MCS Based Quantification Approach for Seismic PRA Considering Seismic Correlation and its Application to Hypothetical Nuclear Power Plant

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Abstract: The seismic failure correlation among structures, systems and components(SSCs) in nuclear power plants(NPPs) is an important issue for evaluating the seismic risk of NPPs. In conventional seismic probabilistic risk assessment(PRA), it is common practice to assign complete correlation to redundant components while assuming zero correlation to other components, even though the actual correlation is likely to be partial. The impact of this assumption has been confirmed by the sensitivity analysis under the condition that zero correlation for the redundant components has been assumed. One of the challenges in considering seismic partial correlation is the evaluation method required to manage the large number of possible SSCs' combinations. A possible solution is to utilize the direct quantification of fault trees using Monte Carlo simulation(DQFM) method, however it is not practical to handle large scale Fault Trees(FTs) of an actual NPP in the DQFM method. This paper presents a quantification approach which integrates the DQFM method with the Minimal Cutsets(MCSs) method. The presented approach enables to handle large scale FTs and to perform an evaluation considering seismic correlation. A case study of a hypothetical PWR plant, in which hundreds of components are considered, is conducted to demonstrate the applicability of this approach for seismic risk evaluation.

1. INTRODUCTION

Japanese utilities of NPPs are mandated to conduct Seismic PRA regularly and the outputs (e.g., Core Damage Frequency, Containment Failure Frequency) have been utilized for identifying vulnerabilities of NPPs. The identified vulnerabilities subsequently addressed, leading to enhancements in the overall safety of NPPs.

Seismic PRA inherently involves many assumptions, which should be acknowledged as uncertainties in seismic PRA. A significant assumption pertains to the treatment of seismic failure correlations. Seismic events can impact multiple SSCs within a facility simultaneously, so it is essential to incorporate the seismic failure correlation among SSCs in seismic PRA. The traditional practice in Seismic PRA is to assign complete correlation to redundant components while presuming zero correlation for other components, even though the actual correlation is likely to be partial [1]. The impacts of this assumption have been validated through sensitivity analyses conducted under the premise of zero correlation for redundant components.

A major challenge in accounting for seismic partial correlation is the evaluation method needed to manage the extensive combinations of large number of possible SSCs' combinations. One potential solution is the direct quantification of fault trees using the Monte Carlo simulation (DQFM) method[2]. In the DQFM approach, the states of each SSC are judged by comparing generated response values with their corresponding capacity values. Based on the judged state of each SSC, the occurrence of system failure (e.g. Core Damage) is evaluated through FT analysis. However, applying the DQFM method to large scale FTs in actual NPPs poses practical challenges, as there can be thousands of FTs within the seismic PRA model.

The approach described in this paper integrates the DQFM method with the MCSs method, offering a viable option to address the afore mentioned challenges associated with seismic correlation in the seismic PRA for actual NPPs.

Section 2 outlines the methodology which integrates the DQFM method with the MCS method. Section 3 presents a case study of seismic PRA utilizing the proposed approach, applied to a hypothetical PWR plant.

2. THE QUANTIFICATION APPROACH

2.1. Overview of DQFM method and MCS method

DQFM method was proposed and developed by the Japan Atomic Energy Research Institute [2]. In this method, the response and capacity values for each SSC are generated based on correlated random numbers. These generated response and capacity values are then compared to determine the states (success or failure) of each SSC. Based on the determined states, the occurrence of system failure (e.g., Core Damage) is evaluated through FT analysis. If a system failure occurs, the occurrence is counted. After conducting a specified number of trials, the probability of system failure is calculated by dividing the number of system failure by the total number of trials.

In the DQFM method, it is necessary to consider the response and capacity values separately, which can sometimes increase computational time. To address this issue, Ohtori and Muta proposed an improved DQFM method that utilizes copula random numbers [3]. The calculation flow is shown in Figure.1. A copula is a mathematical tool that describes the dependence structure between random variables, allowing the use of copula random numbers to avoid treating the response and capacity values separately. The state of each SSC is determined by comparing the failure probability, which is calculated based on the fragilities of the SSCs and the generated random numbers.

