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3D Flood Analysis and Comparison in Coastal Urban Areas Under Extreme Overtopping

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1. Introduction

Climate change is expected to exacerbate natural disasters including heat waves, droughts, wildfires, floods, storm surges, and sea-level rise. The risks to nuclear power plants from these hazards include off-site power loss, damage to systems and equipment, and reduced cooling capacity, which may result in reduced plant operations or shutdowns. Fig. 1 illustrates potential water-related hazards that could occur at nuclear power plant sites due to climate change.

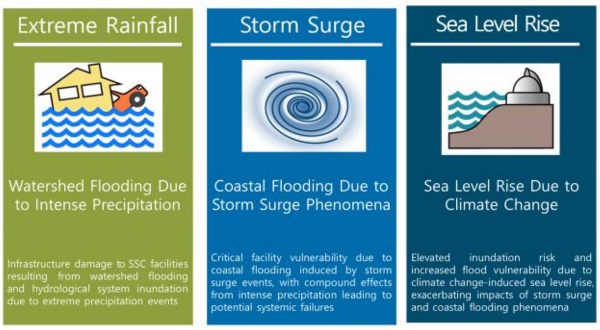

Fig. 1. Occurrence and impact of water-related hazards by climate change

NOAA (National Oceanic and Atmospheric Administration) and NRC (Nuclear Regulatory Commission) report that 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]. And 9 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]. NCA report predicts that climate change will exacerbate all three of these hazards [3].

Inundation events can impede site accessibility for personnel, critical equipment, and essential supplies due to submerged roads. It can damage buildings, equipment, and electrical systems, potentially requiring reduced operations or complete shutdown. According to the NCA, global climate change is predicted to exacerbate flood events in coastal areas, driven by typhoon-induced storm surges and extreme rainfall.

Combined water-related hazards at nuclear power plant sites are crucial safety concerns as flooding from external events can compromise safety-related functions. Insufficient defensive measures or failure to maintain functionality can lead to operational issues in various existing disaster prevention systems due to flooding.

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.

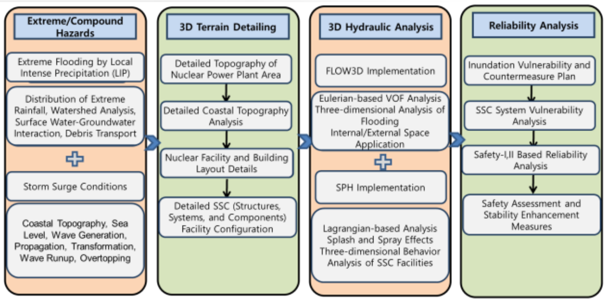

Fig. 2. Impact of water-related hazards by climate change

This study analyzed inundation caused by extreme return periods wave overtopping due to storm surges in coastal cities using a Lagrangian-based DualSPHysics and Eulerian-based Flow-3D, 3D(three-dimensional) model. The research utilized the national deep-water design wave specifications provided by the Ministry of Oceans and Fisheries of the Republic of Korea to predict extreme return periods (1-in-1,000,000-year) specifications. These predicted specifications were used as input data for wave estimation models to derive extreme waves. The derived wave conditions were used to calculate extreme overtopping rates through the EurOtop overtopping calculation formula. Subsequently, the inundation caused by the calculated extreme overtopping was analyzed using Lagrangian and Eulerian based model for 3D flood analysis and results evaluation.

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 the Shin-Kori nuclear power plant in Busan, South Korea, for terrain construction. Fig. 3 illustrates location of study area, while Fig. 4 presents the STL files of the 3D detailed terrain and building configurations of nuclear power plant constructed using SketchUp.

Fig. 3. Location of Study Area (Shin-Kori NPP)

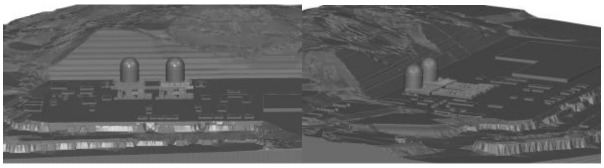

Fig. 4. 3D Detailed Terrain and Building Configuration of NPP

2.2 Simulation Condition Configuration

3D inundation analysis was conducted using the DualSPHysics model and Flow-3D model for the study domain. The simulation parameters were configured as follows: The simulation duration was 1,800 seconds, and the analysis domain were established at approximately 250 m width, 350 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. 5 presents the 3D external inundation analysis results of the nuclear power plant using the DualSPHysics and Flow-3D model.

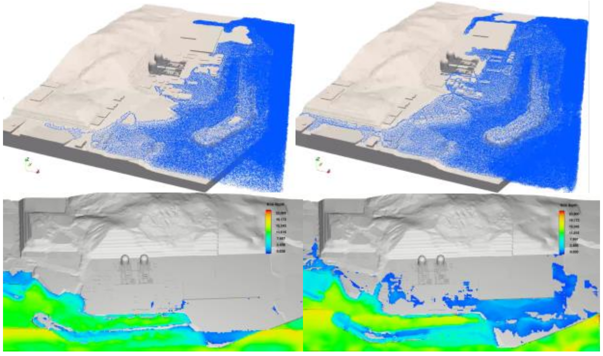

Fig. 5. 3D Flood Analysis Results (Wave Overtopping Conditions, Up: DualSPHysics, Down: Flow-3D)

3. Results

Through this study, Lagrangian and Eulerian based models were employed to simulate 3D inundation patterns under extreme return periods (1-in-1,000,000-year) wave overtopping scenarios at a nuclear power plant located in a coastal urban area. This confirmed the methodology's capability to precisely reproduce inundation characteristics. The analysis results demonstrated effective temporal prediction of inundation extent and water level variations due to wave overtopping. During the 30-minutes of extreme wave overtopping, waves surpassed the breakwater, resulting in site inundation and anticipated SSC flooding damage.

Future research objectives include conducting extreme compound water-related hazard analyses by integrating the wave overtopping conditions utilized in this study with future intense precipitation conditions based on climate change scenarios. Additionally, a comprehensive uncertainty quantification framework will be implemented to assess the statistical reliability of extreme-condition simulation results through probabilistic analysis methodologies.

ACKNOWLEDGMENT

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