Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 23-24, 2019

Requirement for Seismic PSA Quantification Software under Development in KAERI

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1. Introduction

KAERI is developing a technology for probabilistic seismic risk assessment, which consists of 1) seismic fragility assessment technology, 2) seismic failure assessment considering seismic correlation, and 3) seismic PSA (Probabilistic safety assessment) quantification software development.

In this paper, we present the functions of seismic PSA quantification software that can construct a seismic PSA model and perform quantitative evaluation when seismic hazard, fragility, and correlation are given.

2. Review of seismic PSA methodologies

2.1. Seismic PSA Procedure

In probabilistic seismic risk assessment [1], the fragility of the system is evaluated by calculating the failure probability considering uncertainty for each seismic intensity level (Fig. 1), and the seismic risk is evaluated by convoluting the fragility with seismic hazard (Fig. 2).

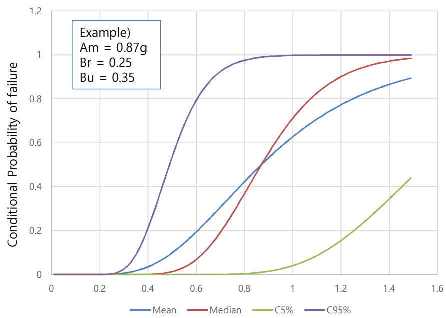

Fig. 1. An example for seismic fragility curve

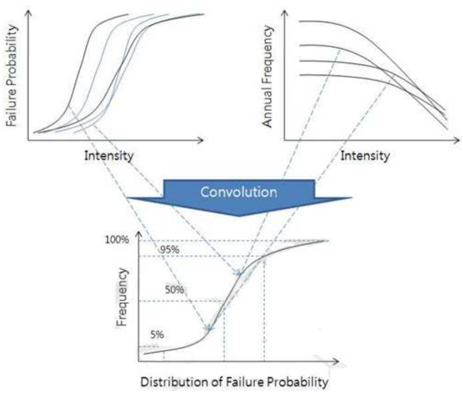

Fig. 2. Convolution of seismic hazard and fragility

The seismic PSA is to calculate the core damage probability for a plant. It is performed by the following procedure (Fig 3) [2];

- Derive the seismic initiating event (IE) by performing the analysis of initial behavior following an earthquake.
- Develop detailed scenarios for each seismic IE and combine those with the system fault tree models to build a base PSA model.
- Construct the seismic PSA model by combining component failure probability due to an earthquake with the base PSA model.
- Quantify the seismic PSA model.

The seismic risk can be evaluated by repeating the above quantification for each seismic intensity level and combining it with the seismic frequency.

The methodology of seismic PSA changes over time [2, 3];

- Previous seismic PSA methodology: Seismic IE model and seismic event tree for each seismic IE are evaluated separately. From the viewpoint of seismic analysis, only seismic IE model, including seismic failures, is analyzed in detail.
- Recent seismic PSA methodology: Seismic IE model and seismic event tree for each seismic IE are combined and analyzed. Seismic failures for all SSCs (Structures, Systems, and Components) are also included in the seismic PSA. However, complete correlation is assumed between redundant components.
- Future seismic PSA methodology: More realistic correlation is evaluated in addition to the recent seismic PSA methodology.

2.2. Seismic correlation in NUREG/CR-7237

The basic approach for evaluating the failure probability considering the seismic correlations of similar SSCs is to use multiple integration introduced in the SSMRP (Seismic safety margins research program) method. The Reed-McCann method for separating independent and common variables and the Monte Carlo method can be alternative approaches. Features of these methods are summarized in NUREG/CR-7237 [4].

Table 1. Approaches to handle seismic correlation

Approach	Characteristics
Monte Carlo or LHS	- Correlated Monte Carlo approach - LHS (Latin hypercube sampling) or direct Monte Carlo
DPD	- DPD (Discrete probability distribution) for distribution of uncertainty - Only handle zero or full correlation
SSMRP	- Multiple integration method - Correlation coefficient matrix - z=Response-Capacity
Mankamo Model	- Multiple failure expressed by geometric mean - P[A]. P[B] < P[AB] < min {P[A], P[B]} - $P[AB] = P^x$, $1 \le x \le n$
Reed-McCann	- Divide independent and common factors - $\beta u \rightarrow \beta u'^k$ (several independent factors), βu^{*i} (several common factors)
Split Fraction or CCF model	- Fleming and Mikschl Procedure - Pellissetti and Klapp model - Two factors (independent, dependent) - $Fj\{A * B\} = Fj^D \{A*B\}$ - $+ [1-Fj^D \{A*B\}] Fj^I \{A\} Fj^I \{B\}$ - (Similar to β Factor method)

