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VALIDATION OF SASSI2010 SOLUTION METHODS THROUGH INDEPENDENT VERIFICATION USING SAP2000 FOR DEEPLY EMBEDDED STRUCTURES WITH LARGE FOOTPRINTS

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ABSTRACT

A System for Analysis of Soil-Structure Interaction (SASSI) is a frequency domain finite element computer program commonly used to solve Soil-Structure Interaction (SSI) problems. In this paper, the SSI response of a large deeply embedded structure is determined using SASSI2010 and independently verified using SAP2000.

A 3-D SASSI2010 model is created for a structure with a footprint of 200' by 300' and an embedment depth of 140'. The SASSI2010 solution is performed using the Extended Subtraction Method. The analysis is completed using a SASSI2010 model where a soil profile and motion are adopted to represent the site of interest. A 3-D SAP2000 model is also generated and inherits the structural model of SASSI2010, while the surrounding soil layers are modeled using solid elements. The free-field soil response simulation is ensured by modeling the soil layers to a lateral extent where the response is insensitive to boundary condition effects.

BACKGROUND

The consideration of Soil-Structure Interaction (SSI) effects on dynamic response is required for the design of nuclear safety-related structures founded on soil-sites. Some new designs introduce large excavated volumes that are considered first of a kind. The embedded nature of these new designs introduces significant challenges to the SSI analysis of the soil-structure system, including an increase of the analysis solution time due to the large area of soil-structure interface, as well as the lack of available benchmark results for the analysis of deeply embedded structures.

The complexities associated with the SSI analysis, under examination in this paper, are significantly greater than those faced in the current state of practice. The level of complexity of SSI analysis is most sensitive to the embedded portions of a given structure and how the structure interacts with the soil at these locations. As the nuclear structure considered is almost fully embedded and to a considerably large depth (140 ft), the level of SSI analysis complexity is much greater than typical operating, nuclear safety-related structures.

The method of SSI analysis to be employed is the "extended subtraction method" using SASSI2010 Version 1.1 (Ostadan et.al, 2011). The subtraction method became the industry standard for sub-structuring methods in the late 1990's. This solution technique only requires the definition of interaction nodes on the outer perimeter of the excavated soil volume. Hence, compatibility of free-field and excavated soil dynamic responses is imposed only at the perimeter. For conditions where, the embedment depth to structure width is large and it is evident that the excavated soil volume must be restrained further, the subtraction method is extended to include additional layers of interaction nodes, as needed, at mid-height and/or at the ground surface layer of the excavated volume. This is referred to as the "extended subtraction method".

The purpose of this Calculation is to produce an independent verification of the "extended subtraction method" solution technique for the SSI analysis of a deeply embedded, large footprint structure. This verification is accomplished by comparing the solution to that using SAP2000 computer program (Computers & Structures, Inc., 2000).

DEVELOPMENT OF 3-D STRUCTURAL MODEL

A 3-D SASSI2010 model is created for the structure with a footprint of 200’ by 300’ and an embedment depth of 140’. The 3-D model generated herein is intended only to represent the maximum footprint and embedment of the structure and the global SSI response. This decreases the computational effort as well the complexity of the structural responses, so that the global SSI effect can be easily identified.

A plan view of the 3-D model is shown in Figure 1. Note that the dimensions shown on the Figure are not drawn to scale. The analysis considers two lines of symmetry (shown as X and Y in Figure 1). Two main interior shear walls are considered as denoted by a solid line in Figure 1.

