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A Case Study on Floor Response Spectra Variance of Detailed Model of Auxiliary Building

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ABSTRACT

Floor response spectrum (FRS) or in-structure response spectrum is often used to calculate seismic demands applied to secondary structures installed inside nuclear power plants (NPP). In the case of NPP structures, it is customary to use a lumped-mass stick model (LMSM) to simplify all responses within the floor. However, since there is a difference between individual responses depending on the location, in this study, FRS was generated and compared through the 3-D finite element analysis of the NPP auxiliary building (AB). As a result, it was confirmed that significant variability existed even though it was the same floor.

INTRODUCTION

Conventionally seismic analysis of NPP structures was conducted using LMSMs, as it is computationally efficient. They would be sophisticatedly adjusted to exhibit similar dynamic properties to those of the detailed finite element model (FEM) so that both results show reasonably close agreement. With the rapid development of computer technology though, the use of FEM is becoming commonplace.

Damolini et al. (2019) compared LMSM and FEM in terms of FRS, which is one of the important results from the seismic analysis of NPP, required for seismic analysis of secondary systems housed in NPP structures. The authors reported that in general, the FRS of LMSM and the averaged FRS from the FEM showed good agreement, especially for the horizontal direction. Nonetheless, a variance within the same floor is significant enough for consideration.

However, the averaged FRS may deviate from the actual response experienced by the secondary structures. Herein a case study of the representative AB is performed to show a difference between the FRS generated in 3-D FEM and LMSM. The potential consequences of this variance on fragility analysis are discussed.

CASE STUDY

Structure Model

A target NPP structure is the AB where numerous safety-related structures, systems, and components (SSCs) are installed. The AB is often located in the vicinity of a reactor containment building (RCB), in this case, the AB wraps around it. The FEM of the AB was generated using commercial finite element analysis software Ansys. An overview of the model is shown in

Figure 1. Two buildings, the AB and the RCB share an identical basemat or a nuclear island, while a minimum of a 2-inch seismic gap separates them above the base. The two buildings are thought to be structurally independent with this condition, allowing the RCB to be omitted from the modeling. It can be observed in
Figure 1 that the place where the RCB should be located is empty.

