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Inertial Soil Structure Interaction at a Hard Rock Site

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ABSTRACT

The Electric Power Research Institute (EPRI) technical report, Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near Term Task Force Recommendation 2.1: Seismic (EPRI, 2013), provides guidance for fixed-base seismic response analysis at hard rock sites. The report states that inertial soil-structure interaction (SSI) effects significantly diminish for structures at nuclear power plants founded on rock with shear wave velocities (V_S) greater than 5,000 ft/s. It indicates that it is reasonable to conduct fixed-base seismic response analysis of structures founded on rock with V_S greater than 5,000 ft/s to develop in-structure response spectra (ISRS) intended for use in fragility analysis. For structures founded on rock with V_S between 3,500 ft/s and 5,000 ft/s, SPID suggests that inertial SSI effects may be captured by peak broadening or peak shifting of fixed-base ISRS.

The SPID (2013) guidelines for fixed-base analysis and V_S are based on the results of two Nuclear Energy Institute whitepapers that consider two sample nuclear structures with typical horizontal frequencies and structural configurations. However, experience has shown that certain combinations of structure configurations and ground motions can result in significant inertial SSI effects occurring at rock sites with V_S significantly greater than 5,000 ft/s.

The structures at Indian Point Energy Center (IPEC) are founded on rock with V_S exceeding 9,000 ft/s. Response analysis of the IPEC Intake Structure considered SSI, despite the high rock V_S, to account for ground motion incoherence (GMI). Results indicated that seismic response was influenced by inertial SSI in addition to the anticipated GMI. Follow up sensitivity studies concluded that the inertial SSI effects were realistic for the Intake Structure considering its unusually large mass relative to its foundation footprint. Additional studies investigated the potential for inertial SSI at hard rock sites to affect seismic fragilities.

BACKGROUND

"Hard rock" is defined differently for different applications. For design of most commercial buildings and some industrial buildings, ASCE/SEI 7-16 (2017) designates sites with V_S greater than 5,000 ft/s as hard rock sites. This definition of hard rock is an empirically based value based on supporting rock stiffness, foundation/structure characteristics, and ground motion characteristics. This definition leads to an appropriate level of conservatism in the design response spectrum, recognizing that amplification due to wave propagation through soil layers is not present. For new design of nuclear structures, ASCE/SEI 4-16 (2017) and NRC (2013) allow fixed base analysis for structures founded on rock with V_S equal to 8,000 ft/s or greater.

For seismic hazard analyses, the definition of hard rock is the low strain Vs equal to or greater than 9,200 ft/s (NRC, 2009). This defines the soil/rock interface whereby soft rock and soil layers above this hard rock require consideration by site response analysis to calculate strain-dependent soft rock/soil properties and to generate motions in upper layers as foundation input response spectra (FIRS) or at other locations in the site profile, such as top of grade (NRC, 2009).

Two aspects of SSI are kinematic interaction and inertial interaction. Kinematic interaction accounts for the effects of spatial variation of free-field motion over the dimensional envelope of the surface-founded or embedded foundation. Inertial interaction accounts for the dynamic response of the combined soil-structure system, including radiation damping of response motions propagating away from the foundation interface. Both aspects require consideration when assessing the importance of assuming a hard rock supporting media is adequately represented by a fixed-base condition. Generally, assuming fixed-base behaviour for a hard rock site is based on inertial interaction considerations except when considering GMI. Other considerations include type of foundation and its effective stiffness, taking into account the supported structure characteristics.

For seismic probabilistic risk assessment (SPRA) of nuclear structures, the SPID (2013) advises that fixed base analysis may be appropriate for nuclear structures founded on rock or soil with shear wave velocity lower than the hard rock definition of 8,000 ft/s provided in ASCE/SEI 4-16 (2017). The SPID indicates inertial SSI effects significantly diminish for nuclear structures founded on rock with V_S greater than 5,000 ft/s. It indicates that it is reasonable to conduct fixed-base seismic response analysis of structures founded on rock with V_S greater than 5,000 ft/s to develop ISRS intended for use in fragility analysis. For structures founded on rock with V_S between 3,500 ft/s and 5,000 ft/s, SPID suggests that inertial SSI effects may be captured by peak broadening or peak shifting of fixed-base ISRS.

