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Using Plant-Level Fragility Curves for Seismic Safety Assessment

Jongsoo Choi*, Dongwon Lee
Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon 34142
**Corresponding author: k209cjs@kins.re.kr*

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. The Seismic Probabilistic Safety Assessment (SPSA) method has been widely used to assess the seismic safety of a NPP. The SPSAs of Korean NPPs have been performed since the early 1990's.

This paper proposes an approach to use the plant-level seismic fragility curves of NPP without seismic hazard information. The curves are obtained by efficient Monte Carlo simulations.

2. Seismic Safety Assessment

There are two primary methodologies used to assess the seismic safety of a NPP. They are the SPSA and the Seismic Margin Assessment (SMA). Fundamentally, both methodologies use the same input data from past reports on the seismic activity in the vicinity of the facility, state of soil, materials used in construction of facility, and so on.

The scope of safety evaluations is important for controlling the amount of information that must be collected and analyzed. A holistic assessment of the seismic safety of a NPP is unreasonably labor-intensive, so engineers instead choose selected structures, systems, and components (SSC) to evaluate. Both methodologies require peer review from engineers and administrators knowledgeable of the capacities evaluated and additional documentation for record-keeping and for reference in future safety evaluations.

2.1. Seismic Probabilistic Risk Assessment

SPSAs attempt to fully model the probability of success through event trees and fault trees. Particular concern for SPSA is the fragility function, which is the conditional probability that a component would fail for a specified ground motion or response-parameter value as a function of that value. The probabilities are both in the known and controlled uncertainties of various SSCs but also in our understanding of what we do not know our uncertainties in our models. Once fragility functions are defined, then the risk is fully quantified. SPSAs attempt to return a full probability distribution for the successful and safe shutdown of a power plant given a set of seismic conditions and actions in response to them.

2.2. Seismic Margin Assessment (SMA)

SMAs focus on evaluating High Confidence Low Probability Failure (HCLPF) capacities. These are defined as the level of earthquake ground motion at which there is a 95% confidence of an at most 5% probability of failure. Each SSC receives an HCLPF capacity. However, because each SSC factors into the overall operational safety of the plant in different ways (success or failure of a given component could lead to different probabilities of success or failure depending on the type of seismic event considered), the HCLPF capacities must also be considered in the context of 'success paths', which are the series of actions that result in the safe shutdown of the plant. Thus, the HCLPF capacity of a success path is the SSC with the lowest HCLPF capacity (a success path is judged by its weakest link). However, because multiple success paths exist for safely shutting down a plant, the overall HCLPF capacity of the power plant is defined by the success path with the highest HCLPF value: the ability of a plant to avoid failures is dependent on the most successful path towards shutdown.

3. Component-Level Fragility Curves

The seismic fragility of a structure or equipment is defined as the conditional failure probability at a given level of ground motion. The objective of a fragility evaluation is to evaluate the capacity of critical failure modes of SSCs, for both structural failure and equipment functional failure, relative to a ground acceleration parameter. The uncertainty of the component fragility is represented by a family of fragility curves.

At each Peak Ground Acceleration (PGA) value, the fragility $F(a)$ can be represented by a subjective probability (confidence) that is 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. 1 as an example.

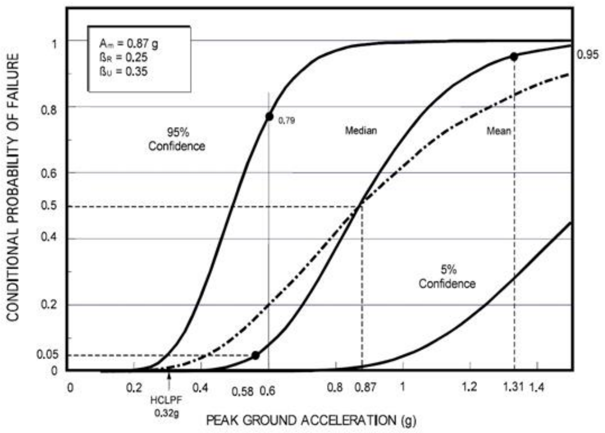

Fig. 1. Example of component-level fragility curves

The 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%.

4. Plant-Level Fragility Curves

The U.S. nuclear industry estimated the seismic margins based on the U.S. Nuclear Regulatory Commission (NRC) staff's guidance for performing the individual plant examination of external events program [1], which permitted the use of either SPSAs or SMAs. Although the SMAs could not produce the same risk insights as the SPSAs, a well-executed SMA based on either the Electric Power Research Institute (EPRI) method or the NRC fault-tree approach can demonstrate the robustness and considerable safety margin of the seismic design for an operating NPP, expressed in terms of a plant-level HCLPF capacity.

The plant-level HCLPF capacity should be determined based on the sequence-level HCLPF values for all sequences as identified in the design-specific plant system and accident sequence analysis. The Min-Max method is acceptable for computing sequence-level HCLPF values. The plant-level HCLPF is therefore the lower bound of the sequence-level HCLPF values. The design-specific plant-level HCLPF value should be demonstrated to be equal to or greater than 1.67 times the certified seismic design response spectra (CSDRS) PGA. [2]

In the Oyster Creek study (conducted in the late 1970s) the plant-level fragility curve was formulated from fragilities of individual SSCs using event tree/fault tree logic models of the plant systems. The fragility was defined using a lognormal model and was described in terms of a median ground acceleration capacity, logarithmic standard deviations of randomness in the capacity, and uncertainty in the median capacity. [3]

In this paper, the plant-level fragility is defined as the conditional core damage probability (CCDP) at a given PGA similarly to the conditional failure probability in a component-level fragility.

