Transactions, SMiRT-23
Manchester, United Kingdom - August 10-14, 2015
Division VII, Paper ID 330

Reliability Enhancement of Seismic Risk Assessment of NPP as Risk Management Fundamentals
Part I: Uncertainty Analysis with the SECOM2 Code

Hitoshi Muta[1], Ken Muramatsu[2], Osamu Furuya[3]
Tomoaki Uchiyama[4], Akemi Nishida[5] and Tsuyoshi Takada[6].

[1] Assistant Professor, Department of nuclear Safety Engineering, Tokyo City University, JP (hmuta@tcu.ac.jp)
[2] Professor, Department of nuclear Safety Engineering, Tokyo City University, JP
[3] Associate Professor, Department of nuclear Safety Engineering, Tokyo City University, JP
[4] Manager, CSA Japan, JP
[5] Principal Researcher, Center for Computational Science and e-Systems, Japan Atomic Energy Agency, JP
[6] Professor, Department of Architecture, The University of Tokyo, JP

ABSTRACT

After the severe accident in Fukushima dai-ichi nuclear power station, safety improvement and enhancement have been installed. In mid term and long term, continuous efforts to improve and enhance safety are required, and technical basis and fundamentals are needed to achieve them.

Probabilistic Risk Assessment for seismic event (Seismic PRA) is an effective measure to consider the countermeasures and improvement plans to secure the further safety of nuclear power plants regarding to seismic risk for the earthquake exceeding the reference ground motion. However, the application of the seismic PRA has not been utilized sufficiently so far. One of the reasons is that there is not enough consensus among stakeholders regarding to the evaluation methods and consideration of uncertainty for decision-making.

This study proposes the mathematic framework to treat the uncertainty properly related to the evaluation of Core Damage Frequency induced by earthquake, the method to evaluate the fragility utilizing expert knowledge, the probabilistic model to cope with the aleatory uncertainty as well as the development of analyzing code including these considerations for the improvement of the reliability of the method and enhancement of utilization of the products of Seismic PRA.

1. BACKGROUND

After the Fukushima dai-ichi accident, the importance of seismic probabilistic risk assessment (Seismic PRA) as a tool to identify potential accident scenarios caused by earthquakes, to estimate their likelihood and consequences and to support assessing the effectiveness of measures to enhance safety against earthquakes has been widely and strongly recognized. As the use of Seismic PRA expands, the quantification and reduction of uncertainties in numerical results of Seismic PRA is becoming more and more important.

This study, focusing on uncertainty assessment framework and utilization of expertise, and finally to improve reliability of seismic probabilistic risk assessment (Seismic PRA) by developing relevant computer codes and to promote its further use of the SPRA, develops methodology for quantification of uncertainty associated with final results from Seismic PRA in the framework of risk management of NPP facilities.

In this study, a new mathematical framework of Seismic PRA is proposed. Reviewing the current status of assessment procedures of accident sequence analysis in Seismic PRA, this study will develop a new mathematical framework for estimating uncertainty in SPRA results in a more comprehensive way taking into account uncertainties related to correlation effect of components failures which has been difficult to quantify so far. A computer code will be developed to materialize the proposed framework on the basis

of the SECOM2-DQFM developed by JAEA to estimate the accident sequence occurrence probability and its uncertainty.
The proposed mathematical framework is characterized by the following points;

- Representation of seismic hazard by a set of time histories of seismic motions using methods currently being developed by Nishida et. al.,
- Use of probabilistic response analysis by three dimensional building model for determining responses of components to the seismic motions including the correlations among the component responses,
- Use of Monte Carlo simulation for quantification of fault trees in accident sequence analysis, and
- Use of high performance computing technology for realizing the use of above technologies in Seismic PRA.

Current status and some results from scoping calculations will be presented.