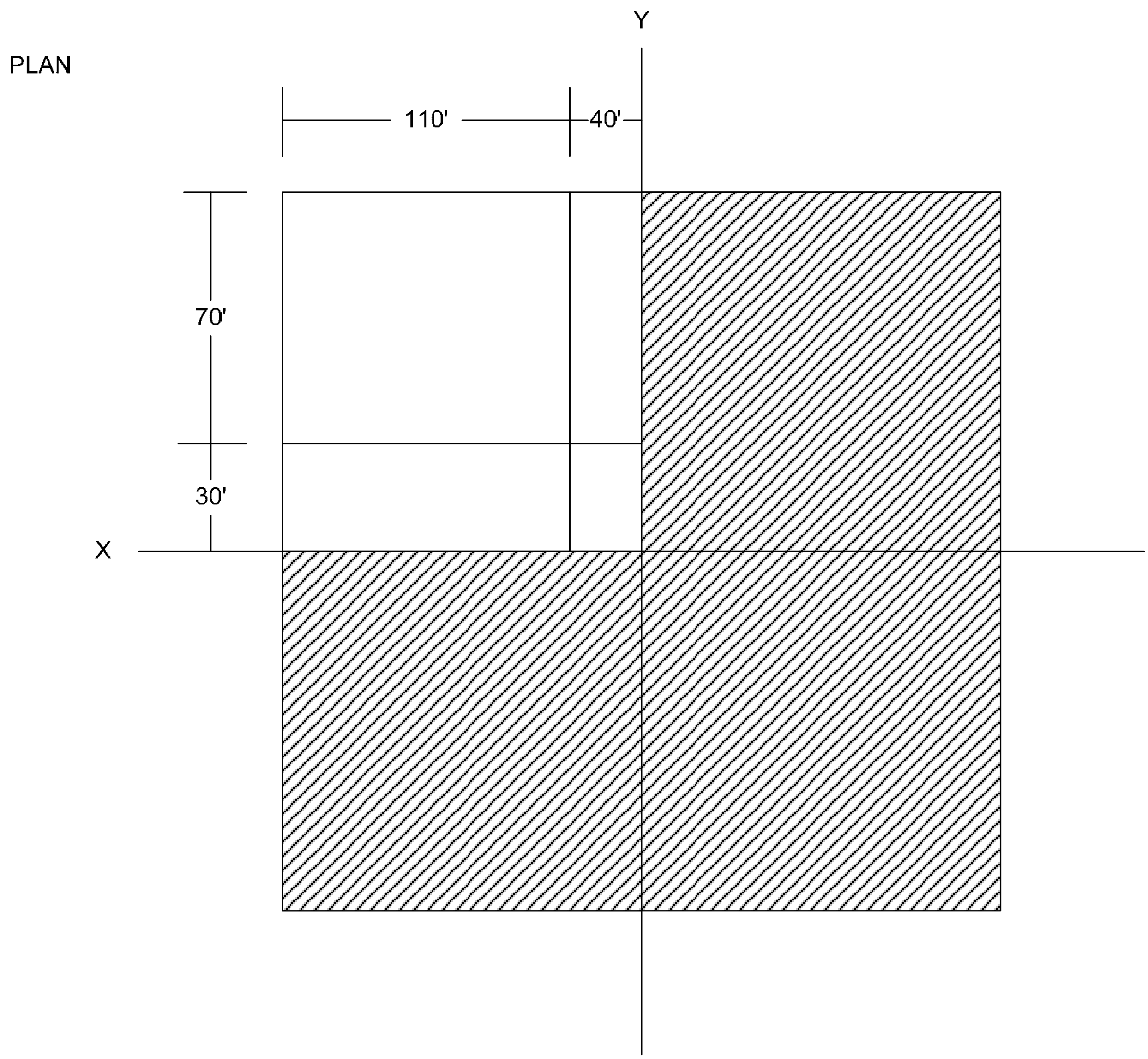

Figure 1. Plan View of the 3-D Structural Model.

An elevation view of the 3-D model is shown in Figure 2. The section is taken parallel to the X-direction as denoted on Figure 1. As shown in Figure 2, the total height of the structure is 190'. Of the 190' height, 140' of the structure is embedded. The interior includes two internal shear walls as shown in Figure 1 and six floor slabs in additional to the roof and mat elevations. The shear wall parallel to the Y-Direction is offset 40' from the line of symmetry, while the shear wall parallel to the X-Direction is offset 30' from the line of symmetry. In order to simplify the load path, no penetrations or discontinuities are considered.

