Soil-Structure Interaction Effects on Seismically Isolated Nuclear Power Plants

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ABSTRACT: Seismic isolation systems have been extensively used in a number of critical structures to protect important civil infrastructure from risks posed by earthquakes. Despite the maturity of this technology, the application of seismic isolation to Nuclear Power Plant (NPP) facilities is quite limited. The effectiveness of the isolation system on NPPs has been questioned due to the significant and well-documented soil-structure interaction (SSI) effects on the response of large structures. The tendency of SSI to significantly shorten the predominant frequencies of the excitations felt by the heavy structure could reduce the effectiveness of isolation. On the other hand, base isolation leads to considerably lower frequency and significantly smaller base shear. Thus, the effect of SSI on seismically isolated NNPs is of great interest, since base isolation offers the opportunity to use existing standard designs in regions with higher seismicity. In this paper, an isolated NPP model is used to study the effects of soil-structure interaction effects on the seismic response of the system. Different ground motions are used to estimate the dispersion of the NPP response. Similarly, different soil profiles are examined parametrically to assess the influence of soil properties on the system behavior. The response of the isolated structure is compared to that of the conventional structure to illustrate the effectiveness of the seismic isolation system. Issues related to the numerical simulation of the problem are discussed as well.

INTRODUCTION

Seismic isolation systems have been extensively used in a number of critical structures to protect important civil infrastructure from risks posed by earthquakes. Despite the maturity of this technology, the application of seismic isolation to Nuclear Power Plant (NPP) facilities is quite limited. The effectiveness of the isolation system on NPPs has been questioned due to the significant and well-documented soil-structure interaction (SSI) effects on the response of these structures. Specifically, SSI tends to alter the ground motion felt by the heavy structure and significantly shorten the predominant frequencies of the excitations. At the same time base, isolation leads to considerably lower frequency and significantly smaller base shear. Thus, the effect of SSI on seismically isolated NNPs is of great interest, since base isolation offers the opportunity to use existing standard designs in regions with higher seismicity.

Seismic design of isolated buildings often assumes a rigid base and SSI effects are ignored. Among others, Constantinou et al. (1988) and Zhou et al. (2004) claim that SSI effects on the response of isolated structures are minor compared to non-isolated ("fixed") structures. Other studies, however, argue that seismic design assuming a rigid base is not always safe. For example, Spyrakos et al. (2007), considered a simplified model and concluded that the effective period and effective damping of the isolated system will shift, especially for stiff/squat structural systems on soft soils. Song et al (2009) carried out a finite element study of an isolated 9-story shear wall building. Assuming elastic soil, they concluded that SSI has negligible effects on story drifts, but influences the isolator displacement, which could be somewhat bigger or smaller than predicted for a rigid base isolated building. Mahmoud et al (2012) compared responses of isolated buildings with and without SSI under different ground motions, and concluded that SSI may considerably influence the response of a stiff superstructure and may only slightly influence the response of a flexible structure. The contradictory findings of the above studies suggest that the topic is in its infancy and that additional research is needed.

In this paper, the results of a baseline study of the effects of soil-structure interaction on the seismic response of the system are presented. Specifically, the potential SSI influence on the effectiveness of the base isolation system is examined through a comparison with the fixed structure and the rigid base case.

PROBLEM STATEMENT AND ANALYSIS METHODOLOGY

A typical NPP, like APR1400, which is an advanced light water nuclear reactor designed by the Korea Electric Power Corporation [KEPCO] (IAEA, 2011), modified appropriately to accommodate a base isolation system is considered in this study to investigate the SSI effects on the response of the structure. A three-dimensional finite element model of the structure is presented in Figure 1. The "nuclear island" (NI) consists of the reactor containment building (RCB) and the auxiliary building (AUXB) sharing one common basemat. The RCB consists of the containment shell

