Soil Structure Interaction Effects on a Nuclear Containment Structure

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EXECUTIVE SUMMARY

This report provides a study of the Soil-Structure Interaction (SSI) effects on a nuclear containment structure supported on rock subsurface as an example to evaluate the industry position on the structural dynamic analysis approach for existing plants that are rock-founded.

The key findings of this report are summarized below. Note that given the limited accuracy of the Lumped-Mass and Stick Model (LMSM) above 10 Hz, and that the applicable frequency range in the context of Seismic Probabilistic Risk Assessment (SPRA) is below 10 Hz, the response of the structure below 10 Hz is emphasized.

1. Comparing the free field motion calculated from the SSI analysis using the same foundation motion, the Soil-Structure Interaction (SSI) effects on the translational foundation motion are noticeable for all three rock profiles considered at frequencies of above 3 Hz. In general, these effects below 10 Hz are reasonably small and can be neglected for cases with Vs > 5,200 fps.
2. The SSI effects on the structure (with the same foundation motion) are discussed. These effects are usually characterized by a small shift in frequency and reduction of the peak In-Structure Response Spectra (ISRS) over a narrow band of frequencies. These effects are mainly due to foundation rocking and are more pronounced for the lower bound (LB) case (top Vs of 3,450 fps).
3. The ±15% peak broadening of the fixed base results reasonably envelop the results from the examined SSI analysis cases. These results suggest that the rocking SSI effects are not significant for the evaluated structure. Moreover, the SSI effects on the translational foundation motion are insignificant below 10 Hz, especially for the rock Vs of 5,200 fps or more. Therefore, within the frequency range of interest (<10Hz) a fixed base analysis can be reasonably performed for seismic evaluation of the subject structure.
4. The SSI effects on the foundation motion above 10 Hz are generally more significant and cannot be discounted. This is especially manifested in the large differences between the free field input motion and foundation ARS at and above 14 Hz and in the SSI analysis results of the LB case.

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1 INTRODUCTION

This report provides a study of the effect of Soil-Structure Interaction (SSI) on a nuclear containment structure supported on rock subsurface. The current industry position is that structural dynamic analysis for existing plants that are rock-founded (i.e. with shear wave velocity > 3500 fps) may be completed without consideration of SSI effects. The structure considered will provide an example to evaluate this position.

In-Structure Response Spectra (ISRS) at the operating deck in the internal structure and at the top of the external containment structure are generated and compared for the fixed-base analysis and SSI analysis on representative rock profiles.

2 ASSUMPTIONS

The following assumptions are made throughout this report:

1. The Lumped Mass and Stick Model (LMSM) of the containment building structure is used for the purpose of this study. All inherent assumptions, limitations, and simplifications of the LMSM are implied in this report.
2. Both the internal structure and the external containment structure are considered uncracked.
3. In the SSI analysis of the containment building for this study, the effects of embedment in surrounding backfill, and any structure-soil-structure interaction (SSSI) effects from adjacent structures are considered to be small and neglected in this study.
4. The foundation of the containment building is assumed to be rigid in both in-plane and out-of plane directions. This assumption is reasonable given that the foundation mat is 10 ft thick and necessary for proper connection between the LMSM and the added foundation finite element (FE) mesh.

3 METHODOLOGY

Structural Model of the Building

The LMSM of the containment building consists of two sticks, representing the internal structure and the external containment structure. These LMSMs are summarized in Figure 1 and Figure 2, respectively.

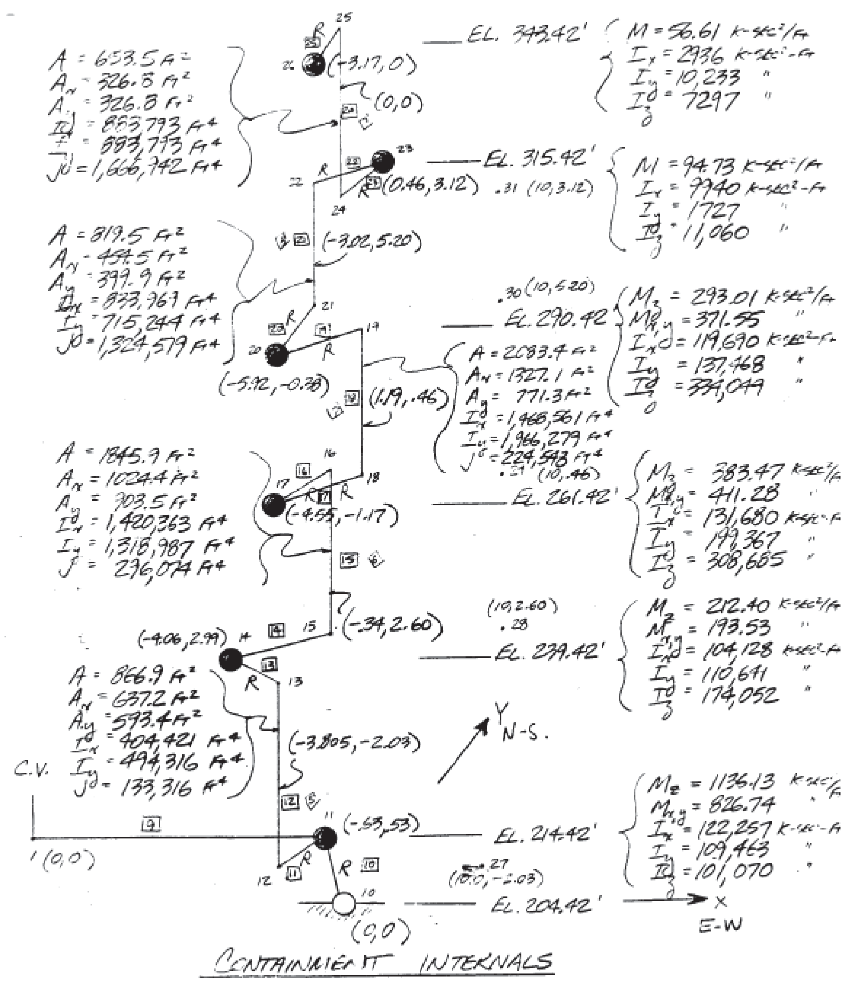

Figure 1. LMSM of the Internal Structure

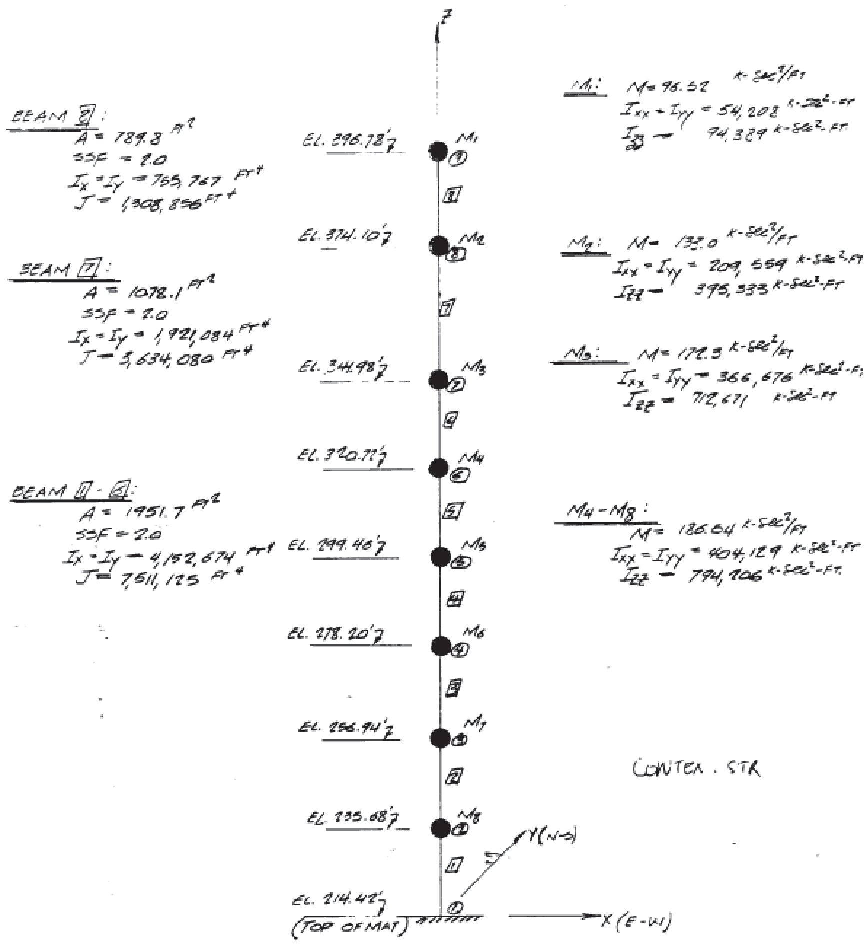

Figure 2. LMSM of the External Containment Structure

The major frequencies of the containment building internal structure are determined as 5.44 Hz, 16.0 Hz and 16.5 Hz in the East-West (X) direction, 5.07 Hz and 15.7 Hz in North-South (Y) direction, and 16.0 Hz and 16.54 Hz in the Vertical (Z) direction. The major frequencies of the containment building external structure are determined as 5.39 Hz and 13.9 Hz in the X and Y directions and 15.0 Hz in the Z direction.

Note that the model X, Y, and Z directions correspond to the plant East-West, North-South, and vertical directions, respectively.

Soil-Structure Interaction Analysis

Structural Models

The two LMSMs provided above for the internal structure and external containment building are rewritten in the input format of the SASSI2010 HOUSE module and combined in the same model (represented with two sticks). The LMSMs consist of beam elements and nodal masses. The beam elements either represent the stiffness of the structural elements (concrete walls) in the containment internal and external structure or represent a rigid constraint between the center of rigidity (where the sticks are located) and center of mass (or center of gravity where nodal mass are defined). Rigid beams are also used where the stiffness of the structural element is deemed to be very large compared to other elements in the model (e.g. in-plane bending and shear stiffness of the mat foundation across its thickness). The nodal masses include both translational and rotational inertia calculated at several elevations in the structure. These beams and nodal masses are strictly translated into the SASSI2010 house format with the following exceptions:

1. The original LMSM of the external containment was constructed for use in the fixed base analyses. As such, the mass of the bottom half of the walls between Nodes 1 and 2 were not included in the LMSM. This mass is calculated and added to Node 1 in the combined model.
2. The original LMSM of the internal structure was constructed for use in the fixed base analyses. As such, the mass of the bottom half of the mat (between Nodes 10 and 11) and the rotational inertia of the mat were not included in the LMSM for the internal structure. These values are calculated and added to Node 10 in the combined model.

The SASSI2010 SSI analysis of the containment building requires the representation of the foundation geometry and interface between the structure and underlying media for the calculation of the foundation impedance functions. The foundation of the containment building is represented in SASSI2010 model using shell finite elements with maximum element size of 9.4 ft. The shell elements are 10ft thick, massless, and use the concrete elastic modulus for 3000 psi concrete. The foundation mesh can adequately transmit waves with frequency of up to 75 Hz for the lowest shear wave velocity case considered (3500 ft/sec). The FE mesh of the foundation is supplemented with radial rigid beams (EA = 4.5×10^{14} kips and EI = 4.5×10^{15} kip-ft^2) which extend to the rim of the foundation and ensure a rigid connection between the foundation mesh and the beam elements representing the bottom walls of the structure (from the LMSM).

