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In-structure Response Spectrum of Nuclear Power Plant Structure Considering High-frequency Motion

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1. Introduction

After the Fukushima nuclear accident in 2011, anxiety about the earthquake safety of nuclear power plants has become a significant social issue. Domestic nuclear power plants also experienced an unprecedented situation in which the Wolsong nuclear power plant was manually shut down due to the 2016 Gyeongju earthquake, which caused public anxiety about the seismic safety of the nuclear power plant. In particular, in the Gyeongju and Pohang earthquakes that occurred recently in Korea, it was confirmed that the high-frequency component was dominant, unlike the R.G. 1.60 design spectrum [1] used in the design of nuclear power plants. In the case of the high-frequency component of ground motion, although it may not affect the safety of the structure, it can significantly affect safety-related equipment in nuclear power plants with high natural frequencies. In this study, we describe a method of evaluating in-structure response spectra (ISRS) considering high-frequency characteristics for a representative domestic nuclear power plant model.

2. Methods and Results

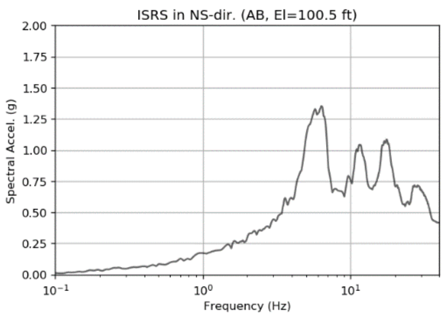
This section describes a method of deriving realistic spectral acceleration through spectrum averaging considering high-frequency characteristics and a method of clipping narrowband frequency components that may occur locally in a high-frequency range through spectral clipping.

2.1 Spectral Averaging for ISRS

In the high-frequency range, the peak value of the ISRS tends to be localized because it is a response to the local mode. At this time, ISRS may have a relatively narrow peak, and if the natural frequency of the equipment is located at the peak value of the ISRS, an excessively conservative result may be derived.

The Electric Power Research Institute (EPRI) recommends averaging the spectral acceleration over a frequency range assuming an uncertainty of 10% to 15% in the natural frequency of the equipment [2]. In this case, by extracting a probabilistic sample of the spectral acceleration within the equipment natural frequency range, the median and variability of the internal response spectral acceleration due to the uncertainty of the equipment natural frequency can be derived.

The effects of spectral averaging were investigated by selecting equipment with natural frequencies in the high-frequency region and ISRS of structures with peak values at the corresponding natural frequencies. A battery charger located at 100 ft of an auxiliary building with a natural frequency of 11 Hz and a battery rack located at 125 ft of an auxiliary building with a natural frequency of 25.3 Hz is selected as target equipment. The logarithmic standard deviation of the natural frequency of the equipment is assumed to be 0.15, and frequency samples are extracted through LHS sampling.



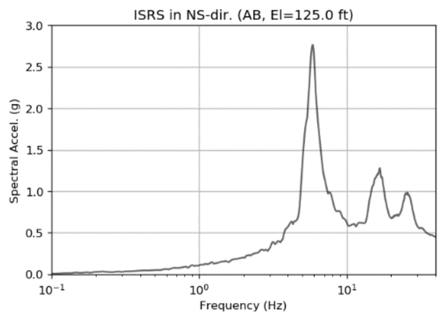


Fig. 1. Is-structure response spectrum of Auxiliary building at h=100.5 ft and 125.0 ft.

In the case of the battery charger, the averaged spectral acceleration using a probabilistic sample (S_{a_ave}) is 0.79 g, whereas the spectral acceleration (S_a) at 11 Hz is 0.93 g. It is confirmed that the seismic demand decrease of about 15.1% occurs through spectrum averaging. The variability of the spectral acceleration is calculated as 0.16 if the variability of the device frequency is 0.15. In the case of the battery rack, the seismic demand reduction occurs by 21.6%, and the variability of the spectral acceleration due to the variability of the equipment frequency is 0.19.

2.2 Spectral Clipping Procedure

In ISRS, a narrowband frequency component may be amplified, particularly in a high-frequency range., and a broadband demand spectrum can be derived from the ISRS through a clipping factor [2]. In the case of ISRS derived through seismic response analysis, it is necessary to determine the median response and variability of the structural response and spectral clipping.

