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VALIDATION OF LUMPED MASS STICK MODELS FOR SURFACE FOUNDED STRUCTURES

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ABSTRACT

Seismic events are perceived to be an important contributor to the Core Damage Frequency (CDF) for a majority of nuclear power plants (NPP). It is been demonstrated that Seismic PRA (SPRA) is a tool that provides a good understanding of a plant's response to a seismic event. The results of the SPRA tool can be used for the development of processes and programs that allow targeted improvements to structure, systems, and components (SSCs), resulting in an improved design and operational safety. Lumped Mass Stick Models (LMSMs) have been commonly used in the prediction of In-Structure Response Spectrum (ISRS) for NPPs. Detailed Finite Element Models (FEMs) are becoming popular for calculating ISRS. But, developing FEM for the existing buildings for the legacy plants is a resource intensive process. Therefore, a study is performed to compare the calculated ISRS of the LMSM and FEM for Symmetric-Surface Founded (SSF) structures. Additionally, the study is used to gain better insights into the dynamic behavior of LMSM. To this end, the structural model of the Diesel Generator Building at Vogtle 1 and 2 Electric Generating Plant (VEGP) is generated using LMSM and FEM methods; fundamental frequencies, deformation and ISRS generated by the LMSM are compared with those obtained from FEM.

INTRODUCTION

Over the last several decades, the world has experienced an increase in reported natural disasters and it is anticipated that these challenges will continue for the remainder of the 21st Century (Vaughn-2013). Earthquakes are among the most costly natural hazards affecting Power Plants worldwide, in terms of both economic damage and loss of life. SPRA evaluates the Power Plant by Performance Based Engineering (PBE). PBE is the process through which a facility is economically designed or an existing one is evaluated to meet certain performance requirements as specified by owners, end-users (public) and stakeholders (Griffis-2013). SPRA can assist in accurately estimating the risk due to the seismic activities and guidance to mitigate the potential losses due to a seismic event. Mitigation measures can be classified into different categories depending on the component they enhance and their corresponding risk reduction in the SPRA model; uncertainty analysis and cost-benefit analysis can evaluate the effectiveness of the mitigations techniques (Torkian-2013). SPRA model includes many modules that calculate failure probability of SSCs. As part of computing the conditional seismic failure probability for any given component, it is necessary to develop accurate structural models for estimating the in-structure seismic responses and calculate the ISRS. This study is used to evaluate the use of SSF-LMSM for the risk informed applications like SPRA. The Diesel Generator Building at Nuclear Plant Vogtle 1 and 2 is chosen for this study.

STRUCTURE CONFIGURATION

The Diesel Building (DB) (one for each unit) is a two-story rectangular, reinforced concrete building. The walls, slabs, and columns supporting the DB laterally and vertically are all reinforced concrete. Steel beams are also part of the vertical load-resisting system. The height between the base mat and the highest point of the structure is 71ft. The DB is 92 ft-0 in. length in the east-west direction, and is

114 ft-0 in. length in the north-south direction (2). The DB has a 9 ft thick reinforced concrete base mat with a top of concrete elevation of 220 ft-0 in. The bottom of the DB base mat is at Elevation 211 ft-0 in. The Plant grade is at Elevation 220 ft. See Table 1 for floor top-of-concrete elevations for all roof and floor slabs. The building is shallowly embedded in ground. The hazard for the 4 ft below grade is assumed to be the hazard for the DB as the hazard for the 9ft below grade was not available at the time of this study.

Table 1: Floor and Roof Elevations

Top of Concrete Elevation (ft-in.)	Slab Thickness Range Primary Thickness (in.)
280’-0”	24
255’-0”	24
220'-0"	108

TIME HISTORIES

Five sets of three statistically independent acceleration time histories (two horizontal components and one vertical component H1, H2, and V) representing the input ground motion in NS, EW, and vertical direction, respectively are applied to the structure. The suitability of a given time history as a seed is evaluated in terms of similarity of spectral shape. The analysis team was interested in comparing the effect of the strong ground motion on the structure; therefore an artificial hazard was selected as an input motion. Vogtle is an eastern US site, and very few central and eastern US (CEUS) strong motion records are available. Therefore, the seed selection included western US (WUS) sites as advocated for CEUS sites in NUREG/CR-6728. The acceleration time histories are compatible to the 1E-4 artificial-hazard level outcrop Uniform Hazard Response Spectra (UHRS) and are matched to comply with the requirements of ASCE 43, ASCE 4-98, and NUREG/CR-6728. Figure 1 shows the response spectrum for one of the matched time histories (Seed H1a) that is used as an input ground motion for SSI analyses.

