Seismic and Tsunami Capacity Relocation of Nuclear Power Plants using NSGA-II and Two-Stage DQFM

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1. Introduction

Critical infrastructure systems (CISs) including nuclear power plant (NPP) are often expose to more than one natural disasters. For example, Fukushima-Daiichi NPP (Japan, 2011) experienced the core damage accident due to simultaneous effect of the earthquake-tsunami. The destructive effect of this multihazard event is still under recovery stage even after decades. Therefore, quantifying the multihazard risk of NPP and optimizing the capacity of the NPP against the multihazard is significant issue to NPP risk management authorities. However, when compared to the single-hazard risk quantification, those of multihazard is little studied in the field of nuclear safety [1], and cost-effective the system capacity relocation of NPP against the multihazard had not been investigated yet. To resolve this issue, we proposed seismic and tsunami capacity relocation framework for NPP using non-dominated sorting genetic-algorithm II (NSGA-II) and two-stage direct quantification of fault tree using Monte Carlo simulation (two-stage DQFM) [2, 3].

2. Proposed Methods

A multi-objective genetic algorithm (MOGA) is often used to resolve the optimization problems of various CISs [4,5]. To investigate the optimal relocation of the system capacity of NPP against the multihazard, NSGA-II [2] which is known to have superior performance among the various MOGA is adopted. To identify the most cost-effective capacity relocation for the NPP system through NSGA-II, one of the objective functions should represent the multihazard risk under sample condition. To this end, we adopt the two-stage DQFM [3] to evaluate the multihazard risk of NPP system with consideration of partial correlation between the system components. The procedure of the NSGA-II and two-stage DQFM are briefly summarized in section 2.1 and 2.2, respectively.

2.1 NSGA-II

The flowchart of NSGA-II is illustrated in figure 1. As plotted in the figure, NSGA-II is iterative procedure that repeat generating offspring sample set using parents sample set, evaluating the objective functions of sample set, assigning Pareto rank and crowd distance sorting, and replacing parents sample set. By generating new sample set resemble to the sample set which shown better fit based on the objective function, eventually sample set converge to the group of optimal sample set. To apply this method to the multihazard capacity relocation, genetic representation of the sample set and the objective functions should be determined accordingly.

To represent the seismic and tsunami capacity of the NPP system, string of the seismic capacity of system component and the tsunami capacity of each building is adopted (Figure 2). While seismic capacity can be relocation for each component, tsunami capacity can be assigned for each building.

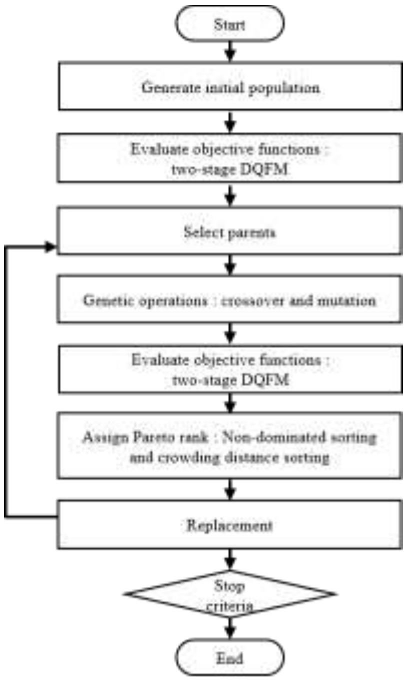

Fig. 1. Flowchart of proposed framework which combining NSGA-II and two-stage DQFM.

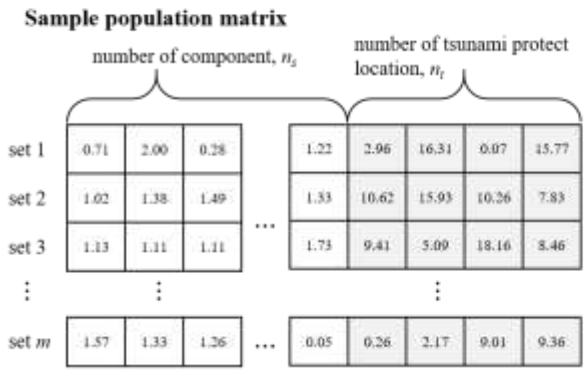

Fig. 2. Genetic representation of multihazard capacity relocation of NPP

To identify the NPP system capacity which can minimize both cost and multihazard risk, following objective functions are proposed: (1) multihazard risk, (2) normalized total mean multihazard capacity (TMMC). First objective function is directly representing the yearly multihazard risk, while the second objective function is used to represent the cost for NPP system. Under assumption that cost for building NPP system is proportional to the capacity, this indirect index is proposed. This inspired by the previous work of authors on optimal seismic capacity relocation of NPP [6]. Since the cost of the seismic capacity and tsunami capacity is different due different unit (i.e., ground motion *g* and height *m*), scaling parameter α is adopted. Finally, normalized TMMC can be expressed as follow:

