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A study of quantification for seismic probabilistic safety assessment

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1. Introduction

Probabilistic safety assessment(PSA) is an integrated and structured approach to evaluate the risk of a nuclear power plant. For several decades, internal events PSA has been carried out and matured to estimate the core damage frequency[1]. However, specialized methods are required in a seismic PSA and one of them is related to quantification[2]. This is because data analysis such as initiating event frequencies and failure probabilities of systems, structures and components(SSCs) is determined by ground motion levels of a seismic event.

In a seismic PSA, high failure probability events may exist with the increase of the ground motion level, which are not rare events[1, 2]. For this reason, quantification methods of internal events PSA such as rare event approximation and delete-term approximation may not be applicable to a seismic PSA. This study identifies quantification methods for a seismic PSA and proposes an improved quantification method.

2. Quantification methods of a seismic PSA

When most of basic events have low failure probability, it may be appropriate to use rare event approximation(REA) and delete-term approximation(DTA) both of which are commonly used in internal events PSA. However, if success branches of an event tree are deleted or REA is applied in a seismic PSA, significantly conservative results may be obtained. Recently, a new method of expanding the success branches (NOT gates) to success events using de Morgan's theorem is introduced as shown below. FTREX(fault tree reliability evaluation expert) which is a PSA quantification engine implements the new method called the negate-down.

$$\overline{A \cup B} = \bar{A} \cap \bar{B} \quad (1)$$
$$\overline{A \cap B} = \bar{A} \cup \bar{B} \quad (2)$$

Additionally, binary decision diagram (BDD) provides more accurate quantification results instead of REA in a seismic PSA. However, due to the computational resource limitation, only a limited number of minimal cut-sets can be converted to BDD. Therefore, the combination of BDD and minimal cutset upper bound (MCUB) is usually used with a software tool such as the Advanced Cutset Upper Bound Estimator (ACUBE).

Kim et al.[3] examined the complicated interactions in Boolean variable manipulation, approximation, and quantification. They also summarized the three conclusions learned from the effects of the negate-down of success branches on the seismic PSA quantification results. The conclusions imply several complicated interactions between the negate-down and the quantification methods may lead to the results that are not intended such as underestimation and overestimation.

3. A proposed quantification method for a seismic PSA

In this study, we propose an improved method by expanding the success branches of an event tree to success events to be mutually exclusive. While NOR logic is expanded by the same way of the existing negate-down method as Eq.(1), NAND logic is expanded by Eq.(3):

$$\overline{A \cap B} = \bar{A} \cup A\bar{B} \quad (3)$$

In the proposed method, failure branches should be also considered along with the success event to make it mutually exclusive as shown Eqs. (4) and (5). If we cannot make the failure branch be mutually exclusive, the conservatism of REA remains.

$$A \cup B = A \cap \bar{A}B \quad (4)$$
$$A \cap B = A \cup B \quad (5)$$

Fig. 1 illustrates fault tree logics for the existing method with delete-term approximation, the negate-down method and the proposed method. The initiating frequency, $\%I$, is given as 0.1, the failure probabilities of basic event, A and B, are given as 0.2, and the probability of C is given as 0.3. Table 1 shows the minimal cut-sets and probability of the onetop model depending on the quantification methods.

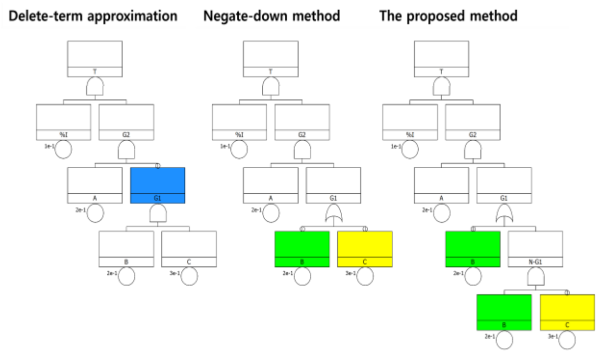

Fig. 1. Fault tree logics for the existing method with delete-term approximation, the negate-down method and the proposed method

Table I: Minimal cut-sets and probability of the onetop model depending on the quantification methods

	Delete-term approximation	Negate-down method	The proposed method
Minimal cut-sets (probability)	$\%I\ A$ (0.02)	$\%I\ A\ \bar{B}$ (0.016)	$\%I\ A\ \bar{B}$ (0.016)
		$\%I\ A\ \bar{C}$ (0.014)	$\%I\ A\ B\ \bar{C}$ (0.0028)
REA	0.02	0.03	0.019
MCUB	0.02	0.0298	-

The existing method does not consider any success events by applying DTA and then produces conservative quantification results. The negate-down method has competing effects which are the effect of lowering the probability of each minimal cut-set by considering a success event and the effect of increasing the probability due to the number of minimal cut-set. In this case, the negate-down produces the most conservative quantification results. However, since minimal cut-sets are mutually exclusive in the proposed method, the accurate result can be obtained with REA.

4. Conclusions

Since the proposed method makes the logic mutually exclusive, it can be calculated by REA which is usually used in internal events PSA. Therefore, the method can obtain more accurate results without BDD-based quantification. We can also avoid the complicated interaction between the negate-down method and quantification methods such as BDD and MCUB.

However, when the complexity of a seismic PSA model increases, the proposed method cannot be applied to an entire plant-size PSA model like the negate-down method. This is because the methods also require more time and efforts to modify the fault tree or computing resources. For this reason, the proposed method is recommended to apply the simple logic with high failure probabilities such as a primary seismic event tree.

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