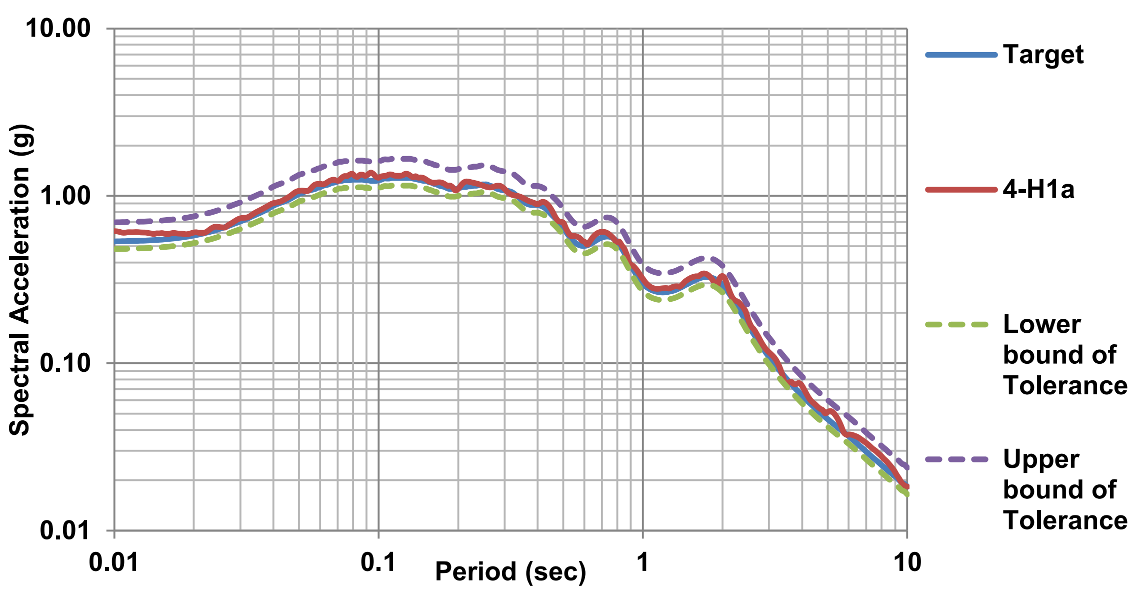

Figure 1. Comparison between Artificial Target Spectrum and Final Modified Response Spectrum for Set a, H1direction

SITE CONDITIONS

Vogtle Site Response Analysis for Units 1 & 2 report (7), provides input soil/rock properties for the SSI analyses that are compatible with the strains generated by the input ground motion which envelope the effects of geological, geotechnical, and hydrological site parameters for the Vogtle Site. The simulated soil profiles developed in Vogtle Site Response Analysis for Units 1 & 2 report (7) are used for the SSI analyses. Their median strain-compatible properties, shear-wave (Vs) and compression wave (Vp) velocities and corresponding hysteretic damping values provide a representation of properties that address soil conditions for Vogtle site. The site profile considers the elevation of ground water table located 55 ft below the plant grade. Figure 2 shows the variation of shear-wave velocity along the top 330ft of the soil.

