Enhancement of Seismic Fragility Evaluation of Equipment Considering Correlation and Impact Analyses on Seismic Risk Quantification

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Abstract: Methods currently employed for evaluating seismic fragility are inefficient in reflecting the true seismic risk because they do not consider element correlation. Hence, this paper discusses the incorporation of partial correlations for enhancing seismic fragility evaluations of nuclear equipment. We conducted sensitivity analyses for a system that significantly influenced seismic risk. First, we classified the system into two groups and set analytical cases with different values of correlation coefficient. Subsequently, we performed seismic fragility analysis via the Reed–McCann method for the cases. The results of the sensitivity analyses quantitatively demonstrated the effect of the degree of correlation on seismic fragility evaluations. Moreover, we performed seismic risk quantification for a boiling-water-reactor model plant, focusing on seismic correlation. We compared and analyzed the risk-quantification results obtained by considering correlation and those based on conventional assumptions (complete dependence and complete independence conditions). The findings of this study provide valuable insights for improving and optimizing risk profiles in seismic probabilistic risk assessment.

Keywords: Seismic PRA, Seismic Fragility, Correlation, Dependency

1. INTRODUCTION

It is widely accepted that decision making must be grounded on the current knowledge of the decision maker [1]. Currently, the concept of risk-informed decision making (RIDM) is widely employed in nuclear and non-nuclear facilities [2]. It is imperative to apply RIDM concepts for critical facilities to ensure their safety. Probabilistic risk assessment (PRA) can be conducted to provide crucial information within the RIDM framework. External-event PRA involves considerable uncertainties. Hence, the validity of external-event PRA must be enhanced to achieve successful RIDM and ensure the safety of nuclear power plants.

Safety systems are fundamentally redundant in nuclear power facilities and installations. In conventional seismic PRA, it is recommended to model the seismic fragility of a safety system on the premise of "complete dependency." All elements that comprise the system are assumed to fail simultaneously due to vibratory motions. The fragility of the system is then used for seismic risk quantification. However, the as-computed seismic fragility is not sufficiently realistic because the safety of the elements depend on their response to seismic ground motions. In addition, it does not consider the seismic correlation between the elements. Hence, in this study, we aimed to develop a more practical method for evaluating seismic fragility, which is required for performing seismic PRA for real plants, by considering element correlations.

2. SEISMIC CORRELATION

In conventional seismic PRA for actual nuclear power plants (NPPs), two seismic correlation conditions are assumed: complete independence and complete dependence. However, it is estimated that true correlation exists between the two conditions above. In other words, realistic conditions are partially correlated. Hence, partial correlations among target structures, systems, and components (SSCs) must be considered when evaluating seismic fragility. Several studies have investigated this issue from the perspective of common cause failures [3].

Seismic Safety Margins Research Program, conducted at the Lawrence Livermore National Laboratory, was a pioneering attempt to evaluate dependencies in the seismic responses and capacities of components. The key finding of the project was that a joint lognormal distribution can effectively represent and model the responses of various components installed on different floors.

Reed et al. [4] developed a distinctive method to quantify dependencies between component failures. This method searches for common factors of variability in the response and capacity calculations, which are required for seismic fragility evaluation. Case study analyses using this method are discussed in NUREG/CR-7241 [5]. It has been determined that the method can be adopted for seismic PRA with a reasonable level of practicality.

In addition to the aforementioned methods, several other methods have been developed to quantify the dependencies [6-10].

3. SEISMIC FRAGILITY ANALYSIS BASED ON CORRELATION

3.1. Reed–McCann Method

In our study, we adopted the method developed by Reed et al. [4] to quantitatively evaluate partial correlations. Hereafter, the method is referred to as the "Reed–McCann method." It was used to evaluate the dependencies of SSCs excited by earthquake ground motions because of following.

- This method can be used to analyze the independent and common parts of variabilities separately. We believe that the treatment of uncertainties, particularly the epistemic uncertainty, becomes more significant in advanced response analyses such as nonlinear analysis of civil structures and elasto-plastic analysis of equipment,
- In NUREG/CR-7237, this method is called "the most adaptable method" that can be feasibly implemented in seismic PRA.