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. In general, the basic procedures of level 1 Seismic PRA can be shown as followings;

a. Collecting the plant information and analyzing brief accident scenarios
   To investigate the seismic source around the target site, characteristics of soil and structures, and safety system configuration, the brief accident scenarios induced by earthquakes are extracted.
b. Seismic hazard analysis
   Based on the information about faults around the target site and historical earthquake, occurrence frequencies of seismic ground motion exceeding a certain capacity such as maximum ground acceleration.
c. Fragility analysis
   To analyze the response and capacity of structures and components, the failure probabilities of structures and components can be expressed as fragilities i.e. the function of capacity of seismic ground motion.
d. Accident sequence analysis
   To analyze seismic induced core damage accident sequences using event-tree (ET) and fault-tree (FT) techniques, core damage frequencies are evaluated based on these accident sequences, results of hazard analysis and fragility analysis.

(2) Mathematical Framework of Current Method

In this study, focusing on above item c. and d., mathematical model considering uncertainties of components and system failures will be studied. The mathematical framework for evaluating frequencies of accident sequences of Seismic PRA are as followings;

- The results of hazard analysis will be expressed as exceeding probabilities that is occurrence frequencies of seismic ground motions depending on the capacity on the target site. The levels of seismic ground motions are expressed as maximum accelerations of the surface.
- The wave used for response analysis is one of the time histories of waves such as design basis seismic ground motion. The impacts of variability of ground motion spectra are considered as variability of response factors explained later.
- The fragilities of components can be expressed as the probability that response exceeds capacity of the components, based on the assumption that probability distributions of response and capacity depending on the levels of seismic ground motion are the log-normal distribution respectively.
- The median values of response depending on the seismic level are evaluated by linear extrapolation for the component response results associated with design basis seismic motion or interpolation for the results associated with several seismic ground motion.

- Standard deviations on the log scale for the response can be evaluated by expert opinion based on the results of the similar response analysis or comparison among observation points. Usually response can be analysed by the Sway-rocking model.
- Since responses are usually analysed based on the design basis framework, response factors are introduced to consider impacts included in the assumption to secure conservatives of the design and to describe impacts of the uncertainty of model or data.
- Component capacities are expressed by median value and standard deviation, these parameters are set based on the results of structural analysis or verification test, and, if necessary, expert opinion.
- Occurrence conditions of accident sequences are expressed as groups of minimal cutsets (MCS) equivalent to logical expression of accident conditions expressed by ET and FT. To calculate occurrence probabilities of these MCSs, the probability of certain accident sequence can be evaluated associated with the certain level of seismic ground motion.
- Core damage frequencies can be evaluated by the integration of the product of the probability of accident sequence associated with the certain ground motion level and seismic frequencies all over seismic ground motion levels.

2.2 Studies about Uncertainty Analysis Framework

(1) Mathematical Framework of Current Method

Current method was proposed to evaluate component failure probabilities by Kennedy et. Al. in 1980. The characteristics are as followings;

- Uncertainty of seismic hazard is expressed by the fractile curves that are composed of multiple curves corresponding to the percentage of the confidence level.
- Main causes of variability of model and data expressing response and capacity can be categorized to “aleatory uncertainty” (or “uncertainty due to randomness”) and “epistemic uncertainty” (or “uncertainty due to lack of knowledge”). The first one can not be reduced by the insights of experiments or theoretical study because this variability actually exists and means that natural phenomena are essentially varies with randomly. The second one can be reduced by the insights of expansion of experimental data and enhancement of analysis model because this variability comes from lack of knowledge or simplification of analysis model.
- Usually uncertainty of analysis model of accident sequence are considered by sensitivity studies.

(2) Issues of Current Mathematical Framework

Seismic PRA is expected that it can provide insights and information for the quantitative evaluation of the safety level comparing core damage frequency and safety goal, and extraction of important accident sequences in a viewpoint of contribution to the total risk to enhance the safety features and accident countermeasures. So the followings are desirable and these are enhanced after Fukushima dai-ichi accident.

- To evaluate core damage frequency as far as precisely and its uncertainty.
- Plant damage states should be analysed in detail. For example, how many systems failed simultaneously, how many structures such as buildings or pipes failed or how they failed? In the multiple units site, what are the impacts of simultaneous occurrence of accidents in the multiple units?