$$\frac{1}{1+\alpha}\left(\frac{\sum A}{\sum A'}+\alpha\frac{\sum H}{\sum H'}\right) \qquad (1)$$

where, A is mean seismic capacity of each component and A' is current value before the capacity relocation. H is the mean tsunami capacity of each building and H' is current tsunami capacity of NPP buildings.

2.2 Two-stage DQFM

To evaluate first objective function, multihazard risk is estimated using two-stage DQFM [3]. The flowchart of the two-stage DQFM is summarized in Figure 3. The Two-stage DQFM uses conventional DQFM as base algorithm. Algorithm requires a system model (i.e., fault tree), fragility curve of each component, and hazard curve as an input, and begins with setting discrete multi-hazard grids into the uniform interval. For each hazard condition point, large number of the hazard response *R* and the capacity of the components *C* are sampled (N=10^4). However, the contribution of each hazard point to the final multihazard risk value varied by the hazard point. When the contribution of certain multihazard is trivial to final risk, the system failure estimated by small N_1 and large N_2 can have negligible difference.

With this inspiration, two-stage DQFM that generates a relatively small N_1 (e.g., 10^2) sample set for multihazard points that make a little contribution to the final multihazard risk while generating large enough N_2 (e.g., 10^4) sample set for others. In the first DQFM stage, a system failure probability is determined for all multihazard points with a small N_1. Using the results of first DQFM stage, importance of each multihazard points are identified in terms of its contribution to the final risk. Later, multihazard points that identified to have a non-negligible contribution to the final risk are sampled again at the second DQFM stage with large N_2. Finally, the multihazard risk of the NPP system is determined by a convolution of the hazard curve and the updated fragility curve.

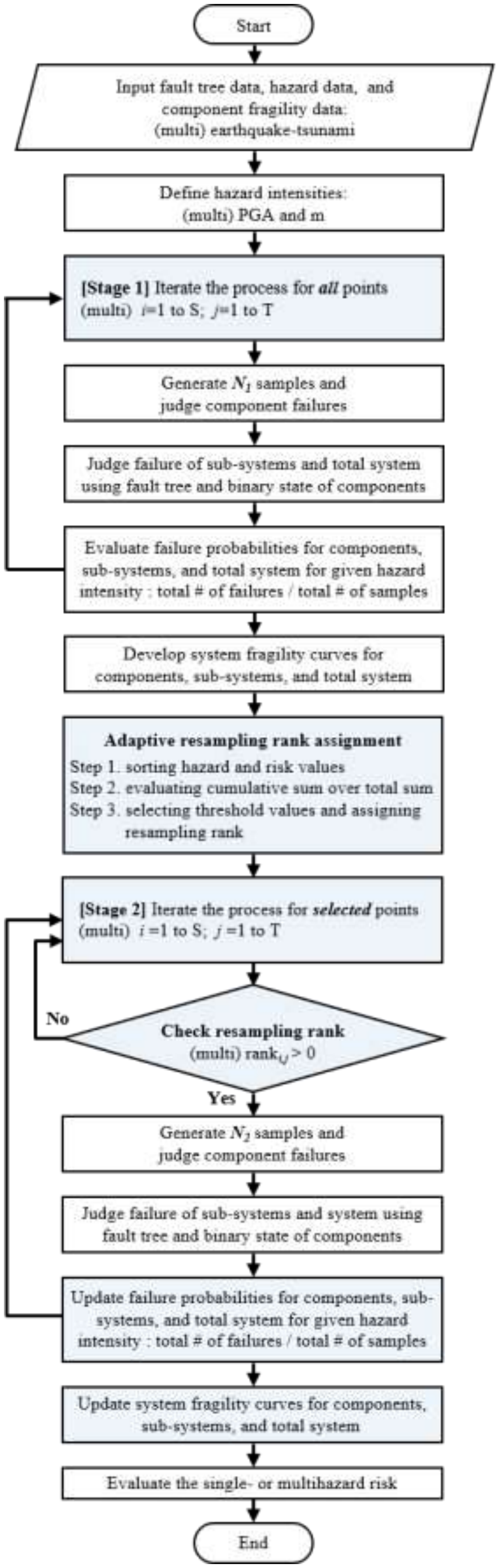

Fig. 3. Flowchart of two-stage DQFM.

