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3D Flood Analysis of Coastal Nuclear Power Plant Sites under Extreme Wave Overtopping Scenarios

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1. Introduction

Climate change is expected to intensify the frequency and magnitude of various natural disasters, including heat waves, droughts, wildfires, floods, storm surges, and sea-level rise. These phenomena pose significant threats to the safety and operation of nuclear power plants. For instance, storms or flooding may disrupt external power supplies, damage critical systems and equipment, and reduce cooling capacity, potentially leading to power decreasing or even complete shutdown of nuclear facilities. Such hazard conditions may occur independently, but they can also arise concurrently or sequentially, thereby amplifying their overall impacts.

According to a comprehensive analysis of data from the National Oceanic and Atmospheric Administration (NOAA) and the Nuclear Regulatory Commission (NRC), approximately 23% of U.S. nuclear power plants—17 out of 75—are located in areas at risk of inundation from storm surges generated by major hurricanes (Category 4–5) [1]. Similarly, about 63% (47 out of 75) of nuclear plants are situated in regions exposed to either hurricane-induced storm surges or high flood hazards, with nine of these facilities located along coastlines projected by NOAA to be within the range of future sea-level rise [1]. Furthermore, nearly 20% (15 out of 75) of nuclear plants are exposed to both storm surge and flood risks simultaneously [1]. The National Climate Assessment (NCA) report projects that climate change will significantly intensify storm surge strength, wind speeds, and rainfall intensity in the future [1]. This indicates that the flood risk to coastal nuclear power plants is expected to become even more severe.

Extreme heat	Upward trend	High confidence of increase
Cold spell	Downward trend	High confidence of decrease
Snow and glaciers	Downward trend	High confidence of decrease
Heavy precipitation	Upward trend	High confidence of increase
Drought	No assessment given	Medium confidence of increase
Fire weather	Upward trend	High confidence of increase in Western NA, medium confidence of increase in Central and Eastern NA
Coastal and river flooding	Upward trend	High confidence of increase
Tropical cyclone, severe wind	No assessment given	Medium confidence of increase

Fig. 1. Climate change–induced disaster impacts (EPRI, 2023).

According to the analysis by the Electric Power Research Institute (EPRI, 2023), the observed trends of extreme rainfall, coastal flooding, and sea-level rise induced by climate change have already been firmly established with high confidence and are projected to intensify significantly in the future [2,3]. Consequently, it is essential to establish and continuously reinforce preparedness and response measures against conditions such as heavy rainfall, storm surges, and sea-level rise. As the intensity and frequency of these climate-induced hazards are expected to further increase, comprehensive countermeasures and continuous risk assessments addressing external site inundation are required to ensure the safe operation of nuclear power plants. Figure 1, compiled by the Electric Power Research Institute (EPRI, 2023), synthesizes the impacts of climate change-induced disasters, concluding that trends in intense rainfall, coastal flooding, and sea-level rise are established with high confidence and projected to intensify significantly in the future.

For these reasons, it is necessary to analyze potential urban inundation scenarios at coastal nuclear power plants caused by wave overtopping of seawalls or coastal levees under extreme wave and storm surge events associated with climate change. In conventional coastal inundation studies, overtopping discharges have typically been estimated using empirical formulations such as EurOtop, and these values were then applied to simulate inland flooding [4]. However, such traditional approaches present limitations in terms of the accuracy of overtopping estimation and the reliability of inundation prediction in urban areas. Moreover, under extreme conditions, there is a significant risk of underestimating or overestimating the extent and magnitude of flooding, underscoring the need for more physics-based and sophisticated methods for coastal inundation prediction.

In this study, a coupled wave–hydrodynamic modeling framework is employed to reduce such uncertainties. Specifically, the Simulating WAves Nearshore (SWAN) model is utilized to simulate nearshore wave conditions under extreme storm scenarios. The results are then coupled with FLOW-3D to directly model dike overtopping and inland inundation processes. This physics-based modeling approach offers the advantage of accurately reproducing overtopping discharges and inundation characteristics, even in urban areas with complex topography.

2. Methodology

Intense precipitation and storm surges can cause inundation damage within nuclear power plant sites, resulting in flood waters infiltrating nuclear power plant structures. This can compromise Structures, Systems, and Components (SSC) facilities, potentially leading to severe accidents. Fig. 2 summarizes the analysis process for compound flood hazard assessment at nuclear power plant sites.

