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Seismic capacity re-evaluation of aging electrical cabinet of NPP using Bayesian updating

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1. Introduction

As the life extension of the nuclear power plant becomes a critical issue to the global nuclear community, various regulatory and technical needs are raised as well. One of the technical issues is the seismic capacity of the aging equipment. For the nuclear power plants reviewing their life extension, it is often challenging to collect the initial seismic information at construction. Add to this lack of information, it is also difficult to predict the age degradation effect on the NPP equipment. Therefore, to resolve this issue, the authors use the Bayesian updating method to re-evaluate the seismic capacity of the aging electric cabinet of NPP. Especially, to overcome the lack of initial information, expert judgment values are used as prior knowledge. On the other hand, to represent the aging effect of the NPP equipment, shake table test (STT) results of degraded concrete in the literature [1] are adopted for build likelihood functions. The rest of this paper is organized as follows. In Section 2, the basic idea of Bayesian approach and slice-sampling methods is introduced. Sections 3 demonstrate seismic capacity re-evaluation of aging cabinet equipment with various concrete crack conditions. Section 4 summarizes the paper and offers concluding remarks.

2. Bayesian Updating for seismic capacity re-evaluation

The basic idea of Bayesian updating is predicting the current state ("posterior") by combining prior knowledge ("prior") and new information ("likelihood"). In the following sub-sections, key elements of Bayesian updating (i.e., prior, likelihood, posterior) for seismic re-evaluation proposed in U.S. EPRI reports [2,3] and slice sampling method are introduced.

2.1 Prior model

Bayesian updating method for the seismic capacity re-evaluation starts with defining the expert judgment on the NPP equipment (e.g., electric cabinet) using the lognormal model two parameter median capacity C_m and lognormal standard deviation β_c. Again, each parameter can be modeled through the lognormal distribution as well as using the best estimation and the uncertainty. The prior distribution of seismic capacity of NPP equipment can be estimated as a joint probability density function by multiplying these two lognormal probability density functions of two parameters (i.e., C_m and β_c), as follows:

$$p(C_m, \beta_{\hat{C}}) = \varphi\left(ln\left(\frac{C_m}{C_{mbe}}\right)/\beta_{\hat{C}_m}\right) \cdot \varphi\left(ln\left(\frac{\beta_{\hat{C}}}{\beta_{\hat{C}be}}\right)/\beta_{\beta_{\hat{C}}}\right) \quad (1)$$

where p is the prior distribution, and $\varphi(\bullet)$ denotes the standard normal density function. C_{mbe} and β_{Cm} denote the best estimation and uncertainty of the median capacity, and β_{Cbe} and $\beta_{\beta c}$ denote the best estimation and uncertainty of the lognormal standard deviation, respectively. The values of the C_{mbe}, β_{Cm}, β_{Cbe}, and $\beta_{\beta c}$ of a wide range of NPP equipment are given based on the expert judgement [4] as 4.8g, 0.42, 0.42, and 0.2, respectively.

2.2 Likelihood model

Add to the prior knowledge, new information achieved from the earthquake event or STT results (i.e., Table response spectrum (TRS)) can be used to update the seismic capacity of the NPP equipment. For the Bayesian updating, failure probability and likelihood of the observations can be expressed as follows:

$$P_F = \Phi\left(ln\left(\frac{Sa_{bl}}{C_m}\right)/\beta_{\hat{C}}\right) \quad (2)$$

$$L'(\{n, f, amb, Sa_{bl}\}|C_m, \beta_{\hat{C}}) = \prod_{i=1}^{m}\left\{\binom{n_i}{f + amb_i} P_{Ss} P_{Fs} P_{ambs}\right\} \quad (3)$$

$$P_{Ss} = \left(1 - (P_f)_i\right)^{n_i - f_i - amb_i} \quad (4)$$

$$P_{Fs} = (P_F)_i^{f_i} \quad (5)$$

$$P_{ambs} = \left[(P_F)_i^{Q} \cdot \left(1 - (P_F)_i^{100-Q}\right)\right]^{\frac{amb_i}{100}} \quad (6)$$

Where $\boldsymbol{P_F}$ is the probability of single component fail at local acceleration level at location Sa_{bl}. In addition, n_i, f_i, amb_i denote total number of components, number of failure with 100% confidence, number of failure with Q% failure. P_{Ss} is the probability of observing (*n-f-amb*) survivals. P_{Fs} is the probability of observing f failure with 100% confidence. P_{ambs} is the probability of observing *amb* data set with Q% confidence.

