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

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ABSTRACT

This study proposes an innovative fragility method that overcomes the problems in the existing method by using multiple ground motion parameters, providing more realistic seismic capacity and fragility estimates of structures and components. By incorporating the correlations among spectral accelerations at structural dominant modes and the commonly used ground motion parameter such as peak ground acceleration, the conservatism in seismic responses is effectively reduced, in turn resulting in higher seismic capacity estimates of structures and components. Given the advantages of the proposed method, the computational cost is deemed acceptable for applications. The proposed fragility method should be implemented in Seismic Margin Assessment and Seismic Probabilistic Risk Assessment, improving the seismic capacity estimates of the critical structures and components that limit the overall plant seismic capacity. The companion paper (Part II) presents an application of the proposed method to a horizontal heat exchanger in Darlington nuclear generating station in Ontario, Canada to illustrate its procedure and to demonstrate its benefits.

1. Introduction

1.1. Background

In nuclear power industry, nuclear facilities are designed to withstand Design Basis Earthquake ground motions. In recent past, beyond Design Basis Earthquake events jeopardized the design concept of redundancy and defense in-depth related to nuclear facilities. Nuclear industry and regulatory commissions frequently face the issue whether modifications of existing nuclear power plants (NPPs) are required. Accurate seismic risk estimates of existing NPPs are undoubtedly crucial in the decision-making. To quantitatively evaluate the seismic risk of existing NPPs, Seismic Probabilistic Risk Assessment (SPRA) has been implemented in nuclear power industry since late 1970s (Kennedy et al., 1980; Ellingwood, 1994; Huang et al., 2011). The SPRA is the formal process in which the randomness and uncertainty in seismic hazard and seismic fragility are propagated through an engineering model leading to a probability distribution of the frequency of occurrence of failure or other adverse consequences.

Historically, a generic smooth ground response spectrum (GRS) such as 5%-damped median NUREG/CR-0098 response spectrum anchored to a selected GMP was defined as the seismic input in seismic fragility analysis. However, it is recognized that generic response spectra are not appropriate for the regions where the representative response spectral shapes are significantly different over the frequency of interest from the prescribed generic response spectrum (Ni et al., 2015). In recent past, site-specific uniform hazard spectrum (UHS) based on scalar probabilistic seismic hazard analysis (PSHA) was defined as seismic input (EPRI, 2013). The UHS is determined by the aggregation of seismic hazards from different earthquake magnitude and site-to-source distance scenarios; therefore, it is not appropriate to characterize the ground motions induced by an individual potential earthquake. In order to resolve this issue, seismic hazard deaggregation is performed to obtain the controlling earthquakes at a specified probability of occurrence (e.g. 1×10^{-4}) with respect to a selected GMP. Nevertheless, the inherent correlations among spectral accelerations at different vibration periods are not addressed. Studies have showed that spectral accelerations at different periods are not fully correlated (Baker and Jayaram, 2008; Baker, 2011). Ignoring the correlations in the seismic input would overestimate the structural responses and in turn underestimate the median seismic capacities of structures, systems, and components (SSCs) (Cai, 2017). Therefore, the existing fragility methods would result in underestimate of seismic capacities of SSCs.

The main aim of this study is to propose an innovative fragility method that overcomes the problems of existing fragility methods by

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Acronyms

CCDF	complimentary cumulative distribution function
CSA	Canadian standard association
DMF	damping modification factor
EPRI	electric power research institute
FRS	floor response spectrum
GMP	ground motion parameter
GRS	ground response spectrum
HCLPF	high confidence of low probability of failure
NPPs	nuclear power plants
NUREG	nuclear regulatory
PDF	probability density function
PGA	peak ground acceleration
PSHA	probabilistic seismic hazard analysis
$S_a(f)$	spectral acceleration at vibration frequency f
SMA	seismic margin assessment
SPRA	seismic probabilistic risk analysis
SSCs	structures, systems, and components
UHS	uniform hazard spectrum
USNRC	U.S. nuclear regulatory commission
MGMPs	multiple ground-motion parameters
VPSHA	vector-valued probabilistic seismic hazard analysis

using multiple ground motion parameters (MGMPs). In this method, spectral accelerations at the dominant modes of structures are chosen as MGMPs. A newly proposed seismic fragility analysis considering MGMPs method is performed first to develop seismic fragility surfaces, a newly proposed weighting approach is then applied to calculate the weights of input GRS, and seismic fragilities in terms of MGMPs and the weights are finally combined to determine weighting seismic fragility curves and High Confidence of Low Probability of Failure seismic capacities of SSCs in NPPs. Another motive of this study is to help stakeholders make risk-informed decisions based on more realistic plant seismic capacity and risk estimates.

