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Seventh International Conference on
Case Histories in Geotechnical Engineering
and Symposium in Honor of Clyde Baker

CASE STUDY OF THE SOIL-STRUCTURE INTERACTION RESPONSE OF EMBEDDED STRUCTURES WITH VARYING BACKFILL SOIL PROPERTIES

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ABSTRACT

Soil-Structure Interaction (SSI) analysis is the study of the dynamic response of a structure as influenced by the interaction with the surrounding soil. The SSI response is sensitive to the characteristics of the soil, structures, and ground motion, as well as the depth of embedment. Availability of soil dynamic properties is, therefore, of paramount importance for performing such SSI analysis. However, detailed soil information and associated engineering properties may not always be available at the beginning of a project. Therefore, the analyst may rely on simplified yet conservative methodologies to estimate the dynamic response of the coupled soil-structure system to generate preliminary or interim seismic responses.

This paper examines a particular case of nuclear power structures founded on competent rock material, in which the diminished SSI effects allows for a fixed-base treatment of the various safety related buildings. To evaluate the adequacy of this simplified approach for interim type of analysis, two structures are considered in this study. The first structure has a large footprint and shallow embedment and is mostly subject to rocking responses. The second structure has a small footprint and relatively large embedment. The two structures are studied with varying backfill conditions and modeling approaches.

SSI analysis is completed using SASSI2010 [2011] and the following outputs are considered for evaluation purposes: transfer functions, zero-period accelerations, and acceleration response spectra. Results are presented in the paper to demonstrate the validity of the approach as well as the limitations when considering embedment effects.

BACKGROUND

A site of an existing complex of nuclear power structures is currently being requalified to current code standards. Part of this process includes performing a Soil-Structure Interaction (SSI) analysis of the safety-related structures.

In order to perform an SSI analysis, a site subsurface investigation must be completed first to determine the underlying soil dynamic properties. However, for this particular site preliminary or interim In-Structure Response Spectra (ISRS) results were requested prior to the site subsurface investigation being completed to support early preparation of equipment procurement specifications.

The complex of structures is located on a site consisting of competent rock. Therefore, a fixed-base or Hard Rock (HR) analysis was proposed as a simplified yet conservative approach for calculating interim ISRS results.

Even though all the safety-related buildings are directly founded on competent hard rock, some portions of a few buildings are backfilled with compacted excavation spoils with low characteristic shear wave velocities. Embedment effects were considered by taking the envelope response of two bounding cases in which a) embedment effects were completely neglected by considering the structure as surface mounted, and b) the embedment effects were incorporated by considering the structures completely fixed below the grade level.

This paper presents the results of the SSI studies performed on two of the safety related structures to validate the adequacy of the fixed-base methodology as a simplified yet conservative way to approximate interim ISRS results in a hard rock site while considering the impact of different backfill situations.

DESCRIPTION OF THE STRUCTURES

The first structure considered is a Diesel Generator Building (DGB). The structural footprint is approximately 110’-0” x 110’-0” in plan. The seismic weight is approximately 39,000 kips, which represents a foundation pressure of 3.2 ksf.

The DGB is embedded approximately 12’-0”, except for a small vault that extends an additional 20’-0” below grade.

A Finite Element Model (FEM) representation of the structure is shown in Figures 1 and 2.

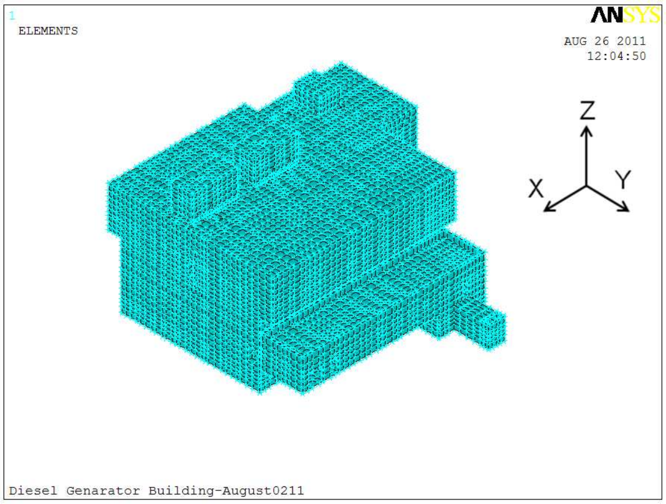

Fig. 1. Diesel Generator Building – Isometric View

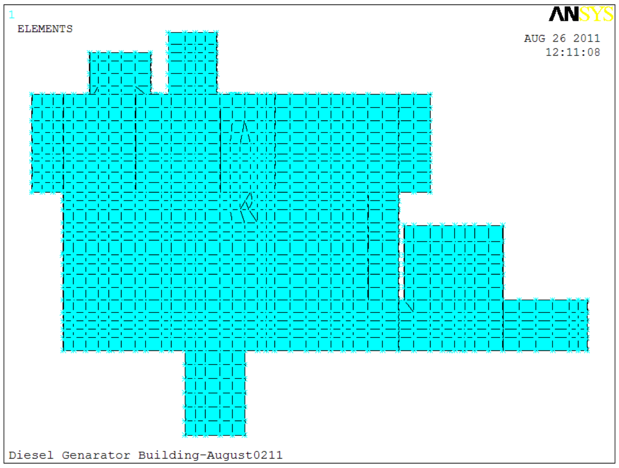

Fig. 2. Diesel Generator Building – Elevation View

Modal analysis is completed using ANSYS [2009] computer code considering the structure to be surface-founded (except for the small embedded vault which is ignored).