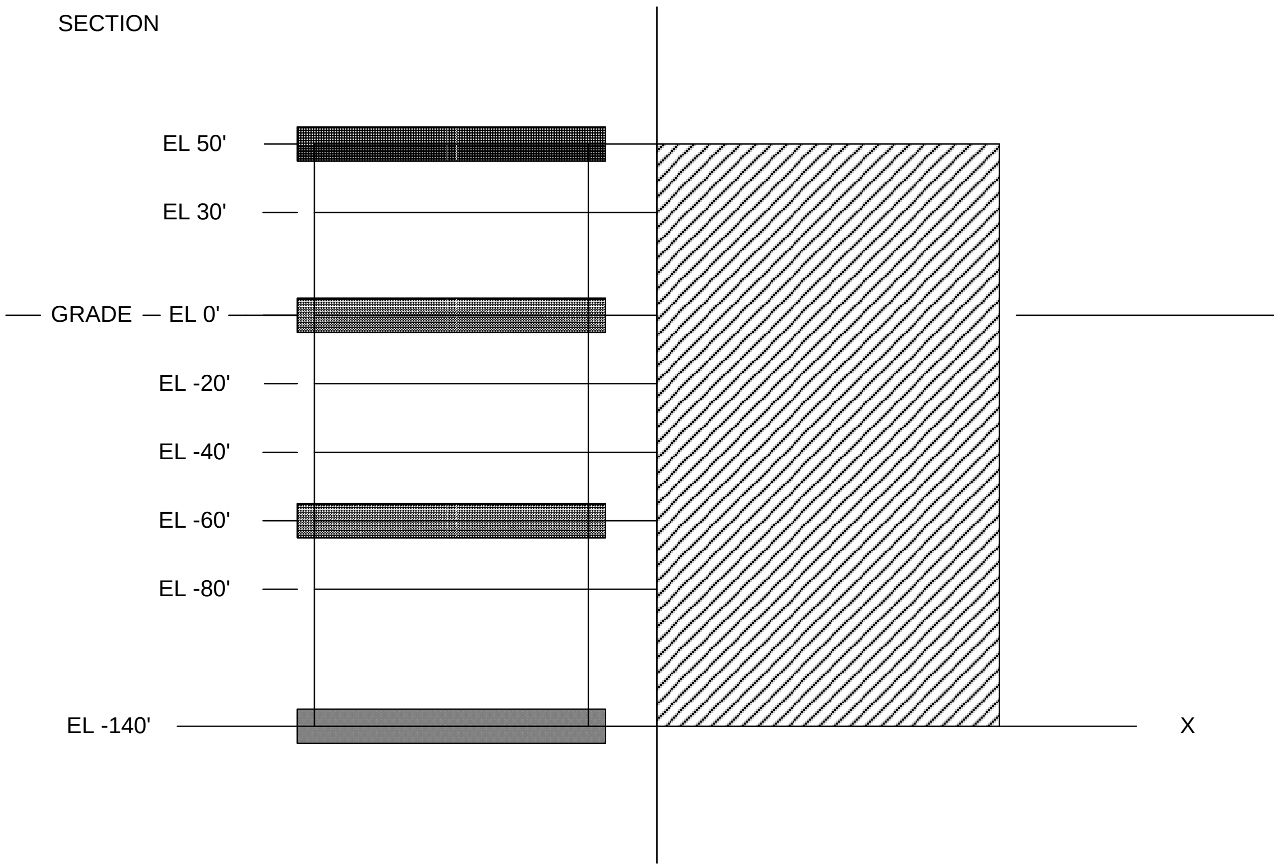

Figure 2. Elevation View of the 3-D Structural Model.

All walls and slabs are modeled using thick shell elements with concrete properties corresponding to 5000 psi concrete (E = 580464 ksf, ν = 0.17). A density of 0.150 kcf is considered for the walls. All slabs are assigned a density of 0.250 kcf. This includes the density of concrete (150 pcf) with an additional 100 psf to account for additional loads due to commodities and live loads. A uniform 10' mesh is considered for all shell elements in the model. The following element thicknesses are considered: 5' for walls, 3' for floor and roof slabs, and 10' for the basemat. The structural damping ratio is taken as 5% of critical damping.