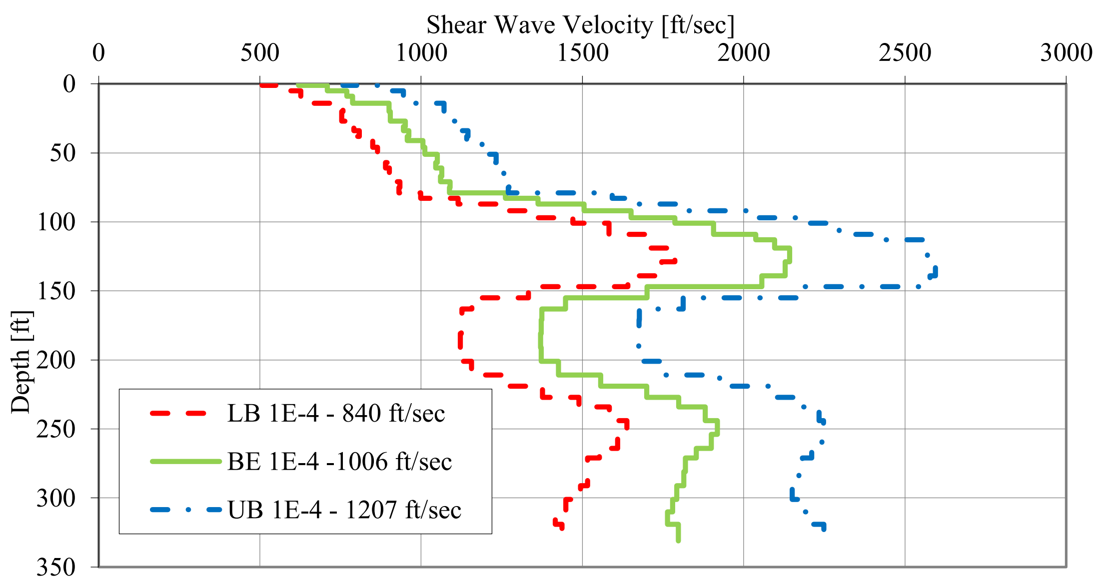

Figure 2. Top 330 ft of the Shear-Wave Velocity Profile and Associated depth.

The Soil Structure Interaction (SSI) analyses considers the base mat of the DB resting on the surface of the sub grade located approximately 9 feet below the plant nominal ground surface elevation. The soil profile used for the analyses are obtained by removing the top 9 feet of soil from the three profiles (namely, Lower Bound (LB), Best Estimate (BE), and Upper Bound (UB)) developed in the Vogtle Site Response Analysis for Units 1 & 2 report (7). The site sub grade models in the SASSI2000 (1) analyses use infinite horizontal layers to represent the top of approximately 330 feet of sub grade materials for the DB. An elastic half-space that is modeled by an additional 10 layers represents the dynamic properties of the sub grade located at approximately 1125 feet below the bottom of the base mat for the DB. The input properties are derived from the soil profiles that are documented in Vogtle Site Response Analysis for Units 1 & 2 report (7) by adjusting the layering to ensure the capacity of transmitting shear waves through the sub grade of the DB. In addition, for the DB, the SASSI2000 (1) site input layering and properties are adjusted to match the FEM mesh size. To ensure the capacity to transmit the shear/compression waves, the layering of both sub grade sets is adjusted to ensure that the thickness of the soil layers is not greater than 20% of the minimum wave length corresponding to the selected cut-off frequency of analysis.

FIXED BASED LUMPED MASS STICK MODEL

The DB is modeled as a system of lumped masses located at the floor elevations. The equipment and components are lumped into the supporting mass. The DB building has three lumped mass nodes and the inertial properties for these are computed. The walls in the DB are modeled as multiple beam elements running from floor to floor. Hence all the ends of the beam elements at each floor level are rigidly linked to the node where the masses are lumped. The base mat is modeled as a rigid beam running along the length of the base mat. The model is fixed at the bottom of the base mat. The global coordinate system is designated with X axis along the east-west direction, Y axis along the north-south direction and Z axis along vertical upward. The LMSM is shown in figure 3

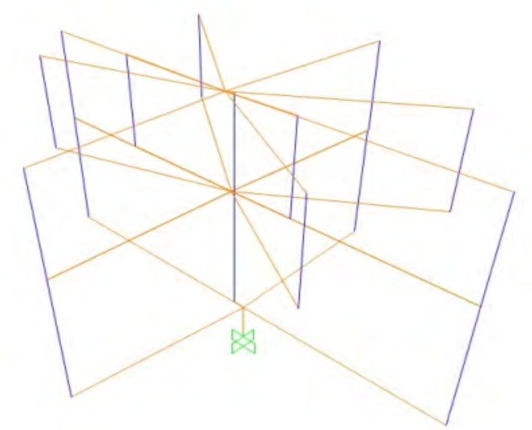

Figure 3. General Configuration of the LMSM.

