Study on a Method for Evaluating the Seismic Fragilities Considering the Response Correlation for Seismic PRA

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Abstract: Seismic probabilistic risk assessment (PRA) is a method for evaluating the risk of nuclear facilities against earthquakes. Correlations exist between the seismic responses of structures, systems, and components (SSCs) installed on the same site and must be considered in the calculation of the simultaneous failure probability for seismic PRA.

The previous evaluation methods for simultaneous failure probability considering the response correlation include the “Evaluation method using the damage correlation coefficient” and the “Method of evaluating the damage correlation using the Monte Carlo method”. These evaluation methods assume that the realistic response and realistic capacity follow a probability distribution. However, identifying the probability distribution of the realistic response is not always easy, and the response may not follow a specific probability distribution.

Therefore, this paper proposes a method for calculating simultaneous failure probability that does not require the assumption of a probability distribution of the realistic response. Using the proposed method, a seismic response analysis of SSCs considering the uncertainty of physical properties, such as concrete strength and seismic ground motion, is conducted. Thereafter, the response of the target SSC resulting from the analysis is compared with the capacity sampled from the probability distribution of the realistic capacity on a trial-by-trial basis. If the response exceeds the realistic capacity, the evaluation target SSC is determined to have failed. The number of times that several target SSCs are simultaneously determined to have failed relative to the number of seismic response analyses is defined as the simultaneous failure probability.

The simultaneous failure probability was calculated for SSCs installed in a hypothetical reactor building using the previous and proposed methods. The results of both methods were generally consistent with each other when the probability distribution of the realistic response follows a lognormal distribution. This study confirmed that the proposed method can calculate the simultaneous failure probability without assuming a probability distribution of the realistic response.

Keywords: Probabilistic Risk Assessment, Seismic PRA, seismic fragility and response correlation

1. INTRODUCTION

Japan is an earthquake-prone region, and earthquakes of magnitudes exceeding $M = 6.0$ have occurred in the past, including the 2011 off the Pacific coast of Tohoku earthquake, Niigataken Chuetsu-oki earthquake in 2007, 2016 Kumamoto earthquake and Noto Peninsula earthquake. The Fukushima Daiichi Nuclear Power Plant accident caused by the 2011 off the Pacific coast of Tohoku Earthquake highlighted the importance of risk assessment for external events with large uncertainties [1]. Risk assessment for earthquakes is particularly important because Japan is an earthquake-prone region.

Seismic probabilistic risk assessment (PRA) is a method for evaluating the risk of nuclear facilities against earthquakes. A characteristic of the effects of earthquakes is that structures, systems, and components (SSCs) installed on the site are affected at the same time. Therefore, correlations exist between the seismic responses of SSCs installed on the same site. If there is a correlation in response, the probability of multiple components being failed at the same time may be high. Seong et al. [2] and Ravindra et al. [3] showed that the core damage frequency (CDF) and accident sequences vary when the response correlation is considered. According to both studies, it is important to consider this correlation effect in the calculation of the simultaneous failure probability for seismic PRA.

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The Atomic Energy Society of Japan (AESJ) has issued “A Standard for Procedure of Seismic Probabilistic Risk Assessment for Nuclear Power Plants” [4], describing the procedures for conducting seismic PRA (herein after referred to “AESJ standard”). The AESJ standard provides examples of the “Evaluation method using the damage correlation coefficient” and the “Method of evaluating the damage correlation using the Monte Carlo method” as methods for calculating the simultaneous failure probability considering the response correlation (herein after referred to “previous method”). These evaluation methods assume that the realistic response and realistic capacity follow a probability distribution. However, since various factors contribute to the uncertainties in the realistic response, including those associated with seismic ground motion, ground, and buildings, it is not always easy to identify the probability distribution. In particular, when the response of the ground or building is in a nonlinear region or when the evaluation target resonates with the seismic input motion or building, it may not follow a specific probability distribution. In addition the “Evaluation method using the damage correlation coefficient” solves multiple integrals numerically. Therefore, this methodology has limitations to handling a number of combinations of SSCs due to computational capacity. When using this method, component that contributes to CDF through importance analysis will be made the target component for failure correlation handling.

In addition to the aforementioned methods, the “Reed – McCann” method [5] and another method proposed by Anup et al. [6] can be employed to evaluate the simultaneous failure probability considering the response correlation. However, both require the assumption of a probability distribution of the realistic response. No method has been explicitly studied for calculating the simultaneous failure probability without assuming a probability distribution of the realistic response.

Thus, this study proposes a calculation method for the simultaneous failure probability that does not require the assumption of a probability distribution of the realistic response. In addition, we calculated the simultaneous failure probabilities using the proposed and previous methods and compared them. This study confirmed that the proposed method can successfully calculate the simultaneous failure probability without assuming a probability distribution of the realistic response.

