Standardizing nuclear power plants through seismic isolation

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Abstract

Recent studies have showcased great potential of seismic isolation to enable standardized designs of nuclear power plants across multiple sites, achieving substantial reductions in both seismic demands and capital costs. This study attempts to further generalize the standardization framework across wider regions and vendors. There are two major issues at play: varying hazards across locations and varying requirements from vendors. To standardize the seismic hazards across varying locations, the response spectra for 7044 United States and Canadian sites are tiered into six site groups, with an envelope response spectrum developed for each group. Base isolation is implemented to mitigate the seismic hazards, and the isolation system, along with the upper reactor building, is designed based on the envelope response spectrum for the site group. To accommodate the requirements from varying vendors, an upper bound on the equipment weight is employed for the design of the reactor building envelope and its isolation system without presupposing specific equipment locations or dynamics, allowing vendors to develop their own installation approaches. Again, base isolation can be utilized to lessen the effects of the changes in equipment masses and frequencies on building demands, while mitigating hazards to the equipment itself. A case study is presented to validate the feasibility of the present standardization approach. It is demonstrated that a base-isolated reactor building, designed for a specific site group, can be directly deployed at a real site within that group, without requiring additional design checks. This is true even with the installation of different equipment properties.

Keywords: nuclear power plant; seismic isolation; standardized design; seismic hazard; response spectrum

1 Introduction

Despite advances in nuclear technology, the construction of new nuclear power plants (NPPs) in the United States has remained limited in recent decades. A key barrier to broader deployment of NPPs is the lack of standardization, which drives up both the capital cost and the levelized cost of energy. Seismic design is a major impediment to standardization due to the site-specific nature of seismic hazards and their large impact on the structural design of NPPs. As a result, each new NPP tends to become a high-cost and time-consuming First-of-a-Kind (FoaK) project, which requires extensive site-specific analysis, design, review, licensing, and construction. A promising solution is to develop a limited number of standardized designs that can accommodate a range of seismic hazards, enabling cost-sharing across multiple NPP units, i.e., transitioning from FoaK to Nth-of-a-Kind (NoaK) projects.

In recent years, the merit of standardization has been realized within the nuclear community, and seismic isolation has been increasingly recognized as a pathway to achieve standardized design of NPPs across different sites (Whittaker, 2023). Seismic isolation is a mature structural technology that can be utilized to reduce the accelerations and story drifts/forces of the superstructure albeit at the cost of increased displacements in the flexible isolation layer (Naeim and Kelly, 1999). The benefit of seismic isolation for reducing earthquake demands in NPPs, and more significantly, in nuclear equipment, has been acknowledged for some time (Tajirian et al., 1990; Huang et al., 2007; Whittaker et al., 2018). However, there is still limited research focused on its use for standardized design. Parsi et al. (2022) investigated the possibility of applying a standardized advanced reactor design across four sites with varying seismic hazard. They found that a fixed-base reactor building designed for the lowest-seismicity site can be deployed at other three sites of higher seismicity via appropriate isolation system selection. On this basis, Lal et al. (2022) further quantified the capital cost benefit of safety-class equipment attributed to standardization, showing that seismic isolation reduced the capital cost by an average of 50% for FoaK equipment and by approximately 80% for NoaK equipment. These studies showcased great potential for standardized design with isolation, and the current study seeks to further generalize the framework across wider regions and vendors. Therefore, two key challenges toward standardization are addressed in this work: varying seismic hazards across potential sites and varying building requirements across reactor technologies and vendors.

2 Standardizing Seismic Hazards

The seismic hazard is typically defined in terms of the acceleration response spectrum, and it varies depending on the location and the local site soil properties. The site-specific response spectra can be assessed online using the USGS Earthquake Hazard Toolbox, based on the shear-wave velocity time-averaged over the upper 30m (Vs30) and the mean annual rate of exceedance. To explore the range of seismic demands, data for Vs30 measurements from 7044 sites across the United States and Canada (McPhillips et al., 2020; Geyin and Maurer, 2022) are utilized. The response spectra corresponding to a damping ratio of 5% and a mean annual rate of exceedance of 10^{-4} (recurrence interval of 10000 years) for all these 7044 sites are presented in Figure 2.1.