The dominant mode in the North-South (X) direction occurs at 9.5 Hz. The dominant mode in the East-West (Y) direction occurs at 10.9 Hz.

The second structure considered is a Main Steam Valve Room (MSVR). The structural footprint is approximately 72’-0” by 40’-0” in plan. The seismic weight is approximately 17,100 kips, which represents a foundation pressure of 6 ksf.

The structure is embedded approximately 31’-0”, which represents approximately 50% of the total structural height. The excavated volume of the MSVR is backfilled with compacted soil material.

A FEM representation of the structure is shown in Figures 3 and 4.

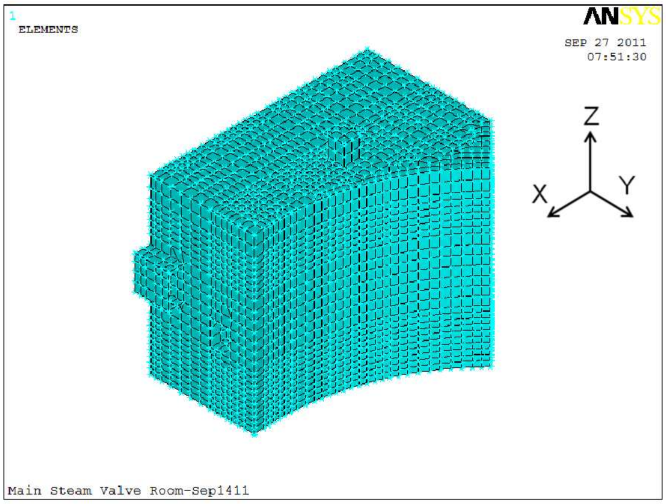

Fig. 3. Main Steam Valve Room – Isometric View

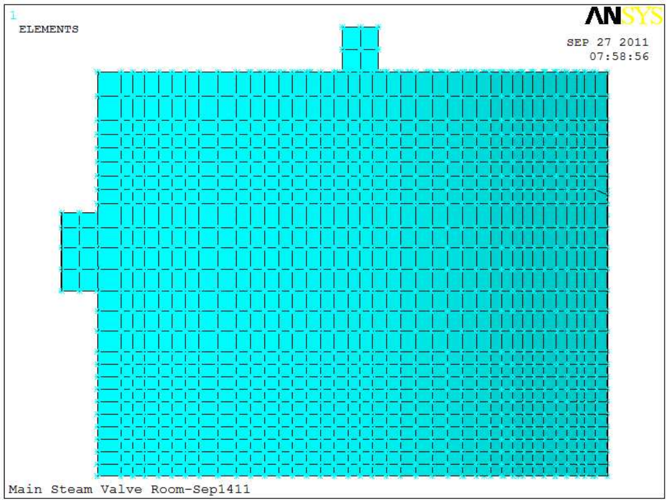

Fig. 4. Main Steam Valve Room – Elevation View

Modal analysis is completed considering the structure to be surface-founded.

The dominant mode in the North-South (X) direction occurs at 15.0 Hz. The dominant mode in the East-West (Y) direction occurs at 10.5 Hz.

STUDY OF SOIL-STRUCTURE INTERACTION EFFECTS

Objective.

The objective of the first SSI study is to assess any translational or rocking effects induced by the site-specific soil (rock) responses.

The study is completed by comparing SSI results generated using SASSI2010 [2011] with a "fixed-base" or very hard rock case with those results generated assuming a rock profile more representative of the anticipated site conditions. For both cases, a ground motion typical of the Central Eastern United States is applied.

The DGB is selected for this study, since it is relatively shallowly embedded and is anticipated to be most susceptible to any rocking responses. The structure is embedded into the soil-profiles considered for this particular location. The assumed grade elevation is noted in Figures 5 and 6.

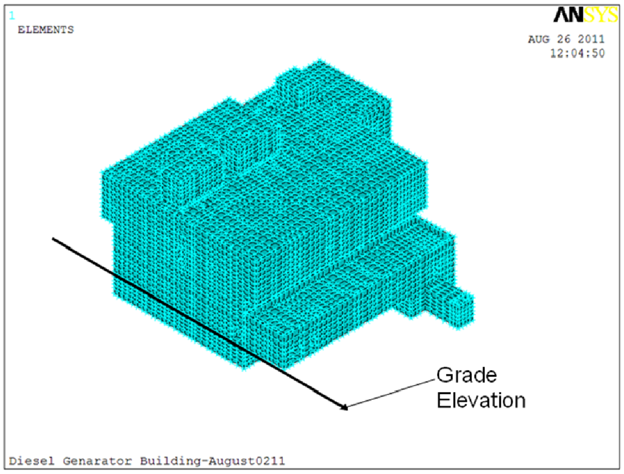

Fig. 5. Diesel Generator Building – Isometric View

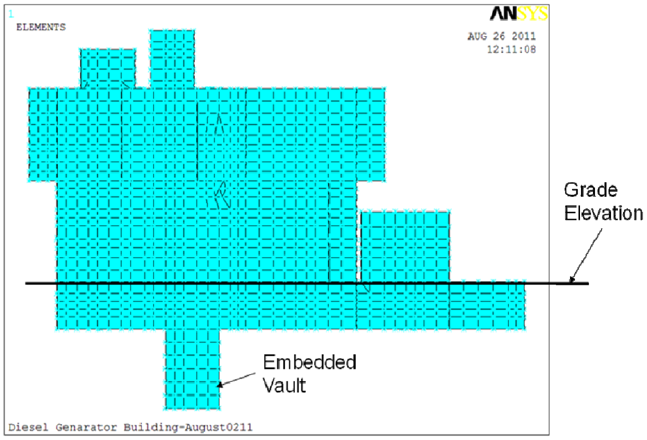

Fig. 6. Diesel Generator Building – Elevation View

SSI analysis is completed with the two models using SASSI2010 [2011]. The first, "HR" considers a shear wave velocity of 20,000 fps. This model represents the "fixed-base" case. The second, "9200" considers a shear wave velocity of 9,200 fps. This is more closely representative of the site condition as it is the average shear wave velocity of the near surface layers as determined from a previous site soil subsurface investigation.

