An Analysis of Effect of Correlation of Response in the System Reliability Analysis in a Seismic PSA of a Nuclear Power Plant

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Abstract
In seismic probabilistic safety assessments of nuclear power plants, it has been recognized important to consider the effect of correlation among responses and/or capacities of components. The authors developed a new method to calculate a failure probability of a system considering the effect of correlation of component failures by a direct Fault Tree quantification using the Monte Carlo method. By this method, the failure probability of a system can be calculated with the effect of arbitrary correlation not only on the occurrence probabilities of intersections of component failures but also on the occurrence probability of a union of component failures, which has been ignored by the calculation method developed in the phase-1 of the Seismic Safety Margins Research Program in the U.S.A. The usefulness of this method was demonstrated by the calculation of the failure probability of a Residual Heat Removal (RHR) system in a Boiling Water Reactor. This result showed that the correlation of response significantly lowered the occurrence probability of the union of component failures and influenced the calculated failure probability of the RHR system, indicating that the neglect of effect of correlation on the union of component failures might cause an excessive overestimation of failure probability of a system.

1 Introduction

Seismic probabilistic safety assessments (PSAs) of nuclear power plants (NPPs) have been widely conducted since early 1980s, especially in the U.S.A. to evaluate core damage frequency (CDF) induced by earthquakes and to identify vulnerability of NPPs to earthquakes. Many large earthquakes have occurred historically in Japan. The Japan Atomic Energy Research Institute (JAERI) has developed a methodology for a seismic PSA of a NPP.

The seismic PSA procedures developed at JAERI have the following four steps[1].

(1) Evaluation of seismic hazard: The seismic hazard of a given site is defined as the frequency of exceedance at every level of intensity (expressed by peak acceleration) of earthquake motion at bedrock.
(2) Evaluation of responses of components in systems: Responses of components are calculated from design responses by the use of a 'response factor method'.
(3) Evaluation of component capacities and failure probabilities: Component failure probabilities are calculated as functions of the peak acceleration at bedrock by comparing the responses with capacities of components, both of which are expressed in terms of local response parameters of components.
(4) Evaluation of conditional probabilities of system failures and CDF: Conditional failure probabilities of systems and conditional occurrence probability of core damage at every level of earthquake motion are evaluated using a system model such as Fault Tree (FT) and the component failure probabilities. CDF is calculated by integrating the product of the occurrence frequency of earthquake motion and the conditional probability of core damage over a whole range of earthquake motion.

In a seismic PSA, the failure probabilities of components are obtained from the comparisons of responses and capacities of components that are given as random variables and the failure probabilities of systems are calculated based on the failure probabilities of components and the system model.

In the JAERI method, failure probabilities of systems are calculated by a computer code named SECOM (Seismic Core Melt Frequency Evaluation)-2[2]. They can be calculated by the following two methods:

(1) the Boolean Arithmetic Model (BAM) method[3], which gives an exact numerical solution and
(2) the Minimal Cut Set (MCS) method that gives an upper bound approximation results.

Correlation of responses and/or capacities influences the probability of simultaneous failure of multiple components (an intersection of component failures). Thus, failure probabilities of systems estimated with consideration of the correlation of responses and/or capacities of components can be significantly different from those without consideration of the correlation.

In the phase-1 of the SSMRP (Seismic Safety Margins Research Program)[4], analysis procedures for estimating the risk of an earthquake-caused radioactive release from a commercial nuclear power plant was developed. In this program, a system analysis code SEISIM (Systematic Evaluation of Important Safety Improvement Measures) was developed to evaluate occurrence probabilities of accident sequences as a part of its functions.

In the SEISIM code, the occurrence probabilities of accident sequences are calculated from those of MCSs with consideration of the effect of correlation on the intersections of component failures. However, in this method, the effect of correlation on the union of component failures is ignored.

We developed a pilot program, which can calculate a failure probability of a system by a direct FT quantification using the Monte Carlo method. With this method the failure probability of a system can be easily calculated with consideration of the effect of arbitrary correlation on both union and intersection of component failures.