The mean of these 7044 response spectra, is then scaled by factors of 0.5, 1.0, 1.5, 2.0, and 2.5; these five scaled spectra are employed to categorize the demands into six groups. The grouping of response spectra is illustrated in Figure 2.2. The envelope response spectrum for each group is also depicted in Figure 2.2, which is used as the design basis earthquake (DBE) response spectrum for that group. For any given site, the design should be based on the group whose envelope spectrum fully exceeds the local spectrum at all frequencies. The beyond design basis earthquake (BDBE) response spectrum can then be computed as 150% of the DBE response spectrum (ASCE/SEI 4-16, 2016). Note that the DBE and BDBE response spectra are used for the isolated superstructure design and the isolator design, respectively.

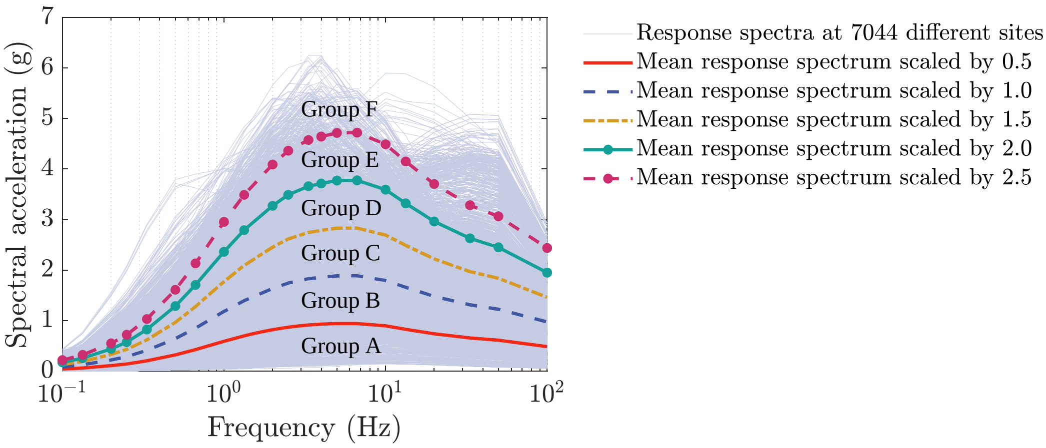

Figure 2.1 Response spectra for 7044 United States and Canadian sites (Damping ratio 5%)