Note that for all models, the Z-direction corresponds to vertically upward.

Comparison of Results.

For this study, the 5% damped raw Acceleration Response Spectra (ARS) are compared. Four corner nodes are considered at the foundation elevation, EL 616' as shown in Figure 7. In addition, four corner nodes are considered at the main roof elevation, EL 677' as shown in Figure 8.

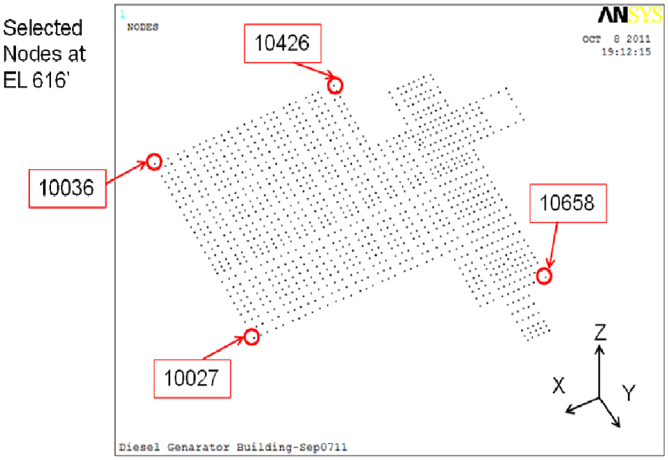

Fig. 7. EL 616' Node Selection at Foundation Elevation

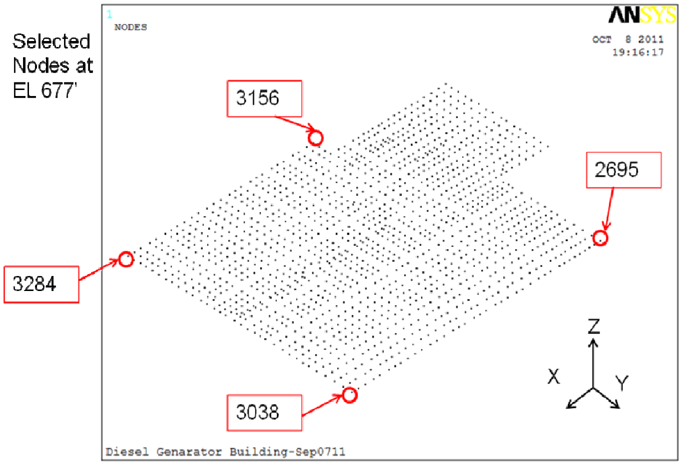

Fig. 8. EL 677' Node Selection at Roof Elevation

X-Direction Translation Sensitivity.

First, the translational sensitivity is examined by comparing the X-direction responses due to X, Y, and Z motion. The combined X-direction response is also compared. The combination is completed by using the Sum Root Sum of Squares (SRSS) method.

A comparison of the combined responses for the foundation level nodes is shown in Figure 9.

The Input Response Spectra (IRS) is show in solid black in the subsequent figures. The solid lines represent the HR profile response and the dashed lines represent the 9200 profile response.

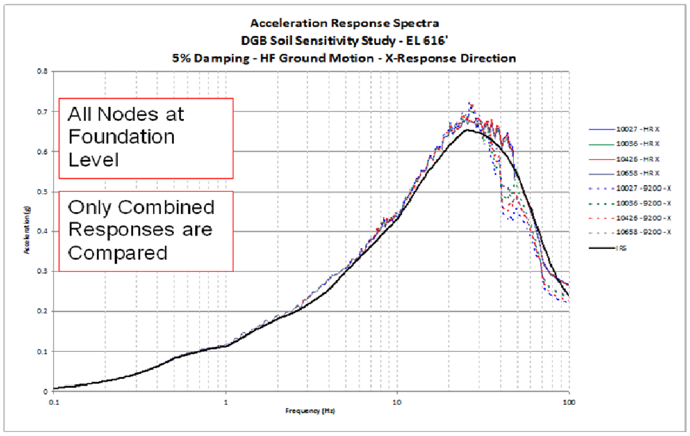

Fig. 9. EL 616' Translation Comparison

A comparison of the combined responses for the roof level nodes is shown in Figure 10.

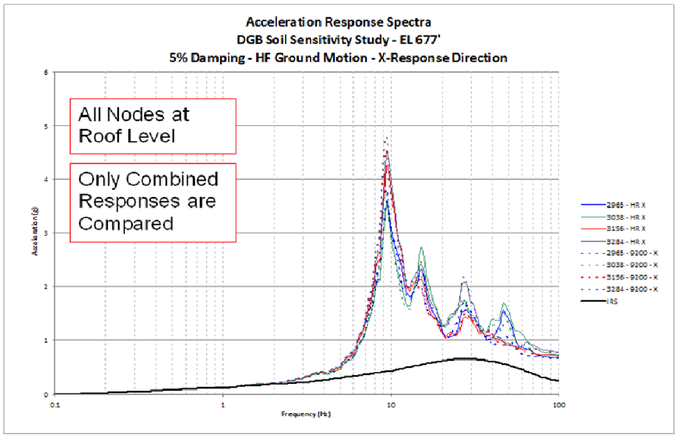

Fig. 10. EL 677' Translation Comparison

A comparison of the component responses of a single foundation node is shown in Figure 11.

