SEISMIC INCOHERENT SOIL-STRUCTURE ANALYSIS OF REACTOR BUILDING COMPLEX ON A ROCK SITE

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ABSTRACT

This paper presents a case study of the soil-structure interaction (SSI) effects on the seismic response of reactor containment and reactor building (RB Complex) structures at a rock site in the Eastern US with input ground motion that is characterized with high frequency content and high peak ground acceleration (PGA). The study includes the effects of 40 ft thick embedment backfill soil on the SSI response and the effects of seismic motion incoherency on the structural response at high frequencies. The responses obtained from these site-specific SSI analyses are compared with results of a set of site-independent SSI analyses that envelope the response of the R/B Complex structures at a wide range of sites characterized with seismic ground motion with frequency content similar to the US NRC RG 1.60 and PGA of 0.3 g. The focus of the study is on the responses obtained from the SSI analyses that serve as basis for defining the demands for seismic design of the building structural members and in-structure response spectra (ISRS) used for seismic design of subsystems, components and equipment. The results of this case study indicate that the seismic design of R/B Complex structures based on SSI responses with a design ground motion which content is reach in the frequencies corresponding to the natural frequencies of vibration of the R/B Complex structures, covers with a significant safety margin the site-specific seismic demands for the hard rock site with high frequency ground motion. Due to the high-frequency seismic input for the site-specific SSI analyses, the site-specific ISRS can be significantly larger in the high-frequency range than the ISRS used for generic design that can affect the operation of high frequency sensitive equipment.

INTRODUCTION

Figure 1 shows the seismic inputs used for the site-independent SSI analyses and the SSI analyses specific to hard rock site with high frequency input motion. The site-specific soil profiles of lower bound (LB), best-estimate (BE) and upper bound (UB) shear wave (Vs) velocity of the rock subgrade used as input for the site-dependent analyses are shown in Figure 2. The values of the rock subgrade shear wave velocity vary between 3,800 fps and 11,200fps.

The reactor containment and reactor building structures sit on the same common R/B Complex basemat. Finite element (FE) model represents the stiffness and mass inertia properties of the basemat and the below ground portion of the building. The dynamic properties of R/B structures above ground elevation are represented by lumped-mass stick models. Three lumped mass stick models that are decoupled from each other represent the stiffness and mass inertia properties of the following R/B Complex structures:

- Reactor Building (R/B) and Fuel Handling Building (FH/B)
- Prestressed Concrete Containment Vessel (PCCV), and
- Containment Internal Structure (CIS)

The CIS model is coupled with the Reactor Coolant Loop (RCL) lumped-mass stick model representing the stiffness and mass inertia properties of Reactor Vessel (RV), four Steam Generators (SG), Reactor Coolant Pumps (RCP) and major piping.

The foundation size in horizontal plane is 309 ft x 210 ft. It should be noted that this foundation size is much larger than the foundation of the EPRI AP1000 3 stick model used by EPRI to benchmark different incoherent SSI methodologies that was only 150 ft x 150 ft [1]. Thus, the effects of incoherency for this case study are expected to be larger for the R/B model used in this case study than for the EPRI AP1000 NI stick model.

To investigate the effects of the backfill soil on the site-specific SSI response of the R/B Complex structures, the results obtained from the SSI analyses of surface and embedded models are compared. Final site-specific ISRS are developed that include the effects of both incoherency and embedment in the backfill.

INCOHERENT SSI METHODOLOGY

The methodology used for incoherent SSI analysis is based on the Stochastic Simulation approach implemented in the ACS SASSI code [2] that was validated by EPRI [1]. The Stochastic Simulation approach (called SASSI-Simulation in the EPRI studies) is similar to the Monte Carlo simulation used for probabilistic analyses. The theoretical basis of the Stochastic Simulation approach is described elsewhere [1, 3]. The (mean) incoherent SSI response is computed as the average of the results computed from a set of statistical SSI analyses using random field realizations of the incoherent free-field motion input. Besides the mean incoherent SSI responses, the SSI the Stochastic Simulation approach could provide insightful information on the scatter of the SSI responses that can be useful for both design and probabilistic risk assessment studies.