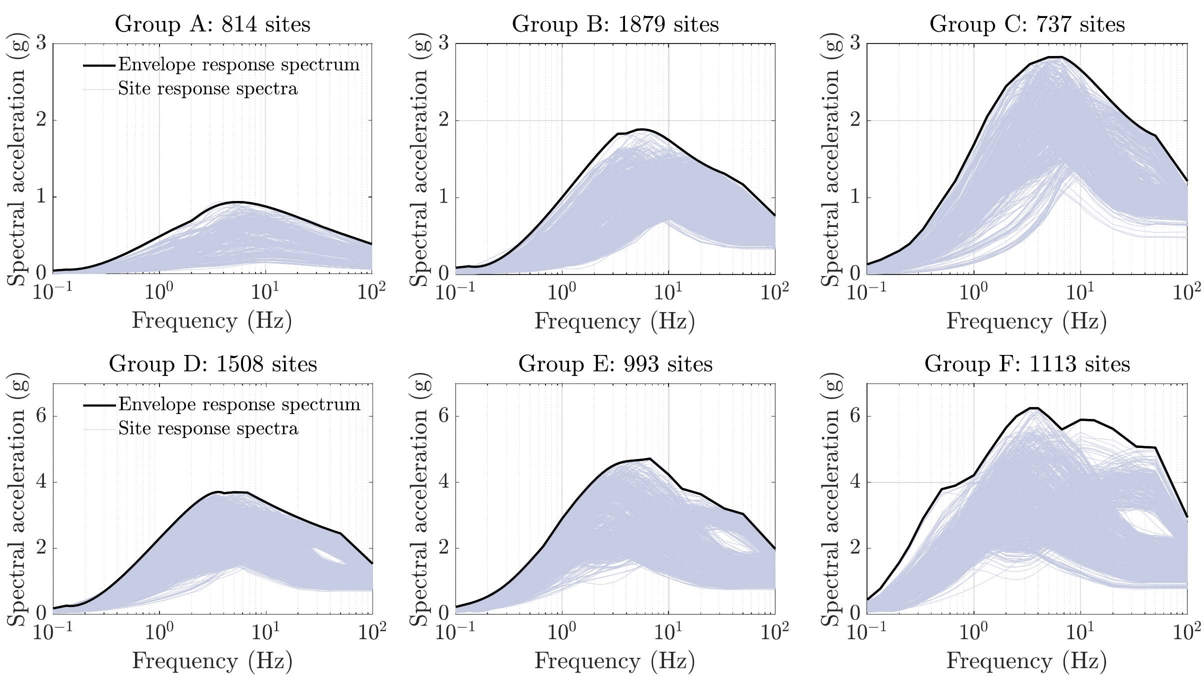

Figure 2.2 Grouping of response spectra

3 Standardizing Isolation System Designs

Given the envelope DBE and BDBE response spectra for the groups, a preliminary standardized design of the base isolation system can be conducted based on the equivalent linearization analysis (Liu et al., 2014). In general, isolator displacement and acceleration are competing performance metrics; lower acceleration often corresponds to higher displacement. Therefore, three potential performance needs are considered. Where higher acceleration can be tolerated by content, a lower isolation displacement capacity is sufficient; when lower acceleration is required to protect content, a significantly higher isolation displacement capacity is necessary; and lastly, a middle ground is considered with both moderate acceleration and displacement.

The isolation system preliminary design results for Groups A through E are presented in Table 3.1, while the results for Group F are not included, as the necessary displacements would likely not be feasible. It is seen from Table 3.1 that different values of the isolator displacement under BDBE response spectra, D_{BDBE}, are used to target different performance needs and different site groups, while the values of the isolator acceleration under DBE response spectra, A_{DBE}, are close for some cases (similar accelerations are marked in the same color). This suggests that the reactor building designs could be similar in those cases, as the superstructure design is primarily governed by the isolator acceleration. Hence, Table 3.1 indicates that only seven distinct reactor building designs are required to accommodate various tiers of seismic hazards and performance needs, due to the use of seismic isolation techniques. In fact, the number of reactor building designs can be further reduced. For instance, the designs corresponding to the blue and red colors can be combined by adopting an upper-bound design.

It is important to note that the results presented in Table 3.1 are linear approximations of the mean accelerations and displacements given the response spectra. In practice, the isolator accelerations should be calculated at the 80th percentile level under DBE ground motions, while the isolator displacements should be evaluated at the 90th percentile level under BDBE ground motions (ASCE/SEI 43-19, 2019). Thus, the values from Table 3.1 are only starting points for the design; the final values will be determined via nonlinear time history analysis in a later section.