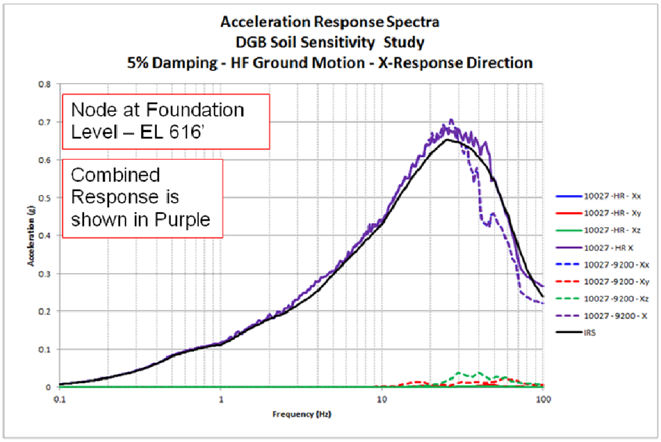

Fig. 11. EL 616' Component Comparison

A comparison of the component responses of a single roof node is shown in Figure 12.

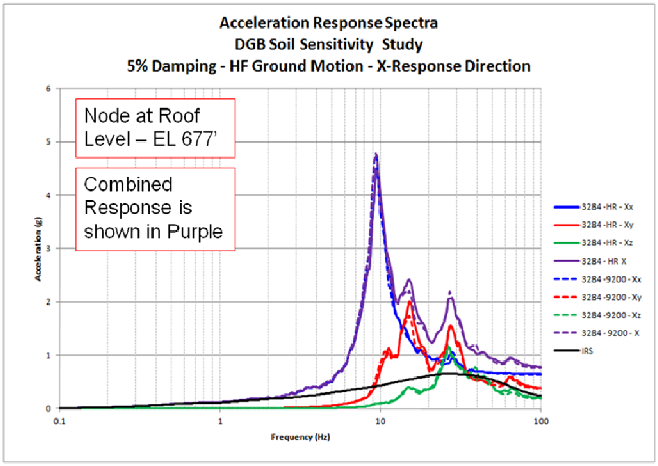

Fig. 12. EL 677' Component Comparison

Observations

For the X-direction translation sensitivity, ARS for the fixed-base case are on average 1% more conservative than for the site-specific cases.

However, maximum peak values of ARS, without correlation of frequency, are at most 6% less conservative for the fixed-base case than for the site-specific cases.

Y-Direction Translation Sensitivity.

First the translational sensitivity is examined by comparing the Y-direction responses due to X, Y, and Z motion. The combined Y-direction response is also compared. The combination is completed by using the Sum Root Sum of Squares (SRSS) method.

A comparison of the combined responses for the foundation level nodes is shown in Figure 13.

The Input Response Spectra (IRS) is show in solid black in the subsequent figures. The solid lines represent the HR profile response and the dashed lines represent the 9200 profile response.

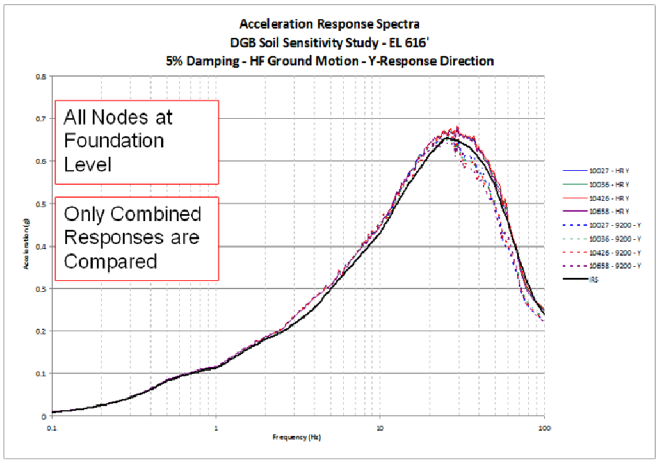

Fig. 13. EL 616' Translation Comparison

A comparison of the combined responses for the roof level nodes is shown in Figure 14.

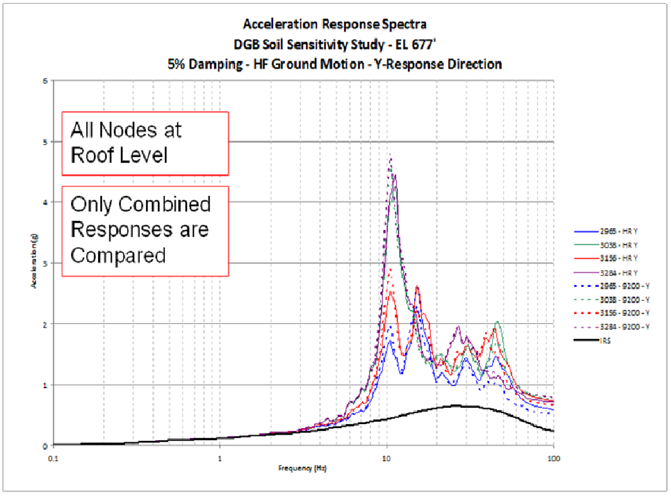

Fig. 14. EL 677' Translation Comparison

A comparison of the component responses of a single foundation node is shown in Figure 15.

