INVESTIGATING THE EFFECTS OF THE BASE RIGIDITY OF NUCLEAR POWER PLANT STRUCTURES THROUGH SEISMIC SOIL STRUCTURE INTERACTION ANALYSES

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ABSTRACT:

Recognized industry standards on seismic analysis of nuclear power plant structures allow the effect of mat flexibility for mat foundations to be neglected and state that SSI analysis with rigid base assumption may be performed to establish seismic responses. Considering that the flexibility of a mat foundation may be a function of its thickness together with the local site conditions, validity of this assumption in the industry standards is investigated in a sensitivity analysis approach. Firstly, a model is developed representing a double containment pressurized water reactor, a Russian VVER in this case, possessing thick external walls and a network of interconnected shear walls. Then, several site conditions representing a wide variety of sites ranging from soft soil to hard rock are adapted from the generic design of a well-accepted reactor design – Westinghouse's AP1000, to be used in the analyses. Couples consisting of these site conditions and structural model are then subjected a synthetically developed ground motion representing an earthquake that could pose a serious hazard for a nuclear power plant. All these steps are repeated by changing the base mat thickness of the generated model, in addition to a case where fully rigid base mat is defined. In the final step, floor response spectra obtained at different levels of the generated model – site condition couples are compared. Different site condition and base thickness cases that make it possible to consider the foundation as rigid or those that diverge from this assumption are outlined. Results are aimed to guide engineers and decision makers about when it is reasonable to ignore base flexibility and adopt analysis procedures that embrace this assumption or conversely when using analysis procedures that consider base flexibility should be the method of choice.

KEYWORDS: Nuclear Power Plants, Soil Structure Interaction, Rigidity, Flexibility, Base Mat, Seismic Design and Analysis of Structures, Seismic Design Codes

1. INTRODUCTION

The ground motion propagates through the soil media and its dynamic properties affect the seismic behavior of on the structures that it supports. This phenomenon is referred to as soil-structure interaction (SSI) in the literature.

Mainly two different approaches are used to calculate SSI effects, namely direct method and substructuring method. The substructuring method requires determination of the motions in the free-field surface soil deposit. The soil is assumed as horizontally stratified and seismic waves propagate vertically. Also, in this approach, it is commonly assumed that vertically propagating shear waves produce only horizontal translations and vertically propagating compressional waves produce only vertical motions. Hence, the free-field wave-propagation problem is reduced to one dimension.

Most commonly preferred methodology using the substructuring approach are SASSI (A System of Analysis of Soil-Structure Interaction) (Lysmer F. Ostandan, and C.C. Chin., 1999), CLASSI (Continuum Linear Analysis of Soil-Structure Interaction) (Wong and Luco, J.E., 1970) and hybrid methods (Johnson et al., 2010) (Tyapin, 2010). SASSI is formulated using the flexible boundary method and uses linear finite element modeling (FEM) and the frequency-domain methods. The subsurface soil is taken into account as horizontally layered, uniform, elastic or viscoelastic media lying over a uniform half-space. The nodes in the boundaries between the finite elements of structures and the soil are considered as common. All interconnected nodes are located at the floor layer interfaces with degrees of freedom.

ASCE 4-16 “Seismic Analysis of Safety-Related Nuclear Structures and Commentary” (ASCE, 2017), a US national standard developed by the American Society of Civil Engineers, is a United States Nuclear Regulatory Commission (US NRC) referenced code used in the seismic analysis of safety-related nuclear structures. This standard, which also globally acclaimed, defines the requirements on soil-structure interaction modeling and analysis. In article 5.1.6 of the standard, it is stated that “The effect of flexibility of mat foundations and exterior embedded walls of the structure need not be considered in the SSI (soil structure interaction) analysis to develop overall SSI seismic responses”. This approach is adopted by numerous researchers and software developers around the globe, as in the methods other than SASSI, the main assumption is that the foundation behavior is rigid.

In this paper, the extent of the validity of this assumption, that the base mat can be considered as rigid for seismic SSI analyses, is investigated in a sensitivity analysis approach. Five different site conditions ranging from soft soil to hard rock sites are adapted from the generic design documentation of Westinghouse AP1000 design. The soil nonlinearity is taken into consideration by using an equivalent linear model with dynamic high-strain properties of the soil. A synthetic ground motion representing an earthquake with 10000 year return period is incorporated into the SSI calculations. The structural model is chosen as a Russian-type pressurized water reactor with double containment called VVER. 3D model of this structures is done using SAP2000 software and then imported to ACS SASSI software. Then, dynamic soil-structure interaction analyses are performed in frequency domain using ACS SASSI software. All these steps are repeated by changing the base mat thickness of the SASSI model, in addition to a case where a massless rigid foundation mat is defined. Base mat thicknesses of 1m, 2m, 4m, and 8m are considered along with rigid foundation. For comparison purposes, floor response spectra (FRS) are generated at certain regions in each case.

In the preceding chapters, site profiles considered in the study, generation of the earthquake ground motion to be used in the SSI analyses and the developed structural model are described. Comparison of FRS generated at specific parts of the reactor building is presented in the analysis and results chapter. The discussion of results is presented as the conclusions.

