

Seismic Core Damage Frequency Quantification Using Multivariate Probability Integration Considering Correlated Seismic Fragility

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***Keywords :** semiconductor detectors, SiC diode, bipolar amplifier, single channel analyzer

1. Introduction

In seismic probabilistic risk assessment (Seismic PRA), seismic core damage frequency (SCDF) is evaluated by combining seismic hazard with the seismic fragility of structures, systems, and components (SSCs) [1, 2]. SSCs exposed to the same earthquake may show correlated failure behavior, and this correlation may affect the core damage frequency [3, 4].

In this study, a multivariate probability integration method considering seismic correlation was applied to the calculation of conditional core damage probability at each peak ground acceleration (PGA) level. In addition, using a hypothetical nuclear power plant model, the conventional quantification method based on the independence assumption was compared with the method proposed in this study, and the effect of seismic correlation on SCDF was evaluated.

2. Methods and Results

2.1 Conventional quantification approach

In Seismic PSA, seismic core damage frequency is calculated by combining seismic hazard with the conditional core damage probability at each ground acceleration level. For this purpose, as shown in Eq. (1), PGA is divided into N intervals, and SCDF is quantified by weighting the earthquake occurrence frequency of each interval by the seismic-induced core damage probability at the representative PGA of that interval and summing the results over the entire PGA range.

$$SCDF = \sum_{k=1}^N P(CD|a_k) \Delta\lambda_k \quad (1)$$

where $\Delta\lambda_k$ represents the annual occurrence frequency of the k th PGA interval, a_k is the representative PGA of the corresponding interval, and $P(CD|a_k)$ represents the conditional core damage probability under the corresponding PGA condition.

To evaluate the conditional core damage probability, the seismic fragility of each SSC should be considered. If seismic fragility is assumed to follow a lognormal distribution, the failure probability at a specific ground acceleration a can be expressed as follows.

$$P(F_i|a) = \Phi \left[\frac{\ln(a/A_{m,i})}{\beta_{c,i}} \right] \quad (2)$$

where F_i represents the failure event of equipment i , $A_{m,i}$ is the median capacity, and $\beta_{c,i}$ is the logarithmic standard deviation.

If the core damage accident scenario is assumed to consist of the simultaneous failure of two SSCs, as shown in Eq. (3), and the two failure events are independent, the conditional core damage probability can be calculated as shown in Eq. (4).

$$CD = F_1 \cap F_2 \quad (3)$$

$$P(CD | a) = P(F_1 | a)P(F_2 | a) \quad (4)$$

However, when the failure events of SSCs affected by the same earthquake are correlated, the product of independent events as shown in Eq. (4) may not sufficiently represent the joint failure probability [3]. Therefore, in this study, the conditional core damage probability was obtained using multivariate probability integration to reflect the correlation among SSCs.

2.2 Multivariate probability integration approach

To quantify the conditional occurrence probability of a core damage accident scenario considering seismic correlation, the standardized random variable vector Z is defined as a multivariate standard normal distribution with a mean of 0 and a correlation matrix R , as shown in Eq. (5).

$$Z = [Z_1, Z_2, \dots, Z_n]^T \sim N(0, R) \quad (5)$$

where the diagonal elements of the correlation matrix R are 1, and the off-diagonal elements represent the correlation coefficients between equipment i and j .

The failure state of each SSC is determined based on the failure threshold at a specific ground acceleration a , $z_i(a)$, and the failure event and success event of each SSC can be divided as shown in Eqs. (6) and (7). $z_i(a)$ is given by Eq. (8).

$$F_i : Z_i \leq z_i(a) \quad (6)$$

$$S_i : Z_i > z_i(a) \quad (7)$$

$$z_i(a) = \frac{\ln(a/A_{m,i})}{\beta_{c,i}} \quad (8)$$

For seismic events, the effect of correlation among accident scenarios cannot be ignored. Therefore, through BDD conversion, the accident logic should be developed into mutually exclusive accident scenarios expressed as combinations of equipment failure and success events to calculate the core damage probability accurately.

