Reliability Enhancement of Seismic Risk Assessment of Npp As Risk Management Fundamentals
- Development of A New Mathematical Framework for Uncertainty Analysis-

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After Fukushima Dai-ichi NPP accident, nuclear safety in Japan have been improved and enhanced. Continuous efforts to establish technical basis and fundamentals are required to achieve these aims. Probabilistic Risk Assessment for seismic event (Seismic PRA) is the effective tool to consider the profile of seismic risk and provide risk insights for further safety of nuclear power plants. However, Seismic PRA has not been applied maturely so far in Japan. The reason is that the consensus among stakeholders has not been established from the viewpoints of the evaluation methodology and consideration of uncertainty for decision-making process.
This study provides application of the mathematic framework to treat the uncertainty properly related to the evaluation of core damage frequency (CDF) induced by earthquake, importance to the risk considering uncertainty of the index, the methodology to evaluate the fragility utilizing expert knowledge, the probabilistic model to handle the aleatory uncertainty as well as the development of SECOM2-DQFM code considering the improvement of the methodology and enhancement of utilization of Seismic PRA.

I. BACKGROUND

After Fukushima accident, safety enhancement of NPPs in Japan is required by Japanese regulatory body. Especially, continuous efforts to enhance the risk management and the technical basis have been required to support it. The importance of Seismic PRA to identify potential accident scenarios, to estimate their likelihood and consequences and to assess the effectiveness of countermeasures against earthquakes has been widely and strongly recognized. However, Seismic PRA has not been applied enough to achieve the aim described above. Because there has not been sufficient discussion about the quantification of uncertainties in quantification of seismic accident sequences and application for decision making.
In this study, based on the new mathematical framework of Seismic PRA proposed by Muramatsu et Al.[1)], a computer code will be developed to utilize the proposed framework on the basis of the SECOM2-DQFM developed by JAEA[2)], which can estimate the probabilities and their uncertainties of accident sequences. The proposed mathematical framework is characterized by the representation of seismic hazard by a set of time histories of seismic motions by Nishida et Al.[3)], probabilistic response analysis by three dimensional building model including the correlations among the component responses, and Monte Carlo simulation for quantification of fault trees in accident sequence analysis.

2. CURRENT FRAMEWORK AND CHALLENGES OF SEISMIC PRA METHODOLOGY

2.1 Current Method of Seismic PRA

(1) General Procedure of Seismic PRA

This study focuses the method of level 1 Seismic PRA that evaluates the frequency of core damage accident. Fig.1 shows the outline of Seismic PRA process. In general, the basic procedures of level 1 Seismic PRA can be carried out as following steps;

i. Collecting the plant information and analyzing brief accident scenarios
ii. Seismic hazard analysis
iii. Fragility analysis
iv. Accident sequence analysis.

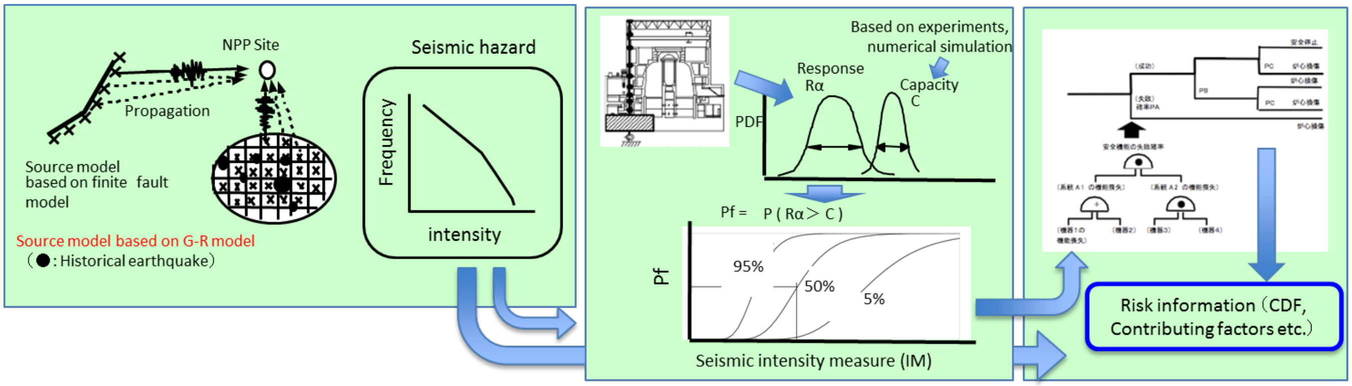

Fig.1 Outline of Seismic PRA Methodology

(2) Mathematical Framework of Current Method

The mathematical framework for quantification of accident sequences is based on the concept by Kennedy et Al.[4]. Since the most important characteristics of the current framework is the extensive use of design information and the safety factors that express the conservatism in the models used response and capacity evaluations in design.
On the other hand, the method of Seismic Safety Margins Research Program (SSMRP)[5] is the other mathematical framework which adopts more detail model and input than that by Kennedy et Al, however, SSMRP method is not been fully used because of its complexity. Based on SSMRP method, new mathematical framework of this study will be established and presented in the next chapter.