1.2. Literature

In the commonly used lognormal fragility model proposed by Kennedy and Ravindra (1984), the aleatory *randomness* and epistemic *uncertainty* in the seismic input, the structural response, and the component response are propagated into the seismic capacity on the basis of the assumption that all basic variables are lognormally distributed and independent. While the aleatory *randomness* that is inherent in a random phenomenon, e.g., actual dynamic behaviour of the building structure and the effect of random aspects, cannot be reduced, the epistemic *uncertainty* that results from the lack of knowledge may be reduced. Some efforts have been made to eliminate part of uncertainties and thus of conservatism in the existing fragility methods by employing response surface method and Monte-Carlo simulations (De Grandis et al. 2009; Perotti, 2013). Nevertheless, a single GMP is used in evaluating seismic fragilities of SSCs, which is consistent with the lognormal fragility model.

Earthquake engineering community has recognized that using MGMPs would predict more accurate seismic responses. Bazzurro (2002) chose two GMPs, i.e., spectral accelerations at the first two natural frequencies of a 20-story SAC steel moment resisting frame, to predict the maximum interstory drift δ_{max}. Based on two GMPs, more accurate median δ_{max} and smaller uncertainty about median δ_{max} are obtained. It is also found that neglecting the effect of the second GMP

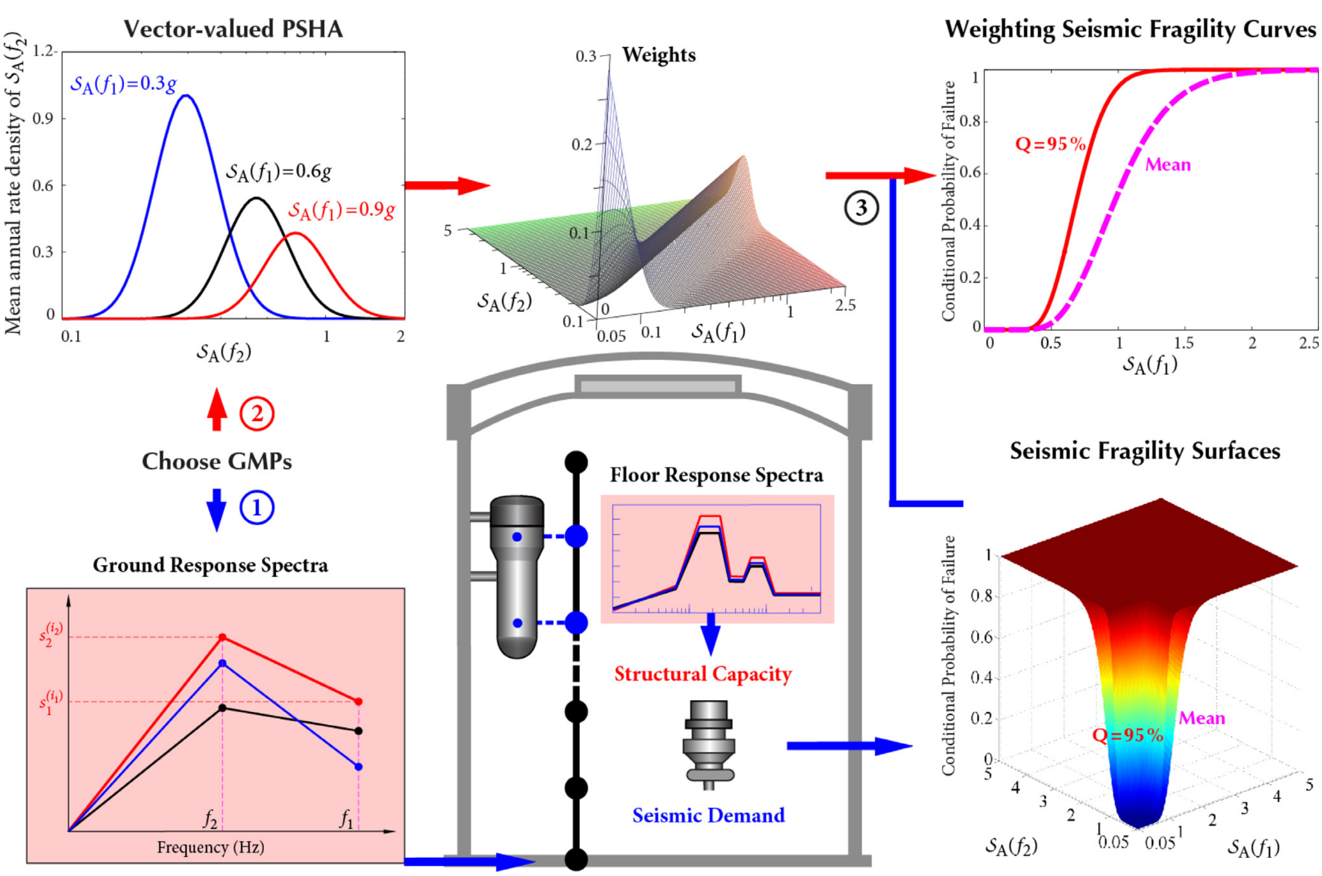

Fig. 1. A general procedure of the innovative fragility method.