Seismic Capacity Re-Evaluation of Korea NPP Equipment using Earthquake Experience and Shake Table Test Data

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1. Introduction

To date, due to the significance of the nuclear power plant (NPP) safety, the seismic capacity of the NPP equipment is estimated conservatively during the safety assessment process. In these circumstances, the seismic capacity of various equipment in the NPP was underestimated than its actual performance against the seismic events. However, recent earthquake events in the Korea peninsula (i.e., Gyeongju and Pohang earthquakes in 2017 and 2018, respectively) increase the interest in the evaluation of the more realistic seismic capacity of NPP equipment. To address this issue, the authors adopt the Bayesian approach, and re-evaluate the seismic capacity of the Korea NPP equipment using earthquake experience and shake table test data. As a case study, the seismic capacity of the 480V motor control center (MCC) is updated with various data conditions.

2. Data Set for Seismic Capacity Updating

Both earthquake experience data and shake table test data are used in this work to updating the seismic capacity of the 480V motor control center (MCC) of Korea NPP.

2.1 Earthquake Experience Data

The earthquake experience database requires four information: 1) seismic demand information, 2) the number of independent equipment, 3) location of equipment, and 4) state of equipment (e.g., survival, damage). However, an earthquake experience database with such information had not been constructed yet for the Korea NPP equipment. Therefore, in this work, the earthquake record collected in the NPP sites and the general location of the NPP equipment are combined to construct the earthquake experience database.

A total of 24 earthquake record collected from four database site (i.e., UCN, YGN, KRN, and WSN), and seismic demand occurred at ground level is estimated from a broad-banded average 5% damping earthquake spectra acceleration "Sa_b". In the previous work [1], the frequency ranges 2.5Hz to 7.5Hz is the Pareto region of the response spectrum, and therefore chosen as a broad-band. However, such fixed broad-banded can underestimate the seismic demand of the earthquake records with the high-frequency contents. Therefore, seismic demand using both fixed and optimized seismic demand is evaluated (Fig.1).

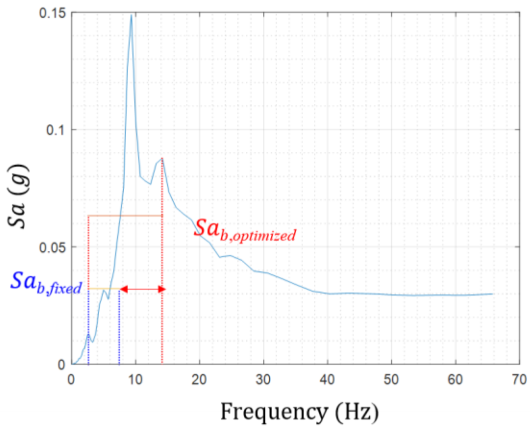

Fig. 1. Example of a broad-banded average 5% damped spectra acceleration of fixed and optimized frequency range

Also, the location information of MCC in general (i.e., 78ft, 100ft, 120ft, and 137.5ft) is used to estimate in-structure seismic demand with the amplification factor. The amplification factor is given as 1.5 and 2 for the equipment located higher than 20ft and 40ft higher than ground level (70ft), respectively. Lastly, the post-earthquake condition of all equipment is assumed to be a survival state without any damage or failure.

2.2 Shake Table Test Data

In shake table test data (STT), seismic demand is estimated from the test response spectrum (TRS). In this work, a total of 36 STT data using nuclear regulatory commission (NRC) TRS and uniform hazard spectrum (UHS) TRS is used for seismic capacity re-evaluation. Same as earthquake experience data, Sa_b is estimated with both fixed (3Hz to 16Hz) and optimized frequency range, and the effect of broad-band optimization on the seismic capacity updating is investigated in the case study.

3. Bayesian Models

Bayesian formulations to update the seismic capacity of NPP equipment [1] are summarized in this section.

3.1 Prior Distribution

The prior distribution of seismic capacity can be expressed by the lognormal distribution with two parameters (i.e., median capacity C_m and lognormal standard deviation β_C). A joint probability density function is obtained by multiplying two lognormal probability density function as follow:

$$p(C_m,\beta_{\hat{c}}) = \varphi(\ln(C_m/C_{mbe})/\beta_{\hat{c}m})\cdot\varphi(\ln(\beta_{\hat{c}}/\beta_{\hat{c}be})/\beta_{\beta\hat{c}} \quad (1)$$

where, $\varphi(\cdot)$ is standard normal probability density function. C_{mbe} and $\beta_{\hat{c}be}$ are prior best estimation of C_m and $\beta_{\hat{c}}$, respectively. $\beta_{\hat{c}m}$ and $\beta_{\beta\hat{c}}$ indicates the prior lognormal standard deviation of C_m and $\beta_{\hat{c}}$ respectively.