2 Definition and Nature of Correlation in Seismic PSAs

When one considers the simultaneous failure probability of multiple components in a seismic PSA, correlation of component failures is an essential issue in a seismic PSA. Reed et al.[5] defined and explained the correlation of component failures as follows (Their explanation was rearranged by the present authors):

"Physically, dependencies exist due to similarities in both response and capacity parameters. Dependency occurs between components and between components and structures due to common responses and capacities. For example, if two components are located side by side in a building, there is high response dependency. The structural capacities of two identical pumps are highly correlated. Thus, if one pump fails due to an earthquake, it is likely that the other pump will also fail." The effect of such dependency is called correlation of component failures. Here, the former means the correlation of responses; the latter means the correlation of capacities.

The correlation of responses is caused by common sources of variability of responses such as variability of seismic motion, amplification characteristics of soil, response characteristics of buildings, etc. Similarly, the correlation of capacities arises from common sources of variability of capacities such as variability caused by design, manufacturing, maintenance of the components, etc.

In the case of no correlation (so called an independent case), the simultaneous failure probability of two components is the product of the failure probabilities of them. On the other hand, in the case that the component failures are fully correlated, it is the smaller failure probability of them and the merit of redundancy is lost. If the order of a MCS is high, its occurrence probability can be varied quite significantly.

3 Existing Works for Treatment of Correlation of Response

3.1 SSMRP and NUREG-1150

3.1.1 Evaluation of responses and treatment of correlation of response in SSMRP and NUREG-1150

In the phase-1 of the SSMRP, the SMACS (Seismic Methodology Analysis Chain Statistics) code was developed to calculate the seismic responses of structures, systems and components. In "Application of the SSMRP Methodology to the Seismic Risk at the Zion Nuclear Power Plant"[6] (hereinafter called the application of the SSMRP to the Zion plant), a large number of multiple time history analyses of responses were performed by the SMACS code. Correlation and variability values of responses were determined from the results of those response analyses. Finally, the occurrence probabilities of accident sequences were calculated by the SEISIM code using these values.

In the risk assessments for the Surry and Peach Bottom nuclear power plants of NUREG-1150 risk assessments[7] (hereinafter called NUREG-1150), a set of rules were formulated as shown in Table 1, which predicted the "exact" correlation with adequate accuracy. These rules were based on the examination of a large number of responses in the application of the SSMRP to the Zion plant, which showed a distinct pattern to the values of correlation that existed between the various types of responses.

Table 1 Rules for Assigning Response Correlation for NUREG-1150

1. Components on the same floor slab, and sensitive to the same spectral frequency range (i.e. Zero Period Acceleration (ZPA), 5-10 Hz, or 10-15 Hz) will be assigned response correlation = 1.0.
2. Components on the same floor slab, sensitive to different ranges of spectral acceleration will be assigned response correlation = 0.5.
3. Components on different floor slabs (but in the same building) and sensitive to the same spectral frequency range (ZPA, 5-10Hz or 10-15 Hz) will be assigned response correlation = 0.75.
4. Components on the ground surface (outside tanks, etc.) shall be treated as if they were on the grade floor of an adjacent building.
5. "Ganged" valve configurations (either parallel or series) will have response correlation = 1.0.
6. All other configurations will have response correlation = 0.

On the other hand, because of the lack of data for the correlation of capacities, the effect of correlation of capacities was examined by a sensitivity analysis, assuming that the capacities of components were perfectly correlated or independent in the application of the SSMRP to the Zion plant. In NUREG-1150, the capacities of components were assumed to be independent.

3.1.2 Calculation of occurrence probabilities of accident sequences with consideration of correlation in SSMRP and NUREG-1150

By using the SEISIM code, the occurrence probabilities of MCSs that contained correlated component failures were calculated and incorporated in the calculation of occurrence probabilities of accident sequences.

