Effect of ground motion uncertainly on seismic risk in the frame of RI-PB

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Abstract: Current seismic design in Japan may be conservative, lack flexibility, and be insufficient for comprehensive risk assessment. The Risk-Informed Performance Based (RI-PB) seismic design is expected to address these issues by incorporating not only risk information but also other factors. In RI-PB seismic design, ground motions with an appropriate level of risk are used to verify the appropriateness of component design. However, the uncertainty of ground motion may distort the final results. This paper describes the uncertainties associated with fragility curves used as a risk quantification method in the RI-PB design approach, with the aim of enhancing understanding of these uncertainties. Consequently, we quantitatively assessed the uncertainty of the fragility curves. Furthermore, by assuming a hazard curve and jointly considering fragility curves, we calculated the annual damage probability in nuclear power plants. As a result, the annual damage probability depends on the slope of the hazard curve and the nonlinearity of the equipment. When evaluating the final results, it was observed that in regions with active seismic activity, less intense earthquakes are required compared to regions with low seismic activity.

Keywords: PRA, RI-PB, Fragility curve, Hazard curve.

1. INTRODUCTION

The Fukushima Daiichi Nuclear Power Plant experienced a severe accident resulting in the release of a large amount of radioactive material. This accident, characterized by a meltdown and hydrogen explosions, was triggered by the 2011 Tohoku region Pacific Ocean earthquake, with its epicenter offshore from the Sanriku coast in Miyagi Prefecture. In earthquake-prone regions like Japan, ensuring strong robustness is crucial not only within design standards but also for events exceeding design criteria to maintain the seismic safety of nuclear power plants. However, the current seismic design review guidelines for nuclear reactor facilities in Japan [1] are based on deterministic evaluations. In the event of an earthquake surpassing the design basis seismic motion, the guidelines advocate efforts to minimize residual risk as reasonably as possible using risk-informed considerations. Therefore, relying solely on these guidelines poses challenges to the pursuit of nuclear power plant safety.

Therefore, Sakai et al [2]. proposed a framework for performance-based design methods that incorporate high flexibility and sufficient risk assessment by utilizing probabilistic evaluations, in addition to conventional deterministic assessments, as part of pursuing enhanced safety in nuclear power plants. This approach entails setting seismic motions based on a uniform risk spectrum for each structure and conducting nonlinear seismic response analysis to derive fragility curves. However, the impact of uncertainty in the phase characteristics of the design seismic motion on fragility curves has not been thoroughly studied. Moreover, the influence of this uncertainty on the annual damage probability assumed in the hazard curve remains unexplored, leaving the impact of design seismic motion on the final outcomes uncertain.

Therefore, this paper quantitatively evaluates the uncertainty in the phase characteristics of the design seismic motion used in RI-PB and discusses its impact on annual damage probability.

2. Generating Design Earthquake Motions for RI-PB Design Method

To assess the uncertainty in the phase characteristics of the design seismic motion used in RI-PB, a case study was conducted. Miyagi Prefecture in the Tohoku region of Japan was selected for this study, given its high seismic activity owing to its proximity to the boundary between the Pacific Plate and the Eurasian Plate. In 2011, a magnitude 9.0 earthquake occurred along this plate boundary in Miyagi Prefecture, leading to the Fukushima Daiichi nuclear power plant accident.

In nonlinear response analysis that considers risk, time history analysis using seismic waveforms is common. Therefore, the time history waveforms of the design seismic motions used in RI-PB were created as simulated seismic waves with spectra matching the uniform hazard spectrum at the Miyagi site. There are various methods for creating time history waveforms; however, in this study, we employed a method that fits the target response spectrum by superimposing sine waves.

The acceleration time history *y(t)* was defined as a combination of multiple sine waves with different amplitudes and frequencies, as shown in Equation (1) [3]. Additionally, a uniform random number was used for the first phase angle φ_i.

$$y(t) = e(t)\sum_{i}^{N} A_i \cos(\omega_i t + \varphi_i) \tag{1}$$

Where, *N* represents the number of components, *e(t)* is the envelope function providing non-stationarity, A_i is the amplitude of the *i*-th component, ω_i is the angular frequency of the *i*-th component, and φ_i. is the phase angle of the *i*-th component.