The 3-D model is first created in SASSI2010 and an identical structural model is generated in SAP2000. The nodal coordinates, nodal identification numbers, element incidences, and loading defined in the SASSI2010 model are identical to that of the SAP2000 model.

SOIL MODEL GENERATION

A uniform soil profile is considered that is representative of a soft to medium soil site. The uniform soil profile has a shear wave velocity of 2,500 fps, a compression wave velocity of 4,677 fps, and damping ratio of 5%. The structural elements are uniformly meshed with 10' divisions, both horizontally and vertically. Using the 2,500 fps shear wave velocity and a wavelength limitation of $V_s/5$, the corresponding frequency cutoff is 50 Hz. The comparative analysis is taken out to a frequency of 15 Hz, since the primary modes are captured within that range.

The soil column is extended 100' below the structure foundation where it transitions to a rigid halfspace. This distance was selected based on sensitivity analyses using SAP2000 to determine an appropriate location of the halfspace where the effects of boundary conditions are of little consequence. A 3D view of the quarter of the structure used for SAP2000 and SASSI2010 modeling is shown in Figure 3.

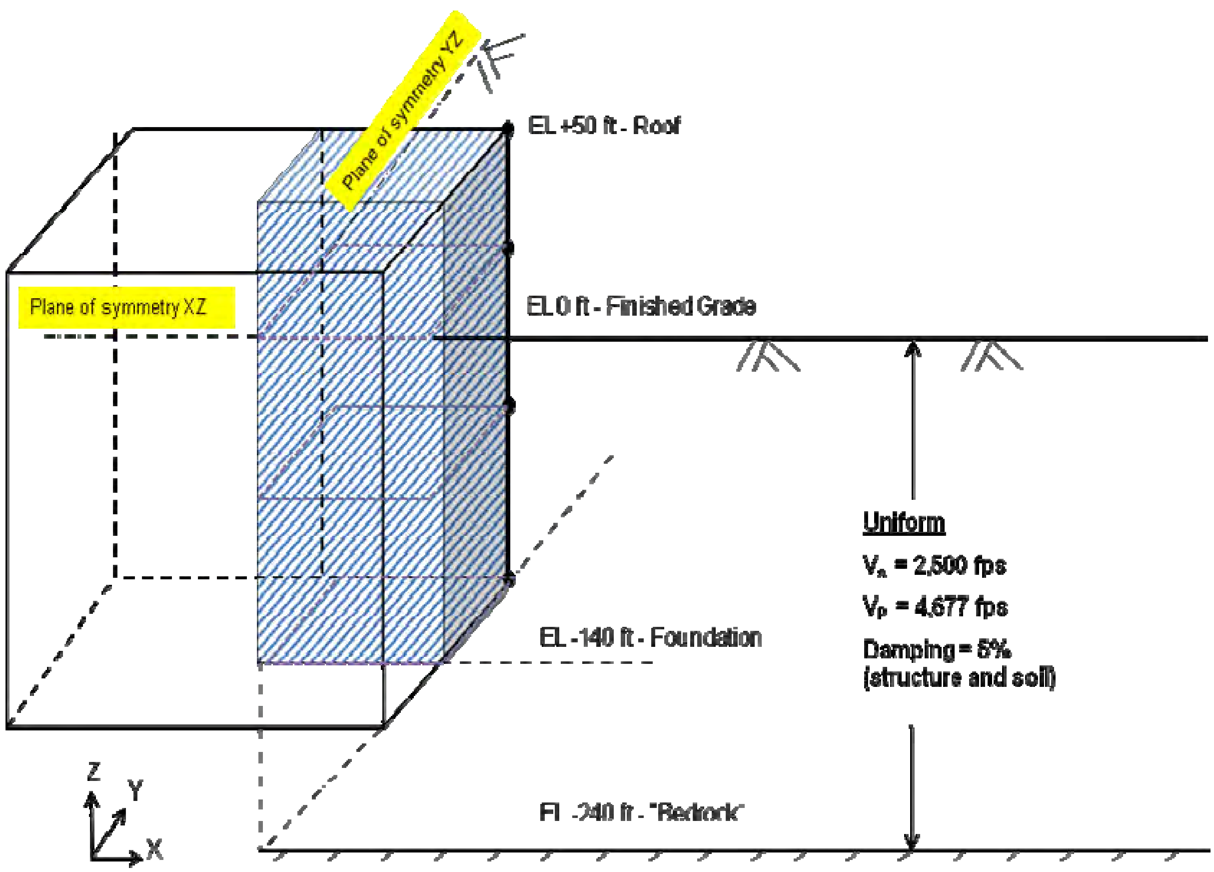

Figure 3. 3D view of the Deeply Embedded Structure with Two Planes of Symmetry used for Modeling.

The soil model is simulated in SASSI2010 using infinite horizontal layers as part of the SITE module. In SAP2000 analysis, the soil is modeled explicitly using solid soil elements. The 3-D solid elements have properties equivalent to the corresponding soil layer. The modeling geometry for the SAP2000 model, including soil elements, is shown in Figure 4.

The analysis is completed using SAP2000 and SASSI2010 for each orthogonal direction. Only X-Direction results are reported within this paper. In SASSI2010, analysis is completed up for a frequency of 70 Hz. Time history modal analysis is completed in SAP2000, using 280 modes to a frequency of 15 Hz, which covers approximately 97% of the total mass participation. Note that the first mode is at approximately 2.6 Hz and accounts for 84% of the total mass participation.

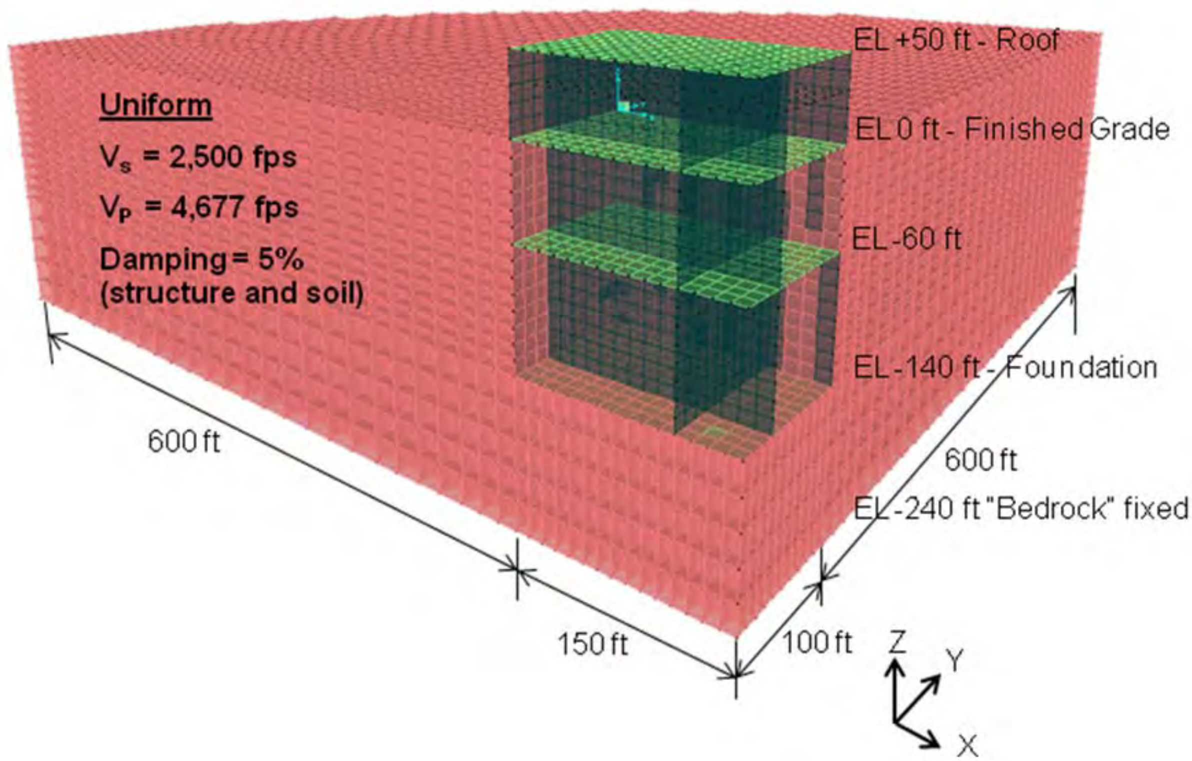

Figure 4. SAP2000 Soil and Structural Model Geometry and Properties.