2. SITE CONDITIONS

Local site conditions play a significant role in the SSI response of structures (Chen, 2006). In order to be able to compare the effect that different site conditions may have on the SSI response together with changing base mat thicknesses and rigidity, a comprehensive set, ranging from a soft soil site to a hard rock site, is needed to be considered. For this purpose, a readily developed set, used in the combined license application of Westinghouse AP1000 reactor to the US NRC is adopted (Westinghouse, 2011). In an actual design case, performance of site response analyses, i.e. subjecting the initial soil profiles to ground motions developed to be compatible with the seismic hazard at the site and obtaining high-strain soil profiles by means of modulus reduction and damping curves, would be necessary. However, since the aim of this study is the assessment of the effect of base mat rigidity rather than the effect of seismic hazard or site conditions, high strain profiles used for AP1000 are directly imported. The shear wave velocity comparison graphs for initial and high strain cases, which are also used in this study, are provided in Figure 1:

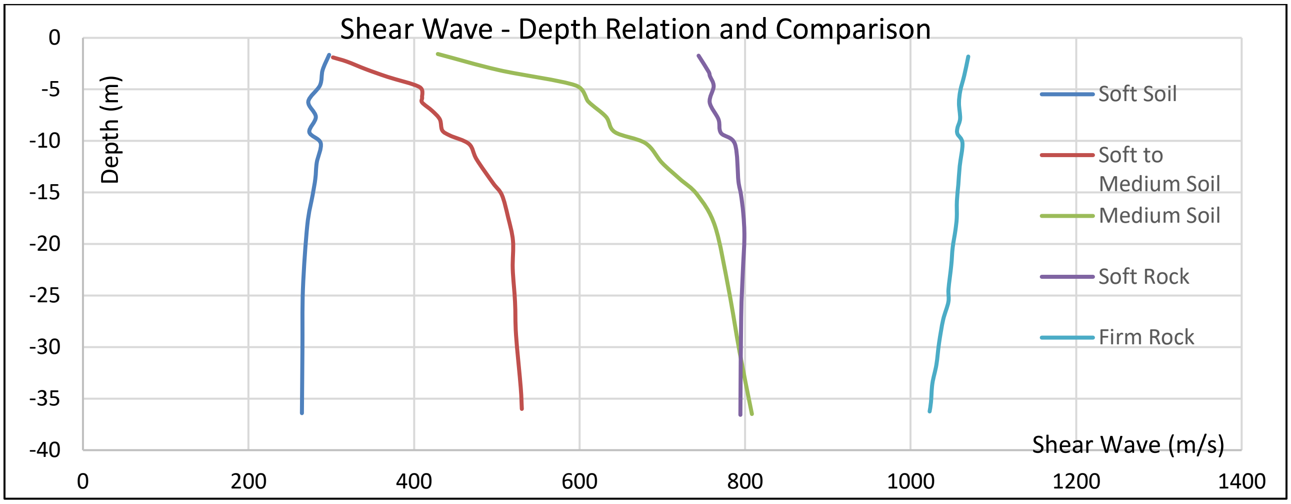


Figure 1: High-Strain soil profiles used in the SSI analyses (Westinghouse, 2011)

Consequently, five soil profile sets are used for the SSI analyses:

- Site 1: Soft Soil Site
- Site 2: Soft to Medium Soil Site
- Site 3: Medium Soil Site
- Site 4: Soft Rock Site
- Site 5: Firm Rock Site

3. GROUND MOTION

The severity of seismic hazard is one of the most important site selection criteria for NPP's, as it affects the investment costs (Algohary and Aly, 2018) directly. Therefore, for most cases hazardous areas are avoided altogether. At the same time, a significant level of seismic hazard is considered necessary to be able assess the base mat rigidity in the case of an earthquake. Consequently, in order to avoid having unrealistic results by using seismic hazard from a random location, data from a potential nuclear power plant site, namely Igneada site located in the Tekirdag province of Turkey (WNA, 2018) is employed.

Next, for the Igneada site, seismic hazard data in the form of return-period-specific design response spectra were obtained from European Facilities for Earthquake Hazard & Risk (EFEHR) project website. EFEHR project provides seismic hazard curves for up to 1% exceedance in 50 years, i.e. 4975 year return period. However, in the evaluation of safety classified items within an NPP a probability of exceedance in the range of 10^{-4} to 10^{-5} per reactor per year are considered (IAEA, 2003). For the purposes of this study, an approximation of this value is considered sufficient and thus the procedure in Eurocode 8 was adopted to extrapolate 4975 year return period earthquake response spectrum to the generate design response spectrum for a 10000 year return period earthquake.

