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Review of the importance analysis method in seismic probabilistic safety assessment

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1. Introduction

In general, probabilistic safety assessment (PSA) evaluates the plant safety by considering failure events of systems or components in a nuclear power plant due to the internal events such as loss of offsite power (LOOP) accident or external events such as earthquake. And PSA uses core damage frequency as a risk measure. An importance analysis is performed to determine the impact of these events on the plant safety.

In this study, an importance analysis method performed in the PSA for internal events (internal PSA)is reviewed to confirm its applicability in the PSA for seismic events (seismic PSA).

2. Methods and Results

2.1 Importance analysis in the internal PSA

Internal PSA is performed on accidents that cause reactor shutdown due to failure of systems or equipment in a plant. The risk is evaluated by considering random failures of systems or components and recovery failure due to the operator in relation to mitigation measures after an accident.

To calculate the core damage frequency by internal events, the minimal cut-set (MCS) for the accident sequence that causes the core damage is obtained. This MCS can be expressed as follows:

$$R = IE * \{S(x_i \in MCS) + S(x_i \notin MCS)\} \quad (1)$$

where $S(x_i \in MCS)$ is union of all MCSs including x_i.

Since the failure event considered in the internal PSA is a random event, the failure probability is low. Therefore, when calculating the core damage frequency using the MCS, the quantification methods such as Rare Event Approximation (REA) or Minimal Cut-set Upper Bound (MCUB) are used. The core damage frequency can be calculated as shown in Table I according to each method.

Table I: The quantification method to evaluate the core damage frequency in the internal PSA

Method	Frequency
REA	$F(R) = F(IE) * \{\sum_{x_i \in MCS} P(S) + \sum_{x_i \notin MCS} P(S)$ (2)
MCUB	$F(R) = F(IE) * \{1 - \prod_{x_i \in MCS}(1 - P(S)) * \prod_{x_i \notin MCS}(1 - P(S))\}$ (3)

An importance analysis is performed to determine the impact on the core damage frequency for each failure event considered in the PSA model. The importance measures considered in this analysis include Fuss el-Vesely (FV), Risk Achievement Worth (RAW), Risk Reduction Worth (RRW). Each measure can be presented as shown in Table II using the REA method [1].

Table II: Importance analysis method in the internal PSA

Importance measure	Calculation
FV	$\mathrm{FV}(x_i) = \frac{F_i}{F_0} = \frac{F(R) - F(x_i \notin MCS)}{F(R)}$ (4)
RAW	$\mathrm{RAW}(x_i) = \frac{F_i^+}{F_0}, \quad (F_i^+ \leq F(IE)) = \frac{F(x_i \in MCS, x_i \to 1) + F(x_i \notin MCS)}{F(R)}$ (5)
RRW	$\mathrm{RRW}(x_i) = \frac{F_0}{F_i^-} = \frac{F(R)}{F(x_i \notin MCS)}$ (6)

*$F_i = F(x_i \in MCS) = F(IE) * \sum_{x_i \in MCS} P(S) = P(x_i) * F(x_i \in MCS, x_i \to 1)$, $F_i^- = F(R(x_i \to 0))$, $F_i^+ = F(R(x_i \to 1))$

where $F(x_i \in MCS, x_i \to 1)$ means the core damage frequency under the condition that x_i fails for all MCSs including x_i.

As an example, assuming a system consisting of three components as shown in Fig. 1, failure probability of this system can be calculated according to the REA method as follows:

$$\mathrm{P(S)=P(A+BC)=P(A)+P(B)P(C)} \quad (7)$$

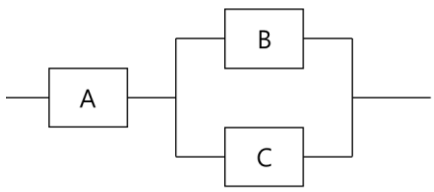

Fig. 1. Example of a system consisting of A, B, and C.

The importance measures for each component are calculated as shown in Table III.

Table III: Importance analysis results for A, B, and C (method in the internal PSA)

Component	Prob.	FV	RAW	RRW
A	0.1	0.49	4.88	1.95
B	0.3	0.51	2.20	2.05
C	0.35	0.51	1.95	2.05

2.2 Importance analysis in the seismic PSA

Seismic PSA analyzes accidents that cause core damage due to damage to structures or equipment in a plant when an earthquake occurs. In the seismic PSA model, not only the random failure events considered in the internal PSA, but also the seismic induced failure events of structures or equipment are included.