2.3 Posterior model and Slice Sampling

The "posterior" joint distribution on C_m and β_c can be achieved by Bayes' theorem as follows:

$$f(C_m, \beta_{\hat{C}} | \{n, Sa_{bl}\}) = L'(\{n, Sa_{bl}\} | C_m, \beta_{\hat{C}}) \cdot p(C_m, \beta_{\hat{C}}) \quad (7)$$

In addition, equation (7) can be simplified as a joint distribution of statistically independent parameters C_m and β_c, as follows:

$$f(C_m, \beta_{\hat{C}} | \{n, Sa_{bl}\}) = \varphi\left(ln\left(\frac{C_m}{C'_{mbe}}\right) / \beta'_{\hat{C}_m}\right) \cdot \varphi\left(ln\left(\frac{\beta_{\hat{C}}}{\beta'_{\hat{C}be}}\right) / \beta'_{\beta_{\hat{C}}}\right) \quad (8)$$

To resolve this posterior distribution, the slice-sampling technique [5] is introduced.

3. Numerical Experiment

3.1 Problem setting

To represent the aging of the NPP, an electric cabinet structure with fresh and various degraded concrete conditions is experimented with in the work of Jeon *et al.* [1]. From this work, the Authors adopted the TRS data and the survival and failure information to re-evaluate the seismic capacity of fresh and aging NPP electric cabinets. The authors calculated the broad-banded average spectral acceleration S_{ab} of TRS using the method proposed by Choi et al. [6] and it is summarized in Table 1. With this data set, seismic capacity re-evaluation is performed with 5 different conditions. (1) without damage, (2) 0.5mm crack in 2 locations, (3) 0.5mm crack in 4 locations, (4) 1mm crack in 2 locations, and (5) 1mm crack in 4 locations.

Table I: Data Description

Sample	Survival data S_{ab} (g)	Failure data S_{ab} (g)
S 1-1 (base)	2.32, 4.55	5.56
S 1-2 (1mm crack, 2 point)	2.32, 4.55, 5.56, 6.55	7.44
S 1-3 (1mm crack, 4 point)	2.32, 4.55, 5.56, 6.55, 7.44, 8.32, 9.03	-
S 2-1 (base)	2.31, 4.47, 5.50, 6.49	7.43
S 2-2 (0.5mm crack, 4 point)	2.31, 4.47	5.50
S 2-3 (0.5mm crack, 4 point)	2.31, 4.47, 5.50, 6.49, 7.43, 8.27, 9.04	-

3.2 Results and Discussions

The seismic capacity of the electric cabinet with five different concrete conditions is illustrated in Figure 1. Results indicate that degradation of the concrete base does not necessarily indicate a reduction of seismic capacity. While some of the concrete degradation conditions cause the decrease of the seismic capacity (case 2), others (i.e., cases 3,4,5) show larger seismic capacity than the base cases. From these results, authors infer that the crack of the concrete base may affected as the damper for the equipment.

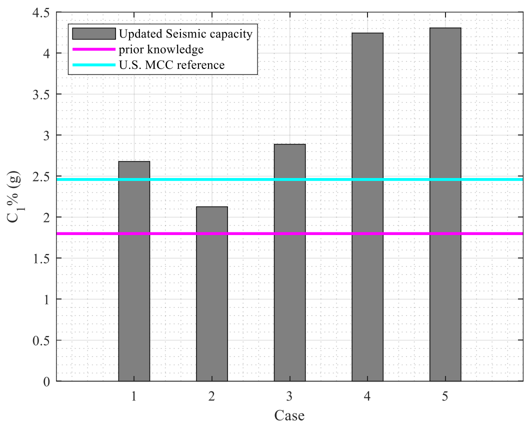

Fig. 1. Updated seismic capacity of the electric cabinet with five different concrete degraded conditions.

4. Conclusions

Using the Bayesian updating method, the seismic capacity of the NPP electric cabinet with five different base concrete conditions is re-evaluated. The authors believe that this work prompts the understanding of the aging effect of the NPP equipment of NPP under consideration of life extension.

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