

Compound Flood Design Conditions at a Nuclear Power Plant Site Based on Joint Exceedance Probability and Comparison with the Conventional Event Combination

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1. Introduction

In September 2022, Typhoon Hinnamnor produced extreme rainfall and storm surge simultaneously and caused extensive inundation of coastal industrial facilities in Korea. The likelihood of such compound water-related hazards is expected to increase under climate change [3], and the reassessment of external events required after the Fukushima accident has made flood hazard evaluation at nuclear power plant (NPP) sites an important issue.

The design-basis flood for an NPP is defined at a return period of 10,000 years, corresponding to an annual exceedance probability (AEP) of $1E-4$. When compound hazards are considered, the question arises of which events should be combined and at what severity. ANSI/ANS-2.8 provides deterministic combination rules for this purpose [1,2]. These rules do not recommend combining two or more extreme events such as the probable maximum flood and the probable maximum storm surge; only one event in a combination is taken at the probable maximum level while the others are taken at more commonly occurring levels.

For a shore location such as the Shin-Kori NPP site, the prescribed combination consists of the probable maximum surge and seiche with wind-wave activity together with an antecedent 10 percent exceedance high tide [2]. Rainfall is not included, so the simultaneous action of extreme rainfall and marine forcing during a typhoon is not addressed. Furthermore, NUREG/CR-7046 states that these combinations are thought to have an AEP of less than $1E-6$, but that rigorous statistical analyses have not been completed for these estimates [2]. Whether a combination constructed from deterministic rules actually corresponds to the target frequency therefore remains unverified.

This study presents a procedure that constructs a joint distribution of storm surge, waves, and rainfall using a Bayesian network with the typhoon as a common parent, and derives compound flood design scenarios satisfying a target annual exceedance probability. The derived scenarios and the conventional combination are each supplied to a three-dimensional numerical model so that the resulting inundation can be compared.

2. Methods

2.1 Joint Distribution with a Typhoon Common Parent

Three probabilistic factors are considered: storm surge, waves, and rainfall. They are not mutually independent, being generated by a common cause, the typhoon, and tending to intensify together. A Bayesian network was therefore adopted in which the typhoon is a common parent node and the three factors are child nodes (Fig. 1). The correlation among the factors is not imposed through a separate joint distribution model but is induced by the common parent.

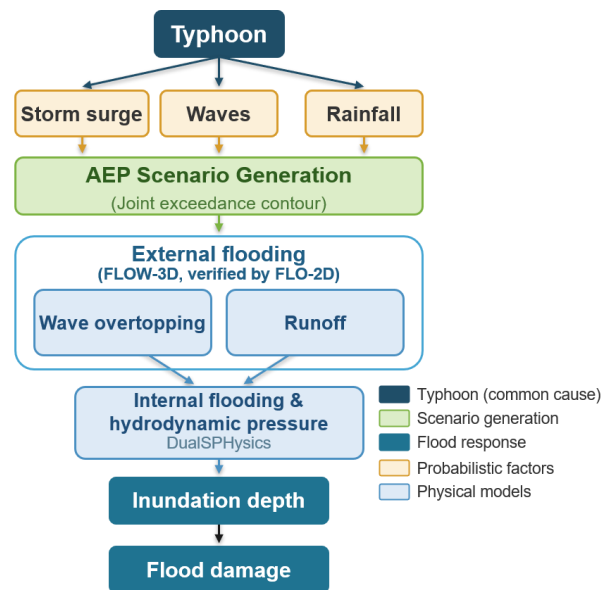


Fig. 1. Compound flood analysis framework at the NPP site. The typhoon acts as the common cause of storm surge, waves, and rainfall; design scenarios are generated on the joint exceedance contour for a target AEP; and the resulting external and internal flooding are analyzed with the corresponding physical models.

The typhoon node is discretized into four states following the Korea Meteorological Administration classification: no influence, strong, very strong, and super strong. The astronomical tide is not treated as a random variable but fixed at the approximate highest high water and handled as a constant in the sea level equation, maintaining consistency with the existing

analysis framework. Rainfall is defined as the maximum one-hour intensity in accordance with the local intense precipitation criterion of NUREG/CR-7046.

For each factor, a continuous conditional distribution is fitted for each typhoon class and weighted by the class occurrence probability to obtain a mixed marginal distribution. The joint exceedance probability of the three factors is then evaluated, and the set of factor combinations whose joint exceedance probability equals the target value is determined. Representative points on this set are selected as design scenarios. The target AEP is set to $1E-6$ to match the level that the ANSI combination is stated to achieve, and the same procedure is applied to $1E-4$, which corresponds to the design basis.

2.2 Inundation Analysis and Reference Condition

The study site is the Shin-Kori NPP. A detailed three-dimensional terrain model was constructed from topographic and bathymetric data of the National Geographic Information Platform and the Korea Hydrographic and Oceanographic Agency, and the geometry of coastal structures and the vulnerable openings through which inundation may enter were incorporated from a site walkdown conducted in May 2026.

The derived scenarios and the conventional combination are each supplied to the FLOW-3D model to obtain overtopping discharge and site inundation depth. The conventional combination follows the ANSI/ANS-2.8 shore-location rule: the probable maximum surge and seiche with accompanying wind-wave activity, together with an antecedent 10 percent exceedance high tide, and without rainfall.

3. Items for Comparison

Three quantities are examined. The first is the actual joint AEP of the conventional combination, which indicates whether a combination assembled from individual design frequencies corresponds to the design-basis frequency. The second is the factor composition of representative scenarios satisfying the target joint AEP; because more than one combination satisfies the same target, both marine-dominated and rainfall-dominated scenarios are obtained, and their distribution indicates which composition governs from a design perspective (Fig. 2). The third is the difference in inundation between the two conditions, for which cumulative overtopping discharge and maximum site inundation depth are used as indices, with particular attention to the contribution of rainfall.

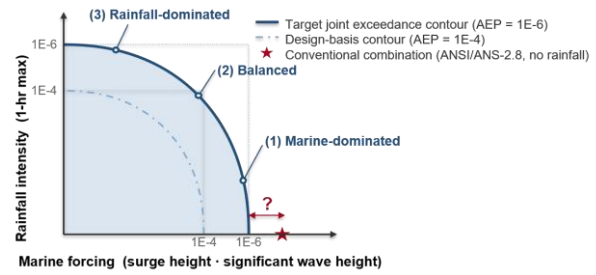


Fig. 2. Schematic of the target joint exceedance contour and scenario locations. The three-factor contour is projected onto the marine forcing–rainfall plane, and axis values are arbitrary. The conventional combination of ANSI/ANS-2.8 includes no rainfall, and its joint exceedance probability has not been verified.

Typhoon records and frequency-based sea state data are currently being compiled, and quantitative results for these three items will be presented at the meeting.

4. Conclusions

This study presents a procedure that defines compound flood design conditions at an NPP site on the basis of joint exceedance probability rather than a combination of individual factor frequencies. By using a Bayesian network with a typhoon common parent, the correlation among storm surge, waves, and rainfall is reflected without additional assumptions, and rainfall, which is excluded from the current design-basis combination, is brought into the assessment framework. Because the joint frequency of a combination can be computed explicitly, the procedure can supplement the probabilistic basis of deterministic combination rules. The same procedure applies to conditions beyond the design basis, and it will be extended to the assessment of structures, systems, and components by coupling with DualSPHysics-based internal inundation analysis.

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