The Confirmation for the Assumption of Full Seismic Correlation in multi-unit Seismic Probabilistic Safety Assessment

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1. Introduction

The seismic failures of redundant components are highly correlated since those components are adjacent to each other, mostly identical, and have a similar response to the earthquake[1]. However, the high correlation among the redundant components is assumed to be a full correlation in a practical seismic probabilistic safety assessment (PSA)[2]. When this assumption is applied, all the seismic failures of redundant components in each correlation group are converted into a single failure.

In a practical model, seismic failures of redundant components are under AND gates in seismic single-unit PSA (SUPSA). And, the AND gate probability increases by seismic correlation as Fig. 1 shows.

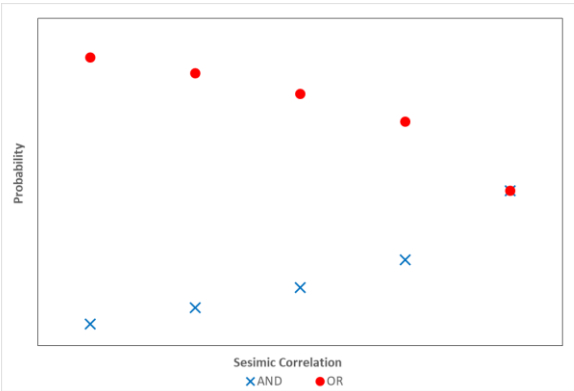


Fig. 1. Gate probability by seismic correlation

Accordingly, the assumption - to assign a full correlation to the identical components - guarantees the conservative single-unit core damage frequency (CDF) in SUPSA, since the seismic failures of redundant components only exist under AND gates in SUPSA.

However, it cannot be guaranteed that this assumption of a full correlation to the redundant components results in the conservative risks in seismic multi-unit PSA (MUPSA). That is because all the identical components in SUPSA existing under AND gates are merged through OR gate at the top-level MUPSA fault tree. In other words, the assumption of a full correlation to the redundant components does not guarantee the conservative multi-unit CDF (MUCDF) and site CDF (SCDF) since the redundant component failures are combined through nested AND and OR gates.

Hence, this study is necessary to confirm that the assumption of a full correlation to the highly correlated seismic failures results in the conservative MUCDF and SCDF in seismic MUPSA. Benchmark calculation for each sequence has been performed to confirm that this assumption guarantees conservative risks.

2. Calculation procedure

The procedure of this study to trace the changes in MUCDF and SCDF is shown in Fig. 2. The correlated seismic failures are converted into seismic CCFs by COREX (CORrelation Explicit) [4], [5], [6], [7]. FTREX (Fault Tree Reliability EXpert) solves the fault tree where seismic CCFs exist[8]. BeEAST (Boolean Equation Evaluation Analysis and Sensitivity Tool) calculate CDFs of each sequence precisely[5], [7], [9].

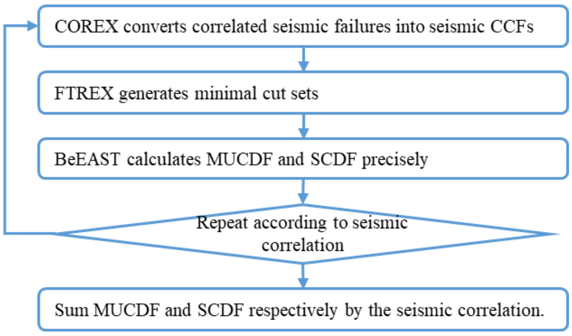


Fig. 2. The procedure for calculating MUCDF

3. Benchmark model

2.1. *Seismic parameters*

Seismic failures and their seismic capacity in Table I are utilized to calculate the failure probability.