In this method, correlation of component failures was treated as follows: If the correlation between the responses and the correlation between the fragilities (the fragility means the capacity in this paper) are known for two correlated components, then the coefficient of correlation between the failures of these two components ('correlation of component failures') was defined as the following equation[7]:

$$\rho = \frac{\beta_{R1}\beta_{R2}}{\sqrt{\beta_{R1}^2+\beta_{F1}^2}\sqrt{\beta_{R2}^2+\beta_{F2}^2}}\rho_{R1R2} + \frac{\beta_{F1}\beta_{F2}}{\sqrt{\beta_{R1}^2+\beta_{F1}^2}\sqrt{\beta_{R2}^2+\beta_{F2}^2}}\rho_{F1F2} \qquad (3\text{-}1)$$

where ρ is a correlation coefficient between the component failures 1 and 2, β_{R1} and β_{R2} are standard deviations of the logarithms of the responses of components 1 and 2, β_{F1} and β_{F2} are standard deviations of the logarithms of the fragilities of components 1 and 2, ρ_{R1R2} is a correlation coefficient between responses of components 1 and 2, ρ_{F1F2} is a correlation coefficient between the fragilities of components 1 and 2. Mathematically, this correlation coefficient is defined by that between logarithms of ratios of responses to capacities for components 1 and 2.

The occurrence probability of an accident sequence that leads to core damage (P(ACC SEQ)) described as the sum of occurrence probabilities of MCSs was calculated by the following equation:

$$P(\text{ACC SEQ}) = 1 - \prod_i \left[1 - P\left(\text{MCS}_i\right)\right] \qquad (3\text{-}2)$$

where $P(\text{MCS}_i)$ is the occurrence probability of the i-th MCS.

This equation, gives an exact solution only when the component failures among MCSs are independent of one another, otherwise it gives an upper bound approximation when the component failures are not independent.

The occurrence probability of a MCS in the equation was obtained by n-dimensional numerical integration of a multivariate lognormal distribution with correlation coefficients of all pairs of component failures in the MCS that were defined by equation (3-1).

3.1.3 Limitations of treatment of correlation in SSMRP and NUREG-1150

Since the occurrence probability of an accident sequence was calculated by equation (3-2), with consideration of the effect of correlation on the intersection of component failures (component failures combined by AND-gate, i.e. MCS), the effect of correlation on the union of component failures (component failures combined by OR-gate) was ignored. Justification for this simplification was that the correlation of component failures would strongly influence the component failures combined by AND-gates and the effects of the correlation on those combined by OR-gates would be much smaller[6]. It was also noted that this simplification would yield a conservative result.

Since FTs for safety systems of an NPP have many component failures combined by OR-gates normally, the correlation among them might significantly influence the failure probabilities of the systems. However, it is quite difficult to analyze this effect by using MCS-based methods.

3.2 Consideration of correlation of response in the JAERI method

3.2.1 Evaluation of responses

One of the characteristic features of evaluation of responses in the JAERI method is the use of the response factor method[8]. The response factor (F_R) for each building or component (structure, piping and other equipment) in NPP accounts for the difference between the response (q_R) and the response evaluated in design (q_D), which generally has a large conservatism.

Assuming a linear relationship between the response and acceleration at bedrock, the response $q_R(\alpha)$ to an arbitrary acceleration (α) is obtained using design acceleration (α_D) as:

$$q_R(\alpha) = \frac{q_D(\alpha_D)}{F_R} \cdot \frac{\alpha}{\alpha_D} \qquad (3\text{-}3)$$

The response factor for each element is derived from the product of the following subfactors (F_i), which represent the degree of conservatism introduced in various stages of the response calculations in Japanese seismic design practices for NPPs:

F_1 : generation of seismic wave for design at bedrock
F_2 : propagation of seismic wave in soil and basemat of a building for design
F_3 : response of building
F_4 : response of component

Assuming that each subfactor is independent of one another and has a probability density function represented by a lognormal distribution, the median value of F_R is the product of all the median values of the subfactors and the logarithmic standard deviation of F_R is obtained from ones of the subfactors using the square root of the sum of the squares method.