Note that the SSI analyses provided here, assume that the foundation of the containment building is a surface founded structure and the effects of nearby buildings, and surrounding backfill are neglected.

An isometric and plan view of the SSI model for the containment building are shown in Figure 3.

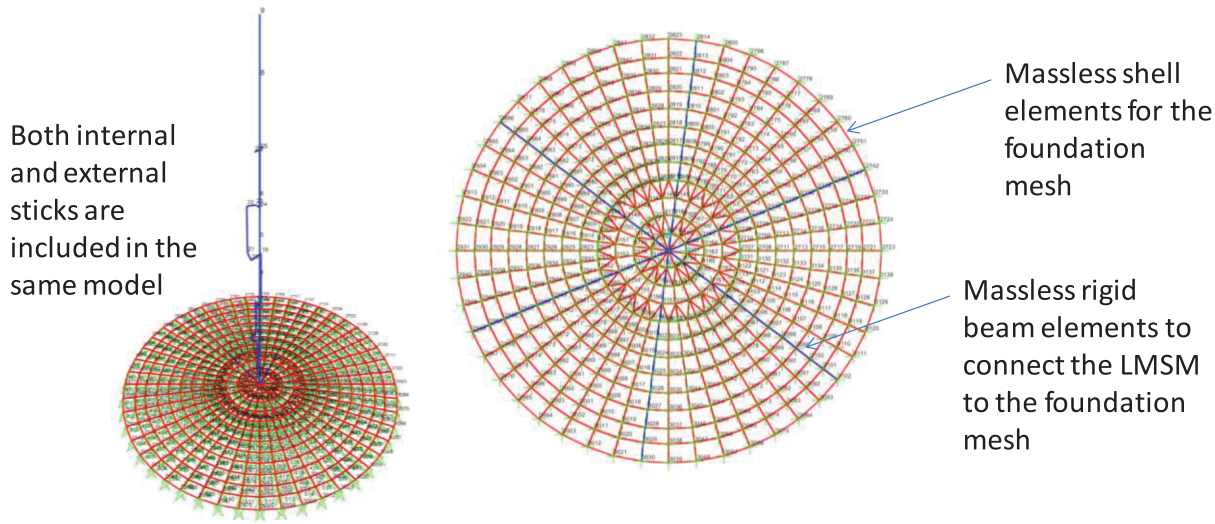

Figure 3 – SSI Model

The fixed base analysis is performed using the analysis of the containment building situating on a hypothetical hard rock medium – referred to as the hard rock analysis. The hard rock analysis results are used for obtaining the hard rock ISRS which are used to assess the SSI effects. For the hard rock analysis the shear wave velocity is taken as 20,000 fps, with a Poisson ratio of 0.30, and 1% damping ratio. The rock density is taken as 0.15 kcf. The adequacy of the assumed shear wave velocity is verified by ensuring that the translational transfer functions at the base of the building are close to unity and that the coupled transfer functions (e.g. X transfer function due to input in the Y direction) are negligible (at the frequencies of interest).

The hard rock (HR) transfer functions for the internal structure are shown for response in the X, Y, and Z directions in Figure 4, Figure 5, and Figure 6, respectively. The analysis is carried out up to 50 Hz frequency; however, the results are shown up to 30 Hz with calculated frequencies indicated in each plot.

The frequencies of the peaks of the HR transfer functions align with the corresponding dominant modal frequencies of the structures. This confirms the accurate translation of the LMSM to SASSI2010 computer code format.

Also note that the transfer function amplitude for Node 10 (bottom of the foundation) is unity for the frequency range of interest (below 50 Hz) which confirms the adequacy of the shear-wave velocity assumed for rock as well as adequate rigidity of the added foundation elements.

The HR transfer functions are shown for the coupling terms, X-Response due to Y-Motion (XY), Y-Response due to X-Motion (YX), Z-Response due to X-Motion (ZX), and Z-Response due to Y-Motion (ZY) in Figure 7 through Figure 10.

The coupling transfer functions for the HR case identify the major structural torsional modes (XY and YX responses, e.g. at approximately 25 Hz) as well as important rocking modes (ZX and ZY responses). Also note that the response of Node 10 (bottom of the foundation) is negligible which confirms the adequacy of the selected hard rock properties.

Similar results for the external containment structure are shown in Figure 10 through Figure 17.

