Transactions, SMiRT-23
Manchester, United Kingdom - August 10-14, 2015
Division VII, Paper ID 727

SEISMIC FRAGILITY ANALYSIS FOR STRUCTURES, SYSTEMS, AND COMPONENTS OF NUCLEAR POWER PLANTS: PART I — ISSUES IDENTIFIED IN ENGINEERING PRACTICE

Shunhao Ni[1], Zhen Cai[2], Wei-Chau Xie[3], Mahesh D. Pandey[3], Wei Liu[4], and Ming Han[5]

[1] Civil Engineering Analyst, Candu Energy Inc., Canada
[2] Research Assistant, Department of Civil & Environmental Engineering, University of Waterloo, Canada
[3] Professor, Department of Civil & Environmental Engineering, University of Waterloo, Canada
[4] Candu Energy Inc., Canada (Current: China Nuclear Power Engineering Co., Ltd., China)
[5] Director, Civil and Project Engineering, Candu Energy Inc., Canada

ABSTRACT

Seismic Fragility Analysis (FA) has been widely used to calculate the seismic capacities of Structures, Systems, and Components (SSCs) of Nuclear Power Plants (NPPs). The seismic capacity of individual SSC from the FA, in terms of seismic fragility curves or High Confidence of Low Probability of Failure (HCLPF) value, is utilized as an input to Seismic Margin Assessment (SMA) or Seismic Probabilistic Risk Assessment (SPRA) of an NPP. In the seismic FA, a single ground-motion parameter, such as Peak Ground Acceleration (PGA), Spectral Acceleration (SA), or the averaged SA over a frequency range of interest, is used to represent the seismic capacity of an SSC. However, a number of deficiencies of the FA, due to the use of a single ground-motion parameter, have been recognized in the engineering practice of nuclear power industry.

In this study, the deficiencies of the FA methodology, in which a single ground-motion parameter is used to represent the seismic capacity, are identified and discussed from the point of view of engineering practice. A case study has been performed to obtain a general observation that the fragility curves or HCLPF seismic capacities obtained from the FA method are significantly influenced by a number of factors, such as the input spectral shape, ground-motion parameter selected, the characteristics of the supporting structures. A methodology to improve the current FA and to eliminate the deficiencies will be proposed and presented in a separate study: Part II — Use of Multiple Ground-Motion Parameters.

Keywords: Seismic Fragility Analysis, Seismic Margin Assessment, Seismic Probabilistic Risk Assessment

INTRODUCTION

Seismic Fragility Analysis (FA) has been widely used to calculate the seismic capacities of Structures, Systems, and Components (SSCs) of Nuclear Power Plants (NPPs) (EPRI, 1994, EPRI, 2002, EPRI, 2009). The seismic capacity of individual SSC from the FA, in terms of seismic fragility curves or High Confidence of Low Probability of Failure (HCLPF) value, is utilized as an input to Seismic Margin Assessment (SMA) or Seismic Probabilistic Risk Assessment (SPRA) of an NPP. The results of SMA or SPRA are then used by regulators and utilities for their risk-informed decision making.

In the seismic FA, a single ground-motion parameter, such as Peak Ground Acceleration (PGA), Spectral Acceleration (SA), or the averaged SA over a frequency range of interest, is used to represent the seismic capacity of an SSC. However, a number of deficiencies of the FA, due to the use of a single ground-motion parameter, have been recognized in the engineering practice of nuclear power industry. These deficiencies have prevented the nuclear industry from accurately predicting the seismic capacity and risk of an NPP.

In this study, the deficiencies of the FA methodology, in which a single ground-motion parameter is used to represent the seismic capacity, are identified and discussed from the point of view of engineering practice. A case study has been performed to obtain a general observation that the fragility curves or HCLPF seismic capacities obtained from the FA method are significantly influenced by a number of factors, such as the input spectral shape, ground-motion parameter selected, the characteristics of the supporting structures. A methodology to improve the current FA and to eliminate the deficiencies will be proposed and presented in a separate study: Part II — Use of Multiple Ground-Motion Parameters.