The Stochastic Simulation approach is applicable to both simple stick models with rigid mat foundations and complex FE models with flexible mat foundations. For *flexible foundations*, the incoherency-induced stochasticity of the basemat motion, especially for higher frequency ranges and in vertical direction for which the mat flexibility is much higher, is driven by the local spatial variations that include significant short wave length components of free-field motion. It should be noted that rigid mats (assumed to be infinitely rigid) have the tendency to over-filter the short wave components and by this underestimate the incoherency effects in high-frequency range. The Stochastic Simulation approach captures all the details of local spatial variation aspects of the free-field motion. For flexible foundations, the free-field motion local spatial variations are directly transmitted to the flexible basemat motions since the kinematic SSI is reduced, so that differential free-field motions are less constrained by the foundation. The structure behaves dynamically like a multiple-support excitation structure, especially for flexible mats and in vertical direction.

It should be noted that by default the Stochastic Simulation approach includes all the extracted coherency matrix eigenvectors (called also incoherent spatial modes) for computing incoherent SSI response. This is very important for the high frequency range were the participation of higher-order incoherent spatial modes is large, especially in vertical direction and more flexible foundation mats. The inclusion of all incoherent spatial also produces an “exact” recovery of the free-field coherency matrix at the SSI interaction nodes that is a key input quantity for the incoherent SSI analysis. The accuracy of coherency function recovery can be checked for each SSI frequency.

A set of 10 stochastic simulations were used to compute the mean incoherent ISRS at different locations within R/B Complex structures. This set is sufficient for accurately predicting mean incoherent ISRS. Confirmatory analyses done for 25 simulations confirmed that 10 simulations were sufficient to accurately predict incoherent SSI responses.

The site-specific incoherent SSI analyses were performed using the 2007 Abrahamson hard-rock plane-wave coherency functions provided by EPRI [4].

PROCEDURE FOR SEISMIC SSI ANALYSIS

Three sets of SSI analyses were performed to evaluate the effects of motion incoherency and soft backfill layer vibration on the site-specific ISRS:

1) Surface foundation subjected to coherent input ground motion (SC),
2) Surface foundation subjected to incoherent input ground motion (SI), and
3) Embedded foundation subjected to coherent ground motion (EC).

The above SSI analyses were performed for three site-specific soil properties including lower-bound (LB), best-estimate (BE) and upper-bound (UB) which profiles are shown in Figure 1. Figure 2 presents the 5% damping ISRS of the site-specific design ground motion used as input for the surface and embedded foundation SSI analyses that are characterized by rich high frequency content. The control elevation of the input ground motion for all of the SSI analyses presented herein was at foundation bottom elevation.

The baseline site-independent SSI analyses were limited to coherent input motions for the surface foundation SSI model. The standard design site-independent analyses included 8 soil profiles that represent the subgrade conditions that envelope the SSI response of the building at a vast variety of sites. Figure 1 presents the acceleration response spectra of the input ground motion used as input for the standard design site-independent SSI analyses.

The co-directional SSI responses computed for each seismic input direction, NS, EW and Vertical, were combined using the SRSS rule.

A simplified approach was used to include the combined effects of embedment and incoherency in the ISRS results. The final site-specific ISRS were obtained by multiplying the surface model incoherent ISRS by the amplification factors that were computed using the ISRS results of SSI analyses with coherent input ground motion. The embedment amplification factors were computed as ratio of the coherent ISRS enveloping the response of the surface and embedded models to the coherent ISRS enveloping the response only of surface model SSI analyses for the three soil property sets, lower-bound (LB), best-estimate (BE) and upper-bound (UB).

