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Evaluation of Correlation Coefficient for Seismic Fragility Response Variables

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ABSTRACT

There is a seismic fragility analysis, which is one of the processes of seismic probabilistic safety assessment. It is to evaluate the probability of failure to the seismic intensity on structures or components. In nuclear power plants, two or more components that are important for power plant safety are installed to create redundancy. These components have different response to vibration depending on the installation location or component's characteristics. However, when the characteristics of seismic waves and failure modes of each structure or component are similar, there is a seismic correlation in which the probability of multiple failure is linked by this similarity. This multiple failure probability considering the seismic correlation can finally be convolved with the seismic hazard, which can be a factor that affects the calculation of the annual frequency of multiple failure. In this study, the seismic correlation coefficients according to the combination of probability variables constituting the seismic fragility curve were evaluated. Probability variables should be evaluated independently according to the assumption of the seismic fragility, but it is also necessary to verify the evaluation by combing variables considering the actual earthquake event. We present the difference in results through these methods and discuss a reasonable method of calculating the seismic correlation. On the other hand, it is practically unreasonable to calculate the frequency of multiple failure in consideration of the seismic correlation of all components in nuclear power plant. Therefore, the annual frequency of multiple failure was calculated by adjusting the variables that determine the seismic hazard and seismic fragility in the assumed seismic correlation coefficient. Through this, the variables that determine the frequency of multiple failure were to be normalized, and the necessity of evaluating the seismic correlation for components with different properties was discussed.

INTRODUCTION

To evaluate the seismic probabilistic safety assessment of critical systems in nuclear power plant, the failure probability of a system is calculated using the seismic fragility curve of the components that contribute to the function of the system according to the accident scenario. The seismic fragility curve consists of the median capacity A_m and the logarithmic deviation β, and these are calculated under the assumption that they are independent variables. There are two or more components installed in nuclear power plants that contribute to the safety of the plants. In general, in the seismic fragility analysis, these components are evaluated assuming an independent or a dependent relationship. If there is a correlation between the components, the approximate seismic correlation coefficient of components is presented in the NUREG/CR-4840 report. In this study, these seismic correlation coefficients were evaluated through analytical methods using the probability variables constituting the seismic fragility. The calculation of seismic fragility and the types of probability variables are presented in detail in EPRI's technical report(3002012994). The logarithmic deviation β consists of square root sum of square(SRSS) of

probability variables for response and capacity, and we selected three probability variables for structure response variable category with reference to this report: "structure damping", "structure frequency", and "time history sets". These variables were sampled with each standard deviation, and the seismic correlation coefficients between components were numerically evaluated through the seismic analysis. Generally, the seismic fragility variables are analyzed independently, so one method is to calculate the correlation coefficient by variability of the probability variable according to the conventional treatment. But assuming an actual earthquake event, it is necessary to combine these probability variables at once. . In addition, the possibility of using the simplified model was discussed by evaluating the difference in seismic correlation using a model similar to the actual building and a simplified model based on the characteristics of the actual model.
The value indicating the seismic safety assessment is generally expressed in terms of the annual exceedance failure probability. This value is calculated by convolutional calculation of the failure probability of the component and the annual exceedance frequency of the seismic hazard. For the variables required for this calculation, the effect of the seismic correlation coefficient was evaluated.

METHODOLOGY

Seismic fragility curve

This seismic fragility curve is generally expressed as the probability of failure to the seismic intensity in "*g*" units. This curve is expressed as a cumulative logarithmic probability distribution, and its shape is determined by the standard deviation and median capacity of the structure or component.

$$F(a) = \emptyset[\frac{\ln\left(\frac{a}{A_m}\right)}{\beta_C}] \quad (1)$$

where Φ is the cumulative normal distribution function, A_m is median capacity and β_C is the square root sum of square of the standard deviations of uncertainty β_U and randomness β_R. Each variable is evaluated independently by the assumption of the separation of variables(SOV).