Based on Equation (1), we created time history waveforms for 10 design seismic motions by using different random phase angles φ_i . An example of the resulting time history waveform is shown in Figure 1. Additionally, we present the response spectrum of the created time history waveforms and the target Miyagi site uniform hazard spectrum in Figure 2.

Furthermore, to verify whether the created response spectra conform to the target response spectrum, we set the coefficient of variation from the target response spectrum to be less than 0.05.

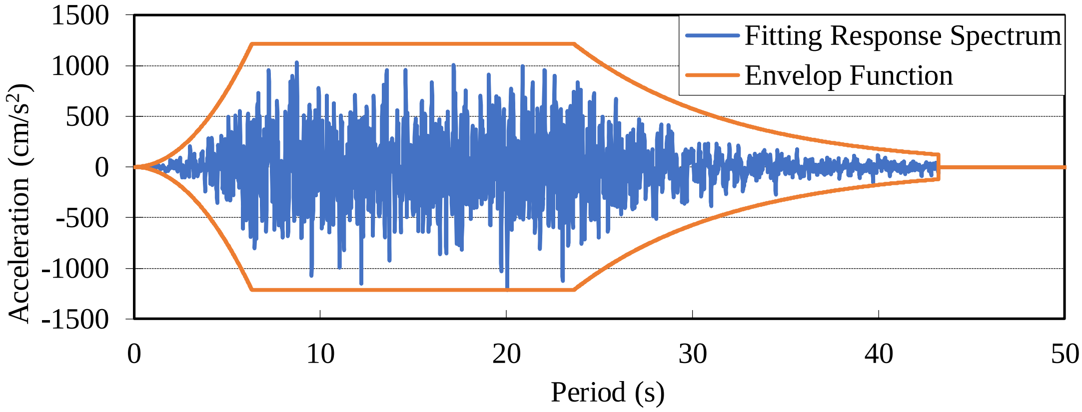

Figure 1. Time history of ground motion

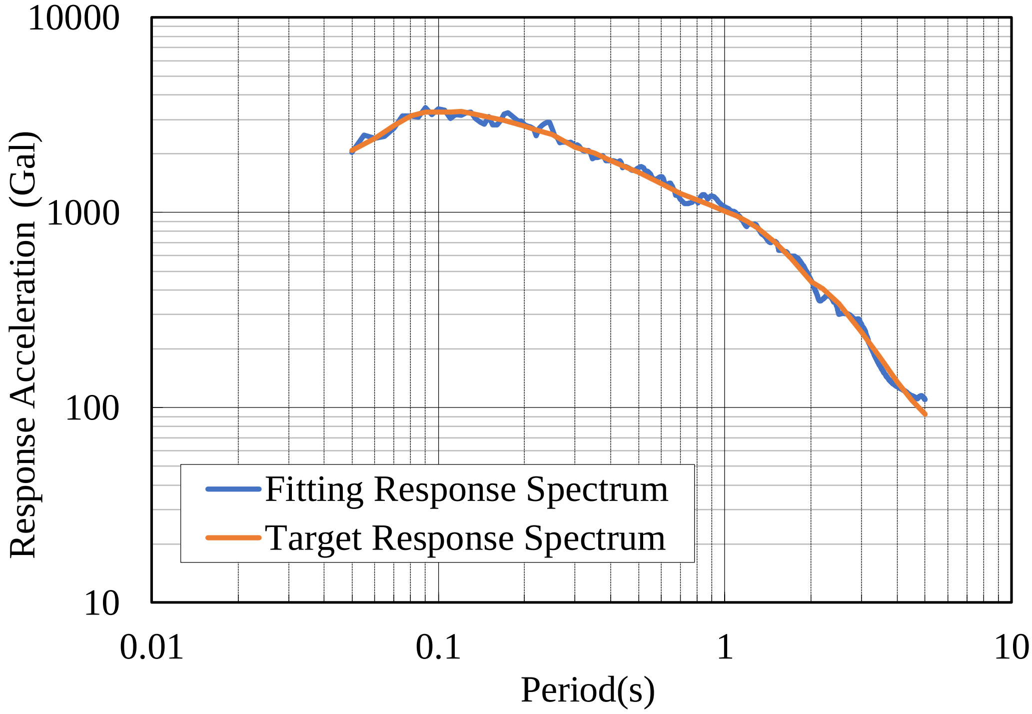

Figure 2. Target Response Spectrum

3. The Impact of Phase Characteristics Uncertainty on Fragility Curves

The fragility curve represents the conditional probability of structural system component (SSC) given a specific seismic intensity. Generally, fragility curves are represented by a lognormal cumulative distribution function parameterized by the median capacity, A_m, and the logarithmic standard deviation, β, prioritizing ease of handling in numerical analysis [4]. Here, A_m represents the seismic intensity corresponding to a 0.5 probability of damage. On the other hand, β is used as a parameter to represent the uncertainty in equipment strength, and when β is large, the slope of the fragility curve is gentle, typically recognized to be around 0.2 to 0.4. [2]