The SPID (2013) guidelines are supported by two sensitivity studies conducted by Bechtel (2012a, 2012b). The first study used an example containment building and internal structure to compare fixed base analysis and SSI analysis. The example containment structure for the first study had significant frequencies at about 5 Hz and 10 Hz, and a recorded Central and Eastern Unites States (CEUS) ground motion was used as input. The study compared results for three soil profiles with 35ft thick upper layers assigned V_S values of 3,450 ft/s, 5,200 ft/s, and 7,700 ft/s. The second study used an example valve house with significant modal response frequencies of about 6 Hz and 10 Hz. The second study compared fixed base response analysis results to SSI results from two soil profiles with 35ft thick upper soil layers assigned V_S values of 3,500 ft/s and 5,200 ft/s. In addition to varying the soil profiles, the second study also used three different ground motion inputs. The first two were matched to a design basis earthquake (DBE) and a CEUS site specific hazard, respectively. The third ground motion input was a recorded CEUS time history set.

The main conclusions of the studies are echoed in the SPID (2013), as discussed above. Both studies clarify that the conclusions regarding fixed-base versus SSI analysis are applicable to structure response below 10 Hz, due to limited accuracy of the models at higher frequencies. This limitation may not be significant, however. As described later, when high frequency response is important, it may be advisable to conduct SSI to capture the effects of GMI regardless of the site V_S. Due to the relatively low energy content of the second ground motion (site specific CEUS hazard), results from the different soil profiles had less difference below 10 Hz than for the other ground motions. The study notes that considering different time history inputs did not otherwise alter results or conclusions.

EXAMPLE OF HARD ROCK SOIL STRUCTURE INTERACTION

Indian Point Energy Center Unit 2 (IP2) in Buchanan, New York is a Westinghouse Pressurized Water Reactor (PWR) operated by Entergy Corporation. Entergy has recently conducted an SPRA for the plant's updated seismic hazard. Simpson Gumpertz & Heger Inc. (SGH) conducted seismic response analysis of the IP2 structures and calculated structure and component fragilities to support the SPRA. Structures at IP2 (including the Intake Structure) are founded on rock with a best-estimate shear wave velocity of V_S = 9,280 ft/s. This exceeds the lower limits of 8,000 ft/s for design and 5,000 ft/s for SPRA set by ASCE/SEI 4-16 (2017) and the SPID (2013), respectively, above which fixed base analysis is not expected to calculate significantly different results than SSI analysis. However, SGH considered SSI in the IP2 Intake Structure response analysis to capture the effects of GMI.

The Intake Structure is a reinforced concrete structure located below grade on the bank of the Hudson River. It is a one-story shear wall structure supported on a 132 ft by 66 ft by 24 ft high tremie concrete pedestal that is founded on bedrock. The finite element model of the Intake Structure used for response analysis is shown in Figure 1.

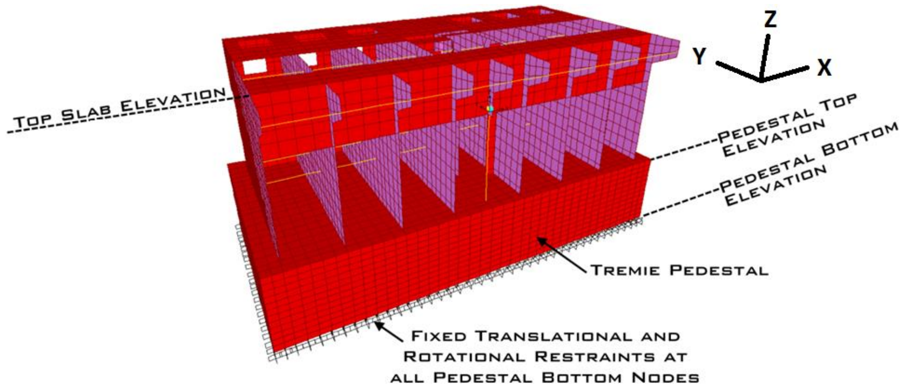

Figure 1. IP2 Intake Structure Finite Element Model

SGH also calculated seismic response for coherent SSI analysis (i.e., without considering GMI) as a benchmark to compare against the GMI results. Based on this comparison, SGH found that response of the Intake Structure is affected by inertial SSI effects, in addition to GMI. These inertial SSI effects were unexpected due to the high shear wave velocity of the underlying rock, and are evident from the deviation of the foundation response spectra from the freefield input motion spectra. For coherent analysis on hard rock, the foundation and freefield spectra are expected to be the same or exhibit only very minor deviations. We conducted additional studies to investigate the observed inertial SSI effects and check that they are realistic (i.e., not due to errors in the analysis).