2.2 Studies about Uncertainty Analysis Framework

(1) Uncertainty Analysis of Current Method

Current method was proposed to evaluate component failure probabilities by Kennedy et Al.[4] The characteristics are as followings;

- Uncertainty of seismic hazard is expressed by the fractal curves.
- Main causes of variability of model and data are categorized to “aleatory uncertainty” and “epistemic uncertainty”.
- Uncertainties in hazard analysis, fragility analysis and in parameters of accident sequence are propagated to the uncertainty in core damage frequency.

(2) Major Issues of Current Mathematical Framework

Seismic PRA is expected to provide useful insights and information for various decision-making. However, current Seismic PRA method has several difficulties to prohibit improvement of its accuracy to identify important contributors, and they are related to simplification in the models as followings;

- Seismic motion is expressed by the only one parameter such as peak ground acceleration.
- One-dimensional wave propagation model for the ground and Sway-rocking model for the building, which are mainly used in current Seismic PRA, sometimes may not be sufficient. Three Dimensional Finite Element (3D-FEM) Model is one of the solutions for it.
- Coefficients of correlation should be evaluated to consider the correlation of component response.
- MCS methodology for quantification of accident sequences sometimes brings unacceptable errors to consider simultaneous occurrence of multiple MCSs or dependency among multiple MCSs.

3. NEW MATHEMATICAL FRAMEWORK FOR SEISMIC PRA

A new framework[1] to resolve the issues above should be characterized by the following features.

3.1 Basis of a New Mathematical Framework

(1) Seismic Hazard Analysis

- Seismic hazard can be expressed by set of the groups including a set of seismic waves weighted by the occurrence frequencies by the methodology of Nishida et Al[3)].
- Uncertainty will be evaluated by expert opinion as necessary.

(2) Fragility Analysis

- Structures and soil interaction are evaluated by 3D response analysis which calculates a lot of cases associated with all of the set of seismic waves given to each level of hazard and uncertainty.
- Response and uncertainty of large scale structures and components are analysed coupling with building as a part of building response analysis.
- Floor response spectrum and its uncertainty of other than large scale structures and components are analysed using the results of building response analysis. Response and its uncertainty i.e. median and log-scale standard deviation are calculated using individual specific frequency and attenuation factor of each component.

(3) Accident Sequence Analysis

- Improving SECOM2-DQFM code that can use the results 3D probabilistic response analysis based on the DQFM method, it is possible to analyse the conditioned core damage probabilities for each input time history seismic wave.
- Core damage frequencies are calculated to integrate the products of frequencies of occurrence of all of time history seismic waves and conditioned core damage probabilities respectively.

This framework requires large-scale calculations in the three fields, i.e. composing a set of waves of seismic hazard, large-scale probabilistic structure response analysis and quantification of accident sequences by Monte-Carlo method. To develop the analyzing system based on the concept of framework, following two options are proposed.

3.2 Option A: Using High Performance Computing Results Directly

Fig. 2 shows the process this option. In some cases, this option requires more than 10,000 times of calculations of large-scale 3D structure response analysis, because it is needed to set probabilistic distributions for soil-structure parameters that can be focused on about 20 parameters, associated with 300 or more of time histories of seismic motions. It is possible to treat such size of calculations by simplification of 3D detail model to some extent and usage of super computers. However, since several sensitivity studies are required to analyze dominant factors, it is not practical.