First, earthquake response analysis using the Newmark β method was conducted on the created design seismic motions, assuming ground-installed structural equipment with assumed fundamental periods $T = 0.1, 0.2, 0.5$ seconds, and ductility ratios $\mu = 1, 2, 4$, resulting in 12 combinations in total. Additionally, the damage probabilities were determined using the Monte Carlo method by calculating the resistance term (R) and load term (S), and then determining the frequency of R > S, which was divided by the number of trials. Subsequently, fragility curves were developed. Figure 3 shows an example of the fragility curve created.

As shown in Figure 3, the fragility curves created from the ten waveforms of designed ground motions exhibit variability, highlighting the influence of the phase characteristics of the ground motions. To quantitatively assess these influences, we estimated the values of A_m and β and calculated their coefficients of variation. The mean values of the estimated A_m and β are presented in Table 1, along with their coefficients of variation in Table 2.

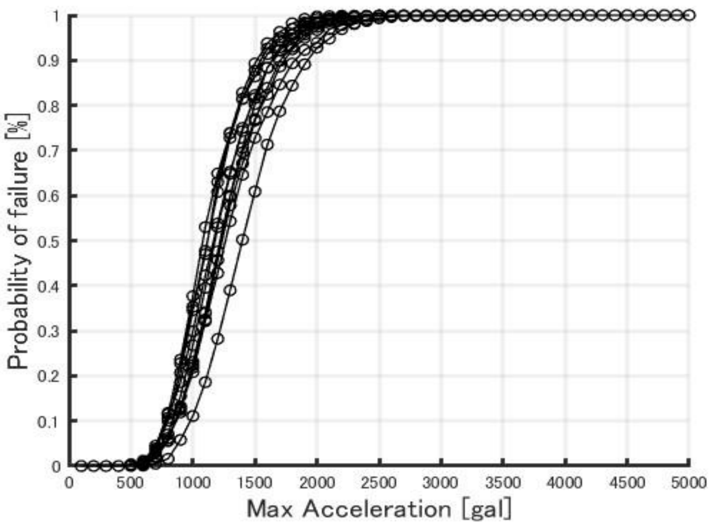

Figure 3(a). Fragility curve [μ = 1, T=0.1]

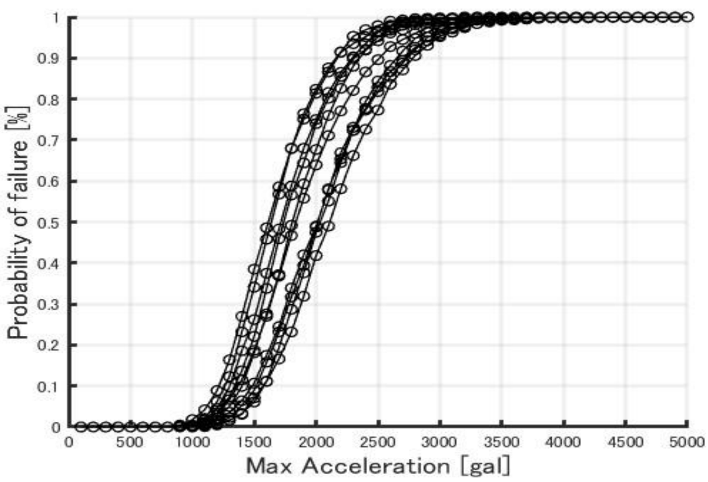

Figure 3(b). Fragility curve [μ = 2, T=0.1]

