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Multi-unit Seismic Risk Quantification using Partial Binary Decision Diagram

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1. Introduction

Many risk quantification methods have been developed in the field of probabilistic safety assessment (PSA) [1-5]. Delete-term approximation (DTA) effectively quantifies the risk of internal PSA because the failure probabilities of basic events are generally small enough to neglect the success gates. In addition to DTA, rare event approximation (REA) or minimal cut upper bound (MCUB) generally has been utilized for calculating risk of internal event [1]. However, seismic risk quantification requires special methods because the failure probabilities of basic events are large at the large magnitude of earthquake. Neglecting success gates leads to large errors compared to exact risk, and there have been some efforts to deal with it. The binary decision diagram (BDD) can lead to an exact risk regardless of whether the failure probability is large or small, however, it cannot be used to assess the risk of large PSA models, especially multi-unit PSA (MUPSA), due to the complicated logic of BDD. Monte-Carlo approach (MCA) enables you to assess the seismic risk of large PSA model including MUPSA [2], however, the limitation that the cut set cannot be obtained through the MCA remains. In addition to these approaches, the method which treats some important cut sets by using BDD can approximately quantify the risk, however, cannot derive the information of cut set. Recently, partial BDD has been developed to obtain both near-exact risk and cut sets. Partial BDD partially converts some important gates having large failure probabilities of basic events into new ones solved by BDD, and the other non-important success gates are solved by DTA. By using partial BDD, it was shown to calculate a near-exact single-unit risk [4], however, it should be proved that the multi-unit risk is also near-exactly calculated. This study briefly introduces how to quantify multi-unit seismic risk using partial BDD and the results of a case study applying partial BDD to the MUPSA model.

2. Methods

Site core damage frequency (CDF), which means a sum of single-unit CDF (SUCDF) and multi-unit CDF (MUCDF) is represented by Equation (1), assuming a multi-unit site with two units.

Site CDF = 1CDF• /2CDF + 2CDF• /1CDF + 1CDF• 2CDF (1)

here, 1CDF and 2CDF mean CDF of Units 1 and 2, respectively, and '/' means negate.

For internal events, negates have been treated by DTA, while DTA leads to quite over-estimated results for the seismic event. To overcome the limitation, partial BDD should be applied to some negates and the SUCDF of Unit 1, the first term in the right-hand side of Eq. (1), is expressed as follows.

1CDF• /2CDF = 1CDF• /(2CDF_F + 2CDF_R)
= 1CDF• /2CDF_F• /2CDF_R (2)

here, 2CDF_F and 2CDF_R mean the important cut sets for SUCDF of Unit 2 and the rest of cut sets for SUCDF of Unit 2.

PBDD(1CDF• /2CDF)
≈ PBDD(1CDF)• BDD(/2CDF_F)• /2CDF_R
= PBDD(1CDF)• BDD(/2CDF_F)• /2CDF (3)

According to Eq. (3), the important cut sets for SUCDF of Unit 2 are fully converted into BDD logic and the rest of cut sets are treated using DTA.

Finally, Eq. (1) is converted into partial BDD logic as expressed to Eq. (4).

PBDD(Site CDF)
≈ PBDD(1CDF)• BDD(/2CDF_F)• /2CDF
+ PBDD(2CDF)• BDD(/1CDF_F)• /1CDF
+ PBDD(1CDF)• PBDD(2CDF) (4)

To utilize the method, the one-top fault tree (FT) needs to be modified. Multi-unit risk has been quantified by constructing a one-top FT to easily treat a multi-unit site with a lot of units [6]. Figure 1 shows an example of one-top FT of a multi-unit site with two units. It was modified according to Eq. (4) for the seismic multi-unit risk assessment as shown in Figure 2.

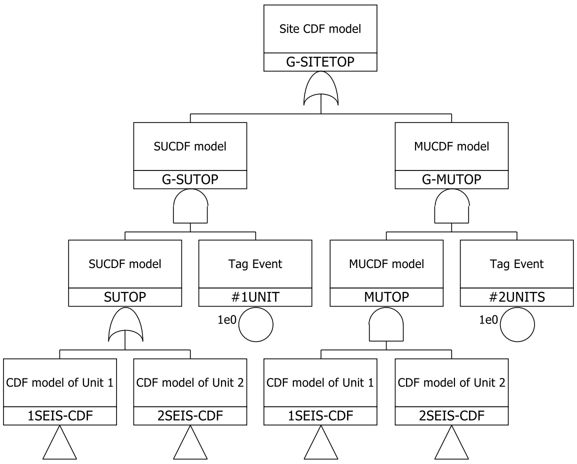

Fig. 1. Example of one-top FT of a multi-unit site having two units (before modification).