3.2.2 Calculation of failure probability of a system with consideration of correlation in the response factor method

Abe et al.[9] examined the effect of correlation of responses on failure probabilities of systems by sampling the response factors with the Monte Carlo method. In their method, the response factors were sampled to determine the responses with condition that response factors of all components were fully correlated and the failure probabilities of components were obtained from the capacities and the sampled responses at one trial. The failure probabilities of components were assigned into the FT and the failure probability of a system was calculated by using the BAM method at this trial. This procedure was iterated sufficient times and the distribution of failure probabilities of a system was obtained. Mean value of the distribution was calculated as the failure probability of a system. The effect of correlation of responses on component failures combined by AND-gates and OR-gates can be considered in this method. However, they considered solely the effect of fully correlated responses on the failure probability of a system as a bounding analysis.

4 New Calculation Method Using the Monte Carlo Simulation with Consideration of Correlation

In order to solve the limitations of the existing methods described in section 3, the authors developed a pilot program adopting a new method for the calculation of failure probability of a system based on the direct FT quantification using the Monte Carlo method. With this method, correlation of responses can be easily and flexibly considered in the calculation.

4.1 Calculation flow of the Monte Carlo method

The calculation flow of the pilot program to calculate the failure probability of a system consists of the following six steps as shown in Fig. 1. In the Monte Carlo simulation, the values of response and capacity of each component are sampled according to their probability distributions. Here, the correlation of responses are considered as described below. The value of response and the value of capacity of each component are compared and the failure of each component is judged. The failure or success of each component is assigned as either TRUE or FALSE to a Truth Table that represents the FT of a system to judge the system failure. This trial is iterated sufficient times and the failure probability of the system can be obtained from the all iteration numbers and the occurrence numbers of system failures in the simulation.

Since the failure or success (non failure) of each component is assigned directly to FT and system failure is judged at each trail, the failure probability of the system can be calculated with consideration of the correlation among component failures combined by not only AND-gates but also OR-gates with this method.

The calculation flow of the Monte Carlo simulation is as follows:

Step 1 Set up of inputs: FT structure of a system, capacity data and response data of each component in a system are inputted.

Step 2 Determination of response and capacity values for each component with consideration of correlation: The values of the response (R_i) and the capacity (C_i) for each component are assigned based on random numbers sampled according to their probability distributions. Since the values of responses of components are estimated by the response factor method of JAERI, the correlation of responses are considered in this step.

Step 3 Judgment of failure of each component: The failure of each component is judged by the condition that R_i is lager than C_i (R_i>C_i).

Step 4 Judgment of system failure: Assigning failure or success of each component to a Truth Table, which describes the logical structure of the FT, the system failure is judged. Then the number of trials that result in the system failure (N) is counted.

Step 5 Calculation of failure probability of a system: The failure probability of the system is defined as N/N_t, where N_t is the all iteration numbers.

Step 6 Calculation of failure probability of a system at every level of seismic motion: The calculation steps 1 to 5 are repeated to calculate the failure probability of a system at every seismic level.

4.2 Consideration of correlation of response of component by the Monte Carlo method

In the framework of the response factor method of JAERI, correlation of responses can be considered by two concepts as described below. Here, the two concepts are introduced and treatment of responses of components by the Monte Carlo simulation is discussed.

(1) Consideration of correlation of response using correlated response subfactors

Reed et al. proposed a treatment of correlation between two components[5]. Based on their concept, correlation of responses of components was caused by the common sources of variability of the responses. Referring to their concept, correlation of responses of components can be treated as described below with the response factor method of JAERI:

Examining the sources of variability of each response subfactor for the components, if the response subfactors of the components share the common sources of variability, those response subfactors will be assumed to be fully correlated and, if not, they will be assumed to be independent. Since the response factor is the product of the response subfactors, the response factors are fully correlated if all the response subfactors are fully correlated. If only some of response subfactors are fully correlated, they are partially correlated. In the former case, the responses are fully correlated and in the latter case, they are partially correlated.

In the Monte Carlo simulation, the same value is sampled for the response subfactors that are fully correlated. In this treatment, the responses can be made discretely correlated since the response factor is the product of each response subfactor that is fully correlated or completely independent.

(2) Consideration of correlation of response using given correlation coefficient

If the data of correlation coefficients can be obtained, it is not necessary to examine the sources of variability of response subfactors and the need for engineering judgment is reduced.