VALIDATION OF THE SSI RESPONSE

As the global SSI response is of interest, responses are compared at the corner node of the structure (furthest from the lines of symmetry) at the four major elevations (i.e. Roof at EL 50', Grade at EL 0', Mid-depth at EL -60', and Foundation at EL -140').

Transfer function results are compared which represent the amplification function of the Fast Fourier Transform (FFT). In SASSI2010, the transfer functions are taken directly from the output of the program. In SAP2000, the FFT is first calculated of the acceleration time history at the considered node and the reference node. Then the transfer function is calculated as the ratio of the conjugate of the reference node FFT multiplied by the FFT of the considered node to the conjugate of the FFT of the reference node multiplied by the FFT of the reference node. For clarity, only the dominant direction response is compared (i.e. X Response due to X Motion).

The transfer function comparisons for the four locations considered are shown in Figure 5. The corresponding nodes for each location are: Node 1 (EL -140'), Node 2401 (EL -60'), Node 4201 (EL 0'), and Node 5701 (EL 50'). The SAP2000 generated responses are shown with solid curves. The SASSI2010 generated responses are shown with dashed curves.

Acceleration Response Spectra (ARS) are also computed due to an applied input motion representative of the Central Eastern United States. This motion has high energy in both the low frequency and high frequency ranges. The 5% damped within input response spectra compatible with this motion for the horizontal direction is shown in Figure 6. The motion is generated to be applied at the level of foundation, EL -140'.

For the purpose of the study, this control point is considered at the level of the rigid halfspace, EL -240', in both the SAP2000 and SASSI2010 models.