3.3 Option B: Using Intermediate Parameters such as Capacity Factors Derived from Building Response Analysis

In seismic PRA process, so many trial and errors are needed to determine the analysis model, i.e. level of detail for system model and fragility. This means that above “option A” requires a lot of calculation times and is not practical. So combination of 3D analysis and response coefficient method is proposed as the intermediate method.
Preparing a number of calculations enough to simulate the probabilistic distributions of 3D analysis results at a certain degree of accuracy, then median, standard deviation and coefficient of correlation are determined to reproduce the those results by response coefficient method using statistical analysis such as least-square method.
Fig. 3 (a) and (b) show the optioned process related to the time history grand motions and floor responses described above, and these processes are named as “The intermediate method”.
The most important point is that “response coefficient should be set to express the characteristic of probabilistic distribution very well by statistical analysis of the results of building 3D response analysis.” described in item (3). This point is considered to be reasonable approximation if the three factors such as median, log-scale standard deviation and correlation are maintained properly in quantification process of CDF.
Based on this proposal, it could be expected that it is possible to model the more detail of 3D response characteristics of buildings and the more proper correlation that are the most important advantages of “Option A” by the practical calculation time.

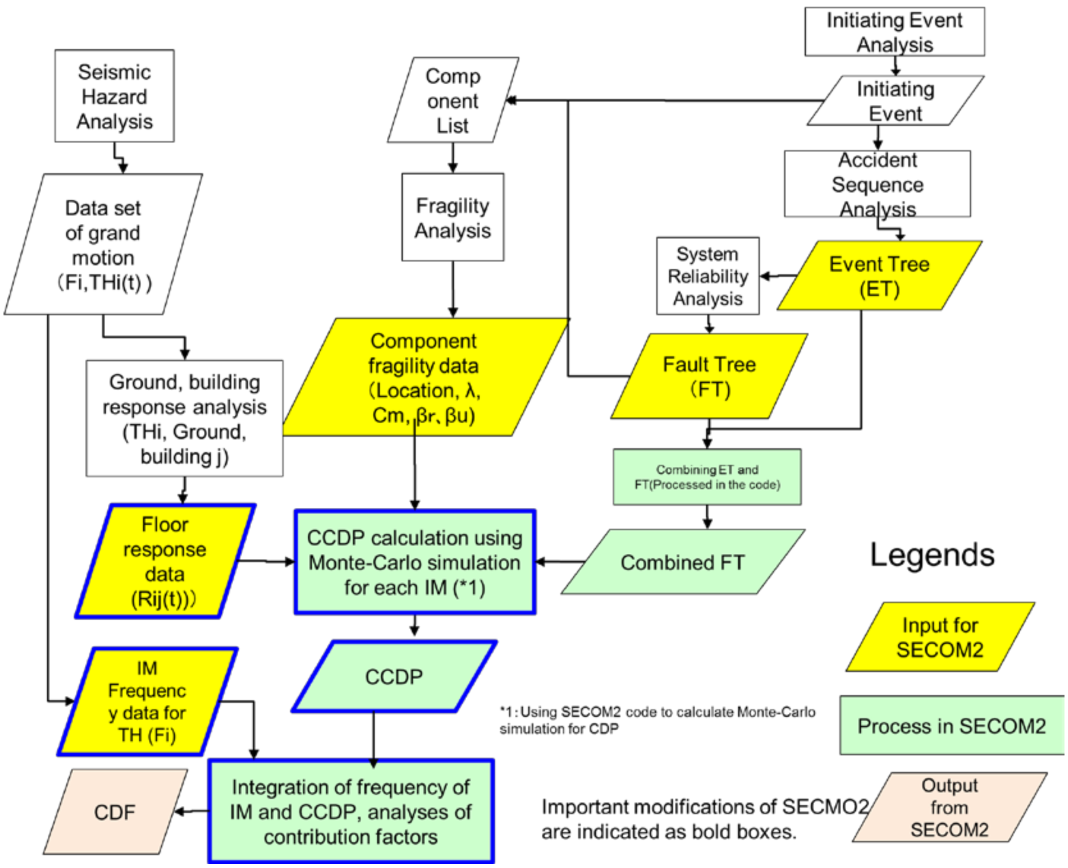

Fig.2 Process of Option A: Using High Performance Computing Results Directly

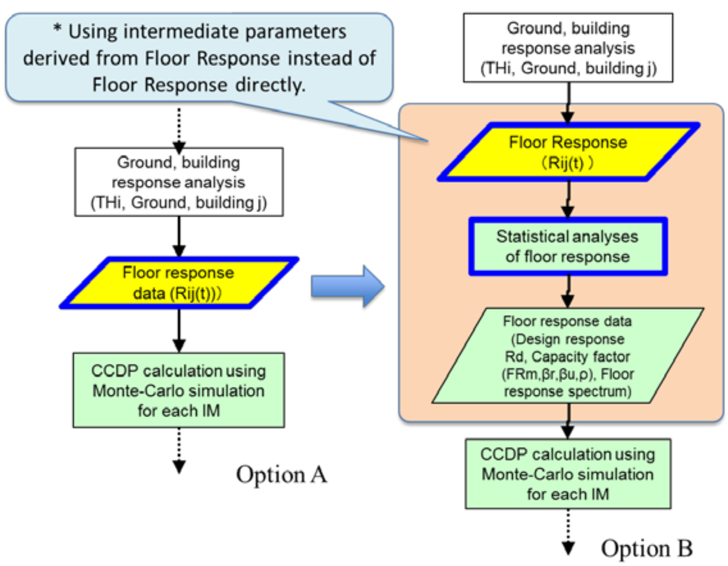

Fig.3(a) Comparison of Options: Treatment of Floor Response

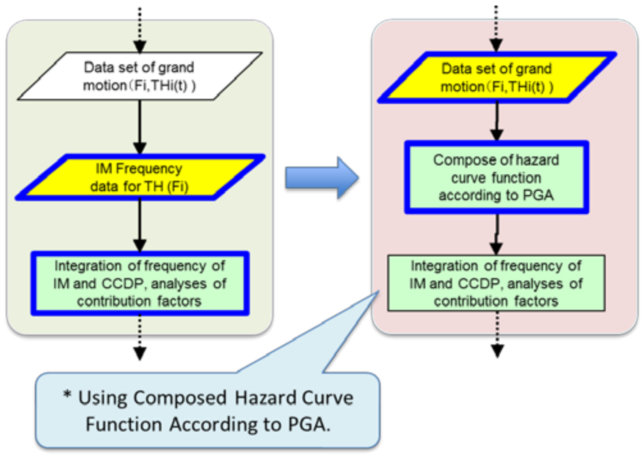

Fig.3(b) Comparison of Options: Treatment of Grand Motion

4. INSTALLATION OF UNCERTAINTY ANALYSIS FUNCTION USING RESPONSE FACTOR METHOD FOR SECOM2-DQFM

4.1 Improvement of SECOM2-DQFM Code

The function of uncertainty analysis for core damage frequency (CDF), accident sequence frequency and intermediate event frequency is installed in SECOM2-DQFM. In detail, followings are implemented;