In this case, a mathematical technique that can make responses correlated arbitrarily according to any given correlation coefficients in the Monte Carlo method is needed. The following method gives a solution to this problem. In general, correlation among responses of many components, which are treated as random numbers, can be expressed by a covariance matrix showing covariance among all pairs of responses of them. In the SEISIM code, the covariance matrix was used to calculate the occurrence probabilities of MCSs that contained correlated component failures.

The correlation among responses of components is defined by the following covariance matrix (V):

$$\mathbf{V} = \begin{bmatrix} \mathrm{Var}(\mathbf{R}_1) & \mathrm{Cov}(\mathbf{R}_2,\mathbf{R}_1) & \cdot & \cdot & \mathrm{Cov}(\mathbf{R}_n,\mathbf{R}_1) \\ \mathrm{Cov}(\mathbf{R}_2,\mathbf{R}_1) & \mathrm{Var}(\mathbf{R}_2) & & & \\ \cdot & & \cdot & & \\ \cdot & & & \cdot & \\ \mathrm{Cov}(\mathbf{R}_n,\mathbf{R}_1) & \mathrm{Cov}(\mathbf{R}_n,\mathbf{R}_2) & & & \mathrm{Var}(\mathbf{R}_n) \end{bmatrix} \qquad (4\text{-}1)$$

where $\mathrm{Cov}(R_i,R_j)$ is the covariance between the logarithms of responses of components i and j and $\mathrm{Var}(R_i)$ is the variance of logarithm of the response of component i defined by the following equations:

$$\mathrm{Var}(R_i) = E((\ln(R_i))^2) - (E(\ln(R_i)))^2 \qquad (4\text{-}2)$$
$$\mathrm{Cov}(R_i, R_j) = E((\ln(R_i)(\ln(R_j)) - E(\ln(R_i))E(\ln(R_j)) \qquad (4\text{-}3)$$

where E(x) and E(xy) are defined by following equations using probability density function f(x) and f(x,y):

$$E(x) = \int_{-\infty}^{\infty} x \cdot f(x)dx$$

$$E(xy) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x \cdot y \cdot f(x,y)dxdy$$

The value of 1.0 is assigned as the value of each $\mathrm{Var}(R_i)$ in the matrix for simplification of the calculation since a covariance coefficient can be equal to a correlation coefficient.

The random numbers that are subject to normal standard distribution and are correlated according to the covariance matrix (V) can be obtained by transforming independent random numbers of normal standard distribution with the following equation:

$$\begin{bmatrix} y_1 \\ y_2 \\ \\ y_n \end{bmatrix} = \mathbf{M} \begin{bmatrix} x_1 \\ x_2 \\ \\ x_n \end{bmatrix} \qquad (4\text{-}4)$$

where x_i is the independent random numer and y_i is the correlated random number and M is a lower triangular matrix that holds for equation (4-5).

$$\mathbf{V} = \mathbf{M}\mathbf{M}^t \qquad (4\text{-}5)$$

where M^t is the transposed matrix of M. The matrix (M) can be obtained by decomposing the covariance matrix (V) into M and M^t with the use of Cholesky decomposition[10].

The correlated response of component (i) that are subject to lognormal distribution can be obtained as follows:

$$R_i = R_{im} \exp(\beta_i y_i) \qquad (4\text{-}6)$$

where R_i is the response of component (i), R_{im} is the median of R_i and β_i is the standard deviation of logarithm of R_i. With this technique, logarithms of the responses can be made correlated in accordance with the covariance coefficients determined by the covariance matrix V.

In the case that responses of some components are fully correlated, these components can be grouped into 'a response group' and correlation (covariance) coefficients among the response groups are assigned into the covariance matrix like in NUREG-1150. By grouping, the dimensions of covariance matrix can be reduced to make calculation more effective.

The correlation of capacity can be treated similarly if the data is available.

5 Calculation of Failure Probability of a System Using the Monte Carlo Method.

In order to examine the effect of correlation on component failures combined by OR-gates, which was not considered in the SSMRP, a system that contained enough number of components in series was chosen as a sample system. A multiple train system was suitable for examining the effect of correlation on component failures combined by AND-gates.