SEISMIC FRAGILITY ANALYSIS

Seismic fragility of the SSC is defined as the probability that the seismic capacity in terms of a Ground-Motion Parameter (GMP) A of a SSC is less than a given threshold a of that GMP, i.e.,

$$p_F(a) = P\{A < a | GMP = a\}. \tag{1}$$

The GMP seismic capacity A of a SSC is often expressed as a product of three variables, i.e.,

$$A = A_m \varepsilon_R \varepsilon_U , \tag{2}$$

where A_m is the median GMP seismic capacity, ε_R is a random variable representing inherent randomness (aleatory uncertainty) of A, and ε_U is a random variable representing uncertainty (epistemic uncertainty) of A due to lack of knowledge. The random variables ε_R and ε_U are taken to be lognormally distributed with unit median values and with logarithmic standard deviations of β_R and β_U, respectively.

Based on equation (2) and the assumption that ε_R and ε_U are lognormally distributed, the seismic fragility curve, i.e., the probability of failure given a GMP threshold a at a confidence level $Q = q$, is expressed as (Kennedy and Ravindra, 1984)

$$p_F(a,q) = P\{A < a | GMP = a, Q = q\} = \Phi\left[\frac{\ln(\frac{a}{A_m}) + \beta_U \Phi^{-1}(q)}{\beta_R}\right]. \tag{3}$$

In equation (3), Φ (*) stands for standard normal distribution function. The confidence levels Q are often taken as several discrete values, such as 5%, 50%, and 95%. Equation (3) gives a family of seismic fragility curves for various levels of confidence, as shown in Figure 1.

Take 5% probability of failure and 95% confidence level, and solve for a, in equation (3), a High Confidence of Low Probability of Failure (HCLPF) seismic capacity in terms of a selected GMP a can be obtained (EPRI, 1994)

$$C_{HCLPF} = A_m \cdot e^{-1.65(\beta_R + \beta_U)}. \tag{4}$$

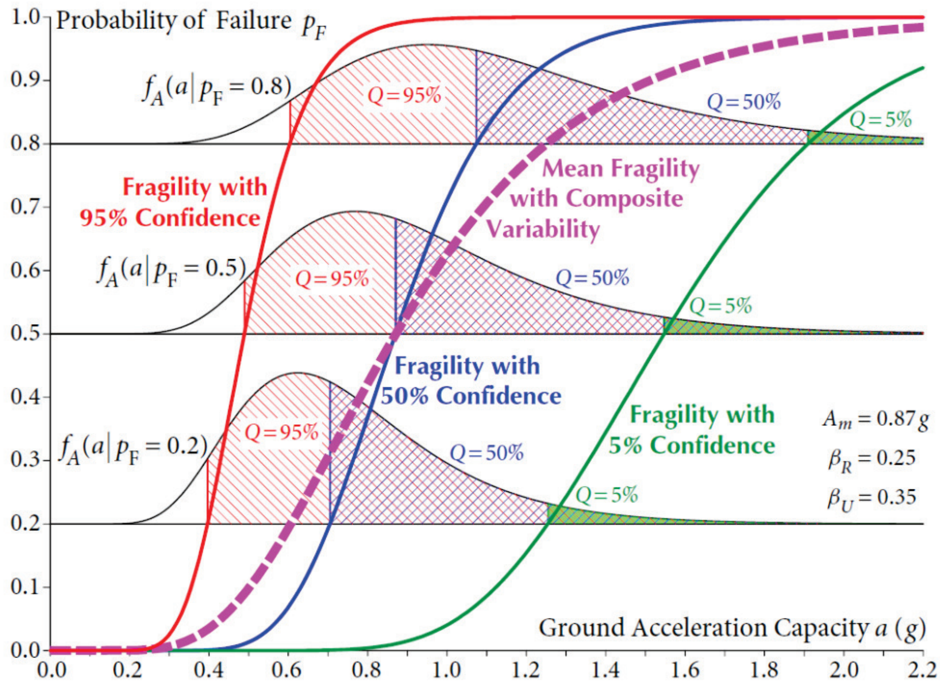

Figure 1. Fragility Curves

As can be seen in equations (3) and (4), to calculate the seismic fragility curves and the HCLPF seismic capacity of a SSC, the major task is to determine the median capacity A_m, and the associated randomness β_R and uncertainty β_U.