However, current Seismic PRA method has several issues described later, and many of them are tightly related to the simplification in the mathematical framework described above, and are shown as followings.

a. <u>Issues Mainly Related to the Hazard Analysis</u>

- The characteristic of seismic motion is expressed by the only one parameter i.e. maximum acceleration. This means that dependency between the characteristic of epicentre i.e. distance and magnitude, and component failures is not modelled precisely enough.

b. <u>Issues Mainly Related to the Fragility Analysis</u>

- Since Sway-rocking model is basically used to analyse the response of buildings, structures and components, analysis of local stresses are very rough and failure modes of structures and components are not expressed precisely.
- Since Sway-rocking model is basically used to analyse the response of buildings, the impacts of characteristics of 3D response of buildings to the structures and components are not analysed precisely in some cases.
- In case that response factor method is adopted in components response analysis, coefficients of correlation should be evaluated separately to consider the correlation of component response.

c. Issues Mainly Related to the Accident Sequence Analysis

- In case that MCSs are used to evaluate core damage frequencies, since quantification considering simultaneous occurrence of multiple MCSs or dependency among multiple MCSs, error of calculation of core damage frequency tends to be increased.
- Since the range of correlation will be restricted, uncertainty of core damage frequency or contribution of each accident sequences tends to be increased.
- In case that initiating events are expressed by using hierarchical event-tree, it is not obvious that the impacts of the simultaneous occurrences of multiple initiating events are considered sufficiently in the analysis. Moreover, since accident scenario analysis is very rough, resolution of the method could be reduced.

(3) Previous studies Possibly to Resolve the Issues of Mathematical Framework

Issues described above are possibly going to be resolved by the several previous studies. Individual insights and achievements to resolve the issues are followings;

a. Previous Studies Related to Hazard Analysis

- Studies related to prediction of seismic motion regarding to modeling of seismic source using fault model, Green function method, Semi-empirical Green function method and the combination of these methods can provide time historical wave considering seismic source characteristics.
- Nishida et. Al. proposed the method expressing seismic hazard by multiple time historical waves weighted by frequencies based on these above studies.

b. Previous Studies Related to Fragility Analysis

- 3D response of structures and components evaluated by the techniques of structure response analysis such as Finite Element Method (FEM) are gradually used to confirm the validity of seismic design.
- The enhancement of grid computing method that makes high speed computing of structural response analysis possible using super computers, makes large-scale FEM practical.
- Nishida et. Al. proposed the method to build large-scale 3D nuclear power plant model based on the building structural response method, that makes
- Nishida et. Al. proposed the construction method of large-scale 3D plant model based on the structural analysis method, and it makes gradually possible that the response analysis of major components of nuclear power plant using one linked model and the prediction of the failure point by detail analysis of local stress of components.
- So many studies about probabilistic structural response analysis of components and structures have been done, for example, analysis of primary containment vessel by Takasaka et. Al., failure probability analysis of piping system by Whitaker et. Al. Though preparation of time history wave associated with the level of seismic motion will be needed to link these insights to seismic PRA, however, those kinds of studies have not been done so far.
- For correlation of response of components, generic rule that describes how to evaluate the correlations among many components and to give the coefficients of correlation considering the relationship among correlation of component, specific frequency of each component and specific location in the building based on the probabilistic response analysis of structures were proposed in the SSMRP study. This is applied to the assessment of two nuclear power plants in NUREG-1150. Moreover, JNES, TSO of the former regulation body of Japan, studied to evaluate the correlation of

response based on the soil-structure conditions using similar method and disclosed the results. These studies presented that it is possible to evaluate the correlation using probabilistic response analysis, and implied that it could be possible to derive the rule to give the correlation coefficient from a series of detailed calculations in the simplified manner.

c. Previous Studies Related to Accident Sequence Analysis

- Muramatsu et. Al. proposed the method that makes many samples of capacity and response by Monte-Carlo simulation for quantification of FT in seismic PRA, named DQFM (Direct Quantification of Fault Tree using Monte Carlo Simulation). DQFM method is possible to quantify FT accurately better than MCS method and to consider the correlation of response among components in more general way. Moreover, SECOM2-DQFM that includes DQFM method is disclosed.
- DQFM method can calculate core damage frequency precisely even multiple initiating events occur simultaneously. So it could be useful to resolve the issue that accident sequence might be too much simplified by the hierarchical event tree method if appropriate improvement is installed.