The fact that the effects of the embedment in the soft backfill soil are not coupled with the effects of incoherency justifies the approach taken to include the embedment effects into the final incoherent motion design ISRS by adjusting the ISRS obtained from incoherent simulations of the model with surface foundation. The 40 ft thick stratum of soft backfill soil rests above a stiff rock formation as shown in the soil profiles shown in Figure 2. Since the large foundation of R/B structures sits on the stiff rock formation, the soft backfill soil has only a minor impact on the foundation dynamic stiffness and the main effect of the soft backfill layer is produced by its resonant vibration at the natural frequency of the soil column that is below 10 Hz. Therefore, for the particular site-specific conditions investigated in this study embedment effects manifest in the low frequency range well below the high frequency range where incoherency effects are manifested. The results of the site-specific SSI analyses shown in the next section confirm the engineering judgment applied in developing the final design ISRS.

The main benefit of the above decoupled approach for incoherency and embedment effects is that it avoids running an incoherent embedded model with an extremely detailed mesh required for the excavated soil to transmit high frequency components up to the SSI cut-off frequency that should be at least 50 Hz. Such an incoherent embedded SSI model might need to include tens of thousands of interaction nodes that will make the SSI analysis run practically impossible, even if a large number of parallel processors or supercomputers are used.

RESULTS

Effects of Incoherency

Figures 3 and 4 show the 5% damping ISRS computed using Stochastic Simulation at the base the PCCV structure and at the top of the FH/B structure for the Y and Z directions for all the three soil profiles, LB, BE and UB. At the base of the PCCV, for frequencies higher than 10 Hz, the incoherent ISRS are significantly lower than the coherent ISRS for all three soil profiles. However, at the top of the FH/B stick that is located at the edge of the building in the longitudinal direction, the incoherent ISRS are larger in Y direction (transverse direction) than coherent ISRS in the 8-10 Hz frequency band. This increase in the ISRS amplitudes in the 8-10 Hz frequency band is due to the incoherency-induced torsional motion of the building that amplifies the dynamic response of the FH/B structure in the Y direction (transverse direction) at around 9.0 Hz, where a significant structural vibration mode exists.

It should be noted that the incoherency effects are usually more significant in vertical direction than in horizontal direction. This is mainly due to the fact that the frequency content of the SSI response in vertical direction is usually larger than in horizontal direction, since the nuclear structures are stiffer in their axial direction than in lateral direction.

SSI Effects of Backfill Embedment

Since the building being analyzed has a large-size and stiff foundation that sits on a rigid rock formation, the effects of the soft backfill soil layer on the overall dynamics of the R/B structures is small, and it could be considered practically negligible. The effects of the backfill are shown in Figure 5 that compares the computed ISRS at the basement center for the BE soil profile for the surface and the embedded SSI models of R/B Complex structures.

The most significant embedment effect is the ISRS spectral peak that occurs at the backfill soil column frequency (at about 6.0 Hz in Figure 5). In the high frequency range the embedment effects are almost negligible and favorable, as shown in Figure 5. These results confirm the fact that embedment effects manifest in the low frequency range below 8-10 Hz where the backfill soil column frequency occur. Therefore, the embedment effects are decoupled from the incoherency effects that manifest in the high frequency range above 8-10 Hz.

Final Results Including Incoherency and Embedment Effects

Figure 6 shows the final, 15% broadened site-specific (incoherent) ISRS at the base of CIS structure. For comparison purposes, Figure 10 also includes the site-specific coherent ISRS and the baseline standard design ISRS. As expected, for the low and mid frequency range, the standard design ISRS envelope the site-specific ISRS with a large safety margin. However, in the high frequency range the site-specific (incoherent) ISRS could be, on a case-by-case basis, significantly larger than the standard design ISRS.

Finally, Figure 7 shows a comparison between the site-specific and the standard design structural forces in the PCCV structure. As expected, the standard design forces envelope than site-specific forces with a large safety margin.