We conducted surface founded SSI analysis using computer program CLASSI, in which the foundation is assumed to behave as a rigid body. However, the Intake Structure is founded on a 24 ft high pedestal of unreinforced concrete (the tremie pedestal). Due to its height, the tremie pedestal is sufficiently flexible to affect the Intake Structure natural frequencies. Treatment of the entire tremie pedestal as a rigid body would be unrealistic, and therefore we included it in the Intake Structure finite element model using solid elements. In our SSI modelling, the combined Intake Structure and tremie pedestal is essentially founded on an infinitely thin, massless rigid body in the shape of the tremie pedestal footprint. Only the interface between the tremie pedestal and the top of rock behaves rigidly. The rest of the tremie pedestal is free to deform and therefore influence the seismic response of the Intake Structure.

To assess the level of inertial SSI affecting seismic response of the Intake Structure, we compared foundation response spectra from coherent SSI analysis to freefield spectra. The foundation response spectra are measured at the foundation reference point, which is at the bottom of the tremie pedestal at its geometric centre in plan. Since the interface between rock and the bottom of the tremie pedestal behaves rigidly and the input motion is not modified to account for GMI, the input motion to the foundation reference point is equivalent to the freefield motion. Therefore, any differences between the foundation response and freefield input result from modification of the foundation input by inertial SSI.

Freefield and foundation response spectra for coherent SSI analysis are compared in Figures 2, 3, and 4. In these plots, the spectra labelled *100%* correspond to the foundation response calculated for coherent SSI analysis with best estimate structure properties and the full mass of the tremie pedestal. All spectra are plotted at 5% spectral damping.

We observed that the foundation response deviates significantly from the freefield motion in all three directions. As an example, the Y-direction foundation response (Figure 3) exhibits amplification relative to the freefield motion near the Y-direction soil-structure system frequencies at about 14 Hz and

24 Hz and de-amplification at frequencies greater than about 40 Hz. These phenomena are commonly observed inertial SSI effects for structures founded on softer soils. Feedback of the structure response into the foundation can cause amplification near the soil-structure system frequencies, while radiation damping commonly causes high frequency de-amplification. However, as discussed above, we did not expect these inertial SSI effects to be significant for the Intake Structure since it is founded on hard rock with V_S = 9,280 ft/s.

Notably, inertial SSI appears to have essentially no effect on structure response below 10 Hz, which is consistent with the findings of the two Bechtel (2012a, 2012b) studies cited by the SPID (2013). For the IP2 Intake Structure specifically, it is likely that inertial SSI does not affect response below 10 Hz because the ground motion input does not have significant energy content below 10 Hz.

STUDY OF STRUCTURE MASS

Since the tremie pedestal is a solid block of unreinforced concrete, the total mass of the Intake Structure is relatively large and atypical for structures with footprints similar to the Intake Structure foundation. Due to the high mass relative to the foundation area, feedback at the soil-structure system frequencies and radiation damping can occur despite the high rock stiffness.

We conducted a study to investigate the influence of the tremie pedestal mass on seismic response of the Intake Structure and the associated inertial SSI effects. We re-ran the coherent SSI analysis with three modified mass matrices. In these three cases, we reduced the tremie pedestal mass to 50%, 25%, and 1% of its total mass. CLASSI calculates seismic response using a structure mass matrix, modal frequencies, and mode shapes to define the structure. By modifying the mass matrix directly, we changed the tremie pedestal mass without affecting the Intake Structure response frequencies. Therefore, any change in the response spectrum shape is due to altered inertial response, and not due to shifted structure frequencies that would normally occur due to changes in mass.