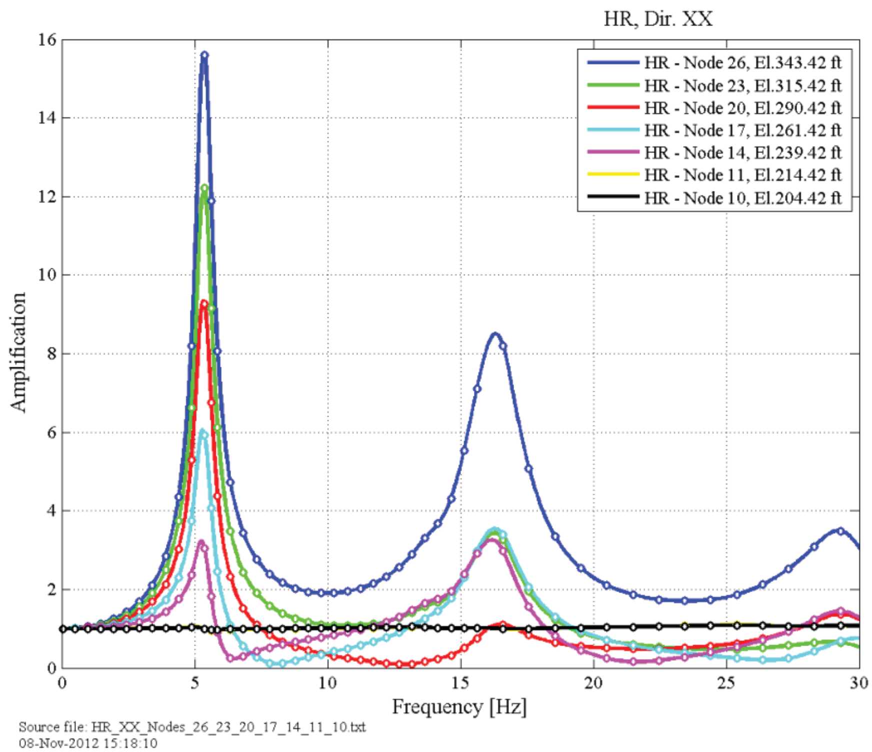

Figure 4 – Internal Structures Hard Rock X-Direction Transfer Functions

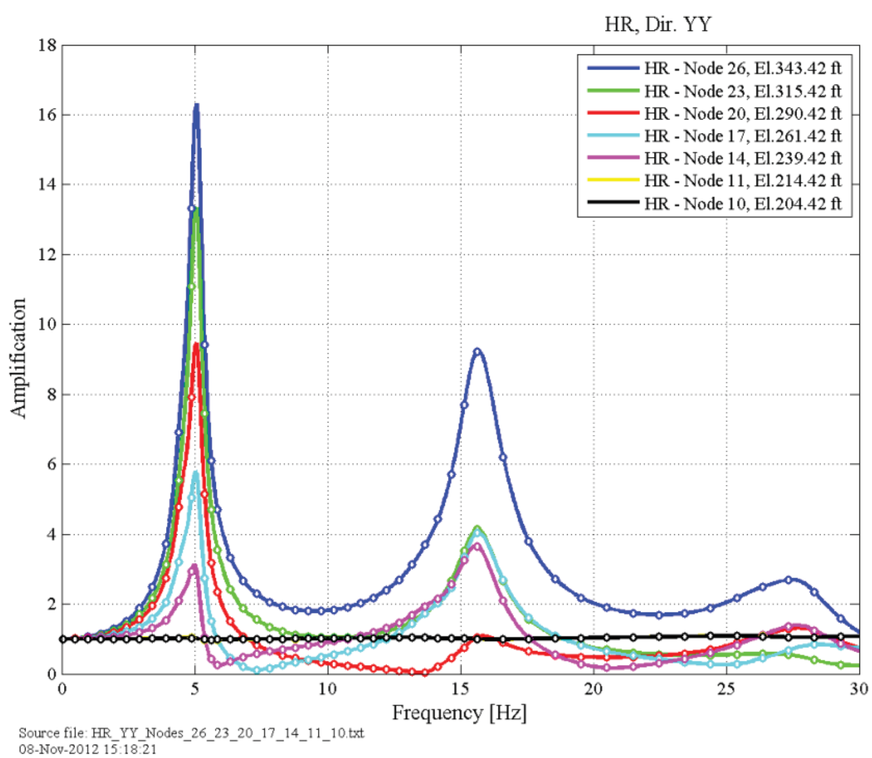

Figure 5 - Internal Structures Hard Rock Y-Direction Transfer Functions

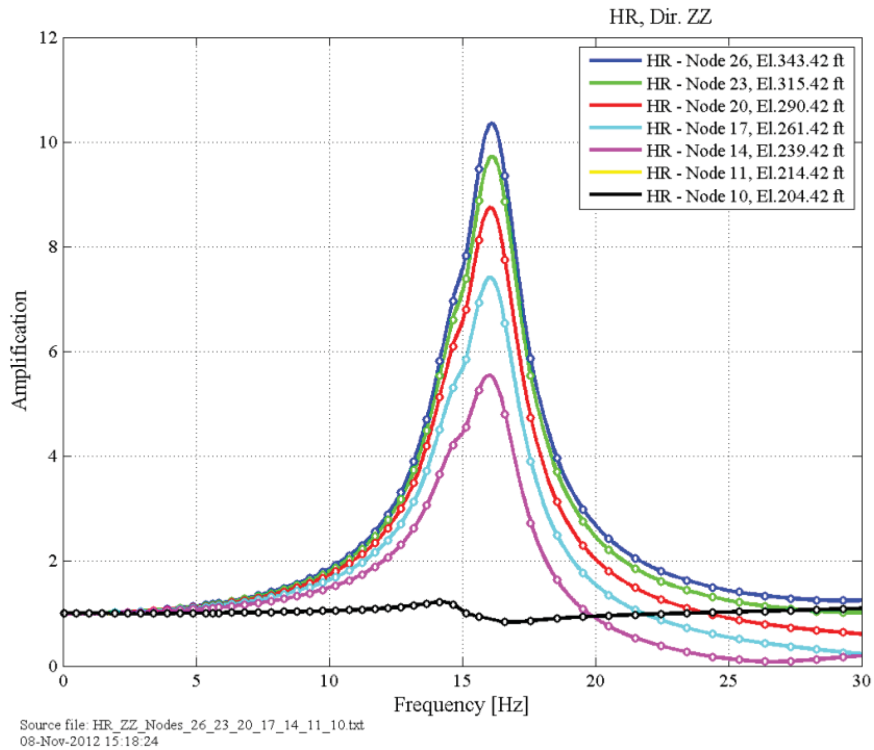

Figure 6 - Internal Structures Hard Rock Z-Direction Transfer Functions

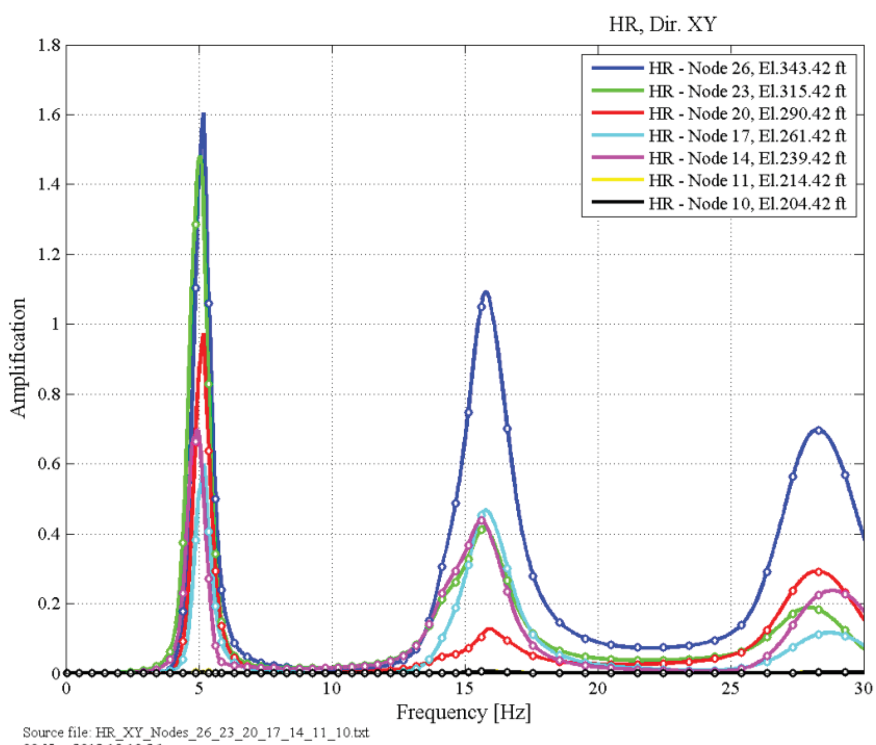

Figure 7 – Internal Structures Hard Rock XY Transfer Functions

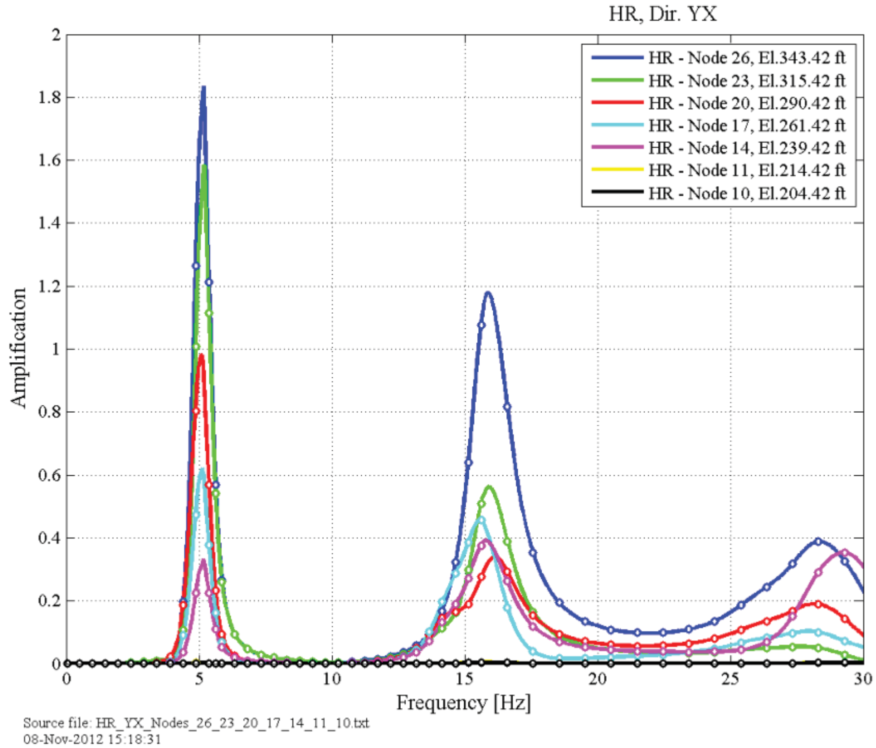

Figure 8 - Internal Structures Hard Rock YX Transfer Functions

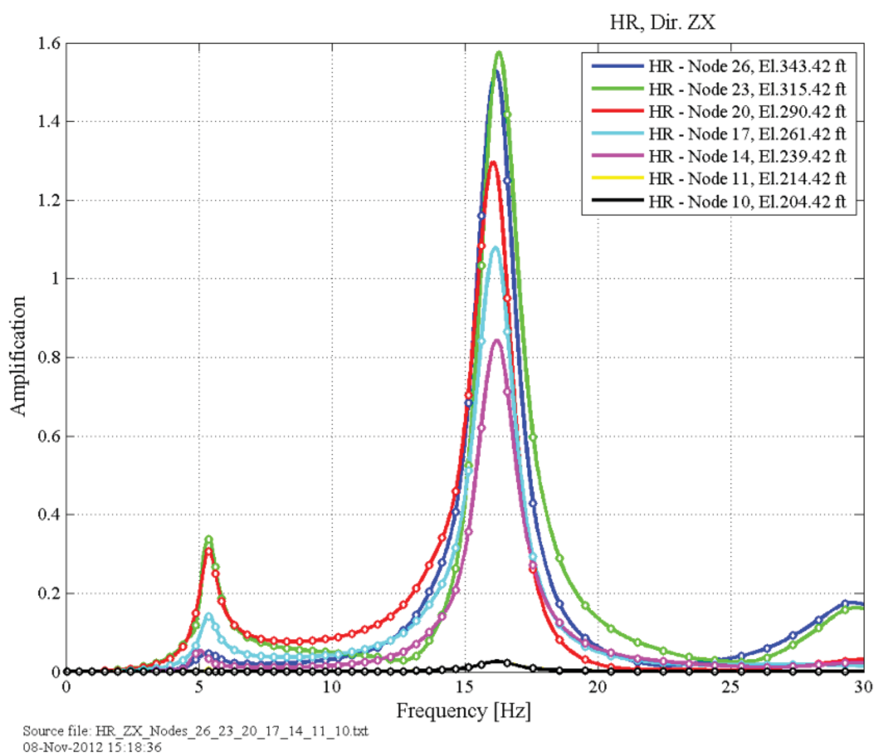

Figure 9 - Internal Structures Hard Rock ZX Transfer Functions

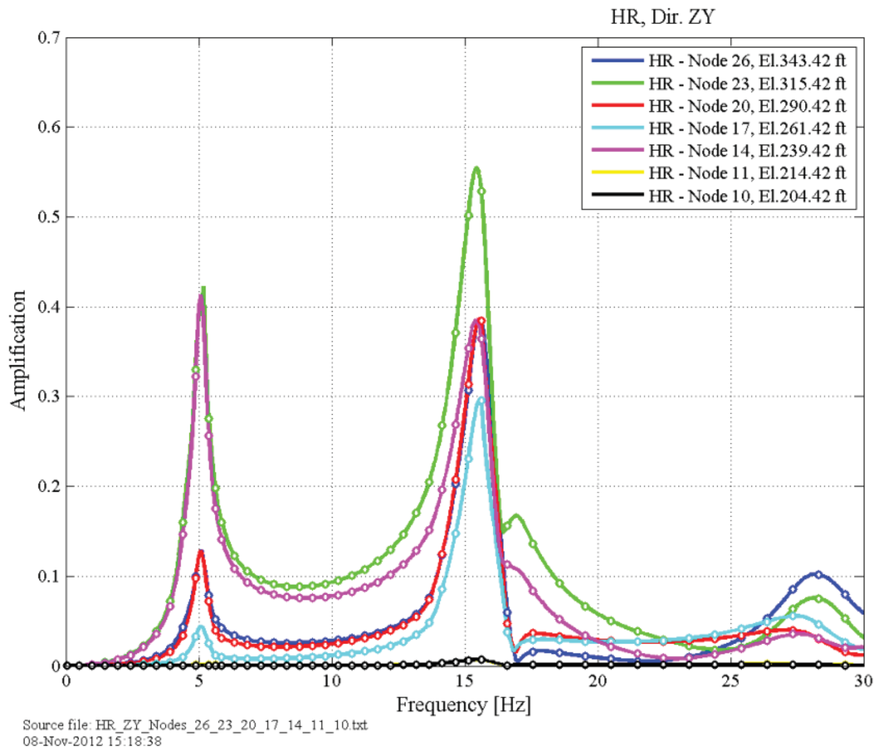

Figure 10 - Internal Structures Hard Rock ZY Transfer Functions

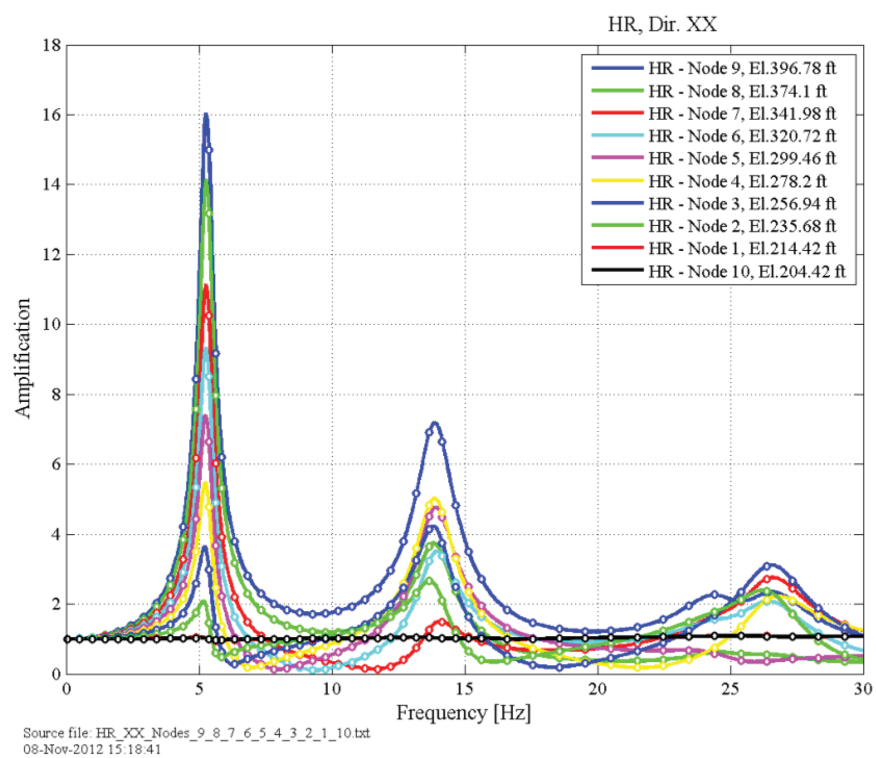

Figure 11 – External Structures Hard Rock X-Direction Transfer Functions

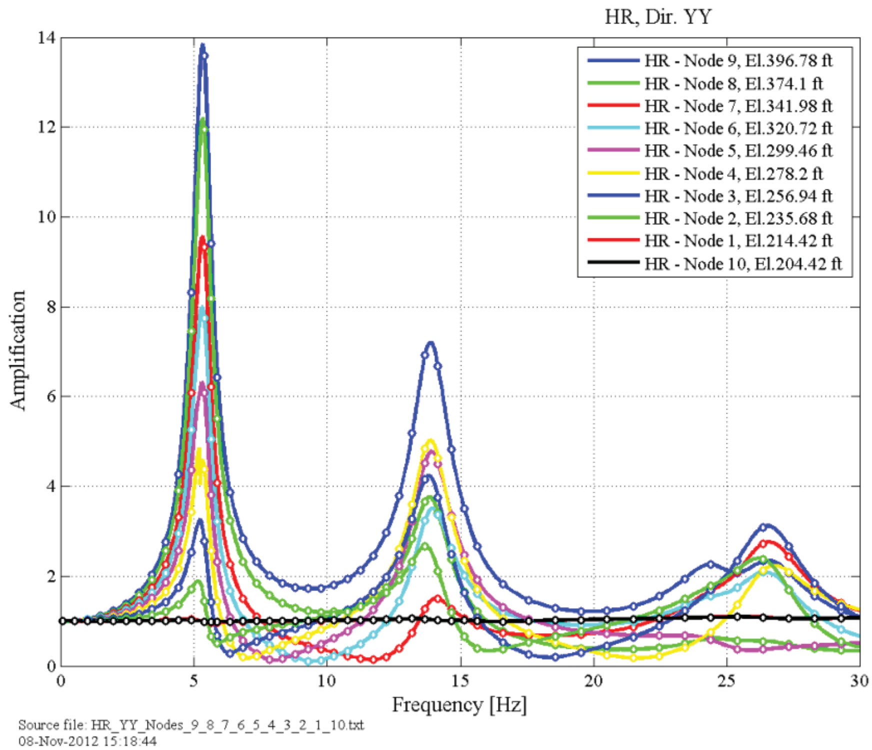

