Seismic risk study of typical BWR plant considering inter-period correlation among SSCs

Ryui Tomita[a*], **Hitoshi Muta**[b], **Yasuki Ohtori**[c]
[a,b,c]Tokyo City University, Tokyo, Japan

Abstract: In order to properly evaluate seismic risk, it is necessary to properly treat damage correlations of large structures. This study evaluates the risk of core damage from earthquakes on a full plant basis. It focuses on how changing the natural period to reduce damage correlations affects this risk.
In addition, the necessity of countermeasures for the intake, which is an integral structure, considering the contribution of CDF will be discussed.

Keywords: PRA, DQFM method, periodic correlation

1. INTRODUCTION

1.1 Background

Since the accident at the Fukushima Daiichi Nuclear Power Plant caused by the 2011 off the Pacific coast of Tohoku earthquake and subsequent tsunami, the importance of responding to the simultaneous loss of function of multiple safety systems due to common causes has been highlighted, and there is an urgent need to improve nuclear power plant safety against external factors.

In the event of an earthquake, components and structures installed in nuclear facilities vibrate and are similarly affected, causing correlated responses among different structures and components. To properly assess seismic risk, it is essential to accurately handle the damage correlations for large structures.

In traditional Probabilistic Risk Assessment (PRA), risk is evaluated through the sequence of hazard assessment, fragility assessment, and accident sequence evaluation. However, redundant component is treated as having complete correlation, leading to a conservative risk evaluation. As a result, the effectiveness of the risk reduction measures introduced in this study cannot be adequately assessed. Additionally, there have been very few cases where the correlation of damage in large structures has been appropriately evaluated.

1.2 Purpose

The acceleration response of component and structures due to an earthquake depends on their period characteristics. There is a correlation between responses at different periods. In particular, in nuclear facilities, it is important to consider inter-period correlation when evaluating the response of component and structures installed at specific locations. Ignoring inter-period correlation in such evaluations prevents an accurate assessment of the actual risks at nuclear power plants and the effectiveness of risk reduction measures.

In this study, we focused on periodic correlations as those that have a significant impact on the frequency of core damage. By evaluating multiple scenarios of earthquake-induced core damage in a full plant model, we aim to clarify the extent to which these correlations contribute to risk. Specifically, we intend to determine how correlations of damage to components and structures contribute significantly to risk by changing the natural period and lengthening it. The purpose of this study is to evaluate the effectiveness of measures designed to reduce these correlations, thereby mitigating the risk associated with core damage.

In addition, the analysis will be performed for each seismic wave to investigate changes in core damage frequency and component importance depending on the value of seismic acceleration. The results of this study are expected to contribute to the safety improvement of nuclear facilities by absolute evaluating the effects of risk reduction measures.

1.3 Prior Research

In order to evaluate the risk considering the inter-period correlation, this study uses the **Direct Quantification of Fault Tree Using Monte Carlo Simulation (DQFM)** method instead of the common **Minimal Cut Set (MCS)** method. Component damage correlations are treated as partial correlations that are closer to reality, and correlation coefficients are adopted by applying the concept of inter-period correlation proposed by Baker and Jayaram [1] [Fig.1-1].

Ohara et al [2] also developed a method to determine the core damage frequency considering the period correlation of component and structures at different installation locations in the building for each seismic wave based on the source information including epicenter location, magnitude, and probability of earthquake occurrence using a Monte Carlo method.

In addition, Katayama et al [3] developed a method to quantitatively evaluate the reliability improvement effect of a diversified design that reduces the correlation among multiple components in a redundant safety system of a nuclear power plant. Based on this method, it is no longer necessary to consider and calculate the correlation coefficients when performing calculations on a real plant basis, which is expected to be of great benefit.