Table 1 shows the specific procedures used for estimating dependency via the Reed–McCann method. This method consists of two stages.

Table 1. Reed–McCann Method Procedure

	Step	Modelling / calculation
Stage 1: Median Capacity Calculation	1	Calculate dependent component β'_u using the following equation. $$\beta'_U = \left(\beta_U^2 - \sum \beta_U^{*2}\right)^{1/2}$$
	2	Calculate the median in the unit. Conduct a random sampling by following the lognormal distribution LN (A_m, β_U')
	3	Conduct a random sampling of dependent components by following the lognormal distribution LN (1.0, β_U*)
	4	Calculate the median capacity by multiplying the results from steps 2 and 3.
Stage2： Calculation of Independent Component/Calculation of Failure Frequency	5	Calculate dependent component β'_{Ri} using the following equation. $$\beta'_{R_i} = \left(\beta_{R_i}^2 - \sum \beta_R^{*2}\right)^{1/2}$$
	6	Conduct a random sampling of dependent components by following the lognormal distribution LN (1.0, β_{Ri}')
	7	Evaluate failure frequency of target equipment. For three target components A, B, and C, failure frequency is obtained using the following distributions. $LN\{A_m(A)_{i/x}, \beta_R(A)_i\}$, $LN\{A_m(B)_{i/x}, \beta_R(B)_i\}$, and $LN\{A_m(C)_{i/x}, \beta_R(C)_i\}$

The correlation between uncertainty β and correlation coefficient ρ are formulated as follows.

$$\rho = \beta_C^2 / (\beta_1 \times \beta_2), \tag{1}$$

where β_C is the common β value between any two target components.

3.2. Target SSCs for Correlation-Based Seismic Fragility Analysis

We (CRIEPI/Nuclear Risk Research Center (NRRC)) used a plant model to enhance the validity of seismic PRA results. We defined two models, "model plant" and "pilot plant," as follows.

- The pilot plant was defined as an "as is" model. It serves as a direct representation for which utilities perform quantitative risk evaluation. The model must replicate the actual plant to ensure accurate risk assessment.
- The model plant serves as a platform for developing a methodology or method. It combines and represents the features of a real nuclear power plant; however, some features can be flexibly model led or replaced on the basis of new models and findings, facilitating the verification of various effects.

The objective of the NRRC study was to enhance the effectiveness of seismic PRA by implementing the developed techniques. The "model plant" was an experimental R&D plant model. Notably, the model plant was not a "virtual" model but a "realistic" model. In addition, the study aimed to optimize the probabilistic seismic hazard analysis methodology. Composite site and seismic source characterization or ground motion characterization models can be adopted for seismic hazard analysis.

As per the results of this study, seismic core frequency damage was predominated by the failure of steam safety relief valves (SRVs); it contributed significantly to seismic risk quantification.

In current seismic PRA methods, which employ the advanced boiling water reactor (ABWR) model plant, the SRV fragility is represented by the lowest fragility among eighteen SRVs. Additionally, a complete dependence condition is assumed for seismic correlation. However, in a realistic scenario, the eighteen SRVs are unlikely to fail simultaneously. It is more plausible that only a few SRVs fail while others remain operational (not fail). Therefore, seismic risk profiles obtained using the existing seismic fragility of SRVs may not accurately reflect the true risk.

3.3. Problem Settings: Grouping and Correlation

3.3.1 SRVs Installed in an ABWR Model Plant

Figure 1 shows a schematic SRV installation in an ABWR model plant. Eighteen SRVs were installed on four main steam pipings, which were designated as A, B, C, and D. This naming convention is explained in detail in the next subsubsection. Using the seismic response acceleration of SRVs with respect to design basis seismic ground motion Ss, as evaluated by the Tokyo Electric Power Company, SRVs with maximum and minimum response were identified for each piping, as shown in Figure 1.