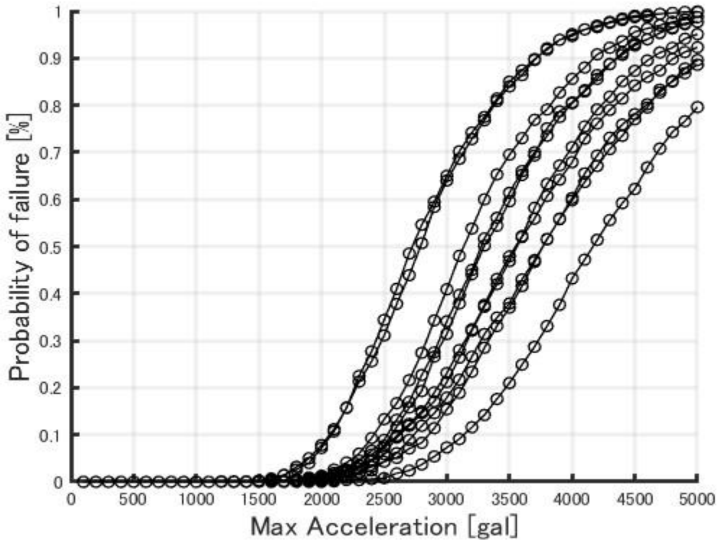

Figure 3(c). Fragility curve [μ = 4, T=0.05]

Table 1. Average Estimate Parameter

Average				
ductility	Parameter	Period(s)		
		0.1	0.2	0.5
1	Am	1196	1203	1233
	β	0.265	0.270	0.295
2	Am	1853	2096	2567
	β	0.220	0.295	0.290
4	Am	3410	3963	4888
	β	0.224	0.267	0.271

Table 2. Coefficient of Variation

Coefficient of Variation				
ductility	Parameter	Period(s)		
		0.1	0.2	0.5
1	Am	7.52%	7.97%	7.88%
	β	4.85%	2.74%	5.78%
2	Am	9.42%	3.72%	11.22%
	β	5.74%	12.01%	10.98%
4	Am	13.08%	9.47%	16.61%
	β	4.29%	13.71%	14.43%

As shown in Table 2, the phase characteristics of the designed ground motions introduce an uncertainty β in the fragility curves, resulting in an error of approximately 10%. Furthermore, based on the results in Table 1, the uncertainty in β ranged from approximately 0.1 to 0.3.

4. Regarding the impact on the damage probability

To evaluate the impact of the phase characteristics of the designed ground motions on the fragility curves, as quantified in Table 2, we calculated the damage probability assuming of a hazard curve. A typical hazard curve is defined by NEA (2000) [5] as shown in Equation (2) and (3).

$$\boldsymbol{H_{(a)} = K_I a^{-K_H}} \tag{2}$$

$$K_H = \frac{1}{log_{10}(A_R)} \tag{3}$$

Where $H_{(a)}$ is the annual frequency of exceedance of ground motion level “a”, K_I is an appropriate parameter for hazard curve, and K_H is a slope parameter.
Additionally, Kennedy (2011) [6] derived the probability of damage as shown in Equation (4) using the parameter β of the fragility curve and equation (3).

$$P_F = K_I C_{50\%}^{-K_H} e^{(1/2)(K_H \beta)^2} \tag{4}$$

$C_{50\%}$ is synonymous with the median capacity Am. The seismic motion ratio A_R was defined using values ranging from 1.5 to 6.0 as defined in ASCE (2005) [7].
We present the mean and logarithmic standard deviation of the calculated and plotted these values in Table 3 and figure 4. From Figure 4, it can be observed that as the slope of the hazard curve increases, the logarithmic standard deviation also increases. Therefore, when applying the designed ground motions in RI-PB, it is important to consider this uncertainty and design accordingly.

Table 3. The relationship between log standard deviation and hazard gradients.