In the determination of A_m, β_R, and β_U, an intermediate random variable, the factor of safety F, is often used. It describes the level that the GMP seismic capacity A is above the reference earthquake level in terms of the same GMP quantity A_{Ref}, and is defined as

$$A = F \cdot A_{\text{Ref}} . \tag{5}$$

The physical meaning of F is the ratio of actual seismic capacity of SSC to actual response (demand) of the SSC due to reference earthquake. The reference earthquake is usually represented by a smoothed response spectrum such as Review Level Earthquake (RLE), which has a specified GMP of A_{Ref}. In engineering practice, the factor of safety F is a product of a number of sub-factors of safety accounting for strength, inelastic energy absorption, and responses of SSCs. The associated uncertainties of F can be obtained by using testing and analytical methods, or a combination of them, such as second moment procedure and Monte Carlo simulation (EPRI, 1994).

DEFICIENCIES IN EXISTING SEISMIC FRAGILITY ANALYSIS

From the definition of seismic fragility in equations (1) – (3) and the procedure to obtain the parameters required for a seismic fragility model in equation (5), a single GMP, such as peak ground acceleration (PGA), spectral acceleration (SA), or the averaged SA over a frequency range of interest, is used to represent the seismic capacity of a SSC in the existing methodology. Based on the fact that the SSCs in a nuclear power plant are dynamically complicated and multi-mode dominant in most cases, two major deficiencies have been observed in the existing methodology and are discussed as follows.

1. *Reference Earthquake*. As discussed above, the reference earthquake is usually represented by a smoothed response spectrum, which has a specified value of the selected GMP, such as PGA or SA. This smoothed response spectrum is used as the seismic input to obtain the seismic demand of the SSC, which is part of the determination of the factor of safety in equation (5). The specified value of the selected GMP is the reference quantity A_{Ref} in equation (5). Assume that there are two reference earthquakes, i.e., the smoothed response spectra, having different spectral shapes but the same A_{Ref}, e.g., PGA, the resulting factors of safety and the associated uncertainties of the SSC based on these two reference earthquakes could be very different since the response of the SSC largely depends on the spectral shape of the input response spectrum. This usually results in inconsistent seismic fragility curves and HCLPF seismic capacities of the SSC.
2. *Ground-Motion Parameter*. In the existing seismic fragility analysis, a single GMP is used to represent the seismic capacity of a SSC. Ideally, the seismic capacity of a SSC should be an intrinsic property of the SSC and then independent of the seismic input. In engineering practice, a single GMP, which is deemed to be much correlated with the SSC response, is often used to characterize the seismic capacity. However, this characterization can never be complete due to the fact that the SSCs are dynamically complicated.

CASE STUDY

In this section, a case study for a typical heat exchanger is conducted to demonstrate the deficiencies in the existing fragility analysis method. To eliminate these deficiencies from the mechanism, a methodology is proposed and presented in a separate study: Part II — Use of Multiple Ground-Motion Parameters, using the same heat exchanger case.

The heat exchanger data used in this study is based on the fragility analysis example of a horizontal heat exchanger presented in Section 8 of EPRI (1994). Configuration details of the heat exchanger are shown in Figure 2 and the properties are listed in Table 1.

The heat exchanger has a diameter of 8 feet, a length of 30 feet, and is supported by three equally spaced saddles. Each saddle is secured to the concrete floor by three sets of 2 cast-in-place anchor bolts. Two of the saddle base plates (Support S1) have slotted holes, which allow the thermal expansion of the tank in the longitudinal direction. Each saddle has four stiffener plates to increase the rigidity of the heat exchanger in the longitudinal direction. A total weight of 110 kips is estimated for the exchanger. The heat exchanger is assumed to be located at the ground level on a rock site, and will be subjected to tri-directional excitations during seismic events.

Modal analysis has shown that the longitudinal and transverse vibration frequencies of the heat exchanger are 8.15 Hz and 25.4 Hz, respectively. Since the heat exchanger is very rigid in the vertical direction, spectral acceleration in the vertical direction can be approximated by PGA.

By using different reference earthquakes, i.e., a Uniform Hazard Spectrum (UHS) and a NUREG/CR-0098 median spectrum, as shown in Figure 3, for the fragility analysis, inconsistent fragility curves with a GMP of PGA have been obtained, as shown in Figure 4. As a result, the HCLPF seismic capacities in terms of PGA for the heat exchanger are also different: 0.26g for the NUREG/CR-0098 median spectrum and 0.34g for the UHS (a difference of 24%).