Table 3.1 Isolation system preliminary design results (Groups A through E)

Performance need		Group A	Group B	Group C	Group D	Group E
High accel. & low disp.	D_{BDBE}	20cm	50cm	120cm	150cm	160cm
	A_{DBE}	0.32g	0.47g	0.71g	1.01g	1.45g
Moderate accel. & moderate disp.	D_{BDBE}	35cm	75cm	160cm	210cm	235cm
	A_{DBE}	0.19g	0.30g	0.47g	0.71g	1.01g
Low accel. & high disp.	D_{BDBE}	50cm	100cm	200cm	270cm	310cm
	A_{DBE}	0.11g	0.19g	0.31g	0.48g	0.70g

4 Standardizing Reactor Building Design Envelope

Different reactor technologies typically necessitate distinct components and equipment, leading to specific design requirements for reactor and auxiliary buildings. Even within the same technology, these building designs may differ between reactor vendors. Nonetheless, consultations with subject matter experts from various vendors across different technologies suggest that standardizing the designs of reactor and auxiliary buildings may be feasible for certain technologies, particularly sodium fast-cooled reactors (SFRs) and molten salt reactors (MSRs). This allows each vendor to install its own components and equipment within a standardized framework.

A potential generic layout of the reactor and auxiliary buildings for both SFRs and MSRs is shown in Figure 4.1. The reactor building is a reinforced concrete core structure with an exterior diameter of 22m and a height of 30m. The reactor building is located 10m underground to reduce the total building height while maintaining the above ground clearance potentially needed for fuel handling. The surrounding auxiliary building is a 20m-tall steel frame structure with a significant area for steam generators, turbines, etc. The two buildings are fixedly connected at the base mat of auxiliary building but are separate at all other elevations. To mitigate the seismic hazard, 5 friction pendulum bearings (FPBs) are installed beneath the reactor building at Isolation Layer A, while 56 FPBs are installed below the auxiliary buildings at Isolation Layer B. Note that the FPB designs for different performance needs and different site groups can be carried out based on Table 3.1.

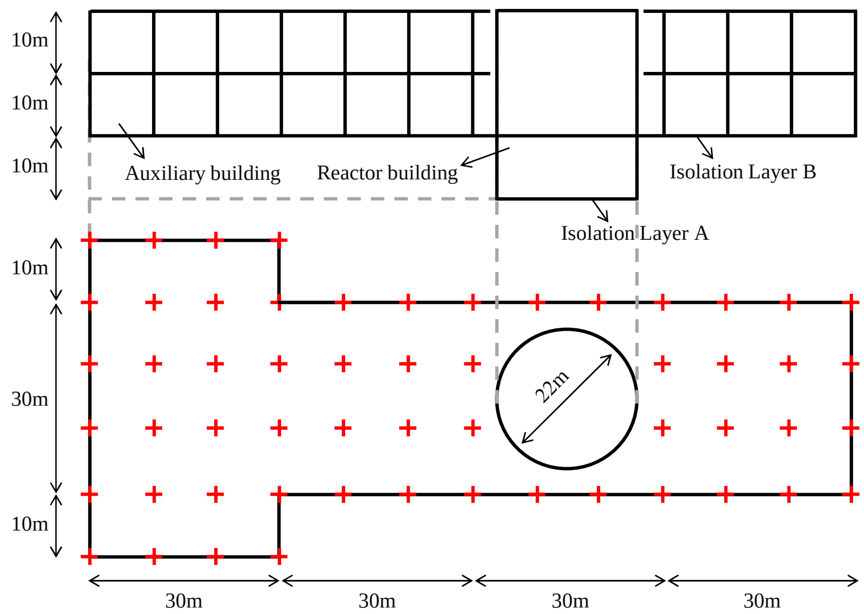

Figure 4.1 Generic layout of reactor and auxiliary buildings for SFRs and MSRs

As an example, the reactor and auxiliary buildings are designed assuming Group B with moderate displacement and acceleration as performance targets. The envelope DBE response spectra for the two horizontal directions are taken from Figure 2.2 (Group B), and the vertical response spectrum is generated by scaling the horizontal response spectrum by the vertical-to-horizontal (V/H) ratios per the Regulatory Guide 1.60 (2014). A set of 30 ground motions (including 20 from the NGA-West and 10 from the NGA-East) is selected from the Pacific Earthquake Engineering Research (PEER) Center Ground Motion Database, and a spectral matching tool is then adopted to scale the selected ground motions such that their mean response spectra can match the target envelope DBE response spectra per ASCE/SEI 43-19 (2019). The BDBE ground motions are computed as 150% of the DBE ground motions.