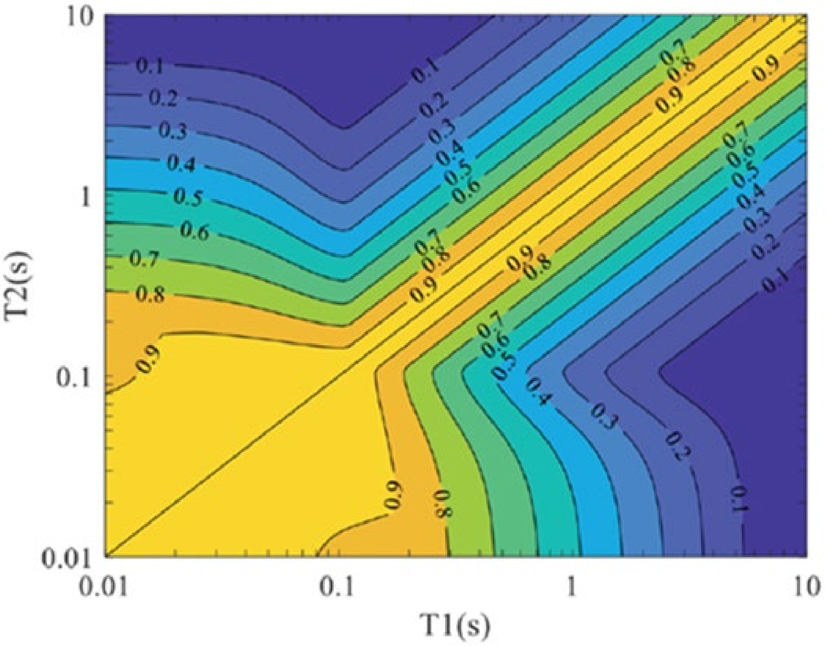


Figure 1-1 Correlation coefficient of periodic correlation

2. METHODS

2.1 Summary of Research Methods

We evaluate the frequency of occurrence of core damage when seismic waves with parameters such as magnitude and frequency of occurrence are input to a model of Kashiwazaki-Kariwa Nuclear Power Station Unit 7, which was created based on component information described in JAERI-Reserch99-35 [4]. The seismic waves used are approximately 400 seismic waves "Table 2-2" that have the potential to cause core damage out of 460,000 seismic waves recorded in Japan in the area including the target model, the Kashiwazaki-Kariwa Nuclear Power Station.

Table 2-1 Component Parameter

COMPONENT	NAME	STRENGTH(gal)	UNCERTENLY	LOCATION	NATURAL PERIOD(s)
HX1_A	Heat exchanger	2638	0.25	T/B－ B1	0.015, 0.03, 0.06
HX1_B		2638	0.25	T/B － B1	0.015, 0.03, 0.06
HX2_A		2638	0.25	R/B － B3	0.015, 0.03, 0.06
HX2_B		2638	0.25	R/B － B3	0.015, 0.03, 0.06
P1_A	Pump	2225	0.25	T/B － B1	0,1, 0.2, 0.4
P1_B		2225	0.25	T/B － B1	0,1, 0.2, 0.4
P2_A		2225	0.25	R/B － B3	0,1, 0.2, 0.4
P2_B		2225	0.25	R/B － B3	0.1, 0.2, 0.4
V_A	Electric valve	6203.4	0.25	R/B － F2	0.025, 0.05, 0.1
V_B		6203.4	0.25	R/B － F2	0.025, 0.05, 0.1
T1_A	Water tank	3324	0.25	R/B － F1	0.03, 0.06, 0.12
T1_B		3324	0.25	R/B- F1	0.03, 0.06, 0.12
C1_A	Control panel	5929	0.25	R/B － B1	0.1, 0.15, 0.2
C1_B		5929	0.25	R/B － B1	0.1, 0.15, 0.2
C2_A		5929	0.25	C/B － F2	0.1, 0.15, 0.2
C2_B		5929	0.25	C/B － F2	0.1, 0.15, 0.2
C3_A		5929	0.25	C/B － F1	0.1, 0.15, 0.2
C3_B		5929	0.25	C/B － F1	0.1, 0.15, 0.2
DG_A	Diesel generator	2156	0.25	R/B － F1	0.025, 0.05, 0.1
DG_B		2156	0.25	R/B － F1	0.025, 0.05, 0.1
BT_A	Battery	6203.4	0.25	C/B － B1	0.025, 0.05, 0.1
BT_B		6203.4	0.25	C/B － B1	0.025, 0.05, 0.1
SWI	Water intake	2500	0.25	T/B － B1	0.2, 0.4, 0.8
LOSP	Insulator	225	0.25	outside	0.2, 0.4, 0.8

