Development of a Two-stage DQFM for Efficient Multihazard Risk Quantification for Nuclear Facilities

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1. Introduction

As a part of the on-going "Development of multi-natural hazard risk assessment" project, we propose a two-stage DQFM (direct quantification of fault tree using Monte Carlo simulation) with an adaptive resampling rank assignment. The new method will overcome the computational challenge of the existing DQFMs, which hinder the application of a sampling-based approach to the large-size system problem. The sample size N will be reduced by assigning sample size to each hazard condition based on its contribution to the final risk value. In the following sections, the detailed process of the proposed two-stage DQFM and its application to multihazard examples are presented with the results.

2. Proposed Method

2.1 DQFM

The proposed two-stage DQFM adopts the DQFM as the base algorithm to quantify the multihazard risk of the nuclear facilities [1,2]. As illustrated in Fig. 1, a conventional DQFM evaluates the system failure probability of a given hazard condition by generating a given number of samples, and, therefore, a large sample number N requires the convergence of the results. Consequently, the sample size increases as the size of the system and number of hazard conditions increase.

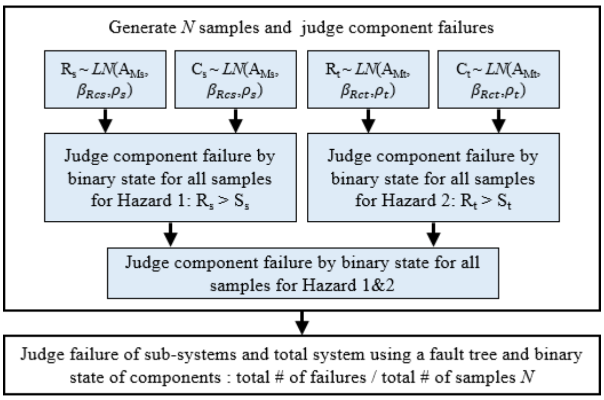

Fig. 1. System failure probability quantification process of the conventional DQFM for a given multihazard condition

2.2 Two-stage DQFM

To reduce the sampling cost without losing the accuracy or robustness of the results, given hazard conditions are divided into two groups with different number of sample set. In the first group, hazard points that have relatively small contributions to the final risk value are selected, and a small number of N_1 (e.g., 10^2) is sampled. Hazard points that have non-negligible contributions to the final risk value are selected for the second group, and a larger sample size N_2 (e.g., 10^4) is generated. A flowchart of the proposed two-stage DQFM is illustrated in Fig. 2.