A core damage accident scenario, CD_j , is composed of a combination of equipment failure and success events, and the conditional core damage probability at a specific ground acceleration a can be expressed as shown in Eq. (9).

$$P(CD_j | a, R) = \int_{\Omega_j(a)} \phi_n(z; R) dz \quad (9)$$

where $\phi_n(z; R)$ is the n -dimensional standard normal probability density function with correlation matrix R , and $\Omega_j(a)$ is the multidimensional integration region determined by the combination of success and failure events that make up CD_j . For example, when the core damage accident scenario is given by Eq. (10), the core damage probability can be calculated as shown in Eq. (11).

$$CD = F_1 \cap S_2 \cap F_3 \quad (10)$$

$$P(CD | a, R) = \int_{-\infty}^{z_1(a)} \int_{z_2(a)}^{\infty} \int_{-\infty}^{z_3(a)} \phi_3(z; R) dz_3 dz_2 dz_1 \quad (11)$$

Therefore, the seismic core damage frequency over the entire PGA range can be expressed as shown in Eq. (12).

$$SCDF = \sum_{k=1}^N \sum_{j=1}^M \Delta \lambda_k \int_{\Omega_j(a_k)} \phi_n(z; R) dz \quad (12)$$

2.2 Application

To confirm the applicability of the multivariate integration method, the failure probability of a system consisting of three pieces of equipment, as shown in Eq. (13), was calculated. The fragility data for the equipment are shown in Table I.

$$SYS = F_A \cap (F_B \cup F_C) \quad (13)$$

Table I: Seismic fragility data of equipment A, B, C

Equipment	A_m	β_c
A	0.3	0.35
B	0.5	0.30
C	0.7	0.35

When BDD conversion is applied to the failure scenario of the system, it can be expressed as shown in Eq. (14).

$$SYS = S_1 \cup S_2 \\ = (F_A \cap F_B) \cup (F_A \cap S_B \cap F_C) \quad (14)$$

Since accident scenario #1 (S_1) is a combination of the failure events of A and B, its conditional occurrence probability can be expressed as shown in Eq. (15), and the conditional occurrence probability of accident scenario #2 (S_2) can be expressed as shown in Eq. (16).

$$P(S_1 | a, R) = \int_{-\infty}^{z_A(a)} \int_{-\infty}^{z_B(a)} \phi_2(z; R_{AB}) dz_B dz_A \quad (15)$$

$$P(S_2 | a, R) = \int_{-\infty}^{z_A(a)} \int_{z_B(a)}^{\infty} \int_{-\infty}^{z_C(a)} \phi_3(z; R) dz_C dz_B dz_A \quad (16)$$

Therefore, the seismic-induced failure probability of the system is given by Eq. (17).

$$P(SYS | a, R) = P(S_1 | a, R) + P(S_2 | a, R) \quad (17)$$

To analyze the effect of seismic correlation, the correlation coefficients (ρ) among the equipment were first assumed to be the same and were increased step by step to examine their effect.

For 0.45 g, the representative PGA of the 0.4–0.5 g interval, the system failure probability (SYS) was 3.66E-01 when the correlation coefficient among all equipment was 0. It slightly increased to 3.73E-01 and 3.69E-01 at $\rho=0.3$ and 0.6, respectively, and then decreased to 3.56E-01 at $\rho=0.9$. In addition, S_1 generally showed an increasing trend, while S_2 , which includes a success event, showed a decreasing trend. As shown in Fig. 1, this is because the probability of simultaneous failure increases greatly as the correlation among the equipment increases, and the failure probability of accident scenario S_1 , which includes failure events of all equipment, accounts for most of the total probability. The conditional failure probabilities according to the correlation coefficient among the equipment are summarized in Table II.