2. EVALUATION METHOD

2.1. Previous Method

The AESJ standard provides examples of the “Evaluation method using the damage correlation coefficient” and the “Method of evaluating the damage correlation using the Monte Carlo method” as methods for calculating the simultaneous failure probability considering the response correlation. Kubo et al. [7] showed that the simultaneous failure probabilities obtained using both methods are equivalent. The “Evaluation method using the damage correlation coefficient” is described herein.

The “Evaluation method using the damage correlation coefficient” was developed by the Seismic Safety Margin Research Program (SSMRP), and Applications have been developed that apply this method. [8]. This method assumes that the realistic response and realistic capacity follow a probability distribution, such as a lognormal distribution, and uses the median and uncertainty of the realistic response and capacity. The simultaneous failure probability, $P_{siml.}(\alpha)$, for any given seismic motion level, α, is calculated from the median and uncertainty of the realistic response and capacity of the component using Equation (1) which is based on the assumption that the realistic response and capacity follow a lognormal distribution.

$$P_{siml.}(\alpha) \;= (2\pi)^{-1}(|\mathbf{V}|)^{-\frac{1}{2}} \int_{-\infty}^{u_j}\int_{-\infty}^{u_k} \exp\left\{-\frac{1}{2\left(1-\rho_{j,k}^2\right)}\left(x_j(\alpha)^2 - 2\rho_{j,k}x_j(\alpha)x_k(\alpha) + x_k(\alpha)^2\right)\right\} dx_j dx_k \qquad (1)$$

where subscripts j and k represent components j and k to be calculated. The symbol x denotes a random variable, and $\boldsymbol{V}$ is the correlation matrix expressed in Equation (2).

$$\boldsymbol{V} \;= \begin{bmatrix} 1 & \rho_{j,k} \\ \rho_{j,k} & 1 \end{bmatrix}. \qquad (2)$$

$\rho_{j,k}$ in Equations (1) and (2) is the failure correlation coefficient between components j and k. It is obtained by Equation (3) using the response correlation coefficient (ρ_R), capacity correlation coefficient (ρ_C), and the logarithmic standard deviations of the realistic response and capacity of components β_R and β_C.

$$\rho_{j,k} = \frac{\beta_{Rj}\cdot\beta_{Rk}}{\sqrt{{\beta_{Rj}}^2+{\beta_{Cj}}^2}\cdot\sqrt{{\beta_{Rk}}^2+{\beta_{Ck}}^2}}\rho_{Rj,Rk} + \frac{\beta_{Cj}\cdot\beta_{Ck}}{\sqrt{{\beta_{Rj}}^2+{\beta_{Cj}}^2}\cdot\sqrt{{\beta_{Rk}}^2+{\beta_{Ck}}^2}}\rho_{Cj,Ck}. \tag{3}$$

The upper limits of integration u_j and u_k in Equation (1) are expressed in Equations (4) and (5), respectively.

$$u_j = \frac{\ln(R_{mj}/C_{mj})}{\sqrt{{\beta_{Rj}}^2+{\beta_{Cj}}^2}} \text{ and} \tag{4}$$

$$u_k = \frac{\ln(R_{mk}/C_{mk})}{\sqrt{{\beta_{Rk}}^2+{\beta_{Ck}}^2}} \tag{5}$$

where R_m and C_m are the median realistic response and realistic capacity, respectively.

2.2. Evaluation Method of Response Correlation Coefficient

One method for evaluating the response correlation coefficient is to obtain it via the seismic response analysis of SSCs considering uncertainty according to the following procedure [9, 10]. The correlation coefficients include the response correlation coefficient and the capacity correlation coefficient, but since this study focuses on the response correlation, only the response correlation coefficient is discussed. (1) Numerous seismic ground motions are generated with various characteristics by considering phase uncertainties, etc. (2) Considering the uncertainties in the ground properties, etc., wave propagation in the ground is analyzed using the seismic ground motion generated in (1), and numerous seismic input motions applied to buildings are generated. (3) Using the seismic input motions generated in (2), a seismic response analysis of the building is conducted, considering the uncertainties in the building properties, etc. (4) The floor response obtained in (3) is then used to evaluate the response of the subject components. The statistical processing of the obtained responses is performed to obtain the response correlation coefficient using Equation (6).

$$\rho_R = \frac{Cov\big(X_j(\alpha), X_k(\alpha)\big)}{\sigma_j\sigma_k}. \tag{6}$$

where $Cov\left(X_j(\alpha), X_k(\alpha)\right)$ is the covariance of the responses among the subject components, and σ_j and σ_k are the standard deviations of the subject components.