Synthetic earthquake acceleration time histories that are compatible with the seismic design response spectrum obtained in the previous step are generated by making use of the EQUAKE module in ACS SASSI (GP Technologies Inc., 2014) software. This module uses both frequency and time domain matching algorithms to simulate acceleration histories with random phases based on "seed records" as described in ASCE 4-16 standard. In the case of this study, a record among the Pacific Earthquake Engineering Research Center's (PEER) NGA WEST 2 database that matched best with the generated design response spectrum was employed as the "seed record”. The generated design response spectrum with 10000 year return period, along with the matched response spectrum of the synthetic earthquake record, is provided in Figure 2 below:

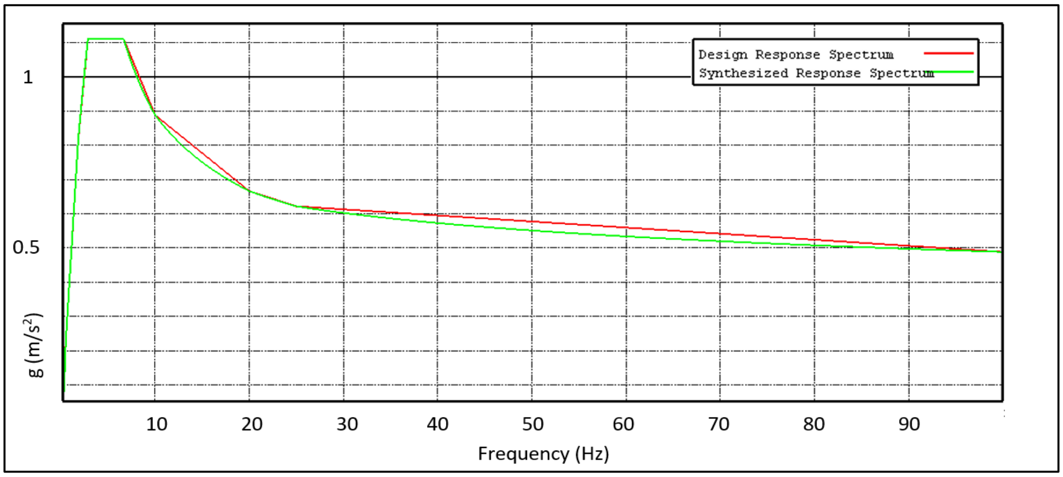


Figure 2: Design response spectrum and response spectrum of the generated record

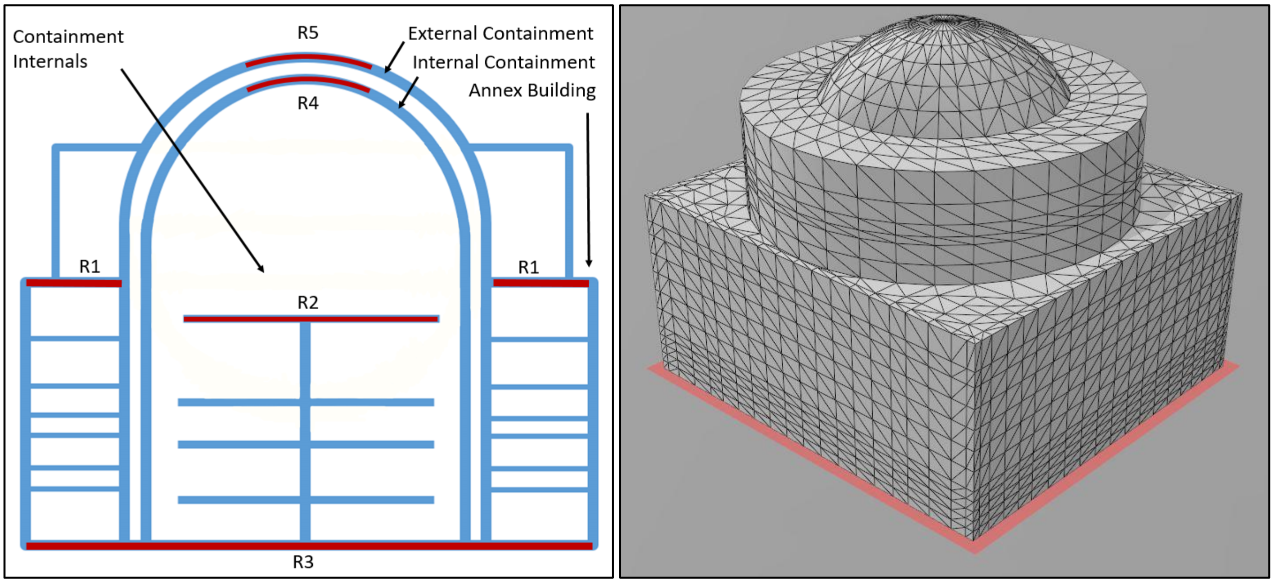
Generated earthquake acceleration time history record is then used in the soil structure interaction analyses to generate the floor response spectra (FRS).