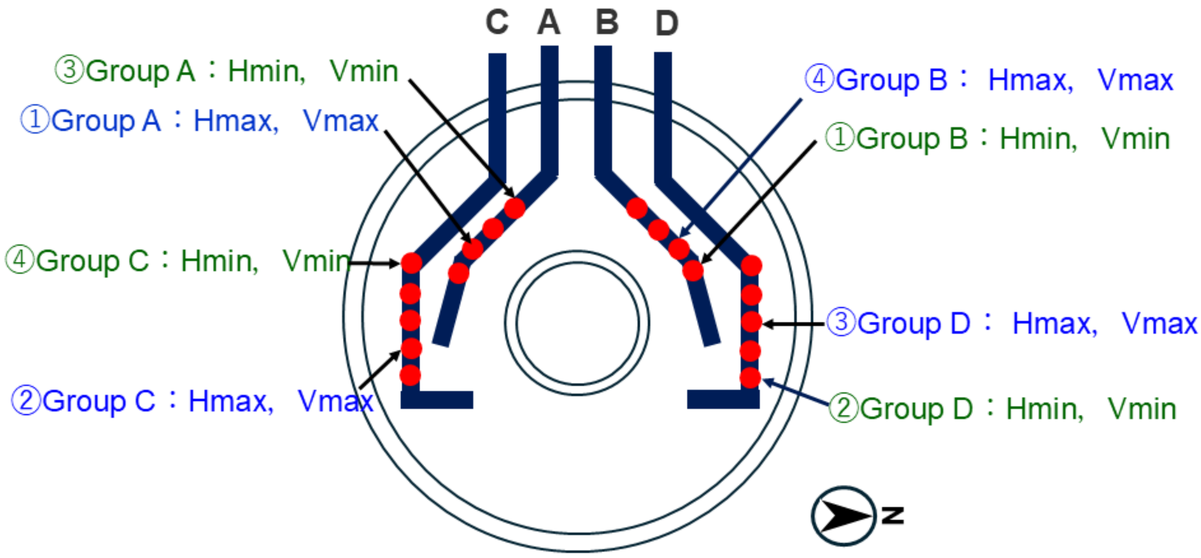

Figure 1. Schematic SRV Installation in an ABWR Model Plant

3.3.2 Grouping of target equipment

First, we conducted sensitivity analyses to evaluate and examine the effect of degree of correlation on the seismic fragility of a target equipment. We grouped the SRVs installed in the model plant as follows.

- Eighteen SRVs modeled individually
- Four groups based on piping: groups C, A, B, and D consisted of 5, 4, 4, and 5 valves, respectively
- Nine groups of valve pairs located symmetrically: 2×9 valves
- Two groups based on directions: north (A and C, 9 valves) and south (B and D, 9 valves)
- Two groups based on locations: inside (A and B, 8 valves) and outside (C and D, 10 valves)

From the perspective of accident sequences, the number of valves per group can be determined via success criteria analysis. Pressure control is possible if at least one valve is operated. Therefore, the number of SRVs that can be grouped is less than or equal to 17. Therefore, the number of groups can be set between 2 and 18.

3.3.3 Seismic Correlation

It is difficult to determine and set seismic correlation using only theoretical or physical evidences. Conducting a parametric study to understand the macroscopic characteristics is more effective. A substantial number of cases should be analyzed, and a small number of groups is more appropriate for numerical analysis. Therefore, it is necessary to determine the correlation coefficient and groups as a single set.

3.3.4 Analytical Cases for Parameter Coupling

First, we used the groups of two and four pipes, as explained in Section 3.3.2, because several cases should be analyzed to assess the effect of correlation coefficient on seismic fragility. Table 2 lists the grouping configuration and parameter values required for the Reed–McCann method.

Table 2. Analytical Cases for coupling of parameters

	Configuration and Parameter Values
Grouping	(i) Inner/outer piping (ii) South/north piping
Epistemic uncertainty β_u	0.25/0.30/0.40
Common variability β_r^*	0.002/0.1/0.2/0.26
Common variability β_u^*	0/0.1/0.2/0.25

For sensitivity analyses, seismic correlation (dependency) was considered as follows.

- For groups of two pipes, we considered the dependency between the SRVs installed in the inner and outer pipes (or the south and north pipes).

- For groups of four pipes, we considered the dependency between the SRVs installed in a couple of two or more pipings among four pipings. Therefore, a total number of $\{{}_4C_2+{}_4C_3+{}_4C_4\}$ cases were used as the analytical cases.

