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Development of a Real-Time Flood Prediction and Early Warning System for Underground Spaces

Song I Lee*, Jinhyeok Kim**, Kwanghyun Kim***, Jonghwan Kang**** , Hwandon Jun*****

Seoul National University of Science and Technology, Civil Engineering Systems, Water Resources Systems, Republic of Korea

Introduction

- Increase in localized torrential rainfalls due to climate change, including the extreme rainfall event that struck South Korea in August 2022
- Urbanization and population density lead to increased underground construction projects, such as the Yeongdong Transfer Center and Metropolitan Express Railway
- Enactment of the Serious Accidents Punishment Act (January 27, 2022), which holds company executives accountable for incidents resulting in one or more deaths or two or more injuries requiring hospital treatment for over six months
- Lack of studies on real-time flood forecasting and early warning systems to prevent casualties during underground flooding and to mitigate situations where evacuation becomes difficult
- In South Korea, excavation sites with depths less than 10 m are not subject to formal underground safety regulations and are only managed through a basic 'Excavation Site Inspection Checklist', leaving them in a regulatory blind spot
- Modeling of 'underground excavation sites' among various underground spaces, such as subway stations and underground roads, considering inflow patterns and worker movement for grid-based hazard value (hv) estimation of evacuation routes
- Development of a real-time flood forecasting and warning system by constructing an 'Early Warning Nomograph' for watersheds containing underground excavation sites, using the 2D hydraulic analysis program XP-SWMM

Methodology

1. Establishment of a Methodology for Flood Risk Assessment

- (Eq. 1) is an empirical formula derived from full-scale hydraulic experiments, where flow rates were increased by 5% increments to evaluate the stability of test subjects (Abt et al., 1989)
- The critical condition for human instability under rapid flow was determined using the height and weight of each test subject

$$hv_c = 0.0929(e^{0.001906Lm+1.09^2}) \cdots (Eq. 1)$$

- (Eq. 2) estimates human instability as a function of flow velocity (V_0) and projected area (A), which is dependent on water depth (Lee et al., 2016)
- To quantify the instability caused by debris flow exerting the same maximum drag force as that generated under general rainfall inflow, the drag coefficient was recalculated based on standard anthropometric data of South Korea

$$F_d = \frac{1}{2} A\rho {V_0}^2 C_D \cdots (Eq. 2)$$

- Since stormwater inflow caused by torrential rainfall at underground excavation sites is highly likely to contain debris flow, the attenuation coefficient of flow velocity is applied to calculate the critical hv value (hv_c) that may lead to human casualties (Table. 1)

Table. 1 Comparison of hv_c on the flood and mud flow condition according to the age and gender (Lee et al., 2016)

Group	Age group	hv_c	
		Flood	Mud flow
Vulnerable group	Children	1.006	0.749
	Elderly	1.150	0.856
Non-vulnerable group	Adult male	1.282	0.955
	Adult female	1.147	0.855

- According to the 2024 Survey on the 'Living Conditions of Construction' in South Korea, average age of construction workers in 2024 was 51.8 years
- At excavation sites, temporary stairs or ramps are typically installed to connect the construction area and the top of the excavation, serving as pedestrian access routes for workers
- In this study, the evacuation route at the underground excavation site was configured as a ramp, and the critical hv values(hv_c) for the evacuation grid cells was set to **0.856**, based on the value corresponding to the elderly group when exposed to debris flow
- Testbed modeled using ArcGIS; 'Hazard occurrence time' defined as the moment any evacuation grid cell exceeds the hv_c threshold of 0.856 through XP-SWMM

2. Modeling of Underground Excavation Sites

- Excavation site selected in the left-bank basin of Yeondeung Stream, Yeosu city —an urban coastal area prone to frequent flooding due to combined effects of tidal, riverine, and inland water (Fig. 1)
- Pedestrian ramp from the testbed entrance to the bottom of the excavation constructed at a 19° slope, with the lower section of the site measuring 5 m in width and 24.51 m in length (Fig. 2)