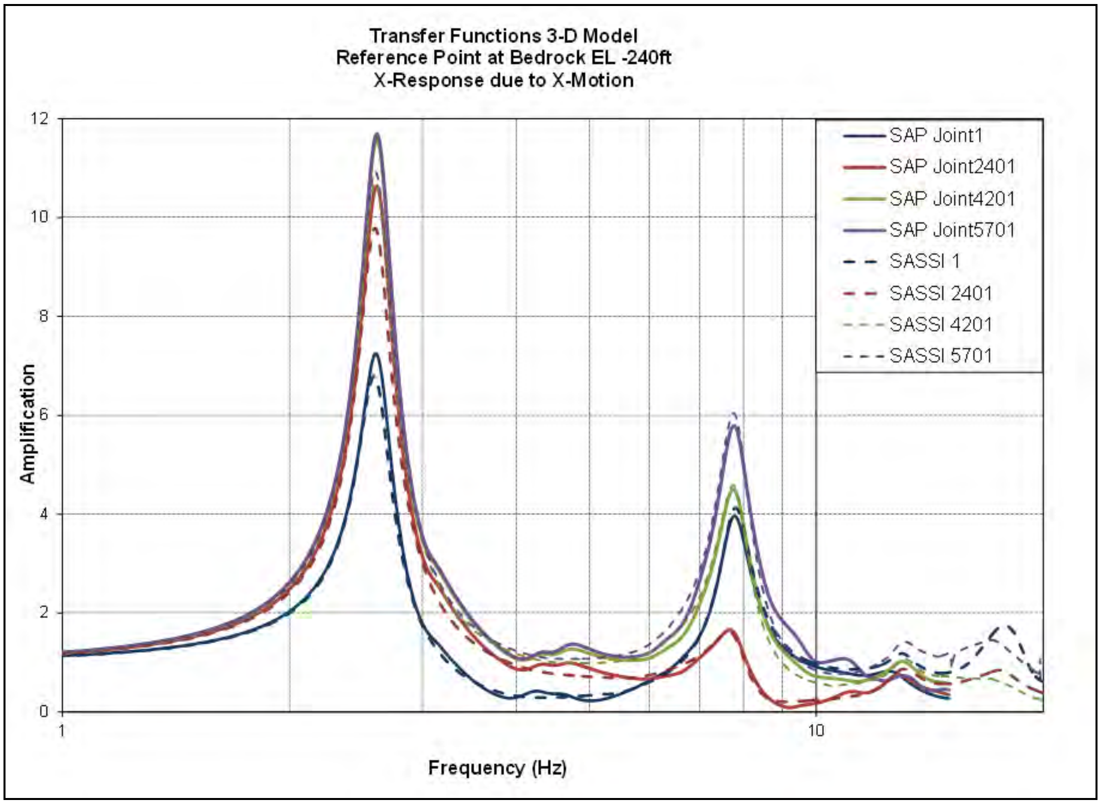

Figure 5. Transfer Function Comparison.

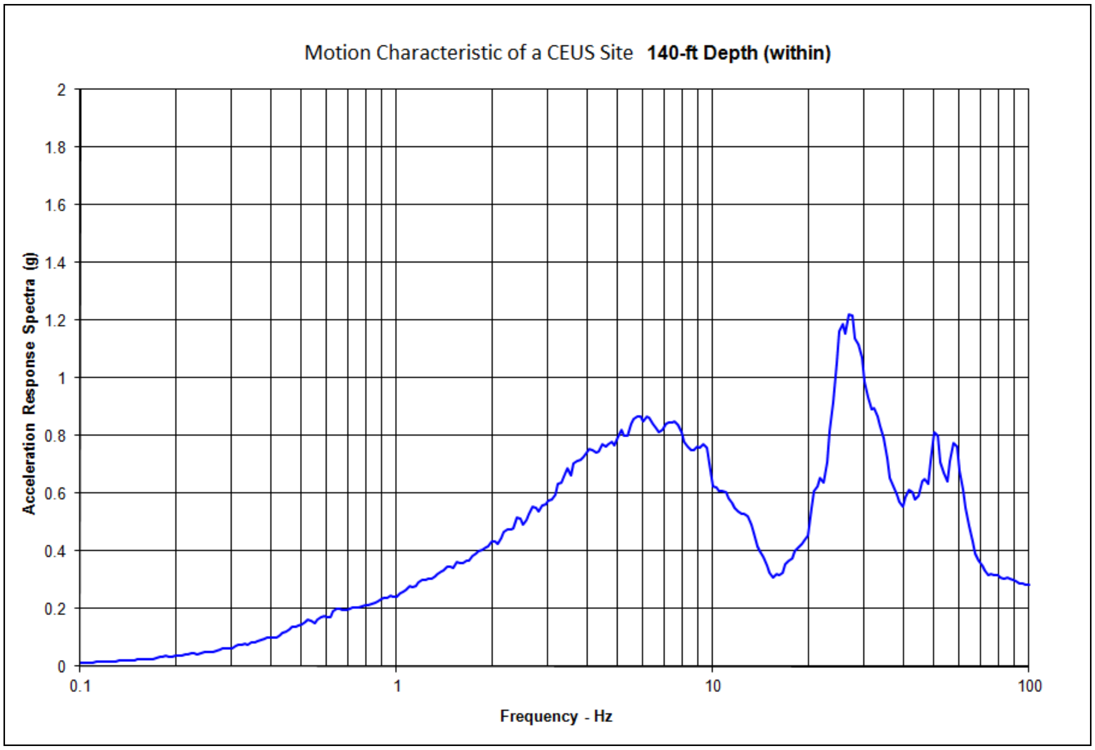

Figure 6. ET Input Motion.

The 5% damped Acceleration Response Spectra (ARS) are computed for the same four nodes where transfer functions were compared. The corresponding nodes for each location are: Node 1 (EL -140'), Node 2401 (EL -60'), Node 4201 (EL 0'), and Node 5701 (EL 50'). Only the dominant direction response is compared (i.e. X-Response due to X-Motion). The ARS comparisons are shown in Figure 7. The SAP2000 generated responses are shown with solid curves. The SASSI2010 generated responses are shown with dashed curves.