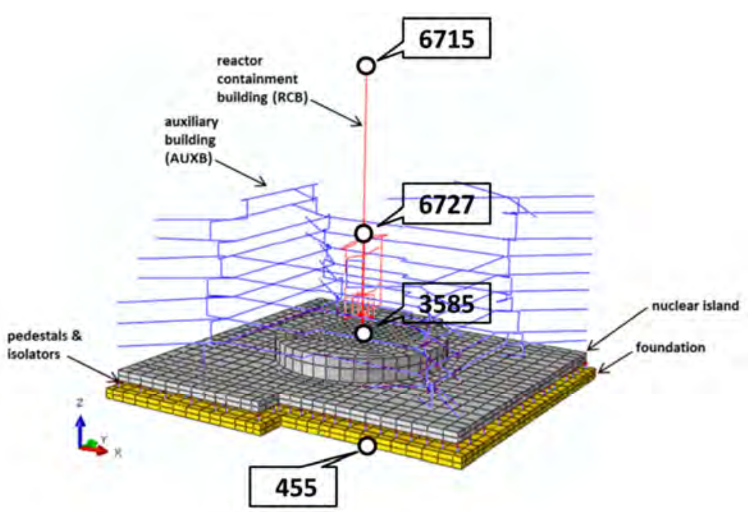
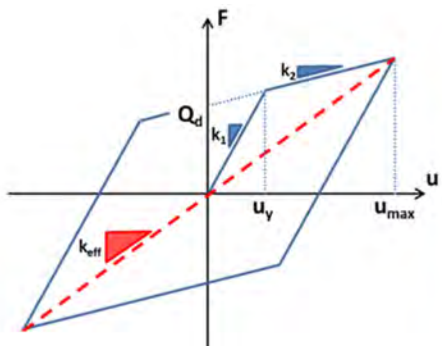


FIG. 1. View of the 3D FEM model of the base isolated NPP used

and the primary shield wall (PSW), the reactor containment internal structures, and the reactor coolant systems. The first and second horizontal mode frequencies of the containment shell are 3.85 Hz (RCB) and 11.02 Hz (PSW), respectively. The first and second horizontal mode frequencies of the secondary shield wall (representative of the internal structures) are 13.00 Hz and 25.76 Hz, respectively. The isolated NPP is designed to have a Safe Shutdown Earthquake (SSE) of 0.5g.

The seismic isolation system consists of 454 lead-plug rubber bearings (LRBs) located under the NI basemat and supported by equal number of pedestals. The bearings (made by Unison eTech) are 1500 mm in diameter and 527 mm high and consist of 32 rubber layers 7-mm thick. It was assumed that the behavior of the bearings is described by the bilinear hysteretic model illustrated in Figure 2. The design effective period of the bearings is 2 sec and their properties are summarized in Figure 2.



Parameter	Value
K_1 [kips/ft]	4814
K_2 [kips/ft]	481
F_y [kips]	104.5
u_y [ft] (=F_y / K_1)	0.021
Q_d [kips] (=$F_y - K_2 u_y$)	94.1
$u_{max\ (target)}$ [ft]	0.98

FIG. 2. Bilinear hysteretic model used for the simulation of the nonlinear behavior of lead-rubber bearings

To investigate the influence of the soil deposit on which the structure is founded, nine generic soil profiles were utilized. These nine profiles cover a broad range of depths to bedrock ($V_{s,rock}$ = 9200 ft/sec) and natural periods of the soil deposits ($T_{0,soil}$ = 0.1 – 0.9 sec). The shear wave velocity distributions with depth of the soil profiles are summarized in Figure 3. The rigid base case was also analyzed as the reference basis.

For the definition of the seismic excitations, the provisions of US NRC/RG 1.60 (NRC, 1973) were followed and the design response spectrum of the ground motion provided was used (Figure 4). To characterize the dispersion of the response a method to characterize the dispersion of the ground motions need to be employed. A recently developed approach has been to disaggregate the hazard at a specific site, select an ensemble of ground motions with appropriate fault mechanisms, magnitudes, rupture distances, soil conditions and so on, and scale them such that on average their spectrum matches the uniform hazard spectrum (UHS) developed for a site. In the case of the more general approach taken here, where no specific site is selected, ground motions are selected and scaled such that on average their spectrum matches the target spectrum of the USNCR RG1.60. Specifically, a set of 20 real record motions were selected and scaled according to the procedure proposed by Baker et al. (2011), in order to match on average the target response spectrum. The individual and