2.3. Proposed Method

Herein, we propose a method for calculating the simultaneous failure probability that does not require the assumption of a probability distribution of the realistic response. Teragaki et al. [11] propose a method for calculating simultaneous failure probability that assumes the use of “Method based on realistic capacity and response factor” [4] for the failure probability calculation. In this method, the response factors, which are assumed to follow a lognormal distribution, are sampled using a Monte Carlo method, and failure probabilities are calculated by comparing the response and capacity values for each trial. When considering the response correlation in this method, the same response factors are used to evaluate the realistic responses.

This study proposes a method for sampling responses from the results of seismic response analysis that assumes the use of “Method based on realistic capacity and realistic response” [4] for the failure probability calculation. Figure 1 shows the calculation flow of the proposed method for calculating the simultaneous failure probability at an arbitrary seismic ground motion level, α . (1) A seismic response analysis is conducted for each seismic ground motion level (α) that considers the uncertainties in the seismic ground motion, ground, and building when obtaining the response correlation coefficient described in Section 2.2. In addition, the response of components j and k is evaluated. (2) The capacity is sampled from the probability distribution of the realistic capacity of components j and k using a uniform random number. Here, a Monte Carlo method or similar method is used for sampling the response and capacity in (1) and (2). (3) The response and capacity of j and k obtained in (1) and (2) for each trial are compared. If the response exceeded the realistic capacity, the subject component is determined to have failed. (4) As shown in Equation (7), the number of failures $N_{j,k}(\alpha)$ that j and k are determined to have failed, relative to the number of trials. $N(\alpha)$, in the seismic response analysis is the simultaneous failure probability. Although two components are mentioned herein as an example, the simultaneous failure probability of not just two but many components can be calculated by evaluating the response and capacity of all target components for each trial and determining if a failure occurred.

$$P_{siml.}(\alpha) = \frac{N_{j,k}(\alpha)}{N(\alpha)}. \tag{7}$$

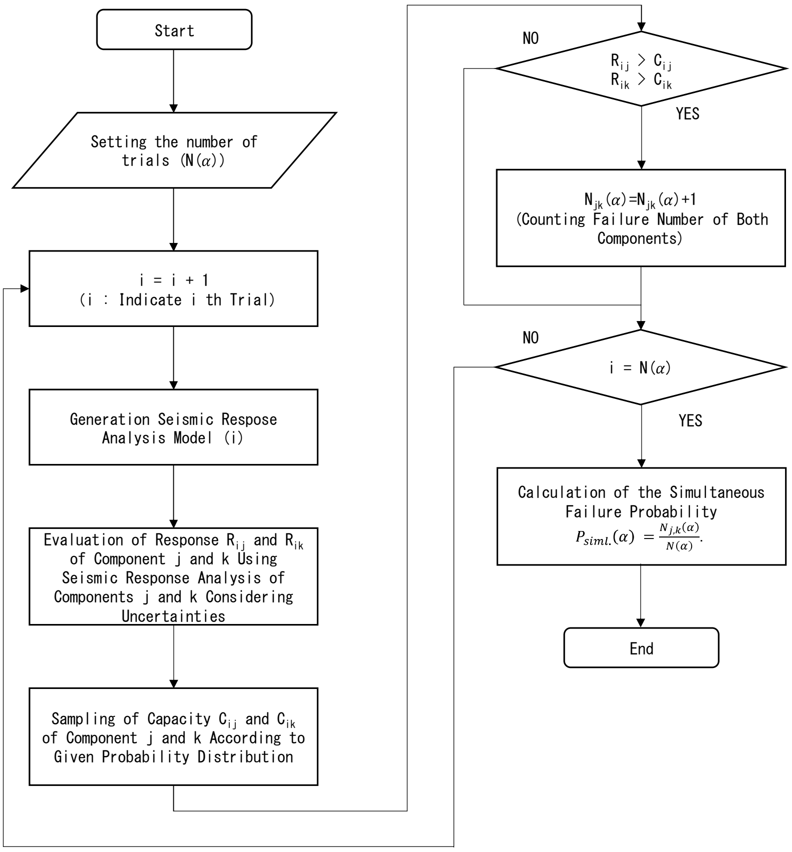


Figure 1. Calculation Flow of Proposed Method

3. EXAMPLE EVALUATION

The single and simultaneous failure probabilities were calculated for SSCs installed in a hypothetical reactor building using the previous and proposed methods. In the calculation, the “Evaluation method using the damage correlation coefficient” described in Section 2.1 was used.