In order to derive variability in ISRS demand, probabilistic seismic response analysis can be performed, and the EPRI recommends four methods of estimating clipping factors and structural response variability from probabilistic ISRS. There is a rigorous method (Method 4) that independently clips each of the 30 probabilistic ISRSs and calculates the structural response and clipping factor variability according to statistical analysis of the 30 clipped ISRSs (Method 4). the other three methods (Method 1-3) are alternative methods that simplify the calculation process for the strict method.

The clipping factor variability and the structural response variability are defined as functions of different aspects of the probabilistic ISRS. Structural response variability is a function of the probabilistic spectral acceleration distribution, and clipping factor variability is a function of ISRS shape.

2.3 Spectral Clipped ISRS

The clipping factor is calculated from the probabilistic ISRS of the specific locations through the seismic response analysis of the auxiliary building assembly, and also the variabilities of the structural response and clipping factor are calculated prof the probabilistic ISRS. The clipped median/84% NEP ISRSs and variability at the representative locations of the auxiliary building are calculated as in Table 1.

The clipped spectral acceleration has a slightly higher value as a result of using Method 4 overall. The logarithmic standard deviation (β_C), which combines the variability of the structural response and the variability of the clipping factor, mainly has a value between 0.4 and 0.5, and Method 4 shows a slightly higher value than other methods. Therefore, the results using Method 4 are more conservative than other methods.

Table I: Summary of clipped spectral acceleration and variability.

Location (ft)	Median Clipped Sa (g)		84% NEP Clipped Sa (g)				β_c			
Method	M1-3	M4	M1	M2	M3	M4	M1	M2	M3	M4
77.0	0.67	0.63	0.95	1.06	0.95	1.02	0.34	0.45	0.34	0.49
100.5	0.75	0.73	1.11	1.07	1.01	1.16	0.38	0.35	0.30	0.46
125.0	1.02	1.10	1.54	1.75	1.66	1.80	0.41	0.54	0.49	0.50
144.0	1.43	1.50	2.10	2.29	2.19	2.42	0.39	0.47	0.43	0.48
164.0	1.57	1.65	2.31	2.60	2.45	2.66	0.39	0.51	0.44	0.48
182.0	1.69	1.73	2.47	2.63	2.51	2.77	0.38	0.44	0.40	0.47

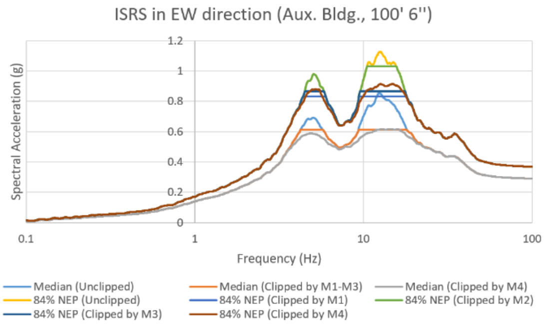


Fig. 2. Clipped/unclipped in-structure response spectrum of Auxiliary building in the horizontal direction at h=100.5 ft.

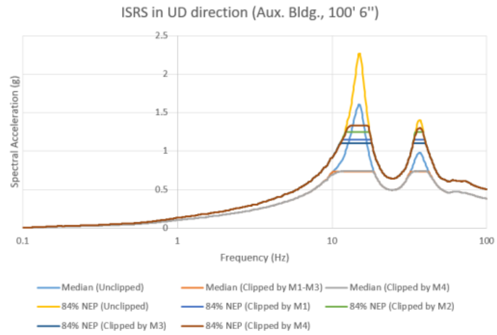


Fig. 3. Clipped/unclipped in-structure response spectrum of Auxiliary building in the vertical direction at h=100.5 ft.

3. Conclusions

In this study, the ISRS of the nuclear power plant structure considering the spectral averaging method and spectral clipping is derived to evaluate the internal response of the structure considering the high-frequency characteristics. Spectral averaging is applied to confirm the reduction in the seismic demand due to the equipment frequency variation, and the clipped ISRS and variability are derived according to the application of spectral clipping. It is expected that the ISRS evaluation method discussed in this study can be used to evaluate the seismic safety of internal equipment of nuclear power plants considering high-frequency components.

Acknowledgement

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[1] US NRC, Regulatory Guide 1.60, Design Response Spectra for Seismic Design of Nuclear Power Plants, 1973.
[2] EPRI 3002012994, A Methodology for Assessment of Nuclear Power Plant Seismic Margin, EPRI NP-6041-SL, Revision 1, Palo Alto, CA.