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SPH-Based Extreme Interior Flooding Analysis of a Nuclear Turbine Building

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1. Introduction

In recent decades, the combined intensification of sea-level rise, storm surges, and extreme waves has significantly increased the risk of coastal overtopping and interior building flooding. IPCC AR6 projects a rise in both the frequency and magnitude of Extreme Sea Levels throughout the twenty-first century, warning of escalating design and operational risks for coastal infrastructure [1]. Large-scale global analyses further indicate that extreme water levels historically associated with "100-year" recurrence are expected to occur with much greater frequency across extensive coastlines.

The Fifth National Climate Assessment (NCA5, 2023) similarly concludes that coastal flooding, including compound events combining surge and heavy rainfall, is already affecting critical facilities and will intensify through mid-century without additional adaptation [2]. At nuclear power plant (NPP) sites, floodwater can penetrate buildings through roll-up door gaps, thresholds, penetrations, and ventilation systems, degrading safety-related structures, systems, and components (SSCs). International safety guidance explicitly recognizes flooding as a potential common-cause failure pathway for SSCs, while U.S. regulatory standards require that SSCs remain functional under the most severe credible design-basis flood conditions [3].

To address these interior flooding risks, this study adopts a smoothed particle hydrodynamics (SPH) framework that directly applies external flood conditions at building openings, such as roll-up door gaps. The framework then simulates the chain of processes from inflow jets to interior stage–storage dynamics and stairwell ingress, providing design-relevant metrics such as time-to-threshold interior depth, onset of basement inflow, and minimum dewatering capacity.

2. Methodology

This study aims to quantitatively simulate the process of interior flooding within a coastal nuclear power plant building under various external flood conditions, including localized intense precipitation (LIP) and storm surges. As illustrated in Fig. 1, combined numerical simulations of LIP and storm surge scenarios were first carried out to evaluate the overall inundation characteristics of the plant site. Subsequently, three-dimensional inundation analyses and reliability assessments were conducted to determine the time series of water levels and inflow discharges reaching the building front wall. Based on these external conditions, the inflow of floodwater through openings such as roll-up door gaps was modeled, and the subsequent propagation of water into underground spaces via stairs was analyzed. This framework enabled the identification of vulnerable areas inside the building and the quantitative evaluation of flood risks under different scenarios.

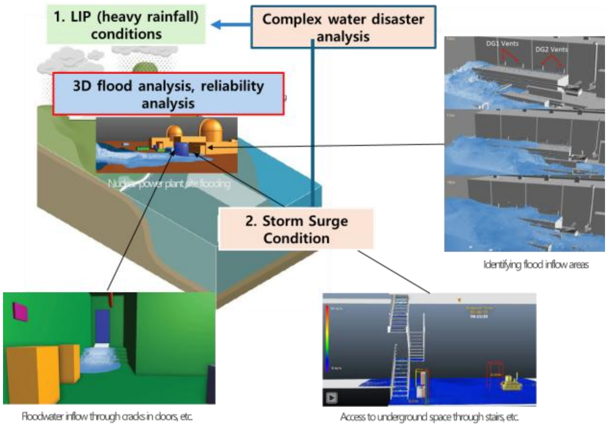

Fig. 1. Research concept map

2.1 External boundary condition setup

The external boundary conditions were obtained using a three-dimensional inundation model. The model calculated the overtopping volume induced by waves and determined the time series of water levels and normal velocities at the building front wall (i.e., the exterior of the roll-up door). These data were then applied as boundary inputs for the SPH simulation, ensuring that the unsteady external water levels and inflow velocities generated after wave overtopping were directly incorporated into the analysis.

