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Development of Sampling-based Risk Quantification Code for Seismic Probabilistic Safety Assessment

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1. Introduction

The recent strong earthquake events show the need to explore scenarios in which the expected seismic hazard exceeds a design basis earthquake. In this regard, the seismic probabilistic safety assessment (SPSA) methodology has been once again in the spotlight since this is almost only one method to assess the overall risk to a nuclear power plant (NPP). But, current risk quantification code for SPSA (hereafter, SPSA code) mostly utilized has some limitation in which a partial seismic correlation cannot be properly handled. Therefore, in this study, we propose a sampling-based SPSA code which can intuitively deal with seismic correlation effect. Especially, the focus of this study lays an emphasis on the verification of the developed code.

2. Proposed SPSA code

We propose a SPSA quantification code based on seismic fragility input of EPRI “separation of variables (SOV)” method. The fragility data of the EPRI SOV method (A_m, $\beta_c = (\beta_r$^2+ β_u^2)^0.5) are used as a basis input, and this input is mapped to the input space of the response (R) and capacity (C) (R_m, C_m, β_{Rc}, and β_{Cc}). The log standard deviation (β_c) is decomposed into the log standard deviations of each of R and C (β_{Rc} and β_{Cc}). Here, the basic assumption in this decomposition of the logarithmic standard deviations is that the logarithmic standard deviations of βc are respectively expressed as the combination of the logarithmic standard deviation of each of R and C (i.e., β_c = (β_{Rc}^2+β_{Cc}^2)^0.5). Specifically, Fig. 1 shows the flowchart of this code. A system model of fault tree is given, basis inputs are entered and are mapped into space of response and capacity. The, R and C of component considering seismic correlation are respectively sampled in a seismic intensity level, and the state of the component is classified into a binary state safe ("0") or fail ("1"), based on a comparison of these samples regarding R and C. Based on the binary state information of components, the states of the sub-system and the top-system are also evaluated as "0" and "1" through the various logic gates on the system tree model. The failure probabilities for the components, sub-systems (i.e., combination of components and/or sub-systems below), and a top-system (i.e., a top event of system model) are evaluated by the ratio of the total number of samples and the number of failure state samples (the number of samples having a value of "1"). By iteratively performing this procedure in each seismic intensity level, the seismic fragilities for components, sub-systems, and top-system are finally derived. Finally, system seismic fragility curve and a value of high-confidence-low-probability-of-failure (HCLPF) are obtained through seismic fragility curves of each component, sub-system and top-system. Based on these results, the risk estimates (typically expressed as annual core damage frequency) are derived by convolving the obtained seismic fragility curves of the top-system with the seismic hazard curves.

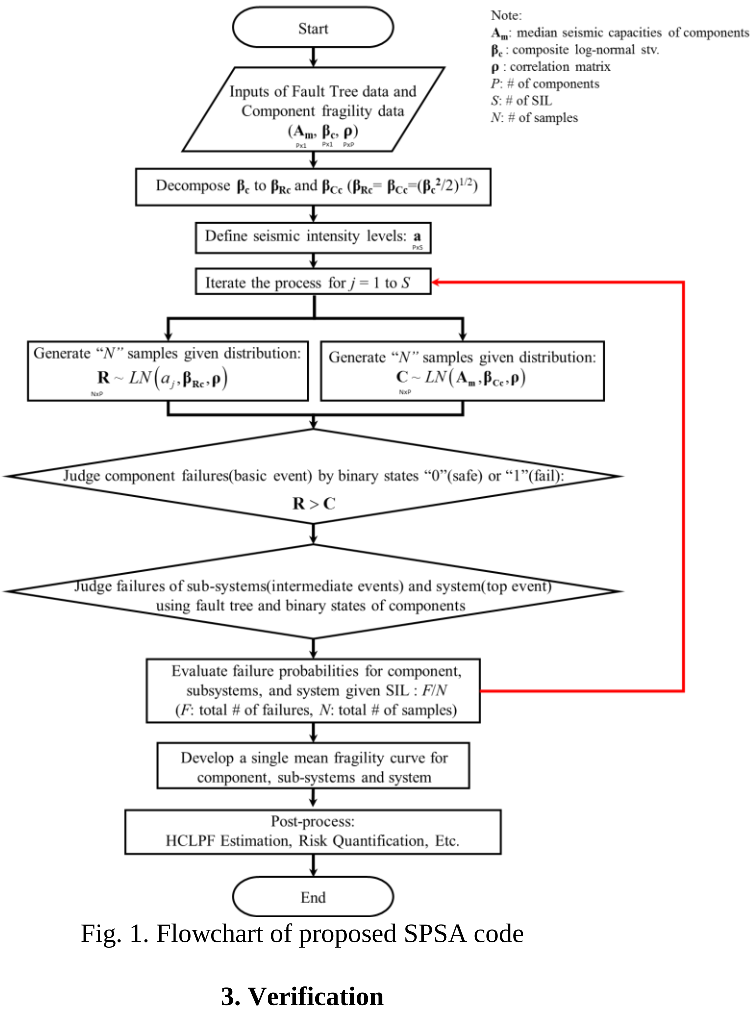

Fig. 1. Flowchart of proposed SPSA code

3. Verification

In this chapter, we apply the proposed code to the SPSA problem on the actual nuclear power plant of Limerick Generating Station (LGS). The detailed information of the seismic hazards, seismic fragilities and system model related to the LGS NPP are described in detail in Ellingwood [1]. We have basically looked at three cases