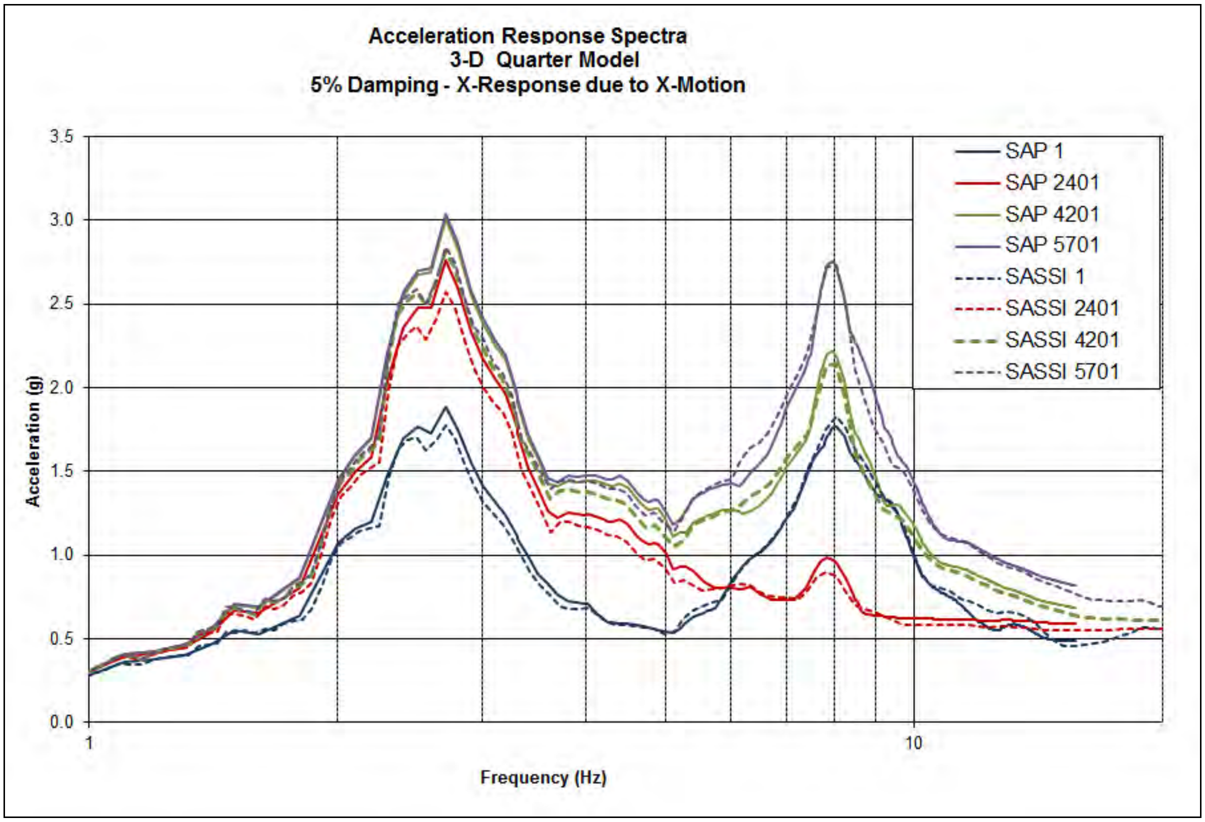

Figure 7. Acceleration Response Spectra Comparison.

CONCLUSIONS

The comparisons of transfer functions and acceleration response spectra indicate a close match between the response obtained by solution of the Soil-Structure Interaction problem using SAP2000 and that using SASSI2010.

The excellent agreement between SASSI2010 and SAP2000 results serves as an independent check on the SASSI2010 solution method and the extended subtraction method used for modeling and confirms the adequacy of SASSI solution for very deeply embedded structures.

REFERENCES

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Computers & Structures, Inc. [2000]. "SAP2000, Integrated Software for Structural Analysis & Design", Version 10.0.1, CSI, Berkeley, CA.