Even though the DQFM method allows for conducting seismic PRA with seismic partial correlation, applying this method to actual NPPs presents significant difficulties. This difficulty arises from the fact that seismic PRA models for actual NPPs contain thousands of FTs, making it impractical to model such a large number of FTs for DQFM evaluation. Additionally, seismic PRA in Japan has predominantly relied on the MCS method (e.g. RiskSpectrum PSA [4]), which complicates the transition from the MCS method to the DQFM method.

In the MCS method, seismic correlation needs considered in the context of Common Cause Failure (CCF) [4]. Analysists are required to set CCF parameter (e.g. beta factors) for each combination of SSCs.

However, given that there can be hundreds of SSC combinations in Seismic PRA that account for seismic correlation in actual NPPs, it becomes challenging for analysts to set CCF parameters for all possible combinations.

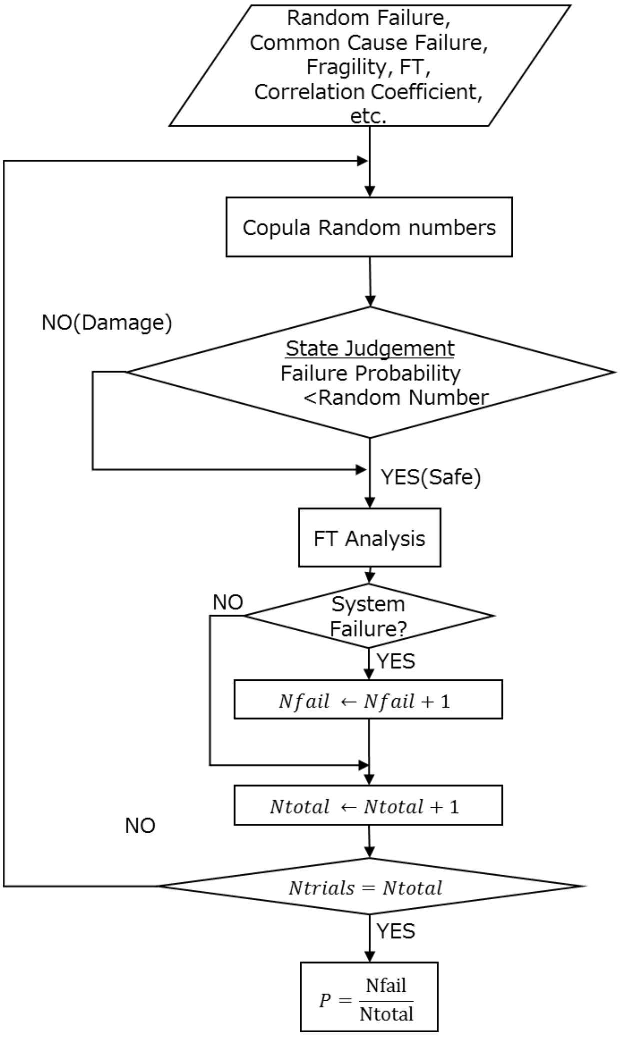

Fig.1 Flowchart of the DQFM method with copula random numbers

2.2. DQFM method integrated with MCS method

To address the afore mentioned challenges associated with the DQFM and MCS methods, this study develops a DQFM method integrated with the MCS method. The flowchart of the developed DQFM method is shown in figure.2.