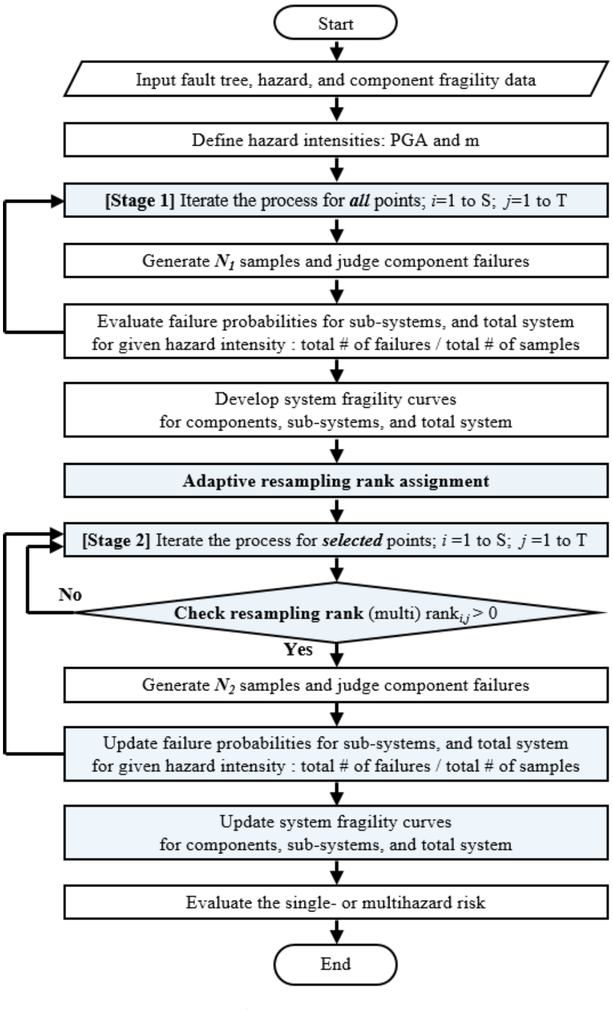

Fig. 2. Flowchart of the proposed two-stage DQFM

By reducing the number of sample for the hazard intensity point, which have negligible contribution to the final risk value, the total computational cost for the multihazard risk is reduced. Since the points only evaluated at the first DQFM stage have relatively small risk value, when compared to the final multihazard risk, the difference between the results by the 10^2 and 10^4 sample set has little difference.

2.3 Adaptive Resampling Rank Assignment

A major module of the two-stage DQFM is the selection of the optimal resampling points, which will be updated in the second DQFM stage with a large number of sample sets (e.g., N_2 = 10^4). The conceptual illustration of the resampling rank assignment process is plotted in Fig 3.

Using hazard information

Hazard intensity	Sorting *dH/dpdq*	Evaluating cumulative sum/total	Selecting threshold	Rank
A	H''_A (Min)	H''_A/H	-	0
B	H''_B	(H''_A+H''_B)/H	≈ Threshold (10^{-T_k})	1
C	H''_C	(H''_A+H''_B +H''_C)/H	-	1
⋮				⋮
D	H''_D(Max)	1	-	1

Using risk information

Hazard intensity	Sorting $P_{f,sys}$×*dH/dpdq*	Evaluating cumulative sum/total	Selecting threshold	Rank
A	R_A (Min)	R_A/H	-	0
B	R_B	(R_A + R_B)/H	–	0
C	R_C	(R_A + R_B+R_C)/H	≈ Threshold (T_r %)	1
⋮				⋮
D	R_D(Max)	1	-	1

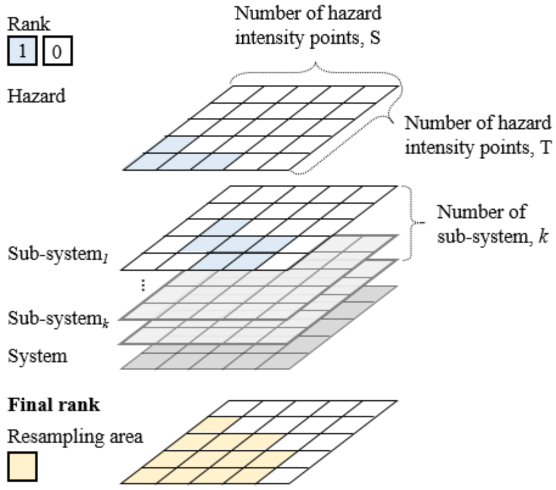

Fig. 3. Conceptual illustration of adaptive resampling rank assignment for multihazard risk quantification.

We employ hazard and risk information as the threshold. While the first hazard threshold is given, the second risk threshold is evaluated by convoluting the hazard information and the failure probability achieved in the first DQFM stage. The adaptive resampling rank assignment process incorporated with the hazard and risk information is as follows:

First, the hazard and risk values are sorted (Hazard: *dH/dpdq*; Risk: $P_{f,sys}$ ×*dH/dpdq*), where *p* and *q* denote each hazard intensity, and *H* is the annual exceedance rate of the hazard. $P_{f,sys}$ is system failure probability evaluated after the first DQFM stage. The hazard and risk values of each point is sorted to prioritize the importance of points. the large *dH/dpdq* value and $P_{f,sys}$ ×*dH/dpdq* value indicates a large contribution to the final multihazard risk.

The next step is evaluating the cumulative sum over total sum of both hazard and risk values for each hazard points. These cumulative rate is evaluated to select the adequate threshold for the first and second DQFM groups. Since the appropriate threshold could be varying by the shapes of the system fragility curve, a measure that represent the relative importance is chosen.