SSMRP method

The probability of multiple failure of two or more components with the same capacity under AND gate condition is the same as the failure probability of one component assuming dependency. However, when assuming independence, it can be expressed as a multiplication of the failure probability to each component. When the components are correlated, it is calculated through a multiple integral also called the SSMRP method.

$$P(a) = (2\pi)^{-\frac{n}{2}} \cdot (|V|)^{-\frac{1}{2}} \int_0^1 \int_0^1 \cdots \int_0^1 exp\left(-\frac{1}{2} Z^T \cdot V^{-1} \cdot Z\right) \cdot \frac{1}{z_1^2 z_2^2 \cdots z_n^2} dz_1 dz_2 \cdots dz_n \quad (2)$$

where n is a number of components, V is a matrix of seismic correlation coefficient ρ, and Z is the failure probability vector of each component.

Seismic hazard and the frequency of multiple failure

The seismic hazard is generally represented in terms of a site-specific hazard curve, H(a). The following Eq. (3) is a frequently adopted approximation.

$$H(a) = K_1 \cdot a^{-K_H},\ K_H = \frac{1}{\log(A_R)} \tag{3}$$

where *H(a)* is the annual frequency of exceedance of ground motion level "*a*", K_1 is an appropriate constant, and K_H is a slope parameter. And A_R is the ratio of ground motions that typically ranges from 2 to 4 corresponding to a ten-fold reduction in exceedance probability.

The frequency of multiple failure is calculated as the convolution of the probability of failure (Eq. (1) or Eq. (2)) with the hazard curve H(a), in terms of the following Eq. (4).

$$P_F = \int_0^\infty P(a)\left(-\frac{dH(a)}{da}\right)da \tag{4}$$

Seismic fragility response variables

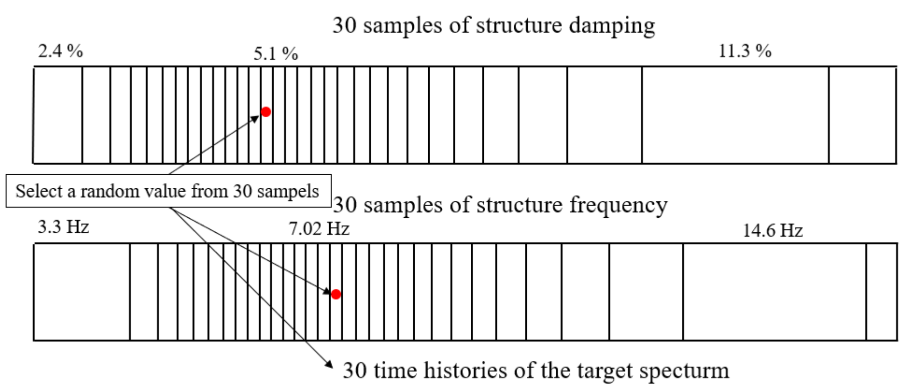
Seismic correlation in seismic fragility analysis is classified into structural capacity and response, and component capacity and response. Referring to the EPRI 3002012994, probability variables for structure response were selected. The probability variables are "structure damping", "structure frequency" determined by structure stiffness, and "time history sets".

Table 1. Structure response variables for fragility evaluation

Response variable	Variable symbol	Variability		Median value
		β_R	β_U	
Structure damping	$F_{\delta s}$	-	0.35	5%
Structure frequency	F_{fs}	-	0.15-0.35	6.92Hz
Time history	F_{TH}	0.15 (single set)	0(5 sets) 0.15(single set)	Reg. guide 1.60 PGA 0.2 g, damping ratio 5%

As shown in Table 1, 30 analysis cases for structure damping and structure frequency were created by applying the probability distribution for the parameters of each probability variable, as shown in Table 1.. The seismic time history was converted into seismic waves after estimating a spectrum with the target spectrum specified in Regulatory guide 1.60, with a peak ground acceleration of 0.2 g and damping ratio of 5%. For seismic analysis through the input of combined probability variables, one of the samples of the three variables was extracted by the Latin hypercube simulation(LHS), as shown in Figure 1.