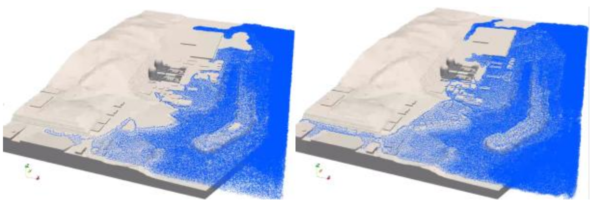
Fig. 2. 3D flood analysis for boundary-condition setup

2.2 Sensitivity analysis of SPH parameters

A sensitivity analysis of key SPH parameters was performed. Numerical parameters such as particle spacing (dp), fluid viscosity coefficient, and boundary treatment schemes were systematically varied because they significantly affect on interior water level rise and inflow discharge through openings. The corresponding changes in door gap inflow discharge, interior water depth, and the onset time of stair inflow were analyzed. This enabled evaluation of model stability as well as the trade-off between resolution accuracy and computational cost. In addition, the modeling framework was validated against benchmark dam-break test cases reported in previous studies, including Kleefsman et al. (2005) and Crespo et al. (2007b), which are widely used references for SPH validation in free-surface flow problems.

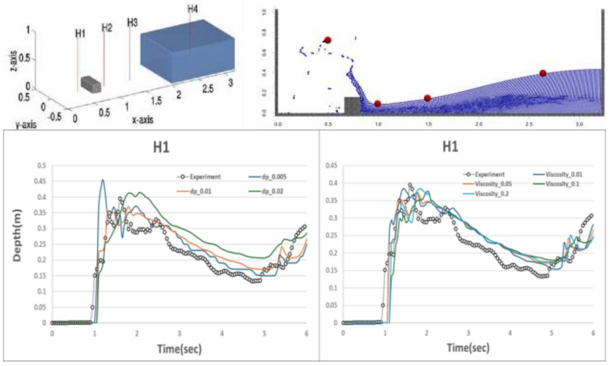

Fig. 3. Validation using the dam-break test case (Kleefsman et al., 2005)

2.3 Model configuration

The computational domain was constructed to represent the actual building geometry. The domain size was set to 98 m × 63 m × 5 m for the ground floor and extended to a total height of 10 m when including the basement level. The main opening was defined as a roll-up door with a width of 6.8 m and a height of 4.8 m, with a 5 cm gap at the bottom to represent the water ingress path. The external boundary conditions for water level and velocity were provided from the three-dimensional inundation analysis described above. This configuration enabled direct simulation of inflow through the roll-up door gap, interior storage of water, and subsequent propagation into basement spaces via stairs.

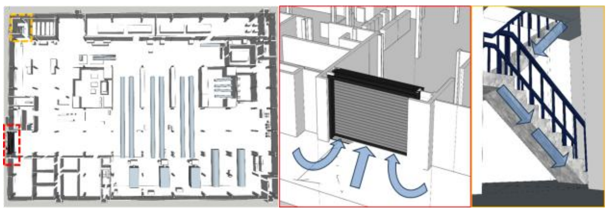

Fig. 4. 3D drawing of the building interior (SketchUP)

3. Results

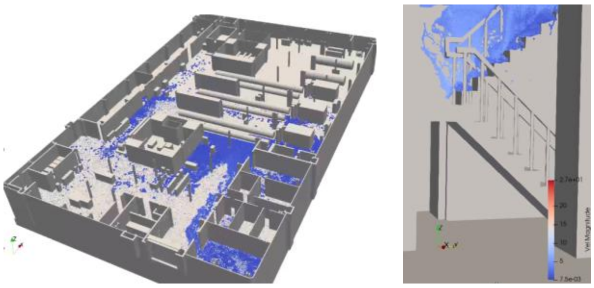

Fig. 5. Results of flooding inside the building and on the stairs

This study presented an analytical framework that links external flood conditions (localized intense precipitation and storm surges) with internal ingress pathways (roll-up door gaps and stairwells) to simulate the flooding process inside a coastal nuclear power plant building. Three-dimensional inundation analysis results were employed as external boundary conditions, and an SPH-based model was applied to simulate the inflow through openings, interior storage, and propagation into basement spaces. Through this approach, the sequential process by which external water levels lead to interior flooding was qualitatively demonstrated, showing that the proposed methodology can be utilized for flood risk assessment of critical infrastructure such as nuclear power plants. In particular, sensitivity analysis of key parameters and comparison with established dam-break benchmark cases confirmed the applicability and reliability of the modeling framework.

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