Seismic Correlation Application Study with COREX

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1. Introduction

Seismic correlation is a kind of dependency among seismically induced failures of structures, systems and components. Therefore, the technically adequate modeling of the seismic correlation is essential for Seismic PRA to have reasonable realistic results[1]. In this study, we performed a seismic PRA with COREX for a virtual plant which has typical modeling characteristics and SSCs similar to the domestic nuclear power plants in Korea. Our pilot application for seismic PRA with COREX focused on 1) the guidance development for partial correlation analysis implementation in seismic PRAs 2) comparison of the results difference between the application of standard thumb rule and partial seismic correlation implementation.

2. Methods and Results

2.1 COREX Development

Jung suggested the methodology and process to model the seismically correlated failure events as CCF events in the fault tree[2]. To Support the methodology and process, COREX was developed.

The main purpose of developing COREX is to easily calculate correlated seismic failures probability, to convert the correlated seismic failures probabilities into seismic CCFs probabilities, and to support modeling seismic CCFs into seismic PSA fault trees.

COREX has two main functions. First, COREX calculates combination probabilities (joint or union probabilities) of correlated seismic failures. Second, COREX solves simultaneous equations for generating probabilities of single seismic failure and seismic CCFs.

COREX calculates combination probabilities (joint or union probabilities) of correlated seismic failures by SSMRP or Reed-McCann integration. COREX casts these combination probabilities into LHS of simultaneous equations, and MCUB or REA probability equations into RHS of simultaneous equations that consist of single seismic failure and seismic CCFs. COREX solves these simultaneous equations, and generates the probabilities of single seismic failure and seismic CCFs[2].

One of the example equations to generate the probabilities of single seismic failure and seismic CCF is shown below in equation (1) for cases using joint failure and MCUB with 3 correlated components group[2].

$$
\begin{aligned}
P_1 &= 1-(1-Q_1)(1-Q_{12})(1-Q_{13})(1-Q_{123}) \\
P_2 &= 1-(1-Q_2)(1-Q_{12})(1-Q_{23})(1-Q_{123}) \\
P_3 &= 1-(1-Q_3)(1-Q_{13})(1-Q_{23})(1-Q_{123}) \\
P_{12} &= 1-(1-Q_1Q_2)(1-Q_{12})(1-Q_{123})(1-Q_1Q_{23})(1-Q_2Q_{13})(1-Q_{13}Q_{23}) \\
P_{13} &= 1-(1-Q_1Q_3)(1-Q_{13})(1-Q_{123})(1-Q_1Q_{23})(1-Q_3Q_{12})(1-Q_{12}Q_{23}) \\
P_{23} &= 1-(1-Q_2Q_3)(1-Q_{23})(1-Q_{123})(1-Q_2Q_{13})(1-Q_3Q_{12})(1-Q_{12}Q_{13}) \\
P_{123} &= 1-(1-Q_1Q_2Q_3)(1-Q_{123})(1-Q_1Q_{23})(1-Q_2Q_{13})(1-Q_3Q_{12})(1-Q_{12}Q_{13})(1-Q_{13}Q_{23})(1-Q_{12}Q_{23})
\end{aligned}
\quad (1)
$$

2.2 Virtual Plant Seismic PRA Input

Based on the experiences on several seismic PRAs in Korea, a virtual plant seismic PRA input was generated below. Seismic hazard for the plant is shown in Table I. In this study, only the seismic interval SEIS-G04 is selected for analysis based on the contribution to CDF and seismic induced failure probabilities of the components.

Table I: Virtual Plant Seismic Hazard

Seismic Interval ID	PGA(g) Interval	Representative PGA(g)	Frequency (/yr)
SEIS-G01	0.1~0.2	0.15	3.77E-04
SEIS-G02	0.2~0.3	0.25	6.55E-05
SEIS-G03	0.3~0.5	0.4	2.92E-05
SEIS-G04	0.5~0.7	0.6	5.28E-06
SEIS-G05	0.7~1.0	0.85	1.81E-06
SEIS-G06	> 1.0	N/A	5.23E-07

Seismic induced sequences are shown in Fig. 1. In this study, only the seismic sequences 4, 5 and 6 are selected for analysis based on the contribution to CDF and analysis simplification.

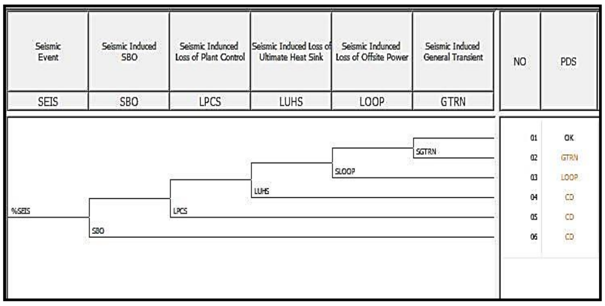

Fig. 1. Virtual Plant Seismic Induced Sequences

Component fragilities for the plant contributing to the selected sequences are shown on Table II.