Figure 12 - External Structures Hard Rock Y-Direction Transfer Functions

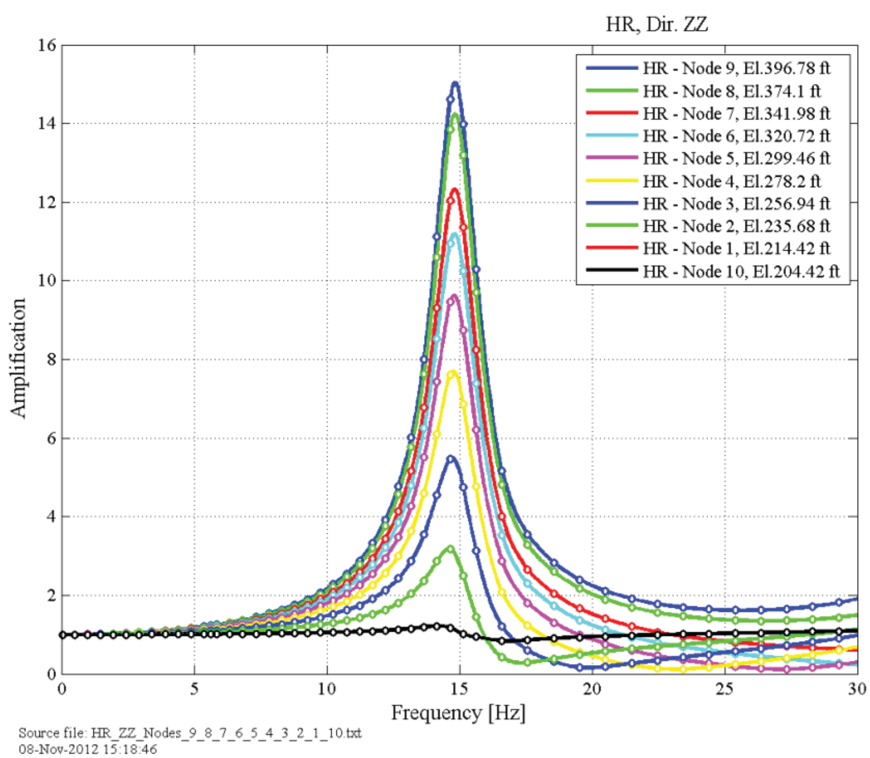

Figure 13 - External Structures Hard Rock Z-Direction Transfer Functions

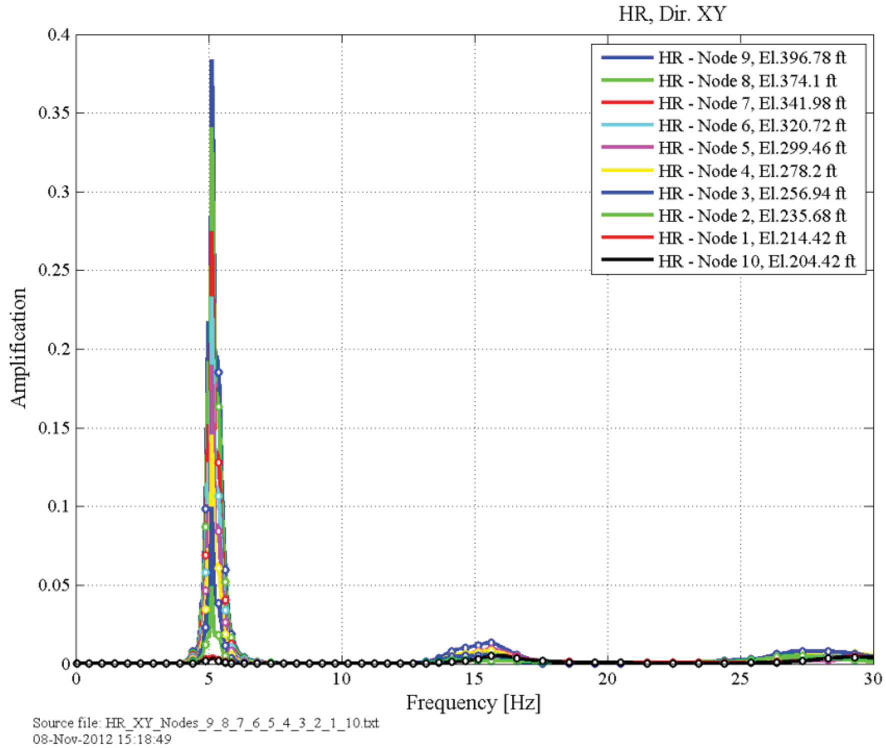

Figure 14 – External Structures Hard Rock XY Transfer Functions

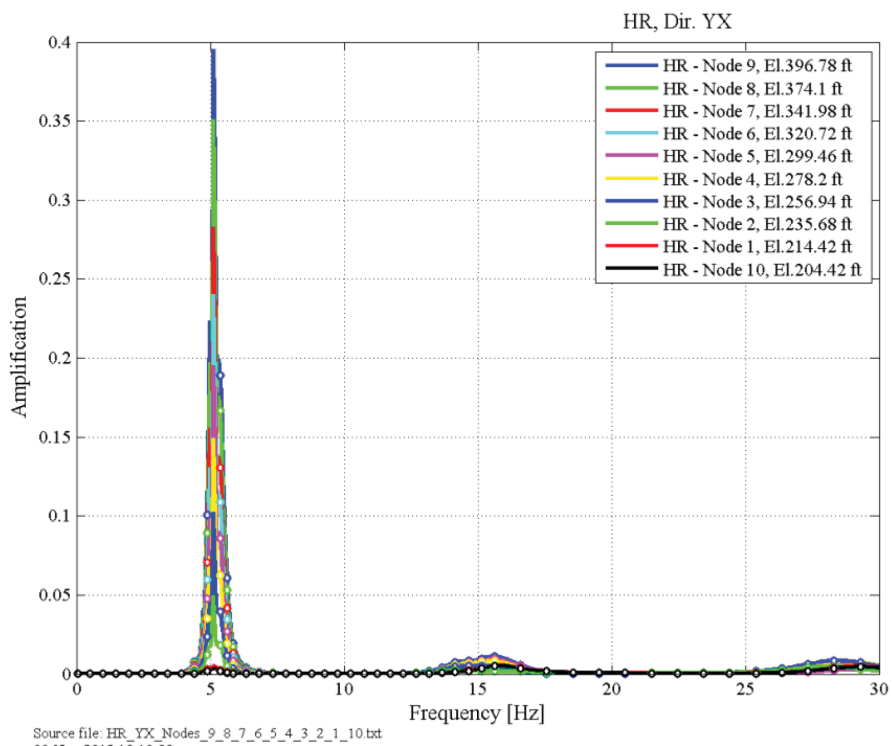

Figure 15 - External Structures Hard Rock YX Transfer Functions

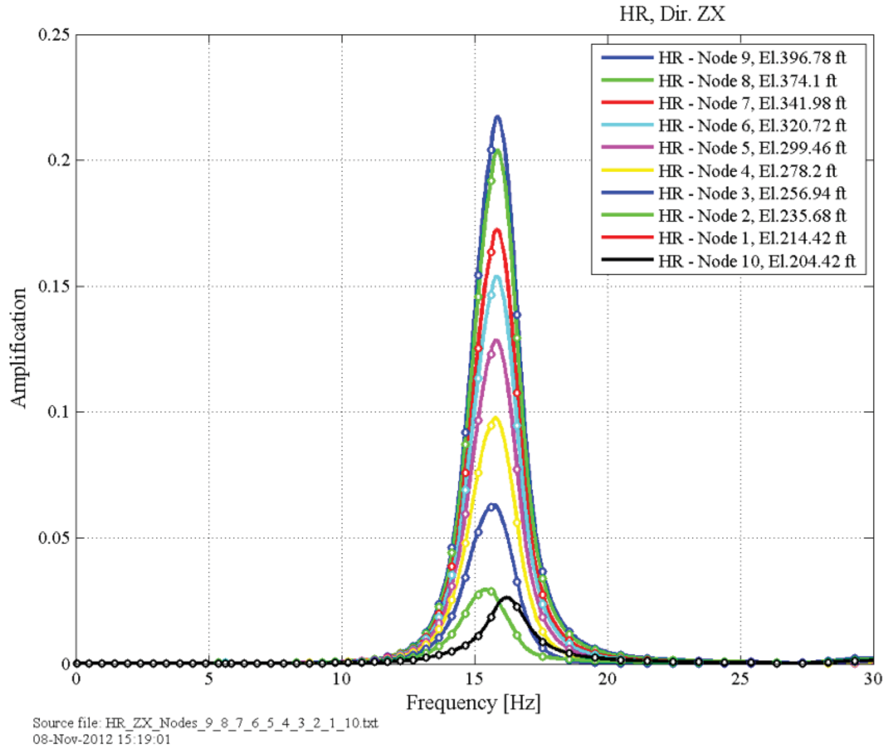

Figure 16 - External Structures Hard Rock ZX Transfer Functions

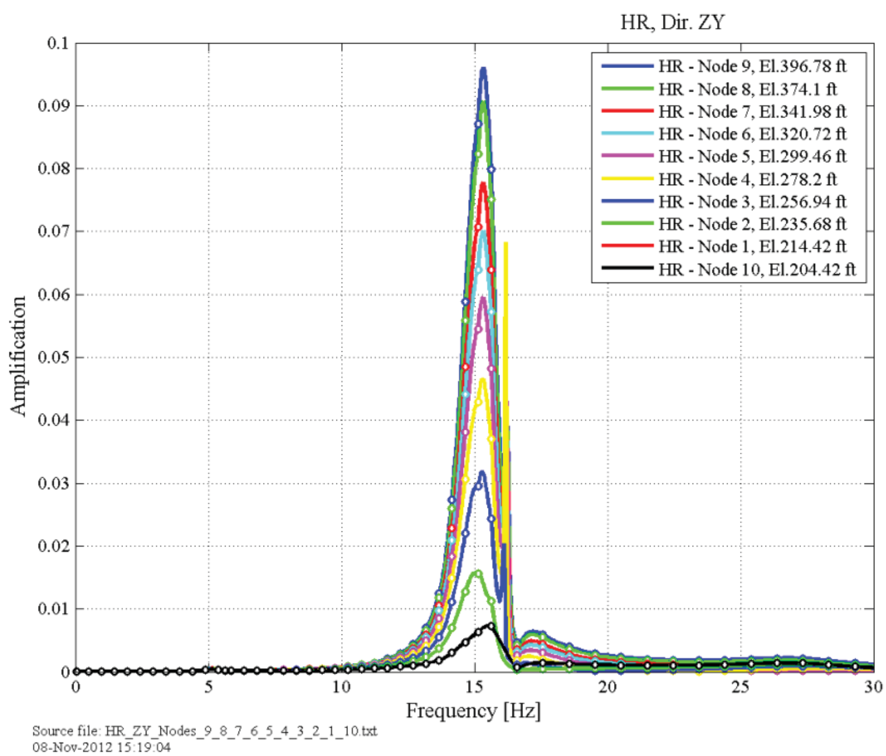

Figure 17 - External Structures Hard Rock ZY Transfer Functions

Soil Profiles

Three rock profiles representing the lower bound (LB), best estimate (BE), and upper bound (UB) conditions for a site in Central and Eastern United States (CEUS) are considered for the SSI analysis of the containment building using SASSI2010 computer code. The HR profile and these rock profiles are described below and shown in Figure 18.