However, since it will be needed huge efforts to make the mathematical treatment consistently from hazard analysis to accident sequence analysis to develop the new framework and method, and to improve the whole mathematical method thoroughly in the application of insights and achievements of these above studies, current method has not been improved so far.

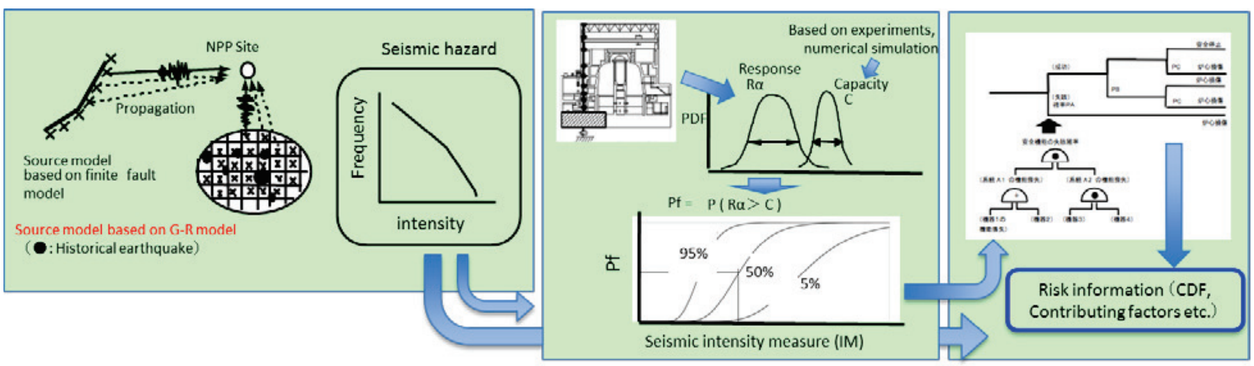

Fig.1 Outline of Seismic PRA Methodology

3. NEW MATHEMATICAL FRAMEWORK FOR Seismic PRA ENHANCED BY HIGH PERFORMANCE COMPUTING

This study proposes that brand new framework to resolve the issues above. This framework should be characterized by the following features.

(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 based on the studies by Nishida et. Al.
- Uncertainty will be evaluated by expert opinion as necessary and expressed by the logic tree method.

(2) Fragility Analysis

- Structures and soil are evaluated by 3D response analysis such as FEM or other method. It 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.
- Current analysing method of capacity and its uncertainty of component are improved using study insights described in chapter 3.2.

(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.

As shown in Table 1, using 3D structure response analysis for fragility analysis, resolution i.e. capability of scenario analysis are enhanced significantly.

Table 1 Expected Enhancement of Resolution of Seismic PRA
by Introducing 1D probabilistic Response Analysis

Related Task of Seismic PRA	Issues	Previous Seismic PRA (AESJ Standard and so on)	Improvements by Probabilistic Response Analysis of whole Plant using 3D FEM.
Modeling of Initiating Events	Needed to consider multiple initiating events such as LOSP simultaneously. Current method consider the only single initiating event.	Simplified by hierarchical event tree method. (Assuming capacity of structures such as Building>RPV>LOCA>Other events>LOSP. Superior events contain subordinate events. Conservative Evaluation)	Possible to consider multiple initiating events simultaneously by large-scale 3D plant model.
Evaluation of failure probability of each component.	Realistic analyses are required separately because capacities of components are evaluated conservatively in seismic design.	For large-scale passive components, analyses in design stage or detail analyses are referred. Active mechanical and electrical components are analyzed by verification tests or vibration test results provided by the venders. (Analysis methods are chosen depending on component types or availability of data.)	Basically, same as the previous method, but detailed analyses can consider the diversity of spectrum characteristics of seismic motions and decrease the dependency on the decisions by analysts.
Correlation among component failures	In analysis of simultaneous failure probability of multiplied systems, simultaneous failures of same design components i.e. consideration of correlations are required.	Quantitative evaluation of degree of correlation is difficult, simultaneous failures of same design components are assumed conservatively.	It is possible to rationalize the analysis of accident scenarios and the evaluation of CDF by introducing detail response analysis method of whole structure that can evaluate precisely.
Analysis of integrity of CV	It is important to analyze a location of CV failure for accident management.	Detail analysis Needed.	Same as the left (It is possible to consider the diversity of spectrum characteristics of seismic motions)
Consideration of ageing effects	It is desirable to consider the impact of the ageing of component for countermeasures of ageing.	Addressed as future work.	It could be easier to evaluate the risk increase by reduction of capacity of components using 3D FEM.