Table. II Virtual Plant Components Fragility

Seq	Component	Description	Am	beta-r	bet-u
4	ESWP	ESW Pump	0.92	0.32	0.36
5	PCSC	PCS Cabinet	0.89	0.34	0.33
6	SWGR	4.16kV SWGR	0.88	0.33	0.33
	LC	480V Load Center	0.95	0.34	0.33
	EDG	Emergency DG	1.01	0.34	0.19
	DCBS	125V DC Bus	1.16	0.29	0.32

2.3 Base Model Quantification

Using the information above, the CDF was quantified by applying the standard thumb rule for seismic correlation. Standard thumb rule is the simplified version of Michael Bohn's thumb rule. Standard thumb rule reads seismic correlation is 1 for same components on the same floor in the same building and is 0 for all the other situations. This means that the redundant components have the full correlation. i.e. correlation coefficient is 1 among redundant components. The calculated failure probabilities of the components mapped to the relevant sequences are shown on table III below.

Table. III Base Case Component Failure Probability

Seq	Component	Failure Probability
4	ESWP	1.87E-01
5	PCSC	2.06E-01
6	SWGR	2.06E-01
	LC	1.70E-01
	EDG	9.42E-02
	DCBS	6.63E-02

CDF is calculated by multiplying seismic event frequency by the core damage event probability i.e. Pf(ESWP+PCSC+SWGR+LC+EDG+DCBS). In this analysis, Pf(ESWP+PCSC+SWGR+LC+EDG+DCBS) is not the sum of Pf(EWSP), Pf(PCSC), Pf(SWGR), Pf(LC), Pf(EDG) and Pf(DCBS) because each failure event is not rare-event. The calculated CDF is 5.28E-6/yr * 6.40E-1 = 3.38E-6/yr.

2.4 Seismic Correlation Affecting Factors Review

In the standard thumb rule, if components are the same and installed in the same floor slab in the same building, it is generally assumed that the components have the full correlation. (i.e. correlation coefficient is 1.)

Through the review of the literatures, the criteria below can affect the standard thumb rule for seismic correlation. In other words, though components are the same and installed in the same floor slab in the same building, the seismic correlation may not be one if the components satisfy one or more of below[1].

- Criterion 1: Difference in component location on the floor i.e in the center of the room or near the wall. It is well known that the supporting motion for the components location difference is significantly different.
- Criterion 2: Difference in component orientation.
- Criterion 3: Relatively long distance among components.

In this study, we applied the elements above for each redundant component. With the-state-of-the-art knowledge for the seismic correlation, it is very difficult to determine the degree of seismic correlation reduction for each criterion above. Therefore, in this study, it is simply assumed that each element may reduce the correlation coefficient by 0.25.

2.5COREX Calculation

By applying the assumption above, the response correlation coefficient among components are summarized on table IV with the applicable criterion. For EDGs, the criterion 2 and 3 was satisfied simultaneously, so the correlation coefficient for EDGs was assumed 0.5 instead of 0.75 which were applied to the other components with one criterion satisfaction.

Table. IV Response Correlation Among Components

Seq	Component	No of Comp	Correlation Coefficient	Applied Criterion
4	ESWP	3	7.50E-01	1
5	PCSC	4	7.50E-01	2
6	SWGR	2	7.50E-01	2
	LC	2	7.50E-01	2
	EDG	2	5.00E-01	2,3
	DCBS	2	7.50E-01	1

With the seismic correlation information above, COREX calculation was performed. COREX requires betas for response and strength and correlation coefficients for response and strength because it uses SSMRP equation. The seismic correlation coefficient equation in SSMRP is shown on equation (2) below[3].

$$\rho_{12} = \frac{\beta_{R1}\ \beta_{R2}}{\sqrt{\beta_{R1}^2 + \beta_{F1}^2}\sqrt{\beta_{R2}^2 + \beta_{F2}^2}}\rho_{R1R2} + \frac{\beta_{F1}\ \beta_{F2}}{\sqrt{\beta_{R1}^2 + \beta_{F1}^2}\sqrt{\beta_{R2}^2 + \beta_{F2}^2}}\rho_{F1F2} \quad (2)$$

In this study, it is simply assumed that the betas for response and strength are the same and seismic correlation coefficient for the strength is 0.