3.2 Likelihood Function

The likelihood of the earthquake experience or the STT data is evaluated by the failure probability of the NPP equipment with given seismic demand. Single component failure probability P_f at acceleration level and the likelihood function are evaluated as follow:

$$P_f = \Phi(\ln(Sa_{bl}/C_m)/\beta_{\hat{c}m}) \quad (2)$$

$$L(n, Sa_{bl}|C_m,\beta_{\hat{c}}) = (1- P_f)^n \quad (3)$$

where, $\Phi(\cdot)$ is cumulative standard normal distribution function. Sa_{bl} denotes in-structure spectral acceleration, and n is number of observation at local spectral acceleration level. For experience data consist more than one event, likelihood function is evaluated as follow:

$$L'(\{n, Sa_{bl}\}|C_m,\beta_{\hat{c}}) = \prod_{i=1}^{m}(1 - (P_f)_i)^{n_i} \quad (4)$$

where, $\{n, Sa_{bl}\}$ is a set of observations, and n_i is number of observation at local spectral acceleration level $Sa_{bl,i}$. m denotes the total number of different local spectral acceleration included in the data set.

3.3 Posterior Distribution

Under assumption that two parameters C_m and $\beta_{\hat{c}}$ are independent, the posterior distribution can be expressed in a joint probability density function as follow:

$$f(C_m,\beta_{\hat{c}}|\{n, Sa_{bl}\}) = \varphi(\ln(C_m/C'_{mbe})/\beta'_{\hat{c}m})\cdot\varphi(\ln(\beta_{\hat{c}}/\beta'_{\hat{c}be})/\beta'_{\beta\hat{c}} \quad (6)$$

Where C'_{mbe} and $\beta'_{\hat{c}be}$ denotes updated estimations. Due to complexity, posterior distribution can be achieved through the sampling approach. In this work, the authors use the slice sampling technique, one of the Markov Chain Monte Carlo (MCMC), with Matlab code to evaluate the best estimations of the posterior distribution of the seismic capacity.

4. Case Study

As a case study, the seismic capacity of 480V MCC of Korea NPP is re-evaluated using earthquake experience and shake table test data. To investigate the sensitivity of the seismic capacity updating against the dataset and the seismic demand optimization, the following five data combinations are used with and without the seismic demand optimization: 1) Only earthquake experience data, 2) NRC STT data, 3) UHS STT data, 4) All STT data, and 5) Earthquake experience data and all STT data. The updated seismic capacities of 480V MCC of Korea NPP are summarized in Table 1. For all data conditions, the 1% failure probability seismic capacity ($C_{1\%}$) of the MCC is increase than the prior assumption based on the expert judgment. In addition, the seismic capacity of the U.S. MCC that was updated with the eSQUG earthquake experience data [1] is most similar to Korea MCC updated with the NRC spectrum STT data of Korea. Results also indicate that there is a non-negligible difference occurred by the frequency range optimization when the seismic data have large seismic demand and contain high-frequency content. Under such conditions (e.g., Case 3-5), $C_{1\%}$ is increased up to 14.5% by optimizing the broad-banded frequency range.

Table. 1. Updated seismic capacity of 480V MCC of Korea NPP with various data conditions.

Case		$C'mbe$(g)	$\beta'_{\hat{C}be}$	$C_{1\%}$(g)	Rate*
Prior		4.8	0.42	1.8040	
U.S MCC [1]		6.28	0.40	2.4728	
1	Fixed	5.7174	0.4372	2.0644	1.0016
	optimized	5.7262	0.4372	2.0677	
2	Fixed	6.6140	0.4292	2.4329	1.0046
	optimized	6.6416	0.4291	2.4440	
3	Fixed	9.2232	0.4292	3.3931	1.1454
	optimized	0.6408	0.4323	3.8862	
4	Fixed	9.3539	0.4261	3.4658	1.1364
	optimized	10.7261	0.4300	3.9387	
5	Fixed	9.3528	0.4260	3.4661	1.1363
	optimized	0.7264	0.4300	3.9384	

Rate* indicates the $C_{1\%,\ \text{optimized}}$ divided by $C_{1\%,\ \text{fixed}}$

5. Conclusions

Seismic capacity of 480V MCC of Korea NPP is re-evaluated using earthquake experience and STT data, and it is identified that seismic capacity of the NPP equipment can be increased with Bayesian approach. We expect that archiving the earthquake experience and STT data can facilitate the seismic capacity updating of the NPP equipment.

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