Table 2-2 Some of the seismic waves used

magnitude	epicentral distance	hypocentral distance	frequency of occurrence	Earthquake tag
6.462	10.098	15.879	5.50E-07	'CGR50008'
6.54	7.32	14.233	5.98E-07	'CGR50008'
6.54	3.828	11.704	5.16E-07	'CGR50008'
5.76	4.728	8.565	4.62E-06	'CGR50008'

2.2 CORRELATIONS TREATED IN THIS STUDY

2.2.1 Response Correlation

Response correlation refers to the correlation of responses at a specific point and indicates how similar the responses at different levels of a building or of different members in the same level are.

Inter-period correlation is a type of response correlation that refers to the correlation between responses of different periods and indicates how much the response to a particular period influences the response to other periods. Even with redundant component, a strong correlation between periods increases the probability of damage at the same time.

2.2.2 Correlation of Strength

It shows the correlation of the strength of component and structures, but in this study, it will not be considered to simplify the discussion.

2.3 **Analysis Method**

Process of This Study

I. Input of Seismic Motion
About 400 seismic waves that could potentially cause core damage to the plant outlined in section 2.1.
II. Analysis Using Tools
The analysis tool used is MATLAB.
III. Calculation of Core Damage Frequency (CDF)
The CDF is calculated by multiplying the occurrence frequency of an earthquake by conditional core damage probability.
IV. Calculation of Core Damage Frequency (CDF) After Implementing Risk Reduction Measures
The CDF is calculated after applying changes to the natural period and lengthening the period.
V. Evaluation of the Impact of Correlation on Structural Damage
The impact of correlation on the CDF is evaluated by comparing the CDF obtained in step 3 with the CDF obtained in step 4.

In this study, the DQFM method is employed for deriving the core damage frequency (CDF). The DQFM method, as illustrated in Figure 2-1, is a quantitative seismic Probabilistic Risk Assessment (PRA) technique that utilizes the Monte Carlo method to derive theoretical values. It involves deriving realistic strength values for each component by using both their inherent strength and random numbers. These realistic strengths are then compared with the realistic responses obtained from building response analysis, and if the response surpasses the strength, the respective component is deemed damaged.

Furthermore, if the combination of damaged component leads to a top event in the fault tree depicted in Figure 2-2, it is determined that core damage has occurred. This process is iterated for a specified number of trials, and the conditional core damage probability for the given seismic motion is calculated by dividing the number of times the top event occurred by the number of trials.

The core damage frequency is subsequently determined by multiplying this conditional core damage probability by the occurrence frequency of the given seismic motion. Additionally, in this study, these operations are repeated for each seismic wave, and all the obtained core damage frequencies are calculated.

