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Determining seismic fragility of structures and components in nuclear power plants using multiple ground motion parameters – Part II: Application

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ABSTRACT

This study presents an application of the innovative fragility method proposed in companion paper (Part I) to a horizontal heat exchanger in Darlington nuclear generating station. To illustrate the advantages of the proposed method, seismic fragility curves and High Confidence of Low Probability of Failure seismic capacity of the heat exchanger are calculated by the conventional and proposed fragility methods. The results show that, by using two ground motion parameters, the median seismic capacity of the heat exchanger has remarkable 53.9% increase, and the High Confidence of Low Probability of Failure seismic capacity is increased by 25.0%. These increases come from the reduction of conservatism of the median seismic demand by incorporating the correlation between two ground motion parameters. Although applications of components mounted on supporting structures are not presented, seismic capacities of components are expected to increase as long as the effect of structural dominant modes on seismic responses are captured by employing the proposed method. For critical structures, systems, and components that limit the plant seismic capacity, the proposed fragility method should be implemented to evaluate their seismic capacities.

1. Introduction

Seismic Probabilistic Risk Assessment (SPRA) has been implemented to quantify the seismic risk of existing nuclear power plants (NPPs) since late 1970s (Kennedy et al., 1980; Kaplan et al., 1983; Ellingwood, 1994; Huang et al., 2011). The SPRA procedure mainly includes three key elements: probabilistic seismic hazard analysis (PSHA), seismic fragility analysis, and system analysis (also called accident sequence analysis). Of these elements, seismic fragility analysis is extremely important, because the failure of a single structure or component probably triggers a severe adverse consequence such as the loss of coolant accident. Overestimate or underestimate of seismic fragilities of structures, systems, and components (SSCs) may result in unreliable plant seismic capacity. Therefore, accurate seismic fragility estimates of SSCs are crucial in estimating seismic risk of NPPs.

The semi-empirical fragility model proposed by Kennedy and Ravindra (1984) is the most widely used fragility model in SPRA studies. In this model, a Review Level Earthquake anchored to a selected ground motion parameter (GMP) is defined as seismic input for evaluating seismic responses of SSCs, ignoring ground motion intensity effect. The aleatory *randomness* and epistemic *uncertainty* in evaluating structural capacity and seismic demand are modelled by a series of multiplicative lognormal random variables. Structural capacity and seismic demand thus yield lognormal distribution from the multiplication of these lognormal random variables. Therefore, the seismic capacity in terms of the selected GMP is lognormally distributed. Seismic fragility curves are determined based on evaluating the median values and logarithmic standard deviations of seismic capacities of SSCs.

Two major problems of the lognormal fragility model are observed in engineering practice:

1. Prediction of median seismic capacities of SSCs. In the lognormal fragility model, a single GMP is chosen to calculate seismic responses of SSCs. The inherent correlations among spectral accelerations at different frequencies are not addressed. However, a substantial studies have shown that ignoring the correlations would introduce conservatism in predicting seismic responses and fail to capture the effect of structural dominant modes on the seismic responses conditional on the selected GMP (Cai, 2017; Ni et al., 2015; Bazzurro and Cornell, 2002; Seyedi et al., 2010). The overestimate of median seismic responses in turn lower the median seismic

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Nomenclature

AFE	annual frequency of exceedance
EPRI	electric power research institute
GMP	ground motion parameter
GRS	ground response spectrum
HCLPF	high confidence of low probability of failure
NGS	nuclear generating station
NBCC	national building code of canada
NPPs	nuclear power plants
PGA	peak ground acceleration
PSHA	probabilistic seismic hazard analysis
ρ	correlation coefficient between logarithmic spectral accelerations at two vibration frequencies
RLE	review level earthquake
$S_a(f_L)$	spectral acceleration at longitudinal frequency of the heat exchanger
$S_a(f_T)$	spectral acceleration at transverse frequency of the heat exchanger
$S_a(f_V)$	spectral acceleration at vertical frequency of the heat exchanger
SMA	seismic margin assessment
SPRA	seismic probabilistic risk assessment
SSCs	structures, systems, and components
UHS	uniform hazard spectrum
MGMPs	multiple ground-motion parameters
VPSHA	vector-valued probabilistic seismic hazard analysis

capacity estimates.