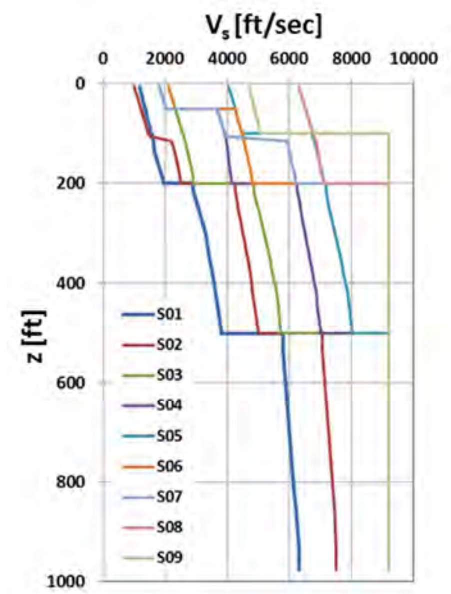


FIG. 3. Shear wave profiles of the nine generic soil deposits used for the analyses of SSI effects on the seismic response of the isolated NPP

mean pseudo acceleration spectra, for the set of 20 dispersion appropriate records are plotted in Figure 4. For each of the ground motions all the three components were applied to the model.

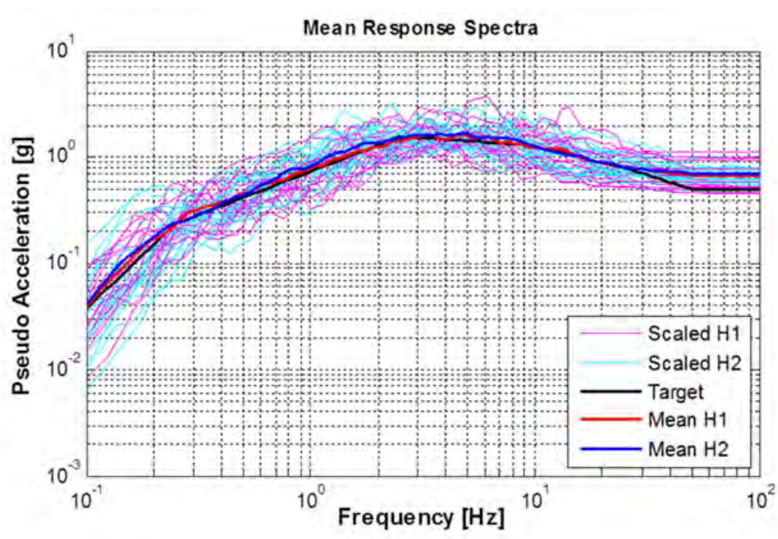


FIG. 4. Horizontal response spectra of the set of 20 dispersion appropriate motions selected to match on average the 5% damped USNRC RG1.60 target spectrum with a PGA=50% g

SASSI numerical code (Ostadan & Deng, 2012) was utilized for the analyses. This code employs a linear elastic, frequency-domain algorithm which uses the sub-structuring method to solve the seismic SSI problem.

The possible nonlinear behavior of the soil due to wave propagation is indirectly considered using the equivalent linear analysis (e.g. SHAKE): i.e. a one-dimensional site response analysis is performed and the iterated, strain-compatible soil properties are used to describe the soil behavior in SASSI. In our case, the family of G-γ and ξ-γ curves proposed by EPRI (1993) was employed to represent the nonlinear soil response.

A major challenge is that the bearings in the above SASSI models are represented by elastic elements that have constant properties (springs of complex stiffness modulus). The effective stiffness and damping ratio for isolation bearings is a function of displacement and the hysteretic characteristics. Since the bearings are highly nonlinear, bearing displacements different from those used in developing the initial model will likely necessitate significant changes in the effective stiffness and damping ratio. Thus, these changes need to be incorporated in the analyses. As mentioned above, the effective properties of the soil are calculated through a series of iterations such that the effective soil shear modulus and the effective soil damping ratio are consistent with the shear strains developed in the soil. A similar iterative procedure described in Zhou et al. (2013) was implemented and automated via a Matlab (Mathworks, 2014) script.

SSI EFFECTS ON BASE-ISOLATED NPP RESPONSE

Figure 5 shows the x-direction pseudo-acceleration floor response spectra calculated for the 20 ground motions for the case of a relatively soft foundation soil deposit (soil profile S01). The effect of the isolation system on the response of the structure is evident. While the seismic excitations input into the structure contains a significant amount of energy at frequencies between 1 and 10 Hz (foundation level), the isolators substantially reduce the energy in this frequency range and shift the natural period of the structure to about 2 sec. The almost identical response of different locations of the superstructure reveals the rigid body motion of the latter and the effectiveness of the isolation system. The small bumps at the spectra of RCB (around 3.5 Hz) and PSW (around 10 Hz) correspond to the natural frequencies of these two structures. Note that the 90^{th} percentile response spectrum is almost twice as large as the mean spectrum. This difference is due to the dispersion of the input ground motions.

