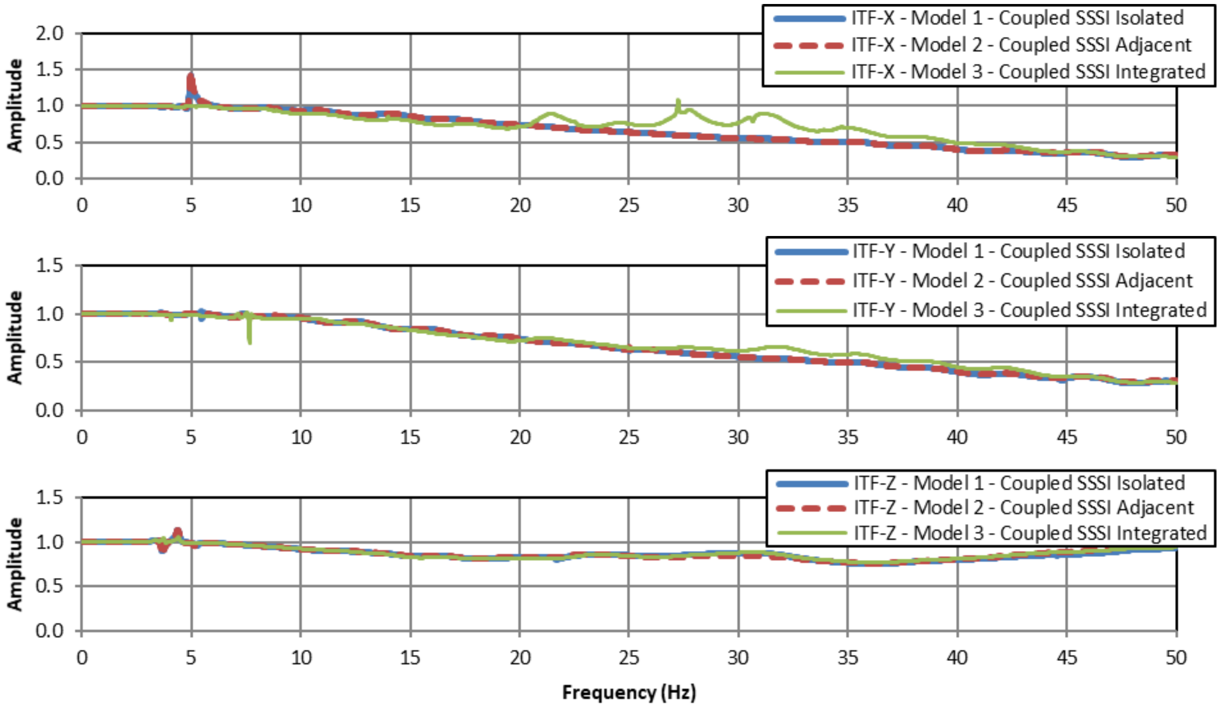

Figure 8. Incoherency Transfer Function (ITF) Response – X (top), Y (middle), and Z (bottom) Direction – Model 1 Isolated vs Model 2 Adjacent vs Model 3 Integrated – Centre of Slab, Model A (AB)