CONCLUSIONS

The paper show key aspects of the site-specific seismic SSI analysis of the R/B Complex structures. The effects of the motion incoherency and foundation embedment were considered. It was shown that these effects are decoupled since the backfill embedment effects manifests in low frequency range below 8-10 Hz, while the incoherency effects manifest in high frequency range.

The site-specific ISRS are lower than the standard design ISRS in the low and mid frequency ranges, but could be larger than standard design ISRS in the high frequency range. The site-specific structural forces are significantly lower than the standard design structural forces for all of the R/B Complex structures. This is due to the fact that most of the structural vibration modes are in low and mid frequency range and because of this, they are less excited by the site-specific high-frequency seismic inputs in comparison with the standard design mid frequency seismic inputs.

Since the foundation basemat of R/B structures has larger footprint dimensions, 309 ft x 210 ft, the incoherent ISRS are larger than coherent ISRS for the structures located close to the edges of the basemat in the longitudinal direction. These amplifications of the incoherent ISRS is due to the additional rotational motions induced by the incoherency effects, that are torsional motions due to the incoherent horizontal inputs, and rocking motion due to the incoherent vertical input.

The effects of basemat flexibility on the site-specific ISRS are larger for the vertical direction, for which the R/B Complex structures behave as a multiple support excitation system.

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4. Abrahamson, N. 2007. "Effects of Seismic Motion Incoherency Effects" Palo Alto, CA, EPRI TR-1015111

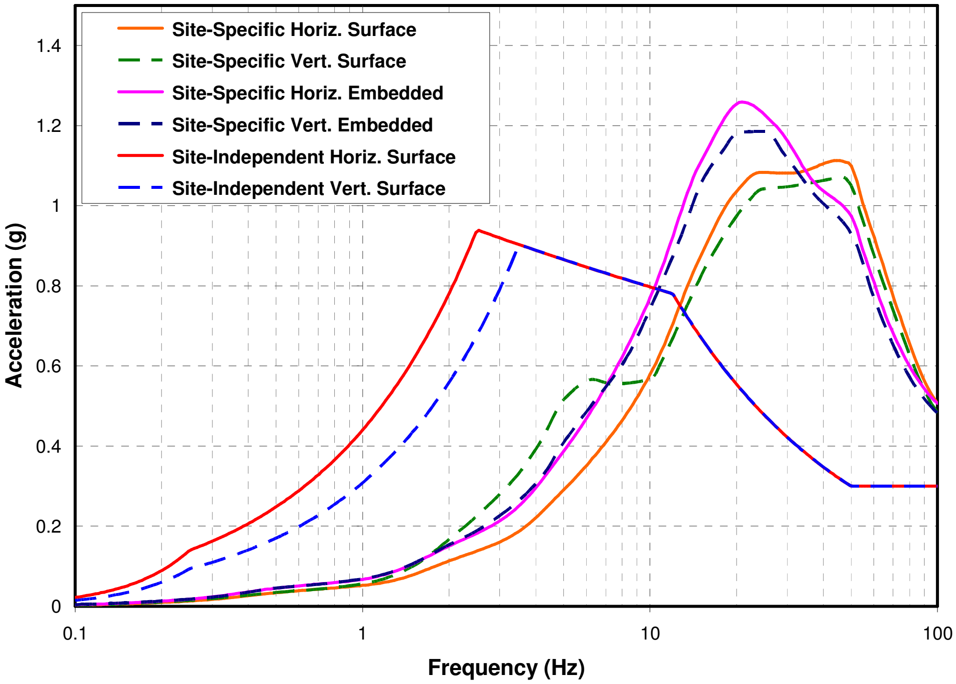


Figure 1: Site-Specific and Standard Design Ground Motion Acceleration Response Spectra

