Comparative Analysis of 3D Flood Dynamics under Extreme Wave Overtopping Conditions Using Lagrangian and Eulerian Approaches

Jaehwan Yoo
School of Architectural, Civil, Environmental and Energy Engineering, Graduate School
Kyungpook National University
Daegu, Republic of Korea
woghks629@naver.com

Gwiun Jeong
School of Architectural, Civil, Environmental and Energy Engineering, Graduate School
Kyungpook National University
Daegu, Republic of Korea
ryryanan1999@gmail.com

Byunghyun Kim
School of Architectural, Civil, Environmental and Energy Engineering, Graduate School
Kyungpook National University
Daegu, Republic of Korea
bhkimc@knu.ac.kr

I. INTRODUCTION

Climate change is expected to intensify various natural disasters, including heat waves, droughts, wildfires, floods, storm surges, and sea-level rise. These phenomena pose significant risks to nuclear power plants, potentially causing off-site power loss, damage to critical systems and equipment, and reduced cooling capacity, which may necessitate operational reductions or complete shutdowns. These hazard conditions may occur independently or concurrently, compounding their effects.

Comprehensive analysis of NOAA and NRC data indicates that approximately 23% (17 out of 75) of U.S. nuclear power plants are situated in regions vulnerable to flooding from hurricane storm surges [1], [2]. The National Climate Assessment (NCA) projects that climate change will substantially intensify storm surges, wind speeds, and rainfall intensity [3].

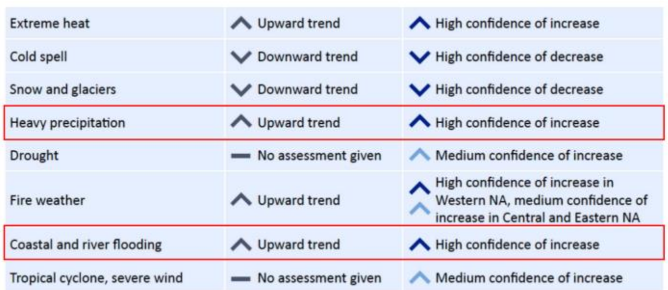
Sea level rise significantly threatens nuclear power plant infrastructure by amplifying storm surges and flooding potential. Elevated sea levels generate higher tides and storm surges, increasing coastal flooding that can penetrate inland areas and potentially compromise coastal nuclear power facilities.

According to NOAA and NRC reports, approximately 63% (47 out of 75) of U.S. nuclear power plants are located in areas exposed to either hurricane storm surges or high flood risks [1], [2]. Nine plants are situated within NOAA's predicted sea level rise range. Furthermore, 20% (15 out of 75) of nuclear power plants are located in areas exposed to both hurricane storm surges and high flood risks [1]. The NCA report predicts that climate change will exacerbate all three of these hazards [3].

Inundation events can severely impede site accessibility for personnel, critical equipment, and essential supplies due to submerged transportation infrastructure. Such events can damage buildings, equipment, and electrical systems, potentially necessitating operational reductions or complete facility shutdowns. The NCA indicates that heavy rainfall and flooding events are projected to increase in both frequency and severity across the United States. Global climate change is anticipated to exacerbate flood events in coastal areas, driven by typhoon-induced storm surges and extreme precipitation.

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 [4].

The convergence of multiple water-related hazards at nuclear power plant sites represents a critical safety concern, as flooding from external events can compromise safety-related functions. Insufficient defensive measures or failure to maintain system functionality can lead to operational failures in existing disaster prevention systems due to flooding events.



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

Figure 1. Impact of water-related hazards by climate change

II. METHODOLOGY

Extreme precipitation events and storm surges can cause significant inundation damage within nuclear power plant sites, with flood potentially infiltrating critical structures. Such infiltration may compromise Structures, Systems, and Components (SSC) facilities, potentially initiating severe accident sequences. Fig. 2 illustrates the systematic analytical framework developed for compound flood hazard assessment at nuclear power plant sites.