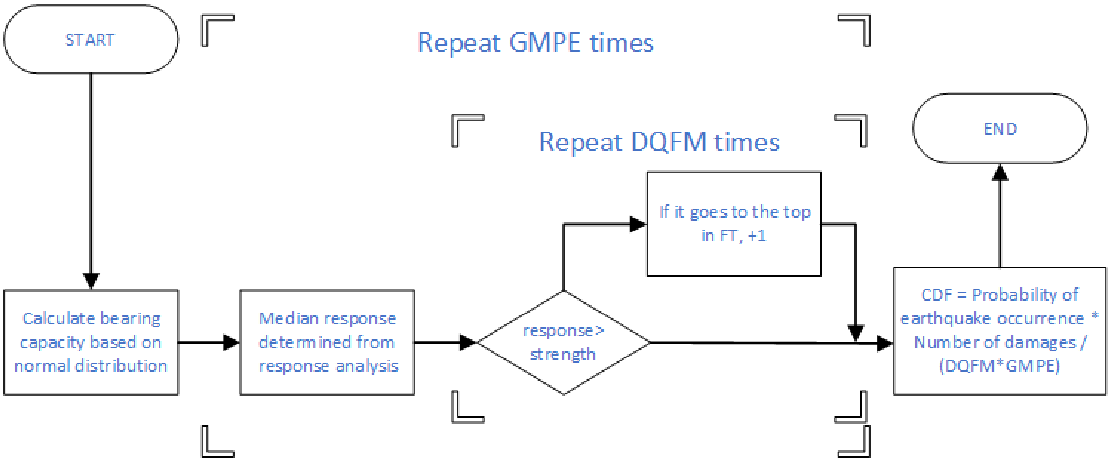


Figure 2-1 Schematic diagram of the DQFM method

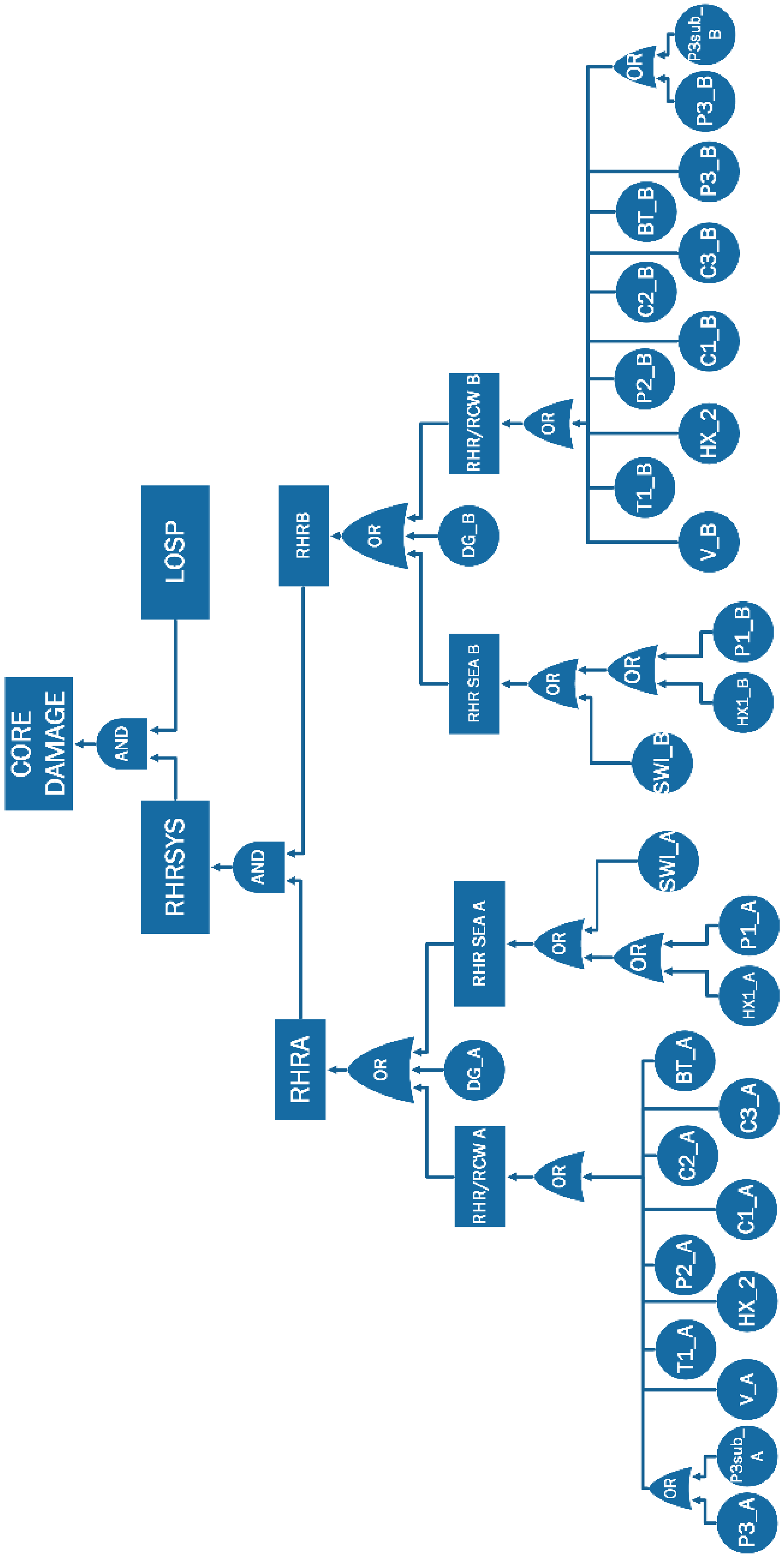


Figure 2-2 Fault Tree for loss of decay heat removal Sequence

2.4 Risk Mitigation Measures

The following two risk reduction measures are envisioned to be introduced in this study: risk reduction measures will be introduced for the component/facilities with the highest contribution to the core damage frequency, to reduce correlation and risk.

I. Reduction of correlation through changes in natural periods.
The reduction of correlation assumes that the natural period can be adjusted through seismic retrofit work. The adjustment range is set to 1 to 1.2 times the original period. Sensitivity analysis will be conducted using the natural period of one of the redundant devices as a parameter to confirm the effectiveness of this measure.

II. Longer period by laminated rubber
Installing the laminated rubber under one of the redundant devices significantly lengthens the natural period of the target device. Evaluate the effect of risk reduction by lowering the correlation of response.

2.5 Correlation Concerns at Water Intakes

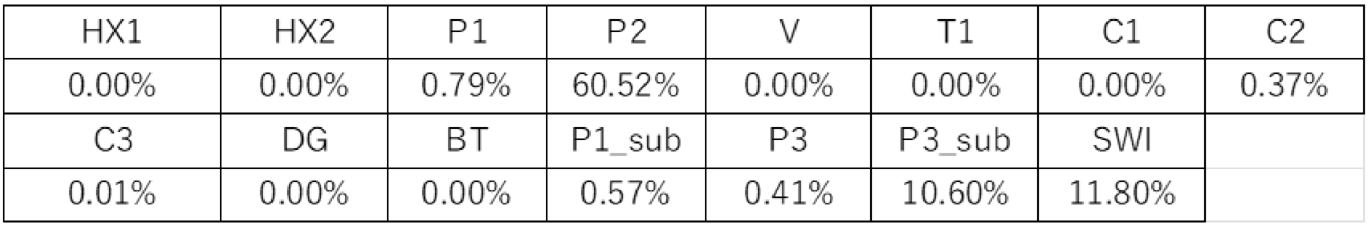
