Determination of minimum seismic performance targets for major NPP equipment

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1. Introduction

Due to the Fukushima accident in 2011 and the Gyeongju and Pohang earthquakes in 2016 and 2017 in Korea, concerns about the safety of nuclear power plants and the level of safety requirements are increasing. In addition, as the scale of earthquakes is increasing around the world, seismic standards for securing the safety of operating plants against earthquakes exceeding the design earthquake are being strengthened.

Currently, operating plants in Korea are designed to withstand a safety shutdown earthquake (SSE) of 0.2g or 0.3g. However, in the event of an earthquake exceeding the design, this requirement cannot be guaranteed, so it can be said that the plant safety against the earthquake is low.

Therefore, we intend to set the minimum seismic performance target required to improve the safety of the nuclear power plant by performing sensitivity analysis on the seismic fragility data considered in the seismic probabilistic safety assessment (PSA) for major equipment installed in plants.

2. Methods and Results

2.1 Seismic Fragility Analysis

Generally, seismic PSA performs seismic hazard analysis to determine the frequency of occurrence of earthquake for each peak ground acceleration (PGA) and seismic fragility analysis to evaluate the probability to failure of structures and equipment in nuclear power plant. Then these data are combined with the PSA model to perform the quantification.

In seismic fragility analysis, failure modes for each structure and equipment are defined and the seismic fragility curves for each failure mode are calculated.

As a result, failure probabilities of structures and equipment at a specific PGA *a* are evaluated the average seismic fragility curve as follows [1].

$$\mathrm{f(a)} = \Phi\left[\frac{\ln(a/A_m)}{\sqrt{\beta_R^2+\beta_U^2}}\right] \tag{1}$$

where, A_m is median ground acceleration, and β_R and β_U are logarithmic standard deviations for uncertainty and randomness, respectively.

In addition, HCLPF (High Confidence of Low Probability of Failure) is considered as an index indicating the seismic performance of structures and equipment.

HCLPF is defined as the ground acceleration with a damage probability of 5% in the 95% confidence curve and can be calculated as follows.

$$\mathrm{HCLPF} = A_m \exp\{-1.65(\beta_R + \beta_U)\} \tag{2}$$

2.2 Process to determine minimum seismic performance targets

Among the data considered in seismic PSA, occurrence frequency of earthquake represents the magnitude of possible earthquakes, so it is possible to compensate for the uncertainty level, but it is impossible to improve it through design improvement. Therefore, to improve the plant safety, it is necessary to reduce the failure probability of structures and equipment through the improvement of seismic reinforcement and seismic isolation design.

However, if excessive design improvements are made, the plant safety can be greatly improved, but a huge economic cost can be required. Therefore, we intend to determine the minimum seismic performance target for structures and equipment according to the procedure shown in Fig. 1.

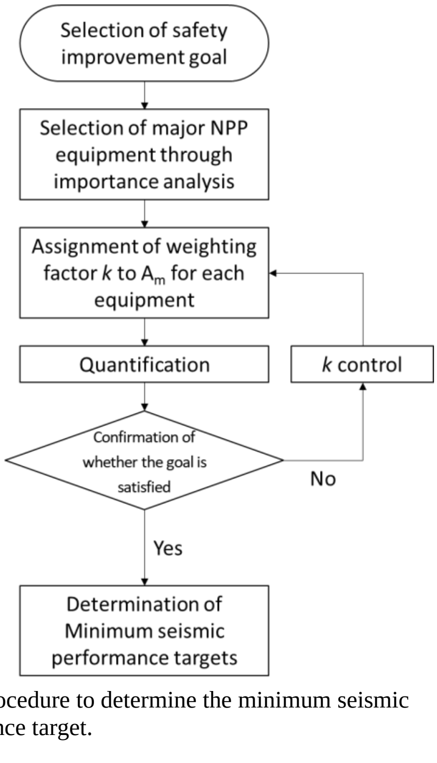

Fig. 1. Procedure to determine the minimum seismic performance target.

Table II: OPR1000 Seismic fragility data

Equipment	Failure mode	A_m (g)	β_R	β_U	HCLPF (g)	Related IE*
Off-site Power	Functional	0.3	0.3	0.4	0.1	SLOOP
Emergency diesel generator	Structural	1.0	0.3	0.2	0.4	-
4.16kV switchgear	Functional	0.8	0.2	0.3	0.4	SLEP
	Structural	0.9	0.3	0.3	0.3	SLEP
480V load center	Functional	0.8	0.2	0.3	0.4	SLEP
	Structural	1.1	0.3	0.3	0.4	SLEP
Battery charger	Structural	1.3	0.3	0.3	0.5	SLEP
125V DC control center	Structural	1.1	0.3	0.3	0.4	SLEP
Inverter	Structural	1.5	0.3	0.3	0.6	SLEP
Instrumentation tube	Structural	1.5	0.3	0.3	0.6	SSLOCA
Safety injection tank	Structural	1.1	0.3	0.3	0.4	SLLOCA
Plant control system cabinet	Structural	0.8	0.2	0.3	0.4	SLCS

*IE: Initiating event, SLOOP: Seismic-induced loss of off-site power, SLEP: Seismic-induced loss of essential power, SSLOCA: Seismic-induced small loss of coolant accident, SLLOCA: Seismic-induced large loss of coolant accident, SLCS: Seismic-induced loss of control system

First, a goal of safety improvement is selected, usually a reduction goal in terms of core damage frequency (CDF) or large early release frequency (LERF).