With the inputs described above, COREX was used to calculate every possible combination of failures for the redundant components and to derive the probabilities of seismic induced single failure events and common cause failure events. The table 5 below shows the result for seismic correlation coefficient for strength is 1. Failure Prob in the Table V is the one calculated by SSMRP equation and Basic event Prob is the one calculated by MCUB equation with the SSMRP-calculated result. The table 6 below shows the result for seismic correlation coefficient for strength is 0. In the SSMRP study, seismic correlation coefficient for strength is also assumed to be 0.

Table. V COREX Result for Strength Coefficient 1

Seq	Component	Failure Combination	Failure Prob	Basic Event Prob
4	ESWP	A	1.87E-01	4.11E-02
		B	1.87E-01	4.11E-02
		C	1.87E-01	4.11E-02
		AB	1.33E-01	2.62E-02
		AC	1.33E-01	2.62E-02
		BC	1.33E-01	2.62E-02
		ABC	1.10E-01	1.06E-01
5	PCSC	A	2.06E-01	3.23E-02
		B	2.06E-01	3.23E-02
		C	2.06E-01	3.23E-02
		D	2.06E-01	3.23E-02
		AB	1.49E-01	1.27E-02
		AC	1.49E-01	1.27E-02
		AD	1.49E-01	1.27E-02
		BC	1.49E-01	1.27E-02
		BD	1.49E-01	1.27E-02
		CD	1.49E-01	1.27E-02
		ABC	1.25E-01	1.63E-02
		ABD	1.25E-01	1.63E-02
		ACD	1.25E-01	1.63E-02
		BCD	1.25E-01	1.63E-02
		ABCD	1.11E-01	1.04E-01
6	SWGR	A	2.06E-01	7.18E-02
		B	2.06E-01	7.18E-02
		AB	1.49E-01	1.44E-01
	LC	A	1.70E-01	6.07E-02
		B	1.70E-01	6.07E-02
		AB	1.19E-01	1.16E-01
	EDG	A	9.42E-02	5.14E-02
		B	9.42E-02	5.14E-02
		AB	4.76E-02	4.51E-02
	DCBS	A	6.63E-02	2.71E-02
		B	6.63E-02	2.71E-02
		AB	4.10E-02	4.03E-02

Table. VI COREX Result for Strength Coefficient 0

Seq	Component	Failure Combination	Failure Prob	Basic Event Prob
4	ESWP	A	1.87E-01	1.26E-01
		B	1.87E-01	1.26E-01
		C	1.87E-01	1.26E-01
		AB	6.63E-02	2.72E-02
		AC	6.63E-02	2.72E-02
		BC	6.63E-02	2.72E-02
		ABC	3.15E-02	1.74E-02
5	PCSC	A	2.06E-01	1.21E-01
		B	2.06E-01	1.21E-01
		C	2.06E-01	1.21E-01
		D	2.06E-01	1.21E-01
		AB	7.71E-02	2.02E-02
		AC	7.71E-02	2.02E-02
		AD	7.71E-02	2.02E-02
		BC	7.71E-02	2.02E-02
		BD	7.71E-02	2.02E-02
		CD	7.71E-02	2.02E-02
		ABC	3.80E-02	9.84E-03
		ABD	3.80E-02	9.84E-03
		ACD	3.80E-02	9.84E-03
		BCD	3.80E-02	9.84E-03
		ABCD	2.19E-02	1.05E-02
6	SWGR	A	2.06E-01	1.62E-01
		B	2.06E-01	1.62E-01
		AB	7.70E-02	5.20E-02
	LC	A	1.70E-01	1.36E-01
		B	1.70E-01	1.36E-01
		AB	5.70E-02	3.94E-02
	EDG	A	9.42E-02	8.47E-02
		B	9.42E-02	8.47E-02
		AB	1.75E-02	1.04E-02
	DCBS	A	6.63E-02	5.65E-02
		B	6.63E-02	5.65E-02
		AB	1.35E-02	1.04E-02

2.6 Fault Tree Development

With the calculated seismic induced single failure events probability and CCF events probability by COREX, a FT was developed by applying stand fault tree development principle.

CDF top gate logic is as follows.

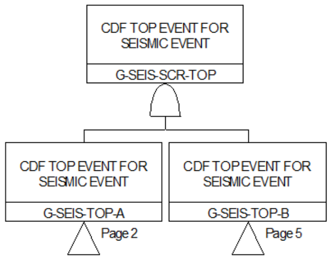

Fig. 2 CDF Top Gate Logic

Train A failure logic is as follows.

