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Insights into Water-Level Discretization in Risk Quantification of Bayesian Network-based Flood PSA

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1. Introduction

Climate-change phenomena such as typhoons and local intense precipitation (LIP) are external hazards that can threaten the emergency safety functions of nuclear power plants (NPPs) [1]. These extreme weather events increase the flooding risk that can affect the major safety functions of an NPP [2, 3]. In particular, in 2014, rainfall of 134 mm/h at the Kori NPP site in Korea flooded the circulating water pump room and led to a manual shutdown of the plant. Accordingly, regulatory bodies, including the USNRC, recommend performing a site-specific external flooding probabilistic safety assessment (PSA) to confirm the flood protection performance and safety margin of the plant [2, 4, 5]. Flooding PSA consists of four steps: (1) hazard analysis to determine the annual frequency of occurrence at each flood depth, (2) fragility analysis to evaluate the water-blocking performance of protective barriers such as watertight doors, (3) systems analysis using static tree models such as event trees (ET) and fault trees (FT), and (4) calculation of the core damage frequency (CDF) by combining these results [3, 6].

However, conventional ET-FT-based static PSA models have limitations in representing complex statistical dependencies among components, transient state transitions over time, and multi-state performance [6]. To address these limitations, Bayesian network (BN)-based PSA approaches have been proposed [4]. However, a static BN maps only a fixed flood depth condition, so it has limitations in calculating the CDF as a function of flood depth while reflecting a water level that varies with rainfall duration and barrier boundary conditions [3]. This study, therefore, constructs a dynamic BN model that supports multi-state modeling and can represent dependencies within the system. Because this multi-state representation requires the flood depth to be divided into a finite number of slices, the CDF error caused by water-level discretization is analyzed from two perspectives: (1) the convergence behavior with respect to the number of slices, and (2) a comparison of uniform and non-uniform allocation schemes.

2. Methods and Results

In external flooding risk assessment, hazard analysis is performed to determine the annual exceedance frequency at a given flood head. Extreme rainfall scenarios and hydraulic analysis models are combined to develop a hazard curve, which relates flood depth to frequency of occurrence [2]. In fragility analysis, a limit state equation for the water-blocking barrier is derived, and the uncertainties contributing to its resistance capacity are simulated by Monte Carlo simulation (MCS) to develop a fragility curve for the failure probability against the load demand [7].

2.1 Dynamic BN

To construct a dynamic BN, the existing ET and FT models are first converted into a one-top FT and then into a static BN. Based on this, the model is constructed as a dynamic BN over flood depth for the Shin-Kori Units 1 and 2 (see Fig. 1). This model can include the dependence between the flood level and the failure rates of the physical mitigating components in the form of conditional probability tables (CPTs). However, mapping the continuous water-depth variable onto the depth-dependent slice states of a dynamic BN requires a water-level discretization step, and this step introduces a numerical discretization error.

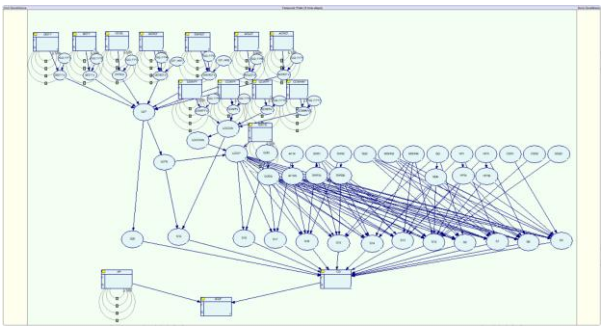


Fig. 1. Dynamic BN model for flooding PSA

2.2 Results

The depth range of 0.1–0.6 m was divided into n slices. The conditional core damage probability (CCDP) was evaluated at the midpoint depth of each slice, and the CDF was calculated by weighting it with the exceedance frequency difference ΔH_i of the corresponding interval. The self-convergence with respect to the number of slices was examined first. Two allocation schemes were then compared: a uniform partition, which divides the depth range into equal intervals, and a non-uniform partition, in which each slice spans the same CCDP increment (see Fig. 2). The number of slices required to keep the error within 5 % was 29 for the uniform partition and 15 for the non-uniform partition.

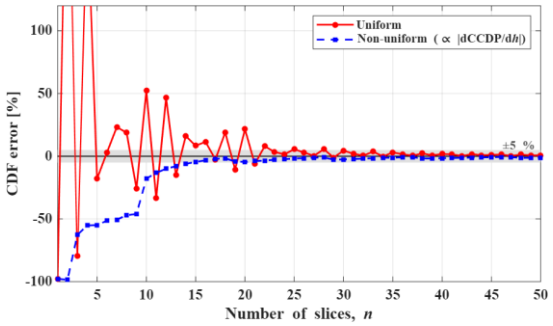


Fig. 2. CDF error for Number of slices

Fig. 3 compares the discretized CCDP of the uniform partition and the non-uniform partition based on the CCDP derivative, for 10 slices. The solid line is the true CCDP, which was evaluated continuously without discretization by substituting the depth-dependent fragilities into the Boolean expansion of the ET-FT model. The reference CDF used for the error evaluation is 1.106E-05 /yr, obtained by trapezoidal integration of this curve over 4E+05 grid points. The uniform partition assigns 5 of its 10 slices to the region below 0.35 m, where ΔH_i is zero, and its remaining boundaries do not coincide with the CCDP transitions, giving an error of +52.2 %. The non-uniform partition places its slices in the transition region and reduces the error to −17.8 %.

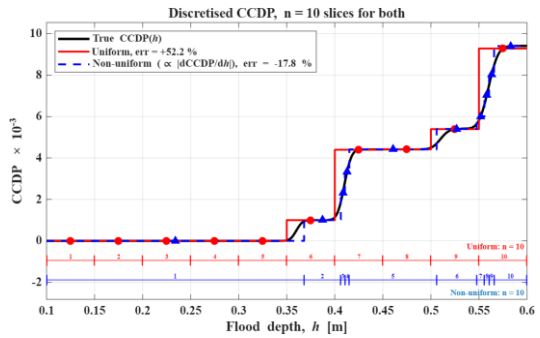


Fig. 3. Discretized CCDP for uniform and non-uniform slicing

These results show that the accuracy of the CDF is more sensitive to the allocation scheme than to the number of slices, and that increasing the number of slices in a uniform partition does not guarantee a smaller error.

3. Conclusion

This study analyzed the CDF error caused by water-level discretization in a flooding-PSA dynamic BN, using the Shin-Kori Units 1 and 2 model. For the uniform partition, the error showed oscillatory rather than monotonic convergence with respect to the number of slices. When the number of slices was increased from 5 to 10, the error changed from −18.0 % to +52.2 %, reversing in sign and increasing in magnitude. In contrast, the non-uniform partition based on the CCDP derivative reached the same accuracy with 15 slices that the uniform partition required 29 slices to reach. These results indicate that the allocation scheme, rather than the number of slices, determines how many slices are required for a given accuracy.

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