2.3. SECOM-2 software

SECOM-2 is a seismic PSA quantification software developed by JAEA in Japan [5]. It supports both the minimal cut set method and the Monte Carlo method (called DQFM, Direct quantification of fault tree using Monte Carlo simulation), as well as uncertainty analysis and importance analysis.

With respect to correlation input, seismic capacity and response are divided into several factors. The way to quantify the seismic PSA considering the correlation is to use the SSMRP approach for the minimal cut set method and the correlated Monte Carlo approach for the DQFM method.

2.4. Correlated Monte Carlo Technology

Fig. 4 shows the procedure for evaluating the seismic failure with correlation using the correlated Monte Carlo technique [4]. Correlated sampling technique is used to handle the seismic correlation and repeat the process of randomly determining the failure due to seismic. This approach can easily and accurately calculate the failure probability of a system modeled in the fault tree format. Non-seismic failures can also be handled.

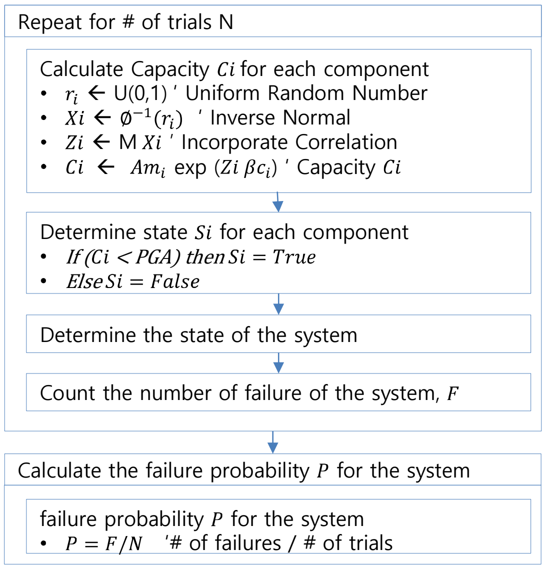

Fig. 4. Correlated Monte Carlo procedure for seismic failure analysis.

Note)
- Σ : Correlation coefficient matrix
- $M = \Sigma^{1/2}$: Result of Cholesky decomposition
- *Ami*, *βci* : Median capacity, composite uncertainty for seismic failure
- *PGA* : Seismic intensity

3. Requirements for Seismic PSA Quantification Software

3.1. Methods to quantify a seismic PSA

Seismic PSA quantification software will be developed in two approaches: the CCF (Common cause failure) modeling approach and the Monte Carlo approach. The overview of software is shown in Fig. 5.

The multiple integration method introduced in SSMRP is not easy to evaluate when combining the AND/OR logic, and the computation time increases exponentially with a large number of components.

On the other hand, the correlated Monte Carlo approach is easy to implement, and the computation time tends to increase linearly with the size of the model. It can be applied to large PSA models of nuclear power plants. Correlated Monte Carlo approach will be used basically in this project.

3.1.1. CCF Modeling Approach

In the CCF modeling approach, CCF-style fault trees are generated by analyzing the seismic failures for each seismic correlation group. Those are modeled according to the CCF methodology of PSA [6].

Correlation Monte Carlo approach is used to evaluate the probability of seismic failures for each seismic correlation group.

The CCF-style fault trees are combined with the base PSA model to construct a seismic PSA model. (Note that a basic event for a seismic failure probability is not included in the base PSA model.)

Minimum cut sets are calculated for the seismic PSA model. This is a typical way of PSA quantification. The advantage of the CCF modeling approach is that traditional PSA quantification methods can be used as is, that is a familiar way to PSA analysts.

It also provides the ability to perform quantification using BDD (Binary decision diagram) method [7]. The BDD method can be used when accurate calculation is required. (Note that the BDD method can be applied to small models.)

3.1.2. Monte Carlo Approach

In the Monte Carlo approach, quantification is performed taking into account seismic failures and non-seismic failures based on the basic PSA model. Of course, seismic failures are treated by the correlated Monte Carlo approach.