Final step is selecting threshold values and assigning the resampling rank. The final resampling rank is achieved by the summation of hazard and risk resampling ranks. In the second DQFM stage, the multihazard intensity points with the positive resampling ranks are re-evaluated with a large number of sample set. By skipping the second DQFM stage for the points that have little contribution to the final multihazard risk, total computational cost for risk quantification is effectively reduced without losing accuracy of results. Considering the fact that performance of the proposed method is subjected to the threshold selection, selecting the adequate threshold is important matter.

3. Numerical Example

To validate the accuracy and robustness, the proposed method is applied to the LGS NPP example [3], and its result is compared with the conventional DQFM. System model and hazard information was adopted from [2, 4]. To perform the two-stage DQFM, $10^{-3.5}$ and 20% are selected as hazard and risk thresholds, respectively. Therefore, any hazard point that has a cumulative rate of differential hazard value greater than $10^{-3.5}$, or a cumulative rate of risk larger than 20%, is resampled. In addition, both the conventional and proposed DQFMs are repeated 50 times with the same conditions, and Monte Carlo simulation is used to generate the sample. The DQFM generates a sample size of 10^4 for all hazard conditions, while the first and second stage of two-stage DQFM generate samples sizes of 10^2 and 10^4, respectively.

The multihazard fragility curve for the LGS NPP estimated by conventional and proposed DQFM is plotted in Figure 4. In addition, the mean μ and standard deviation σ of sub-system and total system failures, which are evaluated from 50 runs each of the conventional and proposed DQFMs, are compared in Table 1. The results indicate that the two-stage DQFM uses only 21% of the sample set of the existing DQFM, while preserving similar accuracy and variability.

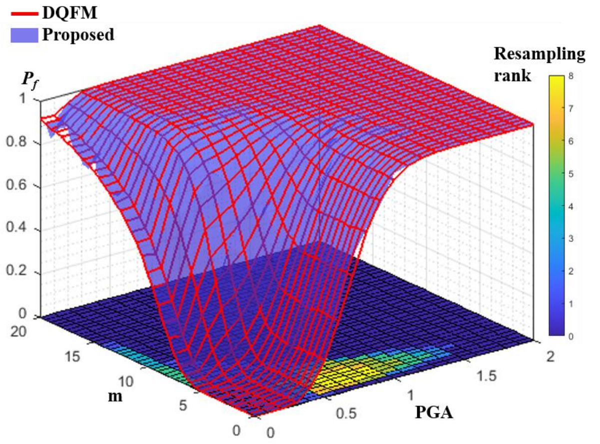

Fig. 4. Earthquake-tsunami fragility curves of the LGS NPP using conventional DQFM and two-stage DQFM

Table I: Results of earthquake-tsunami risk using the conventional DQFM and two-stage DQFM

Case*	**DQFM**		**Two-stage DQFM**	
	μ	***σ***	***μ***	**σ**
1	5.53E–06	3.59E–08	5.53E–06	3.32E–08
2	1.04E–06	5.25E–09	1.04E–06	5.10E–09
3	4.10E–07	2.31E–09	4.10E–07	2.65E–09
4	1.09E–06	6.17E–09	1.10E–06	6.64E–09
5	5.83E–07	2.55E–09	5.83E–07	2.61E–09
6	8.50E–07	2.97E–08	8.59E–07	2.54E–08
7	8.20E–06	4.99E–08	8.21E–06	4.95E–08
N**	1E4		0.21×1E4	

*Case: 1) T_sE_sUX 2) T_sR_b 3) T_sR_{pv} 4) $T_sE_sC_mC_2$ 5) $T_sR_bC_m$ 6) T_sE_sW 7) CM (adopted from [3]); *N***: mean *N* for each hazard point

4. Conclusions

The two-stage DQFM with an adaptive resampling rank assignment was proposed. By assigning the small number of samples to hazard conditions that have trivial contribution to the final risk value, and vice versa, the total sampling cost was significantly reduced. With this improved computational efficiency, we expect that sampling-based risk quantification can be further applied in multihazard risk assessment of the nuclear facilities.

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