3.1. Evaluation Target

Calculations were conducted for components installed in a hypothetical pressurized water reactor (PWR) reactor building. The seismic response analysis model for the building was based on publicly available information [12]. Figure 2 shows the seismic response analysis model [12]. As shown in Figure 2, the sway-rocking model of a multi-mass system was used here.

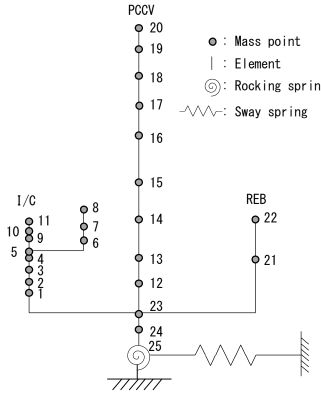


Figure 2. Seismic Response Analysis Model of the PWR Reactor Building

3.2. Evaluation Condition

Table 1 shows the conditions of the seismic response analysis considering uncertainty, conducted during the calculation. The correlation coefficient applied to the previous method in this calculation was also obtained from the results of the seismic response analysis for each combination of components.

Table 1. Conditions of the Seismic Response Analysis

Item	Method	Factor of uncertainty	Probability distribution
Seismic ground motion	Procedure for seismic ground motion development with the uniform hazard spectrum	Phase characteristics	Uniform distribution
Ground	-*	Initial shear modulus	Lognormal distribution
Building	Non-linear time history analysis	Concrete strength	Lognormal distribution
		Damping factor	Lognormal distribution
		Restoring force characteristics	Lognormal distribution

*Only the uncertainty of the initial shear modulus of the ground was considered in the calculation of the soil spring.

To develop the seismic ground motion for the failure probability calculation, the “procedure for seismic ground motion development with the uniform hazard spectrum” was used, and the uncertainty in the phase characteristics was considered. The uncertainty in the phase characteristics was assumed to be random. The target spectral damping factor was set to 5%. Figure 3 shows the target spectrum for developing the seismic motion. In this calculation, the building installed on hard-bedrock sites was targeted. Thus, the analysis of ground wave propagation was not performed. Only the uncertainty of the initial shear modulus of the ground was considered in the calculation of the soil spring. The physical properties of the building were considered for the uncertainties in the concrete strength, damping factor and restoring force characteristics. The probability distributions of the ground and building properties were assumed to follow a lognormal distribution. The median and logarithmic standard deviation were based on publicly available information [4].

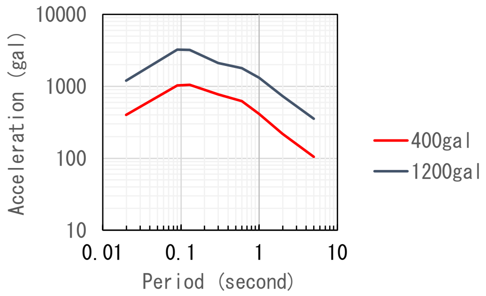


Figure 3. Target Spectrum for Generating the Seismic Ground Motion

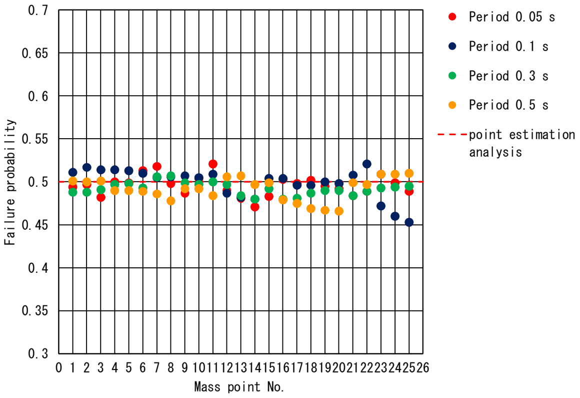
For the median realistic response of the component, a floor response spectrum was prepared for each mass point. Furthermore, the acceleration at the natural period of the component assumed in the prepared floor response spectrum was used. The number of seismic response analyses considering uncertainty was set to 1000. The validity of the results was confirmed by the convergence of the failure probability calculations. The Monte Carlo method was used to sample the input data in the seismic response analysis. The seismic ground motion levels to be evaluated were 400 gal, where the building response is linear, and 1200 gal, where the building response is nonlinear.

The median realistic capacity was set similar to the median realistic response obtained from the results of the seismic response analysis such that the failure probability was 0.5. This is because if the failure probability is extremely low, the evaluation using the proposed method will result in a failure probability of zero, and the difference in failure probabilities between both methods may not be comparable. Considering that this study focused on the correlation of responses and the uncertainty in the capacity is generally smaller than that in the response, the uncertainty in the capacity was not considered.