1. For the HR column, which emulates the fixed-base condition, the halfspace begins 100’-0” below grade. The properties of the half-space are equal to the HR properties described earlier.
2. For the BE profile, the shear wave velocity is 5,200 fps for the first 35 ft below the foundation and then increase to 8,800 fps below that. A soil damping of 1% is used with 0.163 kcf soil density. For the BE column, the halfspace begins 69’-5” below grade. The halfspace shear wave velocity is assumed to be 9,740 fps with 1% soil damping and 0.163 kcf soil density.
3. For the LB rock profile, the shear wave velocity is 3,450 fps for the first 35 ft below the foundation and then increase to 7,200 fps below that. A soil damping of 1% is used with 0.163 kcf soil density. For the LB column, the halfspace begins 69’-5” below grade. The halfspace shear wave velocity is assumed to be 7,952 fps with 1% soil damping and 0.163 kcf soil density.
4. For the UB rock profile, the shear wave velocity is 7,700 fps for the first 35 ft below the foundation and then increase to 10,800 fps below that. A soil damping of 1% is used with 0.163 kcf soil density. For the UB column, the halfspace begins 69’-5” below grade. The halfspace shear wave velocity is assumed to be 11,929 fps with 1% soil damping and 0.163 kcf soil density.

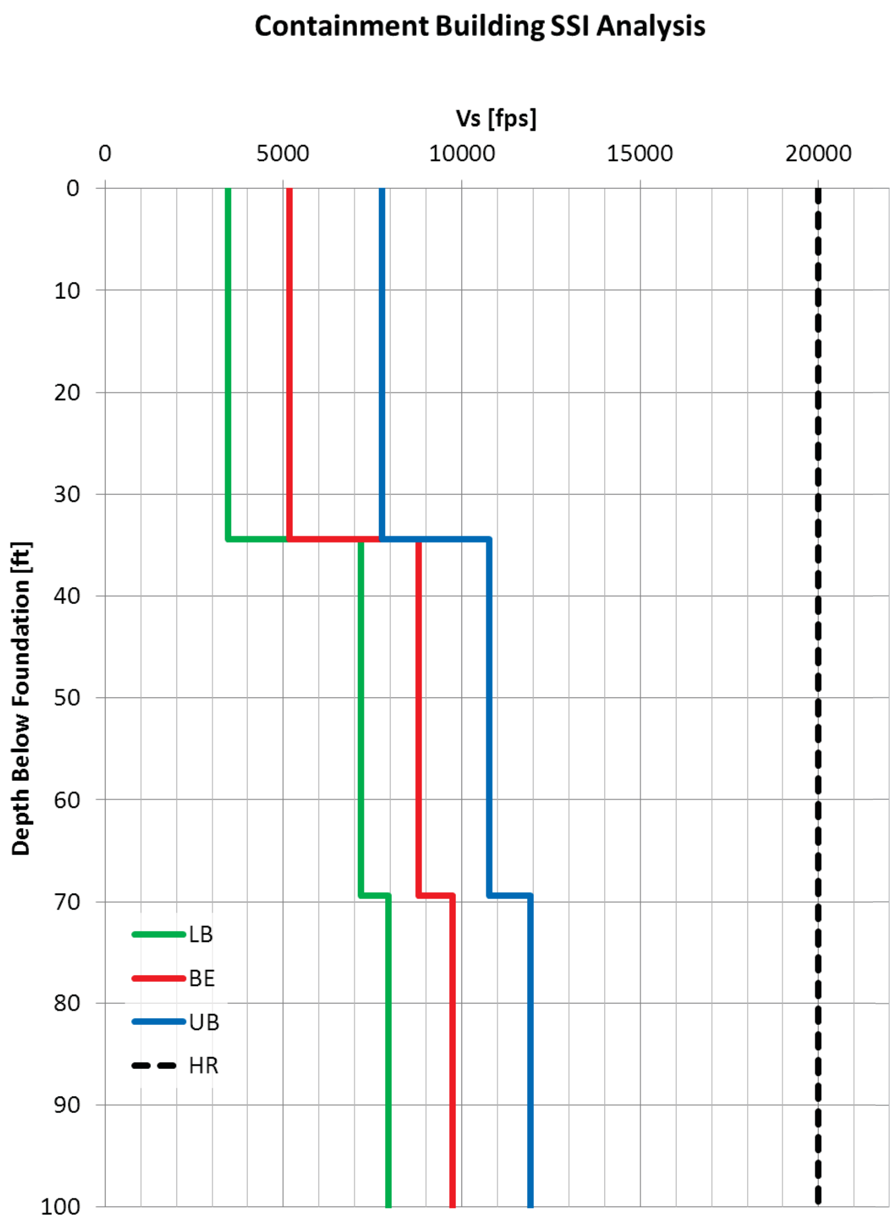

Figure 18 - Shear Wave Velocity Comparison

Input Motions

The motions used for the fixed base and SSI analyses represent a ground motion time-history corresponding to a CEUS earthquake event which was recorded on a containment building foundation. The input acceleration time-histories are applied in the free field at the same elevation as the bottom of the foundation of containment building in SASSI2010.

For the HR case, the free field and foundation motion are approximately equal. For the LB, BE, and UB rock profile analyses, the free field motions are calculated such that approximately the same translational foundation motion as that of the HR analysis case is obtained from each SSI analysis. The calculation of the free field motions uses the SSI model and rock profiles described above. The details of the free field motion calculations are outside the scope of this report and are not discussed here. The Acceleration Response Spectra (ARS) of the motion on the foundation is shown in Figure 22 through Figure 24. The ARS of the free field motions are compared together in Figure 19 through Figure 21. Since the foundation motions are the same in each direction, the differences in the free field motions provide a basis for evaluating the SSI effects on the foundation motion of the containment building. The free field comparisons shown in Figure 19 through Figure 21 suggest that such SSI effects are negligible at low frequencies (lower than 3 Hz) and reasonably small at frequencies below 10 Hz which is the frequency range of interest in this report. Note that the foundation motion exceedance over the free field motions in these figures suggests SSI amplification in the translational directions. Conversely, the exceedance of the free field motions over the foundation motion suggests that the SSI response of the foundation is less than the fixed base analysis response.