Comparisons of foundation response for coherent SSI analysis conducted with 100%, 50%, 25%, and 1% tremie pedestal mass are shown in Figures 2, 3, and 4. The horizontal foundation spectra converge to the freefield spectra as the tremie pedestal mass is reduced. In the Y-direction, some amplification of response is still apparent near the fundamental Y-direction soil-structure frequency of about 14 Hz, although the amplification is less than for the cases with greater pedestal mass. In the vertical direction, de-amplification near the input spectrum peak still occurs, but de-amplification at higher frequencies is less significant.

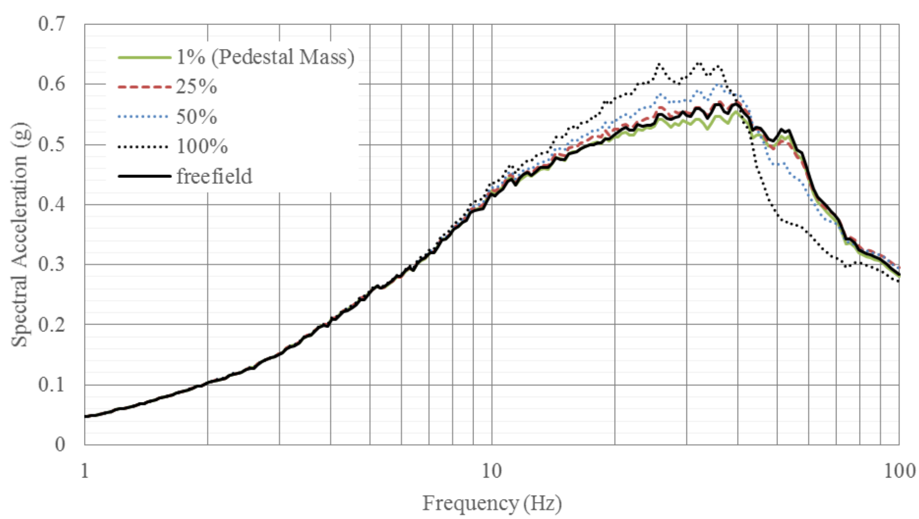

Figure 2. X-Direction Foundation Spectra Comparison to Freefield for Pedestal Mass Study (5% damping)

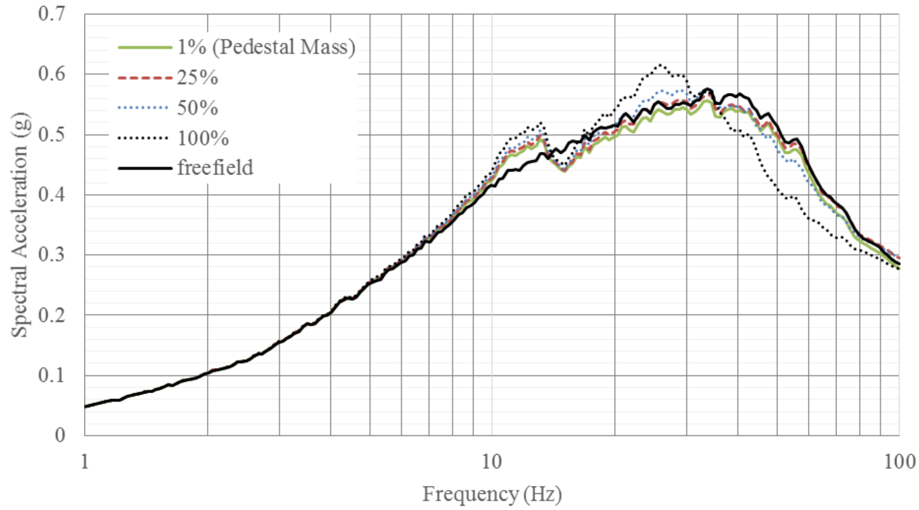

Figure 3. Y-Direction Foundation Spectra Comparison to Freefield for Pedestal Mass Study (5% damping)