FIXED BASED FINITE ELEMENT MODEL

The finite element model is built using “thick shell area” elements for modeling the walls and slabs and the “frame elements” are used to model the beams and columns. “Thick shell area” elements are a three or four-node area object used to model membrane and plate-bending behavior (10). “Frame elements” used to model beams, columns, braces, and truss elements in planar and 3D systems, are straight lines which connect two nodes (11). Walls are modeled as center-lined shell elements with their full uncracked thickness for capturing the membrane and bending behavior. Slabs are modeled as center-lined shell elements with full uncracked thickness for membrane behavior whereas equivalent uncracked thicknesses for plate bending are used. Concrete columns are modeled as frame elements with uncracked sections and the steel beams are modeled as elastic frame elements. Openings and penetrations in the walls as well as slabs are selected and removed locally from the finite element mesh in the model. Slab openings with areas greater than 18 sq ft or greater than 10% of the room area are selected for removal from the finite element mesh. Criteria used for selection of walls door openings and penetrations for removal are the same as the one for the slab. The model origin is established vertically at Elevation 220 ft-0 in., which is the location of top-of-concrete on the base mat slab on Level 1. Horizontally the origin is located at the south-west corner of the DB. The X- and Y-axes are oriented in the horizontal plane and the Z-axis is oriented upward. The X-axis is oriented in the east-west direction, and the Y-axis is oriented in the north-south direction. Nodes of wall shell elements and columns frame elements at EL. 220 ft-0 in. are fixed for all six degrees of freedom. The FEM is shown in figure 4.

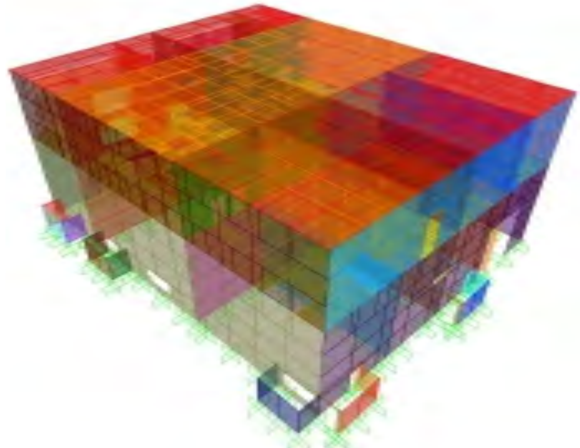

Figure 4. General Configuration of the FEM.

MODAL ANALYSIS

A modal analysis is performed on the building using the Ritz vector method; Frequencies, mode shapes, and mass participation factors are reviewed to check that the model realistically represents the fixed-base structure. Static analyses are performed by applying 1g load on the X- (east-west), Y- (north-south), and Z- (vertical) directions. The fixed base frequencies and the displacements from the 1g tests are shown in table 2 and 3 respectively.

Table 2: Fixed Based Modal Analysis

Description	Frequency	
	LMSM	FEM
	Hz	
X-translational 1st mode of the DB	7.42	9.05
Y-translational 1st mode of the DB	11.89	11.09
Vertical 1st mode of the DB	23.30	12.35
Torsional 1st mode of the DB.	12.94	12.87

Table 3: Results of the 1g Static Test

Elevation (ft)	1gx (East-West)		1gy (North-South)		1gz (Vertical)	
	XFEM(in)	XLMSM(in)	YFEM(in)	YLMSM(in)	ZFEM(in)	ZLMSM(in)
280'	0.15	0.19	0.09	0.09	0.02	0.02
255'	0.10	0.16	0.07	0.07	0.02	0.02

As table 2 indicates FEM is stiffer in X Direction in comparison to the LMSM, because certain non-primary walls are excluded in the design based LMSM, which are modeled in FEM in accordance to the as-built configuration. Table 2 shows that the LMSM has a higher frequency in vertical direction in comparison to the FEM, because LMSM has one beam element with rigid foundation properties and cannot capture the flexibility of the slabs. As table 3 indicates the 1g force resulted in similar displacements in both models. FEM has less displacement in the X direction in compare to the LMSM, because all walls are modeled in the X direction in the FEM. The results of the modal analysis and static test indicate that fixed based LMSM and FEM are well in agreement in terms of structural behavior. The results are inclusive but not conclusive, because the site-specific characteristics such as the soil nonlinearity and shape of the hazard curve have not been considered yet. In the following sections the effect of site-specific characteristics will be discussed