3.2. Input of Seismic correlation

Seismic correlation can be entered in various ways;

- Only the capacity is considered and the correlation matrix is entered for the capacity (Both the method of separating βr and βu and the method of treating βc alone are all possible).
- Response and capacity are entered separately and a correlation matrix is entered for each (Both the method of separating βr and βu and the method of treating βc alone are all possible).
- Response and capacity are separated into multiple factors as in the Reed-McCann method. Here, common factors and independent factors are distinguished between components.

The seismic failure analysis module can accommodate all the possible ways of handling seismic input data. It analyzes the seismic failures by considering seismic correlations. It produces the CCF-style fault tree model for CCF modeling approach. It also produces an input for the Monte Carlo approach where it requires a correlation matrix for capacity.

3.3. Convolution and uncertainty

The method described above is a method of calculating a point value for a given PGA (Peak ground acceleration) value. For uncertainty analysis, it is necessary to perform analysis considering epistemic uncertainty. Uncertainty analysis will use the usual Monte Carlo technique.

- Express epistemic uncertainty as a lognormal distribution.
- Randomly repeat the process of calculating the point value while changing the factor (eU) for epistemic uncertainty. The result is summarized in the form of an uncertainty distribution.

For convolution, it is necessary to repeat the above calculation while changing the PGA value, and to combine the result with the frequency of the PGA value.

3.4. PSA software

The following existing PSA software will be used in the development of seismic PSA quantification software;

- AIMS-PSA : modelling of event trees and fault trees [8]
- FTREX: minimal cut set or BDD calculation [9]
- FTeMC : fault tree quantification using Monte Carlo approach (where correlated Monte Carlo will be incorporated for quantification of seismic PSA) [10]

3.5. Remaining works

Further research is needed on the following issues;

- Convert various correlation input methods to correlation matrix
- Check the errors in correlation matrix (physically incorrect input, or incorrect Cholesky decomposition for physically correct input)
- Improve the uncertainty analysis method (to combine seismic and non-seismic failures, and to reduce the calculation time)
- How to perform importance analysis when using Monte Carlo approach
- How to convert seismic failures into CCF models (calculate the values for CCF events, and simplify the CCF modeling)
- Introduce and check the LHS (Latin Hypercube Sampling) for large number of variables

4. An Example for Seismic PSA Quantification

A simple example is prepared to illustrate the quantification of a seismic PSA model. The example consists of one tank, two pumps, and there is a seismic correlation between the pumps. The probability of system failure will be evaluated for a case where the PGA is 1.0g.

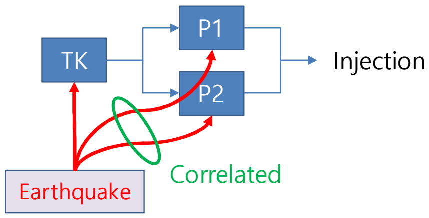

Fig. 6. Example system with 1 tank and 2 pumps

The non-seismic failure probability and seismic fragility data for each component are given as follows.

Table 2. Data for an example model

Comp	Non-seismic Failure Proba.	Seismic Data		
		Am	βr	βu
#1 (Pump)	0.1	1	0.3	0.3
#2 (Pump)	0.1	1	0.3	0.3
#3 (Tank)	0.01	2	0.3	0.3

The correlation coefficients between the pumps are assumed as follows.

Table 3. Correlation coefficient for pumps

Source of uncertainty	Correlation Coefficient
βr	0.3
βu	0.7

4.1. Monte Carlo Approach

The Monte Carlo method uses a base PSA model in which seismic failures are not additionally modeled. Both non-seismic failures and seismic failures are taken into account during the Monte Carlo simulation.

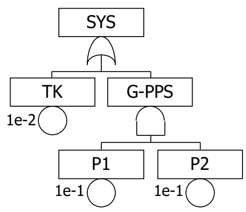

Fig. 7. An example of a base PSA model

4.2. CCF modeling Approach

In the CCF modeling approach, the seismic PSA model is developed as follows;

- Calculate failure probability of each component and multiple failure probabilities due to seismic failure considering correlation for each seismic correlation group.
- The failure probability of each component is obtained from the theoretical formula, and the multiple failure probability is calculated using the correlated Monte Carlo approach.
- Calculate the single failure (Q_1) and double failure probability (Q_2) (Calculate Q_1 and Q_2 by using $P_1 = Q_1+Q_2-Q_1*Q_2$, and 2-tuple = $Q_1^2+Q_2-Q_1^2*Q_2$)
- Develop a CCF model in the fault tree format, add it to the base PSA model to create the seismic PSA model.
- Perform quantification by either BDD or minimal cut set approach.