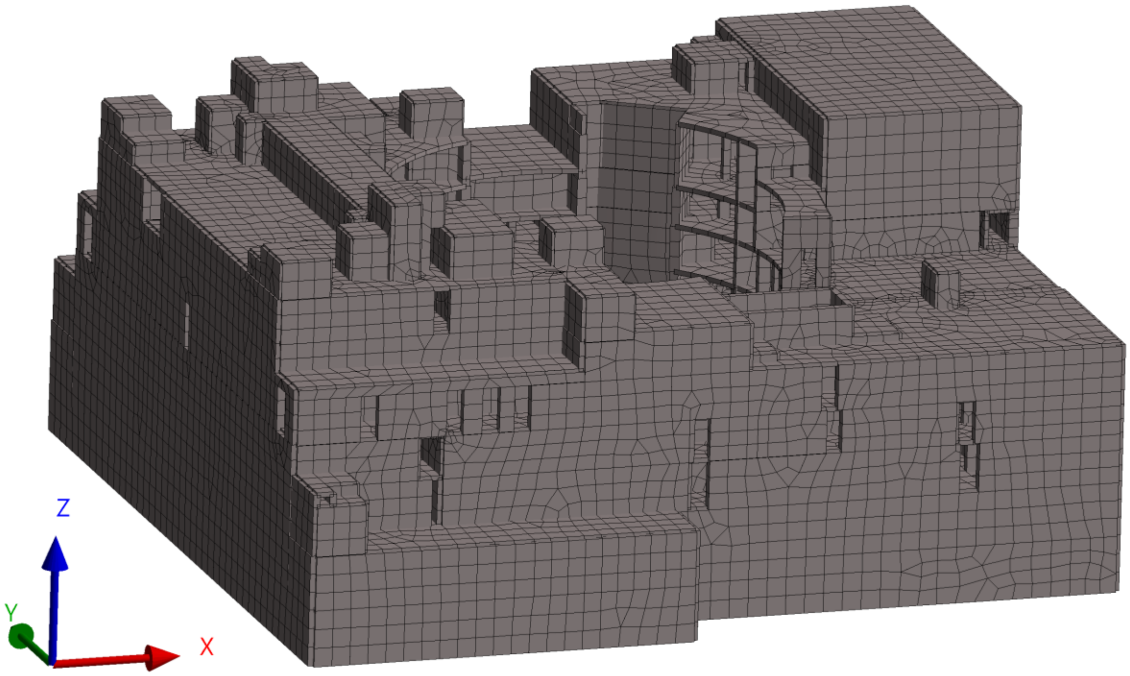

Figure 1. The AB Ansys Model Overview

Properties of the AB model are determined based on ASCE/SEI 4-16 (2017) and summarized in Table 1. The model mainly comprises shell elements (Shell181) and beam elements (Beam188). The former was used to model walls and slabs, and the latter for columns. Young's modulus was calculated based on the 40 MPa compressive strength of concrete. No reinforcement bars were considered in the model, for linear elastic dynamic analysis is performed. For the slabs, material density was modified to account for live loads. Also, mass for equipment was added as a point mass.

For a Seismic category I structure as the AB, soil-structure interaction (SSI) analysis is required. In the present study, however, fixed-base support is applied, assuming a rock foundation beneath the AB. ASCE/SEI 4-16 (2017) allows the fixed-base support for the rock foundation as the SSI effect is minimal.

Instead of developing the LMSM, the rigid diaphragm was applied to the FEM as an alternative. A copy of the AB model shown in
Figure 1 was adjusted so that the seismic responses would approximate those of the LMSM. While maintaining other properties, the thickness of the slab was reduced and the elastic modulus of the slab was increased. To preserve the identical mass of the slabs, their density was increased to compensate a reduction in volume.

Table 1: Properties of the numerical modeling

Property	Value
Element Type	Wall: 4-node shell element (Shell181) Column: 3D 2-node beam element (Beam188) Slab: 4-node shell element (Shell181)
Element Size	Wall: 3m x 3m Column: 2m Slab: 3m x 3m
Boundary Condition	Fixed support at the base

Time Histories

In this study, NUREG/CR-0098 (1978) median spectrum is used for the seismic response analysis. Assuming reference earthquake as beyond design basis earthquake, peak ground acceleration (PGA) of the spectrum was scaled to 0.6 g, which is double of safe shutdown earthquake level.

Thirty artificial records matched to the target spectrum were then generated. By courtesy of Professor Ji-Hun Park of Incheon National University (personal communication, July 14, 2021), the records were prepared. Seed motions satisfying two criteria 1) magnitude between 6 and 7; 2) distance to epicenter shorter than 200 km, were selected from the records listed in NUREG/CR-6728 (2001).

STRUCTURE RESPONSE ANALYSIS

Target Floor Plan

Figure 2 shows a plan of elevation 137’-6” floor at the AB. Total 1513 nodes were created in this slab and FRS were generated at each location. Previously prepared ground motions were used as acceleration inputs and floor acceleration records were acquired as the structure responses. Given the tri-directional accelerograms, these were then used as input for a series of single-degree of freedom (SDOF) oscillators to render the FRS. A damping ratio of 5% was used for the entire FRS.

The floor plan was divided into quadrants. This is because the LMSM of the AB has four main branches each representing the quadrants. The RCB is often represented by LMSM with one branch, as it is axisymmetric. However, for buildings with asymmetry and large openings, such as the AB, it would be impossible to substitute with LMSM in the same manner. Hence the results to follow were compared within each quadrant.

