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A Framework of RI-PB Seismic Design
Part 3: Methodology for Accident Sequence Analysis for Seismic Risk Considering Seismic Diversity

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ABSTRACT

This study presents the methodology which shows how to treat partial correlation considering inter-periodic correlation in accident sequence analysis of Seismic PRA to evaluate the appropriateness of the diversity for seismic design. This Methodology is consisted of a technique to treat inter-periodic correlation among any kinds of combinations of components and the process to evaluate the core damage frequency considering inter-periodic correlation.

1. Background and Purpose

Japanese current nuclear regulations require deterministic and conservative evaluation. However, application of Risk-Informed and Performance-Based (RI-PB) design leads to more rational decision making. Especially, the necessity of RI-PB has been realized after the Fukushima nuclear accident. The authors Sakai et.al., Katayama et.al. have been developing RI-PB design against natural external events such as seismic events.

This paper describes the methodology for accident sequence analysis for seismic risk considering inter-periodic correlation to evaluate the seismic risk properly and to introduce the seismic diversity effectively. The proposal of the framework is composed of 3 papers. Sakai et.al. (2022) and Katayama et.al. (2022) describe the outline of concept and more practical study results for fragility analysis.

The present paper describes Part 3 of the framework and presents the methodology which shows how to treat partial correlation considering inter-periodic correlation in accident sequence analysis of Seismic PRA to evaluate the appropriateness of the diversity for seismic design.

2. Proposed Method

2.1 Issues of Current Method

In general, engineered safety features (ESF) consisted of various types of structures and components. External natural hazard, especially an earthquake might affect such components located in the buildings and structures in the nuclear power station simultaneously. The responses of the components are considered to be similar to each other and to have a substantial correlation, especially same type components located in the same room or same floor. In addition, inter-periodic correlation might be considered in case of different type components, and even beyond the categories of structure and component.

However, the current seismic PRA method does not consider partial correlations, but rather conservative full correlations. This type of risk assessment leads to overly conservative results in determining risk levels

and lacks rationality in its application to design. In addition, the conventional method cannot properly evaluate the effects of design improvements when considering measures to improve seismic safety, and does not provide material for judging the adequacy of the design.
Based on the above, a method which shows how to treat partial correlation considering inter-periodic correlation in accident sequence analysis of Seismic PRA should be needed.

2.2 Proposal of Method Considering Seismic Diversity

a. Inter-Periodic Correlation

Correlation in seismic PRA refers to a relationship in which when equipment A fails, equipment B fails simultaneously with a correlation coefficient of ρ_{AB}. The traditional seismic PRA treats correlation as a perfect correlation, which is conservative; in this case, the correlation coefficient ρ_{AB} is 1.0. When several similarly designed pieces of equipment are similarly installed on the same floor, their seismic vibration behavior is expected to be similar. In such cases, when the response of one piece of equipment becomes larger, the response of other equipment also tends to become larger, and this can be called correlation in equipment response. In seismic PRA, it is important to consider correlation because the magnitude of correlation changes the probability of simultaneous damage to the equipment.
Inter-Periodic correlation is one of the seismic correlations, and refers to a correlation in which equipment is more likely to be damaged due to resonance when the period of maximum acceleration in the floor response spectrum of the floor on which the equipment is installed is close to the natural period of the equipment. A strong correlation between the natural periods of the equipment increases the likelihood that the equipment will be damaged simultaneously during an earthquake. This correlation may not be sufficient to improve the reliability of safety systems against earthquakes by merely making efforts to reduce the damage probability of individual components of the system, and appropriate handling of the correlation must be taken into account in the evaluation of seismic risk for proper design.

b. Outline of the Process

Figure 1 shows the outline of the proposed method considering inter-periodic correlation. This process uses seismic observation records consisting of the epicenter location, magnitude and frequency to calculate seismic motion considering inter-period correlation. Then floor response spectra considering uncertainty of the ground motion prediction equations (GMPE) by Monte-Carlo sampling can be obtained. From these calculated results and capacity data, failure probabilities according to the ground acceleration are derived.