- SECOM2-DQFM can be running on the large computing machine BX900 installed in JAEA.
- Improved to realize the large scale grid-computing.
- The uncertainty analysis function to calculate the uncertainty including aleatory uncertainty that is generally considered so far, that makes possible to reduce the calculation time dramatically using hundreds of CPUs even using proper set of random number for simulation.
- Improved to realize the uncertainty analysis of importance measurements such as FV importance.
- Improved to realize the uncertainty analysis even considering the correlation among any events that is one of the advantages of SECOM2-DQFM.

4.2 Analyses Results

Results of uncertainty analyses obtained by the improved and enhanced SECOM2-DQFM using the BWR5 model plant input are shown in Fig.4.
The point estimate values and the mean value of uncertainty analyses are consistent, and this means that improvement of SECOM2-DQFM by this study is reasonable. From the uncertainty analyses results, 5% lower value of 90% confidence interval could not be obtained because these are too low to plot them on the chart. The error factor of total CDF, that are derived from 95% upper value of 90% confidence interval divided by median value, is 11.0 and is smaller than those of each accident sequence, that are more than 10000 in some cases. It is presumed that smaller EF of total CDF depends on the larger contributing of accident sequences with smaller EFs relatively.
Moreover, the EFs of lower frequency accident sequences are relatively larger, and the EFs of higher frequency accident sequences are relatively smaller. This is because that accident sequences, smaller contributing to CDF, include the components with small fragility or redundancy. Especially, redundant components have complex relations of uncertainty and these are cumulated in the calculation, and this is why the EFs of these accident sequences are so large.
Fig.5 shows results of importance index such as Fussel-Vesely considering uncertainty bars which are 5%, median, mean, 95% and point estimate value. Some of components have very large uncertainties, especially very low 5% value and median.