This framework requires large-scale calculations in the three fields such as composing a set of seismic waves of seismic hazard, large-scale probabilistic structure response analysis and quantification of system reliability model by Monte-Carlo method. It could be possible to realize considering the recent enhancement of super computing and expansion of inexpensive providing super computing.
To develop the analyzing system based on the concept of framework, following two options are proposed.

3.1 OPTION A: USING HIGH PERFORMANCE COMPUTING RESULTS DIRECTLY

Detail processes of this option are as followings;

(1) Seismic Hazard Analysis Including Uncertainty Analysis;
Seismic hazard is expressed by seismic motion that is described by multiple a set of seismic waves. However, to analyze uncertainty, each wave should include information of occurrence frequency, parameters of seismic source and propagation characteristics, uncertainty factor of those parameters such as occurrence probabilities, classification of aleatory and epistemic uncertainty.

(2) Soil-structure Response Analysis Including Uncertainty Analysis;
Probabilistic response of soil-structure are analyzed by 3D analyzing method such as FEM or Sway-rocking model that can treat 3D characteristics to some extent. In these analyses, factors of uncertainty and probabilistic distributions are determined by experts. Moreover, to calculate rationally, random variables treated in the analysis are focused on the dominant parameters. The results should contain the detail location in the buildings, calculation input parameters such as occurrence probabilities and classification of aleatory and epistemic uncertainty.

(3) Accident Sequence Analysis Including Uncertainty Analysis;
Conditioned component failure probabilities and core damage probabilities are calculated using time history floor response obtained from soil-structure response analysis and component capacities for every time history data for seismic motions. In these analyses, uncertainties are analyzed as well using parameters for soil-structure response analysis.

(4) Uncertainty Analysis of CDF;
CDF and its uncertainty are calculated using frequencies of time history data for seismic motions and the results of above item (3).

Fig. 2 shows the process described above and this process is named as “The direct method”.
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