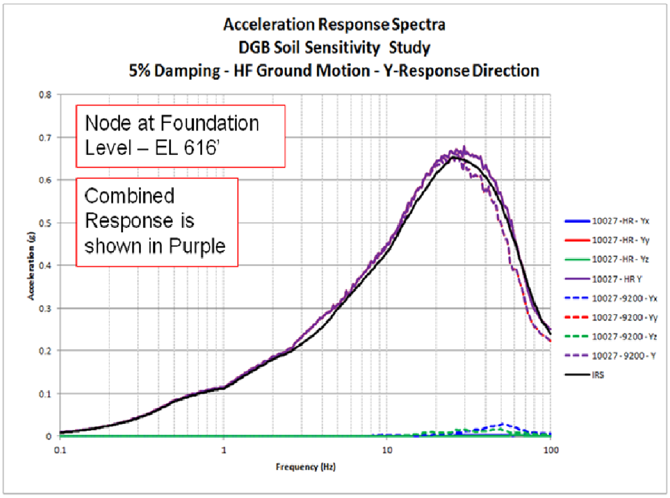

Fig. 15. EL 616' Component Comparison

A comparison of the component responses of a single roof node is shown in Figure 16.

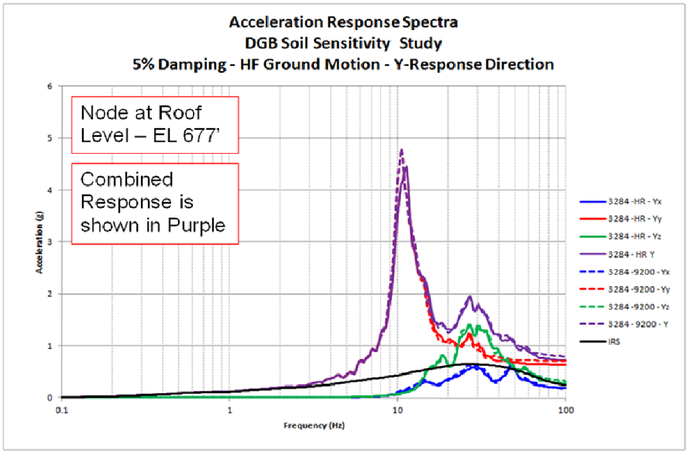

Fig. 16. EL 677' Component Comparison

Observations

For the Y-direction translation sensitivity, ARS for the fixed-base case are on average 2% more conservative than for the site-specific cases.

However, maximum peak values of ARS, without correlation of frequency, are at most 10% less conservative for the fixed-base case than for the site-specific cases.

Rocking Sensitivity.

Sensitivity to rocking is examined by comparing the Z-direction responses due to X, Y, and Z motion. The combined Z-direction response is also compared. The combination is completed by using the Sum Root Sum of Squares (SRSS) method.

A comparison of the combined responses for the foundation level nodes is shown in Figure 17.

The Input Response Spectra (IRS) is show in solid black in the subsequent figures. The solid lines represent the HR profile response and the dashed lines represent the 9200 profile response.

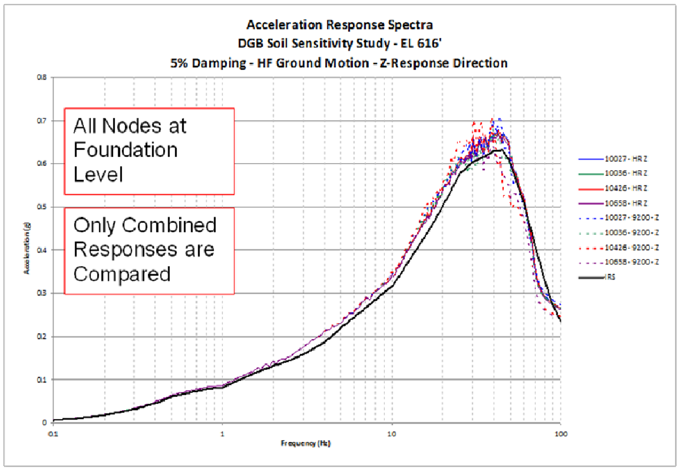

Fig. 17. EL 616' Rocking Comparison

A comparison of the combined responses for the roof level nodes is shown in Figure 18.

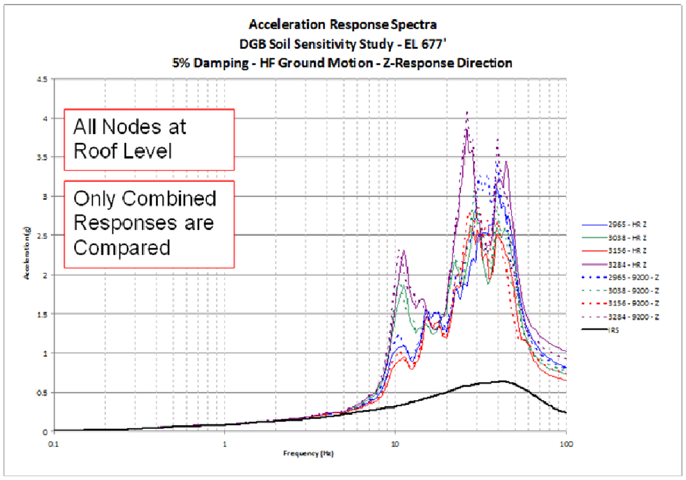

Fig. 18. EL 677' Rocking Comparison

A comparison of the component responses of a single foundation node is shown in Figure 19.