The concrete reactor building is designed in accordance with the design code (ACI 349-23, 2023), with the shear stress demand on the concrete wall calculated at the 80th percentile level under DBE ground motions, while the steel frame auxiliary building is designed according to the design codes (ANSI/AISC 341-22, 2022; ANSI/AISC 360-22, 2022), with the acceleration demand computed also at the 80th percentile level under DBE ground motions. To accommodate the requirements from varying vendors, the reactor and auxiliary buildings are designed assuming an upper-bound equipment mass of 10000T and 7000T, respectively, which are simplified as static loads applied to the floors. The isolation system is designed to be able to reach the 90th percentile displacement under BDBE ground motions.

The structural model of the reactor and auxiliary buildings is established using SAP2000. For the final design of the base-isolated reactor and auxiliary buildings, the isolator accelerations (DBE, 80th percentile) at Isolation Layers A and B are 0.313g and 0.310g, respectively, while the isolator displacements (BDBE, 90th percentile) are 83.6cm and 83.9cm, respectively. In comparison, the isolator acceleration and displacement obtained from the preliminary design based on equivalent linearization analysis are A_{DBE}=0.30g and D_{BDBE}=75cm, respectively. As expected, the seismic demands computed from the nonlinear dynamic analysis at higher percentiles are larger than the preliminary design results from the 50th percentile.

The horizontal mean response spectra at the two isolation layers as well as the horizontal envelope response spectrum for Group B are presented in Figure 4.2(a), from which a significant reduction of spectral acceleration from the horizonal ground motions can be observed, demonstrating the validity of horizonal seismic isolation. The envelope of the 80th-percentile horizontal response spectra at both isolation layers is also shown, providing a basis for designing the nuclear equipment located on the isolation layers. The typical range of the dominant horizontal vibration frequency of nuclear equipment, i.e. $f_{\mathrm{equip}} \in [7,22]$Hz, is also highlighted as a shaded region in Figure 4.2(a).

The vertical envelope response spectrum for Group B, the vertical mean response spectra at the two isolation layers, as well as the envelope of the 80th-percentile vertical response spectra at both isolation layers are depicted in Figure 4.2(b). It is observed that both vertical mean isolation layer response spectra and vertical envelope isolation layer response spectrum are significantly higher than the vertical envelope response spectrum for Group B, indicating that the vertical motions may be amplified for horizontally isolated structures. To address this limitation, vertical equipment isolation could be used locally to enhance protection of the equipment and contents. If the buildings were to be adopted by vendors, it is recommended that the horizontal and vertical envelope isolation layer response spectra be provided to ensure that critical equipment can be designed to withstand these demands.