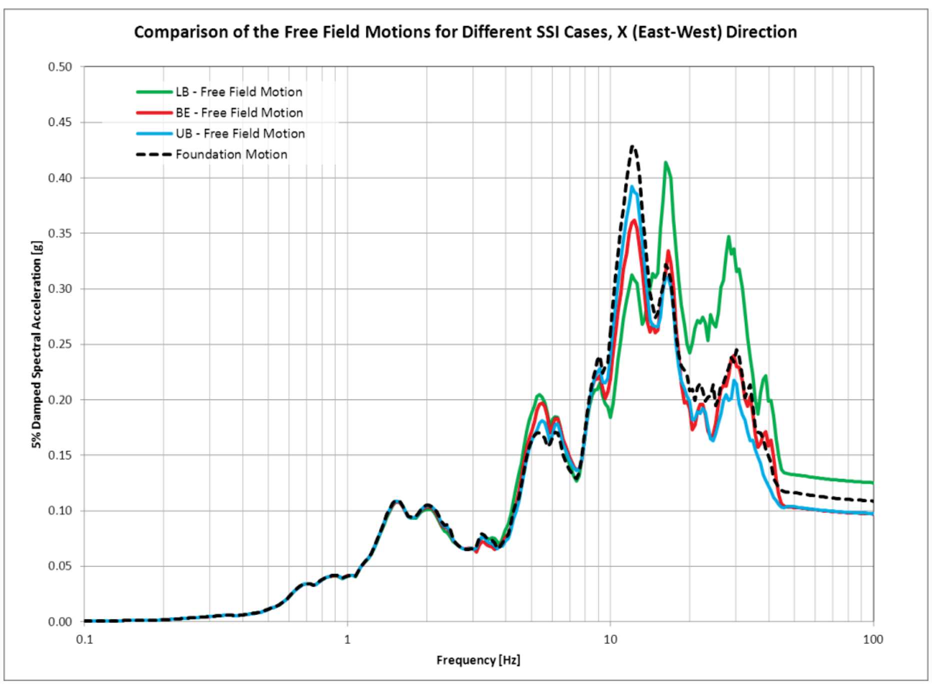

Figure 19 – Comparison of 5% Damping Free Field Motion ARS, X-Direction

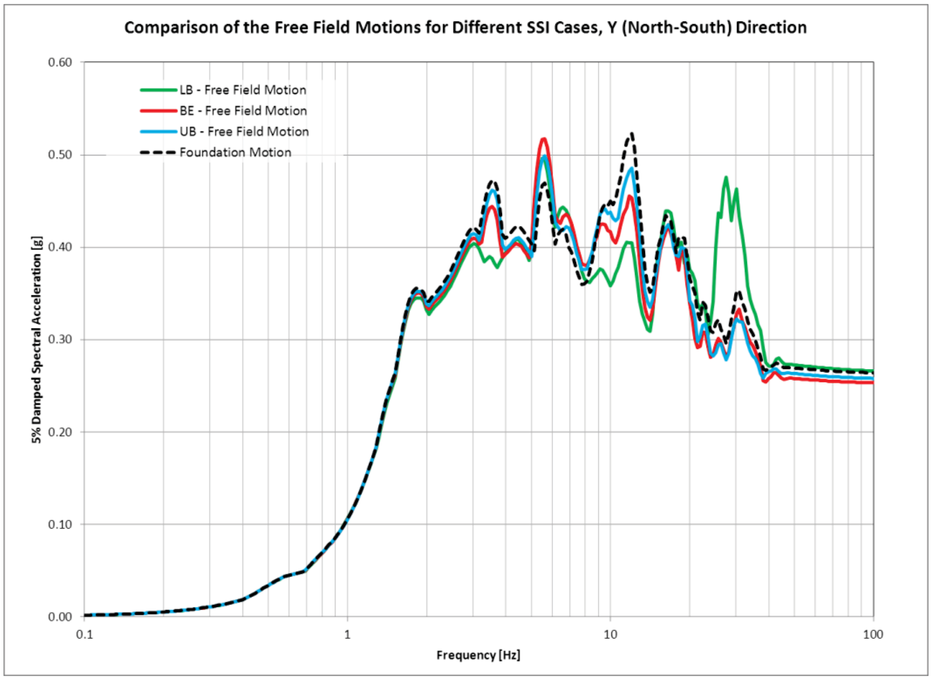

Figure 20 – Comparison of 5% Damping Free Field Motion ARS, Y-Direction

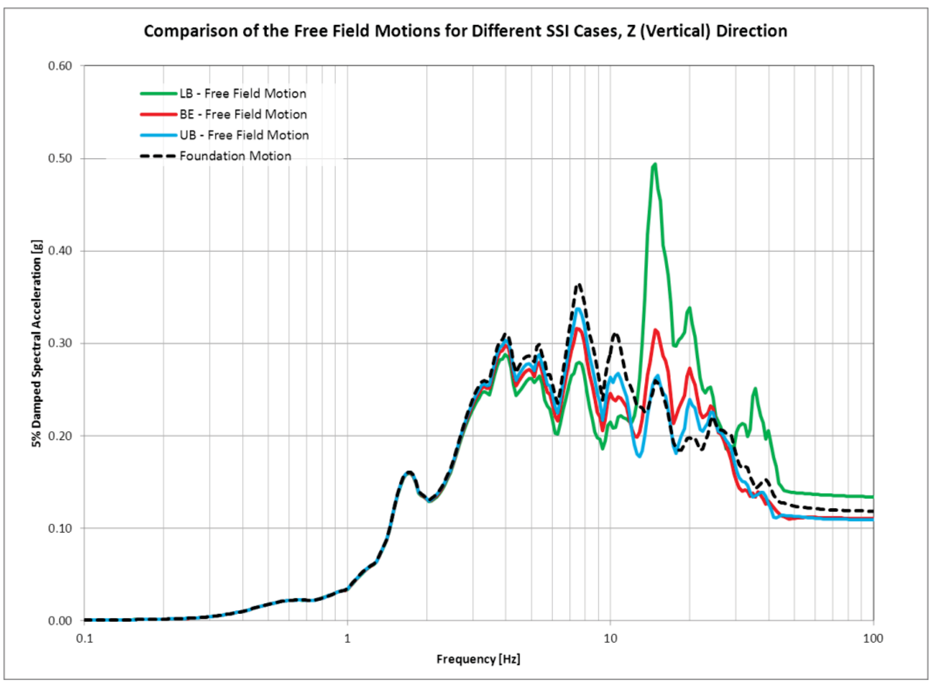

Figure 21 – Comparison of 5% Damping Free Field Motion ARS, Z-Direction

Generation of In-Structure Response Spectra

Raw ARS are produced from each of the four analysis cases (HR, LB, BE, and UB) subjected to their corresponding input time-histories using SASSI2010. The raw ARS includes nine component responses (e.g. XX: X-Response due to X-Motion, XY: X-Response due to Y-Motion, XZ: X-Response due to Z-Motion, etc.) for each node and each analysis case. The component responses are combined using the Square-Root-Sum of Squares (SRSS) method to produce the In-Structure Response Spectra (ISRS) in each direction and for each analysis case.

The ISRS comparison in this study is provided for the following three lumped-mass nodes, as indicated in Table 1.

Table 1 - Lumped-Mass Nodes at Major Elevations

Node ID	Location
11	Top of Basemat
20	Operating Floor (77 ft above top of Basemat)
9	Top of External Structure (182 ft above top of Basemat)

Note that for production of final In-Structure Response Spectra (ISRS), broadening of ±15% would be applied to all curves and some degree of clipping may be allowed to the peak of applicable ARS. However, for the purposes of this comparison study, the ISRS are reported without broadening or peak clipping. For further simplification, only 5% damping curves are compared.

4 RESULTS

The comparison between the fixed base analysis results and SSI analysis results for the containment building structure when subject to the same foundation motion are provided in this section.

ARS Comparisons

The ISRS plots comparing the 5% damping response for each of the four soil cases considered are presented in Figure 22 through Figure 30.

Since the free field motions for the LB, BE, and UB case are derived from the HR motion at the top of foundation, the calculated ISRS at the top of Basemat (Node 11) in the SSI analysis model closely matches that of the HR case as seen in Figure 22 through Figure 24.

However, the comparison between ISRS obtained at higher elevations reveals the SSI effects manifested mainly through rocking of the foundation. The SSI analysis results show a slight shift towards lower frequencies in the peak frequency of the ISRS and generally lower peak values in the response (except for Node 9 – top of external containment structure – where the BE and UB peaks are slightly higher than the peak from the fixed base case). These effects are more pronounced for the LB (top Vs of 3,450 fps) case.

Noting that ±15% peak broadening of the fixed base (HR) results would reasonably envelop the results from the LB, BE, and UB cases, the results suggest that the SSI effects are not significant for the evaluated structure. Also note that the SSI effects on the foundation motion are insignificant below 10 Hz, especially for the BE (top Vs of 5,200 fps) and UB (top Vs of 7,700 fps). Therefore, within the frequency range of interest (<10Hz) a fixed base analysis can be reasonably performed for seismic evaluation of the subject structure.

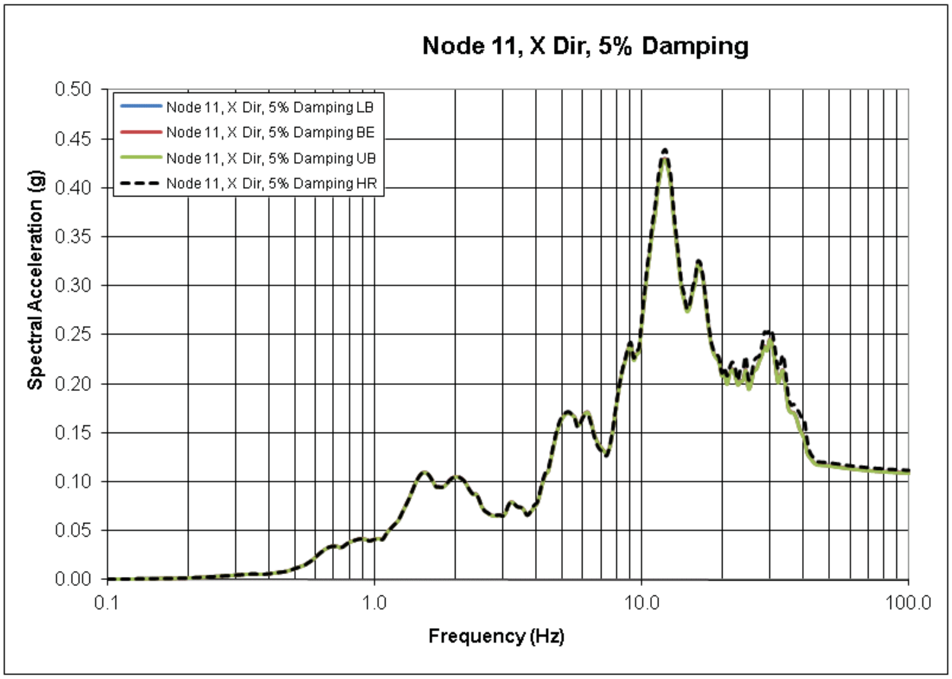

Figure 22 – 5% Damping ARS, Containment Internal Structure, Top of Basemat (Node 11), East-West (X) Direction

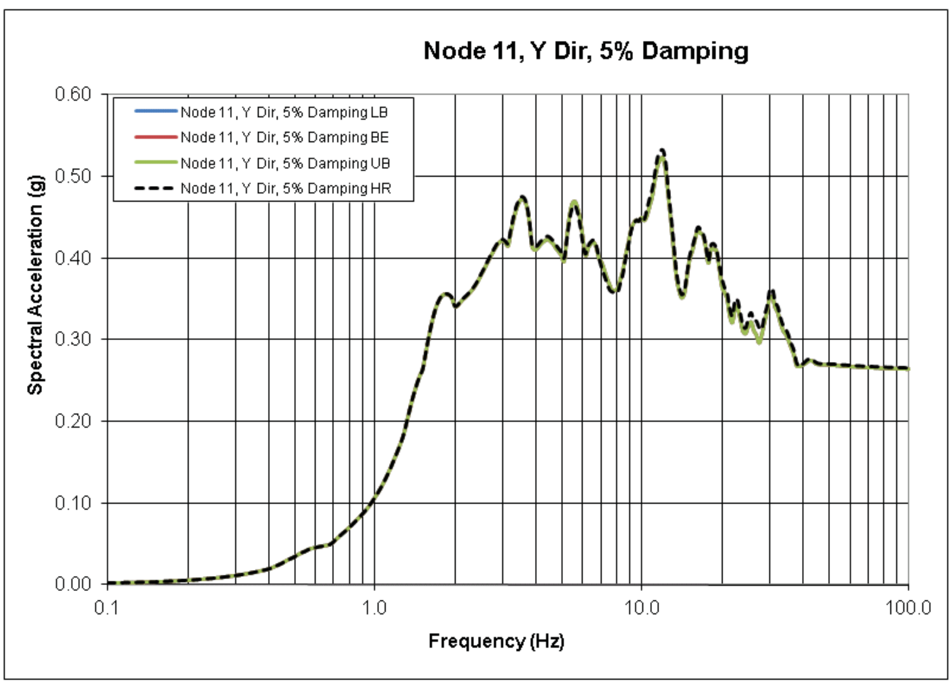

Figure 23 – 5% Damping ARS, Containment Internal Structure, Top of Basemat (Node 11), North-South (Y) Direction

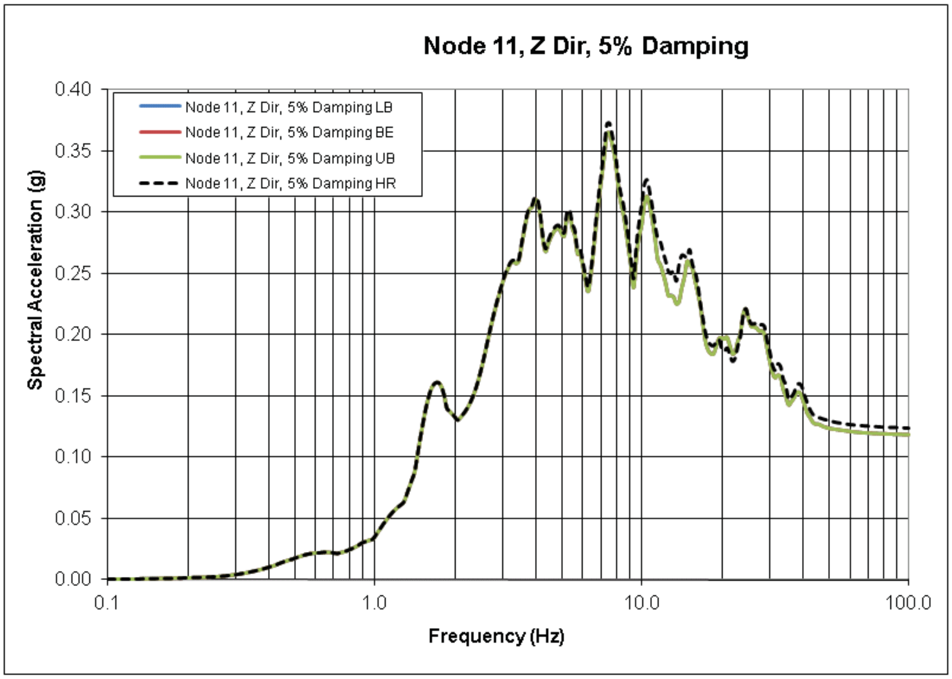

Figure 24 – 5% Damping ARS, Containment Internal Structure, Top of Basemat (Node 11), Vertical (Z) Direction