Table I: Seismic capacity of the components

Event	Component	Failure Mode	A_m	β_R	β_U
DCCSF	125V DC control center	Structural	1.16	0.29	0.32
MVSSF	4.16kV SWGR	Structural	0.88	0.33	0.33
MVFSF	4.16kV SWGR	Functional	0.59	0.29	0.29
LVFSF	480V load center	Functional	0.71	0.30	0.30
LVSSF	480V load center	Structural	1.06	0.34	0.34
MCCSF	480V motor control center	Structural	1.48	0.34	0.34
BCHSF	Battery charger	Structural	1.35	0.29	0.32
EDGSF	Emergency diesel generator	Concrete Coning	1.00	0.34	0.19
INTSF	Instrumentation tube (Primary system)	Piping break	1.50	0.30	0.30
INFSF	Inverter	Structural	1.45	0.34	0.33
LOPSF	Offsite power	Functional	0.30	0.22	0.20
PCCSF	Plant control cabinet	Structural	0.89	0.34	0.33
SITSF	Safety injection tank	Concrete coning	1.09	0.36	0.35

The mean seismic frequency is divided into several intervals by peak ground acceleration (PGA) based on the latest research of seismic PSA, Surry pilot plant review[3] as Table II below.

Table II: Mean seismic frequency intervals by PGA

Interval groups	PGA interval $[m/s^2]$	Representative PGA $[m/s^2]$	Mean seismic frequency $[yr^{-1}]$
1	0.05 ~ 0.10	0.075	1.2070E-03
2	0.10 ~ 0.15	0.125	3.7700E-04
3	0.15 ~ 0.20	0.175	6.9100E-05
4	0.20 ~ 0.25	0.225	2.1000E-05
5	0.25 ~ 0.30	0.275	8.1500E-06
6	0.30 ~ 0.50	0.400	3.6500E-06
7	0.50 ~ 0.70	0.600	2.3400E-06
8	0.70 ~ 1.00	0.850	1.2370E-06

2.2. *Seismic MUPSA model*

The seismic event tree in Fig. 3 is used for benchmark calculation. The sequences that can cause core damage in consequence of random failures are neglected, and human errors are considered as a TRUE event.

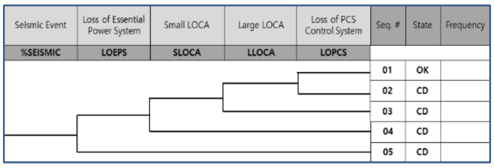
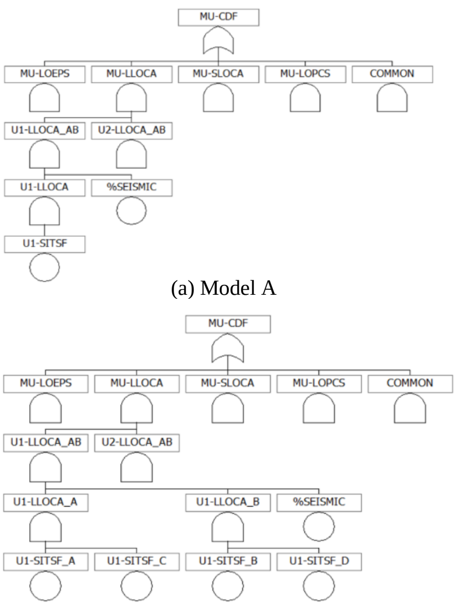


Fig. 3. Seismic PSA event tree

This study is performed to confirm how categorizing seismic failures affects MUCDF and SCDF. Accordingly, two different models are utilized.

In Model A, the seismic failures of identical components in the same unit are converted into a single. Whereas, Model B has all the seismic failures.