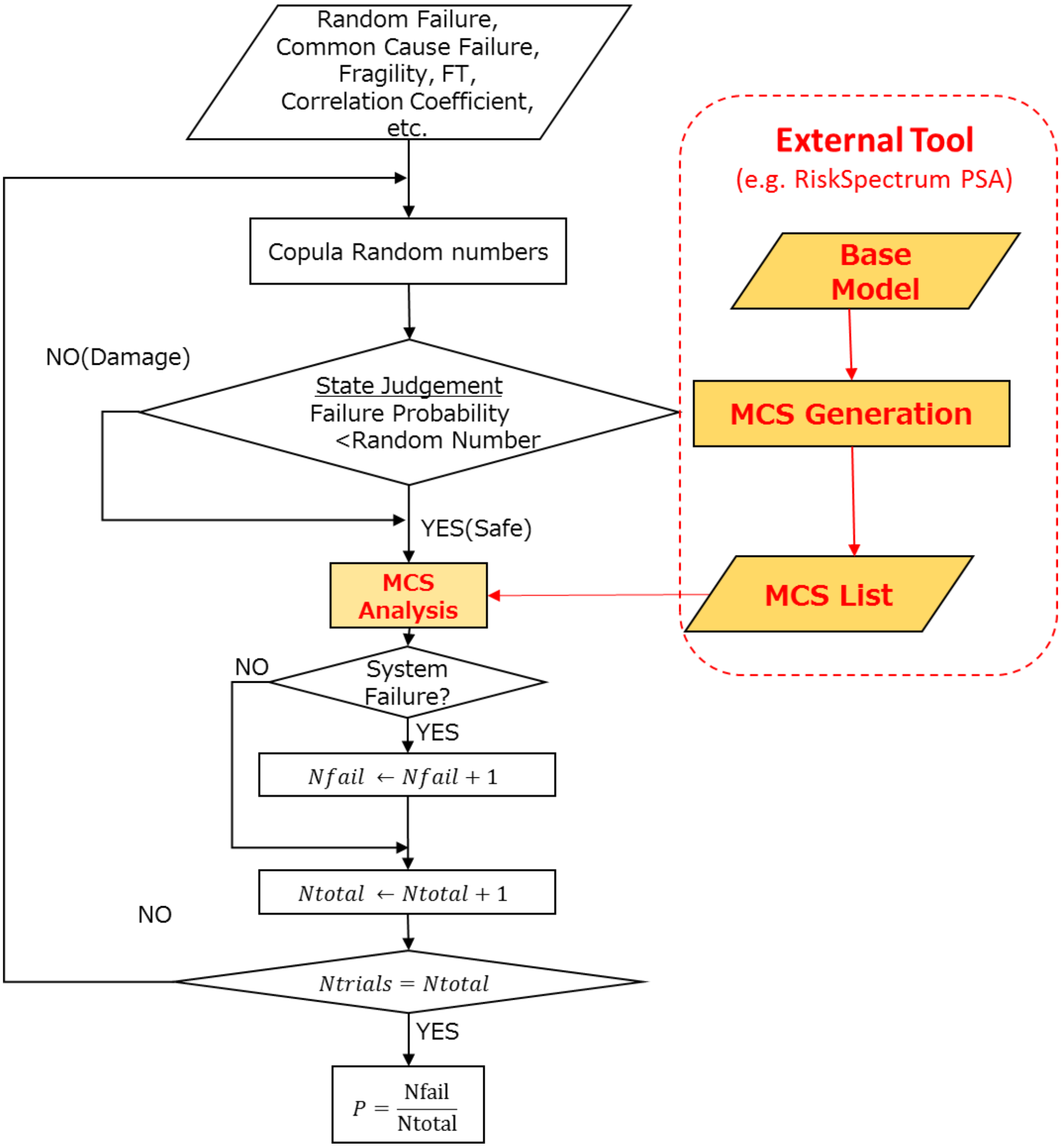

Fig.2 Flowchart of the DQFM method integrated with the MCS method

In the DQFM method, system failure evaluation is performed through FT analysis. However, in this integrated approach, MCS method is employed to assess system failure. A system is deemed to have failed when all events within an MCS are classified as failures. Note that the treatment of seismic correlation is the same as the original DQFM method described in Section II.A, which utilize copula random numbers.

The advantages of utilizing MCSs in the DQFM method are outlined as follows:

- Simplified Representation
  MCS provides a simplified view of the combinations of failures that can lead to system failure. Even when FTs are complex, evaluating system failure using MCSs can be conducted more easily.

- Prioritization
  MCS can be prioritized based on the probabilities or frequencies. By setting a truncation cutoff, analysts can extract the significant MCSs.