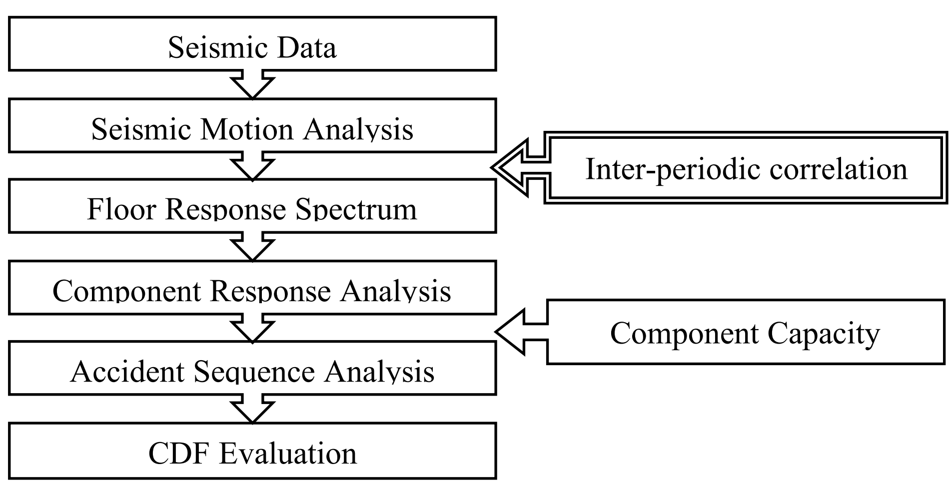

Figure 1 Outline of the Proposed Method

Then the core damage frequency (CDF) is obtained based on the core damage logic expressed by the core damage fault tree. The CDF quantification is performed using DQFM (direct quantification of fault tree using Monte-Carlo).

c. Seismic Motion Analysis

In order to properly consider period correlation in seismic waves, it is necessary to determine correlation coefficients for each period of the response spectrum of the floor of the building in which the target equipment is installed, originating from a single seismic wave. That is, detailed data (location, magnitude, and frequency) must be used for each earthquake.
To account for uncertainty in the distance attenuation from the epicenter, the seismic response is expressed as a probability distribution, which is obtained by Monte Carlo sampling. For the floor response spectrum of a building, a method presented by Ohara et al. for directly obtaining the floor response spectrum from the response spectrum analysis of the building is used.

d. Fragility Analysis

In this stage of the process, the probability of damage is determined by comparing the response of the equipment with the bearing capacity, taking into account the inter-periodic correlation. The response of the equipment used here is the spectral acceleration at the natural frequency of the equipment in question, which is extracted from the floor response spectrum calculated from the Monte Carlo sampling of each distance attenuation equation. This value is used as the median value of the response acceleration, and a probability density function is set up to account for uncertainty. The DQFM method developed by JAEA is used to determine equipment damage. According to this method, the response is compared with the Monte Carlo sampling value from the probability density function of the equipment bearing capacity, and if the response exceeds the bearing capacity, the equipment is determined to be damaged.
Figure 2 and 3 show an outline of calculation process of the definition of the probability density function of floor response spectra.