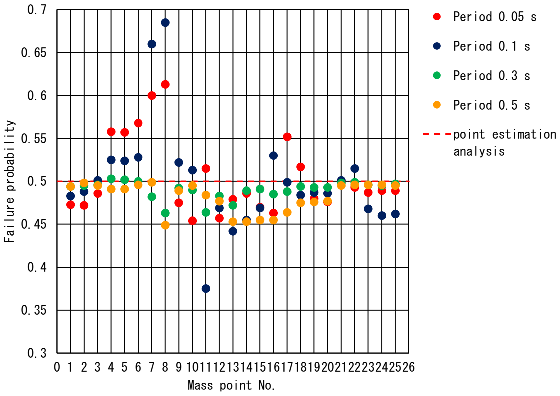
4. RESULT AND DISCUSSION

4.1. Single Failure Probability

To validate the proposed method, the single failure probability of the component was calculated using the proposed method and point estimation analysis, assuming that the responses followed a lognormal distribution. For the calculation, the floor response spectra were prepared assuming a damping factor of 5%. This was because the response spectrum with a damping factor of 5% was used as the target spectrum in the generation of seismic ground motion. The response accelerations at 0.05, 0.1, 0.3, and 0.5 s were used as the main period for calculating failure probability. As shown in Figure 4, the results at 400 gal were generally consistent with each other. Conversely, in the calculations at 1200 gal, differences were observed in the results under certain conditions.



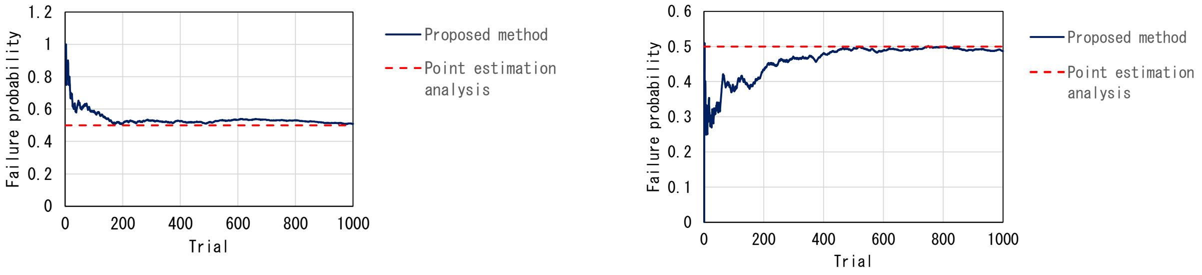
(a) 400 gal



(b) 1200 gal

Figure 4. Single Failure Probability of Component Using the Response Acceleration of Mass Points in the PWR Reactor Building

Figure 5 shows the relationship between the number of trials and failure probability for the case where failure probability was calculated using response acceleration with a period of 0.05 s at mass point 23, which is the top of the building foundation slab. In addition, Figure 5 also shows the results of the point estimation analysis. At both seismic ground motion levels (400 and 1200 gal), the results converged satisfactorily after 1000 seismic response analysis trials, validating of the number of seismic response analyses.



(a) 400gal (b) 1200gal

Figure 5. Relationship Between the Number of Trials and Failure Probability

Figure 6 shows the relationship between the number of trials and failure probability when the failure probability was calculated using the response acceleration of the spectrum of mass point 8, which is the top of the steam generator with a natural period of 0.1 s at 1200 gal. In addition, Figure 6 also shows the result of the point estimation analysis. The difference in these results was relatively large. Figure 7 shows the histograms of response accelerations under the same conditions and at 400 gal. Furthermore, Figure 7 shows the expected frequencies calculated assuming that the responses followed a lognormal distribution. As shown in Figure 6, the failure probability results converged with respect to the number of trials, suggesting that the reason for the difference in the results was not the insufficient number of seismic response analyses. The histogram of response accelerations at 1200 gal shown in Figure 7 does not indicate that the response accelerations followed a lognormal distribution. Conversely, the histogram of response accelerations at 400 gal corresponded relatively well with the lognormal distribution. The reason for the difference between the proposed method and the point estimate analysis in the results for certain of the 1200 gal shown in Figure 4(b) may be that the response accelerations evaluated by the seismic response analysis did not follow a lognormal distribution. A possible reason why the response accelerations did not follow a lognormal distribution is that the building response was in a nonlinear region; however, a detailed analysis is required in the future. The results obtained when the probability distribution of the response did not follow a lognormal distribution need to be verified. However, when the probability distribution of the response followed a lognormal distribution, the results were generally consistent. This confirms that the proposed method can calculate failure probabilities without assuming a probability distribution of responses. In the future, we plan to analyze the factors that cause the response accelerations to not follow a lognormal distribution, focusing on the nonlinear characteristics of the building and the fact that the trend differs depending on the mass point and period.