Since the MCS method is widely used in various evaluations, MCS inputs for the DQFM method can be generated directly from the original PRA model. This approach facilitates consistency between the original PRA model and the DQFM evaluation. To generate the MCS list for the DQFM method, several modifications to the original seismic PRA model might be necessary, as follows:

- In the original seismic PRA model, complete dependency among redundant components is assumed, meaning the basic events for these components are set to be the same to reflect this dependency. To extract MCSs that capture possible combinations of seismic failures, distinct basic events must be established.

- Seismic failure probabilities should be intentionally set to higher values to ensure that all possible combinations of seismic failures are considered.

- Seismic PRA is conducted using discrete seismic bins, each representing a specific range of ground motion. The lowest seismic bin can be utilized to generate MCSs for DQFM input, as it has the highest frequency. Consequently, MCSs that encompass possible combinations of seismic failures can be generated effectively under a specific truncation cutoff setting.

3. DEMONSTRATION OF DQFM METHOD INTEGRATED WITH MCS METHOD

3.1. Overview of the seismic PRA model for a hypothetical PWR plant

A seismic PRA model for a unit of a typical PWR plant was developed to demonstrate the applicability of the integrated DQFM and MCS method. The seismic-induced initiating events were modeled using a hierarchical structures initiating events event tree shown in Figure.3. The hierarchical event tree generally arranges the initiating events in order of their significant impact on the core damage frequency, using these as headings. Additionally, the hierarchical order of the initiating events is defined in such a way that if one initiating event caused by an earthquake occurs, it becomes irrelevant in terms of the occurrence of other lower-level initiating events. For example, when Large Break LOCA occurs, simultaneous Small Break LOCA occurrence need not be considered.

For each sequence within this initiating events event tree, a dedicated plant response event tree that depicts the accident sequences leading to core damage were developed and linked. The accident sequence model was developed using the fault tree linking code RiskSpectrum PSA.

The reliability of the systems and components was modeled using generic data. Component reliability, common cause failures, and seismic fragilities were derived from parameters reported in PRA studies. Approximately 500 SSCs were modeled, assuming complete independence for redundant systems to generate all possible combinations of seismic failures.