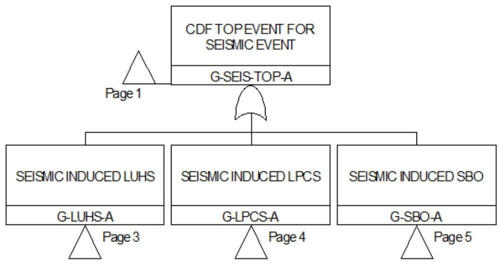

Fig. 3 Train A Failure Logic

Train A failure logic for SBO is as follows. The figure shows how the calculated each Basic Event Prob is implemented in the fault tree logic model.

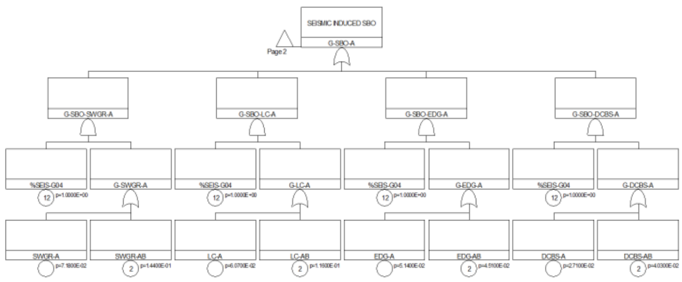

Fig. 4 Train A Failure Logic for SBO

2.7 Fault Tree Quantification

The developed fault tree includes all possible seismic induced single failure events and CCF events. With the FTREX, the fault tree was quantified. With the BeEAST, the cutset was converted into BDD and we get the final CCDP of 5.07E-1 and 3.73E-1 for correlation coefficient for strength as 1 and 0. The calculated CDF is 5.28E-6/yr * 5.07E-1 = 2.68E-6/yr and 5.28E-6/yr * 3.73E-1 = 1.97E-6/yr.

When this CDF is compared with one for the base case full correlation, there is about 20.8% and 41.7% reduction. This means that if we can find some elements reducing the seismic correlation which was generally assumed to full seismic correlation by the standard thumb rule, we can get the much more realistic CDF result in the seismic PRA.

3. Conclusions

In the previous study, COREX was developed which has the capabilities below.

- Calculation of combination probabilities (joint or union probabilities) of correlated seismic failures using the SSMRP MVN equation or Reed-McCann equation.
- Calculation of simultaneous equations for generating probabilities of single seismic failure events and seismic CCF events for fault tree incorporation with the combination probabilities (joint or union probabilities) of correlated seismic failures calculated above.

With the COREX, a pilot application study was performed for a virtual plant and conclusions below were derived.

- With the COREX, partial seismic correlation can be efficiently implemented into the seismic PRA.
- COREX results were easily implemented into fault tree logic model. Thus we can get sufficient risk insights with the seismic PRA result comparable to the one of internal event PRA.
- By reflecting the well-known technical elements which reduce the degree of seismic correlation, the significantly reduced CDF was resulted compared to the one with the standard thumb rule application, though the reduction of the seismic correlation was not very big. It means the partial seismic correlation shall be considered in the seismic PRA.
- When COREX is used for seismic PRA, all the seismic induced failure events were modeled in the fault tree. Thus the cutset post-processor which converts the MCSs into BDD such as ACUBE or BeEAST should be used for exact CDF calculation because the seismic induced failure events are non-rare events.

For the actual plants seismic PRA application with the COREX, the future studies below are required.

- In this study, the seismic correlation coefficient is roughly assumed for the elements which would reduce the seismic correlation. However, for the actual plants seismic PRA application, the seismic correlation coefficient should have sufficient technical basis. Therefore, the degree of seismic correlation should be determined for each element by the structural analysis experts.
- In this study, selected seismic hazard interval and part of seismic induced sequences are analyzed. It is necessary to perform the seismic PRA for all seismic hazard intervals and all the seismic induced sequences. It is also necessary to investigate potential issues when the partially correlated seismic induced failures are modeled in the accident mitigation logic model not directly leading to core damage.
- In this study, we used SSMRP MVN equation for seismic induced failure probabilities of components having partial correlation. It is necessary to perform seismic PRA using Reed-McCann equation for seismic induced failure probabilities of components having partial correlation.

ABBREVIATIONS

ACUBE: Advanced Cutset Upper Bound Estimator (S/W)
BeEAST: Boolean equation Evaluation, Analysis and Sensitivity Tool (S/W)
CCF: Common Cause Failure
CDF: Core Damage Frequency
COREX: CORrelation Explicit (S/W)
LHS: Left Hand Side
MCS: Minimal Cut Set
MCUB: Minimum Cut Upper Bound
MVN: Multi-Variate Normal
PRA: Probabilistic Risk Assessment
PSA: Probabilistic Safety Assessment
REA: Rare Event Approximation
RHS: Right Hand Side
SSC: Structure System and Component
SSMRP: Seismic Safety Margin Research Program

REFERENCES

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