SSI-LUMPED MASS STICK MODEL

In the SASSI2000 (1) SSI model, the foundation base mat along the supporting soil medium is modeled and the base mat is modeled by three dimensional solid elements. The rigid beam representing the base mat in the fixed base LMSM is removed and is replaced by the 3-D solid elements to represent the basemat. The thickness of the base mat is 9ft. The rigid properties are assigned to the base mat as the effect of basemat flexibility is assumed to be small and the mass is assigned as zero, as LMSM has accounted for the mass. The basemat is attached to the LMSM by means of high-stiffness beams. The stiffness of these beams is high enough to safely assume that the connection exhibits rigid linking behavior. The overall LMSM for SASSI2000 is shown in figure 5.

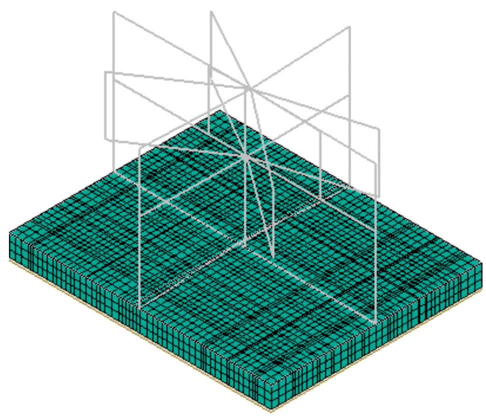

Figure 5. Diesel Generator SSI Model – Lumped Mass Stick Model.

SSI-FINITE ELEMENT MODEL

Structure foundation is modeled as 3-D solid elements with a thickness of 9ft in SAP2000 and was in-turn added to the fixed-base FEM. The mass and stiffness properties of the base mat is the same as that of concrete (f'c = 4000 psi). The finite element model is connected to the base mat at 220 ft-0 in. The overall FEM for SASSI2000 is shown in figure 6.

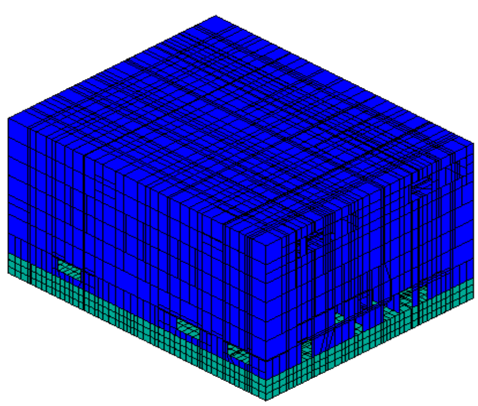

Figure 6. Diesel Generator SSI Model – Finite Element Model.

SSI-METHODOLOGY

SASSI2000 has the capability of simulating the existence of uniformly damped half space below the top soil layers. By this method, it can avoid using very deep soil models with many sub layers. The finite element method is used in the soil-structure interaction analyses for DB. This method is suitable as it considers the variation of soil characteristics with depth and variation of motions with depth. The cutoff frequency for the analysis is chosen as 30 Hz and it is based on the following factors: frequency content of the input motion, dominant frequencies of the soil-structure system, and time increment of the input time history. The frequency at which SASSI analysis is performed is chosen based on the frequencies of the soil-structure system. The direct method is used for the computation of the impedance matrix and transfer functions. The control motion obtained with time history matching process is used as the input and the input motion is applied at the foundation level of the structure. Three sets of analyses are performed for each model in the three orthogonal directions. The analyses in the X and Y directions are performed with ten time histories to simulate the fault parallel and normal conditions.