A summary of the results for all the cases is presented in Figure 6, where the mean spectra at different locations of the structure for each one of the soil profiles are compared to each other. The influence of the soil stiffness is not significant at the foundation level and it is hardly noticeable above the isolation system. This behavior is justified by the presence of the isolation system and the lack of structure embedment. The fact that the structure is founded on the soil surface minimizes the kinematic interaction between the soil and the structure. At the same time, the base isolation reduces significantly the base shear and thus the forces transmitted back to the soil deposit. As a result, the inertial interaction is also limited.

For comparison, the same SSI analyses were performed for the non-isolated ("fixed") structure and the results were compared to those of the isolated structure. Note that in the fixed structure the foundation level coincides with the NI slab level. The horizontal mean response spectra at different locations of the structure for every soil

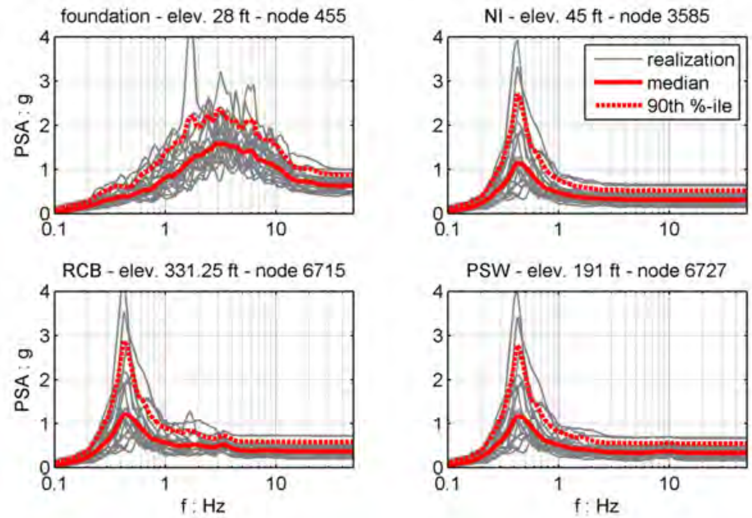


FIG. 5. Pseudo-acceleration floor response spectra at different locations of the isolated structure for the 20 ground motions used (soil profile S01; X direction)

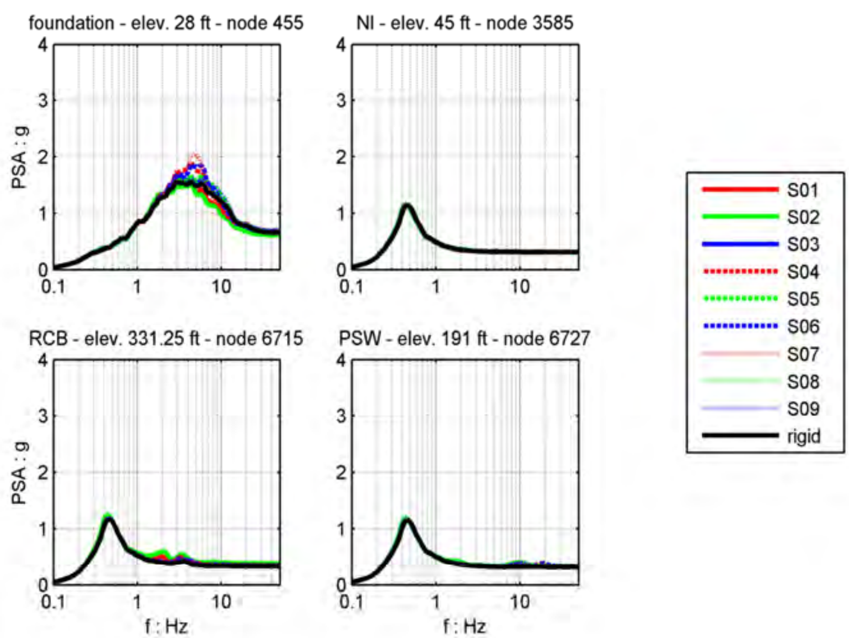


FIG. 6. Pseudo-acceleration floor response spectra at different locations of the isolated structure for the different foundation soil conditions (median spectra of the 20 ground motions; X direction)