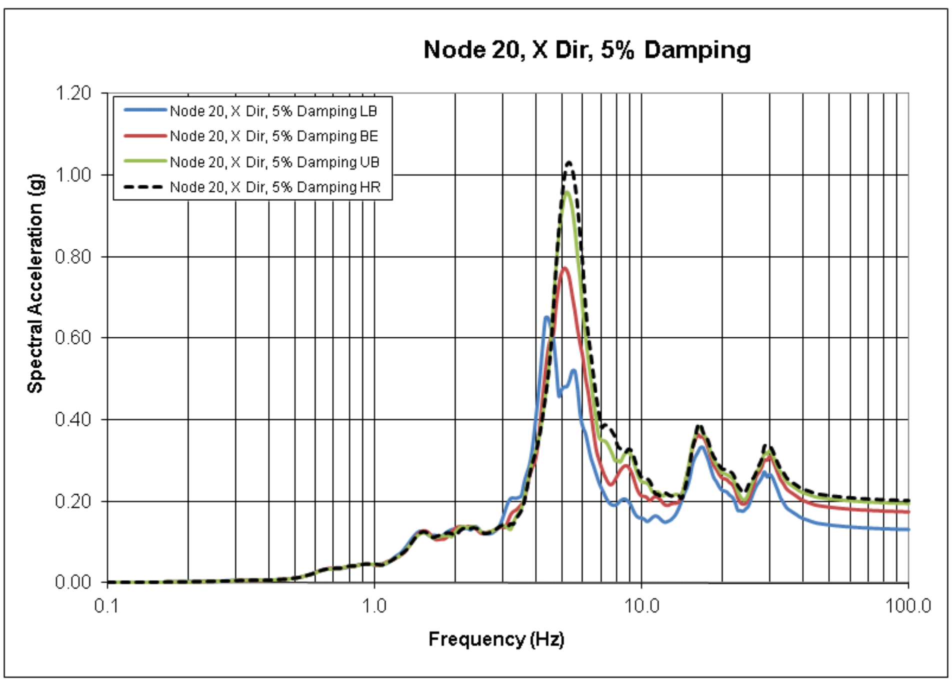

Figure 25 – 5% Damping ARS, Containment Internal Structure, Operating Floor (Node 20), East-West (X) Direction

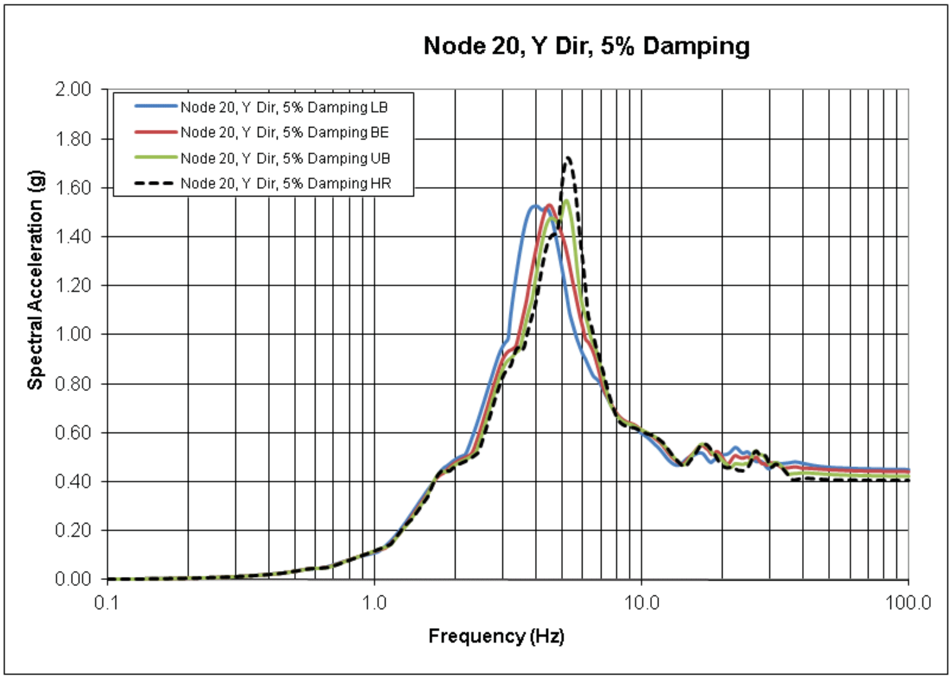

Figure 26 – 5% Damping ARS, Containment Internal Structure, Operating Floor (Node 20), North-South (Y) Direction

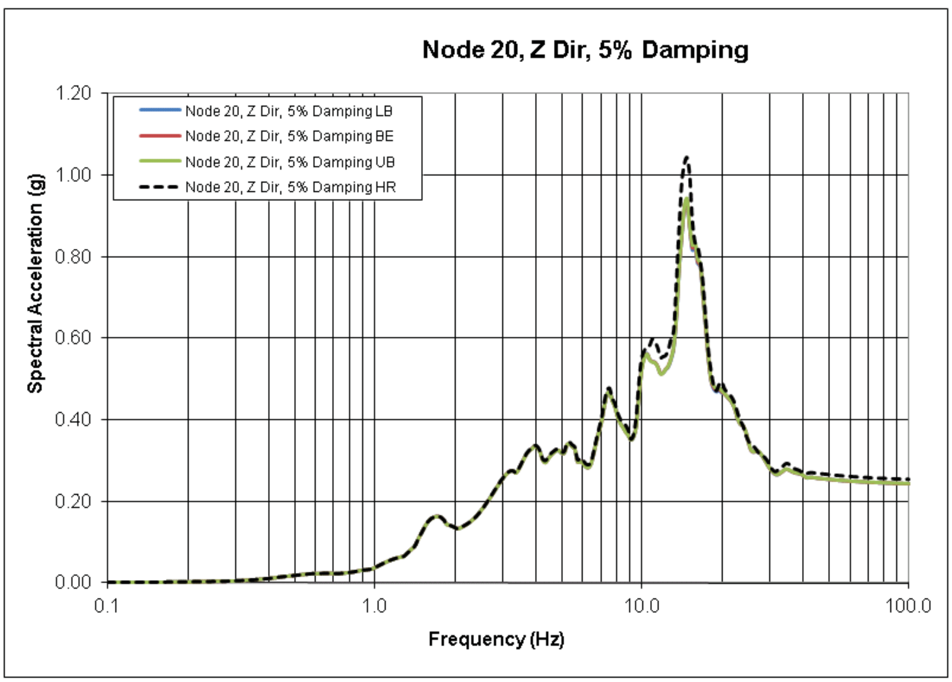

Figure 27 – 5% Damping ARS, Containment Internal Structure, Operating Floor (Node 20), Vertical (Z) Direction

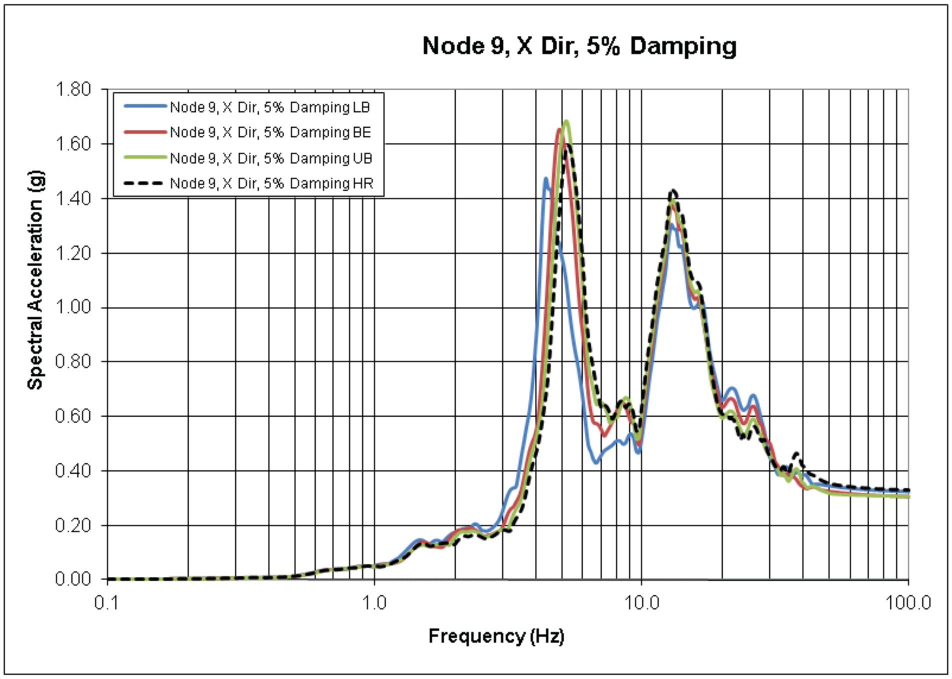

Figure 28 - 5% Damping ARS, Top of External Containment Structure (Node 9), East-West (X) Direction

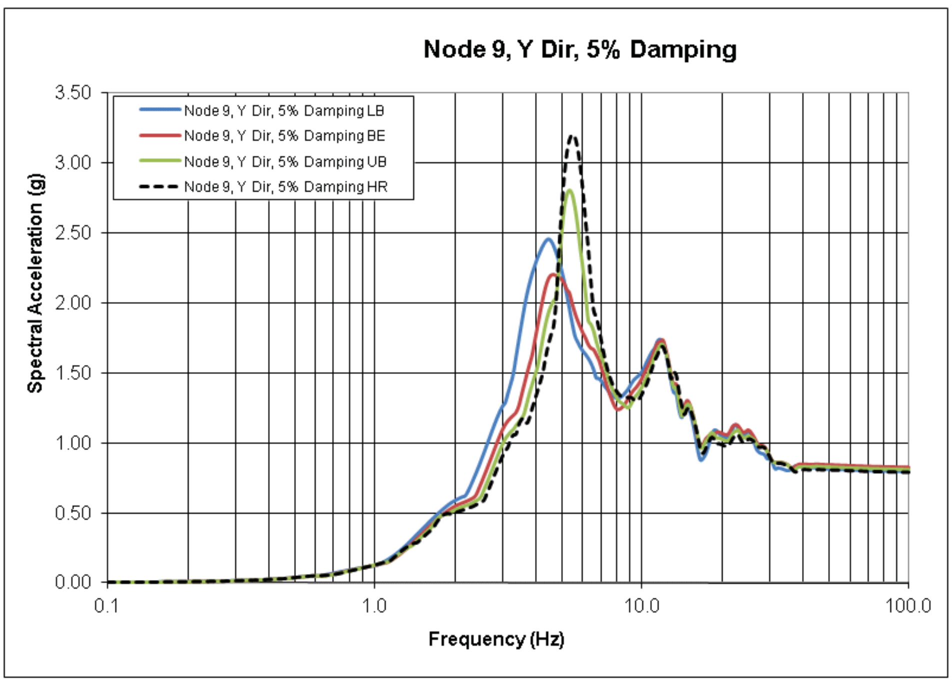

Figure 29 - 5% Damping ARS, Top of External Containment Structure (Node 9), North-South (Y) Direction