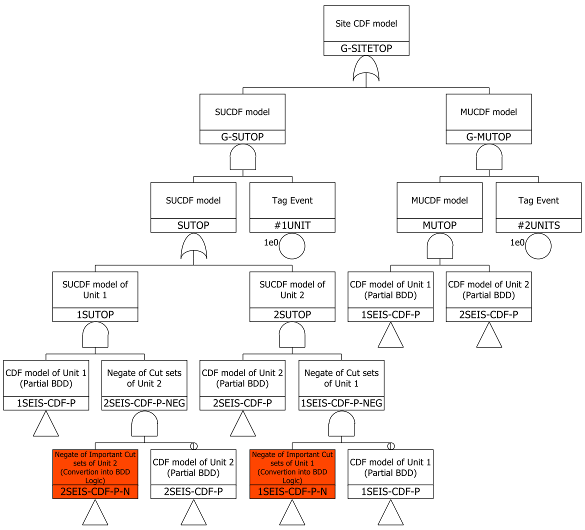

Fig. 2. Example of one-top FT of a multi-unit site having two units (after modification).

3. Case Study

To verify the validation of the method, it was applied to the simplified multi-unit PSA model assuming two identical units with APR-1400 type. Also, a large magnitude of earthquake having a seismic acceleration between 1.0g and 1.5g is assumed in this study. The quantified target is the conditional core damage probability (CCDP) assuming that the frequency of seismic is 1, and the CCDP obtained using partial BDD was compared to that obtained using MCA with 10^8 samplings, which is expected to lead to near-exact risk. Table 1 shows the CCDP obtained using partial BDD and MCA. First, risk-significant core damage sequences in Unit 1 were compared and total single-unit CCDP and multi-unit CCDP were also compared. Diff means the ratio of difference between two results to the CCDP using MCA. It was shown that the partial BDD led to near-exact value. Diff can be reduced when we choose a large number of samplings of MCA and cut sets treated by partial BDD.

Table I: CCDP obtained using partial BDD and MCA

Unit	Sequences	CCDP		
		MCA	Partial BDD	Diff (%)
SU	U1-SEIS-09!	8.22E-02	8.26E-02	0.44
	U1-SEIS-10!	6.25E-02	6.28E-02	0.48
	U1-SLOCA-20!	1.18E-03	1.18E-03	-0.08
	U1-LOFB-3!	5.75E-04	5.76E-04	0.26
	U1-LOFB-2!	5.42E-04	5.45E-04	0.65
	U1-LOCCW-4!	1.07E-04	1.07E-04	0.09
	U1-LOCCW-2!	1.03E-04	1.02E-04	-1.26
	U1-SLOCA-04!	3.92E-05	3.95E-05	0.76
	U1-LOCCS-3!	3.39E-05	3.24E-05	-4.46
	U1-LOCCS-2!	3.25E-05	3.08E-05	-5.17
	U1-LOOP-19!	1.42E-05	1.41E-05	-0.85
	U1-LOOP-17!	8.03E-06	8.17E-06	1.71
	U1-SLOCA-19!	6.69E-06	6.78E-06	1.38
	U1-SEIS-08!	5.15E-06	5.39E-06	4.62
	U1-LOOP-12!	3.09E-06	2.98E-06	-3.46
	U1-LOOP-18!	2.11E-06	2.19E-06	3.65
	U1-MSLB-OC-17!	1.29E-06	1.22E-06	-5.12
	SU Total Seq. (Units 1&2)	2.95E-01	2.96E-01	0.44
MU	MU Total Seq.	6.73E-01	6.73E-01	0.01
Site (SU&MU)		9.68E-01	9.69E-01	0.13

4. Conclusions

The risk quantification method based on partial BDD was developed to evaluate the multi-unit risk under the seismic event. The negate using DTA leads to over-estimated results for seismic events, and therefore it can be overcome by partially converting important cut sets into BDD logic. When quantifying the multi-unit risk having two units, the negation of important cut sets of Unit 2 converted into BDD logic is additionally considered to quantify the single-unit CDF of Unit 1 in the multi-unit PSA model. The top event for multi-unit PSA model was modified to the new one reflecting the BDD logic. Through a case study, it was confirmed that CCDP obtained using partial BDD is almost the same as that obtained using MCA, which concludes partial BDD can lead to near-exact seismic multi-unit risk.

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