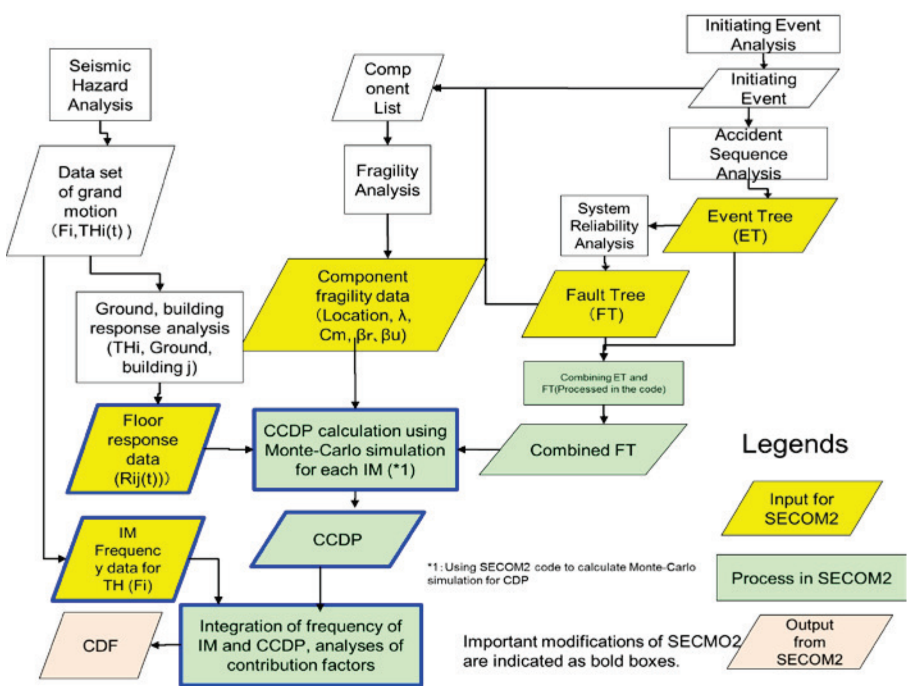

Fig.2 Process of Option A: Using High Performance Computing Results Directly

extent and usage of super computers. However, since several sensitivity studies are required to analyze dominant factors, it is not practical.

3.2 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. Details of this method are followings;

(1) Seismic Hazard Analysis Including Uncertainty Analysis;
This is same as the "Option A".

(2) Soil-structure Response Analysis Including Uncertainty Analysis;
This is same as the "Option A" as well.

(3) Derivation of seismic hazard curve indexed by maximum acceleration in free rock surface and response coefficient:
the basis ground motion, seismic hazard curve associated with maximum acceleration in free rock surface, median and standard deviation of response coefficient, and, coefficient of correlation among components, are calculated to be needed to apply the framework of seismic PRA using conventional response coefficient method to this method. Response coefficient should be set to express the characteristic of probabilistic distribution very well.

(4) Accident Sequence Analysis Including Uncertainty Analysis;
Using information determined in above (3), component failure probabilities associated with the maximum acceleration in free rock surface and conditioned core damage probabilities are evaluated. Along with these analyses, uncertainty is calculated using parameters for soil-structure response analysis as well.

(5) Uncertainty Analysis of CDF;
CDF and its uncertainty are calculated based on the seismic hazard curve indexed by the maximum acceleration in free rock surface, and conditioned core damage probabilities as well as uncertainties calculated in above (4).

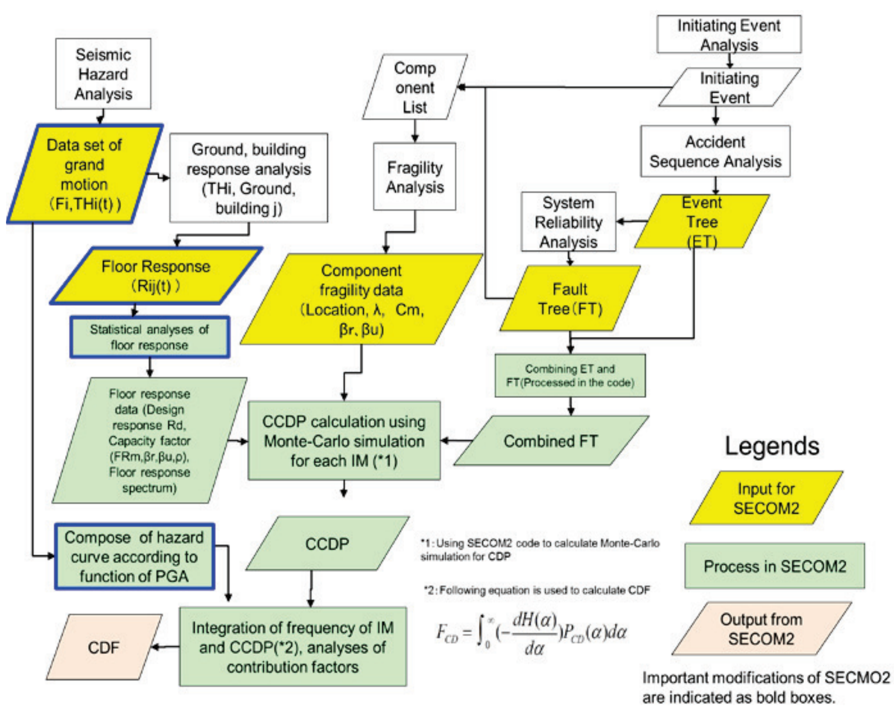

Fig.3 Process of Option B: using Intermediate Parameters such as Capacity Factors Derived from Building Response Analysis