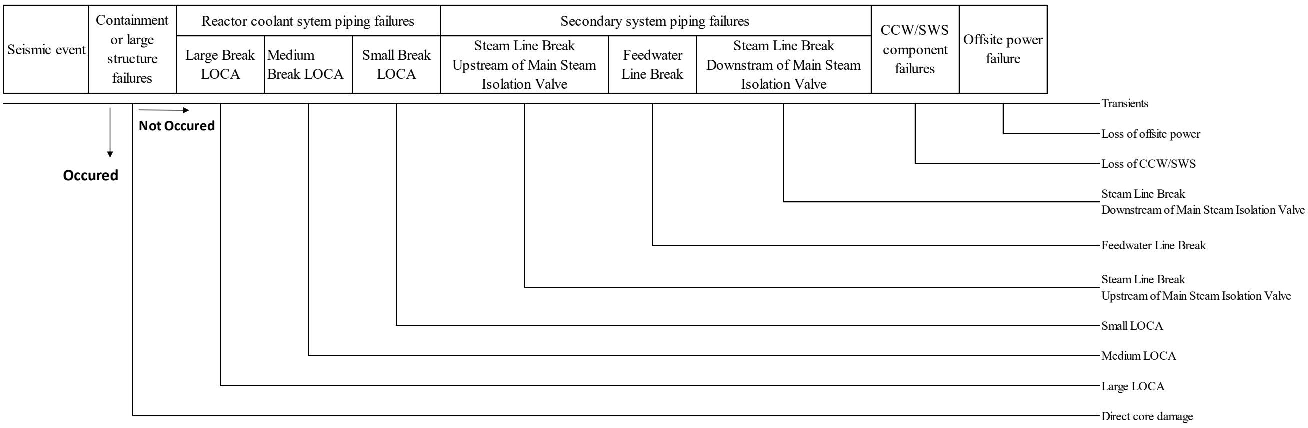

Fig.3 Seismic initiating events event tree used in the demonstration

3.2. Applicability of MCSs for DQFM Method

Using the developed seismic PRA model, a MCS list for the DQFM method was generated. In this demonstration, the probabilities of seismic failures were intentionally set to a higher value of 0.1. The MCSs were generated using RiskSpectrum PSA, resulting in around 500,000 MCSs, of which approximately 100,000 MCSs contained multiple seismic failures.
To confirm the applicability of the generated MCSs, the Conditional Core Damage Probability (CCDP) was quantified by under the assumption of complete independence among seismic failures. The CCDP quantified by both the MCS method and the developed DQFM method is shown in Figure.4. In the MCS method, CCDP is evaluated using discrete seismic bins, each representing a specific range of ground motion. In contrast, the CCDP of the developed DQFM method is assessed by focusing on specific accelerations. For this calculation, the mean acceleration of each seismic bin (e.g., 0.3G for the 0.2G-0.4G bin) was evaluated. The results indicate that the outcome of the DQFM method are overall consistent with those of the MCS method. This consistency confirms the validity of the conditions established for generating MCSs for the developed DQFM method.

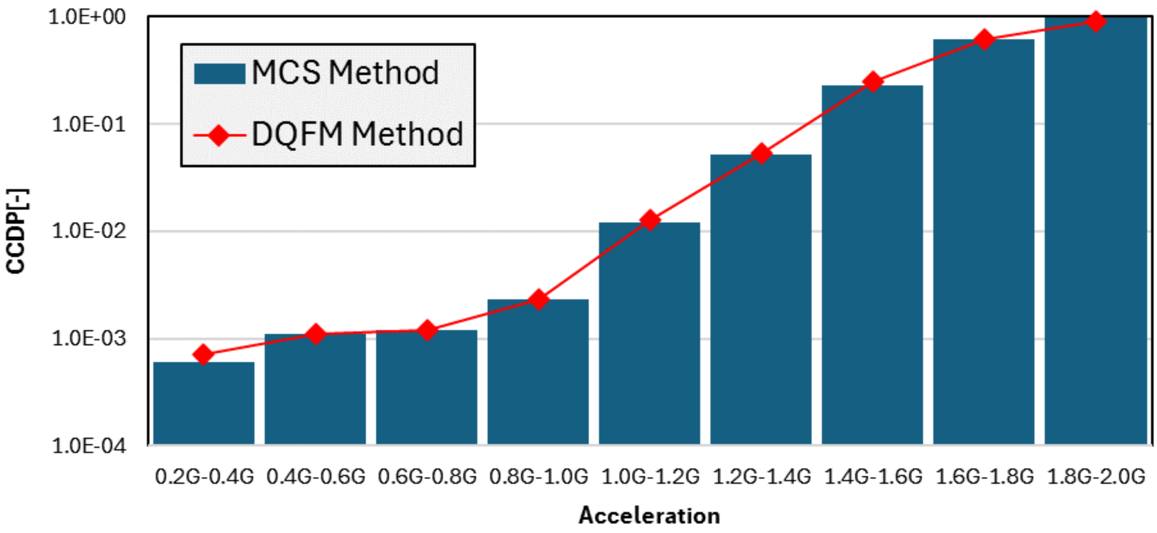

Fig.4 CCDP quantified by the MCS method and DQFM method using MCSs

3.3. Comparison of DQFM method using MCSs and MCS Method Considering Seismic Correlation

This section describes a comparison of the results quantified by the DQFM method using MCSs and by the MCS method under three cases, complete independence, partial correlation among specific components, and complete dependence among redundant components.

3.3.1 Acceleration under Evaluation

For the comparison, specific acceleration levels are selected for evaluation as follows:

- **Low acceleration level**
  This level represents scenarios where core damage is primarily caused by random failures and human errors. At this level, seismic failures do not contribute to core damage scenarios, meaning that considering seismic failure correlation does not have an impact of the results. An acceleration of 0.52G is chosen for this calculation.

- **High acceleration level**
  This level represents scenarios where core damage is predominantly due to seismic failures. In this case, considering seismic correlation significantly impacts the results. An acceleration of 1.46G is chosen for this calculation.