AR	K_H	Pf_Average	Logarithmic standard deviation
1.5	5.679	1.383E-19	0.482
1.75	4.115	2.026E-14	0.346
2.0	3.322	8.560E-12	0.278
2.25	2.839	3.417E-10	0.237
2.5	2.513	4.152E-09	0.210
2.75	2.276	2.544E-08	0.190
3.0	2.096	1.012E-07	0.175
3.25	1.954	3.012E-07	0.163
3.5	1.838	7.306E-07	0.153
3.75	1.742	1.525E-06	0.145
4.0	1.661	2.840E-06	0.138
4.25	1.591	4.844E-06	0.132
4.5	1.531	7.705E-06	0.127
4.75	1.478	1.158E-05	0.123
5.0	1.431	1.663E-05	0.119
5.25	1.389	2.297E-05	0.115
5.50	1.351	3.072E-05	0.112
5.75	1.316	3.999E-05	0.109
6.0	1.285	5.084E-05	0.107

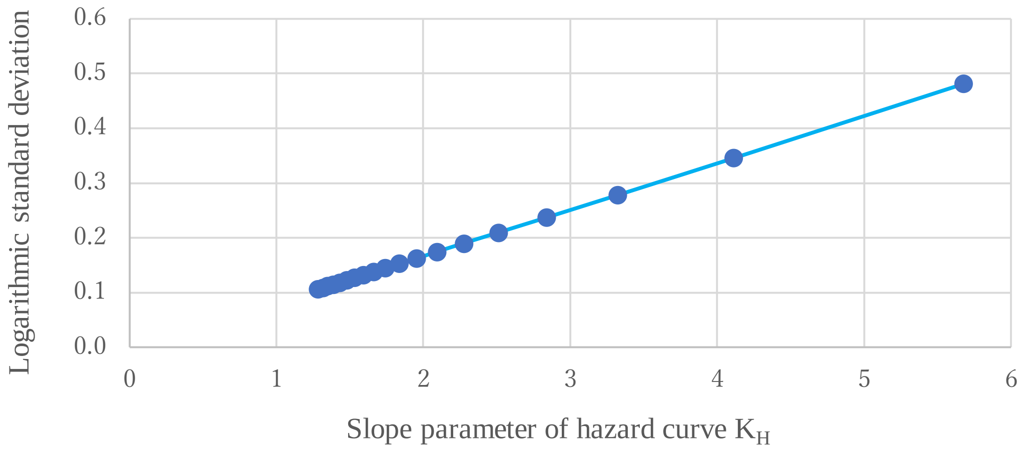

Figure 4. The influence of phase characteristics on damage probability.

5. Conclusion

This paper investigates the effect of uncertainty in ground motion on generated fragility curves and the annual probability of failure, incorporating the seismic hazard curve.

(1) The uncertainty in ground motion phases on fragility curves was assessed, revealing that the degree of nonlinearity affects the characteristics of fragility curves (A_m, β).

(2) The annual probability of failure depends on the slope of the hazard curve and the degree of nonlinearity of components.
(3) The impact on the annual damage probability was found to depend on the parameter $K_{H,}$ which represents the slope of the hazard curve..

References

[1] NUSC, 2006. The seismic design review guidelines for nuclear power plant facilities.
[2] Sakai, T., Ohtori, Y., Katayama, Y., Matsumaru, N and Muta, H. (2022). A Framework of RI-PB Seismic Design/Part 1: Main Characteristics of the Proposed RI-PB Design and Considerations on Balanced Risk Profile, SMiRT-26.2022
[3] BCJ,1992, Guideline for the Methodology of Creating Design Input Seiemic Motions
[4] Kennedy RP, Ravindra MK. Seismic fragilities for nuclear power plant risk studies. Nucl Eng Des. 1984; 79(1): 47-68.
[5] NEA, 2000. Proceedings of the OCED/NEA Workshop on Seismic Risk.
[6] Kennedy. Performance-goal based (risk informed) approach for establishing the SSE site specific response spectrum for future nuclear power plants. Nucl Eng Des. 2011; 241: 648-656.
[7] ASCE, 2005. Seismic Design Criteria for Structures, System and Components in Nuclear Facilities. American Society of Civil Engineers, ASCE Standard 43-05