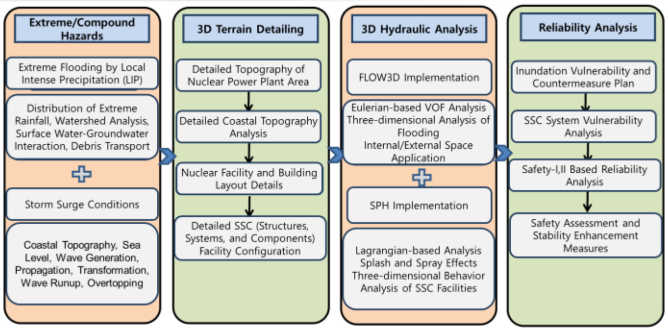


Figure 2. Impact of water-related hazards by climate change

Climate change impacts necessitate advanced simulation methodologies for comprehensive evaluation of flood risks from external hazards at nuclear power plant installations. These sophisticated simulation approaches facilitate enhanced modeling of structural, system, and component performance during external flooding events. The methodology requires integration of multiple analytical components, including comprehensive flood risk characterization, detailed flood vulnerability assessment, high-fidelity SSC response modeling, rigorous safety analysis, and advanced simulation-based flood propagation analysis.

This investigation employed both the Lagrangian-based DualSPHysics and the Eulerian-based FLOW-3D three-dimensional model to analyze inundation patterns caused by extreme-frequency wave overtopping due to storm surges in coastal urban environments. The research methodology utilized national deep-water design wave specifications provided by the Ministry of Oceans and Fisheries of the Republic of Korea to predict extreme-frequency (1-in-1,000,000-year return period) wave characteristics. These predicted specifications served as primary input parameters for wave estimation models to derive extreme-frequency wave conditions. The derived wave conditions were subsequently utilized to calculate extreme-frequency overtopping rates through the established EurOtop overtopping calculation formula. The calculated extreme-frequency overtopping rates were then incorporated into both modeling approaches: a Lagrangian approach-based model utilizing the DualSPHysics and Eulerian grid-based the FLOW-3D model for high-resolution three-dimensional flood analysis. This dual-model approach enabled comprehensive evaluation and comparison of inundation patterns, allowing for critical assessment of the strengths and limitations of each numerical method when simulating complex wave-structure interactions and resulting flood propagation characteristics in nuclear facility environments. Fig. 3 presents an analysis of inundation patterns at a nuclear power plant site under storm surge conditions using both the Eulerian-based FLOW-3D model and the Lagrangian-based DualSPHysics model. The figure aims to evaluate the suitability and validation of each modeling approach through a comparative assessment of the resulting flood simulations.

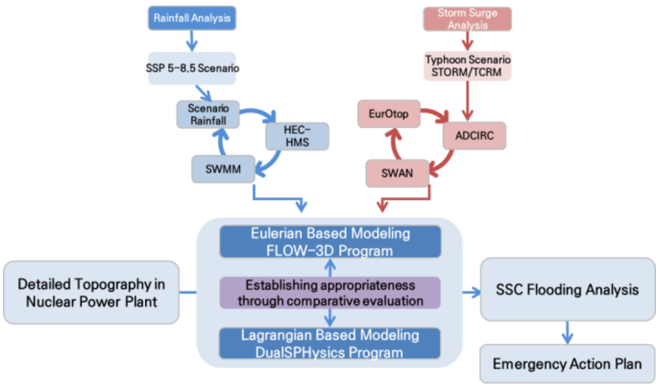


Figure 3. Comprehensive Methodological Framework for Hazard Risk Assessment

A. *Terrain Data Construction*

The initial phase of the methodology involved construction of detailed topographical data for the study area. In three-dimensional inundation analysis, the influence of terrain features and structural elements is of paramount importance, necessitating precise and high-resolution representation of topography and structures. Consequently, multiple methodologies were employed to collect and integrate available data, including detailed topographical information of the Shin-Kori nuclear power plant, in south Korea, for comprehensive terrain construction. Fig. 4 illustrates the Digital Elevation Model (DEM) of the terrain and buildings, encompassing both nuclear power plant facilities, while Fig. 5 presents the STL files of the three-dimensional detailed terrain and building configurations of the nuclear power plant constructed using SketchUp software.