Table II: Conditional probabilities of system failure at PGA=0.45g

ρ	S_1	S_2	SYS
0	3.10E-01	5.65E-02	3.66E-01
0.3	3.32E-01	4.11E-02	3.73E-01
0.6	3.48E-01	2.06E-02	3.69E-01
0.9	3.55E-01	9.97E-04	3.56E-01

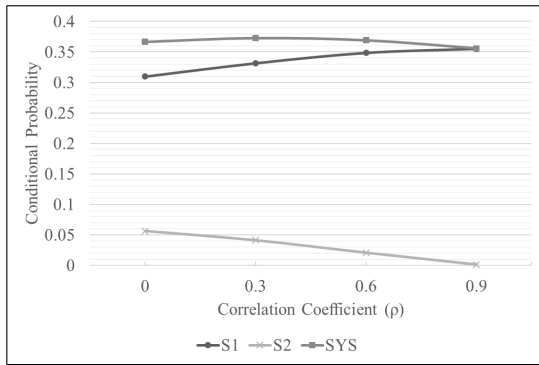


Fig. 1. Effect of correlation coefficient on conditional failure probability.

As shown in Fig. 2, the analysis over the entire PGA range also showed that the effect of correlation varied with the PGA level. When the same correlation coefficient of $\rho=0.6$ was applied, SYS increased greatly in the low PGA range compared with the case of $\rho=0$. However, the difference between the two results became small near 0.45 g, and above 0.55 g, SYS considering $\rho=0.6$ was evaluated to be lower than the result based on $\rho=0$. This is because the failure and success probabilities of each SSC change as PGA increases, and accordingly, the dominant correlation effect for each accident scenario changes.

In addition, the effect of the correlation structure was compared by applying the same level of strong correlation ($\rho=0.7$) only to specific SSC pairs and weak correlations ($\rho=0.2$) to the other pairs. SYS showed different values when a strong A–B correlation ($\rho_{AB}=0.7$) was applied and when a strong A–C correlation ($\rho_{AC}=0.7$) was applied, and the difference was relatively clear, especially in the intermediate PGA range. This means that the conditional core damage probability is affected not only by the size of the correlation coefficient but also by which SSCs are correlated within the accident scenario.

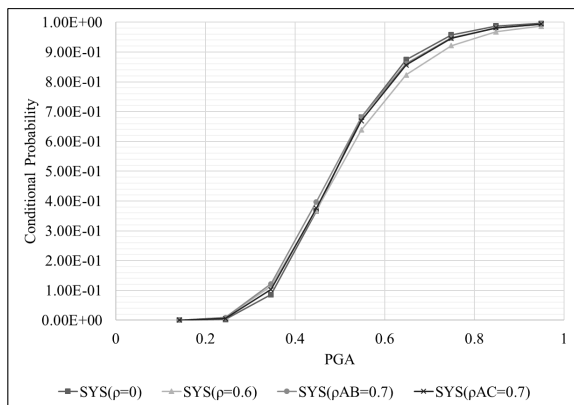


Fig. 2. Conditional system failure probability for different PGA and correlation conditions.

3. Conclusions

In this study, a multivariate probability integration method considering seismic correlation among SSCs was

applied to the calculation of conditional core damage probability at each PGA level.

To confirm the applicability of the method, it was applied to a simple system consisting of three pieces of equipment. The results showed that the correlation among the equipment had different effects depending on the accident scenario. It was also found that the change in conditional failure probability varied depending on the PGA level and the SSC pair to which correlation was applied. These results show that the effect of seismic correlation can be determined not only by the size of the correlation coefficient but also by the combination of accident scenario, SSC fragility, and correlation structure.

The proposed method is expected to allow the conditional core damage probability to be calculated while reflecting the correlation among equipment and to be useful for identifying SSC correlation combinations that are important to risk. However, the application case in this study is a conceptual analysis using hypothetical fragility values and correlation coefficients, and therefore the magnitude of the probability changes presented here cannot be directly interpreted as a change in the SCDF of an actual nuclear power plant. In addition, actual seismic correlation may vary depending on SSC location, structural response, common seismic demand, and the composition of fragility uncertainty. In future work, it is necessary to apply seismic fragility data, SSC correlation data, and seismic hazard data from an actual nuclear power plant to quantitatively evaluate the effect of the proposed method on SCDF and the risk contribution of major accident scenarios.

ACKNOWLEDGEMENT

This research was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korean government (MSIT) (No. RS-2022-00144425).

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