3.3.2 Correlated Seismic Failure Modeling

For the partial correlation case, only specific components are considered to have partial correlations. This is because, in the MCS method, it is necessary to set CCFs for each combination, which is challenging due to the high number of combinations. Therefore, components which have a high importance in the base model are selected for considering seismic partial correlations.

In the MCS method, the beta factor model is applied to address seismic correlation. The difference between the beta factor used for seismic correlations and CCFs for random component failures lies in the fact that the beta factor for the seismic correlations depends on the seismic failure probability of SSCs[6]. The following analytical relationship can be derived from the definition of the beta factor model:

$$\beta = \frac{2Q - 1 + \sqrt{1 - 4Q + 4P}}{2Q} \tag{1}$$

In this equation, β represents the beta factor, Q is the seismic failure probability of an SSC, and P is the simultaneous failure probability of redundant SSCs.

Since the seismic failure probability P considering partial correlation cannot be calculated analytically, the beta factor for each acceleration is calculated through Monte Carlo simulations, with the seismic correlation coefficient set to 0.5. The evaluated beta factors are set to the model in the MCS method.

While the partial correlation case addresses specific components, the other cases - complete independence and complete dependence – consider correlations for all redundant components. In the complete independence case, beta factors are set to 0, while in the complete dependence case, they are set to 1 in the MCS method.

Note that this calibration procedure was adopted only for the comparison with the MCS method; the proposed DQFM method itself does not require beta-factor calibration because seismic dependence is directly represented through correlated sampling.

3.3.3 Results

The CCDPs under complete independence, partial correlation among specific components, and complete dependence among redundant components are quantified using both the MCS method and DQFM method with MCSs as shown in Table.1. The sampling number in the DQFM method is 10^6.

In the 0.52G case, seismic correlation does not impact the CCDP, as noted in 3.3.1. The DQFM method using MCSs demonstrates good consistency with the results obtained from the MCS method. The differences in the 0.52G case are 0.4% and 0.2%. The difference would be originated from the low CCDP values and an error in Monte Carlo Simulation, so these differences do not reflect inconsistency between methods.

In the 1.46G case, the difference in the complete independence case is only 0.3%, indicating strong consistency. However, in the cases of partial correlation among specific components and complete dependence among redundant components, the differences are larger than those observed in the complete independence case. The discrepancies may arise from errors in the beta factor used in the partial correlation scenario and inherent errors in the MCS method itself. Nevertheless, the differences are limited, allowing for conclusion that both the MCS method and the proposed DQFM method – specifically, the DQFM method using MCSs - exhibit good consistency. Through this evaluation, the applicability of the proposed DQFM method is confirmed.

Table.1 CCDP quantified by the MCS method and DQFM method using MCSs considering partial correlation

Acceleration [G]	Complete Independence			Partial Correlation among Specific Components (Correlation Coefficient: 0.5)			Complete Dependence among Redundant Components		
	MCS	DQFM	Difference [%]	MCS	DQFM	Difference [%]	MCS	DQFM	Difference [%]
0.52	1.11E-03	1.12E-03	0.4	1.11E-03	1.12E-03	0.4	1.11E-03	1.12E-03	0.2
1.46	1.67E-01	1.67E-01	0.3	1.76E-01	1.83E-01	3.8	2.25E-01	2.18E-01	3.2

3.4. Demonstration of Impact Considering Seismic Correlation

This section demonstrates the impact of considering seismic correlation using the DQFM method using MCSs under four cases:

- Complete Independence
- Partial Correlation among Redundant Components
- Partial Correlation among All Components
  (including correlation among non-redundant components)
- Complete Dependence for Redundant Components

The seismic PRA model used in this demonstration is the same as that described in Section 3.1. The MCS list used as input for the DQFM method was generated using RiskSpectrum PSA. The seismic correlation coefficient in the partial correlation cases was set to 0.5, and the sampling number in the DQFM method was 10^7. The sampling number was determined based on the result (the order of CCDP). The CCDPs for the four cases are shown in Figure.5 and Figure.6. At lower acceleration levels (up to approximately 0.7G), seismic correlation does not impact the CCDP, as noted in Section 3.3.1. However, at moderate acceleration levels (approximately 0.7G to 1.3G), seismic correlation differentiates the CCDP results, with the complete independence case showing the lowest CCDP value, as expected. Interestingly, at higher acceleration levels (above approximately 1.3G), the complete independence case no longer yields the lowest CCDP. Instead, the lowest CCDP is observed in the case with partial correlation among all components. This result's tendency arises because, at high acceleration levels, the system failure is influenced by "OR logic." The details are as follows.