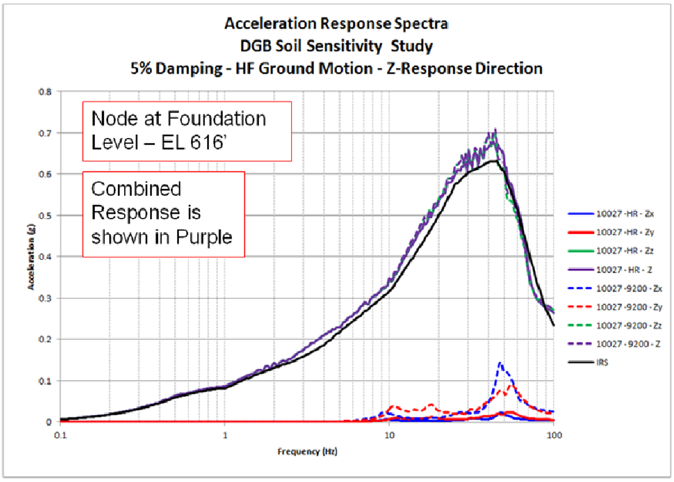

Fig. 19. EL 616' Component Comparison

A comparison of the component responses of a single roof node is shown in Figure 20.

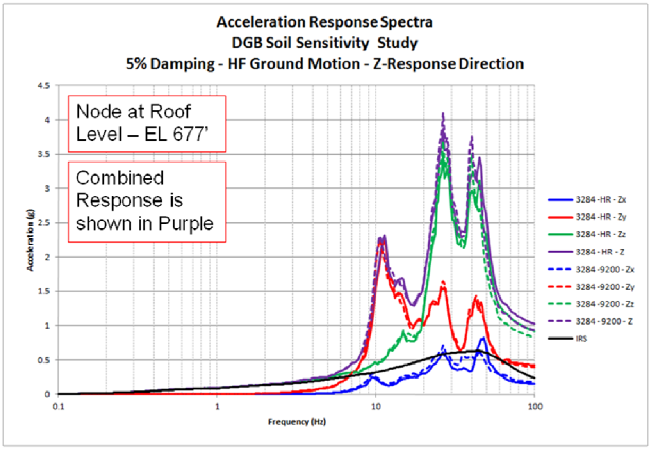

Fig. 20. EL 677' Component Comparison

Observations

For the rocking sensitivity, ARS for the fixed-base case are on average less than 1% more conservative than for the site-specific cases.

However, maximum peak values of ARS, without correlation of frequency, are at most 11% less conservative for the fixed-base case than the site-specific cases.

EMBEDMENT EFFECTS STUDY

Introduction.

The objective of the second SSI study is to determine the effects of embedment depth for generating interim ISRS results. In order to account for unknown backfill conditions, two modeling conditions are considered: 1) fully embedded structure into the hard rock profile (Case I) and 2) surface structure considering no embedment (Case II).

The MSVR is selected for this study, due to the level of embedment which is approximately equal to half of the structure height.

The actual site grade elevation is depicted by the solid black line in Figure 21.

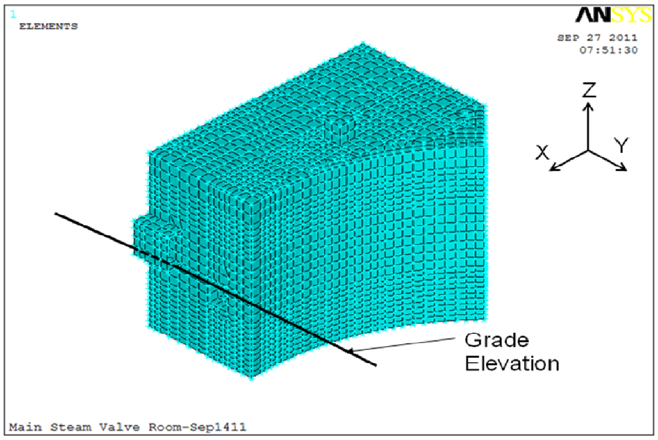

Fig. 21. Main Steam Valve Room – Isometric View

The elevation of grade assumed for each modeling condition, Case I and Case II, is shown in Figure 22.

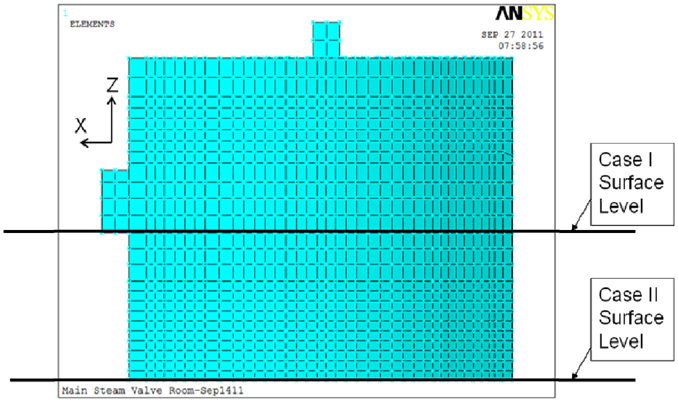

Fig. 22. Main Steam Valve Room – Elevation View – Cases

SSI analysis is completed with the two models using SASSI2010 [2011].

Comparison of Results.

For this study, three types of results are compared: 1) global response, design loads, and above-grade ISRS.

The global response is compared using nodes at major elevations at the same horizontal coordinates. The selected location is at a point that is restrained by multiple shear walls, so as to filter out local responses in the comparison. This node location is shown in Figure 23.