profile examined are displayed in Figure 7. SSI effects are rather prominent in this case. The motion of the foundation is significantly affected by the soil, both in terms of amplitude and frequency content. The significant amplification of the response at the top of the RCB is characteristic: the maximum spectral value approaches the enormous value of 27 g at its natural frequency (≈ 3 Hz). The response of the isolated structure is compared to that of the fixed NPP in Figure 8. For every soil profile the mean response spectrum of the base isolated NPP is normalized to the corresponding spectrum of the non-isolated structure. The beneficial role of the isolation and the minimal SSI influence are apparent. The calculated response spectra at different locations of the structure are almost identical for all the soil profiles examined showing the negligible influence of the soil on the structure response. The effectiveness of the isolation system is reflected by the values of the ratio curves for frequencies greater than 1 Hz: the response of the isolated structure is less than about 30% of the fixed structure response. Of course, for a frequency range around the natural period of the bearings (≈ 0.5 Hz), the response of the isolated structure is greater. However, at that range, the acceleration input is already quite low.

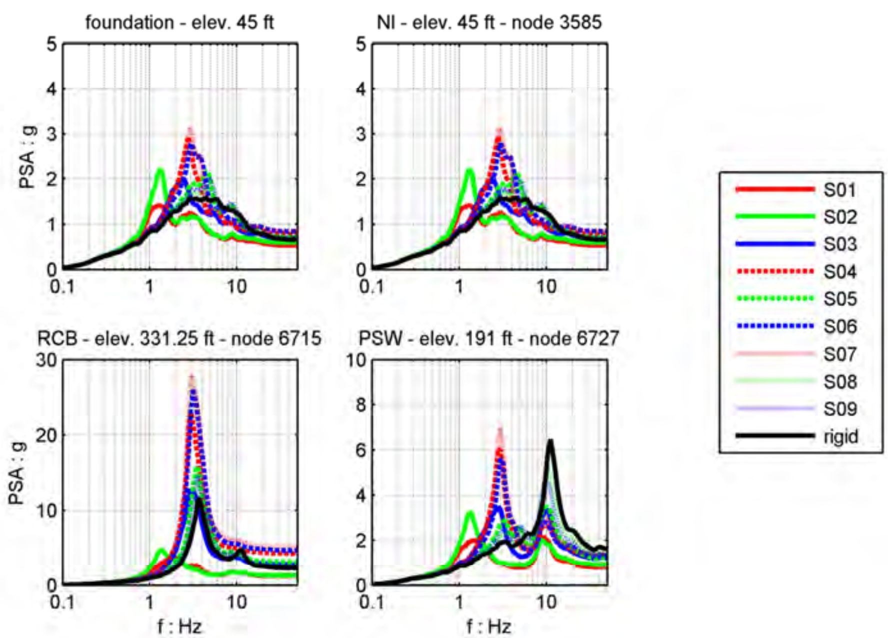


FIG. 7. Pseudo-acceleration floor response spectra at different locations of the non-isolated structure for the different foundation soil conditions (median spectra of the 20 ground motions; X direction)

In terms of displacements, the response of the isolated structure follows the same trend. As shown in Figure 9, the mean displacement spectra are barely influenced by the soil stiffness. The increase on the spectral values observed above the NI slab level for periods longer than the period of the bearings has been anticipated due to the presence of the isolation system. For higher frequencies, a rapid decrease of the displacement spectral values is observed.