Figure 1. Latin hypercube simulation for response variables



Numerical Analysis Models

The target model is an auxiliary building of a conventional nuclear power plant. The model is a lumped-mass stick model consisting of six nodes with two degrees of freedom per node. In addition, to understand the trend of general correlation coefficients, the 2-degrees of freedom model(2-d.o.f model) was used in which the auxiliary building model was simplified into three nodes. Both models allow only lateral displacement, with a natural frequency of 6.92 Hz in 1st mode and 17.36 Hz of 2nd mode, matching the natural frequency of the actual auxiliary building, as shown in Figure 2.

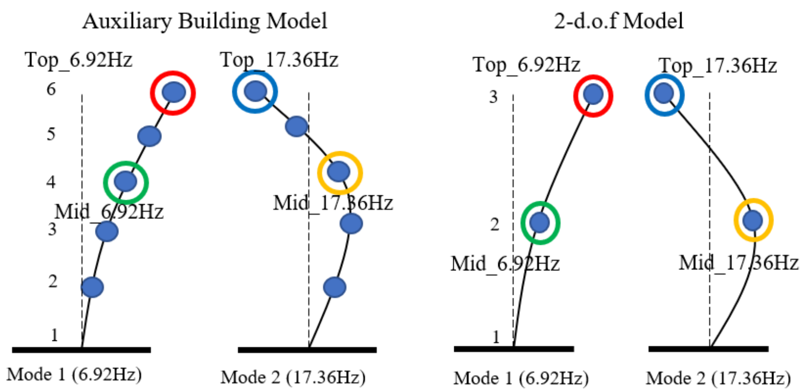


Figure 2. Mode shape of structure models and location and natural frequency of components

Four components were assumed according to the installation location and natural frequency range, which are indicated at the nodes of Figure 2. The component characteristics were hypothetically assumed to have a large correlation effect. Two components are located on the top and the other two components are located on the middle floor. Each component has natural frequencies of 6.92 Hz and 17.36 Hz which is corresponding to structural natural frequency of 1st mode, and of 2nd mode, respectively. The median capacities of all components were assumed to be 1.0 g. After analyzing the time history of 30 times by variable, calculation of the correlation of spectral accelerations for each component`s corresponding location and frequency will be made.

RESULTS

Seismic correlation coefficients for response variables

The analysis was performed in three ways. Table 2 shows the result of the correlation coefficient analysis of each probability variable. Eq. (5) is the expression for the correlation coefficient, in terms of the correlation coefficients and logarithmic standard deviations of the probability variables. And this equation can be used to calculated the first matrix of Table 3. The second and third matrix is the result of calculating the correlation coefficient combined variables input through LHS. Table 3 shows the results of the correlation coefficient analysis for the 2-d.o.f model and the auxiliary building model.

$$\rho_{i,j} = \frac{\beta_{\delta si}*\beta_{\delta sj}}{\sqrt{\beta_{\delta si}^2+\beta_{fsi}^2+\beta_{THi}^2}*\sqrt{\beta_{\delta sj}^2+\beta_{fsj}^2+\beta_{THj}^2}} * \rho_{\delta si,j} + \frac{\beta_{fsi}*\beta_{fsj}}{\sqrt{\beta_{\delta si}^2+\beta_{fsi}^2+\beta_{THi}^2}*\sqrt{\beta_{\delta sj}^2+\beta_{fsj}^2+\beta_{THj}^2}} * \rho_{fsi,j} + \frac{\beta_{THi}*\beta_{THj}}{\sqrt{\beta_{\delta si}^2+\beta_{fsi}^2+\beta_{THi}^2}*\sqrt{\beta_{\delta sj}^2+\beta_{fsj}^2+\beta_{THj}^2}} * \rho_{THi,j} \quad (5)$$

