A Regulatory Approach to Accurately Estimate Seismic CDF

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1. Introduction

The safety of a Nuclear Power Plant (NPP) can be evaluated by Core Damage Frequency (CDF). Probabilistic Safety Assessment (PSA) is a powerful tool to identify the seismic vulnerabilities in a nuclear power plant. Seismic Probabilistic Safety Assessment (SPSA) has been widely used to compute the seismic CDF of a NPP. The SPSAs of Korean NPPs have been performed since the early 1990's.

From regulatory reviews of domestic SPSAs, it is known that the quantification results of SPSAs change according to input condition and calculation tool. So, reviewers of SPSA want to perform audit calculations of SPSA results submitted for licensing.

2. Seismic Probabilistic Safety Assessment (SPSA)

SPSAs are consists of the following main elements to address potential scenarios that could be initiated by a seismic event. [3, 4]

1) seismic hazard analysis
2) seismic fragility evaluation
3) plant response modeling
4) risk quantification

2.1. Seismic Hazard Analysis

Seismic hazard at a NPP site can be represented by a hazard curve, which is a plot of annual frequency of exceedance against Peak Ground Acceleration (PGA). It is developed by seismologists. Because of the large uncertainty in the seismic hazard analysis, a family of hazard curves is usually developed with different confidence levels, such as 15%, 50%, 85%, mean etc. This is called a Probabilistic Seismic Hazard Analysis (PSHA). The hazard curves with different confidence levels are shown in Fig. 1.

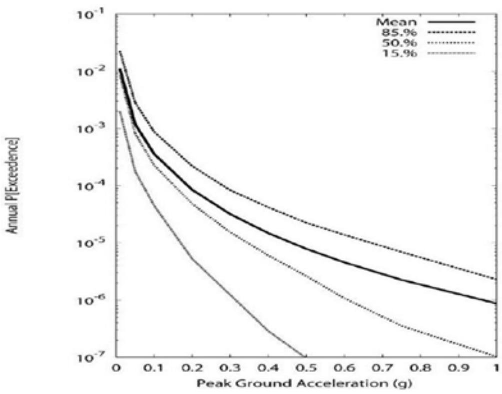

Fig. 1. Seismic hazard curves of the plant site

2.2. Seismic Fragility Evaluation

The seismic fragility of a structure or equipment is defined as the conditional failure probability at a given level of ground motion value (i.e., PGA). The objective of a fragility evaluation is to evaluate the capacity of critical failure modes of structures, systems, and components (SSC), for both structural failure and equipment functional failure, relative to a ground acceleration parameter such as PGA. The uncertainty of the component fragility is represented by a family of fragility curves.

The first step for seismic fragility evaluation is to develop a Seismic Equipment List (SEL). All the SSCs that may have the potential to impact the nuclear safety of the plant should be considered in the SEL. Once a preliminary SEL list is identified, a plant walk-down is necessary to further confirm the completeness and accuracy of the SEL list. Based on the plant walk-down and industry experiences, some SSCs can be screened out from the SEL due to their strong seismic robustness.

At each PGA value, the fragility *F(a)* can be represented by a subjective probability (confidence) that the conditional probability of failure for a PGA *a*. The fragility *F(a)* is defined as

$$F(a) = \Phi\left[\frac{\ln(a/A_m) + \beta_U\,\Phi^{-1}(Q)}{\beta_R}\right] \quad (1)$$

where

A_m = median capacity
β_R = logarithmic standard deviation of the randomness
β_U = logarithmic standard deviation of the median capacity and represents the uncertainties in models
Φ = function of the standard Gaussian cumulative distribution
Φ^{-1} = inverse function of the standard Gaussian cumulative distribution
a = seismic acceleration (typically expressed in PGA)
Q = confidence level for the conditional probability of failure for a given PGA a.

The fragility curves with different confidence levels for a component are shown in Fig. 2 as an example.