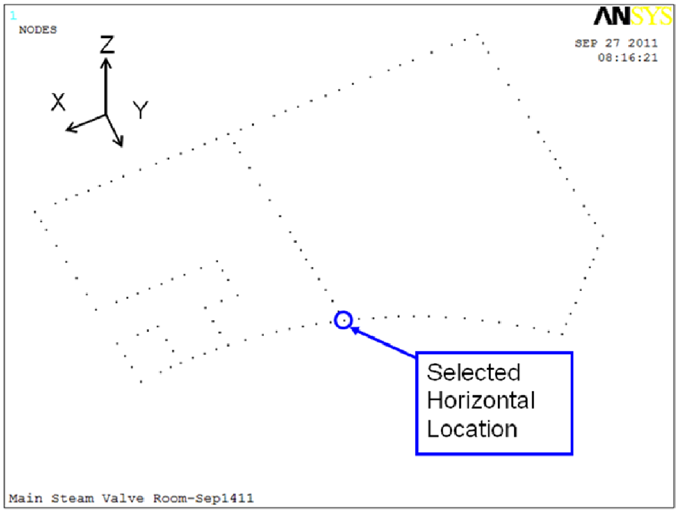

Fig. 23. Global Response Node Location

All nodes in each model are considered for the comparison of design loads.

The above-grade ISRS is compared at the roof elevation (EL 684') considering 5 nodes as shown in Figure 24.

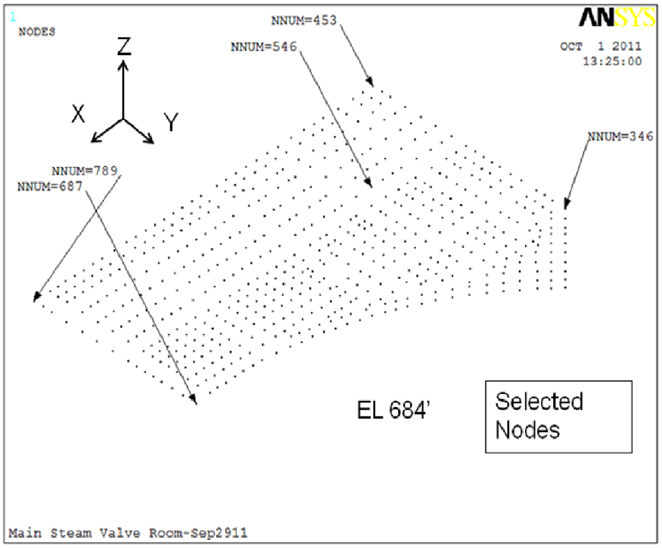

Fig. 24. Above-Grade ISRS Node Location

Comparison of Global Response.

In order to assess the change in global response due to embedment effects, horizontal transfer functions are compared at several elevations. Transfers functions may be computed as the ratio of the Fourier amplitude function of the seismic response as a function of frequency at the considered node to that of a control point node at the free-field where the input seismic motion is applied.

The transfer functions representing the X-Response due to X-Motion are compared for each modeling case in Figure 25.

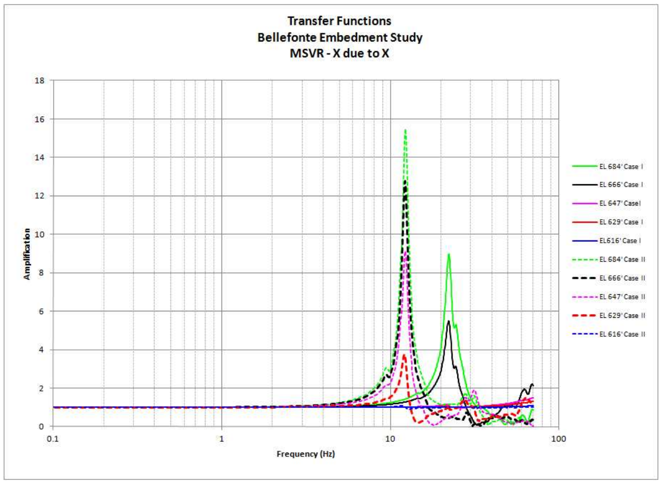

Fig. 25. X-Direction Transfer Function Comparison

The transfer functions representing the Y-Response due to Y-Motion are compared for each modeling case in Figure 26.

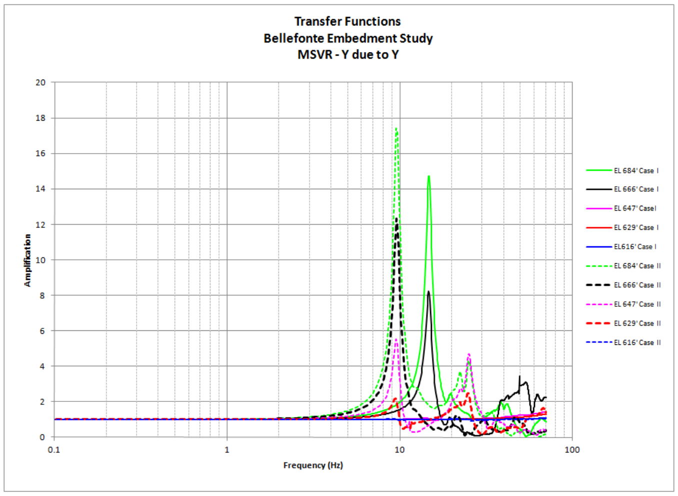

Fig. 26. X-Direction Transfer Function Comparison

Observations

The considerable differences in dominant modes between the two modeling cases confirm that embedment sensitivity is significant for this structure.

Comparison of Design Loads.

The ground motion is applied at EL 616' in each model. Maximum accelerations are extracted for every node. Responses in the dominant direction (i.e. X-Response due to X-Motion) are averaged. A percent difference is calculated of Case II with respect to Case I. The percent differences are noted in Table 1 (accelerations are reported in units of 'g').