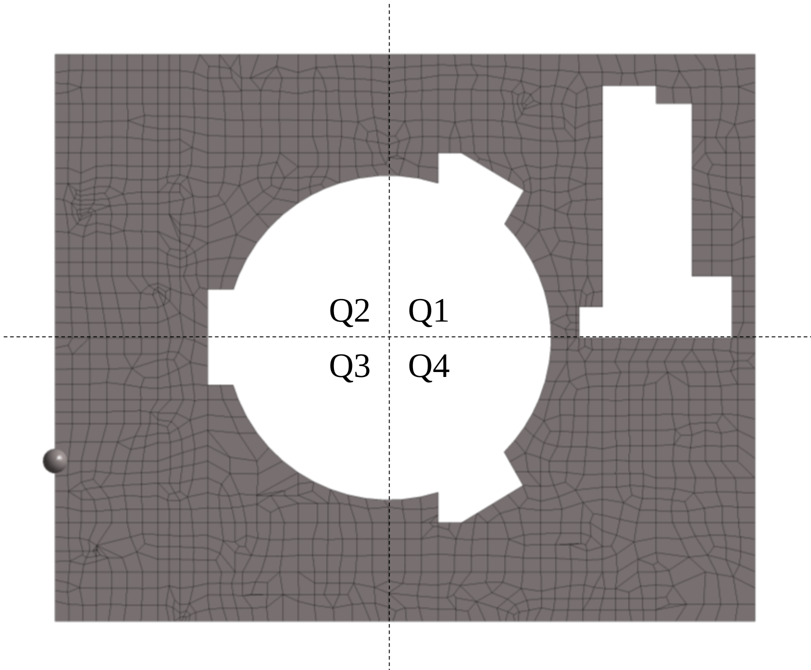

Figure 2. Plan of EL.137'-6" floor and quadrants

Spatial Variation of FRS

Figure 3-6 show the X and Y direction individual and average FRS generated at the FEM and the FEM with the rigid diaphragm assumption. Hereinafter, the latter is referred to as the LMSM as the purpose of the rigid diaphragm adjustment was to approximately calculate the seismic responses of the real LMSM. The individual FRS are plotted with grey lines and the average FRS with black lines. Although the individual FRS are shown in Figure 4 and Figure 6, for the real LMSM only the black lines may be available as the results of the seismic response analysis.

The individual FRS of the LMSM are closely spaced near the average FRS. This holds around the first peak of the FRS corresponding to the first X directional mode. As it is a translational mode, if the slab behaves as a rigid body, the responses at each node must be close to identical. However, a width of the grey lines expands at the second peak near 10 Hz. This is mainly due to torsional mode which the responses at extreme ends of the floor are greater than those closer to the center of rigidity.

The individual FRS of the FEM show comparatively wide variance within each quadrant as shown in Figure 3 and Figure 5. Compared to Figure 4 and Figure 6, an overall width of the grey lines is thicker indicating the variation of spectral accelerations of the quadrant for a given frequency. For instance, at 10 Hz the LMSM FRS gives the spectral acceleration approximately 2 g (Figure 4), while the individual FRS of the FEM ranges from 1 g to 6 g (Figure 3).

For the Z-direction the LMSM FRS were unavailable therefore only the FEM FRS were shown in Figure 7. Even greater magnitude variabilities within each quadrant were observed. Note that zero period accelerations of several FRS are irregularly large. These values were found at the circumference of the central opening, where it is modeled as a free end. Even if these anomalies are removed, the variance is still significant.