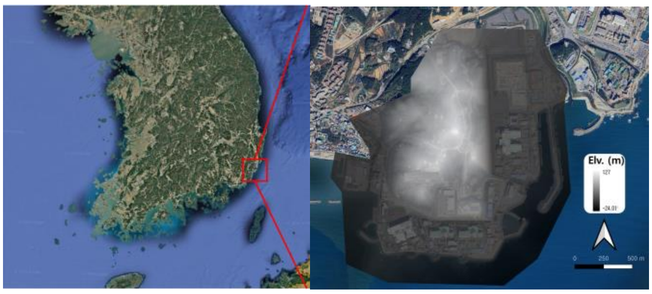


Figure 4. DEM of Detailed Terrain and Structures of NPP

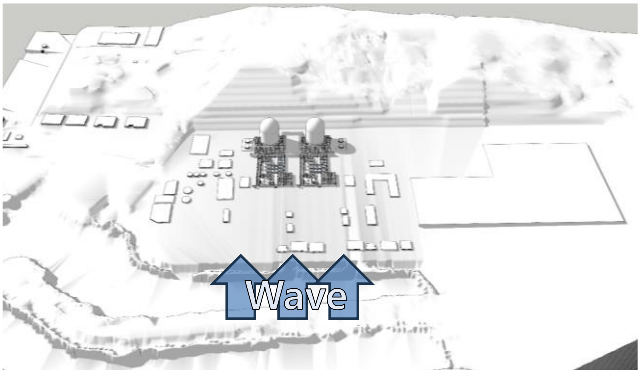


Figure 5. 3D Detailed Terrain and Building Configuration of NPP

B. Simulation Condition Configuration

Three-dimensional inundation analysis was conducted using both the Lagrangian-based DualSPHysics model and the Eulerian-based FLOW-3D model for the defined study domain. For the DualSPHysics simulation, parameters were configured according to rigorous standards: The particle spacing (dp) was established at 0.5 m, comprising 542,966 fluid particles and 318,134 solid particles, totaling 861,100 particles. For the FLOW-3D simulation, a structured mesh with refined grid resolution in areas.

For both models, the simulation duration was established at 1,800 seconds, and the analysis domain dimensions were configured at approximately 250 m width, 350 m length, and 40 m height, with the nuclear power plant structure dimensions specified 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 1-in-1,000,000-year return period sea levels, wave conditions, and wind velocities. Fig. 6 presents the comparative three-dimensional external inundation analysis results of the nuclear power plant using both the Lagrangian-based DualSPHysics model and the Eulerian-based FLOW-3D model.

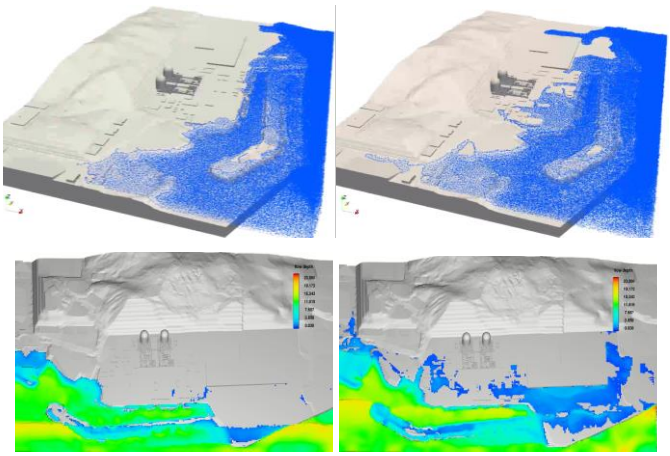


Figure 6. Comparison of 3D Flood Inundation (Up: DualSPHysics, Down: Flow-3D)

RESULTS

The present investigation employed both the Lagrangian-based DualSPHysics and the Eulerian-based FLOW-3D models to simulate three-dimensional inundation patterns caused by extreme-frequency (1-in-1,000,000-year) wave overtopping at a nuclear power plant located in a coastal urban setting. Comparative analysis highlighted both convergences and differences between the two modeling approaches. DualSPHysics was particularly effective in resolving detailed free-surface dynamics and wave-structure interactions, while FLOW-3D demonstrated superior computational stability and scalability for long-duration and large-domain simulations.

The results confirmed that both models are capable of accurately reproducing inundation characteristics with high spatial and temporal fidelity. Notably, the simulations successfully predicted temporal variations in inundation extent and water levels, with waves overtopping coastal defenses and inducing site-wide flooding within the 30-minute simulation period. These outcomes point to a high damage potential due to safety-related system component (SSC) flooding.

The dual-model assessment offered meaningful insights into the respective strengths of each approach. DualSPHysics excelled in capturing localized turbulence and complex wave-breaking, whereas FLOW-3D aligned well with regulatory modeling requirements and long-term inundation processes.

Future work will focus on integrating compound hazard scenarios—combining wave overtopping with projected extreme rainfall under various climate change pathways. Additionally, advanced probabilistic analysis will be applied to quantify uncertainty and improve the statistical reliability of extreme-condition flood modeling. Developing hybrid modeling frameworks that merge the strengths of Lagrangian and Eulerian methods is also recommended.

ACKNOWLEDGMENT

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