As discussed previously, there are two major factors jointly influencing the resulting seismic capacity of the heat exchanger when different reference earthquakes are used. Different spectral shape is one of the factors since three dynamic modes are considered in the analysis. The other factor is that the PGA is selected as the GMP, which is not very correlated with the response of the heat exchanger since the dominant mode of the heat exchanger is at its longitudinal direction with 8.15 Hz.

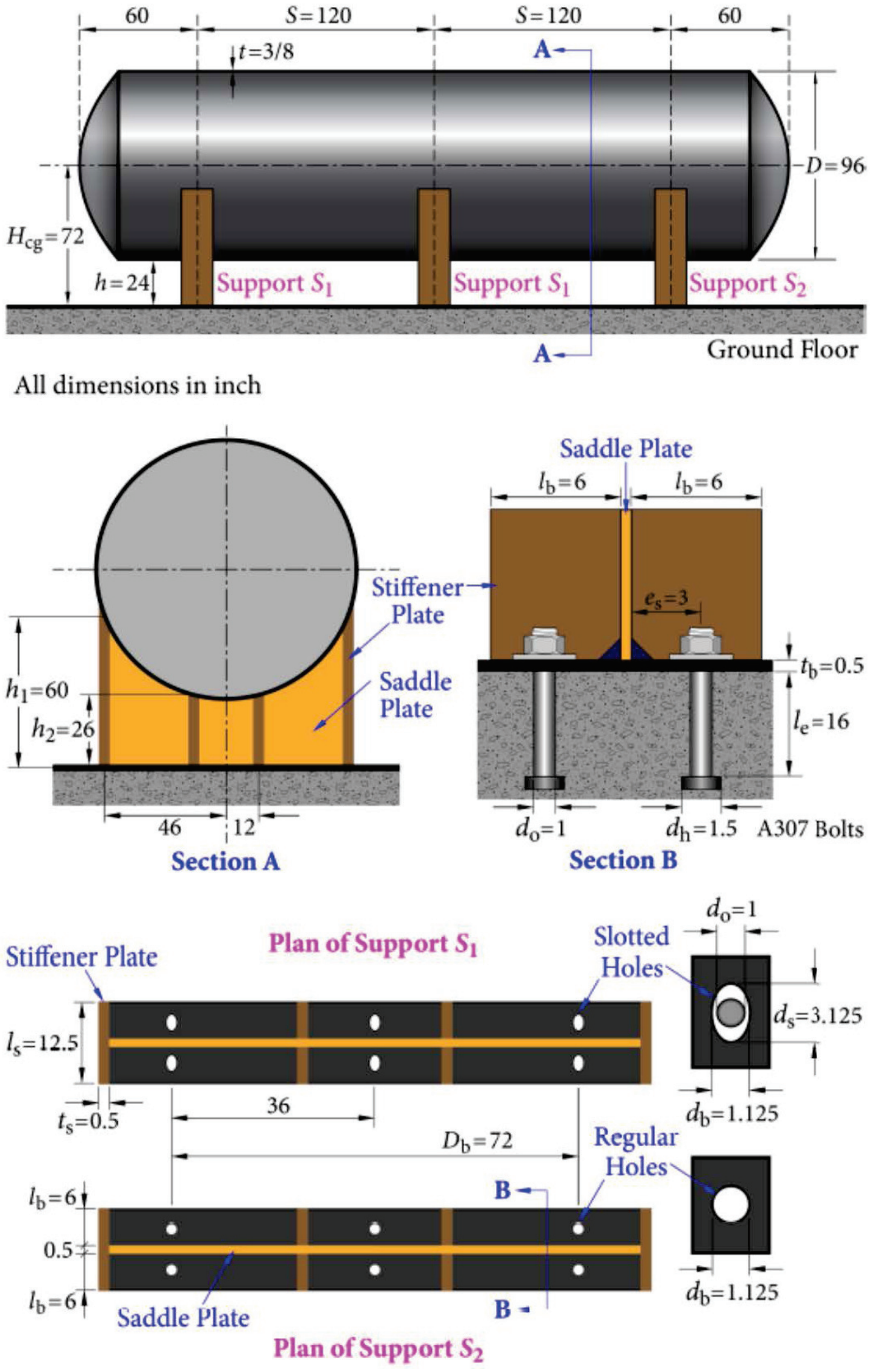

Figure 2. Configuration of Horizontal Heat Exchanger

Table 1: Properties of Horizontal Heat Exchanger

Property	Variable	Value
Heat Exchanger Tank		
Diameter	D	96 in
Length	L	360 in
Floor to bottom tank	h	24 in
Height to center of gravity	H_{cg}	72 in
Shell thickness	t	3/8 in
Weight	W	110 kip
Saddle Supports (ASTM A36)		
Base plate thickness	t_b	0.5 in
Anchor bolt hole diameter	d_b	1-1/8 in
Slotted anchor hole dimension	d_s	3-1/8 in
Saddle plate to edge of base plate	l_b	6 in
Distance between outside bolts in saddle base plate	D_b	72 in
Weld length	l_w	6 in
Weld leg dimension	t_w	1/4 in
Stiffener width	l_s	12-1/2 in
Stiffener height (outside pair)	h_1	60 in
Stiffener height (inside pair)	h_2	26 in
Stiffener thickness	t_s	0.5 in
Number of supports	NS	3
Anchor Bolts (ASTM A307)		
Area through bolt	A_{gross}	0.7854 in^2
Area through threads	A_{net}	0.6057 in^2
Embedment length	l_e	16 in
Bold diameter	d_o	1 in
Head diameter	d_h	1-1/2 in
Eccentricity from anchor bolt centerline to saddle plate	e_s	3 in
Number of anchor bolt locations at each saddle	NL	3
Number of anchor bolts at each location	NB	2