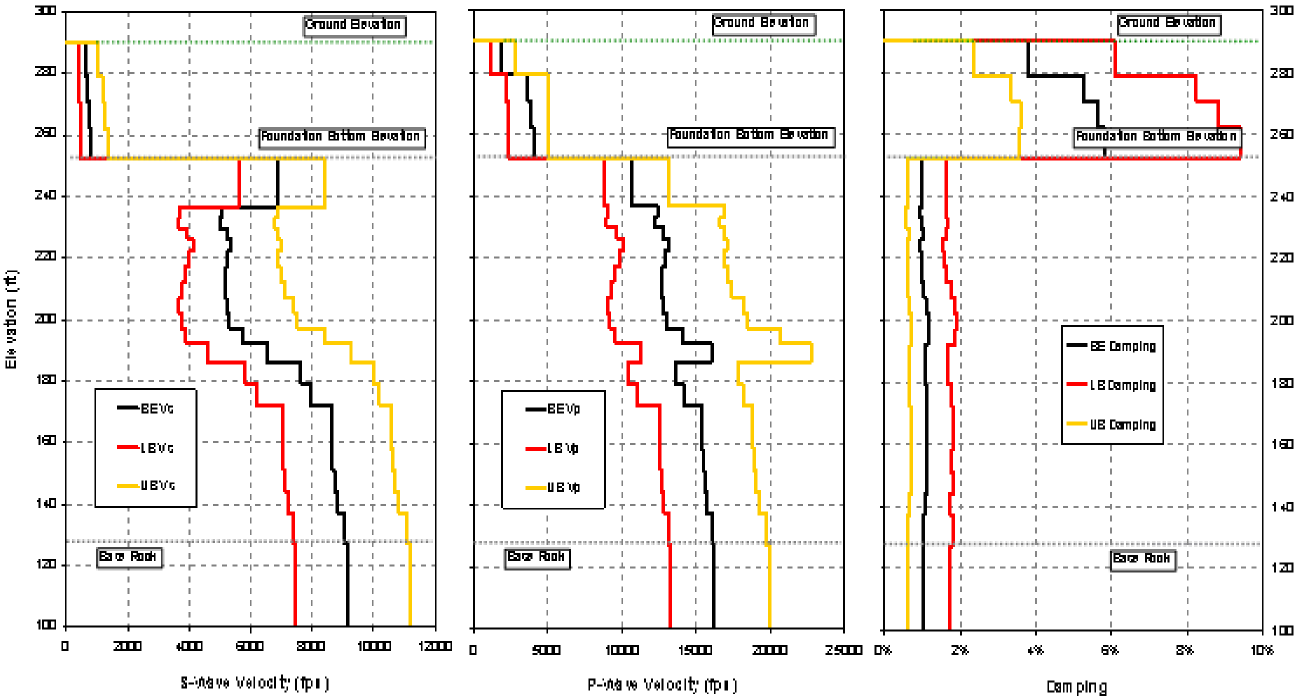
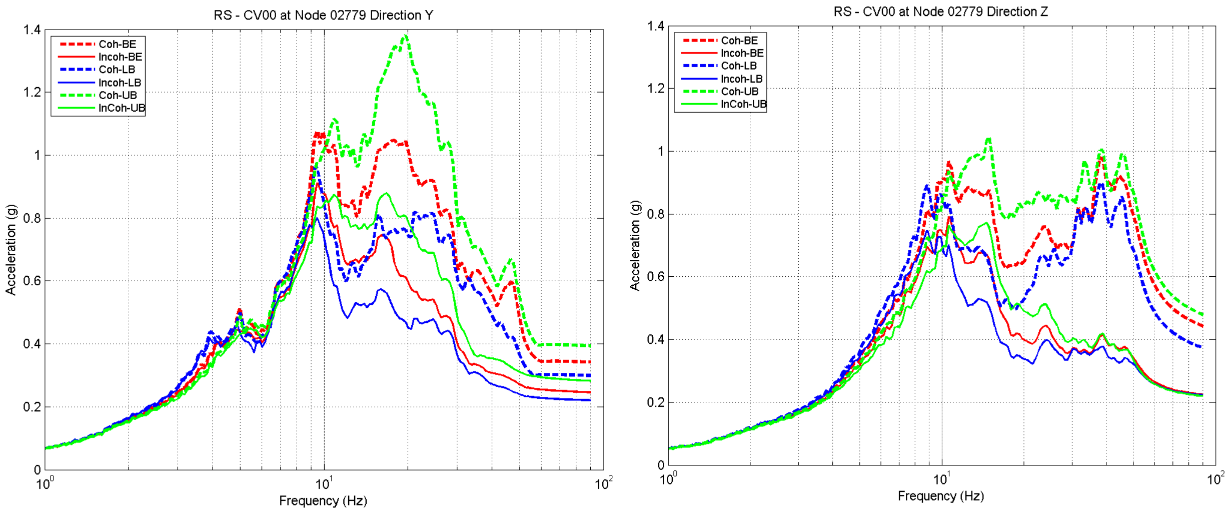