Probabilities for these seismic induced failure events are calculated from seismic fragility curves obtained through seismic fragility analysis. Since the seismic-induced failure probability is very high compared to the random failure events, the core damage frequency calculated using REA or MCUB methods considered in the internal PSA may be overestimated than the exact value.

Therefore, in seismic PSA, it is recommended to evaluate the core damage frequency by converting MCS into a binary decision diagram (BDD) form. When MCS presented in Equation 1 is converted to BDD form using Shannon's decomposition, it can be expressed as Equation 8 [2].

$$\begin{aligned} R &= IE * \{S(x_i \in MCS) + S(x_i \notin MCS)\} \\ &= IE * ite\big(x_i, I(x_i \in MCS, x_i \to 1), I(x_i \notin MCS)\big) \\ &= IE * \{x_i I(x_i \in MCS, x_i \to 1) + \overline{x_i} I(x_i \notin MCS)\} \end{aligned} \quad (8)$$

where $ite(x, F, G) = xF + \overline{x}G$, and $\mathrm{I}(x_i \in MCS, x_i \to 1)$ is a function that converts all MCSs including x_i to BDD form under the condition that x_i is failed.

The core damage frequency for Equation 8 can be calculated as follows:

$$\begin{aligned} F(R) = F(IE) * \{&P(x_i) \textstyle\sum_{x_i \in MCS, x_i \to 1} P(I) \\ &+ (1 - P(x_i)) \textstyle\sum_{x_i \notin MCS} P(I)\} \end{aligned} \quad (9)$$

When the importance measures presented in Table II is considered for seismic PSA, it can be expressed as shown in Table IV. In addition, Criticality Importance (CI) measure, which is considered as an importance measure in the ACUBE code (quantification engine for seismic PSA) [3], can also be calculated as follows.

Table IV: Importance analysis method in the seismic PSA

Importance measure	Calculation
FV	$\mathrm{FV}(x_i) = \frac{F_i}{F_0} = \frac{F(R) - (1 - P(x_i))F(x_i \notin MCS)}{F(R)}$ (10)
RAW	$\mathrm{RAW}(x_i) = \frac{F_i^+}{F_0} = \frac{F(x_i \in MCS, x_i \to 1)}{F(R)}$ (11)
RRW	$\mathrm{RRW}(x_i) = \frac{F_0}{F_i^-} = \frac{F(R)}{F(x_i \notin MCS)}$ (12)
CI	$\mathrm{CI}(x_i) = (F_i^+ - F_i^-)\frac{P(x_i)}{F_0} = \frac{F_i - P(x_i)F(x_i \notin MCS)}{F(R)}$ (13)

$*F_i = F(x_i \in MCS) = F(IE) * \sum_{x_i \in MCS} P(I) = P(x_i) * F(x_i \in MCS, x_i \to 1)$, $F_i^- = F(R(x_i \to 0))$, $F_i^+ = F(R(x_i \to 1))$

When MCS for the system consisting of the three components presented in Fig. 1 is converted into BDD form, it can be expressed as in Equation 14.

$$\begin{aligned} S &= A + BC \\ &= ite(A, 1, ite(B, ite(C, 1, 0), 0)) = A + \overline{A}BC \end{aligned} \quad (14)$$

Applying Table IV, the importance measures for each component are calculated as follows.

Table V: Importance analysis results for A, B, and C (method in the seismic PSA)

Component	Prob.	FV	RAW	RRW	CI
A	0.1	0.51	5.14	1.85	0.46
B	0.3	0.64	2.13	1.95	0.49
C	0.35	0.67	1.90	1.95	0.49

Compared to Table III, the values for RAW and RRW are slightly different, but they are calculated in the same rank. However, in case of FV, FV(B) and FV(C) are calculated identically in Table III, but FV(C) is calculated larger than FV(B) in Table V.

2.3 Case study

For a case study, an importance analysis was performed on the accident sequences in the event of a 0.5g level earthquake using the example model presented in Fig. 2 [4].