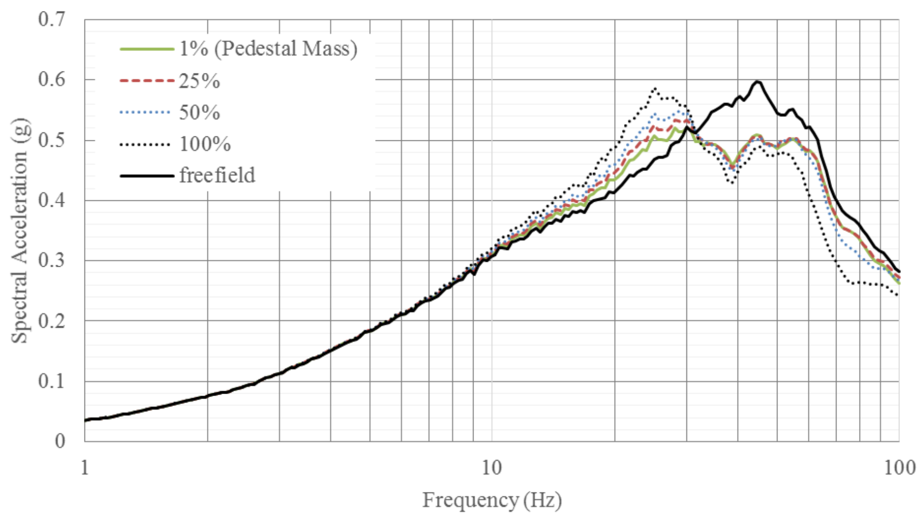

Figure 4. Vertical Foundation Spectra Comparison to Freefield for Pedestal Mass Study (5% damping)

The results of the pedestal mass study suggest that the large mass of the tremie pedestal significantly contributes to the inertial SSI effects observed for the Intake Structure. Furthermore, we concluded that the inertial SSI effects are reasonable, even though significant inertial SSI effects are atypical at hard rock sites.

STUDY OF ROCK STIFFNESS

As part of fragility analyses for the IP2 SPRA, SGH calculated variabilities in component seismic capacities due to randomness and uncertainty in structure response. Since fixed-base analysis would normally be considered realistic for structures founded on the hard rock at IP2, we did not anticipate uncertainty in the rock stiffness would affect any fragility analyses. However, the unexpected inertial SSI effects are related to the rock stiffness, which suggests structure response, and thus fragility variability, may be more sensitive to changing the rock stiffness than normally expected.

We conducted a sensitivity study to investigate variability in the Intake Structure seismic response due to uncertainty in the rock stiffness. We re-ran the coherent and incoherent (i.e., accounting for the effects of GMI) response analyses twice: once with a lower bound (LB) rock shear wave velocity of 8,313 ft/s and once with an upper bound (UB) rock shear wave velocity of 10,359 ft/s. These values are based on the best estimate (BE) shear wave velocity of 9,280 ft/s and a coefficient of variation of 0.11.

We compared response spectra at the Intake Structure foundation reference point and at the top slab of the Intake Structure for the BE, LB, and UB rock stiffness cases. The response spectra suggest that seismic response of the Intake Structure is not particularly sensitive to variation of the founding rock stiffness within the expected range of uncertainty. Coherent foundation response spectra for the three analysis cases are shown for Y-direction response in Figure 5. All spectra are plotted at 5% spectral damping. Results for the other two orthogonal directions are similar, but not shown here. Based on these spectra, we concluded that uncertainty in rock stiffness does not significantly influence the inertial SSI effects noted for the Intake Structure.