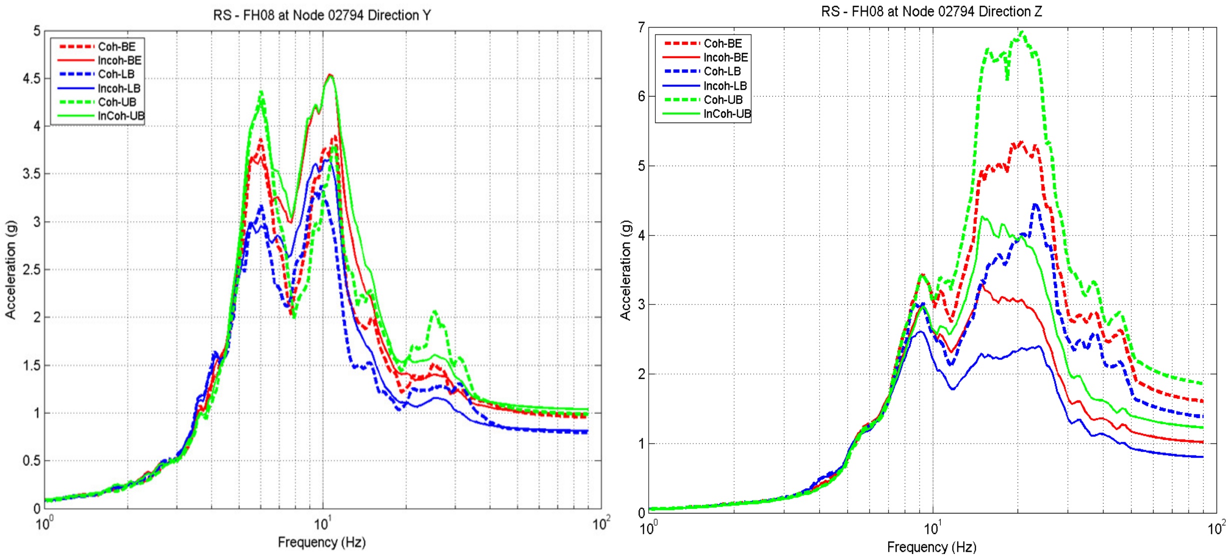