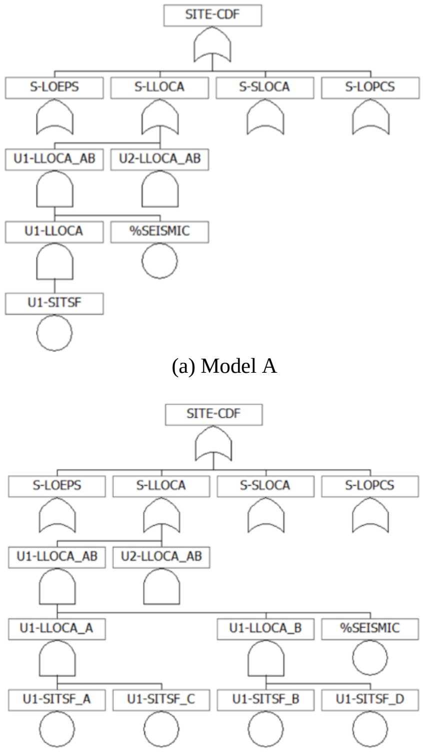


(a) Model A

(b) Model B

Fig. 4 Fault trees for MUCDF

In the case of calculating SCDF, the correlated seismic failures of identical components under AND gates are inevitable to be merged through OR gates at the top-level of the seismic MUPSA fault tree as shown in Fig. 5.



(a) Model A

(b) Model B

Fig. 5 Fault trees for SCDF

The groups of correlated seismic failures for Models A and B are listed in Table III and Table IV respectively.

Table III: Correlation group for Model A

Correlation Group	Event		Failure Mode	Component
	Unit 1	Unit 2		
1	U1-EDGSF	U2-EDGSF	Concrete coning	Emergency diesel generator
2	U1-MVSSF	U2-MVSSF	Structural	4.16kV SWGR
3	U1-MVFSF	U2-MVFSF	Functional	4.16kV SWGR
4	U1-LVSSF	U2-LVSSF	Functional	480V Load center
5	U1-LVFSF	U2-LVFSF	Structural	480V Load center
6	U1-MCCSF	U2-MCCSF	Functional	480V Motor control center
7	U1-PCCSF	U2-PCCSF	Structural	Plant control cabinet
8	U1-DCCSF	U2-DCCSF	Structural	125V DC control center
9	U1-BCHSF	U2-BCHSF	Structural	Battery charger
10	U1-SITSF	U2-SITSF	Concrete Coning	Safety injection tank
11	U1-INFSF	U2-INFSF	Structural	Inverter

In Table IV, the more six seismic failures in the same unit is assumed as a single failure. For instance, U1-DCCSF_A and U1-DCCSF_C are converted to U1-DCCSF_A.

Table IV: Correlation group for Model B

Correlation Group	Event		Failure Mode	Component
	Unit 1	Unit 2		
1	U1-EDGSF_A U1-EDGSF_B	U2-EDGSF_A U2-EDGSF_B	Concrete coning	Emergency diesel generator
2	U1-MVSSF_A U1-MVSSF_B	U2-MVSSF_A U2-MVSSF_B	Structural	4.16kV SWGR
3	U1-MVFSF_A U1-MVFSF_B	U2-MVFSF_A U2-MVFSF_B	Functional	4.16kV SWGR
4	U1-LVSSF_A U1-LVSSF_B	U2-LVSSF_A U2-LVSSF_B	Functional	480V Load center
5	U1-LVFSF_A U1-LVFSF_B	U2-LVFSF_A U2-LVFSF_B	Structural	480V Load center
6	U1-MCCSF_A U1-MCCSF_B	U2-MCCSF_A U2-MCCSF_B	Functional	480V Motor control center
7	U1-PCCSF_A U1-PCCSF_B	U2-PCCSF_A U2-PCCSF_B	Structural	Plant control cabinet
8	U1-DCCSF_A U1-DCCSF_B	U2-DCCSF_A U2-DCCSF_B	Structural	125V DC control center
9	U1-BCHSF_A U1-BCHSF_B	U2-BCHSF_A U2-BCHSF_B	Structural	Battery charger
10	U1-SITSF_A U1-SITSF_B	U2-SITSF_A U2-SITSF_B	Concrete Coning	Safety injection tank
11	U1-INFSF_A U1-INFSF_B	U2-INFSF_A U2-INFSF_B	Structural	Inverter

4. CDFs of sequences

The correlated seismic failures in each group of Table III and Table IV are converted into seismic CCFs, and then FTREX solves the fault tree to generate seismic MCSs. Lastly, BeEAST calculates MUCDFs of sequences accurately.