In order to evaluate CCDPs at a group of selected PGAs, we can use the following main elements from SPSA or PSA-based SMA results.

1) component-level fragility evaluation
2) plant response modeling
3) Monte Carlo simulation for CCDP quantification

4.1. Component-Level Fragility Evaluation

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.

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.

4.2. Plant Response Modeling

Plant response modeling 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) are developed to identify seismic-induced initiating events. Fig. 2 is an example pre-ET.

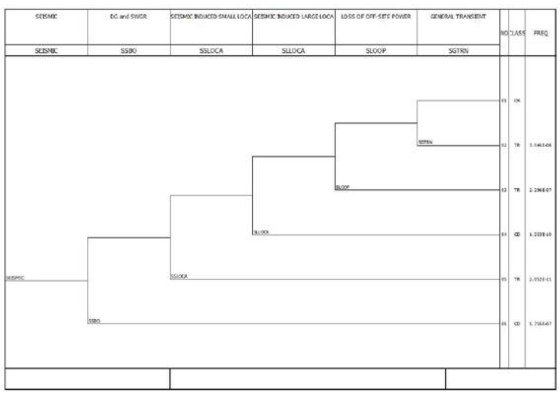

Fig. 2. Example of seismic pre-ET

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.

4.3. Monte Carlo Simulation for CCDP Quantification

At each PGA value, mean failure probabilities for all components appearing in core damage sequences are calculated from their fragility curves. Using the Boolean expression for the logical combination of seismic and non-seismic failures, the point estimates of seismic-induced CCDPs at a given PGA are computed.

The plant-level fragility curves can be obtained from the Monte Carlo simulations of CCDPs for all selected PGA values. By performing several such trials at the same PGA, a probability distribution on the CCDP is obtained. The process is repeated by marching along the PGA axis and storing selected percentiles of the distribution at each acceleration. The Monte Carlo simulations of this paper are based on the Latin Hypercube Sampling (LHS) technique.

If we need the CDF value, the seismic CDF (F_{CD}) can be calculated by convolution of the plant-level fragility curves and the known seismic hazard curve:

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

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

5. Application to NPP Problem

In order to assess applicability of the proposed method, an example SPSA result is selected:

- Seismic pre-ET: Fig. 2
- # of seismic events: 5 (Table 1)
- # of non-seismic events in pre-ET: 2
  - CHKVL (mean = 0.000119, EF = 1.7)
  - OP-HR (mean = 0.01, EF = 5)
- # of headings in ET: 4 (Table 2)
- Seismic CDF: 8.41E-7/years (Table 3)

Table 1. SSC Fragility Results

Component (event)	A_m	β_R	β_U
Off-Site Power (LOOP)	0.3	0.3	0.45
Emergency Diesel Generator (SDGSF)	1.4	0.33	0.36
4.16kV SWGR (SSWRC)	1.33	0.21	0.35
Instrumentation Tube (SICPB)	1.5	0.3	0.3
Safety Injection Tank (SITSF)	1.29	0.42	0.36

The headings in Table 2 are independent of each other. 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 2. Headings in Pre-ET (Fig. 2)

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

Table 3. Seismic CDF (written in the PSA report)

IE	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

Fig. 3 is the simulated plant-level fragility curves of Example plant which is covered the seismic range between 0g and 5g in PGA. This fragility curves are obtained from the Monte Carlo simulations based the LHS technique with sample size 1000.

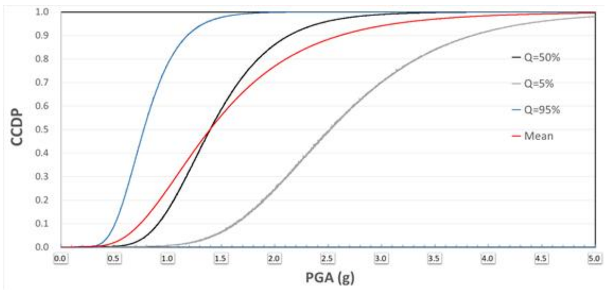

Fig. 3. Plant-level fragility curves for Example SPSA calculated by the proposed Monte Carlo simulation

Table 4 shows the simulation results of mean and 95, 50, 5 percentiles of some selected PGA values in this fragility curves.

Table 4. CCDPs of Fig. 3 (at some PGAs)

PGA	mean	95%	50%	5%
0.4245g	0.00990295	0.03713895	0.00357354	0.00065373
0.4246g	0.01005021	0.03793724	0.00356252	0.00070893
0.4465g	0.01239683	0.05054205	0.00360238	0.00092996
0.4475g	0.01253000	0.04917179	0.00361509	0.00109849
1.0005g	0.24989164	0.78111178	0.15789163	0.00705726
1.3935g	0.50012916	0.96270609	0.49821675	0.04287257
1.3945g	0.50073344	0.96287698	0.49826175	0.04373023

From Table 4 and the definition of HCLPF, the plant-level HCLPF value and the median capacity (A_m) of Example plant are estimated at 0.4465g and 1.3935g, respectively.

5. Conclusions

This study developed a method to formulate the plant-level fragility curves for the seismic safety assessment of NPPs. This proposed Monte Carlo method provides accurate fragility curves without seismic hazard information. The plant-level fragility curves would be one of good information on the seismic capacity of a NPP against core damage.

REFERENCES

[1] Procedural and Submittal Guidance for the Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities, NUREG-1407, NRC, 1991.
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[3] Seismic Probabilistic Risk Assessment Implementation Guide, EPRI-3002000709, EPRI, 2013.