The introduction of risk reduction measures may highlight large structures such as intake gates as facilities where there is potential for significant contributions. While intake gates are designed with redundancy, they are structurally constructed as integrated systems with different subsystems, suggesting correlations in structural damage. If contributions to CDF of intake gates are significant, the magnitude of correlations will be rigorously evaluated, and corresponding measures will be considered based on their magnitude.

3. RESULT

3.1. Before the Introduction of Risk Reduction Measures

In the current design, in the preliminary calculation of the frequency of core damage during an earthquake in the TW sequence, the component that contributes the most to core damage is the RHR pump (P2) in the RCW system. Next in line was the intake gate.

Table 3-1 Importance of equipment and structures (FV)



HX1	HX2	P1	P2	V	T1	C1	C2
0.00%	0.00%	0.79%	60.52%	0.00%	0.00%	0.00%	0.37%
C3	DG	BT	P1_sub	P3	P3_sub	SWI	
0.01%	0.00%	0.00%	0.57%	0.41%	10.60%	11.80%	

HX：heat exchanger

P: pump
V:valve
C: cabinet
DG:diesel generator
BT:battery
SWI: seawater intake

4. CONCLUSION

The importance of the component mentioned is based on the residual heat removal sequence. However, in the future, we will conduct analyses based on full plant basis by extending it to cover all representative accident sequences. Additionally, we will devise means to alter the inherent periods and conduct reassessments. The results obtained will be presented at our assembly.

References

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