4. STRUCTURAL MODEL

The NPP reactor building modeled for this study is adapted from a generic Russian VVER-type reactor building designed by Gidropress (Gidropress, 2011). This particular design features a double containment system: The external containment is designed as reinforced concrete and aims to provide protection from external threats, such as explosions, missiles and aircraft crashes. The internal containment houses the reactor core, the spent fuel pool, steam generators and the rest of the reactor coolant system collectively referred to as the containment internals. The inner containment is designed as prestressed concrete to cope with high temperatures and pressures that may arise in the case of an emergency. Both containment structures are cylindrical in shape with a hemispherical dome. The containment structures are separated from each other by an annulus which is kept at a low pressure to collect any leaking gas if such a condition arises. The outer containment is also enclosed by the annex building that house the auxiliary systems and feature thick interconnected concrete shear walls. The defining dimensions of the reactor building are as follows:

- Internal containment internal diameter: 44m
- Internal containment height at the top of the dome: 61.7m
- Internal containment wall thickness: 1.2m
- External containment internal diameter: 50.8m
- External containment height at the top of the dome: 65.4m
- External containment wall thickness: 1.5m
- Annulus space: 2.2m

A schematic view of the reactor building is provided in Figure 3 (a). The regions highlighted on the sketch are the critical areas where FRS comparisons are made in the Chapter 5. R1 corresponds to the annex building, R2 to the containment internals, R3 to the base mat, R4 and R5 to the internal and external containment building domes, respectively.



(a) (b)

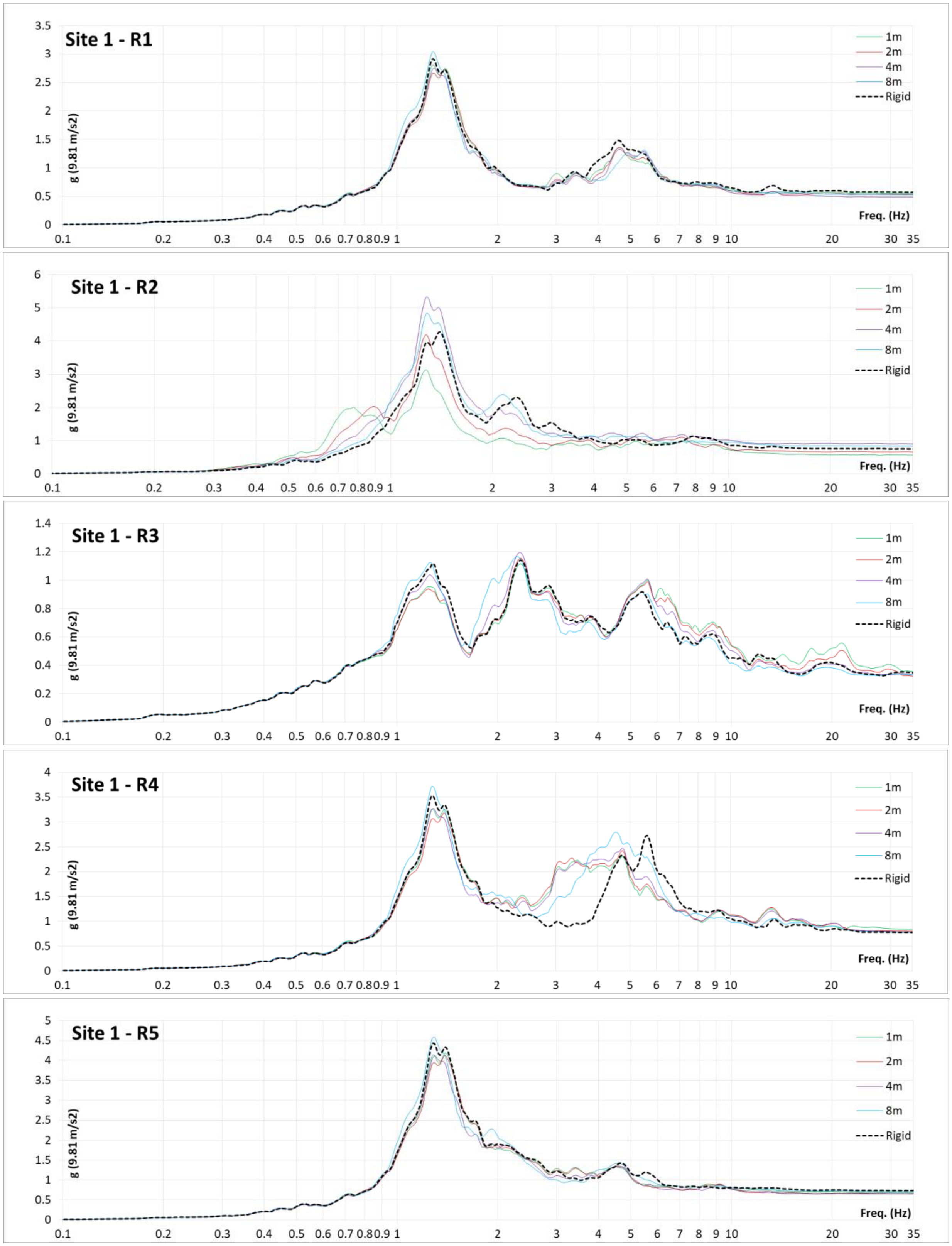
Figure 3: Schematic view of the reactor building along with the selected regions (a) and 3D view of the generated structural model (b)

The structural model used in the SSI analyses is firstly developed in SAP2000 software (Computers and Structures Inc., 2014) and then imported to ACS SASSI software. In this model, mass, shell and beam elements are utilized. Thick shell elements are used to represent the shear walls and slabs while mass elements are used for representing the heavy components. Occasional rigid links are modeled using beam elements. Consequently the model consisted of 6272 nodes and 9058 elements. The analysis model can be seen in Figure 3 (b).