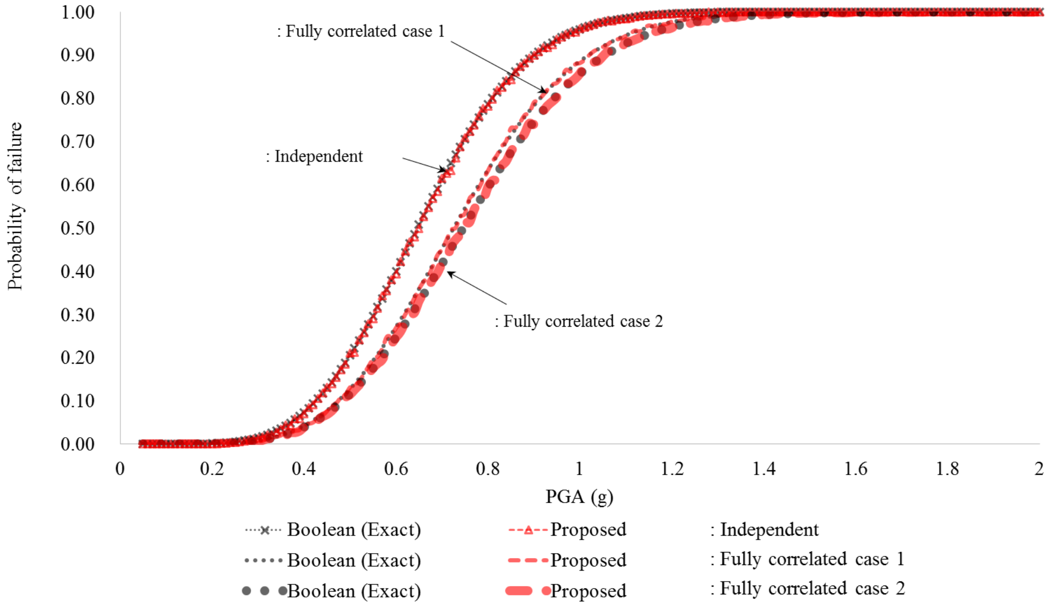

Fig. 2. Comparison of system seismic fragility curve ("Core damage accident sequence")

for this example: (1) an independent condition between all components, (2) a fully dependent condition for components of the reactor building and DG building, respectively, (3) a fully dependent condition for components of two buildings. The system seismic fragility and risk results obtained from proposed SPSA code are compared with those of Boolean expression approach ("exact") in Fig. 2 and Tables 1-3.

Table I: Risk comparison for "independent case"

Sequence	Boolean Expression (Exact)		Proposed	
	HCLPF	Risk	HCLPF	Risk
TsEsUX	0.29	3.84E-06	0.30	3.50E-06
TsRb	0.41	1.14E-06	0.41	1.15E-06
TsRpv	0.54	4.67E-07	0.55	4.66E-07
TsEsCmC2	0.42	1.47E-06	0.43	1.47E-06
TsRbCm	0.51	6.40E-07	0.52	6.41E-07
TsEsW	-	1.24E-07	-	1.58E-07
CM	0.28	5.44E-06	0.28	5.19E-06

Table II: Risk comparison of "Fully correlated case 1"

Sequence	Boolean Expression (Exact)		Proposed	
	HCLPF	Risk	HCLPF	Risk
TsEsUX	0.35	1.76E-06	0.36	1.48E-06
TsRb	0.41	1.14E-06	0.41	1.14E-06
TsRpv	0.54	4.67E-07	0.54	4.66E-07
TsEsCmC2	0.47	8.27E-07	0.46	8.24E-07
TsRbCm	0.51	6.40E-07	0.51	6.40E-07
TsEsW	-	1.27E-07	-	1.19E-07
CM	0.31	3.84E-06	0.31	3.56E-06

Table III: Risk comparison of "Fully correlated case 2"

Sequence	Boolean Expression (Exact)		Proposed	
	HCLPF	Risk	HCLPF	Risk
TsEsUX	0.36	3.93E-06	0.37	1.12E-06
TsRb	0.41	1.14E-06	0.41	1.13E-06
TsRpv	0.54	4.67E-07	0.55	4.68E-07
TsEsCmC 2	0.49	6.61E-07	0.50	6.42E-07
TsRbCm	0.51	6.40E-07	0.52	6.37E-07
TsEsW	-	1.27E-07	-	1.29E-07
CM	0.31	3.57E-06	0.31	3.35E-06

As shown in Figures and Tables, we can confirm that the proposed SPSA code produces results that are almost identical to the exact solutions acquired from the Boolean algebra for all cases.

4. Summary and conclusions

We developed a sampling-based SPSA code that could properly handle seismic correlations. Especially, this study was performed with a focus on the verification of the developed SPSA code. The results of the proposed code applied to actual SPSA problem showed almost identical results compared to exact solutions. Thus, this code can be expected to be utilized as an exact risk quantification tool of SPSA considering seismic correlations.

ACKNOWLEDGEMENTS

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[1] Ellingwood, B. (1990). Validation studies of seismic PRAs. Nuclear Engineering and Design, 123, 189-196.