Due to climate change impacts, simulation methodologies are essential for evaluating flood risks from external hazards at nuclear power plant sites. These simulation approaches enable enhanced modeling of structural, system, and component performance during external flooding events, requiring comprehensive flood risk analysis, flood vulnerability assessment, SSC response modeling, safety analysis, and simulation-based flood analysis.

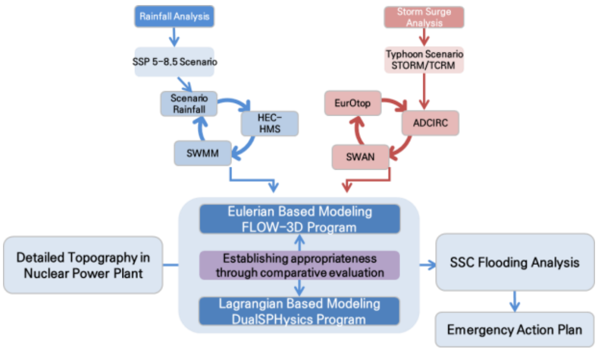

Fig. 2. Impact of water-related hazards by climate change

The offshore wave conditions associated with an extreme storm surge expected at the target coastal city were applied as inputs to the SWAN model to simulate nearshore wave transformation. SWAN computes the wave spectrum including significant wave height, period, and directional distribution of waves propagating toward the coast. By incorporating shallow-water processes such as refraction, breaking, and energy dissipation, SWAN provides more realistic nearshore wave conditions compared to empirical approaches that assume simple propagation up to the structure toe. Figure 3. Spatial distribution of significant wave heights with a return period of one million years in the coastal area near the nuclear power plant, based on the SWAN model.

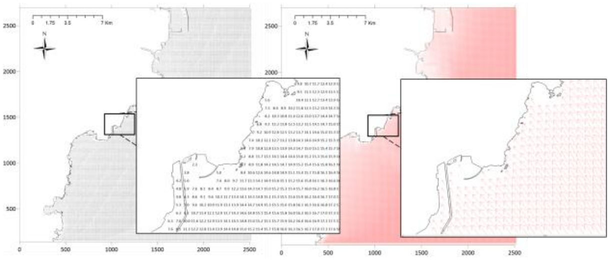

Fig. 3. Wave height analysis results using the SWAN model

2.1 Terrain Data Construction

Initially, detailed topographical data for the study area was constructed. In 3D inundation analysis, the influence of terrain and structural elements is paramount, necessitating detailed representation of topography and structures. Consequently, various methodologies were employed to collect available data, including detailed topographical data of study area, in South Korea, for terrain construction [5]. In addition, to ensure the stability of wave propagation, the boundary of the computational domain was set at a distance of at least one to two wavelengths away from the structure of interest (the seawall) [6]. This configuration allows the generated waves to fully propagate and reach the structure without being affected by reflected waves from the domain boundaries. Furthermore, wave conditions in front of the structure, extracted from the SWAN simulation results, were applied as offshore boundary conditions for the FLOW-3D analysis. Figure 4 illustrates location of study area, while Figure 5 presents the STereoLithography(STL) files of the 3D detailed terrain and building configurations of nuclear power plant constructed using SketchUp.

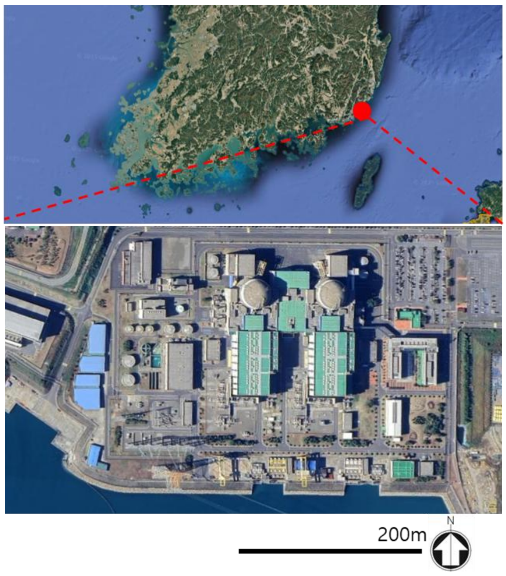

Fig. 4. Location of study area

Fig. 5. 3D Detailed Terrain and Building Configuration of NPP

2.2 Simulation Condition Configuration

3D inundation analysis was conducted using the Flow-3D model for the study domain. The simulation parameters were configured as follows: The analysis domain was established at approximately 600 m width, 1,200 m length, and 40 m height, with the nuclear power plant structure dimensions configured at approximately 170 m width, 220 m length, and 40 m height. Wave overtopping conditions were applied as extreme scenarios for the nuclear power plant site, with boundary conditions derived from SWAN model applications incorporating 10^6-year return period sea levels, wave conditions, and wind velocities. Fig. 6 presents case of the 3D external inundation analysis results of the nuclear power plant using the Flow-3D model.