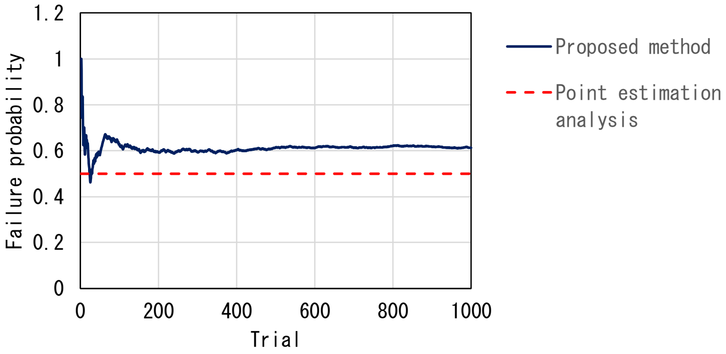
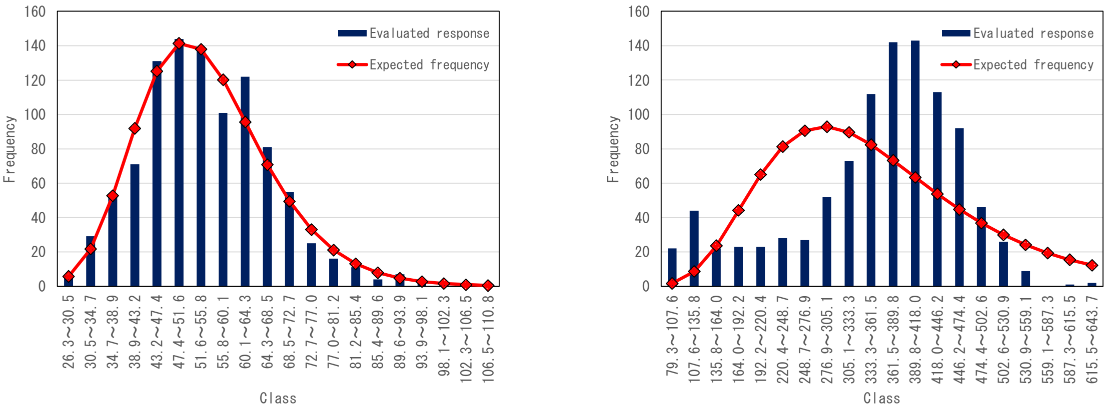


Figure 6. Relationship Between the Number of Trials and Failure Probability
(Mass point, 8; period : 0.1 s; seismic ground motion, 1200 gal)



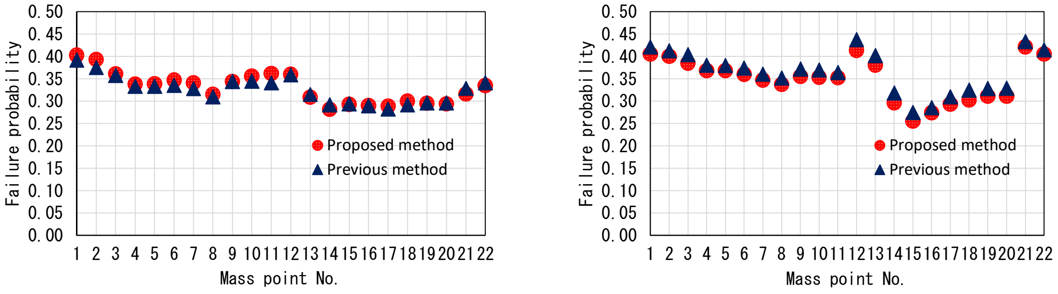
(a) 400gal (b) 1200gal

Figure 7. Histogram of Evaluated Response Acceleration

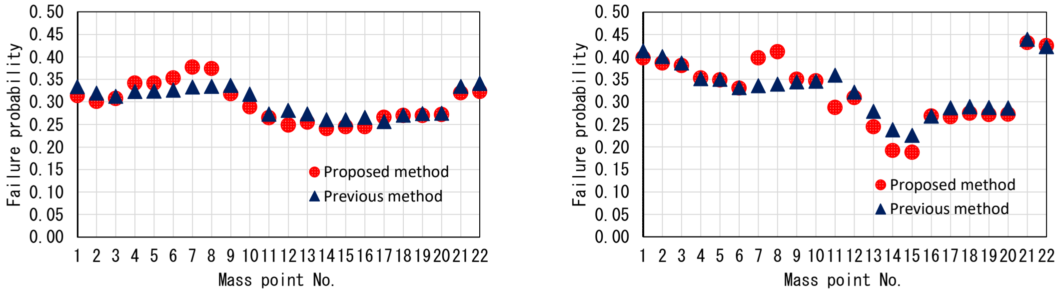
4.2. Simultaneous Failure Probability

Simultaneous failure probability calculations were performed for the two following patterns.
(1) Components of the same natural period installed on different floors in the same building
(2) Components of different natural periods installed on the same floor in the same building