Fig. 1 Location of Hypothetical Excavation Site

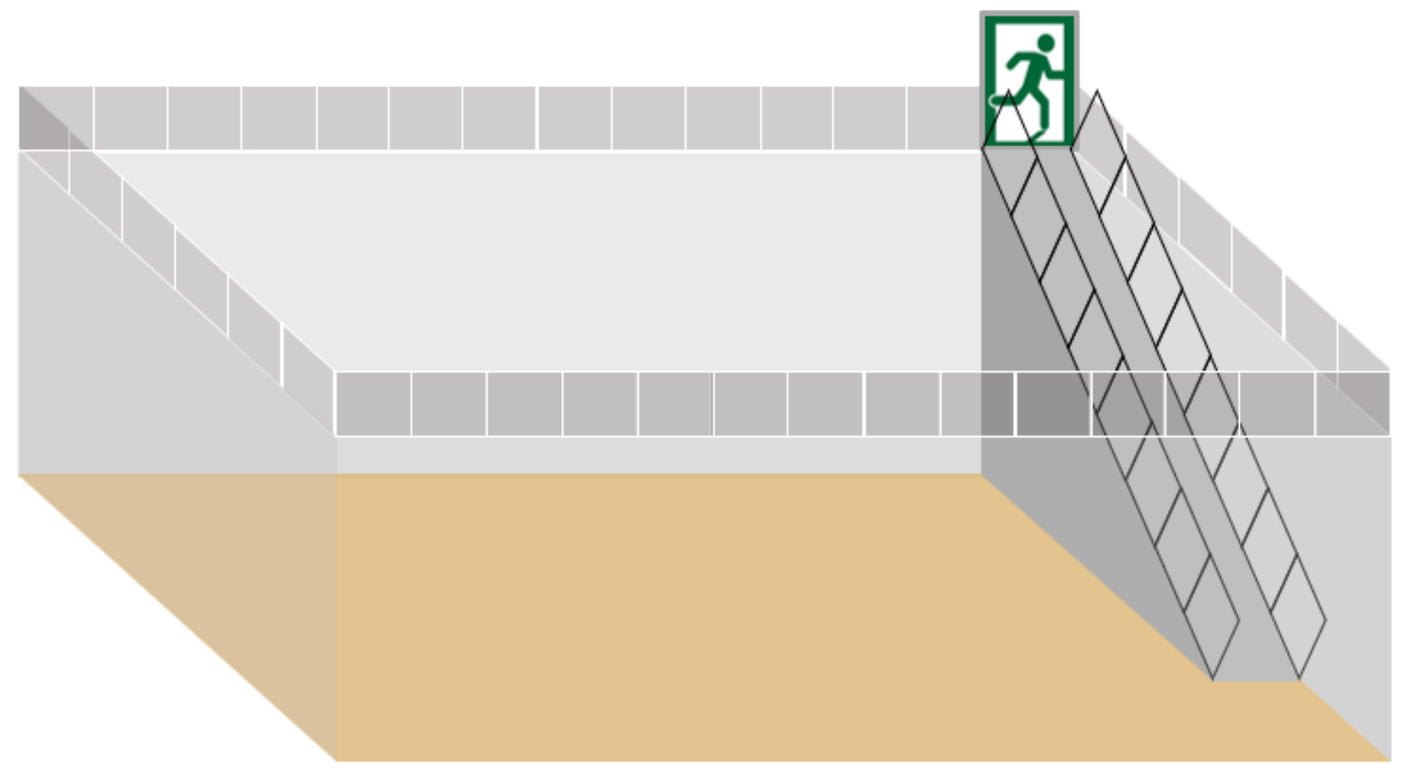

Fig. 2 Schematic Diagram of a Hypothetical Excavation Site

- 5 m × 5 m resolution DEM generated by modifying the original ground elevation to reflect the terrain of a virtual excavation site, including the pedestrian ramp and excavated bottom
- The modified DEM was generated by converting the original raster to elevation points, editing grid-based elevation values, and re-converting to raster using Arc-GIS (Fig. 3)