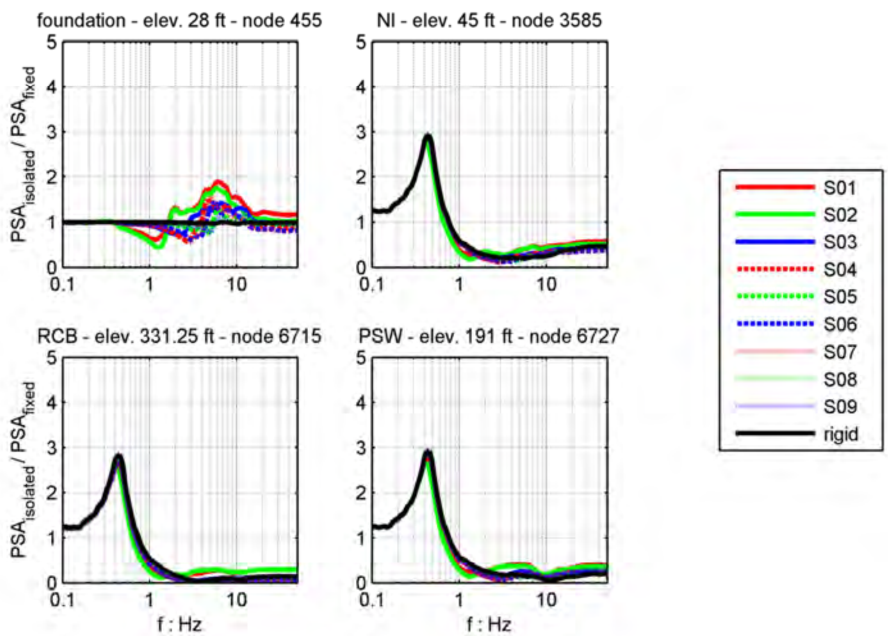


FIG. 8. Pseudo-acceleration floor response spectra of the isolated structure normalized to the respective spectrum of the non-isolated structure (median spectra; X direction)

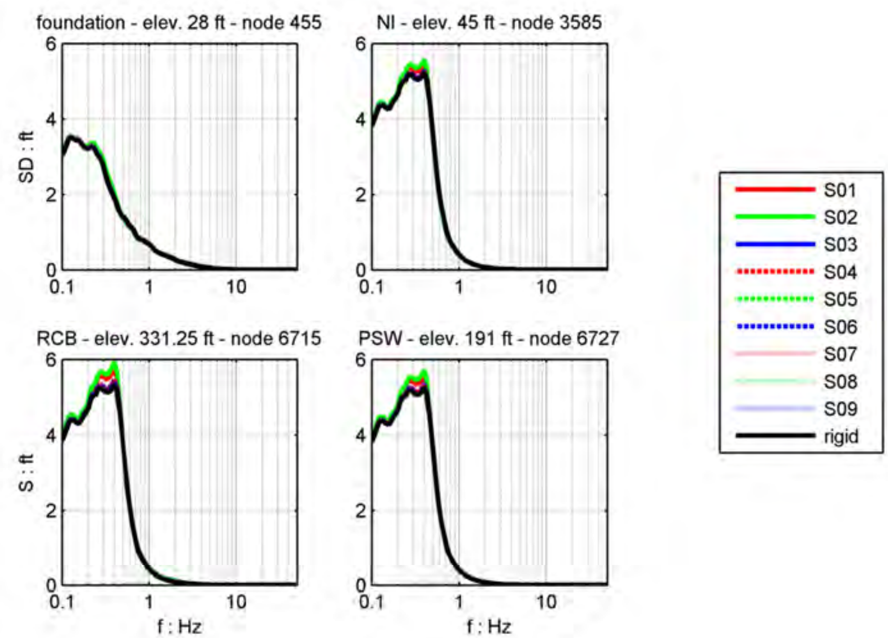


FIG. 9. Displacement response spectra at different locations of the isolated structure for the different foundation soil conditions (median spectra of the 20 ground motions; X direction)

In contrast, quite different behavior occurs in the vertical direction. The axially stiff bearings do not isolate the structure in the vertical direction and the inertial forces can be transmitted from the structure back to the soil. The response is significantly affected by the stiffness of the soil profile and this is evident in the response spectrum at the foundation level (Figure 10): the peak observed around 1.8 Hz is close to the natural period of the profile (=1.1 Hz). The amplitude of the response, however, is relatively small, mainly due to the fact that the natural frequency of the structure corresponds to vertical deformation is quite higher (≈ 10 Hz; notice the peak on RCB's spectrum at this frequency in Figure 10) and there is no resonance effect. Figure 11 summarizes the vertical response of the isolated NPP for the different soil profiles. The response at the top of the RCB soars for the case of the rigid base due to resonance: the natural frequency of RCB at vertical direction coincides with the peak at the spectrum of input motion (≈ 10 Hz). In summary, in the vertical direction, base isolation seems to act neither beneficially nor detrimental relatively to the fixed structure.