A Residual Heat Removal (RHR) system of a Boiling Water Reactor was chosen for our examination. First of all, the failure probabilities of the train and the system were calculated for an independent response case (hereinafter called independent case) to verify the accuracy of the Monte Carlo method. After confirming the accuracy of the Monte Carlo method, the failure probabilities were calculated for correlated response cases with consideration of the effect of correlation on both OR-gates and AND-gates to examine the effect of correlation.

5.1 System Analyzed

The RHR system, which originally consisted of three trains, was simplified to a two train system including support systems. In the sub FT for the train of RHR system(hereinafter called sub FT for the train), there were 26 seismically induced component failures and 8 random ones. Most of the component failures were combined by OR-gates, but two pairs of pumps were combined by AND-gates in the sub FT for the train. In the FT of RHR system, sub FTs for the trains A and B were combined by AND-gates[11].

5.2 Verification of the Monte Carlo method

The failure probabilities of the train A of RHR system and the RHR system were calculated for the independent case by the Monte Carlo method developed and the BAM method in the SECOM-2 code, which gives an exact numerical solution, in order to compare these failure probabilities. The calculation results are shown in Fig. 3 and Fig. 4, respectively. In the Monte Carlo simulation, the failure probabilities were obtained by 10,000 iterations at every seismic level.

Good agreement can be seen between the failure probabilities of the RHR system as well as those of the RHR train A calculated by the Monte Carlo method and the BAM method. From these results, we thought that the new method in the pilot program could calculate the failure probabilities accurately enough.

5.3 Examination of effect of correlation on failure probabilities of train and system of RHR

5.3.1 Condition of correlation

The failure probabilities of the train and the system of RHR for the following two correlated response cases were calculated in order to examine the effect of correlation not only on component failures combined by AND-gates but also on those combined by OR-gates.

(1) Consideration of correlation of response using correlated response subfactors

F_1 represents the conservatism and variability associated with the generation of seismic wave for design. Assuming that F_1 commonly influences responses of all the buildings and components, the common value of F_1 was assigned to all components. F_2 and F_3 are for propagation of seismic wave through the soil and for building responses, respectively. Assuming that the variability of F_2 and F_3 for each building was caused by the same sources, the common values of them were assigned to components in the same building and completely independent values were used for components in different buildings. F_4 is for each component response. The values of F_4 were assumed to be unity and had no variability in the present study.

In this case, the responses of the components in the same building were fully correlated and those in the different buildings were partially correlated (hereinafter called fully correlated case).

(2) Consideration of correlation of response using correlation coefficient

In this case, the components in the system were grouped into 27 response groups based on their locations of installations and natural frequencies of components. Correlation coefficients among the response groups were determined by the rules shown in Table 1, which were used in NUREG-1150, and were assigned into the covariance matrix (V).

As described before, the covariance matrix has to be decomposed into the matrix M and M^t to generate correlated random numbers. However, the covariance matrix V determined by the rules in Table 1 couldn't be decomposed mathematically. This was because unavoidable correlation occurred among the response groups that had to be independent on the rules. The small correlation coefficient 0.3 was assigned as the coefficients among those response groups. Fig. 2 shows the covariance matrix used for the calculation.

In this case, the responses of many components were partially correlated (hereinafter called partially correlated case). Here, the standard deviation of logarithm of the response (β_i) was assumed to be equal to that of the response factor for each component.

5.3.2 Calculation results

The calculated failure probabilities of the RHR train A for the fully correlated case and the partially correlated case (hereinafter, these correlated cases are called correlated cases) are shown in Fig. 3 compared with the independent case. The calculated failure probabilities for the correlated cases were smaller than that for the independent case. The reason for this result could be explained as follows: since responses among components were correlated and a large number of component failures in the train were combined by OR-gates, the calculated failure probability of the RHR train A was significantly lowered by the correlation of responses. The same tendency of the calculation result was also seen on the RHR train B. The calculated failure probability of the train A for the fully correlated case was smaller than that for the partially correlated case. This implies that the correlation among the component failures in the fully correlated case was higher than that in the partially correlated case.