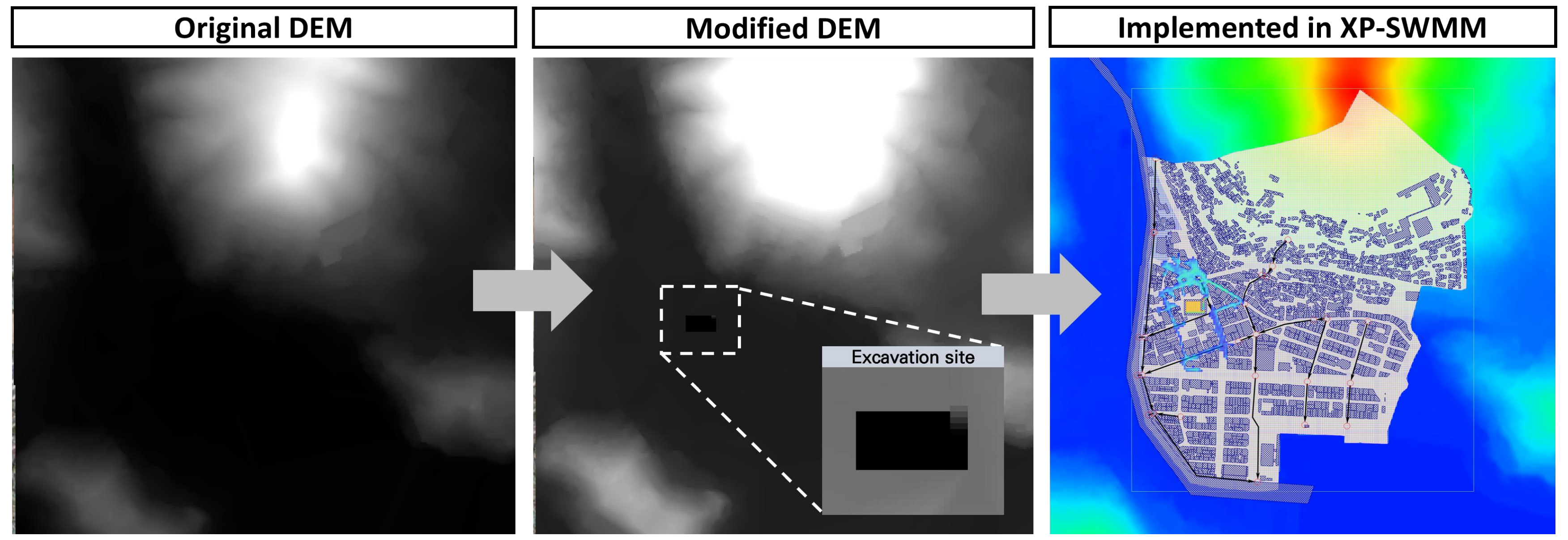

Fig. 3 Modeling and application of an underground excavation site through elevation point adjustment

3. Development of Rainfall Scenarios

- Combination of observed rainfall (via ground gauges) and forecasted rainfall (via radar)
- Observed rainfall divided into 11 intervals from 0 to 50 mm at 5 mm increments; forecasted rainfall similarly divided, resulting in 121 combined rainfall scenarios
- Simulation of worst-case evacuation scenario by combining 1hr observed and 30 min forecasted rainfall, distributed using Huff 4th and 1st quartiles
- Time to reach hv= 0.856 in each grid cell identified through XP-SWMM modeling and plotted on nomograph (Fig. 4)
- During system operation at the excavation site, observed and forecasted rainfall are periodically updated, and the risk level is assessed based on the latest rainfall data

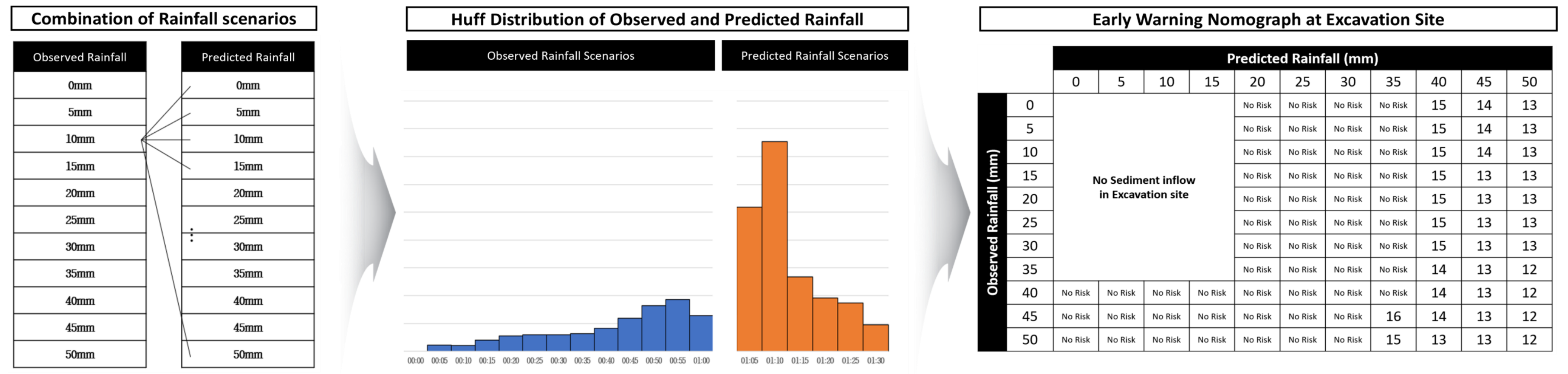

Fig. 4 Process of Creating Rainfall Scenarios Based on Observed and Predicted Rainfall