COMPUTATION OF IN-STRUCTURE RESPONSE SPECTRA (ISRS)

In-structure response spectra (ISRS) are generated for various areas of the Diesel Building in accordance with ASCE-43 to serve as the basis for calculating fragility of category I systems, subsystems and components (SSCs). The SASSI analyses provide results for the response of the LMSM and FEM of the DB structure due to the five sets of three components of the site-specific time histories for the three soil profiles. At representative node locations, 5% damping acceleration response spectra (ARS) in the three orthogonal directions are calculated for each of the three directions of the input ground motion. The ARS calculated at equal frequency points between the 0.1 Hz and 100 Hz. The responses obtained for the three directions of the input ground motion are combined using the square root sum of the squares (SRSS) method (12) as follows:

$$ARS_x = \sqrt{ARS_{xx}^2 + ARS_{yx}^2 + ARS_{zx}^2}$$

$$ARS_y = \sqrt{ARS_{xy}^2 + ARS_{yy}^2 + ARS_{zy}^2}$$

$$ARS_z = \sqrt{ARS_{xz}^2 + ARS_{yz}^2 + ARS_{zz}^2}$$

where:

ARS(m) (n) are the SASSI ARS results for the response in “n” direction due to earthquake in “m” direction,

ARSx, ARSy, ARSz are the combined ARS of the structural response in EW (x), NS (y), and vertical (z) direction.

RESULTS

For comparison study, the acceleration response spectra at 5% damping are computed for twenty seven pair of nodes in LMSM and FEM. For brevity, only six nodes are presented in this paper. The center of the floor slab at EL 255’-0” is taken as the point of comparison for the ISRSISRS with the LMSM’s mass joint at the same elevation. Figures 7, 8 and 9 show the comparison of the ISRSISRS in two models at this location.

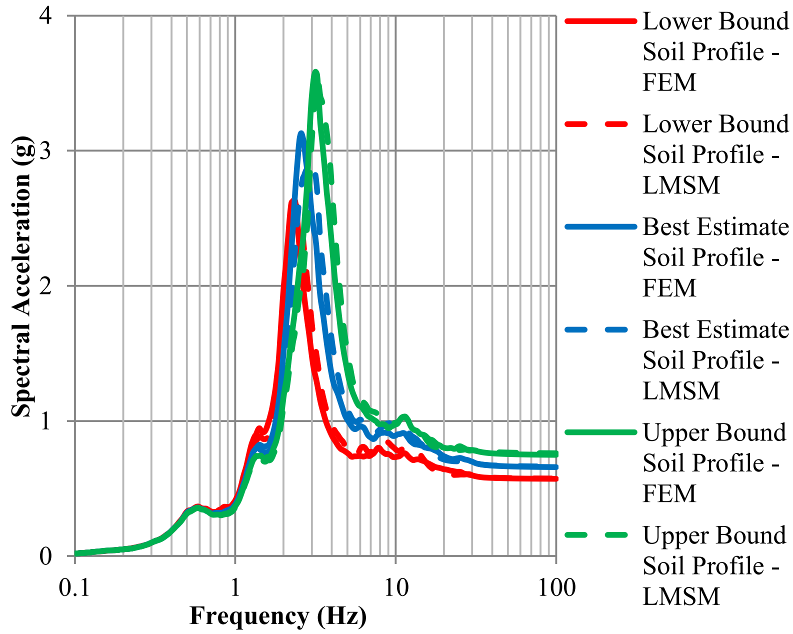

Figure 7.Comparison of Response Spectra of the 3 soil profiles for LMSM and FEM, 5% damping, Center of Mass, Elevation 255 ft-0 in, X Direction