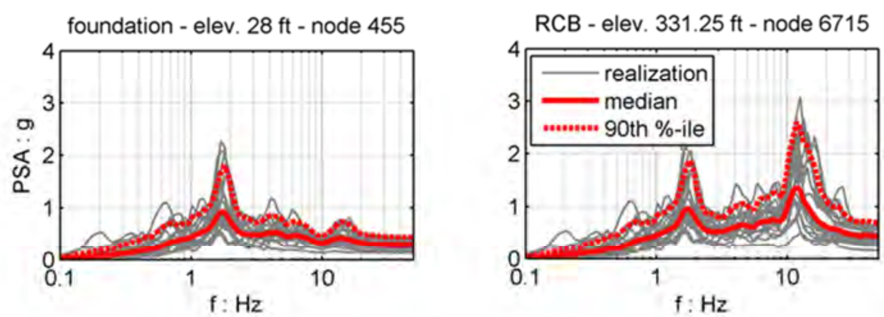


FIG. 10. Pseudo-acceleration floor response spectra at different locations of the isolated structure for the 20 ground motions (soil profile S01; Z direction)

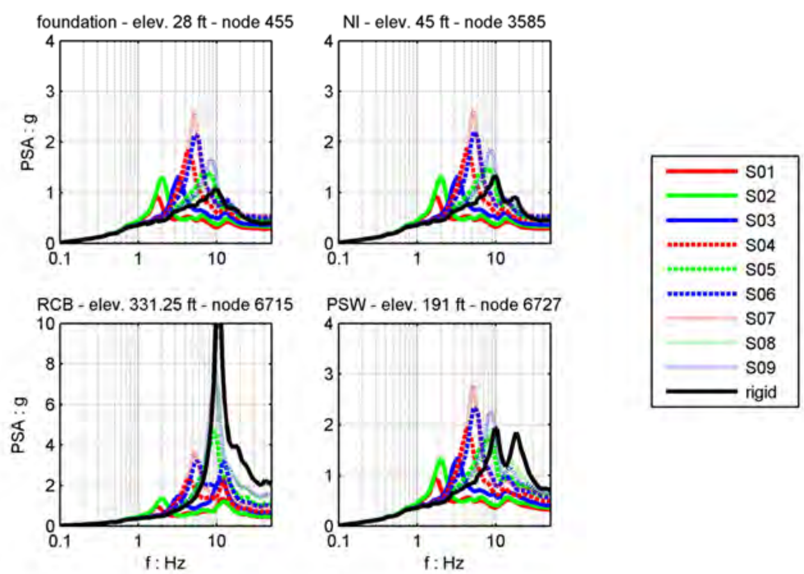


FIG. 11. Pseudo-acceleration floor response spectra at different locations of the isolated structure for the different foundation soil conditions (median spectra of the 20 ground motions; Z direction)

At this point, it should be noted that in the frequency-domain analysis the axial behavior of the bearings is assumed to be linear, with stiffness equal to the maximum compressive stiffness of the bearing ($K_{axial} = 2.06 \cdot 10^6$ kip/ft). The validity of the approximation used depends on the magnitude of the tensile forces acting on the bearings. As long as the bearings remain in the compressive regime, the approximation is expected to predict sufficiently accurate values. However, if there are intense tensile excursions, the stiffness will be inevitably overestimated and the rocking of the structure underestimated. This limitation can be overcome only by performing a nonlinear time-domain analysis.

CONCLUSIONS

The present work investigated the effects of SSI on the response of a base-isolated NPP and on the effectiveness of the isolation system. The frequency-domain analysis, modified to account for the nonlinear behavior of the isolators using the equivalent-linear method, was used for this purpose. Based on the analyses results, two main conclusions are drawn:

- The analyses show that the horizontal accelerations and the displacements on the structure are not sensitive to the soil profile properties (natural period, $V_{s,30}$). On the other hand, vertical response is significantly affected. Both vertical accelerations and axial forces are quite variable for different soil conditions. It should be noted that the analyses were performed with uncoupled horizontal and vertical response of the bearings. The conclusions drawn could be different, had coupled response been considered.
- With respect to the influence of SSI on the effectiveness of base isolation, it was shown that soil compliance minimally affects the effectiveness of seismic isolation.

However, the frequency-domain method for the SSI analysis of base-isolated structures has shortcomings such as the inability of simulating the nonlinear axial behavior of the bearings. Thus, while this method can be used for a preliminary study of the SSI effects on the response of a base-isolated NPP, a more rigorous nonlinear time-domain analysis is required for the design.

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