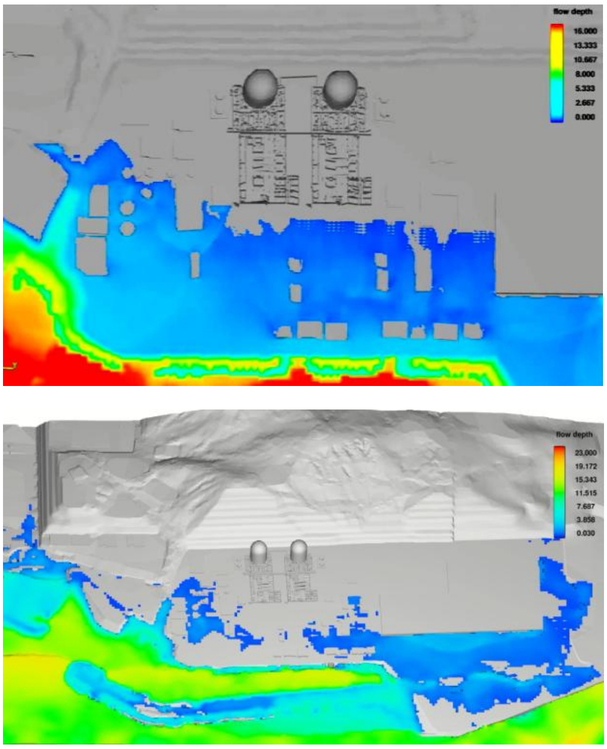

Fig. 6. Comparison of 3D flood inundation results (Up: EurOtop conditions, Down: SWAN conditions)

3. Results

In this study, a coupled SWAN–FLOW-3D framework is employed to conduct three-dimensional inundation analysis for extreme wave overtopping scenarios at the external site of a coastal nuclear power plant. To overcome the limitations of overtopping discharge estimation based on the conventional EurOtop empirical formula, offshore wave conditions derived from the SWAN model are directly imposed as boundary conditions in FLOW-3D, while the computational domain is extended by more than one to two wavelengths to ensure stable wave propagation.

Through this approach, it is expected that extreme wave overtopping events surpassing the breakwater and the resulting site inundation processes can be reproduced with greater realism. Furthermore, inundation extent, depth, and temporal evolution will be analyzed in detail to validate the methodological potential of enhancing the reliability of physics-based simulations.

Future research will incorporate compound water-related hazard scenarios by integrating the overtopping conditions established in this study with extreme rainfall and storm surge events, in order to assess the compound inundation risks to external plant sites. In addition, a probabilistic uncertainty quantification framework will be applied to evaluate the statistical robustness of extreme-condition simulation results, thereby contributing to the long-term resilience assessment and flood protection planning of coastal nuclear power facilities.

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REFERENCES

[1] U.S. Government Accountability Office (GAO), Climate Resilience: Nuclear Power Plants, GAO-24-106326, Washington, D.C., 2024.

[2] Electric Power Research Institute (EPRI), Climate Vulnerability Considerations for the Power Sector: Nuclear Generation Assets, Technical Report, Electric Power Research Institute, Palo Alto, CA, 2023.

[3] IPCC, Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)], IPCC, Geneva, Switzerland, 2023, pp. 35–115, doi:10.59327/IPCC/AR6-9789291691647.

[4] Le Roy, S., Pedreros, R., André, C., Paris, F., Lecacheux, S., Marche, F., & Vinchon, C., Coastal flooding of urban areas by overtopping: Dynamic modelling application to the Johanna storm (2008) in Gâvres (France), Natural Hazards and Earth System Sciences, 15, 2497–2510, 2015, doi:10.5194/nhess-15-2497-2015.

[5] J. Yoo, G. Jeong, B. Kim, "3D Flood Analysis and Comparison in Coastal Urban Areas Under Extreme Overtopping," Korean Nuclear Society 2025 Spring Meeting, Jeju, Republic of Korea, May 22–23, 2025.