Figure 2: LB, BE and UB Soil Profiles for Soil S-wave, P-wave Velocities and Damping Ratios


RS - CV00 at Node 02779 Direction Y

RS - CV00 at Node 02779 Direction Z

Figure 3: 5% Damp ISRS at CIS at PCCV Base in Y and Z Directions; Coherent vs. Incoherent ISRS for LB, BE and UB Soil Profiles


RS - FH08 at Node 02794 Direction Y

RS - FH08 at Node 02794 Direction Z

Figure 4: 5% Damp ISRS at the Top of FH/B Structure for Y and Z Directions; Coherent vs. Incoherent ISRS for LB, BE and UB Soil Profiles

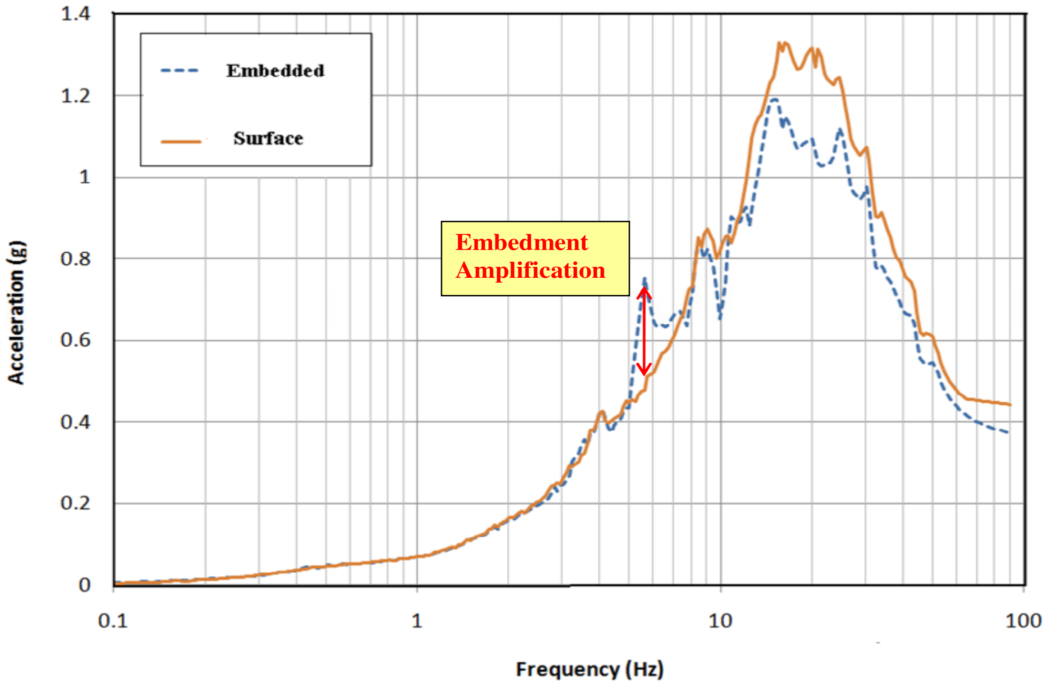


Figure 5: 5% Damp ISRS in X-Direction at the Basemat Center Envelope of LB, BE and UB Soil Cases for the Surface and Embedded SSI Models

