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Comparison of Methods for Considering Seismic Correlation Coefficients Among SSCs in Multi-Unit NPPs

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1. Introduction

Since the Fukushima earthquake in Japan, the safety of multi-unit NPPs(Nuclear Power Plants) has become a prominent concern in the nuclear industry [1]. Although many studies are ongoing, a standardized methodology for probabilistic safety assessment of multi-unit NPPs has not yet been established. Evaluating the seismic safety of multi-unit NPPs requires consideration of the seismic failure correlation among SSCs (Structures, Systems, and Components). Research on this topic can be broadly divided into two areas: studies focused on deriving the seismic failure correlation coefficients among SSCs, and studies that assess risk by considering these correlations. In this study, we conduct a comparative analysis of various methods for deriving seismic failure correlation coefficients among SSCs in multi-unit NPPs.

2. Methodology for Considering Seismic Correlation Coefficients of SSCs

2.1 IAEA SRS No.110 [2]

In this report, the seismic failure correlation among SSCs for multi-unit NPPs is approached in the same manner as for a single unit. The seismic failure correlation coefficients among SSCs for a single unit are conservatively assumed to be either independent or fully dependent. Therefore, it is suggested that the seismic failure correlation coefficients among SSCs for multi-unit NPPs should also be assumed to be either independent or fully dependent. The following criteria can be used to determine whether the assumption should be independence or full dependence.

- Different components at different units, with different seismic demand and different capacity – Independent
- Different components at different units but the same seismic demand – Independent
- Identical components at different units and different seismic demand − Independent or Fully Dependent
- Identical components with the same seismic demand − Fully Dependent

2.2 EPRI TR 3002020765 [3]

EPRI primarily follows the method proposed by Reed et al.[4]. Reed presented a method to derive correlation based on a common factor, as shown in Equation (1)

$$\rho = \frac{(\beta^*)^2}{\beta_1 \beta_2} \tag{1}$$

ρ represents the seismic failure correlation coefficient between SSCs, while β_1 and β_2 are the logarithmic standard deviations used in the fragility curves of SSC_1 and SSC_2, respectively. β^* represents the common factor. The degree of correlation is qualitatively determined based on expert judgment, as shown in the following table 1.

Table I: Qualitative Scale for Degree of Fragility Correlation[3]

Degree of Fragility Correlation	ρ
None	0
Weak	0.2
Moderate	0.5
Strong	0.8
Perfect	1

It is suggested to consider the following factors when determining the degree of correlation.

- What degree of overall partial correlation for the component may influence the risk insights?
- What is the failure mechanism that governs the SSC fragility?
- Which response and capacity variabilities govern the overall variability?
- Where and how are the SSCs supported?
- Which structure response variables strongly influence the variability?

• Which equipment response variables strongly influence the variability?

• Which equipment capacity variables strongly influence the variability?

2.3 Korea Hydro & Nuclear Power Project No. L17S008002 [1]

This project, aimed at risk assessment for multi-unit NPPs, was conducted by the Korea Atomic Energy Research Institute. It followed the research framework of the SSMRP(Seismic Safety Margin Research Program) [5] and extended the concepts to accommodate multi-unit considerations [1]. The seismic failure correlation coefficients among SSCs can be determined using Equation (2).

$$\rho_{12} = \frac{\beta_{R1}\beta_{R2}}{\sqrt{\beta_{R1}^2+\beta_{C1}^2}\sqrt{\beta_{R2}^2+\beta_{C2}^2}}\rho_{R1R2} + \frac{\beta_{C1}\beta_{C2}}{\sqrt{\beta_{R1}^2+\beta_{C1}^2}\sqrt{\beta_{R2}^2+\beta_{C2}^2}}\rho_{C1C2}, \quad (2)$$

where ρ_{12} is the failure-correlation coefficient of components 1 and 2, β_{R1} and β_{R2} are the standard deviations of the logarithms of the responses of components 1 and 2, β_{C1} and β_{C2} are the standard deviations of the logarithms of the capacities of components 1 and 2, ρ_{R1R2} is the response-correlation coefficient of components 1 and 2, and ρ_{C1C2} is the capacity-correlation coefficient of components 1 and 2.

In this project, the correlation coefficients of seismic responses between components were derived from probabilistic seismic response analyses, and the correlation of seismic performance was assumed to be either independent or fully dependent.

2.4 NSTAR-21NS12-129 [6]

The procedure for evaluating seismic correlation coefficients for multi-unit NPP equipment [6] proposes a method for deriving the seismic response correlation coefficients of SSCs based on the methodology suggested by Ohtori et al. [7]. However, while Ohtori et al. categorized four types of response coefficients (free-field ground motion, site response, structural response, and equipment response), they did not specify how to derive the correlations for each of these response coefficients. This study proposes a method for quantitatively determining the four response coefficients, although further academic review is needed.

3. Conclusions

It is essential to consider the seismic failure correlation among SSCs for a reasonable seismic probabilistic safety assessment of multi-unit NPPs. All methods share the common view that seismic response and seismic performance of SSCs lead to failure correlations among SSCs. A summary of the comparative analysis of the four methods is presented in the table 2.

Table II: A summary of the comparative analysis of the four methods [3]

Category	**KAERI Method**	**EPRI Method**	**IAEA Method**	**IAEA Method**
Methodology Background	SSMRP & EEM et al. (2021)	Reed-McCann (1985)	Existing SU evaluation methods	Ohtori(2018)
Variables for Correlation Judgment	F_C (Seismic Performance) F_{RE} (Equipment Response) F_{RS} (Structural Response)	F_C (Seismic Performance) F_{RE} (Equipment Response) F_{RS} (Structural Response)	Required performance Seismic performance Installation location	Free-field motion Site response Structural response Equipment response
Seismic Response Correlation Coefficient	Quantitatively derived through seismic response analysis	Expert judgment	Expert judgment	Expert judgment
Seismic Performance Correlation Coefficient	Expert judgment (‘0’ OR ‘1’)	Expert judgment	Expert judgment	-
Method for Reflecting Failure Correlation Coefficient Among SSCs	Correlation matrix / CCF	MCS considering the correlation coefficients of each variable to derive failure probability for the same group (equipment) + Split fractions	Correlation matrix	CCF
Guidelines for Expert Judgment	-	Qualitative guidelines	Qualitative/quantitative guidelines	Quantitative guidelines
Quantitative guidelines	Correlation coefficient is determined by reflecting the results of SSC seismic response analysis	Correlation coefficient is determined by expert judgment	Correlation coefficient is determined by expert judgment ('0' OR '1')	Proposed guidelines/methods require academic review

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