Table 2. Seismic correlation coefficients of each probability variable

Case	Structure damping (2-d.o.f model)				Structure frequency (2-d.o.f model)				Time history sets (2-d.o.f model)			
Component	Top 6.92 Hz	Top 17.36 Hz	Mid 6.92 Hz	Mid 17.36 Hz	Top 6.92 Hz	Top 17.36 Hz	Mid 6.92 Hz	Mid 17.36 Hz	Top 6.92 Hz	Top 17.36 Hz	Mid 6.92 Hz	Mid 17.36 Hz
Top 6.92 Hz	1			Sym.	1			Sym.	1			
Top 17.36 Hz	0.999	1			0.771	1			0.503	1		
Mid 6.92 Hz	0.998	0.999	1		0.996	0.749	1		0.992	0.453	1	
Mid 17.36 Hz	0.997	0.997	0.997	1	0.748	0.901	0.734	1	0.165	-0.038	0.211	1
STDEV.	0.582	0.121	0.486	0.056	0.596	0.161	0.469	0.075	0.315	0.048	0.248	0.024

Table 3. Seismic correlation coefficients of 3 analytical cases

Case	Combination of each variable (2-d.o.f model)				Combined variables input (2-d.o.f model)				Combined variables input (Auxiliary building model)			
Component	Top 6.92 Hz	Top 17.36 Hz	Mid 6.92 Hz	Mid 17.36 Hz	Top 6.92 Hz	Top 17.36 Hz	Mid 6.92 Hz	Mid 17.36 Hz	Top 6.92 Hz	Top 17.36 Hz	Mid 6.92 Hz	Mid 17.36 Hz
Top 6.92 Hz	1			Sym.	1			Sym.	1			
Top 17.36 Hz	0.825	1			0.840	1			0.800	1		
Mid 6.92 Hz	0.995	0.794	1		0.999	0.837	1		0.995	0.794	1	
Mid 17.36 Hz	0.817	0.981	0.825	1	0.857	0.890	0.857	1	0.817	0.981	0.825	1
STDEV.	-	-	-	-	1.119	0.232	0.864	0.110	0.425	0.670	0.386	0.457

We confirm that the correlation coefficient between components decreases as the model becomes more detailed. As the mode of the structure increases, the peak points of the response spectrum do not become clear, so it was determined that the response may be relatively less correlated. Although it is a more accurate result to perform correlation analysis on an analysis model, there are practical difficulties, such as having to re-calculate when the model is changed.

Table 4. Multiple failure probability of components by models and dependency condition

2-d.o.f model	Independent				Correlated			
Component	Top 6.92 Hz	Top 17.36 Hz	Mid 6.92 Hz	Mid 17.36 Hz	Top 6.92 Hz	Top 17.36 Hz	Mid 6.92 Hz	Mid 17.36 Hz
Top 6.92 Hz				Sym.				Sym.
Top 17.36 Hz	29.59%				24.23%			
Mid 6.92 Hz	76.86%	29.91%			48.34%	24.24%		
Mid 17.36 Hz	0.95%	0.37%	0.96%		1.02%	1.01%	1.02%	
Auxiliary building model	Independent				Correlated			
Top 6.92 Hz				Sym.				Sym.
Top 17.36 Hz	74.28%				79.66%			
Mid 6.92 Hz	80.80%	72.29%			85.87%	78.57%		
Mid 17.36 Hz	65.18%	58.31%	63.43%		70.82%	71.41%	70.40%	

Table 4 shows the probability of multiple failure to the components calculated through the SSMRP method(Eq. (2)) with correlation coefficients from second and third matrix of Table 3. Through these analyses, the seismic correlation coefficient by the probability variable constituting the seismic fragility was calculated according to the model and the method of combining the variables. Referring to the Table 3, the difference in the seismic correlation coefficients according to the model is not large. If only these cases are referenced, it would be effective to use a simplified model(2-d.o.f model) to find the seismic correlation coefficient for the probability variable for fragility evaluation. However, unlike the seismic correlation coefficient, the probability of multiple failure calculation varies a lot because of the difference in the model's floor response seismic intensity itself. Therefore, if it is necessary to calculate the probability of multiple failure, accurate results can be obtained only when evaluating using the target model rather than a simplified model.