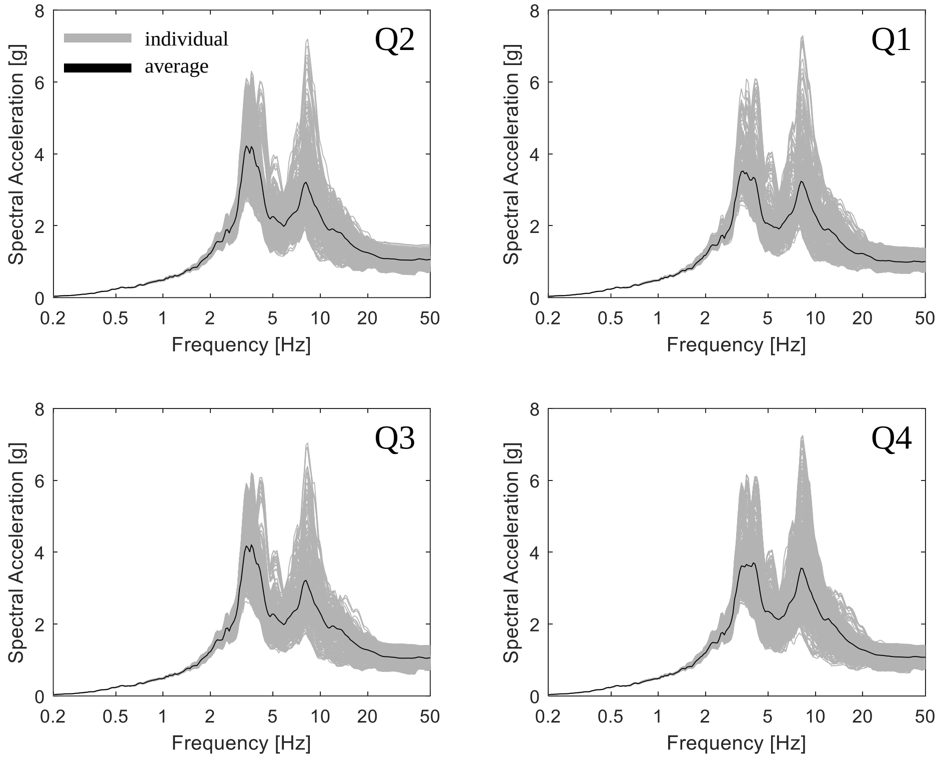

Figure 3. X-dir. Average and Individual FRS by the FEM

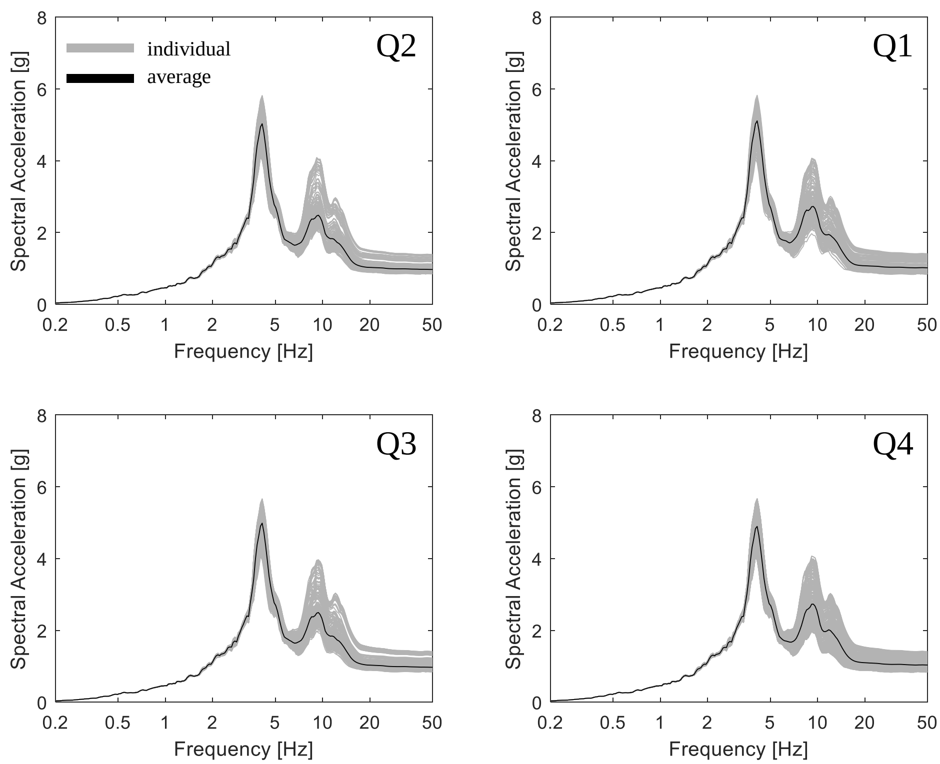

Figure 4. X-dir. Average and Individual FRS by the FEM with Rigid Diaphragm

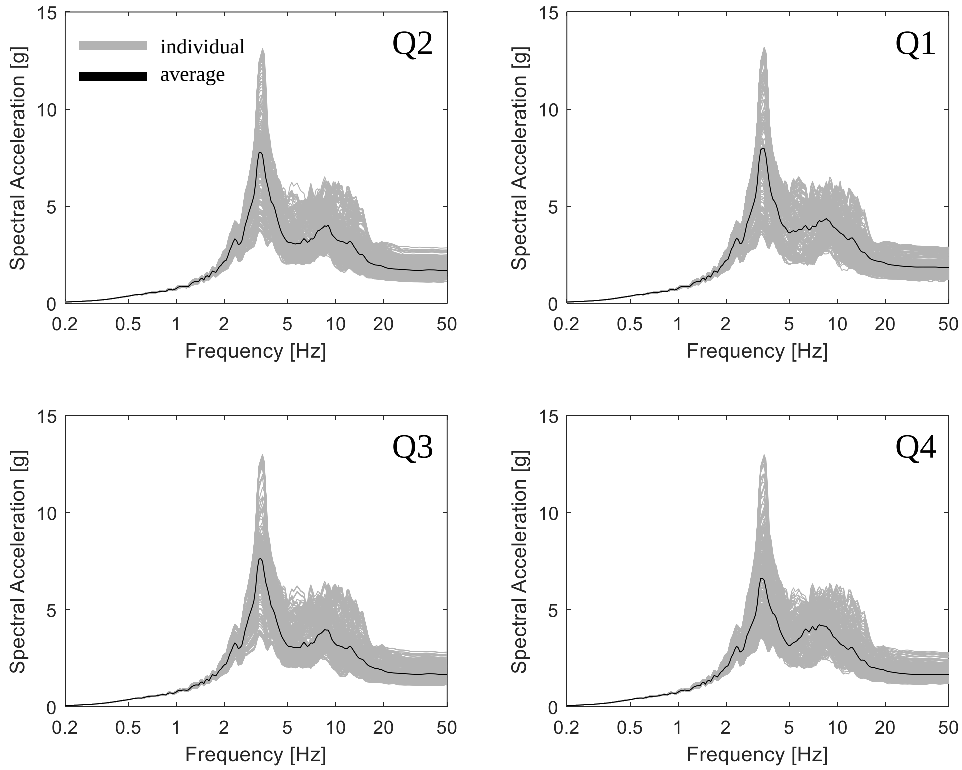

Figure 5. Y-dir. Average and Individual FRS by the FEM

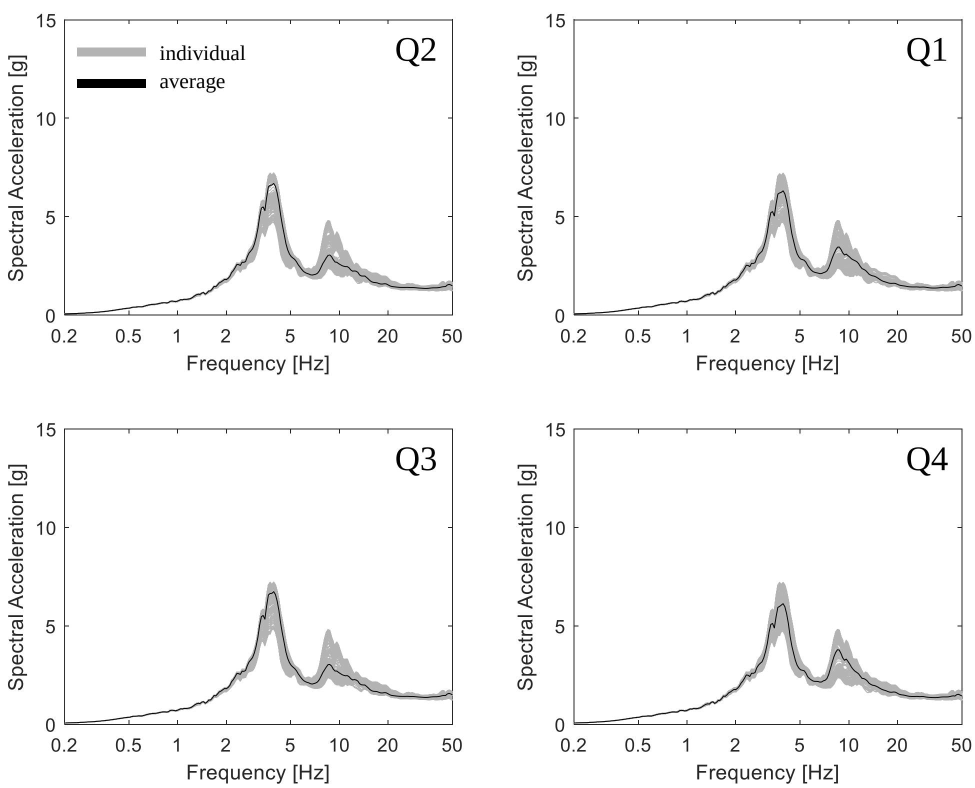

Figure 6. Y-dir. Average and Individual FRS by the FEM with Rigid Diaphragm

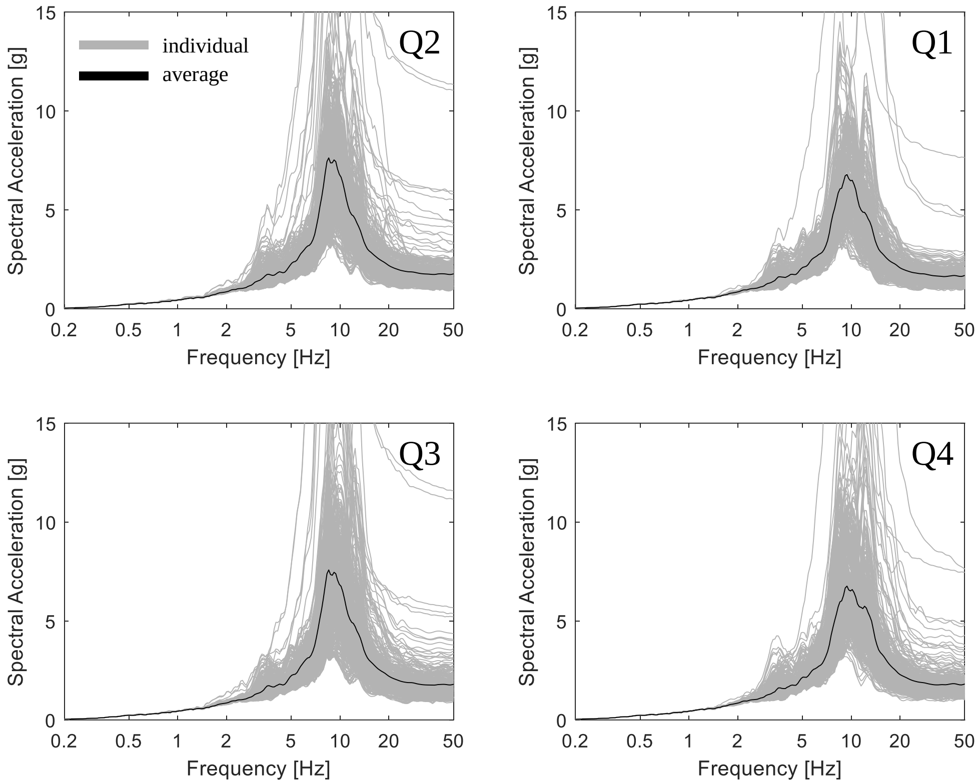

Figure 7. Z-dir. Average and Individual FRS by the FEM

While the above figures show significant variations exist within a floor, spatial information of individual FRS is excluded. Figure 8 shows peak spectral accelerations for X, Y, and Z directions. Circles indicate the locations where the FRS were generated and their color represents the magnitudes. For the two horizontal directions, a global trend was