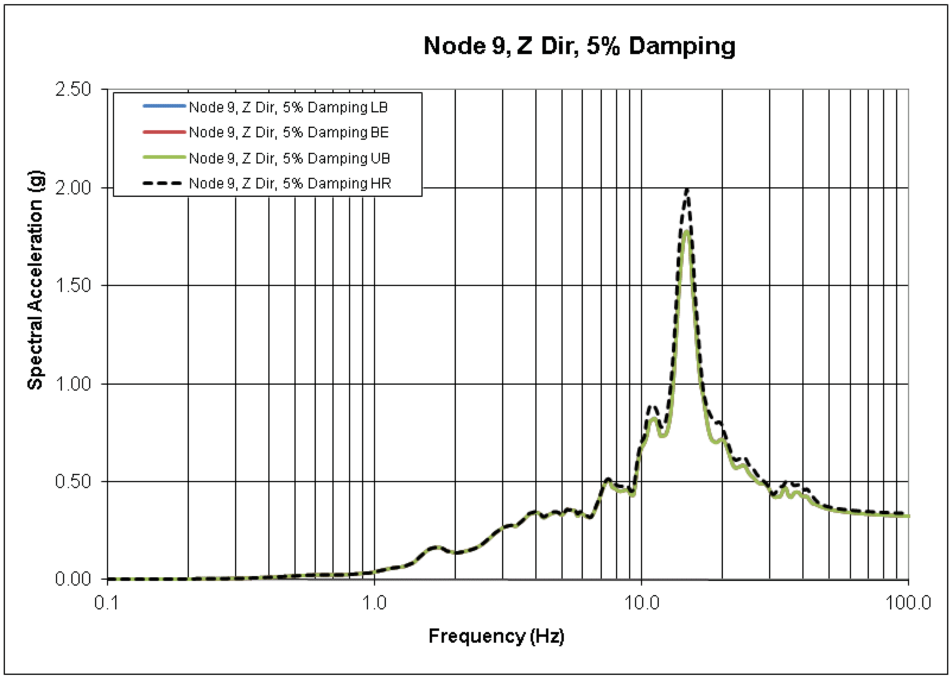

Figure 30 - 5% Damping ARS, Top of External Containment Structure (Node 9), Vertical (Z) Direction

5 SUMMARY AND CONCLUSIONS

The following summarizes the observations and findings of this report. Note that given the limited accuracy of the Lumped-Mass and Stick Model (LMSM) above 10 Hz, and the applicable frequency range in the context of Seismic Probabilistic Risk Assessment (SPRA), the response of the structure below 10 Hz is emphasized.

- Comparing the free field motion calculated from the SSI analysis using the same foundation motion (Figure 19, Figure 20, and Figure 21), the Soil-Structure Interaction (SSI) effects on the translational foundation motion are noticeable for all three rock profiles considered at frequencies of above 3 Hz. In general, these effects below 10 Hz are reasonably small and can be neglected for cases with Vs > 5,200 fps.
- The SSI effects on the structure (with the same foundation motion) are shown (repeated for the Operating floor in Figure 31 through Figure 33 for convenience). These effects are usually characterized by a small shift in frequency and reduction of the peak In-Structure Response Spectra (ISRS) over a narrow band of frequencies. These effects are mainly due to foundation rocking and are more pronounced for the LB (top Vs of 3,450 fps) case.
- Noting that ±15% peak broadening of the fixed base results would reasonably envelop the results from the LB, BE, and UB cases, the results suggest that the rocking SSI effects are not significant for the evaluated structure. Also note that the SSI effects on the translational foundation motion are insignificant below 10 Hz, especially for the BE (top Vs of 5,200 fps) and UB (top Vs of 7,700 fps). Therefore, within the frequency range of interest (<10Hz) a fixed base analysis can be reasonably performed for seismic evaluation of the subject structure.
- The SSI effects on the foundation motion above 10 Hz are generally more significant and cannot be discounted. This is especially manifested in the large differences between the free field input motion and foundation ARS at and above 14 Hz and in the SSI analysis results of LB case.

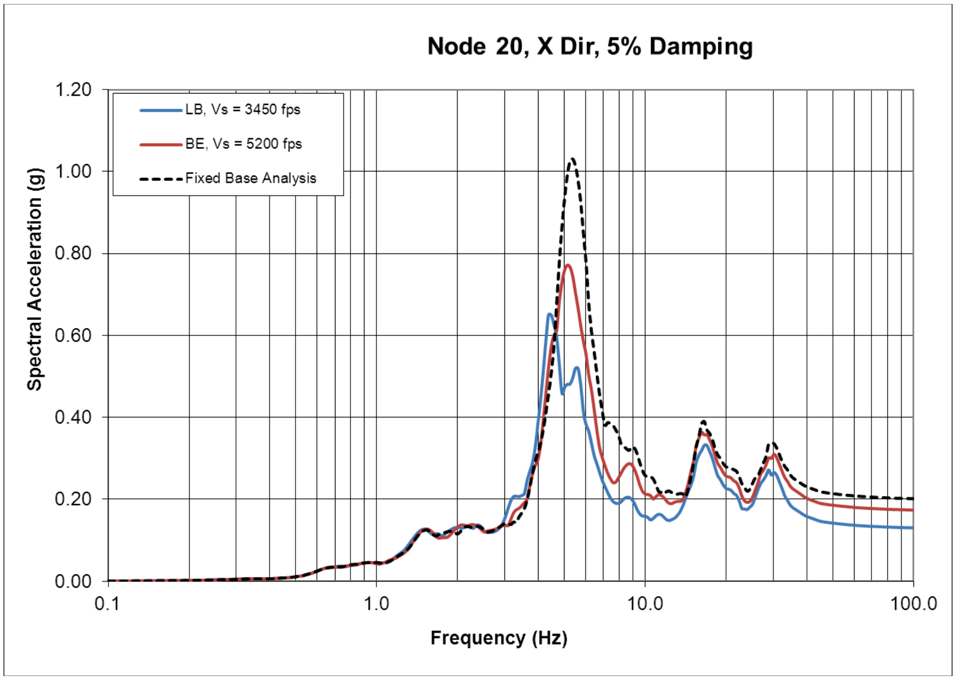

Figure 31 – 5% Damping ARS, Containment Internal Structure, Operating Floor (Node 20), East-West (X) Direction

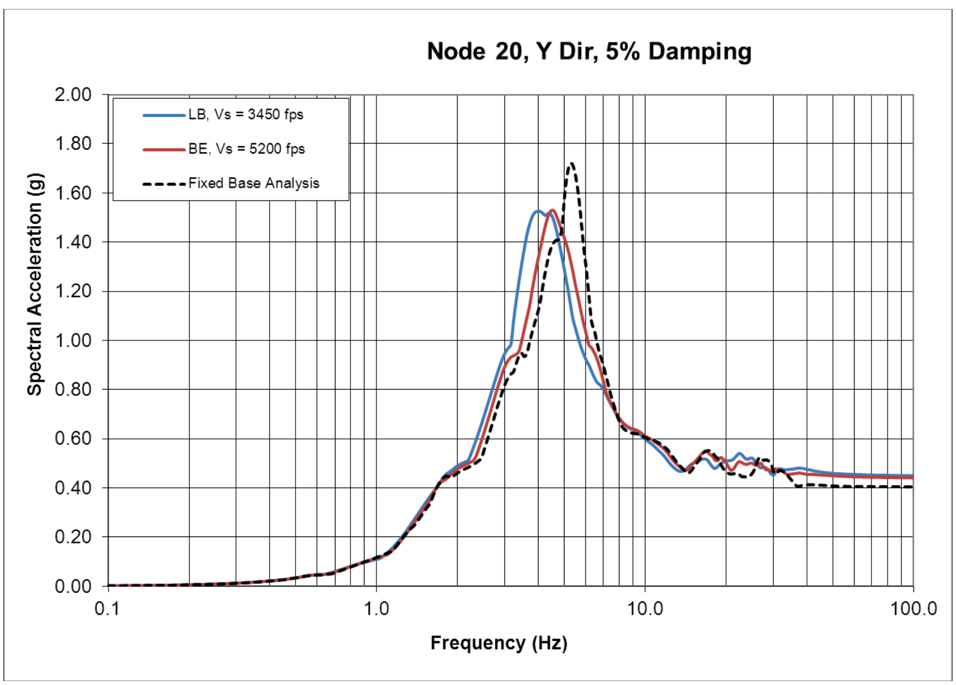

Figure 32 – 5% Damping ARS, Containment Internal Structure, Operating Floor (Node 20), North-South (Y) Direction

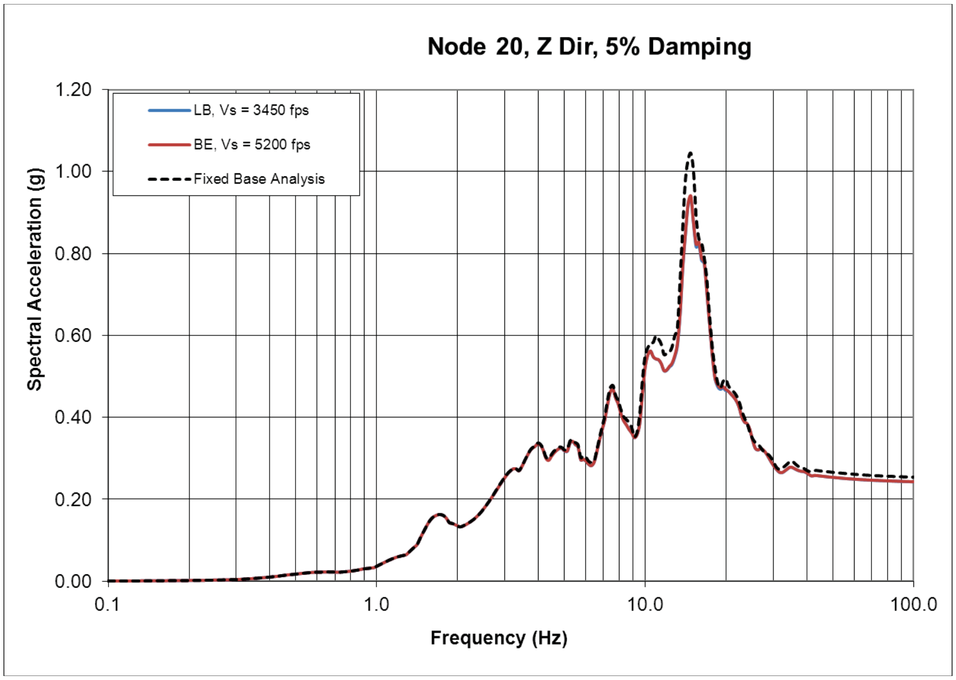

Figure 33 – 5% Damping ARS, Containment Internal Structure, Operating Floor (Node 20), Vertical (Z) Direction