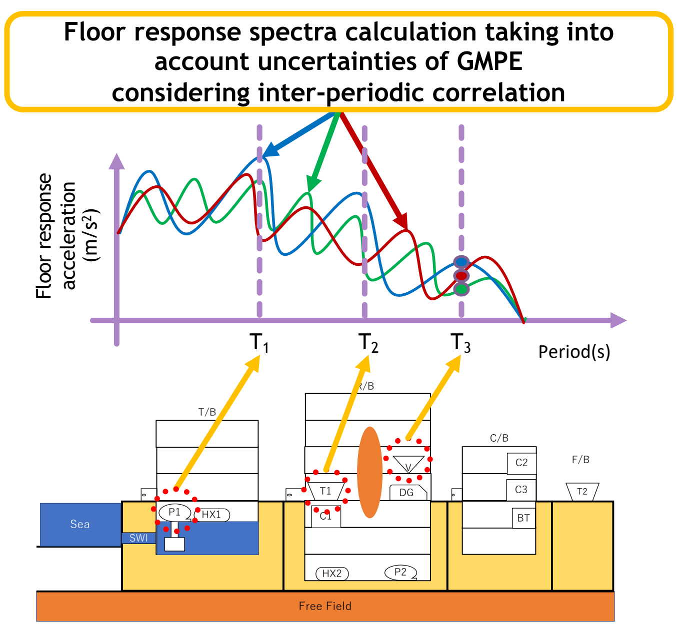

Figure 2 Calculation of Floor Response Spectra

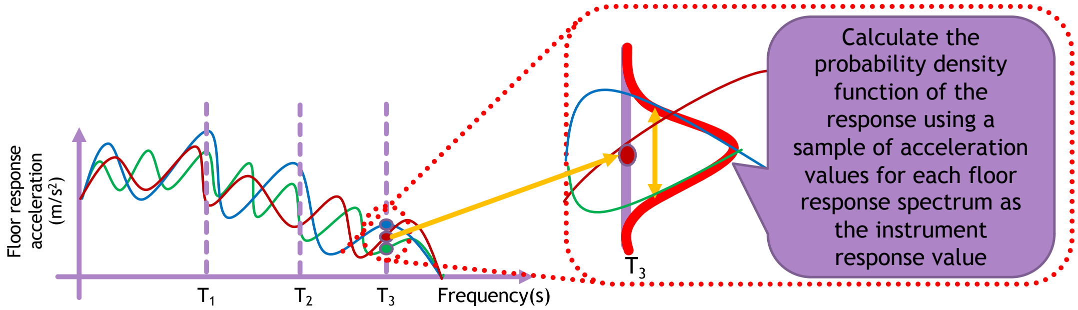

Figure 3 Outline of Definition of Probability Density

e. Accident Sequence Analysis

The DQFM method determines whether or not core damage has occurred in the nuclear plant under evaluation based on the results of all component damage assessments for each sampling of the GMPE equation, by evaluating the core damage logic with DQFM method. The core damage frequency can be obtained by averaging the core damage probabilities for each sampling of the GMPE and multiplying by the frequency of occurrence of each referenced earthquake data. This process can be applied to all earthquake data to obtain the total core damage frequency.
Figure 4 shows the flowchart of the above process.

3. Conclusions

This study proposes a method which shows how to treat partial correlation considering inter-periodic correlation in accident sequence analysis of Seismic PRA to evaluate the appropriateness of the diversity for seismic design. Using this method, the risk profile can be obtained which can contribute RI-PB seismic design by providing the various kinds of insights including relative weak points or importance of the components to seismic risk, contribution of accident sequences and impacts of component failure event.

REFERENCES

Nuclear energy agency Organization for economic co-operation and development (2016), *Implementation of Defense in Depth at Nuclear Power Plants*, NEA NO. 7248.

Takada T. *Importance of risk theory for ensuring nuclear safety after the Fukushima accident*, J Atom Energy Soc Jpn. 2014;56(4): 34–39. Japanese.

Katayama Y, Ohtori Y, Sakai T, et al. *A Framework of RI-PB Seismic Design/Part 2: evaluation of seismic diversity of SSCs focusing on response spectrum characteristics of ground motion*, ESREL2020 PSAM15. Nov; Venice: Italy; 2020.

Baker JW, Cornell CA. *Spectral shape, epsilon and record selection*, Earthquake Eng Struct Dyn. 2006;35(9):1077–1095.

Baker JW, *Conditional mean spectrum: tool for ground-motion selection*, J Struct Eng. 2011;137(3):322–331.