3. Numerical experiment

3.1 Problem setting

To demonstrate the proposed framework, Limerick generating station NPP under earthquake-tsunami disaster is investigated. The hazard map is adopted and illustrated in Figure 4 [7].

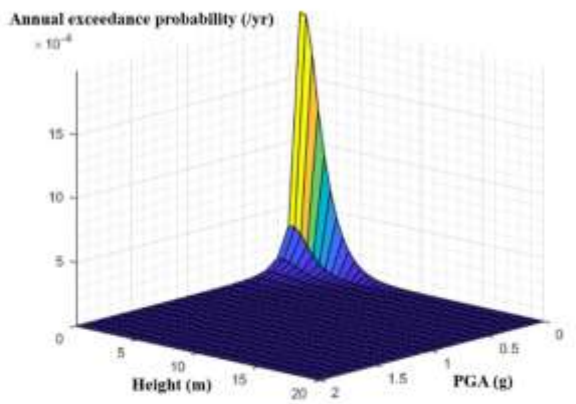

Fig. 4. Earthquake-tsunami hazard information for the LGS NPP

On the other hand, system model is adopted by Ellingwood [8], and core damage (CM) model is as follow:

$$CM = S_4 \cup S_6 \cup S_1 \cap [A \cup (S_3 \cup C_R) \cap (S_{10} \cup SLC_R) \cap (S_{17} \cup W_R)] \quad (2)$$

$$A = S_{11} \cup S_{12} \cup S_{13} \cup S_{14} \cup S_{15} \cup S_{16} \cup DG_R \quad (3)$$

The original multihazard fragility information is adopted from the work of Kwag et al. [7]. To represent the seismic capacity of 13 component and tsunami capacity of the 5 building or location, sting with the size of 18 is used as genetic representation. While performing NSGA-II following parameters were used: population size 100, mutation ratio 1/18, and 700th generation as the stopping criteria. To the best of authors knowledge, sample population is converged toward the final Pareto surface. In addition, to investigate the optimal multihazard capacity relocation under different ratio between seismic and tsunami capacity cost, alpha with 0.5, 1, and 2 values are investigated. After achieving the group of non-dominated sample set, robustness index (RI) is evaluated to select the robust sample set among the Pareto sample set. The variability of the each component is assumed to be a uniform distribution with upper and lower bound that correspond to $\pm$30% of the mean. A total of 100 (=N) set is generated for each Pareto solution and the RI is evaluated as follow:

$$\frac{1}{N}\sum_{k=1}^{N}\left(\frac{\|f(\boldsymbol{x}+\delta\boldsymbol{x}_k)-f(\boldsymbol{x})\|}{\|f(\boldsymbol{x})\|}\right) \quad (4)$$

where $\|\cdot\|$ represent 2-norm of vector and $\boldsymbol{x}$ denotes the design variables set.

3.2 Results and discussions

The Pareto surface with various alpha condition is plotted in the multihazard risk and normalized TMMC domain. It can be noticed in the Figure 5 that Pareto surface with smaller alpha value deliver the Pareto surface that dominant those with larger alpha values. From these results it can be noticed that potential to reduce the both multihazard risk and cost of multihazard capacity in increases as the current cost ratio of tsunami protection over the seismic capacity is small. Currently, the exact alpha value cannot be selected through the publicly available information, yet once these alpha values are given further accurate Pareto surface can be evaluated.

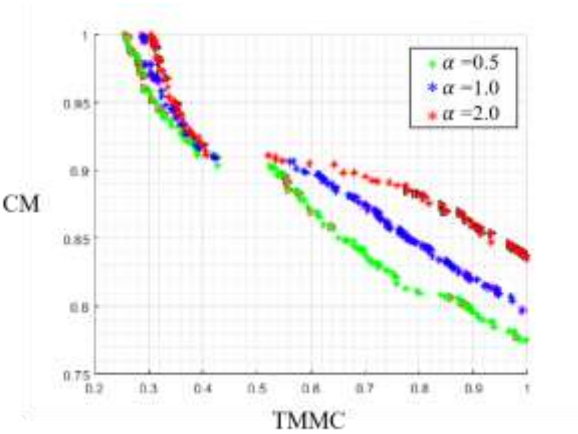

Fig. 5. Pareto solutions of multihazard capacity relocation with various seismic and tsunami capacity cost ratio.