Table. 1.Design Load Percent Differences

	X (NS)	Y (EW)	Z (Vertical)
Case I	0.43	0.44	0.40
Case II	0.54	0.50	0.50
% Difference	22%	11%	21%

Comparison of Above-Grade ISRS.

Acceleration Response Spectra (ARS) are computed for the nodes specified in Figure 24, due to the ground motion applied at EL 616'. The directional responses are combined using the SRSS method and then the nodal responses are enveloped. The curves are then broadened 15% for the upper bound and 30% for the lower bound.

The 5% damped ISRS are compared for the X-Response direction in Figure 27. The IRS is shown in the black line. The Case I result is shown in a red line and the Case II result is shown in a blue line.

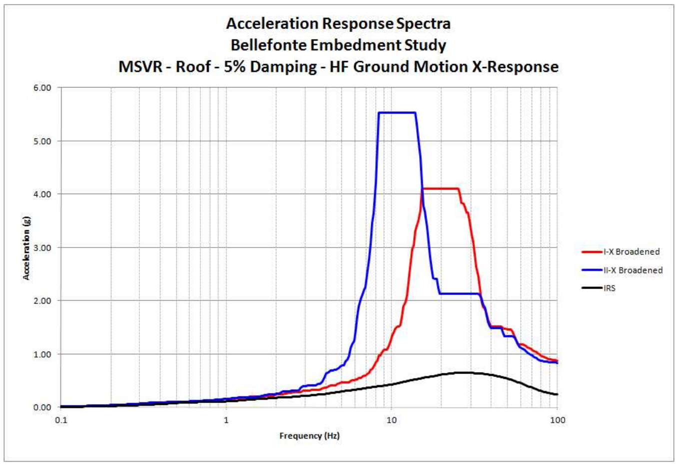

Fig. 27. X-Direction ISRS Comparison

The 5% damped ISRS are compared for the Y-Response direction in Figure 28.

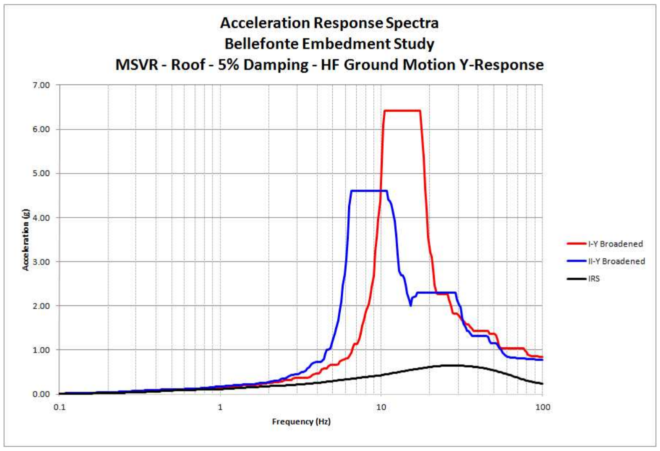

Fig. 28. Y-Direction ISRS Comparison

The 5% damped ISRS are compared for the Z-Response direction in Figure 29.

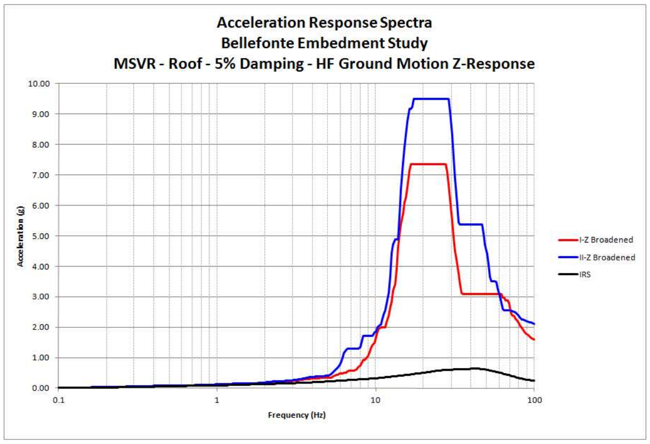

Fig. 29. Z-Direction ISRS Comparison

Observations

The global frequency shift is apparent in the horizontal ISRS. There is no frequency shift apparent in the vertical ISRS. The site conditions are anticipated to be bounded by Cases I and II. For the roof of the MSVR, the Case I and Case II ISRS are overlapping and no dips between the ISRS are present.

CONCLUSIONS

Soil-Structure Interaction Effects

Considering the frequency correlated Acceleration Response Spectra peaks, the difference in response considering a site-specific rock profile of 9,200 fps shear wave velocity compared to a hard rock profile of 20,000 fps shear wave velocity is negligible.

This indicates that for the conditions studied herein, the assumption of using fixed-base or hard rock conditions is valid for the purposes of generating interim results and that any soil induced translational or rocking effects can be ignored from the interim analysis.

Embedment Effects

For the purposes of interim analysis, the ISRS for an embedded case vs. a case considering no embedment may be broadened separately and enveloped.

However, it is noted that each ISRS must be reviewed, specifically for the range of the global frequency shift, so that response between the Case I and Case II conditions is captured and any dips are filled.

REFERENCES

ANSYS. [2009], Element Reference, Release 12.1, ANSYS, Inc., Canonsburg, PA, November.

Ostadan, F. and Deng, N. [2011], "Bechtel Version of SASSI2010 – A System for Analysis of Soil-Structure Interaction", Version 1.1. Geotechnical and Hydraulic Engineering Services, Bechtel National Inc., San Francisco, CA.