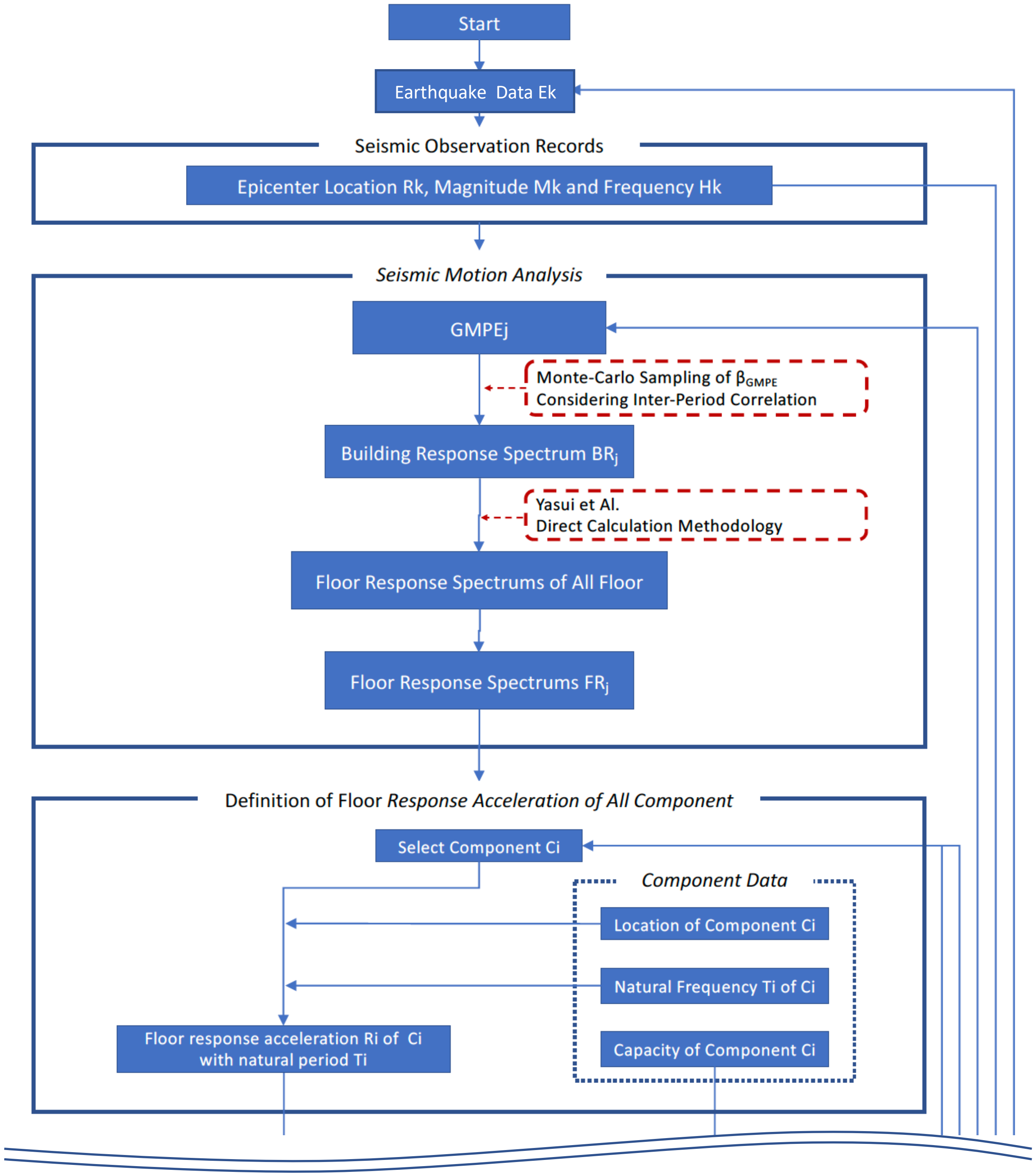

Figure 4 The Flowchart of Accident Sequence Analysis (1st Half)