Considering correlation among components connected by an OR relationship (e.g. system failure occurs if component A or B fails) generally results in a lower failure probability than assuming complete independence. When correlations among all components are considered, not only redundant components but also components related by OR logic (e.g. components within the same system) are included. In this hypothetical PWR plant model, the effect of seismic correlation among all components linked by OR relations has a greater impact in reducing the CCDP than the effect of increasing the CCDP due to correlation among redundant components.

Although this result is based on a hypothetical PWR plant model, actual PWR plants consist of dozens of components. Therefore, considering seismic correlation among non-redundant components may lead to a decrease in CCDP compared to the case without such correlations. This demonstration indicates the potential importance of seismic correlation considerations including not only redundant but also non-redundant components to accurately evaluate the true seismic risk.

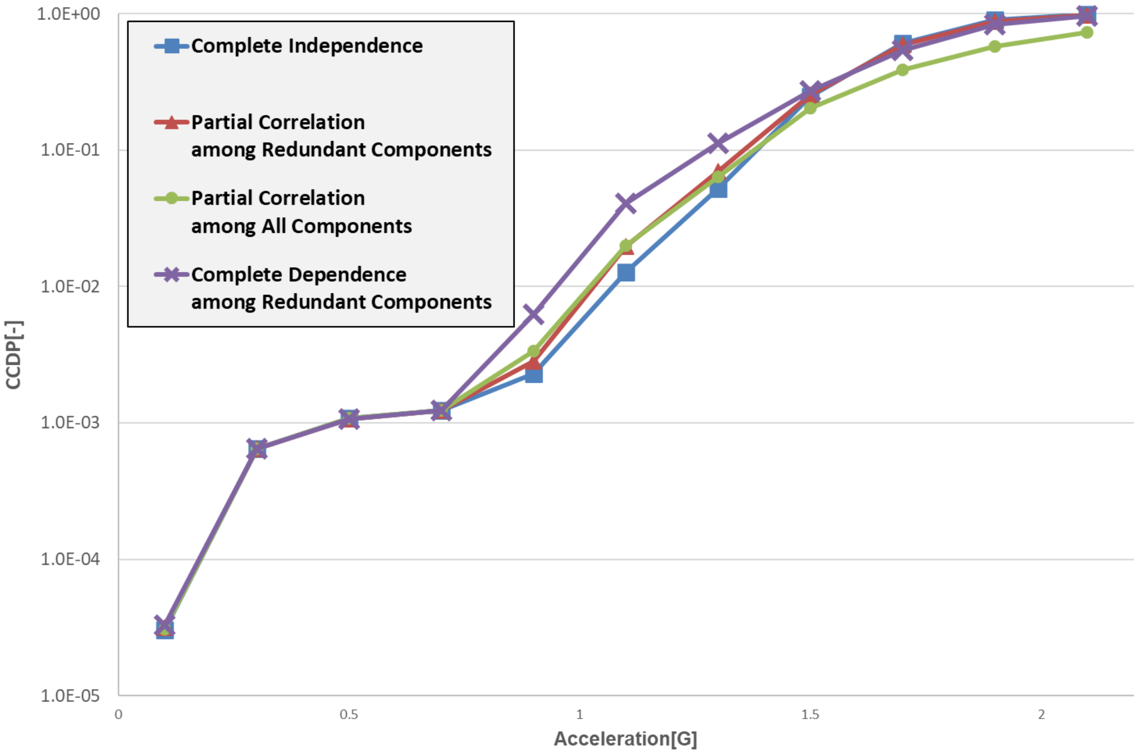

Fig.5 CCDP of various correlation cases quantified by DQFM method using MCSs