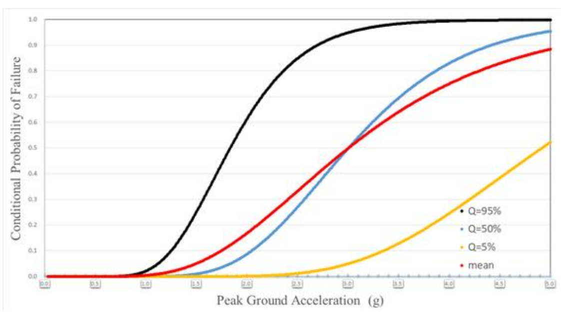

Fig. 2. Example of component fragility curves

The High Confidence of Low Probability of Failure (HCLPF) quantity considers both the uncertainty and randomness variabilities and is the acceleration value for which the analyst has 95% confidence that the failure probability is less than 5%. To further screen out the SSCs, a rough estimation method is used to set an HCLPF criteria. If the HCLPF of a SSC is higher than this threshold value, the SSC can be screened out.

2.3. Plant Response Modeling

Plant response modeling in SPSA is based on the internal events PRA model. It will develop plant and system response models to enumerate seismic-induced accident sequences.

Seismic pre-Event Trees (pre-ETs) only consider the seismic-induced failures. The pre-ET is shown in Fig. 3 as an example.

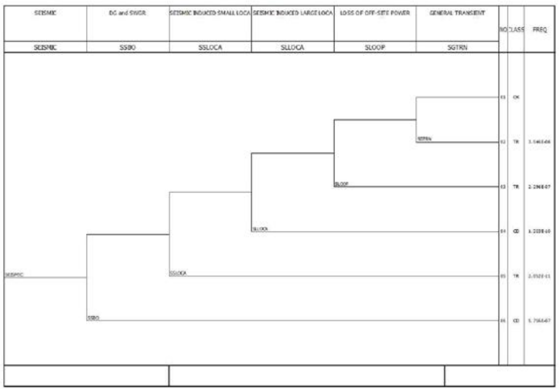

Fig. 3. Example of seismic pre-ET

This event tree uses the critical components and structures whose failures may cause core damage and also uses these failed events as Seismic Initiating Event (SIE). From this seismic pre-ET, some consequences will lead directly to core damage. The rest of the consequences are categorized as either “OK,” or SIEs which will be linked with the corresponding event trees similar to the internal event trees.

The other steps for seismic plant response modeling are the same as for the internal events PSA. The PSA modeling tools (e.g., SAREX, AIMS) are used to generate Boolean expression in terms of basic events for each core damage sequence.

2.4. Risk Quantification

Once the plant response modeling is completed, it needs to integrate the results of the seismic hazard, SSC fragility, and system analysis results to estimate CDFs. By summing the frequencies of seismic sequences over all seismic initiating events, the end-state frequencies for seismic risk are exactly obtained.

The final seismic CDF F_{CD} is given by the convolution integral:

$$F_{CD} = \int_0^{\infty} [dH(a)/da]\, P_{CD}(a)\, da \qquad (2)$$

where

$H(a)$ = seismic hazard at level a

$dH(a)/da$ = frequency with which the earthquake occurs in the size range da about a

$P_{CD}(a)$ = conditional core damage probability at a

In order to integrate seismic CDFs, the analysts of SPSA use a special data processing tool (SIESMIC, EQESRA, PRASSE [5], etc.). They all have different shortcomings (unfriendly environment, complex logic transformation for Boolean equation, slow-running, etc.).

Korean SPSAs provide only the point values of seismic CDF. They don’t provide uncertainties of seismic CDF.

3. Proposed Risk Quantification Method for SPSA

USNRC RASP Handbook (the Risk Assessment of Operational Events Handbook) [6] provides a concise and practical handbook even for SPSA. The risk quantification method proposed in this paper is similar to this handbook for SPSA.

This proposed method quantifies seismic CDFs under the following input conditions which come from other main elements of SPSA (seismic hazard analysis, seismic fragility evaluation, plant response modeling).

1) Seismic hazard vector (frequencies of seismic events)
2) Seismic fragilities of major SSCs
3) Seismic pre-ET (including Boolean logics of headings and end-state sequences)
4) Conditional Core Damage Probability (CCDP) of each SIE transferred to other Event Tree/ Fault Tree models which are calculated by a general tool for the quantification of Minimal Cut Set (MCS).