Evidently, to estimate the seismic dependency of SRVs, which is conventionally defined as the joint failure probability of multiple seismic-induced failures, a higher number of cases should be incorporated as the number of groupings increases.

Using Equation (1), correlation coefficient ρ was evaluated based on combinations of the variability parameter β. We analyzed ninety-six cases for the groups of two pipes and six cases for the group of four pipes.

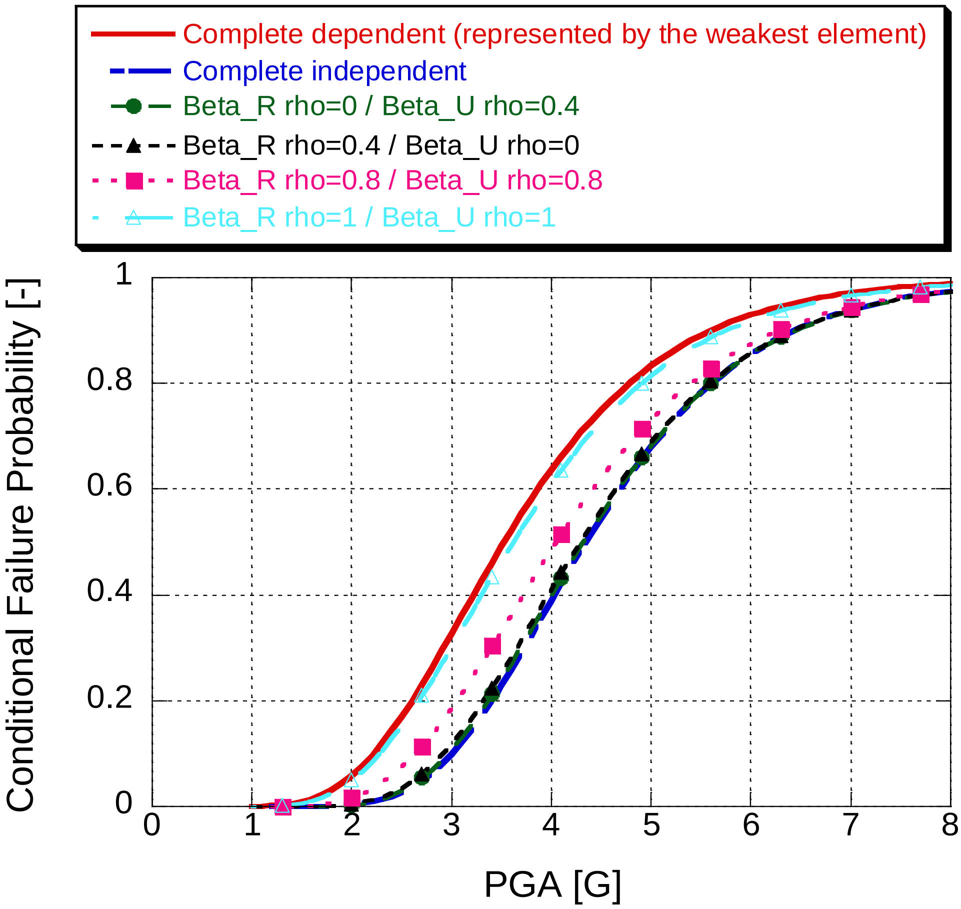

Figure 2. Seismic Fragility Curves of SRVs for groups of two pipes

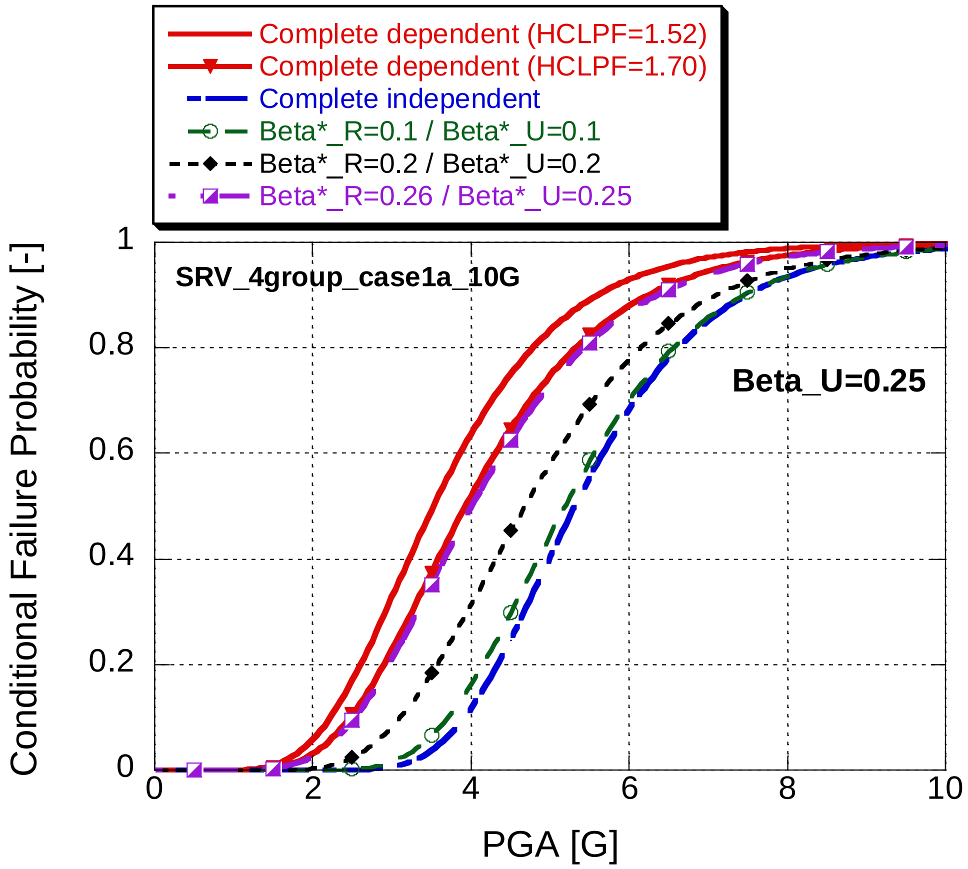

Figure 3. Seismic Fragility Curves of SRVs for groups of four pipes: $\beta_U = 0.25$