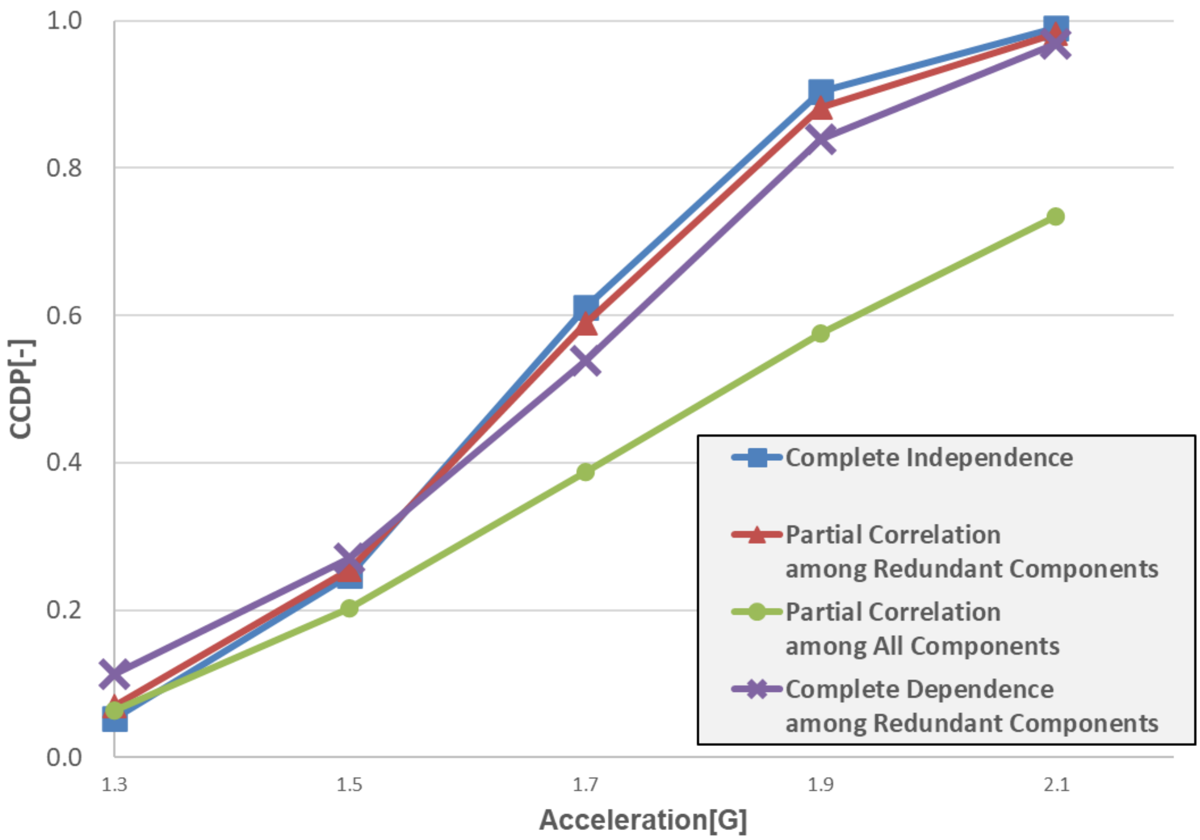

Fig.6 Enlarged view of the region around higher acceleration levels in Fig.5

4. CONCLUSION

This paper has presented the concept of the DQFM method integrated with the MCS method as a means to quantify seismic risk while considering seismic failure correlation. The developed method utilizes MCSs generated from the established PRA model, thereby avoiding the complexities with managing large-scale FTs in the DQFM method.

To demonstrate the applicability of this integrated approach, a case study was conducted for a unit of a typical PWR plant. The results of the case study indicate a strong consistency between the results quantified by the DQFM method and by the MCS method. This integrated method facilitates the consideration of seismic partial correlation within large-scale models. Additionally, a demonstration of the impact of seismic correlation was conducted and the results indicate the potential importance of considering seismic correlation among not only redundant but also non-redundant components. The approach described in this paper can be instrumental in understanding the impact of the seismic partial correlation for actual NPPs.

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