The proposed risk quantification method provides point estimates for frequencies of SIEs and seismic CDF using mean hazard curves, mean fragilities, and mean failure rates. In order to get an exact mean CDF, the method considers the following factors:

3.1. Dividing Intervals of Seismic Hazard Curves

In this proposed method, the range of the seismic acceleration (in PGA) is covered between the chosen lower and upper bound. The covered PGA range is divided into many intervals. In this study, the interval size of 0.001g is chosen to reduce the calculation error from hazard curve. The seismic event frequencies of each PGA interval (i.e., $dH(a)$ in Eq. (2)) is calculated from a mean hazard curve about a. In this study, the representative PGA a for an interval is the center value of the interval (from a-da/2 to a+da/2).

3.2. Evaluating Seismic Fragilities

Based on Eq. (1), the mean fragility curve averaged at a, $F_{mean}(a)$, is defined as

$$F_{mean}(a) = \Phi\left[\frac{\ln(a/A_m)}{\beta_C}\right] \quad (3)$$

where $\beta_C = \sqrt{\beta_R^2 + \beta_U^2}$.

The mean failure probabilities of major SSCs at *a* are exactly calculated by Eq. (3).

3.3. Evaluating Seismic pre-ET

Because the occurrence probability of each heading in a seismic pre-ET varies with *a*, the probability calculation for every interval is needed.

ET begins with the initiating event (IE) where consequences of intermediate event (heading of ET defined using Fault Tree (FT) structures) follow in a binary (success/failure) manner. It creates a path in which a series of successes or failures of headings will occur. When the ET diagram has reached the end state for all paths, the occurrence probability of that path can be calculated. Because the paths of an ET are mutually exclusive, the occurrence frequency of concerned paths (i.e, core damaged paths) can be exactly calculated by a simple summation.

ETs can be categorized into two types:

1) Independent ET:
When the headings are independent of each other, the ET quantification is simply achieved by finding the product of the frequency of IE with the probabilities of passing along each heading leading to each path of ET.

2) Dependent ET:
When there are dependencies between the headings, the quantification of the concerned paths is more complex. The Binary Decision Diagram (BDD) approach and the ACUBE algorithm [4] can offer advantages in the quantification of this type of seismic pre-ET.

Consider the set of mutually independent events, $\{E_1, E_2, E3, \ldots, E_n\}$, and define the event $\bar{E}_i$ as the non-occurrence of E_i, then we have

$$P(E_1 \text{ and } E_2 \text{ and } E_3 \text{ and } \ldots \text{ and } E_n) = P(E_1)\,P(E_2)\,P(E_3)\ldots P(E_n)$$

$$P(\bar{E}_1 \text{ and } \bar{E}_2 \text{ and } \bar{E}_3 \text{ and } \ldots \text{ and } \bar{E}_n) = P(\bar{E}_1)\,P(\bar{E}_2)\,P(\bar{E}_3)\ldots P(\bar{E}_n)$$

$$P(E_1 \text{ or } E_2 \text{ or } E_3 \text{ or } \ldots \text{ or } E_n) = 1 - \{[1-P(E_1)]\,[1-P(E_2)]\,[1-P(E_3)]\ldots[1-P(E_n)]\} \quad (4)$$

Using Laws of Boolean algebra [7], the Boolean logic of a complex heading in an independent ET can be transferred to an equivalent Boolean logic which has a series of independent modules with "OR" operations. Then we can exactly calculate the occurrence probability of the heading using eq. (4).

3.4. Evaluating SIE

In a seismic pre-ET, the outcomes of the ET are SIEs. Through evaluating the Boolean logics of paths, we can get the occurrence probability of each initiating event for a PGA interval. This probability is the conditional initiating event probability (P_i) at the *i*'th seismic interval. The frequency of a IE, *F(IE)*, can be obtained by

$$F(IE) = \sum_{i=1}^{m} F_i \times P_i \quad (5)$$

where F_i is the seismic occurrence frequency at the *i*'th seismic interval and *m* is the total number of intervals.

3.5. Evaluating Seismic CDF

The total seismic CDF can be obtained by

$$CDF = \sum_{all} F(IE_k) \times CCDP_k \quad (6)$$

where $CCDP_k$ is the seismic conditional core damage probability of the *k*'th initiating event. $CCDP_k$ is one of the input conditions for this method.