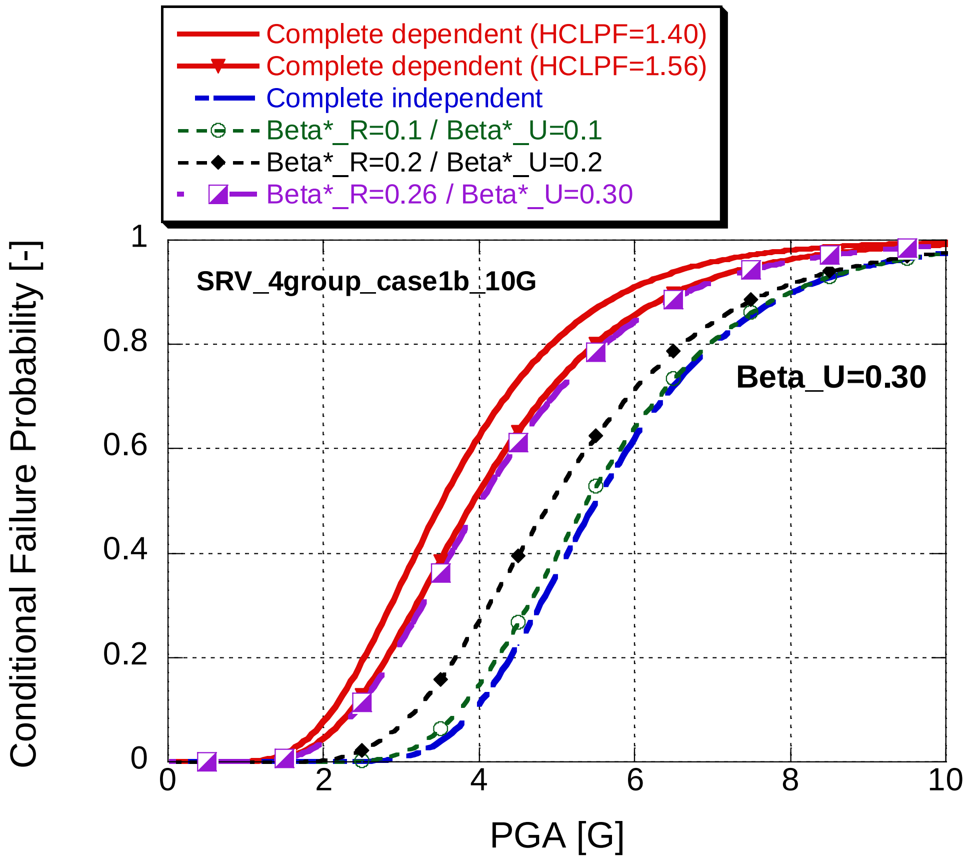

Figure 4. Seismic Fragility Curves of SRVs for groups of four pipes: $\beta_U = 0.30$

3.4. Numerical Analyses

Figures 2, 3, and 4 show the results of the seismic fragility analysis conducted by incorporating partial correlations using the Reed–McCann method. In this study, we examined the results using different grouping models. The results of the numerical analysis are presented below.

3.4.1 Results for Two-Grouping Case

At high correlation coefficients, the fragility curve closely coincided with the curve obtained under the complete dependence condition. When $\beta\_(R\_\rho)$ = 0.8 and $\beta\_(U\_\rho)$ = 0.8, the fragility curves were approximately midway between those obtained under the complete dependence and complete independence conditions. When $\beta\_(R\_\rho)$ = 0.4 and $\beta\_(U\_\rho)$ = 0.4, the fragility curve mostly aligned with the curve obtained under the complete independence assumption.

Hence, the center of the SRV fragility curves based on the seismic correlation was located near the curve obtained under the assumption of complete independence.

3.4.2 Results for Four-Grouping Case

The overall characteristics of seismic fragility curves for the four-grouping case was similar to those obtained for two grouping; seismic fragility curves approached as the values of $\beta\_(R\_\rho)$ and $\beta\_(U\_\rho)$ decrease.

The distance between the fragility curves obtained under the complete dependence and complete independence conditions increased as the value of $\beta\_(U\_\rho)$ increased from 0.25 to 0.30. Hence, β_U can be reasonably identified as a key parameter.

3.4.3 Difference between 2 and 4 Groupings

A more meticulous grouping is expected to enhance the precision of seismic fragility values. However, as more resources are required to conduct such heavy computations, it is crucial to find a fragility curve that can represent the group of fragility curves obtained based on seismic correlation.

3.4.4 Significant Issue

As per sensitivity analysis results, at a certain correlation coefficient, seismic fragility curves approach the curve obtained under the complete independence condition. This implies that the seismic fragility of equipment can be evaluated by considering partial correlations through grouping. However, further studies are required.