Figure 8 shows the calculation results of the simultaneous failure probability of components of the same natural period installed on different floors in the same building. This was performed for the combination of mass point 23 where major components were installed and other mass point using the proposed method and the previous method (Evaluation method using the damage correlation coefficient). Figure 8 shows the results for components with natural periods of 0.05 and 0.1 s which are shorter than primary natural period of the building. As shown in Figure 8, in the case of 400 gal, the results of both methods were generally consistent for each period. In the case of 1200 gal, it was confirmed that there were differences between the two results for certain quality points for each period. This corresponded to a difference in the single failure probability of the components. Therefore, as shown in Figure 7(b), this may be because the probability distribution of the responses did not follow a lognormal distribution.



(a) Period : 0.05 second (400gal) (b) Period : 0.1 second (400gal)

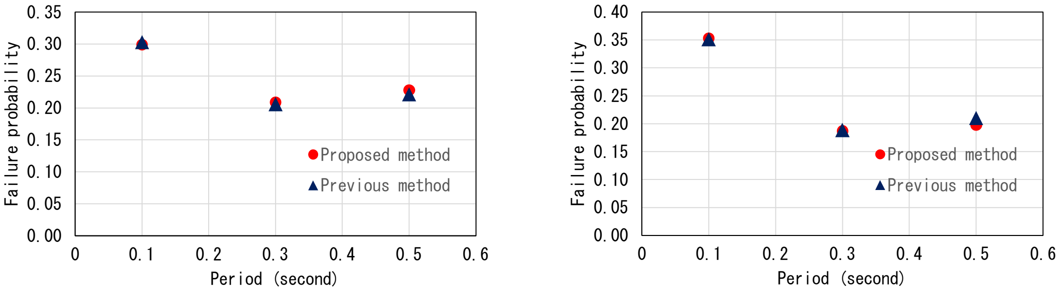


(c) Period : 0.05 second (1200gal) (d) Period : 0.1 second (1200gal)

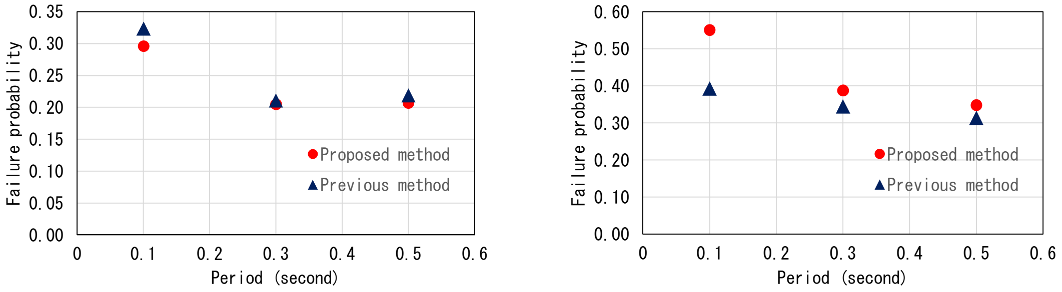
Figure 8. Simultaneous Failure Probability of Component Using Response Acceleration of Each Mass Point in the PWR Reactor Building
(Components of the same natural period installed on different floors of the same building)

Figure 9 shows the calculation results of the simultaneous failure probability of components of different natural periods installed on the same floor in the same building. The results were obtained using the response acceleration with a period of 0.05 s and the response acceleration with periods of 0.1 s, 0.3 s, and 0.5 s with the proposed method and the previous method (Evaluation method using the damage correlation coefficient). The targeted mass points were mass point 23 where major components were installed and mass point 8 where differences in the single failure probability of the components were identified between the proposed and previous methods. Figure 9 shows that at 400 gal, both results were in general consistent regardless of the combination of periods. At 1200 gal, for each combination with a period of 0.1 s for mass point 23 and for mass point 8, differences were observed. This corresponded to a difference in the single failure probability of a component. As shown in Figure 7(b), this may be because the probability distribution of the responses did not follow a lognormal distribution.

Thus, when the probability distribution of the response follows a lognormal distribution, the results of both methods generally consistent. This confirms that the proposed method can calculate the simultaneous failure probability without assuming the probability distribution of the response. However, it is necessary to verify the results of the proposed method when the probability distribution of the response does not follow a lognormal distribution.