As shown in Fig. 6, sequence MUCDFs of Models A and B increase by seismic correlation and concenter into a similar value in MUCDF fault tree.

Nevertheless, sequence MUCDFs of Model A is overestimated from 0.0 to 0.9 because Model A has a single failure of identical components in the same unit.

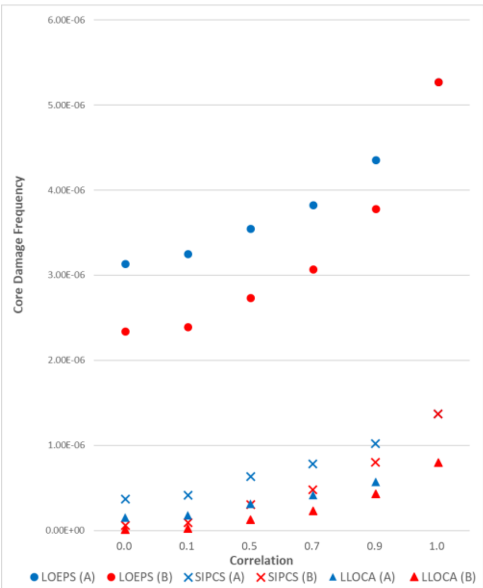


Fig. 6. Sequence MUCDFs fault tree by seismic correlation

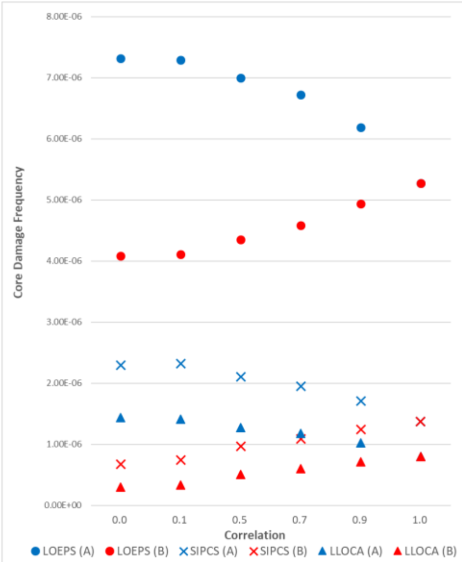


Fig. 7. Sequence SCDFs fault tree by seismic correlation

As shown in Fig. 7, sequence SCDFs of Model A are greater than those of Model B at all the seismic correlation level. Nonetheless, each sequence SCDFs of Models A and B converge into the identical value.

The more seismic failures of identical components are correlated, the higher sequence SCDFs of Model B is. Whereas the sequence SCDFs of Model A decreases as seismic correlation increases. The sequence SCDFs of Model A at a particular correlation level is excessively overestimated comparing those of Model B.

Therefore, all the seismic failures of redundant components must exist in the fault tree to avoid the overestimated MUCDF and SCDF in seismic MUPSA.

5. Conclusions

CDFs of sequences are calculated to confirm that the assumption of a full correlation guarantees the conservative risks. As the seismic correlation increases, CDFs changes as below.

(1) Sequence MUCDFs of Models A and B increase and converge into a similar value.

(2) Sequence SCDFs of Model B increases, whereas that of Model A decrease. Nevertheless, SCDFs of Models A and B converge into a similar value.

However, Sequence CDFs of Model A are greater than those of Model B at all the seismic correlation level. Accordingly, the conclusion can be drawn as follows.

(1) The assumption of a full correlation guarantees the conservative MUCDF, and SCDF regardless of Models A and B.

(2) Model A cannot be utilized to calculate SCDF if a partial correlation exists in seismic MUPSA, because SCDF of Model A is excessively overestimated as unacceptable.

(3) Model B should be used for seismic MUPSA where a partial correlation exists. Namely, all the seismic failures of redundant components that are partially correlated should exist in seismic MUPSA.

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