4. RISK QUANTIFICATION

Risk was quantified after evaluating SRV seismic fragility based on partial correlations. The following problem settings were employed for the SRVs.

- The opening and closing of SRVs are completely independent.
- Once an SRV succeeds in opening, it can be closed successfully.
- An open SRV and the automatic depressurization system are completely dependent.

The risk quantification results obtained using seismic fragility evaluations based on partial correlations will be elaborated in this presentation.

5. CONCLUSION

We improved the accuracy of seismic fragility evaluations for crucial equipment in NPPs by considering correlations. In our study, we targeted SRVs for evaluating seismic correlation because SRV failures predominantly influence the seismic risk of model plants. Subsequently, we conducted sensitivity analyses for systems that significantly influenced seismic risk. Specifically, we classified the system into several groups and set analytical cases with different correlation coefficients. Seismic fragility analysis was then performed via the Reed–McCann method for the cases. The results of sensitivity analyses showed the quantitative effect of correlation degree on seismic fragility evaluation.

Moreover, we performed seismic risk quantification for an ABWR model plant, focusing on seismic correlation. We compared and analyzed the risk quantification results obtained by considering correlation and those from conventional assumptions, namely complete dependence and complete independence conditions.

Based on the results obtained, we plan to develop partial correlation models for seismic fragility evaluation. This approach aims to provide a more realistic assessment of seismic fragility in seismic PRA, which can be applied for other SSCs installed under different conditions.

We believe that incorporating partial correlations into seismic fragility evaluation enhance the accuracy of risk quantification, providing a more accurate and refined risk profiles for seismic events.

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