Fig. 3 shows the process described above and this process is 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.
However, this method is the intermediate and simplified method and all of the advantages of 3D analysis could not be obtained. For example, the following issues are needed to be considered;

- Is it lost that possibility of introducing the index such as displacement, plastic deformation, other than acceleration in failure decision?
- Can it be suitably applied to the plastic region?
- Can the difference between the seismic source characteristics well be reflected in the calculation of the core damage frequency?

To resolve these issues, it can be considered that a set of response coefficient associated with maximum acceleration level in seismic center or site will be introduced and so on.

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 advantage 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

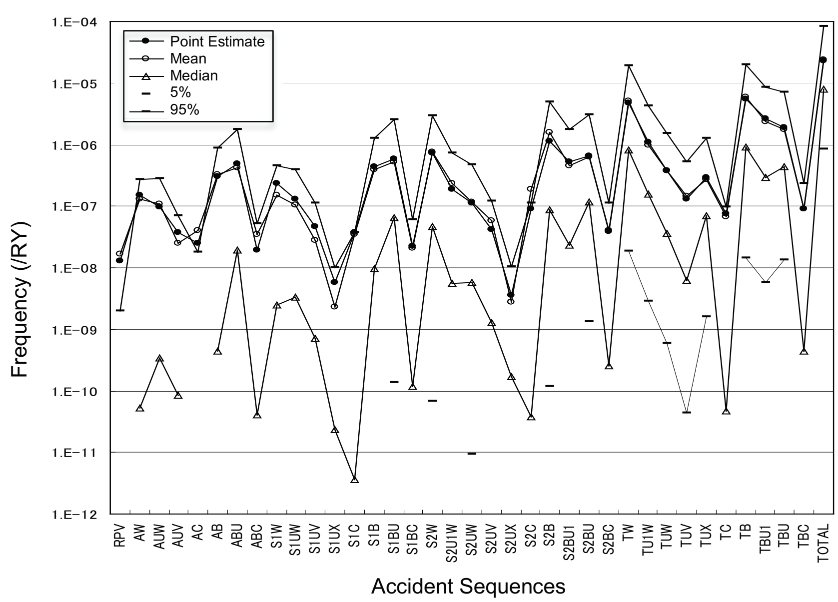

Fig.4 Results Uncertainty Analyses for Accident Sequence Frequencies

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.

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 to treat the uncertainty properly related to the evaluation of Core Damage Frequency induced by earthquake, the method to evaluate the fragility utilizing expert knowledge, the probabilistic model to cope with the aleatory uncertainty as well as the development of analyzing code including these considerations for the improvement of the reliability of the method and enhancement of utilization of the products of Seismic PRA.

ACKNOWLEDGEMENTS

This study is performed as a part of a three-year project "Reliability Enhancement of Seismic Risk Assessment of Nuclear Power Plants as Risk Management Fundamentals", which was started in 2012 and is funded by the Ministry of Education, Culture, Sports, Science & Technology (MEXT) of Japan.

REFERENCES

Nishida, A. et. Al. (2013). "Characteristics of Simulated Ground Motions Consistent With Seismic Hazard," *SRiRT-22*.

Muramatsu, K. et. Al. (2008). "Effect of Correlations of Component Failures and Cross-Connections of EDGs on Seismically Induced Core Damages of a Multi-Unit Site," *Journal of Power and Energy Systems*, JSME, .Vol.2 No.1, pp.122-133.

Kawaguchi, K. et. Al. (2012). "Efficiency of Analytical Methodologies in Uncertainty Analysis of Seismic Core Damage Frequency," *Journal of Power and Energy Systems*, JSME, .Vol.6 No.3, pp.378-393.

Robert T. Sewell et. Al. (2009). "Recent Findings and Developments in Probabilistic Seismic Hazards Analysis (PSHA) Methodologies and Applications," NEA/CSNI/R(2009)1.