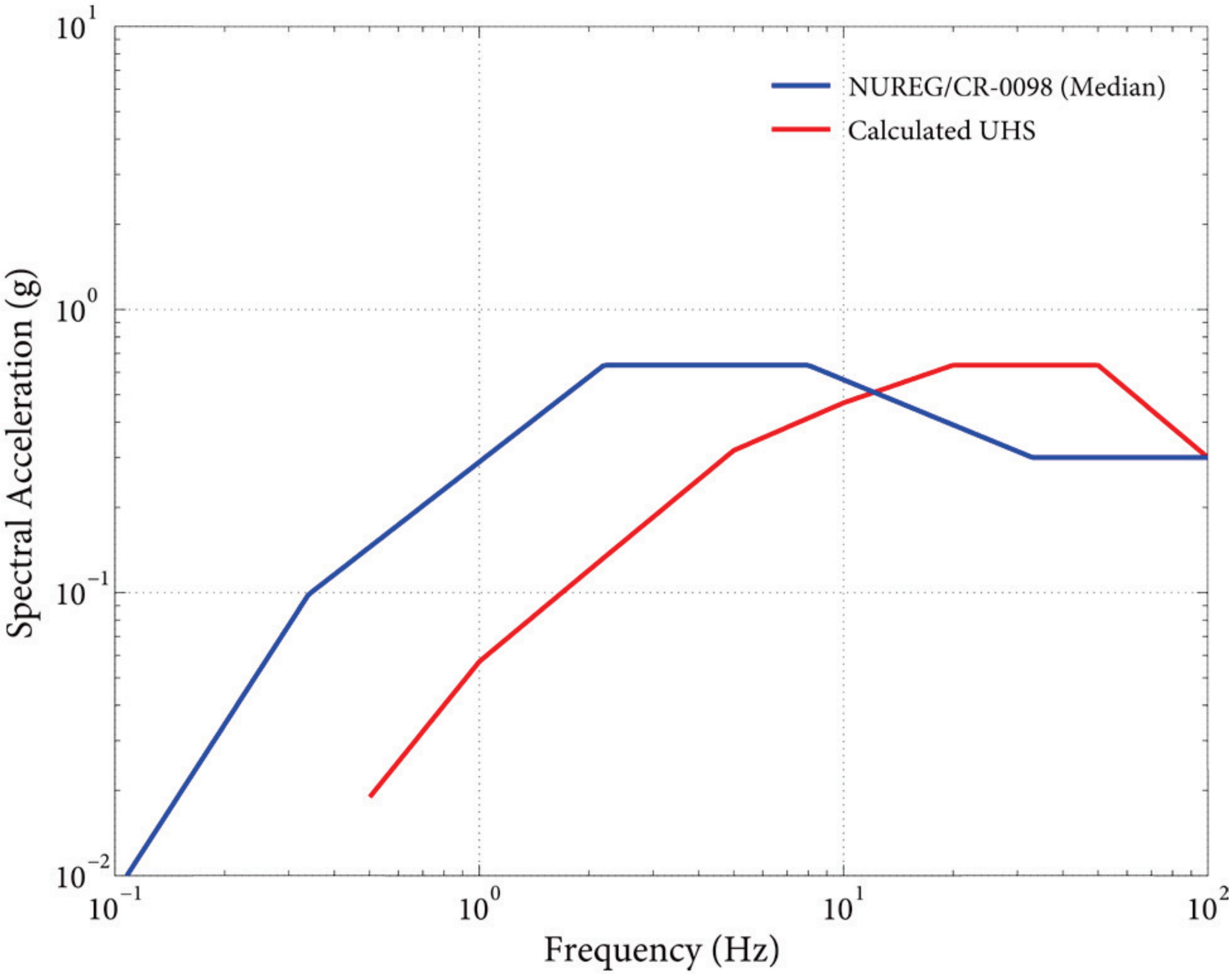

Figure 3. Reference Earthquakes for Fragility Analysis

To reduce this difference, the SA at dominant frequency of the heat exchanger has been used as the GMP. As shown in Figure 5, the difference between the fragility curves using the NUREG/CR-0098 median spectrum and the UHS for the GMP of SA is smaller than that for the PGA. A reduced difference can also be observed from the resulting HCLPF seismic capacity: 0.60g for the NUREG/CR-0098 median spectrum and 0.47g for the UHS (a difference of 22%).

Although the SA at dominant frequency of the heat exchanger has been used as the GMP to characterize the seismic capacity, this characterization can never be complete since the dynamic modes at its transverse and vertical directions contribute to the response as well. The above phenomenon has been generally observed in current nuclear industry practice for the fragility analysis of the SSCs.