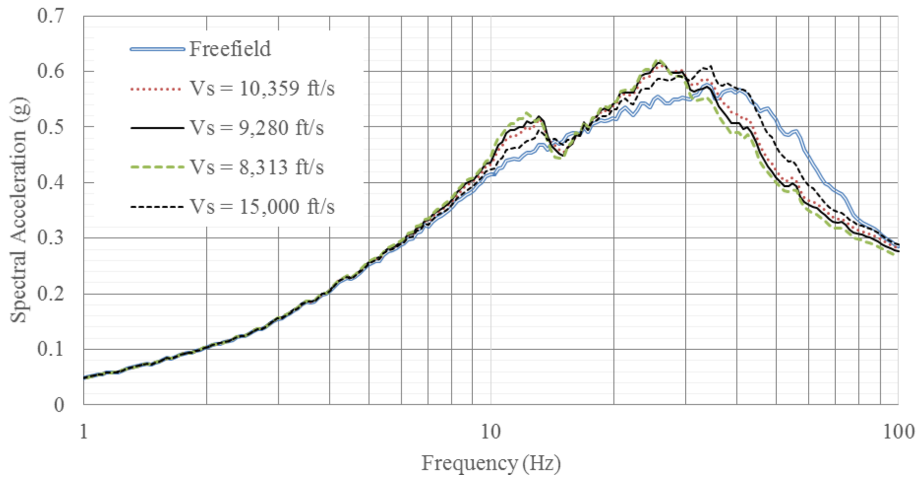

Figure 5. Y-Direction Foundation Response Spectra for Different Rock Stiffnesses
(5% damping)

To further investigate the effect of rock shear wave velocity on inertial SSI effects for the Intake Structure, we conducted coherent SSI analysis with an arbitrarily high rock shear wave velocity of 15,000 ft/s. The Y-direction foundation response spectrum for V_S = 15,000 ft/s is plotted along with the Y-direction freefield spectrum and foundation spectra for the BE, LB, and UB rock stiffness cases. The inertial SSI effects are significantly diminished, but still present. This suggests that some degree of inertial SSI would affect the Intake Structure, even if it were founded on much stiffer rock than is likely realistic.

Incoherent response spectra at the top slab of the Intake Structure are shown for Y-direction response in Figure 6 for analysis with LB, BE, and UB shear wave velocities. We compared incoherent spectra for this study because the effects of GMI were considered in the SPRA fragility analyses. The spectra for all three orthogonal directions exhibit minimal change in peak amplitude or frequency for different rock stiffnesses. Y-direction spectra are shown here to observe the minimal effect of rock stiffness uncertainty on the seismic fragility of the service water pumps (SWPs), which are mounted to the top of the Intake Structure and governed by Y-direction structure response. Based on these spectra, we concluded that uncertainty in rock stiffness does not significantly contribute to variability in the SWP fragility.

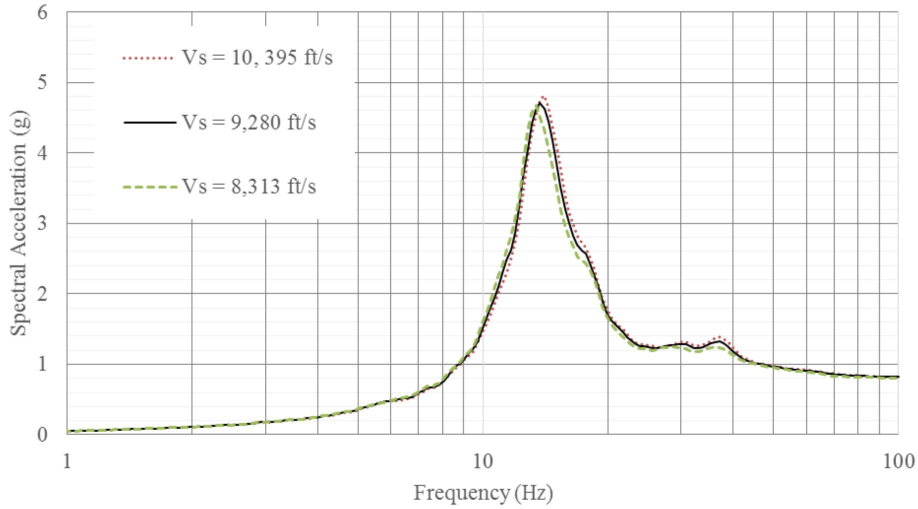

Figure 6. Incoherent Y-Direction Response Spectra near the Service Water Pumps (5% damping)

FRAGILITY CONTEXT

As discussed above, we determined that variability in the SWP fragility is not affected by uncertainty in the rock stiffness, but from results discussed thus far it is not clear whether or not inertial SSI significantly affects the median ground acceleration seismic capacity of the SWPs. We conducted a sensitivity study to examine how inertial SSI influences the IP2 SWP fragility. Our other studies compare relative magnitudes of inertial SSI for different parameter selections, but provide no information about whether the levels of observed inertial SSI are significant to fragility analysis. To evaluate how inertial SSI affects the SWP median ground acceleration seismic capacity, we conducted fixed base response analysis of the Intake Structure, and compared response spectra affecting the SWP fragility to the corresponding response spectra from coherent SSI analysis.