Element rigidities and damping ratios are adjusted based on the ASCE 43-05 (ASCE, 2005) standard. During high intensity earthquakes, due to cracking of concrete, stiffness of structural elements are reduced and damping ratios are increased. For linear elastic models, this phenomenon is modeled by using effective stiffness and damping ratios found in the standard. Consequently, as per the requirements of the standard, for all materials, half of the actual elasticity modulus values and corresponding damping ratios are employed in the analyses.

5. ANALYSES AND RESULTS

SSI analyses are performed in ACS SASSI software using the generated soil profiles, ground motion and the structural model. In the analyses, base mat thicknesses of 1m, 2m, 4m, and 8m are considered along with a control case where the base mat is defined as completely rigid. For each case, FRS are generated at several nodes located at the regions of interest – they are then enveloped to obtain the response of that region. The FRS results for 5 different soil profiles for all 5 base mat thickness cases at 5 different regions are provided in the preceding Figures 4, 5, 6, 7 and 8:



(a)

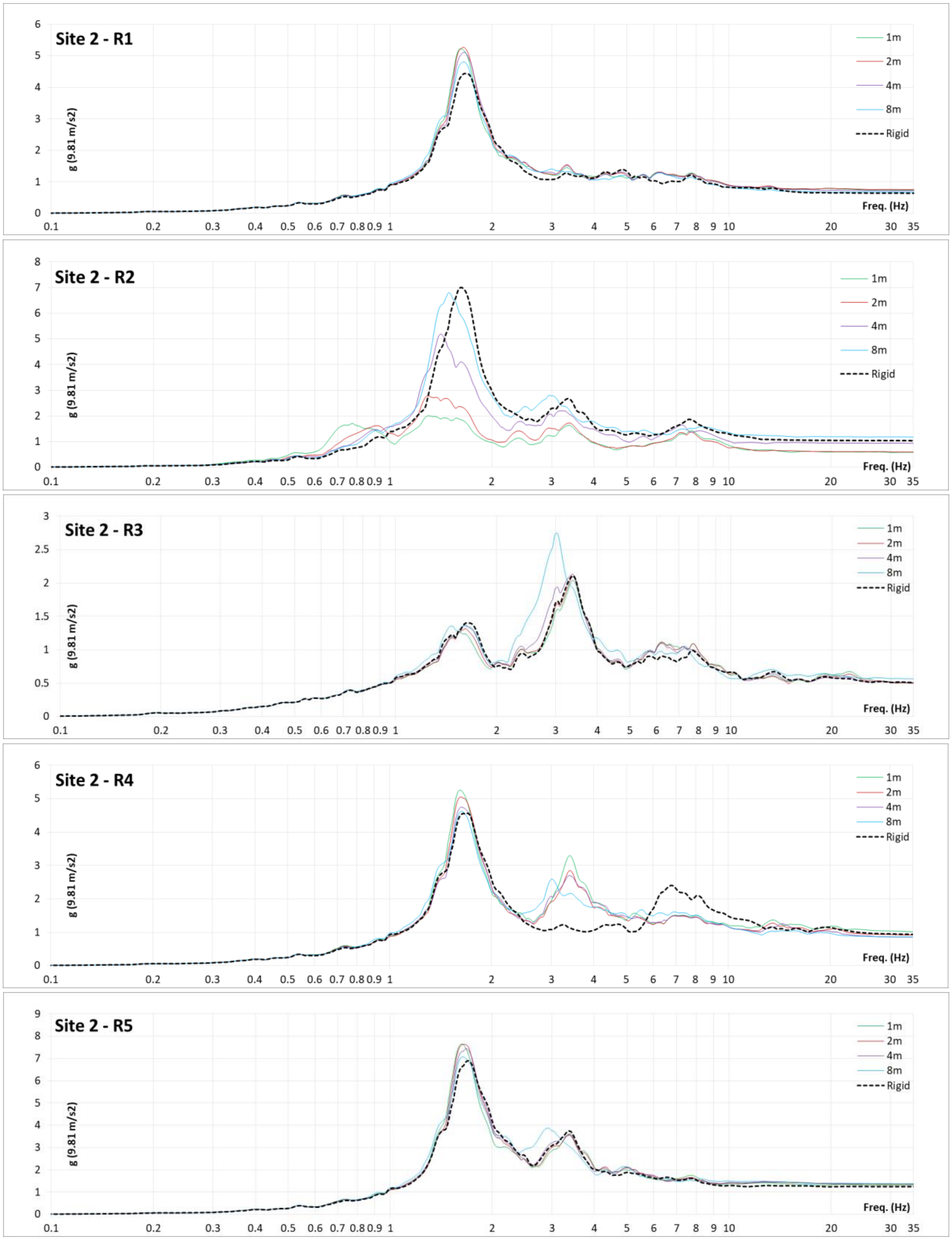
(b)

(c)