After selecting the goal, the major equipment that greatly affect the risk are selected through an importance analysis.

Importance analysis is performed to understand the impact on risk of each failure event considered in the PSA model, and as a measure for this, Fussell-Vesely importance (FV), which indicates the weight of a specific event in the overall risk, is used as follows [2].

$$FV = \frac{R(x_i)}{R(base)} \qquad (3)$$

where, R(base) is the overall risk and R(x_i) represents the risk of the accident sequence including x_i.

In addition, seismic PSA defines seismic acceleration groups and seismic induced risks for each group are estimated. Therefore, as shown in the following equation, the final major equipment is selected by combining the results of the importance analysis performed in each acceleration group.

$$FV_t = \frac{\sum FV_g(x_i) \times R_g(base)}{\sum R_g(base)} \qquad (4)$$

where, $FV_g(x_i)$ means FV value for x_i in seismic acceleration group g, and R_g(base) is the overall risk in group g.

When the major equipment is selected, a weighting factor k is assigned to A_m related to the design feature among the parameter of the seismic fragility curve, and the failure probabilities of the equipment are calculated by reflecting this.

Quantification is performed using the PSA model with those probability, and it is checked whether the selected safety improvement goal is satisfied. When the minimum weighting factor that satisfies the goal is determined by repeating this in such a way that k is corrected by reflecting the degree of difference from the goal, the minimum seismic performance target is determined based on this.

2.3 Case study

The case study was performed for OPR1000, a representative operating nuclear power plant in Korea, and the core damage frequency due to the earthquake was calculated. At this time, a total of 9 groups were defined for the PGA group at 0.1g intervals from 0.1g to 1.0g. The occurrence frequencies of earthquake for each group were summarized in Table I.

Table I: Seismic event frequencies for each PGA group

PGA group (g)	Frequency(/yr)
0.1 ~ 0.2	3.20E-04
0.2 ~ 0.3	4.79E-05
0.3 ~ 0.4	1.38E-05
0.4 ~ 0.5	5.37E-06
0.5 ~ 0.6	2.56E-06
0.6 ~ 0.7	1.34E-06
0.7 ~ 0.8	8.11E-07
0.8 ~ 0.9	5.05E-07
0.9 ~ 1.0	3.65E-07

And the seismic fragility data and related seismic-induced initiating events for 11 types of equipment installed in the reference plant were summarized in Table II.

In the case of functional failure among the above seismic fragility data, recovery failure by the operator was additionally considered, and the recovery action was excluded from the PGA group after 0.4g.

For quantification, an FTeMC (Fault Tree top event probability Evaluation using Monte Carlo simulation) code [3] based on monte carlo sampling was used, and

1.00E+08 samples were considered as the number of samples.

As a result, the total core damage frequency was calculated to be 8.18E-06/yr, and the 4.16kV switchgear and 480V load center were selected as the main equipment according to the importance analysis. The final importance analysis results were summarized in Table III.

Table III: The FV results of OPR1000

Equipment	Failure mode	FV
4.16kV switchgear	Functional	0.3
	Structural	0.3
480V load center	Functional	0.3
	Structural	0.2
Plant control system cabinet	Structural	0.2
125V DC control center	Structural	0.1
Off-site Power	Functional	0.0
Inverter	Structural	0.0
Battery charger	Structural	0.0
Emergency diesel generator	Structural	0.0
Instrumentation tube	Structural	0.0
Safety injection tank	Structural	0.0

The weighting factor k for A_m of the selected major equipment could be assigned to each equipment, but the same weighting factor was assigned to all equipment for the simplification.

As a result of quantification by applying k=1.5 primarily, it was confirmed that the core damage frequency was reduced by 34.5% compared to the base model. Therefore, to determine the minimum weighting factor, k was considered as shown in Table IV, and according to the result, 1.36, which reduced the core damage frequency by 30.1%, was determined as the minimum weighting factor.

Table IV: The results of quantification according to k

Try No.	CDF(/yr)	Δ
Base	8.18E-06	-
1st Try (k=1.5)	5.36E-06	-34.5%
2nd Try (k=1.4)	5.59E-06	-31.6%
3rd Try (k=1.3)	5.94E-06	-27.4%
4th Try (k=1.35)	5.75E-06	-29.7%
5th Try (k=1.36)	5.72E-06	-30.1%

Reflecting this, the minimum seismic performance target values shown in Table V were presented.

Table V: The proposed minimum seismic performance targets of major equipment

Equipment	Failure mode	HCLPF (g)
4.16kV switchgear	Functional	0.5
	Structural	0.4
480V load center	Functional	0.5
	Structural	0.5

3. Conclusions

In this study, the minimum seismic performance target required to improve the safety of the nuclear power plant was determined by assigning a weighting factor k to the A_m among the seismic fragility data considered in the seismic PSA for major equipment installed in a plant.

As the case study, the core damage frequency for the OPR1000 was calculated. As a result, it was confirmed that if the seismic performance was improved by at least 36%, the core damage frequency could be reduced by 30%.

If the minimum seismic performance target is set through the method presented in this study, it is expected that unnecessary design improvements required to improve the plant safety can be reduced, and the economic cost can be also reduced.

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