Figure 4 shows the calculated failure probabilities of the RHR system, which consisted of two RHR trains A and B, for the correlated cases. The calculated failure probabilities of the RHR system for the correlated cases were larger than that for the independent case at low seismic motion levels (below about 400 Gals). At higher seismic motion levels (above about 400 Gals), however, the calculated failure probabilities for the correlated cases were smaller than the calculated failure probability for the independent case. The calculated failure probability of the RHR system for the partially correlated case was higher than that for the fully correlated case at all seismic motion levels.

Generally, the correlation of component failures raises the occurrence probabilities of component failures combined by AND-gates while it lowers those combined by OR-gates. The former effect was more significant at low seismic motion levels and became less significant as the seismic motion level increases in this case.

5.4 Discussion of effect of correlation on component failures combined by OR-gates

The failure probabilities of the RHR system were calculated with consideration of the effect of correlation on component failures combined by both OR-gates and AND-gates. From these results, it was found that the correlation of responses significantly lowered the calculated failure probability of the train, FT of which contained a large number of component failures combined by OR-gates, and varied the calculated failure probability of the system. The effect of correlation on component failures combined by OR-gates have not been considered in the SEISIM code. We think that the neglect of the effect of correlation on the component failures combined by OR-gates might cause an excessive overestimation for the calculated failure probability of a system, which could be too conservative. Additional overestimation might be caused by the SEISIM code because the occurrence probabilities of accident sequences are quantified by the upper bound approximation. We think this excessive overestimation might cause some problems in a seismic PSA. For instance, it might affect identification of important systems and/or components that influence the CDF.

6 Conclusion

The effect of the correlation on component failures combined by OR-gates was ignored for the calculation of occurrence probabilities of accident sequences in the SSMRP since it was recognized that the correlation would not influence the occurrence probability of component failures combined by OR-gates significantly.

In order to examine the effect of the correlation especially on component failures combined by OR-gates, the authors developed a new calculation method, which can calculate the failure probability of a system with consideration of the effect of correlation on component failures combined by both AND-gates and OR-gates, with the direct FT quantification using the Monte Carlo method.

With this method, the failure probabilities of the RHR train and the RHR system as a whole were calculated for the cases that responses among the components were correlated and independent. The calculation results showed that, in the case that a large number of component failures were combined by OR-gates, the correlation of responses significantly lowered the occurrence probability of the component failures combined by OR-gates and influenced the calculated failure probability of the system.

We think that an excessive overestimation of calculated failure probability of a system might occur by the neglect of effect of correlation of component failures combined by OR-gates and it causes some problems in the seismic PSA.

These calculation results also demonstrated the usefulness of our new calculation method to estimate the failure probabilities of systems and CDF in seismic PSAs.

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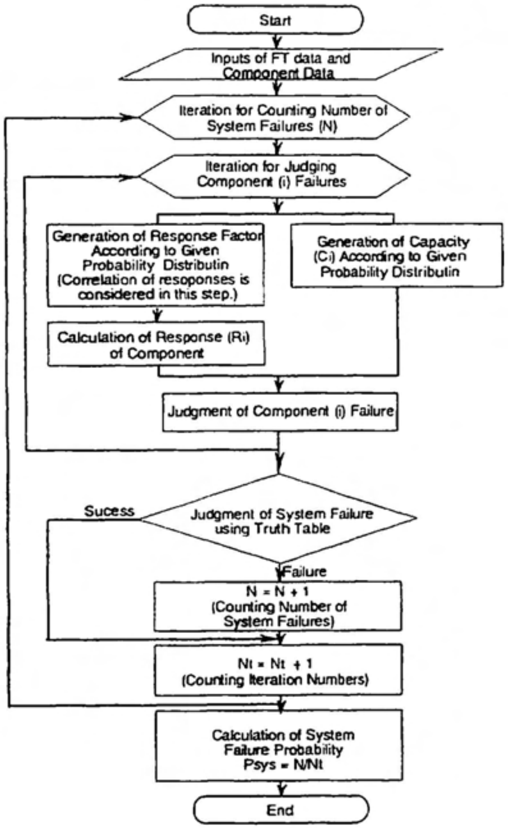