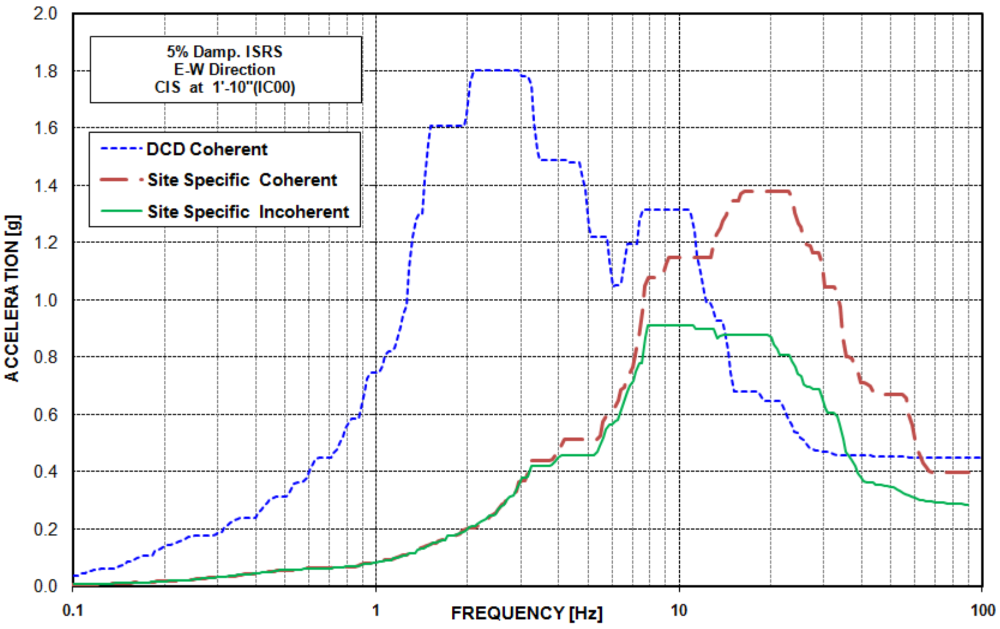


Figure 6: 5% Damp ISRS at the CIS Base for Y Direction; Standard Design vs. Site-Specific Coherent and Incoherent ISRS

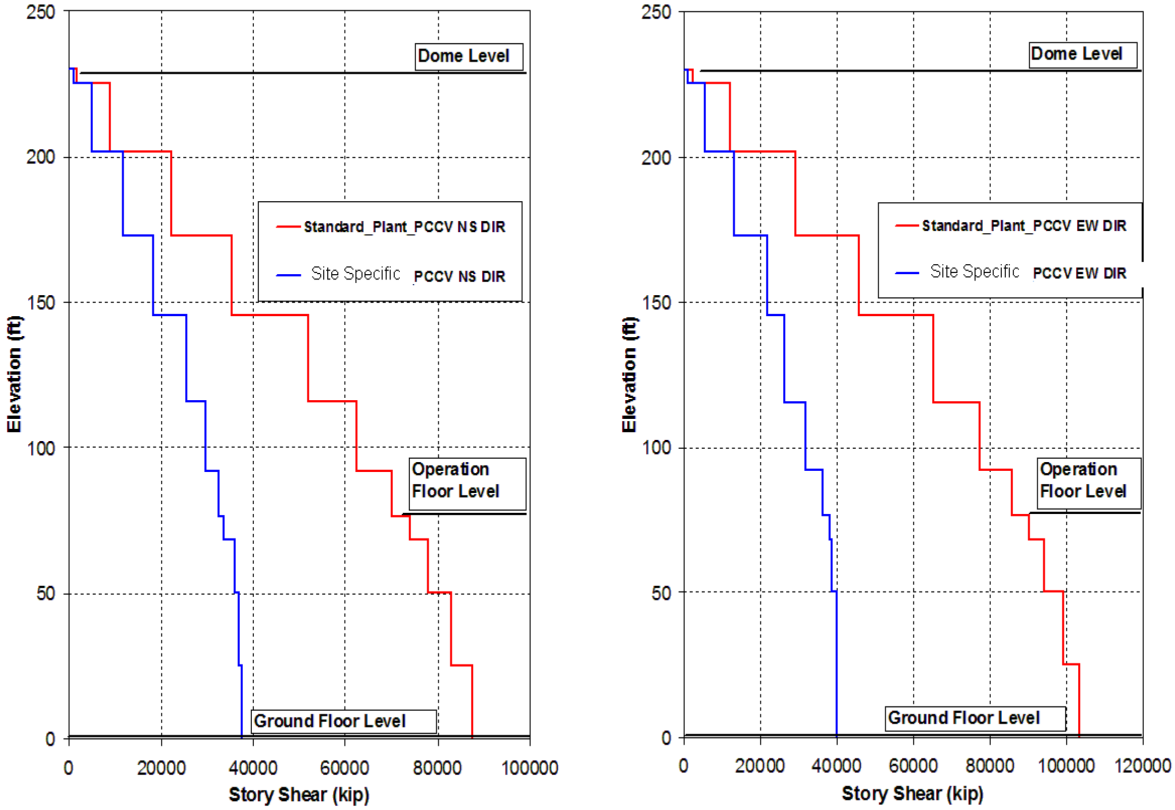


Figure 7: Standard Design vs. Site-Specific Structural Forces in PCCV Structure