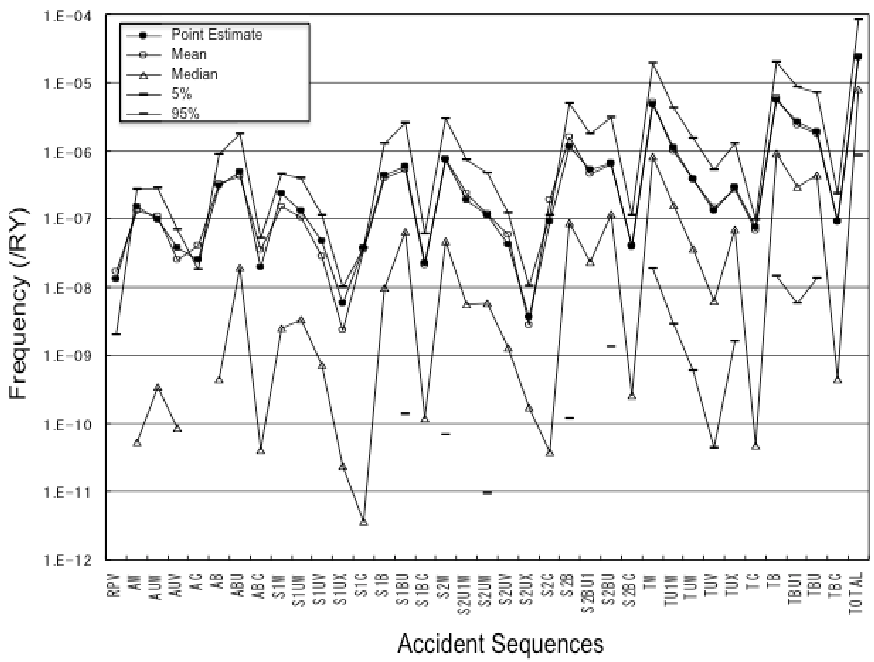

Fig.4 Results Uncertainty Analysis for Accident Sequence Frequencies

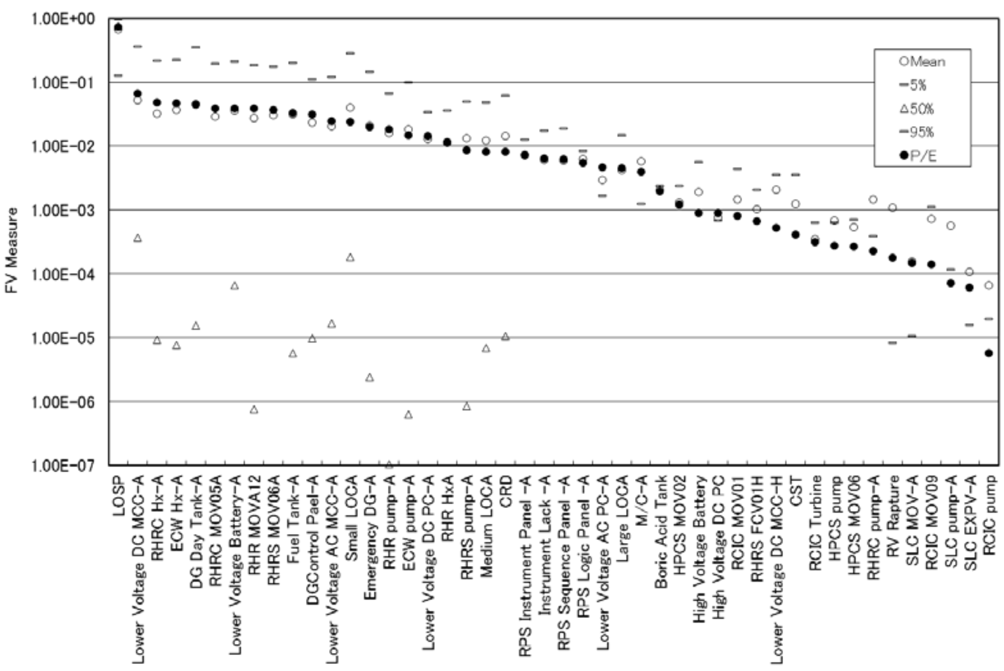

Fig.5 Results of Importance Analyses Considering Uncertainty

5. CONCLUSIONS

A new framework is proposed to improve the resolution capability of seismic PRA. Improvement of computer code SECOM2 for quantification of FTs by Monte Carlo Simulation is done. Based on these, capability of parallel processing was implemented to allow uncertainty analysis in a reasonable time for seismic PRA with the current model framework (response coefficient framework).

This study proposed the mathematic framework for the uncertainty in evaluating Seismic CDF , for the evaluation of fragility utilizing expert knowledge, and the new probabilistic model to handle the aleatory uncertainty . In addition, the usefulness of the newly proposed methods is confirmed through the modified SECOM2-DQFM code, which calculates the Seismic CDF.

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