Fig. 1 Flow Chart for Monte Carlo Simulation

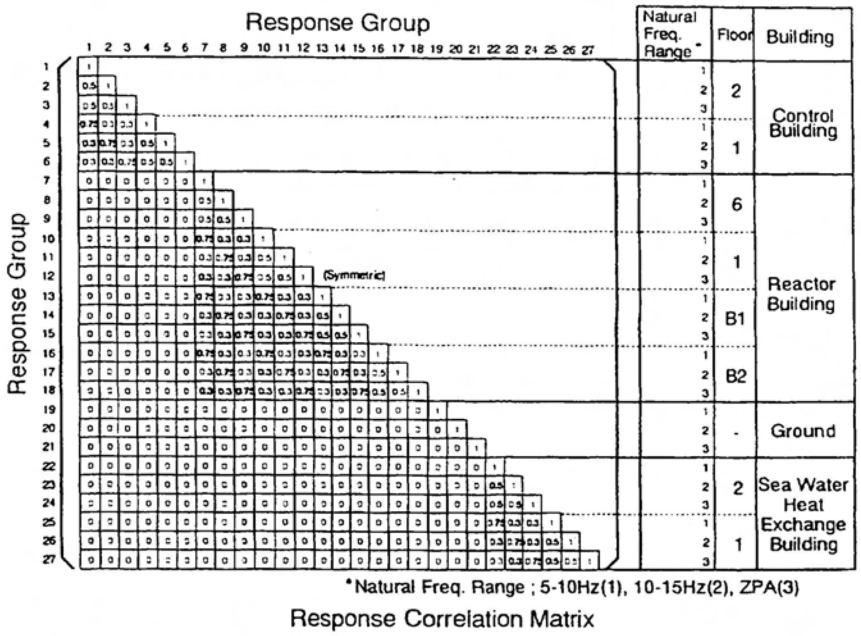

Fig. 2 Covariance Matrix among Response Groups for Calculation of Failure Probability of RHR System

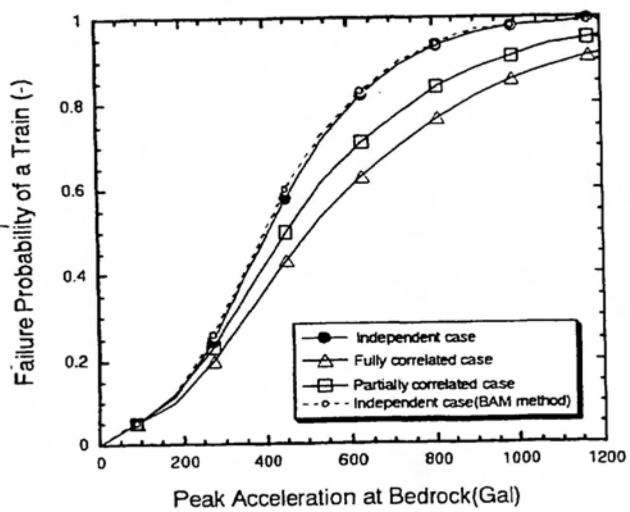

Fig. 3 Failure Probability of RHR Train A

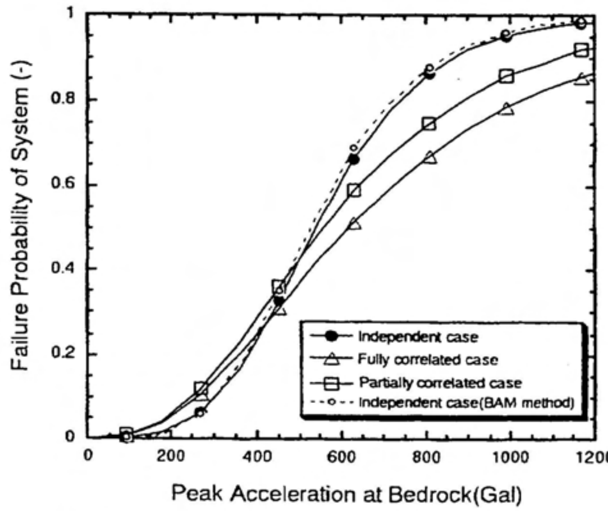

Fig. 4 Failure Probability of RHR System