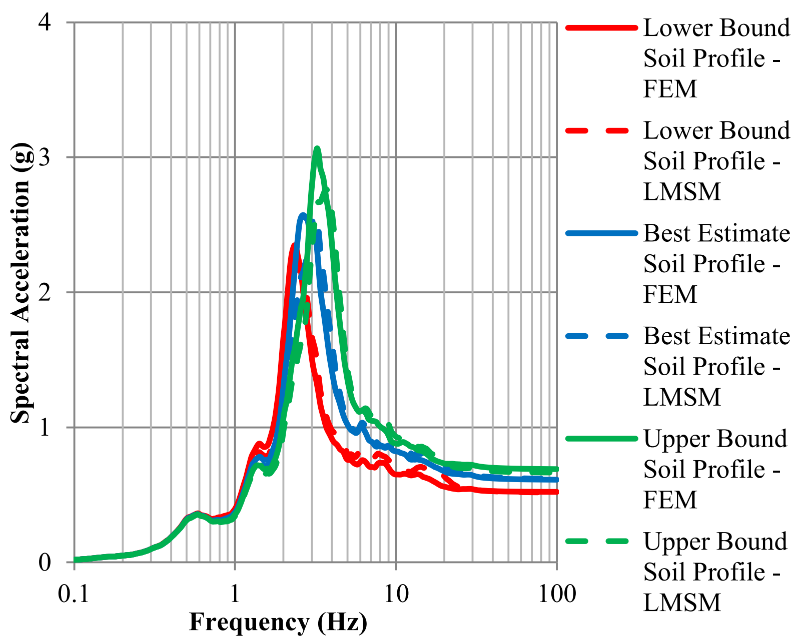

Figure 8. Comparison of Response Spectra of the 3 soil profiles for LMSM and FEM, 5% damping, Center of Mass, Elevation 255 ft-0, Y Direction in

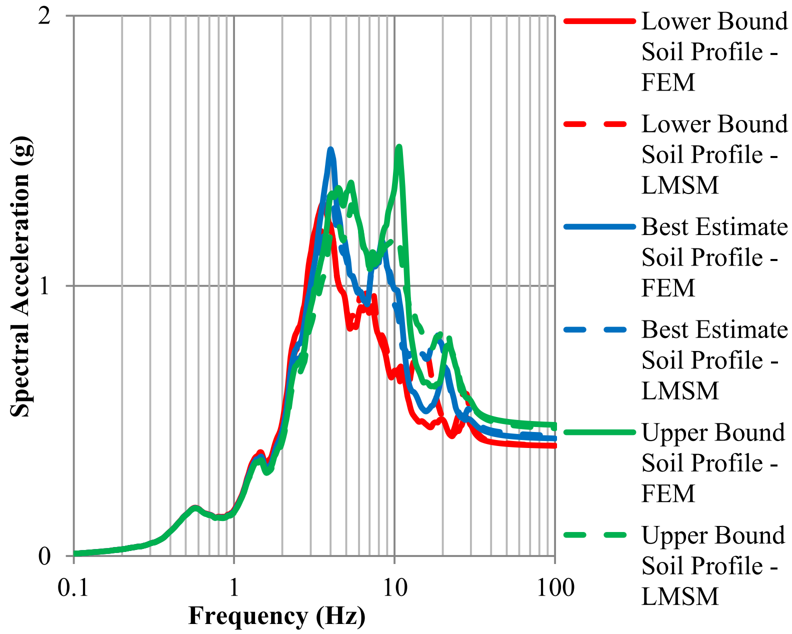

Figure 9. Comparison of Response Spectra of the 3 soil profiles for LMSM and FEM, 5% damping, Center of Mass, Elevation 255 ft-0, Z Direction

There is a maximum of 22% under prediction of the ISRSISRS in the LMSM on comparison with the FEM in the N-S direction for the Best Estimate soil profile, 19% in the E-W direction and 34% over prediction in the vertical direction for the Best Estimate and Lower Bound soil profile respectively. The discrepancy between the responses is primarily seen in the higher frequency range.