observed. Assuming the center of the opening as an origin, the X directional spectral accelerations increase as the Y coordinates approach the origin. In the same manner, the Y directional spectral accelerations are greater near the origin. This trend is due to the existence of the opening. In ordinary buildings, the rigid diaphragm assumption is often applied and is acceptable partially because the area of openings is limited. However, the opening area of the AB is 19 % of the gross floor area, large enough to decrease the in-plane stiffness of the slabs near the opening.

The responses of the vertical direction exhibited different tendencies compared to those of the horizontal directions. As shown in Figure 8, localized responses were observed in Q2 and Q3. For the given frequency, 9.41 Hz, the SDOF oscillators were greatly excited in those two areas, resonating with the slabs. This is only one example, and localized peak responses may occur elsewhere depending on the frequency. As previously mentioned, extraordinarily high spectral accelerations were identified around the circumference of the opening. These may have been overestimated due to the absence of the RCB.

Discussion

It can be inferred from the aforementioned results that the FRS by the LMSM may cause errors in a seismic fragility analysis. In a framework of the seismic fragility analysis, conditional probability of failure so-called fragility is assessed with the capacity of the SSC and the seismic demand imposed on it (Grant et al., 2018). To perform equipment seismic fragility analysis, for instance, the FRS is utilized to calculate the seismic demand. Using the LMSM in this process could either overestimate or underestimate the seismic capacity of the equipment. Both cases must be avoided as the former jeopardizes the equipment in case of a severe accident and the latter requires unnecessary reinforcement.