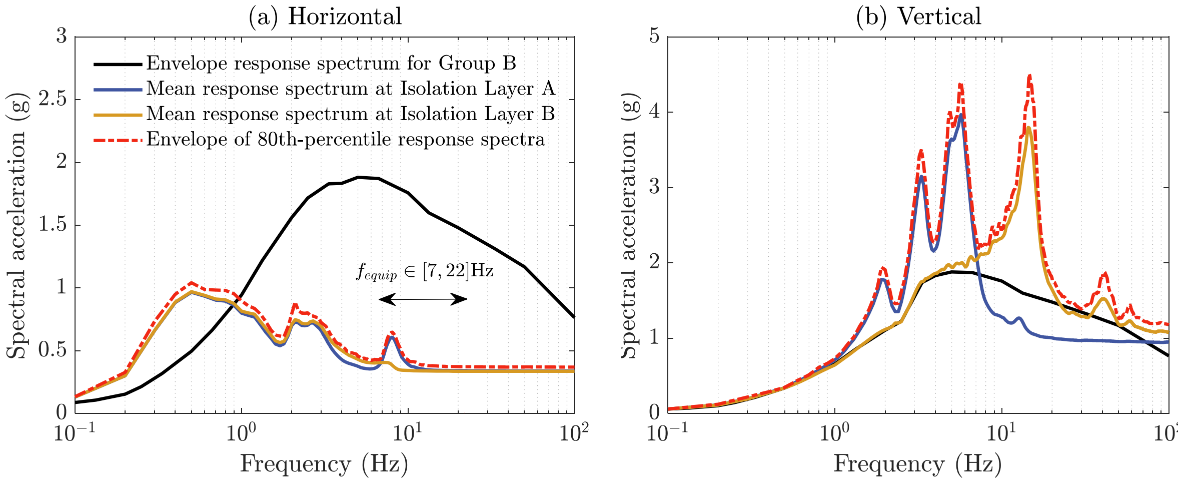

Figure 4.2 Isolation layer response spectra (Group B)

5 Case Study

In this section, the reactor building design envelope for Group B with moderate displacement and acceleration as targets, along with its isolation system, is moved to a real site within Group B. Site-specific nonlinear time-history analyses is performed with two different equipment sets, showing that the envelope design can be directly implemented at a specific site within the same group without the need for recomputing building or isolator design checks or redeveloping floor response spectra for equipment design. The site is located near the Salt Lake City, Utah (Vs30=355 m/s), and the corresponding DBE response spectrum is presented in Figure 5.1. It can be seen that the response spectrum at the site closely follows the envelope response spectrum for Group B in the low-frequency range. A set of 30 ground motions is selected from NGA-West of the PEER Center Ground Motion Database, and then scaled using spectral matching tools to ensure that their mean response spectra align well with the site-specific DBE response spectra, as shown in Figure 5.1. The BDBE ground motions are obtained by scaling the DBE ground motions by 150%.

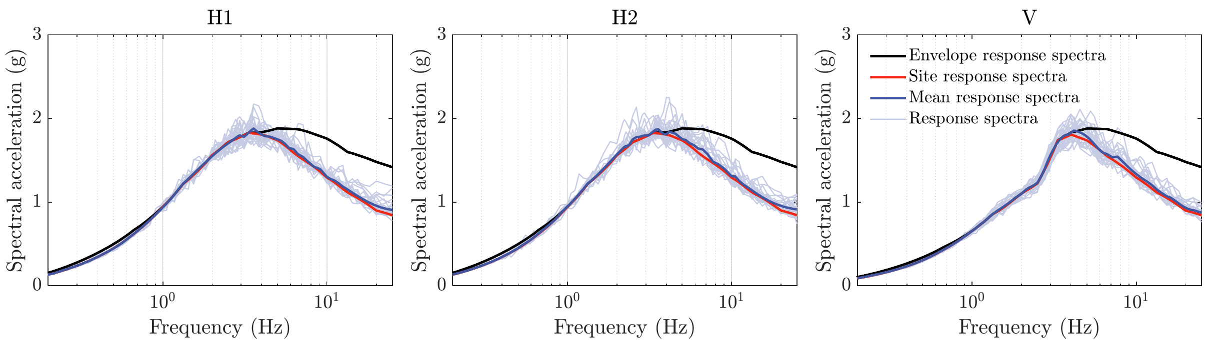

Figure 5.1 Response spectra at the site (damping ratio 5%)

To address the needs for different reactor technologies, two equipment sets, Equipment Set 1 and Equipment Set 2, are chosen. Each equipment set is composed of a reactor vessel housed within the reactor building, along with three steam generators and a turbine located inside the auxiliary building. To showcase that each vendor can have its own equipment requirements and equipment installation approach, the mass, fundamental vibration frequency, and layout of each equipment type are varied for the two equipment sets. The total equipment mass for Set 1 and Set 2 are 17000T and 16660T, respectively.