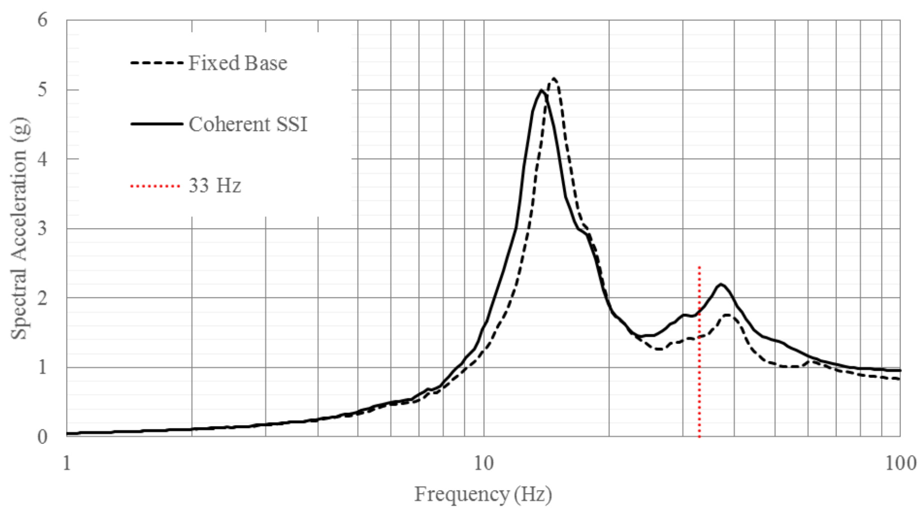

Figure 7. Y-Direction Response Spectra near the Service Water Pumps

Y-direction response spectra at the governing SWP location are shown in Figure 7. The spectra are plotted at 5% spectral damping. Although SGH calculated the SWP fragility for 3% median equipment damping, we expect that relative differences in response spectra measured by this study should be effectively the same for 3% and 5% spectral damping.

The SWP fragility is governed by failure of the motor pedestal. This failure mode is dominated by Y-direction response of the pump motor at a frequency of approximately 33 Hz. Amplification of structure response due to inertial SSI is apparent in the range of about 20 Hz to 60 Hz. At the pump motor frequency of 33 Hz, the coherent SSI analysis calculates seismic demand about 20% greater than predicted by fixed-base response analysis. This indicates that inertial SSI occurring at hard rock sites can significantly affect seismic fragilities.

CONCLUSIONS

Inertial SSI significantly affects seismic response of the IP2 Intake Structure. The observed inertial SSI effects are significant despite the exceptionally hard rock at the IP2 site, which has a best estimate shear wave velocity of 9,280 ft/s. Applicable recommendations for new design and SPRA made in ASCE/SEI 4-16 (2017) and the SPID (2013), respectively, indicate that inertial SSI should not significantly affect seismic response of structures founded on hard rock with this high of a shear wave velocity.

Our experience with the IP2 Intake Structure did not show significant inertial SSI below about 10 Hz, agreeing with the findings of Bechtel (2012a, 2012b). However, our studies suggest that inertial SSI can affect response at higher frequencies and significantly affect seismic fragilities. We examined how inertial SSI affects the fragility of the IP2 SWPs, finding that fixed base analysis under predicts the governing seismic demand by about 20% for one sample foundation input time history.

Based on sensitivity studies, we determined that inertial SSI significantly affects the Intake Structure response because of its unique configuration. The atypically large mass of the tremie pedestal drives inertial interaction with the founding hard rock that is normally only significant for structures founded on softer rock or soil. Based on this observation, we conclude that shear wave velocity may not exclusively indicate whether fixed base analysis is realistic for a given structure. Our experience with the IP2 Intake Structure suggests that careful judgement should be exercised when conducting seismic response analysis of structures with exceptionally high mass. Our studies were not extensive enough to determine if other characteristics of a structure’s configuration (e.g. geometry or mass distribution) may also influence the significance of inertial SSI at hard rock sites.

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