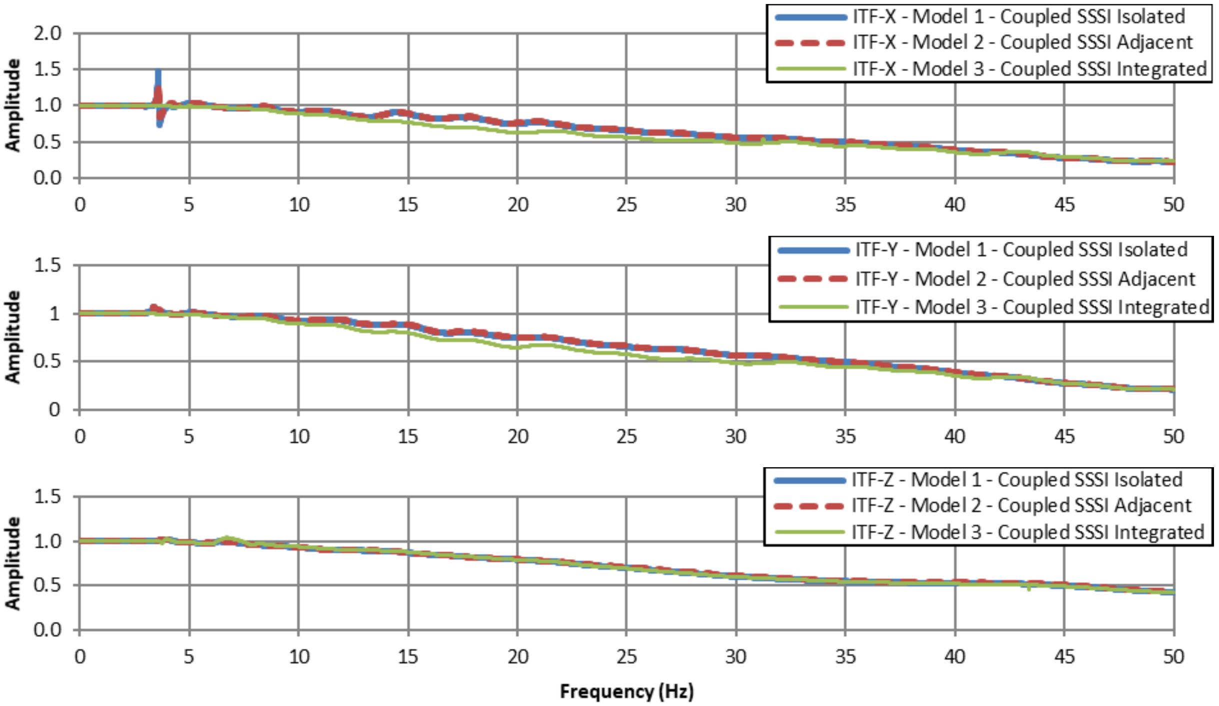

Figure 9. Incoherency Transfer Function (ITF) Response – X (top), Y (middle), and Z (bottom) Direction – Model 1 Isolated vs Model 2 Adjacent vs Model 3 Integrated – Centre of Slab, Model B (CB)

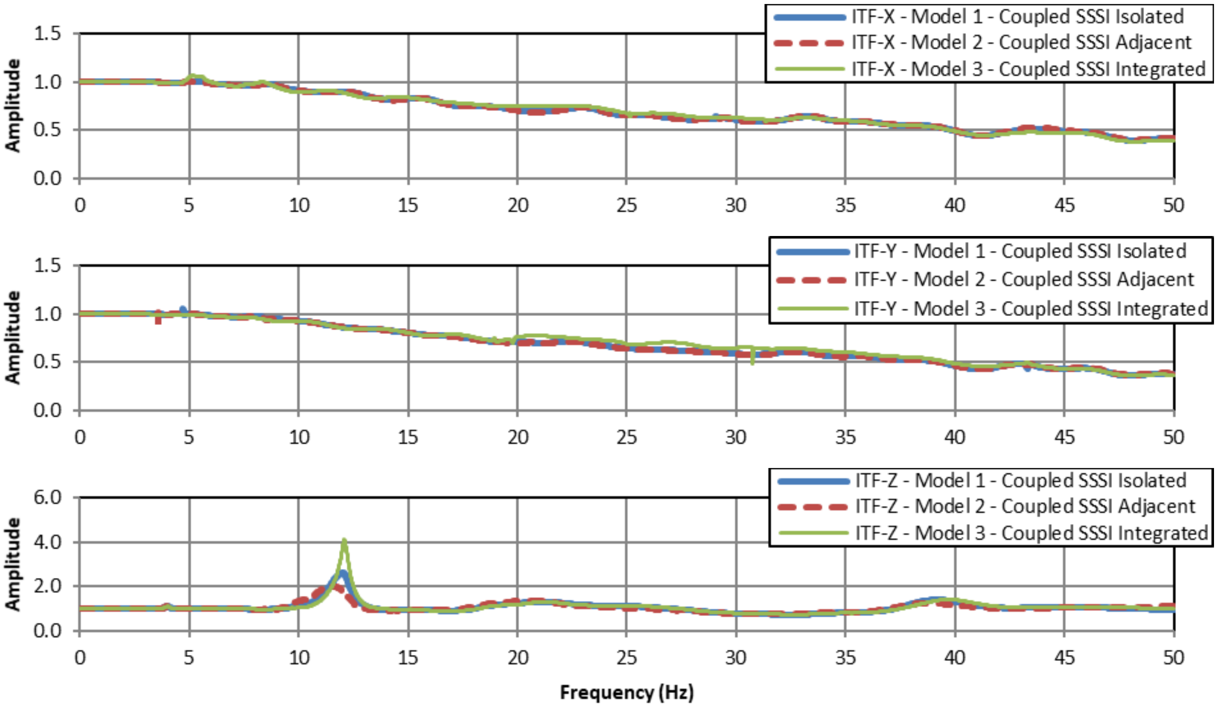

Figure 10. Incoherency Transfer Function (ITF) Response – X (top), Y (middle), and Z (bottom) Direction – Model 1 Isolated vs Model 2 Adjacent vs Model 3 Integrated – Centre of Slab, Model C (TB)

CONCLUSION

This paper provides a study example demonstrating that the spatial configuration of multiple foundations for a particular SSSI model has little influence on the magnitude of incoherent effects on building structural responses. Evaluation of foundation transfer function (TF) and incoherency transfer function (ITF) responses between a comprehensive, coupled SSSI model and analogous individual models shows little difference in magnitude of incoherency effects and demonstrates that the total effective coupled foundation area is not a driver of incoherent response. Similarly, when the individual foundations of the SSSI model are integrated into a single, continuous foundation, incoherency effects are shown to be influenced by the dynamic characteristics of the continuous foundation area while not grossly exaggerating the incoherency effects that one might expect from artificially increasing the foundation.

Based on the observations in this study, for the site-specific soil and analogous structural properties, incoherency effects appear to be mainly a function of the foundation area of each individual structure that comprise a coupled SSSI model. Similar to the structural arrangement for a typical Nuclear Island at commercial power plants in which adjacent structures are arranged such that they are seismically isolated, the inclusion of both SSSI and ground motion incoherency effects within the same comprehensive SASSI model would not be expected to introduce a significant unintended bias in response.

The observations in this study suggest that the total effective coupled foundation area is not a driver of incoherent response. However, the derivation of the underlying mathematics associated with these observations needs further study.

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