The structural models of the reactor and auxiliary buildings installed with either Set 1 or Set 2 are constructed using SAP2000. For each structural model, the nonlinear time-history analyses under DBE and BDBE ground motions at the site are performed using the fast nonlinear analysis solver in SAP2000. The results show that the computed isolator accelerations (DBE, 80th percentile) and isolator displacements (BDBE, 90th percentile) at both isolation layers for both equipment sets are all smaller than or equal to those for the envelope design of Group B, demonstrating that the reactor building design envelope for Group B, along with its corresponding isolation system design, can be directly used at the site.

Figure 5.2(a) shows the envelope of the 80th percentile horizontal isolation layer response spectra for each equipment set case, whereas the vertical envelope isolation layer response spectra for both equipment set cases are presented in Figure 5.2(b). For comparison, the horizontal and vertical envelope isolation layer response spectra for Group B, as depicted in Figures 4.2(a) and 4.2(b), respectively, are also included in Figures 5.2(a) and 5.2(b), respectively. It can be seen that the horizontal envelope isolation layer response spectra for both cases are generally lower than those for Group B in the critical frequency range of nuclear equipment (between 7Hz and 22Hz), while the vertical envelope isolation layer response spectra for the two cases are significantly lower than those of Group B in the high-frequency region (larger than 10Hz), where the dominant vertical vibration frequency of equipment typically resides. This demonstrates that the equipment and content designed and qualified for the envelope isolation layer response spectra for Group B can be directly used for the site.

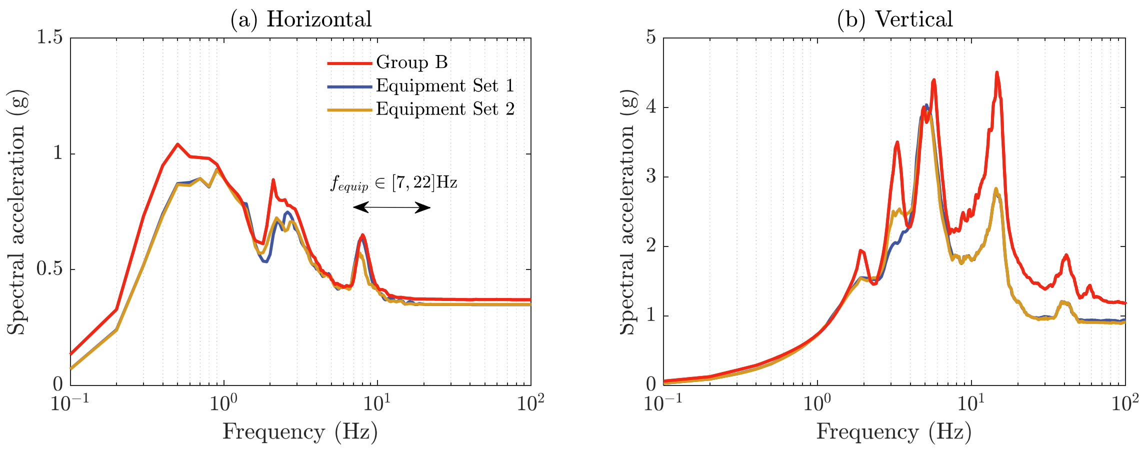

Figure 5.2 Envelope isolation layer response spectra

6 Conclusions

This study proposes a standardized design methodology for advanced reactors facilitated through seismic isolation, addressing two major challenges: varying seismic hazards across site locations and varying requirements across reactor vendors. Base isolation plays a central role in achieving standardization by serving two functions: mitigating seismic demands on buildings and equipment and reducing the impact of variations in equipment mass and frequency on these demands. A case study is presented to validate the feasibility of the present standardization approach. The results demonstrate that a base-isolated reactor building, designed for a specific site group, can be directly implemented at any site as long as it falls within the site group, without requiring additional design checks. This is true even when different equipment properties are considered. Future studies should extend this standardized design to accommodate other vendors and even other advanced nuclear technologies. Ideally, a limited number of building designs should be developed to address the diverse building requirements of different vendors and technologies.

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