

Comparative Analysis of Wave Overtopping at a Coastal Nuclear Power Plant using EurOtop, Deltares Model, and FLOW-3D Modeling

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1. Introduction

Sea level rise driven by climate change and the increasing frequency of extreme storm surges have significantly amplified the overtopping risk of coastal structures. Nuclear power plant (NPP) sites located along the shoreline are therefore directly exposed to such hazards. Overtopping is not a simple overflow over the crest of a coastal defense structure; it is a critical external flooding mechanism that can induce inundation within the plant site and threaten the safety of essential facilities[1].

Traditionally, overtopping discharge for coastal structures has been estimated using empirical approaches such as EurOtop[2]. In addition, methodologies proposed by Deltares, which are based on laboratory experiments and empirical datasets, enable more refined overtopping predictions[3]. However, these empirical methods primarily provide mean overtopping discharge and have limitations in representing the complex wave–structure–topography interactions and the temporal variability of overtopping under extreme sea states. This limitation becomes more pronounced in environments such as NPP sites, where complex layouts and multiple structures coexist, making it difficult for cross-sectional approaches to accurately capture actual overtopping behavior.

In this study, extreme marine conditions were assumed, and overtopping characteristics were comparatively analyzed using the EurOtop empirical formula, a Deltares-based approach, and the three-dimensional CFD model FLOW-3D. Nearshore wave conditions were first estimated using the SWAN model, from which empirical overtopping discharges and physics-based overtopping volumes were calculated. Subsequently, FLOW-3D was employed to directly simulate nonlinear wave transformation and overtopping flow processes in front of the structure, allowing a quantitative comparison with the empirical predictions.

The objective of this study is to examine the differences in overtopping estimates among the applied methods under extreme conditions and to demonstrate the necessity and applicability of three-dimensional physics-based analysis for design and safety assessment of coastal NPP sites.

Offshore extreme waves are propagated to the nearshore using SWAN, and overtopping is simulated

with FLOW-3D based on detailed 3D topography. Results are compared with EurOtop and Deltares NN/XGB predictions.

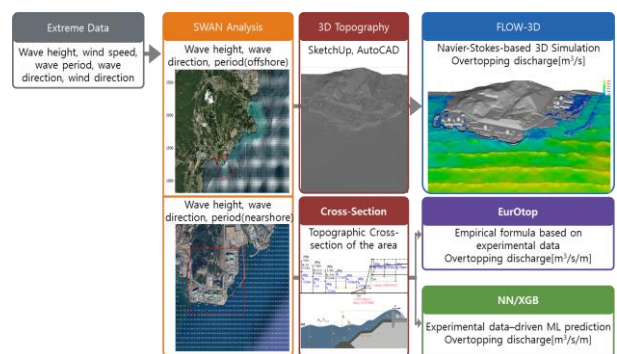


Fig. 1. Framework for Assessment under Extreme Conditions

2. Methodology

To compare empirical overtopping prediction methods (EurOtop and Deltares) with a three-dimensional CFD model (FLOW-3D) under identical conditions, the study was conducted through the following steps.

2.1 Construction of High-Resolution 3D Topography

A continuous three-dimensional terrain model covering the nuclear power plant site and adjacent coastal waters was developed. Onshore DEM data were merged with bathymetric data provided by the Korea Hydrographic and Oceanographic Agency to generate a seamless land–sea topography. The dataset was reconstructed using a TIN framework to accurately represent steep coastal slopes and structural geometries. Contours at 1-m intervals were extracted and imported into SketchUp to create detailed STL models including the breakwater, plant buildings, roads, and major infrastructure. The resulting 3D geometry was directly used as input for the FLOW-3D simulations.

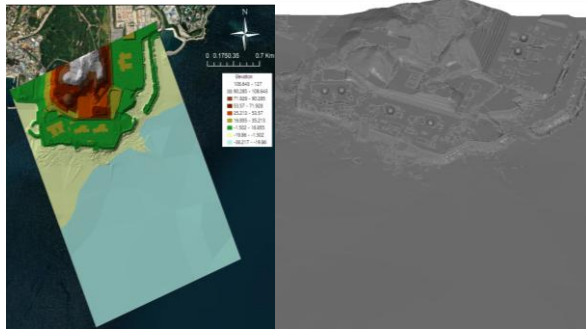


Fig. 2. 3D Detailed Terrain and Building Configuration of NPP

2.2 Analysis of 1,000,000 Year Return Periods Extreme Coastal Condition using SWAN

An extreme scenario exceeding conventional design criteria was defined using a one-million-year return period condition. The total water level was set to 4.582 m by superimposing the approximate highest high water, major tidal constituents, storm surge height, and sea-level rise projected for 2100 under the SSP5-8.5 scenario. Deep-water wave conditions of significant wave height $H_s = 23.7$ m, peak period $T_p = 19.2$ s, and southward wave incidence were applied. The SWAN model was used to simulate offshore-to-nearshore wave transformation, employing a 100-m grid for the regional domain followed by a 20-m nested grid to obtain detailed wave parameters at the breakwater toe. These wave conditions were consistently used as input for the EurOtop and Deltares calculations and as boundary conditions for FLOW-3D.

2.3 Overtopping Estimation using EurOtop and Deltares Methods

Based on the SWAN-derived nearshore wave conditions, the mean overtopping discharge (q) was calculated using the EurOtop empirical formula. In addition, the semi-empirical Deltares methodology was applied, incorporating structural geometry and relative freeboard (R_c/H_s). Both approaches provide cross-section-based mean overtopping rates and do not account for temporal variability.