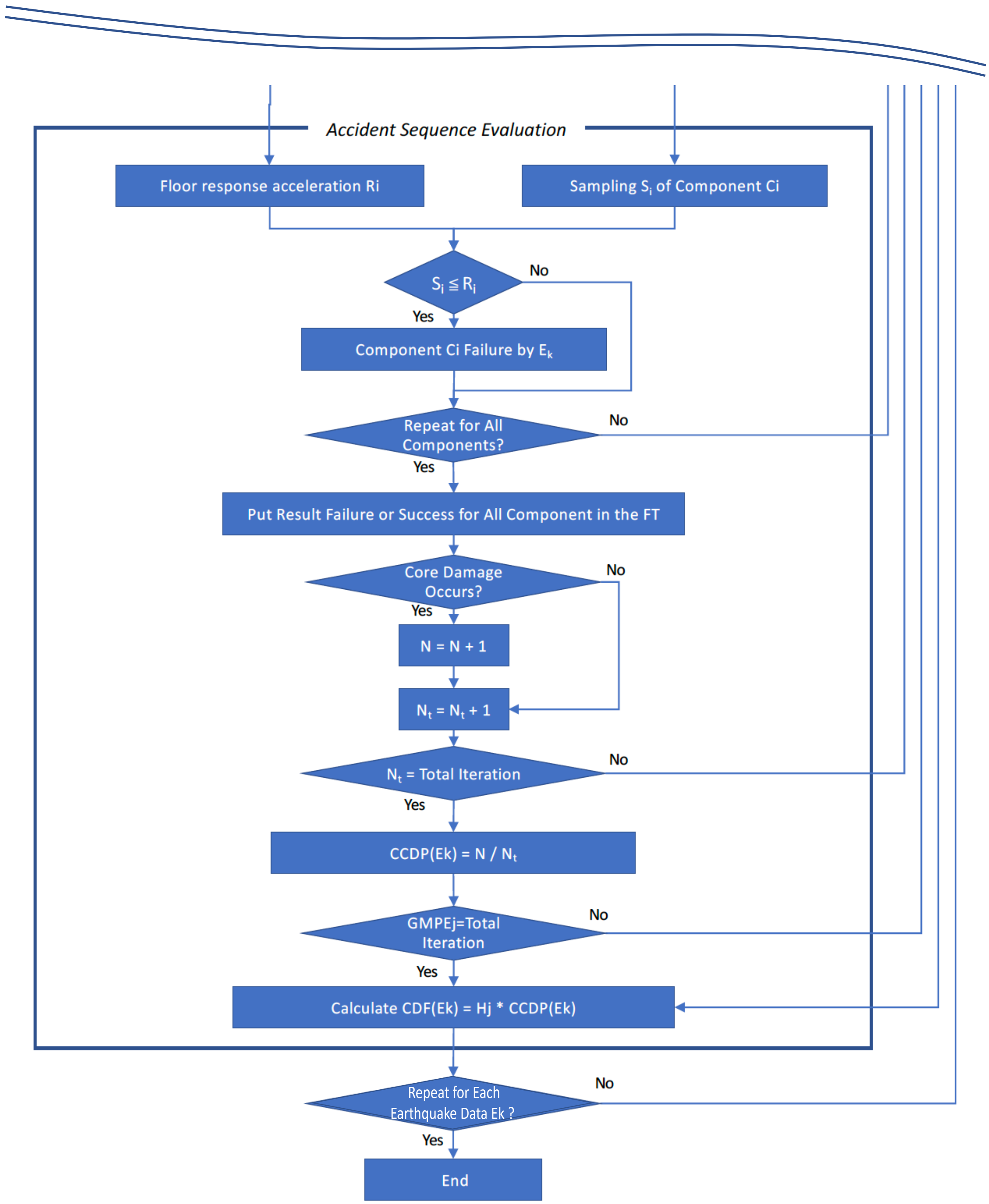

Figure 4 The Flowchart of Accident Sequence Analysis (2nd Half)