(d)

(e)

Figure 4: FRS comparisons at five different regions for soft soil site case



(a)
(b)
(c)
(d)
(e)

Figure 5: FRS comparisons at five different regions for soft to medium soil site case

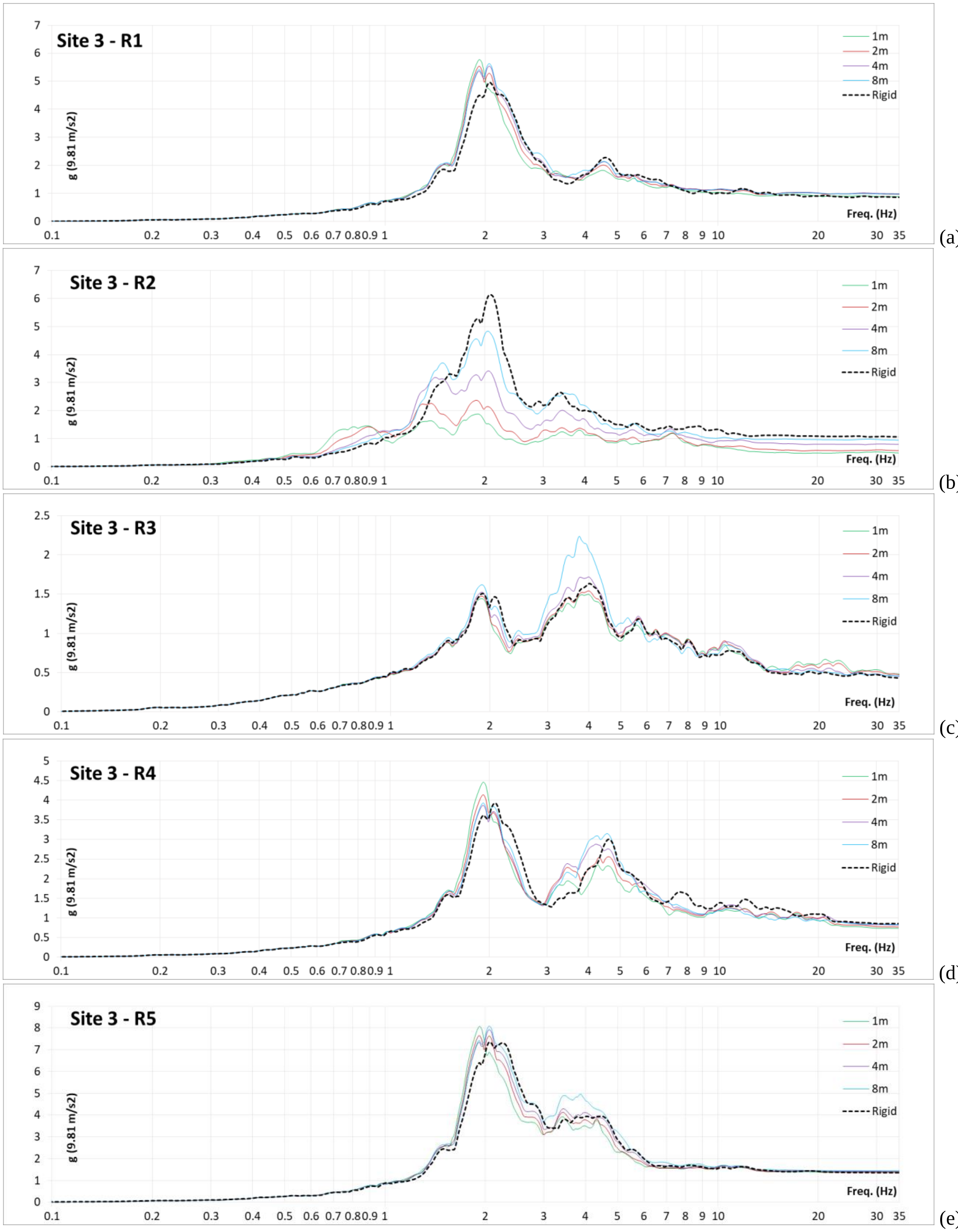


Figure 6: FRS comparisons at five different regions for medium soil site case

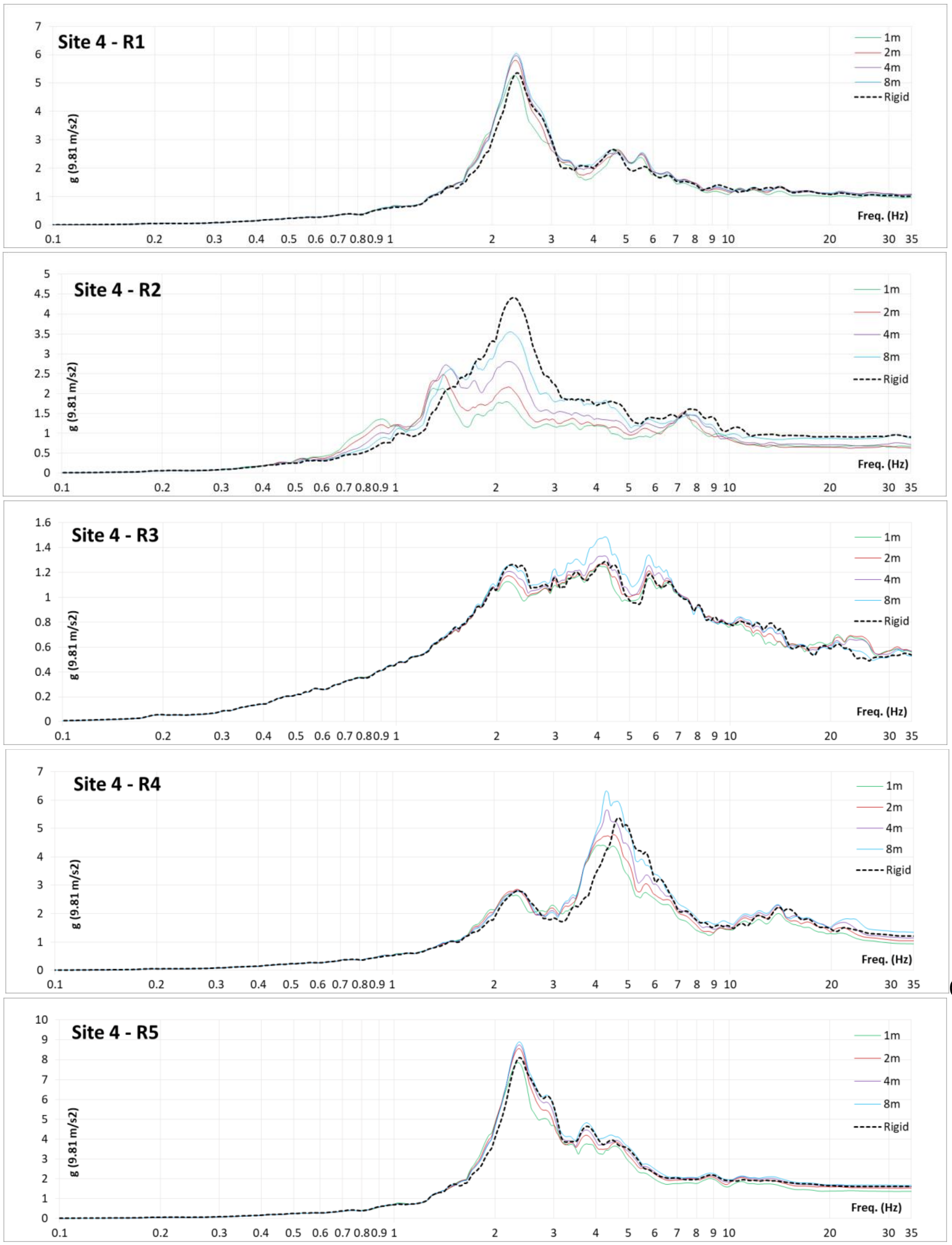
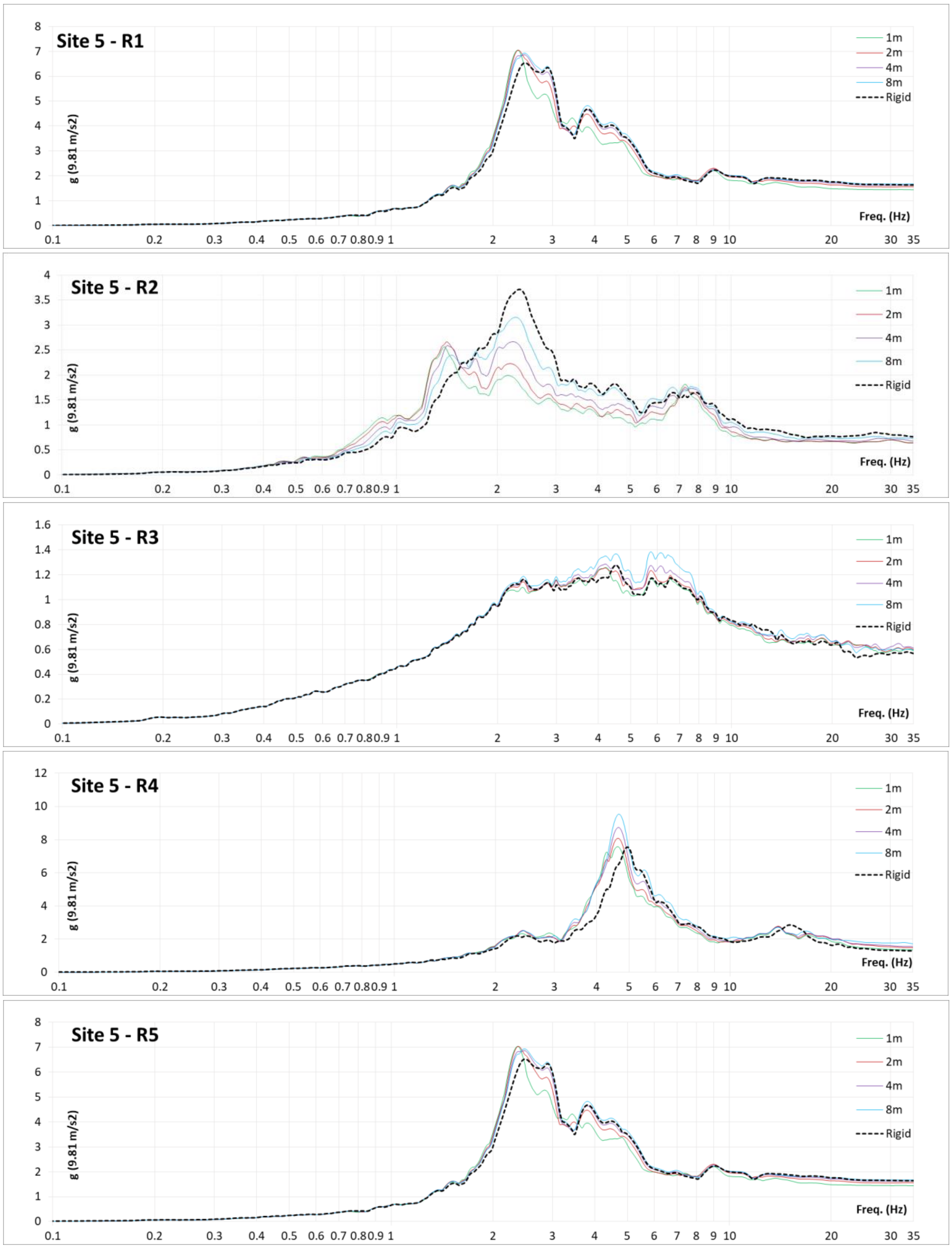