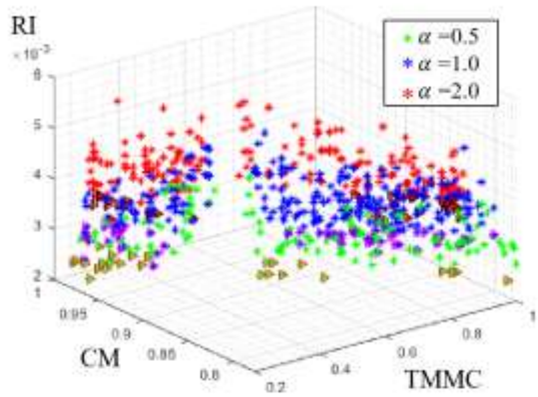

Fig. 6. Robustness index of Pareto solutions with various seismic and tsunami capacity cost ratio.

The robust index of each sample set is evaluated for Pareto sample sets, and sample set with the top 20% RI is selected as the further optimal solutions for each alpha value condition. The results of the RI for Pareto solutions are plotter in Figure 6 and Top 20% solutions are expressed in "►" mark. It can be noted in the figure 6 that Pareto solutions with smaller alpha parameter delivers that more stable solutions which have relatively smaller RI values.

Since the direct comparison it challenging due to different objective values of each sample set, sample set with similar normalized TMMC (i.e., approximately 0.8) are compared with original system in Figure 6. It is shown in the Figure 7 that seismic capacity of the components (component index from 1 to 13 in Figure 7) is tend to decreases and vice versa (location index from 14 to 18 in Figure 7) as the alpha value is decreases. It is also interesting to note that securing the seismic capacity of the component #1, #4, and #5 is common for all conditions.

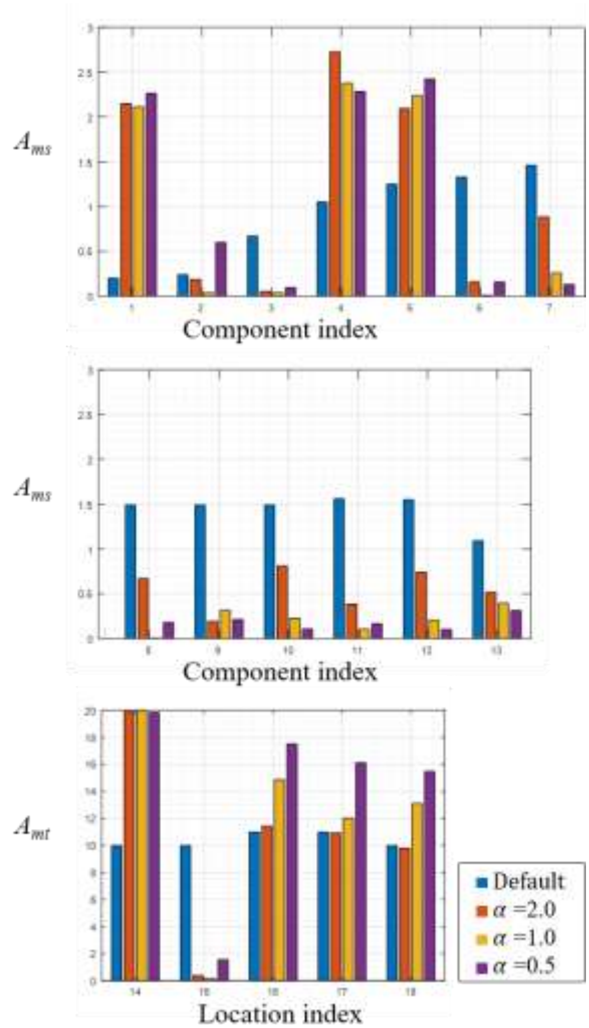

Fig. 7. Example of one of best optimal multihazard capacity relocation solutions for LGS NPP with various seismic and tsunami capacity cost ratio.

4. Summary and conclusions

By combining the NSGA-II and E-DQFM optimal multihazard capacity relocation for NPP was investigated. To this end, genetic representation of the NPP system is and two objective functions (i.e., multihazard risk, normalized TMMC) are proposed. To identify the optimal multihazard capacity of NPP, we performed parametric study for the NPPs with various seismic and tsunami capacity cost ratio.

Acknowledgement

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