How to quantify multi-unit risk under seismic event

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EXTENDED ABSTRACT

As multi-unit risk assessment has been identified as a significant issue in the field of probabilistic safety assessment (PSA), a seismic event, one of the significant initiating events for multi-unit risk, is becoming important. Delete-term approximation (DTA) effectively quantifies the risk of internal PSA models because the failure probabilities of basic events are generally small enough to neglect the success gates [1]. However, seismic risk assessment should be evaluated differently from risk assessment of internal events due to the large failure probability of components in seismic bins with high seismic intensity, and several quantification methods have been developed for this purpose. Some methods are based on Monte-Carlo (MC) simulation techniques, while others are based on binary decision diagram (BDD) techniques that solve logic or cut sets related to large failure probabilities. In practice, these various methods are used to evaluate seismic risk in Korea, and the representative method is not yet decided due to the merits and limitations of each method. In addition, various research institutes in Korea are still developing seismic risk quantification methods for more accurate seismic risk quantification. In this study, we introduce the current status of seismic risk quantification methods and present their characteristics, including strengths and limitations. A BDD adopting sum-of-disjoint-product is a powerful logic to obtain an exact solution and two ways exist to apply the BDD techniques to the PSA models; BDD into minimal cut sets (MCSs) and BDD into fault tree (FT) logics.

First, the MCSs obtained are converted into BDD logic by adopting the negate-down approach, which is introduced to prevent negates from being ignored by the DTA approach [2]. It can lead exact solution if a negate-down approach is applied to all success gates and all MCSs are converted into BDD logic, however, it cannot be applied to a PSA model of large systems such as nuclear power plants (NPPs) because of too many success gates and MCSs even in a single-unit PSA (SUPSA) model. Thus, some attempts have been made to partially adopt BDDs in assessing the seismic risk of NPPs. The success gates having seismic events with simple structures such as seismic initiating event tree (SIET) are expanded by using a negate-down approach and the risk-significant MCSs are converted into BDD logic. For example, if gate A is OR gate of failure events x and y, success gate $\bar{A} = \overline{x + y}$ can be expanded as the product of success events $\bar{x}$ and $\bar{y}$ ($\bar{A} = \bar{x} \cdot \bar{y}$). To do this, seismic events should considered in only an SIET, not in seismic secondary ETs (SSETs). This method can derive near-exact risk, but the MCSs converted into BDD logic are difficult to obtain. As another method, the probability subtraction method (PSM) was developed to assess multi-unit seismic risk by dealing with the complemented gates as subtractions of two gates converted into BDD logic [3]. For example, the risk of gate $A \cdot \bar{B}$ is quantified by subtracting the risk of gate $A \cdot B$ from the risk of gate A in a SUPSA model. This method can derive the risk of core damage (CD) sequences but, similarly as above, cannot also provide the MCSs. Deriving MCSs is important in the part of PSA quantification because MCSs give an insight into whether the PSA model is reliably constructed and how risk can be reduced. For a multi-unit PSA (MUPSA) model, the risk of $U1 \cdot \overline{U2}$ is quantified by subtracting the risk of $U1 \cdot U2$ from the risk of $U1$, but success gates in SUPSA model should be treated by partial BDD approach which will be introduced next.

Second, the logics in a PSA model are totally converted into BDD logic and the risk is quantified based on rare event approximation (REA) which means a summation of MCSs. It cannot also be applied to a PSA model of NPPs, and therefore a hybrid method adopting a partial BDD algorithm was developed to obtain both near-exact risk and MCSs [4]. This method partially converts some important failure and success gates having large failure probabilities of basic events into BDD logic and solves the other unimportant success gates by DTA. After converting the important gates into BDD logic, the quantification of total risk is based on REA, which can derive the MCSs. It is powerful logic for a risk quantification of the SUPSA model, however, post-processing of MCSs is required for a risk quantification of the MUPSA model. The risk of $U1 \cdot \overline{U2}$ can be quantified by regarding the MCSs of $U2$ (success unit) as super events according to what shared events are included in each MCS of $U1$ (failure unit) which is obtained from partial BDD.

In addition to BDD conversion, the Monte Carlo (MC) approach, which is based on random sampling of basic events, has been widely used to assess seismic risk [5]. It has the advantages of being applicable to risk assessments of large systems, including MUPSA models, and also of leading to near-exact risk for large-magnitude earthquakes with a sufficient number of samplings. However, the limitations are that the MC approach cannot generate the cut sets, and a lot of samplings are needed for seismic bins with small seismic intensities. Table 1 shows a comparison between the variable methods including the simple descriptions, strengths, and limitations.

TABLE I. Comparison between the quantification methods for a multi-unit seismic risk assessment

Logic	Method	Descriptions	Strengths	Limitations
BDD into MCSs	Negate-down [2]	• Expand success gates to success event to avoid DTA	• Get near-exact solution • Get insights from the MCSs not converted into BDD	• Difficult to get MCSs • Depend on the number of converted MCSs into BDD • Seismic events should be modeled in a SIET
	PSM [3]	• Treat complemented gates as subtractions of two gates converted into BDD	• Get near-exact solution • Get scenario importance for SUPSA models	• Difficult to get MCSs • Depend on the number of converted MCSs into BDD • Success gates in SUPSA models should be treated by partial BDD for a MUPSA model
BDD into FT logic	Partial BDD [4]	• Convert important gates into BDD and treat rest gates by DTA	• Get near-exact solution • Get MCSs	• Depend on the number of converted FT logics into BDD • Require post-processing of MCSs for MUPSA model
Monte Carlo approach	MC [5]	• Perform random sampling of basic events	• Get near-exact solution • Easy to utilize	• Impossible to get MCSs • Require a lot of samplings for small seismic bins

The case study was performed to confirm the applicability of the methods assuming a simplified seismic MUPSA model with two identical units in a large seismic bin (Acc. 1.0g ~ 1.5g). The seismic failures assumed to be fully correlated between two units were considered in both SIET and SSETs. The risk metric is conditional core damage probability (CCDP) not to consider hazard information. MCSs were obtained from AIMS-PSA software [6] and the MC approach was performed by using FTEMC software [7]. Table 2 summarizes the requirements for constructing SUPSA model which needs to be developed for constructing MUPSA model in the first row and those for risk quantification of the MUPSA model in the second row.

TABLE II. Requirements for risk quantification of the MUPSA model

	Negate-down	PSM	Partial BDD	MC
SUPSA model for MUPSA model	-	• Treat success gates by Partial BDD	• Partial BDD	-
MUPSA model	• Expand only success gates in SIET • Convert 1,000 MCSs to BDD logics	• Separate top logic into several top logics for SU and MU • Convert 1,000 MCSs to BDD logics	• Post-processing of MCSs	• 10^8 Sampling

Table 3 shows the results of the case study. Single-unit CCDP and multi-unit CCDP mean CCDP in one unit and two units, respectively, and site CCDP means a summation of both CCDPs. Although the success gates in SIET were only expanded for the negate-down approach, it yields reasonable results compared with other methods, indicating that the success gates in SSETs are negligible in this simplified PSA model. All methods show similar results, however, we can suggest that the MC approach is better to use if quantified risk value is only required because of the simplest way and the partial BDD approach is better to use if MCSs as well as risk value are required.

TABLE III. Case study results

	Negate-down	PSM	Partial BDD	MC
Single-unit CCDP	9.600E-03	9.479E-03	9.626E-03	9.613E-3
Multi-unit CCDP	8.156E-01	8.156E-01	8.156E-01	8.156E-1
Site CCDP	8.252E-01	8.251E-01	8.252E-01	8.252E-1

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