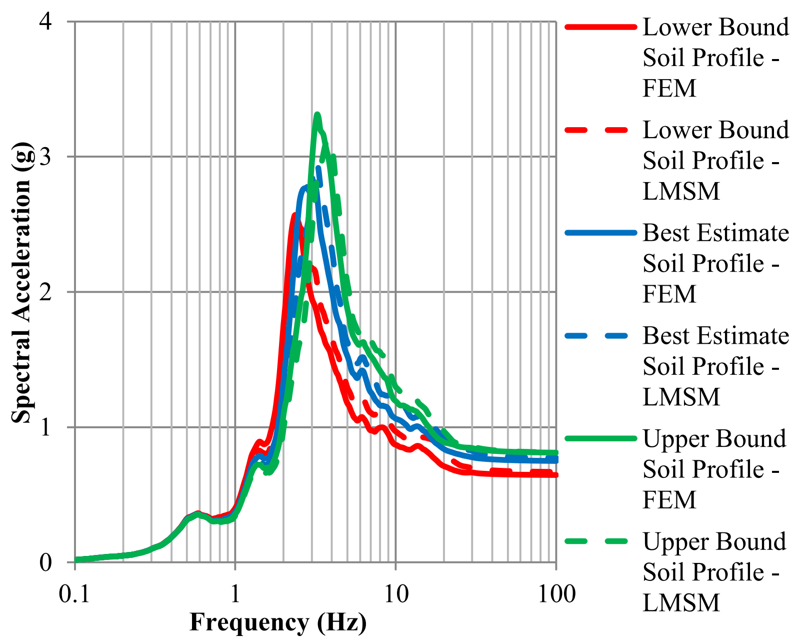

Figure 10. Comparison of Response Spectra of the 3 soil profiles for LMSM and FEM, 5% damping, East-West wall, Elevation 255 ft-0in, Y (North-South) Direction

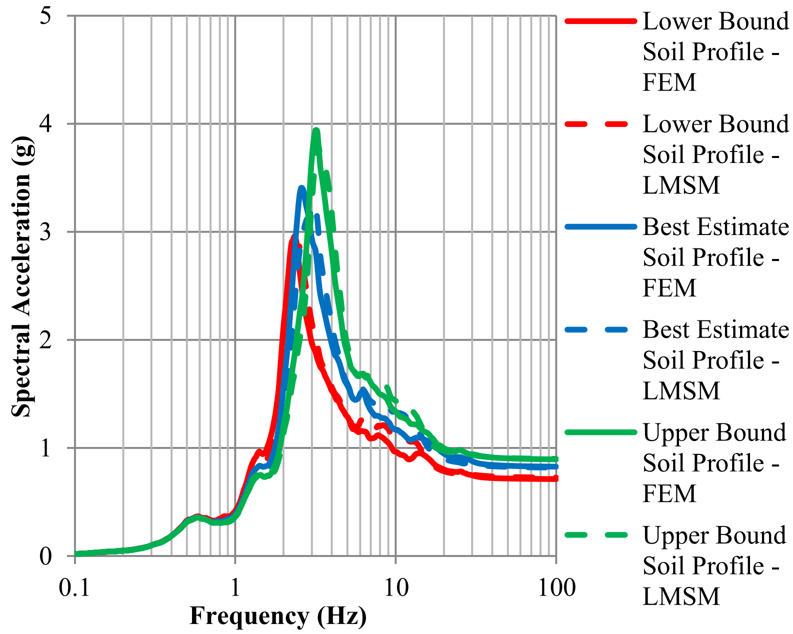

Figure 11. Comparison of Response Spectra of the 3 soil profiles for LMSM and FEM, 5% damping, North-South wall, Elevation 255 ft-0in, X (East-West) Direction

The ISRS of the FEM walls in the N-S and E-W directions are compared with the ones in the LMSM, to analyze the ability of LMSM's capabilities to capture the out of plane behavior. The LMSM's E-W walls under predicts the ISRS by 22%, for the best estimate soil profile, in comparison with the FEM in the N-S direction and the N-S walls under predicts the response by 20%, for the best estimate soil profile, in comparison to the FEM in the E-W direction. This could be seen in figures 10 and 11.

CONCLUSION

One of the main challenges with SPRA is the modeling of complex structures since developing FEMs versus LMSMs is cost intensive. A comparison study was conducted of the calculated ISRS using the LMSM and FEM for a Symmetric-Surface Founded (SSF) structure to evaluate the acceptability of using a LMSM approach in an SPRA which could reduce the overall modeling costs in developing an SPRA. Key findings of the study include the following:

- Conclusions are site specific and can be generalized only into SSF structures that are located on a site with similar soil characteristics. It is recommended to also evaluate the spectral shape, predominant modes and the transfer function of the fixed based structure before deciding to choose a model.
- In all cases, the differences between the LMSM and FEM were observed to be predominantly in the high frequency region.
- The LMSM results are conservative in the vertical direction in the High Frequency range.
- The LMSM is capable of capturing the horizontal responses due to only minor differences in horizontal out-of-plane and horizontal in-plane behaviors.
- The SSI analysis causes the frequency of the structure to shift and based on the spectral shape it lowers the overall response of the structure regardless of the type of the model.

These results can provide a key support to solve many of the problems that are faced by the SPRA projects. In particular, based on the results of the study, it is possible to use this type of LMSM when necessary, to be able to evaluate the structure behavior in the absence of FEM.

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