Effect of the variables on the annual frequency of multiple failure to the components according to the seismic correlation

In general, when evaluating the seismic risk assessment for a system, the annual frequency of exceedance of component's failure is calculated and evaluated by convolution with the seismic hazard. However, it is almost impossible and inefficient to evaluate all components in a nuclear power plant in consideration of the seismic correlation. Therefore, several analyses were performed through variables of annual frequency of multiple failure from the need to evaluate the seismic correlation for components with differences in characteristics. The components in the previous correlation analysis are not actual components. The result of the analysis is the multiple failure probability calculated assuming the components with the same response in the same frequency range for the floor response of the structure. Therefore, the annual frequency of multiple failure was additionally evaluated in a normalized assumption.

The analysis was performed using two components, and Eq. (4) was used to calculate the annual frequency of multiple failure. For *P(a)* of Eq. (4), Eq. (2) was used when there was a seismic correlation, and Eq. (1) was used when the components are independent. Eq. (3) was used for the seismic hazard curve, and the slope parameter A_R was 3 when changing the A_m or β, as shown in the left and middle of Figure 3.

First, assuming two components with the same A_m, the annual frequency of multiple failure according to the change in the standard deviation of component β was calculated. The β increases 0.3 to 0.6. Second, it was performed that the β of the two components was the same and A_m changed. The A_m of components in auxiliary building is difficult to specify due to various categories. It may range from less than 1.0 g to more than 6.0 g. In general, assuming a seismic response intensity that can affect the component, four components were assumed to have A_m that increased by 0.5 g to 2.0 g. Third, it was performed that both A_m and β of two components was the same and the slope variable A_R of the seismic hazard changes from 2 to 5.

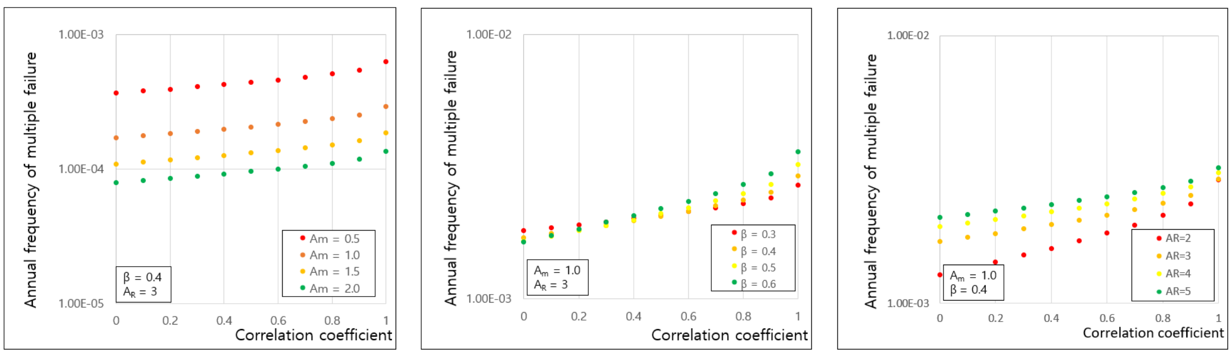


Figure 3. Annual frequency of multiple failure by different conditions

As can be seen from Eq. (4) and Figure 3., the difference in component's A_m does not affect the seismic correlation regardless of its value and has a certain ratio in the frequency of multiple failure. And the slope of the annual frequency graph for seismic correlation increases as the β increases, and the slope increases as the A_R decreases. However, if the ratio is the same as the seismic hazard due to the slope variable A_R and the slope of seismic fragility due to the β, the convolution value will be same.