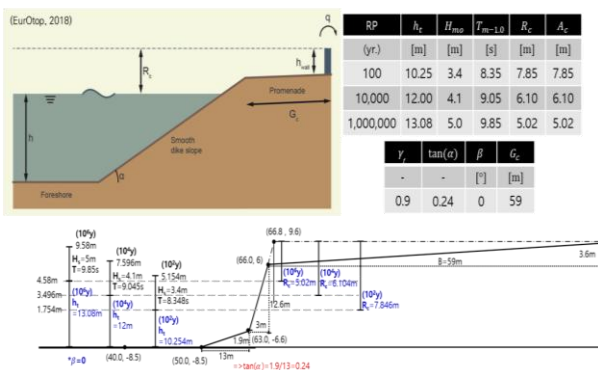


Fig.3. Overtopping Estimation using EurOtop(2018)

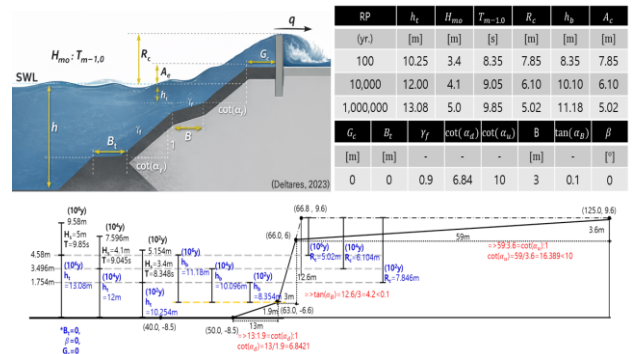


Fig. 4. Overtopping Estimation using Deltares NN/XGB

2.4 Three-Dimensional Overtopping Simulation with FLOW-3D

The same extreme wave and water-level conditions were imposed in FLOW-3D to directly simulate wave-structure interaction, overtopping, and inland flow propagation in three dimensions. The computational domain was approximately $600 \text{ m} \times 1,200 \text{ m} \times 40 \text{ m}$. Wave-generation and open-boundary conditions were applied simultaneously to minimize nonphysical reflections. Flux surfaces placed behind the breakwater enabled measurement of overtopping discharge, allowing analysis of not only mean overtopping rates but also instantaneous peak discharge and spatial concentration of overtopping flows.

This framework enabled a quantitative and qualitative assessment of the differences between empirical and physics-based three-dimensional approaches under extreme marine conditions

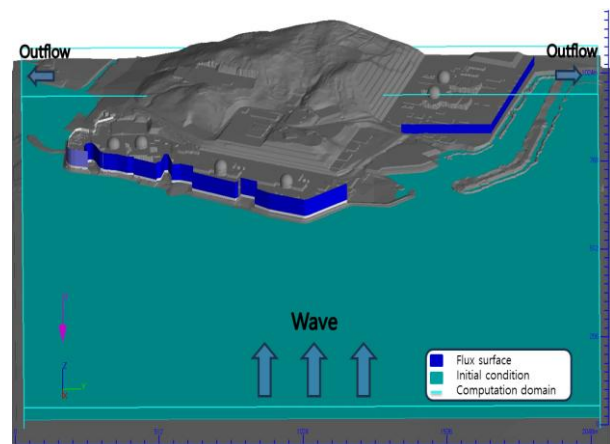


Fig.5. Overtopping Estimation using FLOW-3D

3. Results

3.1 Comparison of Mean Overtopping Discharge

Using the identical extreme wave conditions derived from SWAN, overtopping discharges obtained from EurOtop, the Deltares method, and FLOW-3D were

compared.

Both EurOtop and Deltares estimate the mean overtopping discharge (q) based on structural cross-sectional parameters and the relative freeboard (R_c/H_s), showing similar overall trends. However, the Deltares method yielded slightly more conservative overtopping rates than EurOtop under certain conditions.

The mean overtopping discharge computed from FLOW-3D was generally of the same results of magnitude as the empirical predictions, but deviations were observed for specific R_c/H_s ranges. These differences are attributed to the explicit representation of local wave amplification and nonlinear wave-structure interactions at the breakwater front in the 3D simulations.

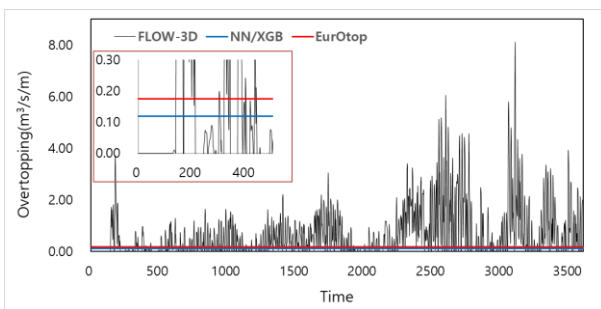


Fig.6. Comparison Results of Overtopping Estimation

3.2 Characteristics of Instantaneous Peak Overtopping Discharge

While the empirical methods provide only the mean overtopping discharge, the FLOW-3D simulations captured the temporal variability of overtopping flows. The results indicate that the instantaneous peak overtopping discharge generated by individual waves was significantly higher than the mean value, reaching several times the average under some conditions. This finding suggests that reliance solely on mean overtopping discharge may lead to underestimation of actual risk in design and safety assessments under extreme conditions.

3.3 Overall Comparison

The comprehensive comparison can be summarized as follows:

EurOtop and Deltares are efficient for estimating mean overtopping discharge but do not account for temporal or spatial variability.

FLOW-3D reproduces not only mean discharge but also instantaneous peak flows and spatial concentration of overtopping.

Under extreme conditions, the physics-based 3D approach identifies additional risk factors not captured by empirical methods.

Therefore, for complex coastal facilities such as nuclear power plant sites with intricate topography and structural configurations, a combined application of empirical methods and physics-based three-dimensional

modeling is recommended for reliable overtopping and safety assessments.

ACKNOWLEDGMENT

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