Failure probability for each component is given below.

Table 4. Results of seismic failure probability

Component	P(Seismic)
P1	0.5
P2	0.5
Tank	0.051154

The seismic multiple failure probability calculated using the correlated Monte Carlo method is given below.

Table 5. Results of seismic multiple failure probability

Pump Failure	P(Seismic)
1-Tuple	0.333392
2-Tuple	0.33326

A fault tree including seismic failures is given below. SP1, SP2, and STK are independent events due to seismic failure of Pump 1, Pump 2, and Tank, respectively. SP12C is a dependent event due to seismic correlation (Note SP1=SP2=Q_1=0.333254, SP12C=Q_2=0.249962).

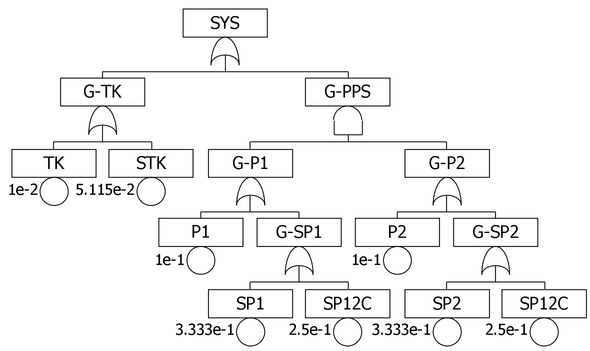

Fig. 8. An example of CCF modeling approach

4.3. Results for the example system

The following table is a summary of the calculation results;

Table 6. Results of example analysis

Case	Monte Carlo	FT (BDD)	FT (REA)
Seismic only	0.3674	0.3674	0.4122
Non-Seismic	0.0199	0.0199	0.02
Seismic + Non-Seismic	0.4082	0.4081	0.4989

Note)

- Seismic only : consider only seismic failure
- Non-Seismic : consider only non-seismic failure
- Seismic+Non-Seismic : consider both seismic and non-seismic failure

Monte Carlo is the result of the correlated Monte Carlo calculation (the number of sampling = 10^7). FT (BDD) and FT (REA) are results of the BDD method and the rare event approximation, respectively, which are calculated for the fault tree created from the CCF modeling approach (seismic failures are modeled in the CCF style).

Results from the Monte Carlo method and the BDD are almost identical. The results of the rare event approximation produces the large difference with the Monte Carlo method.

5. Conclusions

This paper presents the requirements of software to perform seismic PSA quantification when seismic hazard, fragility, and correlation are given. The seismic PSA quantification software will be developed in 2 ways;

- CCF modeling Approach: Seismic failures are modeled in the CCF-style fault tree format according to traditional PSA methods and minimal cut sets are calculated.
- Monte Carlo Approach: Correlated Monte Carlo technique is used to quantify a seismic PSA model with correlation. It will be used as a complementary tool to verify the results of CCF modeling approach.

Currently, we have been developing and testing the basic technical elements, and designing the functions of the seismic PSA quantification software. Then we will develop the seismic PSA quantification software.

ACKNOWLEDGEMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea (No. 20171510102020).