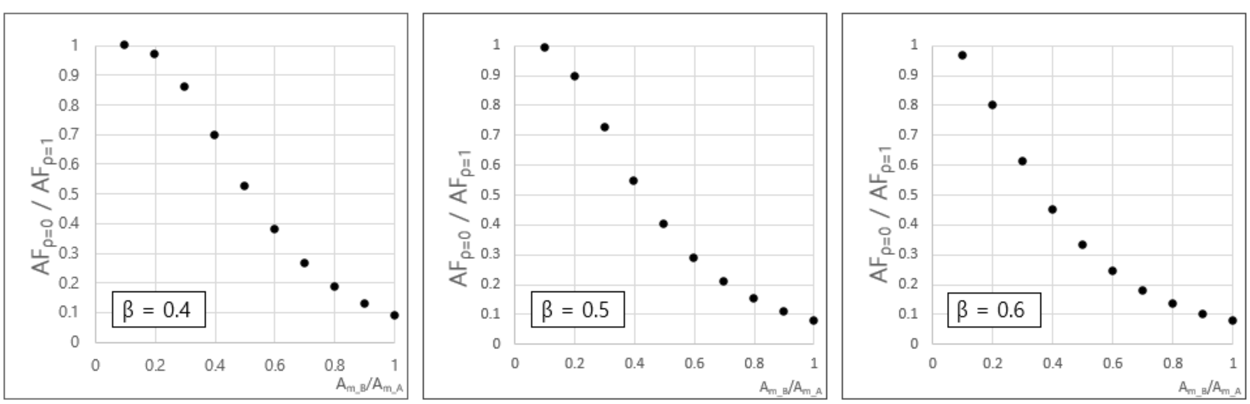


Figure 4. Annual frequency ratio based on differences in A_m, β and the seismic correlation of component

As shown in Figure 4., the standard deviation β was the same, the ratio of A_m of the two components(A and B) was changed from 0.1 to 1.0, and the annual frequency of multiple failure ratio was calculated when the correlation coefficient was 0(independent) and 1.0(dependent). This is to understand the effect of seismic correlation on the annual frequency as the difference in A_m between the two components increases. "$AF_{\rho=0}$" in Figure 4 means the annual frequency of multiple failure when the seismic correlation coefficient ρ is zero. When the ratio of A_m is 1.0, that is, when it is the same component, the frequency of multiple failure according to the seismic correlation differs by more than 90% in the case of "$\beta = 0.4$" in figure 4. In this case, accurate evaluation will be possible only after considering the seismic correlation of the components. However, when the ratio of A_m is less than 0.2, there is little difference in the frequency of multiple failure depending on the seismic correlation. In the case of these components, it is not necessary to consider the effect of the seismic correlation and the components can be assumed independently according to the existing evaluation procedure.

CONCLUSION

The seismic correlation coefficient and the probability of multiple failure varies depending on the method of inputting the probability variable and the model used. When creating the seismic fragility using an analytical method rather than conventional treatment(LN(Am, β)), it can be considered to use combined probability variables to calculate the correlation coefficient for components of structure. If that's not the case, then as usual, the assumption of a fragility curve is to form a formula after evaluating by separating the variables, it is efficient to calculate the seismic correlation coefficient for each variable as well. Regarding which model to use, using the actual model will be able to calculate the most accurate correlation coefficient. However, it is time-consuming and complicated to analytically calculate the coefficients of all target components. In addition, when the model conditions change, the correlation coefficient also changes, which requires re-analysis. Although the example of this study is insufficient to quantify, you can consider how to quickly analyze the correlation coefficient by applying a simple model to reduce the process. This may be helpful in the step of determining the correlation coefficient of components by judgment of an expert.

When evaluating the annual frequency of multiple failure to the same component, the A_m value itself is not affected by the seismic correlation, and the slope of the annual frequency is the same even if A_m changes as shown in Figure 3. As the β increases and the slope variable A_R decrease(i.e., increase the slope of the seismic hazard), the more sensitive the change in the annual frequency of multiple failure due to the seismic correlation becomes. The seismic correlation coefficient evaluation is evaluated not only for the same components, but also for different components. However, it is difficult to evaluate all components in nuclear power plants. If so, the criteria for determining the components for correlation evaluation are needed. Therefore, A_m, which is a major factor in the seismic performance of the component, was used. We graphically represent the risk ratio in the independent(i.e., ρ = 0) and the dependent(i.e., ρ = 1) condition according to the change in the A_m ratio of the different components. Finally, the range of components subject to the evaluation is determined by normalizing the correlation coefficient, component fragility A_m, β, and the hazard slope, which are variables that determine the annual frequency of multiple failure.

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