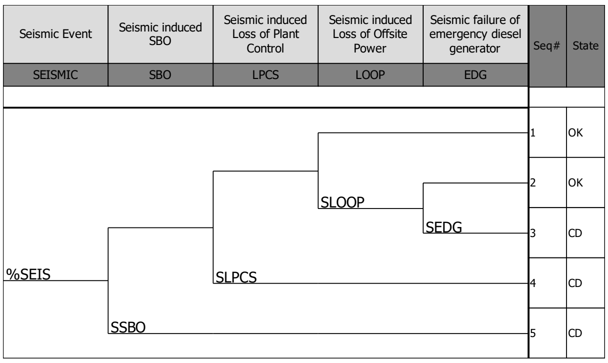

Fig. 2. The example event tree for seismic PSA [4].

The logic for each event tree heading is as follows:

SSBO=SEIS-SWGR+SEIS-LC
SLPCS=SEIS-PCS+SEIS-DC
SLOOP=SEIS-LOOP
SEDG=SEIS-EDG-ALL

Table VII: Importance analysis results for the example model

Event	Prob.	F_i	F_i^+	F_i^-	FV	RAW	RRW	CI
SEIS-LOOP	8.28E-01	2.69E-01	3.25E-01	3.00E-01	8.39E-01	1.01	1.07	6.42E-02
SEIS-SWGR	1.13E-01	1.13E-01	1.0	2.34E-01	3.53E-01	3.12	1.37	2.70E-01
SEIS-PCS	1.12E-01	1.12E-01	1.0	2.35E-01	3.49E-01	3.12	1.36	2.67E-01
SEIS-LC	8.78E-02	8.78E-02	1.0	2.55E-01	2.74E-01	3.12	1.26	2.04E-01
SEIS-EDG-ALL	3.55E-02	3.12E-02	8.80E-01	3.00E-01	9.74E-02	2.74	1.07	6.42E-02
SEIS-DC	2.57E-02	2.57E-02	1.0	3.03E-01	8.02E-02	3.12	1.06	5.59E-02

Since the importance analysis was performed only for a 0.5g level earthquake and therefore the frequency of occurrence of earthquake did not affect the analysis result, the frequency was not considered in this study. The seismic-induced failure events and failure probabilities considered in example model were summarized in Table VI.

Table VI: The seismic-induced failure events and failure probabilities

Event	Description	Prob.
SEIS-SLOOP	Seismic induced loss of offsite power	8.28E-01
SEIS-PCS	Seismic failure of plant control systems	1.12E-01
SEIS-DC	Seismic failure of 125V DC bus	2.57E-02
SEIS-LC	Seismic failure of 480V load center	8.78E-02
SEIS-SWGR	Seismic failure of 4.16kV switchgear	1.13E-01
SEIS-EDG-ALL	Seismic failure of emergency diesel generator (EDG)	3.55E-02

As a result, it was calculated that core damage occurred with a probability of 3.21E-01 when a 0.5g earthquake occurred, and the results of an importance analysis for each failure event were summarized in Table VII.

In terms of FV, SEIS-LOOP was the most important, followed by SEIS-SWGR and SEIS-PCS. In terms of RAW, it was difficult to determine the importance because all values were the same except for SEIS-LOOP and SEIS-EDG-ALL. For RRW and CI, SEIS-SWGR was estimated the highest, followed by SEIS-PCS and SEIS-LC. SEIS-LOOP, which was highly calculated from FV, was evaluated the lowest.

These results were performed on the example model that random failure events and human failure events were not included, and thus a different trend may have appeared from the actual model. However, in terms of seismic-induced failure events, it is possible to determine which importance measure is appropriate to use for the importance analysis in seismic PSA.

Therefore, in seismic PSA, it can be effective to perform importance analysis using FV, RRW, and CI measures, and it is expected that it will be appropriate to select major equipment using RRW or CI measures to determine the importance in terms of safety improvement.

3. Conclusions

In this study, an importance analysis method performed in the PSA for internal PSA was reviewed to confirm its applicability in the seismic PSA.

In the seismic PSA, the seismic-induced failure probability is very high compared to the random failure events. Therefore, it is recommended to evaluate the core damage frequency by converting MCS into BDD form and the importance analysis should also be calculated by reflecting this form.

And as a case study, an importance analysis was performed on an example model for 0.5g earthquake event. As a result, in seismic PSA, it can be effective to perform importance analysis using FV, RRW, and CI measures, and it is expected that it will be appropriate to select major equipment using RRW or CI measures to determine the importance in terms of safety improvement.

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