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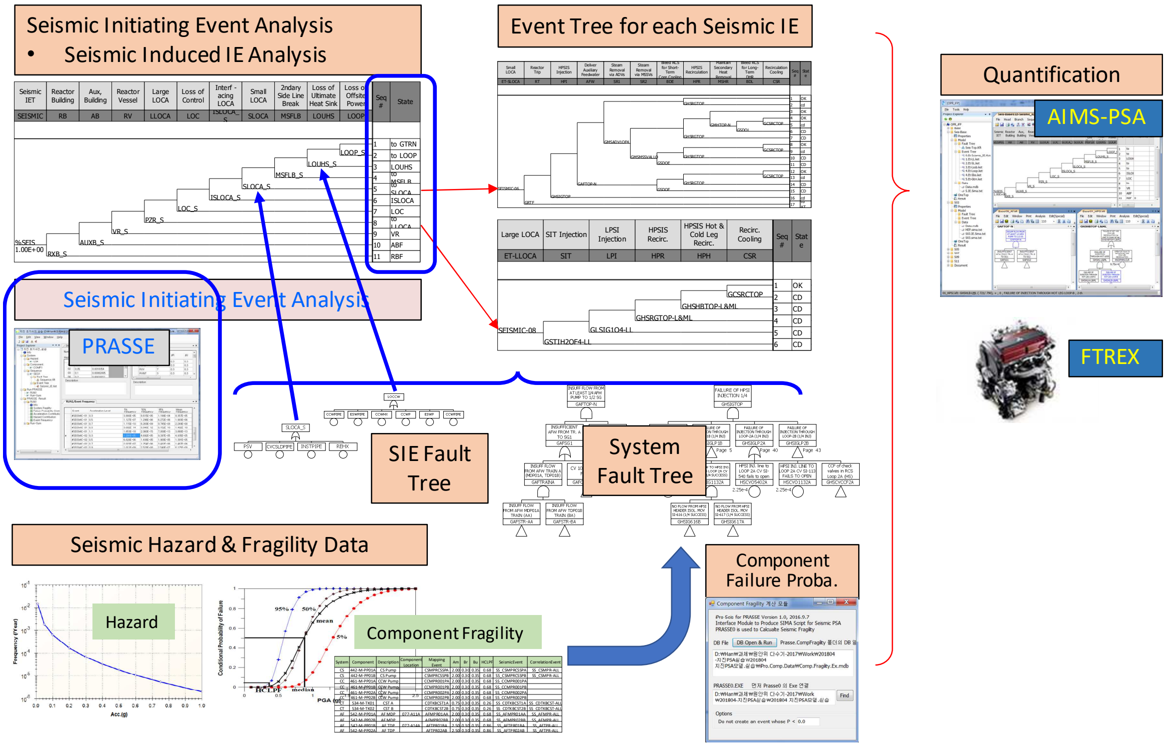
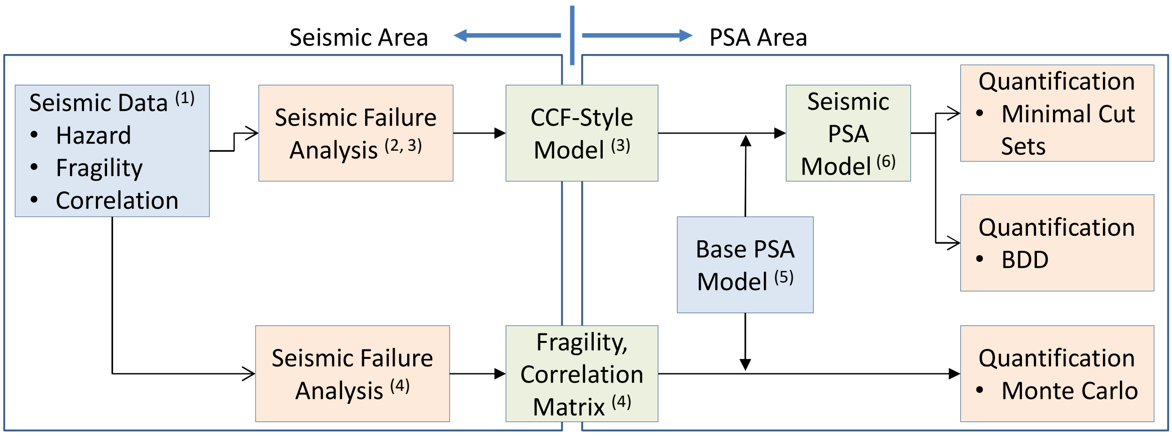


Fig. 3. Seismic PSA procedure



Note 1) Various style of input is allowed.
2) Monte Carlo or multiple integration technique are used.
3) Convert the seismic failures in the CCF fault tree format for each seismic correlation group.
4) Convert the seismic failure data in the form of Am, Br, Bu and correlation matrix for each seismic correlation group for Monte Carlo approach.
5) Seismic failure data is not included in the Base PSA model.
6) The CCF-style fault trees are combined with the base PSA model to construct a seismic PSA model.

Fig. 5. Basic Requirement for Seismic PSA Quantification Software.