4. Application to Example PSA model

In order to assess applicability of the proposed method to real models, an example SPSA model is selected as follows:

- Hazard input: mean curve in Fig. 1.
- # of screened-in SSCs: 5 (Table 1)
- Seismic pre-ET: Fig. 3
- # of headings in ET: 4 (Table 2)
- basic events in the logics: CHKVL, OP-HR
- Seismic CDF: 8.41E-7/years (Table 3)

Table 1. Examples of SSC Fragility Results

	Component	A_m	β_R	β_U
1	Off-Site Power	0.3	0.3	0.45
2	Emergency Diesel Generator	1.4	0.33	0.36
3	4.16kV SWGR	1.33	0.21	0.35
4	Instrumentation Tube	1.5	0.3	0.3
5	Safety Injection Tank	1.29	0.42	0.36

Table 2. Examples of Headings in Pre-ET

	Heading	Logic of Heading
1	SBO	SDGSF + (SSWRC * OP-HR)
2	SBLOCA	SICPB
3	LBLOCA	SITSF * CHKVL
4	LOOP	LOOP

Table 3. Seismic CDF (written in the report)

SIE	*F(IE)*	CDF(IE)
S-SBO	5.76E-07	5.76E-07
S-SBLOCA	1.98E-07	2.05E-11
S-LBLOCA	1.20E-10	1.20E-10
S-LOOP	6.42E-05	2.30E-07
S-GTRN	5.10E-04	3.55E-08
Seismic CDF		8.41E-07

The headings in Table 2 are independent of each other. (This pre-ET is an independent ET.) Because the Boolean logics of the headings and paths are very simple, we can calculate the heading probabilities and the SIE probabilities for all seismic intervals in the covered PGA range without the quantification error.

Table 4 is the occurrence frequencies and the CDFs for SIEs covered the seismic range 1 between 0.1g and 1g in PGA calculated by this proposed method.

Table 4. Results for Range 1 (0.1 ~ 1 g)

SIE	*F(IE)*	CDF(IE)
S-SBO	5.81E-07	5.81E-07
S-SBLOCA	2.21E-07	2.29E-11
S-LBLOCA	1.31E-10	1.31E-10
S-LOOP	6.22E-05	2.23E-07
S-GTRN	3.01E-04	2.09E-08
Seismic CDF		8.25E-07

Table 5 is the CDFs calculated over the seismic range 2 between 0.1g and 2g in PGA.

Table 5. Results for Range 2 (0.1 ~ 2 g)

SIE	*F(IE)*	CDF(IE)
S-SBO	9.20E-07	9.20E-07
S-SBLOCA	3.73E-07	3.87E-11
S-LBLOCA	1.50E-10	1.50E-10
S-LOOP	6.25E-05	2.24E-07
S-GTRN	3.01E-04	2.09E-08
Seismic CDF		1.16E-06

Table 6 is the CDFs calculated over the seismic range 3 between 0.1g and 5g in PGA.

Table 6. Results for Range 3 (0.1 ~ 5 g)

SIE	*F(IE)*	CDF(IE)
S-SBO	9.36E-07	9.36E-07
S-SBLOCA	3.76E-07	3.89E-11
S-LBLOCA	1.50E-10	1.50E-10
S-LOOP	6.25E-05	2.24E-07
S-GTRN	3.01E-04	2.09E-08
Seismic CDF		1.18E-06

5. Conclusions

In this study, a risk quantification method is developed for reviewers of SPSAs. This method can provide an exact point estimate of seismic CDF without conventional SPSA tools (SIESMIC, EQESRA, PRASSE, etc.). In order to evaluate seismic risks accurately, the following factors have to be considered.

- PGA range covered by quantification
- PGA interval size
- Exact manipulation of Boolean logics for pre-ET

REFERENCES

[1] Procedural and Submittal Guidance for the Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities, NUREG-1407, NRC, 1991.
[2] PRA Procedures Guide, NUREG/CR-2300, NRC, 1991.
[3] Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications, ASME/ANS RA-Sa-2009, ASME/ANS, 2009.
[4] Seismic Probabilistic Risk Assessment Implementation Guide, EPRI-3002000709, EPRI, 2013.
[5] Development and Validation of the Seismic Probabilistic Risk Assessment Software PRASSE, KAERI/TR-4649/2012, KAERI, 2012.
[6] Risk Assessment of Operational Events Handbook (RASP handbook), Volume 2 – External Events Rev.1.01, USNRC, 2008.
[7] Fault Tree Handbook, NUREG-0492, USNRC, 1981.