(a) Mass point 23（400gal） (b) Mass point 8（400gal）



(c) Mass point 23（1200gal） (d) Mass point 8（1200gal）

Figure 9. Simultaneous Failure Probability of Component Using Response Acceleration of Each Mass Point in the PWR Reactor Building
（Components of different natural period installed on same floors of same building）

5. CONCLUSION

This paper proposed the method for calculating the simultaneous failure probability without assuming the probability distribution of the realistic response. The single failure probability of a component and the simultaneous failure probability of two components due to an earthquake were calculated for components installed in a hypothetical PWR reactor building using the proposed and previous methods. The correlation coefficients were calculated for each combination of target components using the previous method. It was confirmed that the results of the previous method and proposed method were in consistent with each other when the probability distribution of the realistic responses were assumed to follow a lognormal distribution. This confirms that the proposed method can calculate the simultaneous failure probability without assuming a specific probability distribution of the realistic response. However, it is necessary to verify the results of the proposed method when the probability distribution of the response does not follow a lognormal distribution.

The proposed method requires numerous seismic response analyses; thus, it may not be possible to obtain failure probabilities in a realistic number of seismic response analyses at seismic ground motion levels where failure probabilities are small. In addition, the seismic PRA for nuclear power plants requires numerous fragility evaluations. Thus, if the proposed method, which requires numerous seismic response analyses, is applied, the time required for evaluation may be enormous. Therefore, it is important to clarify the purpose of treating failure correlation in seismic PRA and to select an evaluation method in consideration of cost-effectiveness. We plan to develop a simplified evaluation method that can be applied to seismic ground motion levels with lower failure probabilities, which could be one of its options.

References

[1] IAEA. The Fukushima Daiichi Accident Reported by the Director General. 2015.
[2] Seong Kyu Park, Woo Sik Jung and Koo Sam Kim. Seismic Correlation Application Study with COREX. Transactions of the Korean Nuclear Society Spring Meeting Jeju, Korea, May 23-24, 2019.
[3] M.K. Ravindra and J.J. Johnson. Seismically Induced Common Cause Failures in PSA of Nuclear Plants. Transactions of the Eleventh SMiRT Conference, Tokyo, Japan, August 1991.
[4] AESJ. A standard for procedure of seismic probabilistic risk assessment for nuclear power plants: 2015. AESJ-SC-P006: 2015, 2015.
[5] Reed, J.W.; Mc Cann, M.W. Jr.; Iihara, J.; Tamjed, H.H. Analytical techniques for performing probabilistic seismic risk assessment of nuclear power plants. International conference on structural safety and reliability; Kobe (Japan); 27-29 May 1985.
[6] Abhinav Anup, Mohamed M. Talaat, Frederic F. Grant and Fernando Ferrante. QUANTIFYING PARTIAL FRAGILITY CORRELATION IN SEISMIC PROBABILISTIC RISK ASSESSMENTS. Transactions, SMiRT-26. 2022.
[7] K. Kubo, Y. Tanaka, Y. Hakuta, D. Arake, T. Uchiyama and K. Muramatsu. Application of quasi-Monte Carlo and importance sampling to Monte Carlo-based fault tree quantification for seismic probabilistic risk assessment of nuclear power plants. Mechanical Engineering Journal. 2023.
[8] M.P. Bohn, L.C. Shieh, J.E. Wells, L.C. Cover, D.L. Bernreuter, J.C. Chen, J.J. Johnson, S.E. Bumpus, R.W. Mensing, W.J. O'Connell and D.A. Lappa. NUREG/CR-3428: Application of the SSMRP Methodology to the Seismic Risk at the Zion Nuclear Power Plant. Washington, DC. 1983.
[9] K. Ebisawa, T. Teragaki, S. Nomura, H. Abe, M. Shigemori and M. Shimomoto. Concept and methodology for evaluating core damage frequency considering failure correlation at multi units and sites and its application. Nuclear Engineering and Design 288 (2015) 82–97. 2015.
[10] Si Young Kim, Seung Jae Lee, Jin Wook Lee, Jung Han Kim. Evaluation of Correlation Coefficient for Seismic Fragility Response Variable. 26th International Conference on Structural Mechanics in Reactor Technology, Berlin/Potsdam, Germany, July 10-15. 2022.
[11] T. Teragaki, M. Hirano and K.Mori. Evaluation of Seismic-Response-Correlation Effect on Seismic Risk by the Initiating Event Matrix Method. Transactions of the Atomic Energy Society of Japan, Vol. 22, No.4, p.140-155. 2023 (in Japanese).
[12] The Japan Electrical Manufactures' Association. Technical Guidelines for Seismic Design of Nuclear Power Plants. JEAG4601-1987. 1987 (in Japanese).