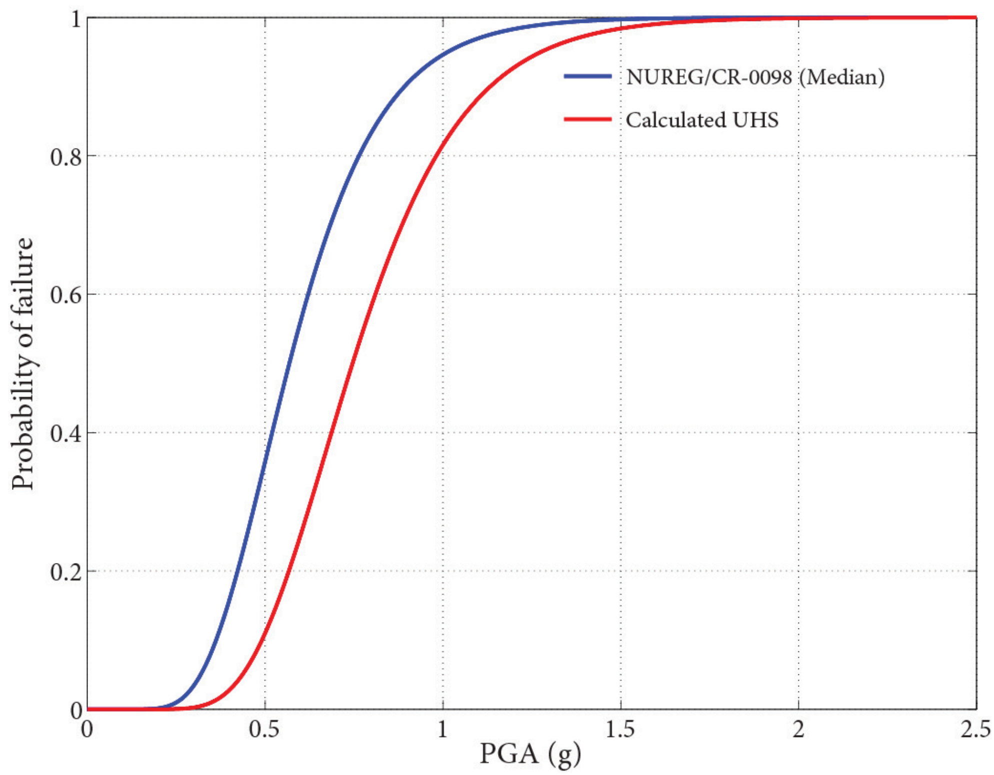

Figure 4. Fragility Curves Using PGA

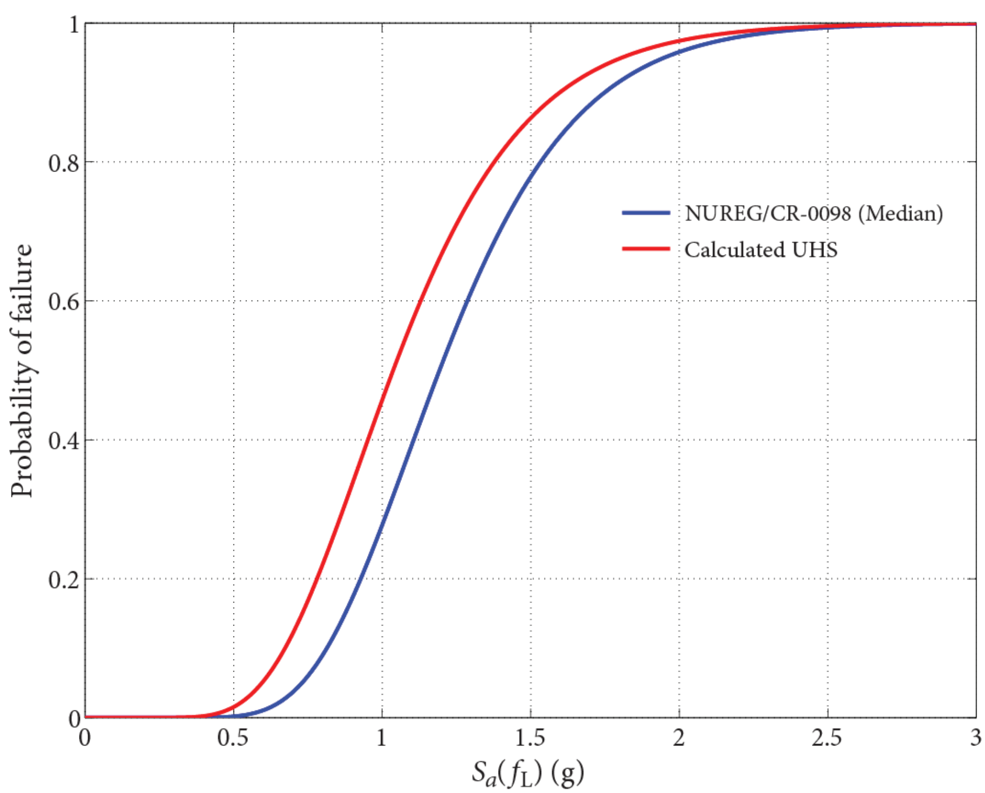

Figure 5. Fragility Curves Using SA at Fundamental Frequency

CONCLUSION

In this study, two major deficiencies have been observed in the existing fragility analysis methodology and are discussed with an example of a horizontal heat exchanger. The reference earthquakes and the ground-motion parameters (GMP) selected jointly induce the inconsistency in the existing fragility analysis methodology, due to the factor that only one GMP is used to characterize the seismic capacity and this characterization can never be complete since the SSCs are usually dynamically complicated. Hence, a methodology to improve the current fragility analysis and to eliminate the deficiencies is proposed and presented in a separate study: Part II — Use of Multiple Ground-Motion Parameters.

REFERENCES

EPRI (1994). "Methodology for Developing Seismic Fragilities, TR-103959," Electric Power Research Insititue, CA.

EPRI (2002). "Seismic Fragility Application Guide, 1002988," Electric Power Research Institute, CA.

EPRI (2009). "Seismic Fragility Application Guide Update, 1019200," Electric Power Research Institute, CA.

Kennedy, R. P. and Ravindra, M.K. (1984). "Seismic Fragilities for Nuclear Power Plant Risk Studies," *Nuclear Engineering and Design*, 79, 47-68.