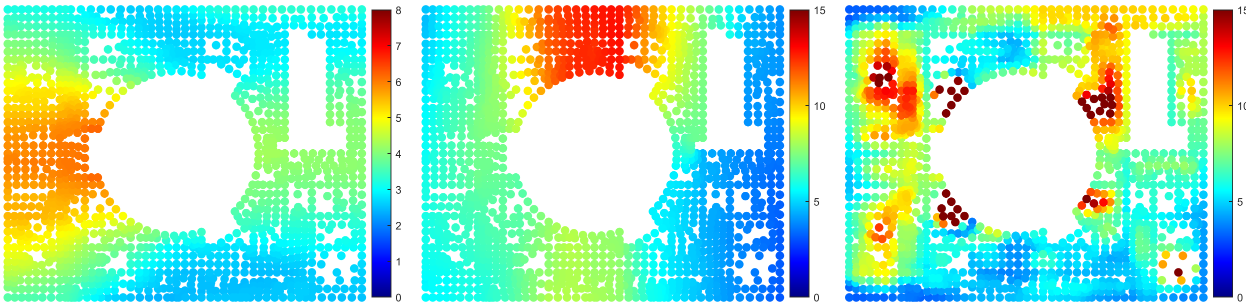

Figure 8. Peak Spectral Accelerations of X, Y, and Z Direction

CONCLUSIONS

A case study of the seismic response analysis was performed with a 3-D FEM of an AB and a FEM simulating the LMSM. The representative AB is asymmetric and has a large opening at the center of the building. The results of the two models were compared in terms of the FRS. It was confirmed that despite the reasonable agreement between the average FRS of the two models, the spatial variance of the individual FRS of the FEM is significant. In addition, it was discussed that caution is needed because this variation can lead to undesirable results in the seismic fragility of the SSCs.

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