2. Evaluation of the variability of seismic capacity. In the lognormal fragility model, by assuming that all basic variables are independent, an approximate second-moment procedure is recommended to evaluate the propagation of aleatory *randomness* and epistemic *uncertainty* of basic variables to the overall variability of the seismic capacity. Although studies have shown that this method is sufficient accurate in most cases, part of epistemic *uncertainty* may be eliminated by utilizing different numerical evaluation procedures.

Some efforts have been made to resolve the first problem. EPRI (2011) attempted to address ground motion intensity effect and the correlations among spectral accelerations by generating a large number of time histories, which are compatible with conditional mean spectra at different vibration frequencies, spanning from small to large values of a selected GMP. However, it requires a large number of computationally expensive and cumbersome dynamic analyses, which compromises its applicability in nuclear power industry.

Grandis et al. (2009) proposed an innovative numerical procedure for computing seismic fragility of SSCs. In this method, response surface method rather than the lognormal fragility model is implemented to establish mean and standard deviation of the dynamic response, and Monte-Carlo simulations are performed subsequently to compute the probability of exceedance, i.e., seismic fragility of the SSC analyzed. The procedure was implemented to evaluate seismic fragilities of a base-isolated reactor building (Perotti et al., 2013). Despite of the advantages of the procedure, it does not address the ground motion intensity effect as well as the correlations among spectral accelerations as discussed in Problem 1. In addition, it is computational expensive to carry on Monte-Carlo simulations when a big number of basic random variables are taken into consideration.

The companion paper (Part I) presented an innovative fragility method for evaluating seismic capacities of SSCs. By taking advantages of MGMPs, ground motion intensity effect and correlations among spectral accelerations are taken into account. Meanwhile, response spectra method rather than time history analysis method is implemented to calculate seismic responses of SSCs. It is noted that, the procedure to evaluate the variability of seismic capacities of SSCs is in accordance with the approximate second-moment procedure, because the engineers in nuclear power industry are familiar and comfortable with this procedure. The method is meant to be applicable in engineering practice.

The objective of this study is to presents an application of the proposed fragility method to a horizontal heat exchanger in Darlington nuclear generating station. To achieve this objective, seismic fragility curves and High Confidence of Low Probability of Failure seismic capacity of the heat exchanger are calculated by the conventional and proposed fragility methods, respectively. The seismic fragility results are then compared to illustrate the advantages of the proposed method.

This study is organized as follows. Section 2 presents a brief introduction of two fragility methods used to calculate the seismic fragility of the heat exchanger. Section 3 shows basic configuration of the heat exchanger. Section 4 performs PSHA to generate uniform hazard spectrum (UHS) which is defined as seismic input in the conventional fragility method. Section 4 develops weighting fragility curves of the heat exchanger. Section 5 conducts the comparison of seismic fragility results based on two methods. Section 6 summarizes this study.

2. Fragility analysis methods

2.1. Conventional fragility method

Seismic fragility of an SSC is defined as the conditional probability that seismic capacity A of an SSC is less than a given ground motion level a in terms of GMP, i.e.,

$$p_F(a) = P\{A < a|\mathrm{GMP} = a\}, \tag{2.1}$$

Seismic capacity A of an SSC is often expressed as the product of three variables

$$A = A_m \cdot \varepsilon_R \cdot \varepsilon_U, \tag{2.2}$$

where A_m is the best estimate of median seismic capacity, which is a deterministic value. ε_R is the random variable representing aleatory *randomness* about the median value, and ε_U is the random variable representing the epistemic *uncertainty* in estimating the median value due to lack of knowledge.

Based on the lognormal assumption of the model, seismic fragility, or the conditional probability of failure given a ground motion level a, at confidence level $Q = q$ (Kennedy and Ravindra, 1984), is calculated by

$$p_{F,q}(a) = \Phi\left[\frac{\ln\left(\frac{a}{A_m}\right) + \beta_U \Phi^{-1}(q)}{\beta_R}\right], \tag{2.3}$$

where β_R and β_U represent logarithmic standard deviations of ε_R and ε_U, respectively.

In applications, A_m is obtained by multiplying the reference ground motion A_{Ref} by a median safety factor F_m, i.e.,

$$A_m = F_m \cdot A_{\mathrm{Ref}}. \tag{2.4}$$

A_{Ref} is obtained from a Review Level Earthquake (RLE) anchored to a selected GMP. In this study, site-specific UHS at Darlington nuclear generating station (NGS) site, anchored to 0.3 g peak ground acceleration (PGA), is chosen as the RLE. For the sake of brevity, readers are directed to EPRI (1994; 2009) for more details on the determination of F_m.