Figure 7: FRS comparisons at five different regions for soft rock site case



(a)

(b)

(c)

(d)

(e)

Figure 8: FRS comparisons at five different regions for firm rock site case

Evaluating the FRS graphs, as a general result it is possible to say that over almost all FRS plots, phase shifts can be observed, which can be attributed to the higher stiffness of the rigid base model. Moreover, the FRS generated under the rigid base mat condition is surpassed by elastic base mat cases for most of the soil conditions and regions. Most significantly, it can be seen that the response of the base mat also affects the response of the internal containment building response in the softer soil cases in the 2-5 Hz range. While this behavior is well captured in the elastic base mat models, the rigid base model fails to predict this response. Conversely, in the rock site cases, internal containment response is over predicted by the rigid base model. This may be attributed to the internal containment's natural frequency with the base mat being close to that of the soils'. Closer response obtained by the 8 m base mat model may support this assumption. The difference between the elastic and rigid cases are less pronounced for the annex building and outer containment zenith regions, also considering the stiffness contribution of shear walls in this part of the reactor building. For these regions, even though elastic base mat responses still surpass that of the rigid base mat case or there are some phase shifts observed, difference is not relatively significant.

6. CONCLUSIONS

In this study, effect of the base mat thickness and rigidity on the reactor building of an NPP in the Seismic SSI case is evaluated by means of a parametrical study that considers different site conditions, base mat thicknesses, full rigidity and different regions of the structure. In order to assess this effect, 5 soil conditions from the literature are adopted and a synthetic ground motion is generated for a 10000 year return period earthquake at a candidate site in Turkey. SSI analyses are then carried out for a generic VVER reactor building model generated specifically for this study. Obtained results are tabulated in Table 1.

Table 1. Tabulated results about the rigid base mat model responses with respect to elastic model responses

	S1 (Soft Soil)	**S2 (Soft to Med.)**	**S3 (Medium Soil)**	**S4 (Soft Rock)**	**S5 (Firm Rock)**
R1 (Annex)	Lower Peak	Lower Peak	Lower Peak	Lower Peak	Lower Peak
R5 (O. Cont.)	Lower Peak	Lower Peak & Phase Shift	Multiple Lower Peaks	Lower Peak	Lower Peak
R3 (B. Mat)	Lower Peak @ High Freq.	Lower Peak @ High Freq. & Uncaptured Peak	Lower Peak @ High Freq. & Uncaptured Peak	Lower Peak @ High & Mid. Freq.	Lower Peak @ High & Mid. Freq..
R2 (C. Inter)	Lower Peak @ Low Freq.	Lower Peak @ Low Freq.	Lower Peak @ Low Freq. & Over Predicted Mid. Freq. Peak	Lower Peak @ Low Freq. & Over Predicted Mid. Freq. Peak.	Lower Peak @ Low Freq. & Over Predicted Mid. Freq. Peak
R4 (I. Cont.)	Missing Peak	Missing Peak	Lower Peak @ Mid. Freq. & Phase Shift	Lower Peak @ Mid. Freq. & Phase Shift	Lower Peak @ Mid. Freq. & Phase Shift

Results have clearly shown that adopting a rigid base assumption in the seismic SSI analyses can lead to both over and under estimation of the responses. The amount of this over and under estimation is dependent on the site conditions and the region of the building considered. Consequently, abandonment of the adoption of a rigid base mat assumption is strongly suggested and performance of comprehensive sensitivity analyses for the SSI analyses at the design phase is recommended.

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