Application results and Discussion

- As predicted rainfall increases under fixed observed rainfall conditions, the number of overflowing nodes rises, expanding the inundation extent within the modeled basin and increasing water depth inside excavation site (Fig. 5)
- In the scenario with 35 mm observed rainfall, predicted rainfall above 35 mm results in grid cells exceeding the hv_c threshold, with risk appearing on the evacuation route within 16 minutes from the current time (Fig. 6)
- hv_{max} values and risk occurrence times for evacuation grid cells vary by terrain and overflow node characteristics within each target watershed

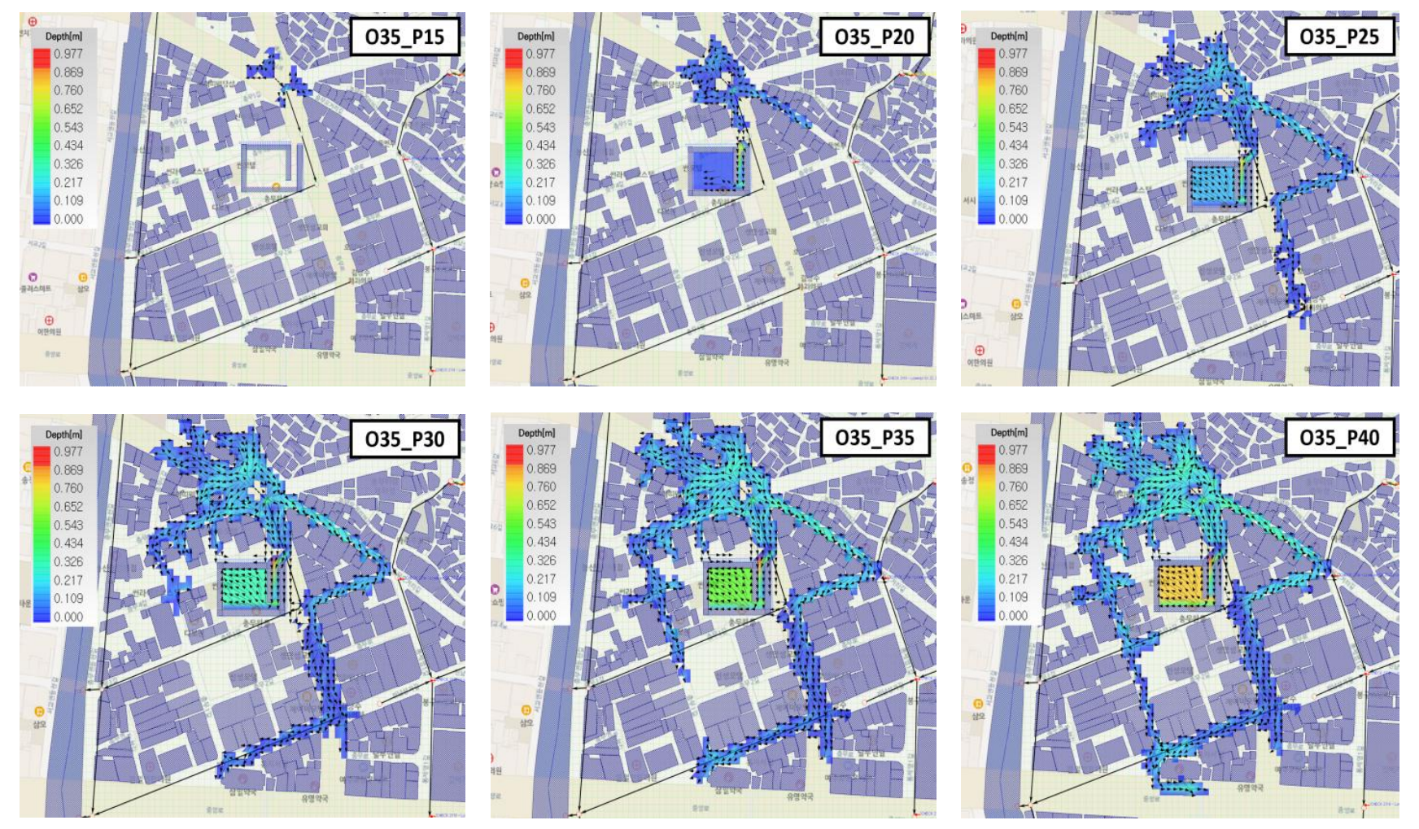

Fig. 5 Inundation Extent for O35 Rainfall Scenario

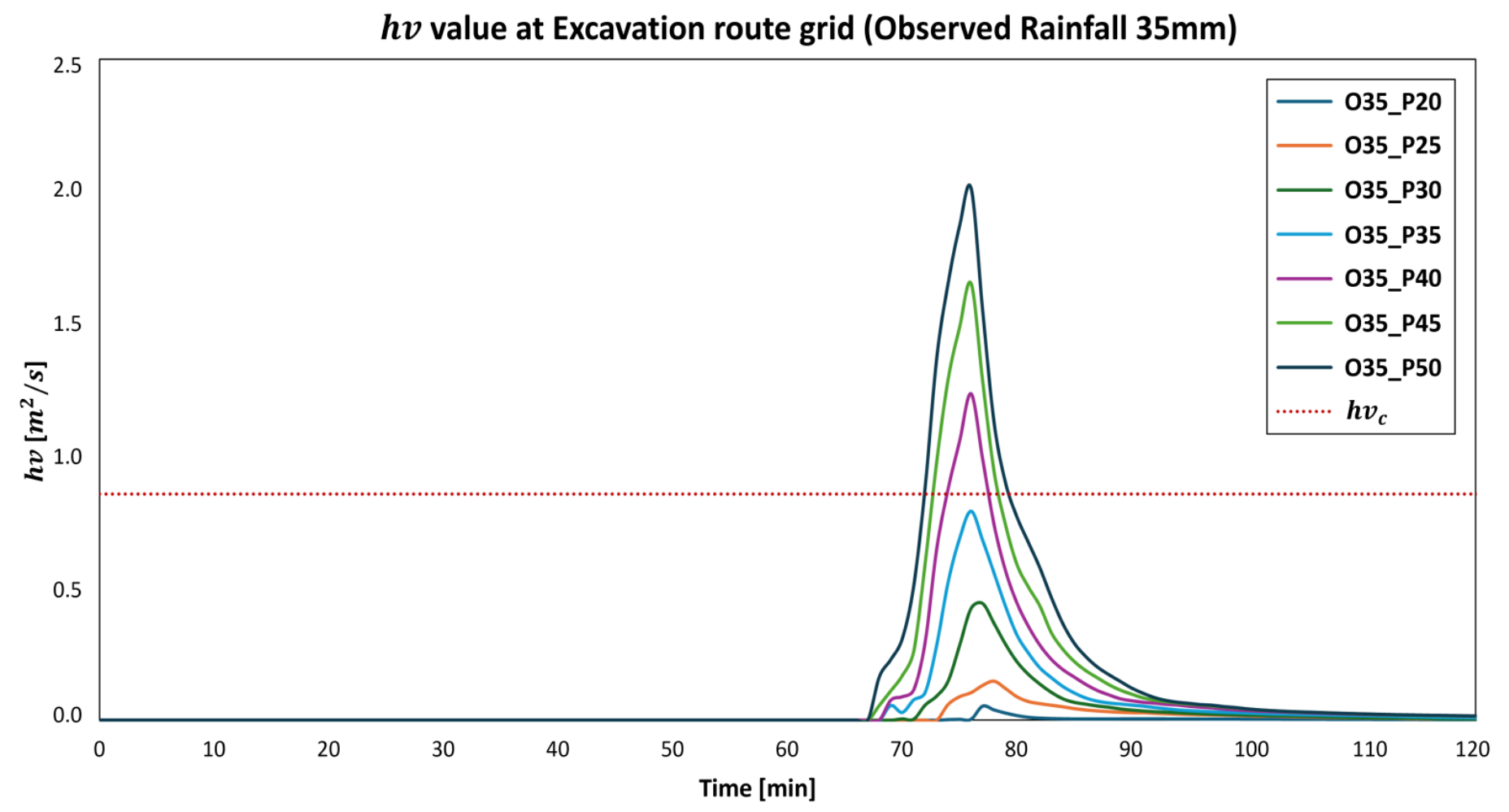

Fig. 6 hv value graph for O35 Rainfall Scenario

- Although hv does not exceed hv_c(=0.856) and is classified as 'No risk' on the nomograph, additional analysis of hv_{max} reveals many cases with values above 0.850
- For such cases, field conditions may lead to sudden risk; if hv_{max} is within 10% of hv_c, 'Warning' is assigned and if within 10-20%, 'Caution' is assigned (Fig. 7)
- Even with observed rainfall, the risk on evacuation routes significantly increases depending on the predicted rainfall
- To secure lead time for evacuation, it is essential to consider not only current observed rainfall but also forecasted rainfall in combination (Fig. 8)
- In the modeled Yeondeung River watershed, steep pipe slopes were found upstream near mountainous areas, while gentler slopes in urban zones near the excavation testbed caused most overflows to occur at nearby nodes (Fig. 9)
- Prior to nomograph development, a time-series overflow volume analysis was conducted at each node

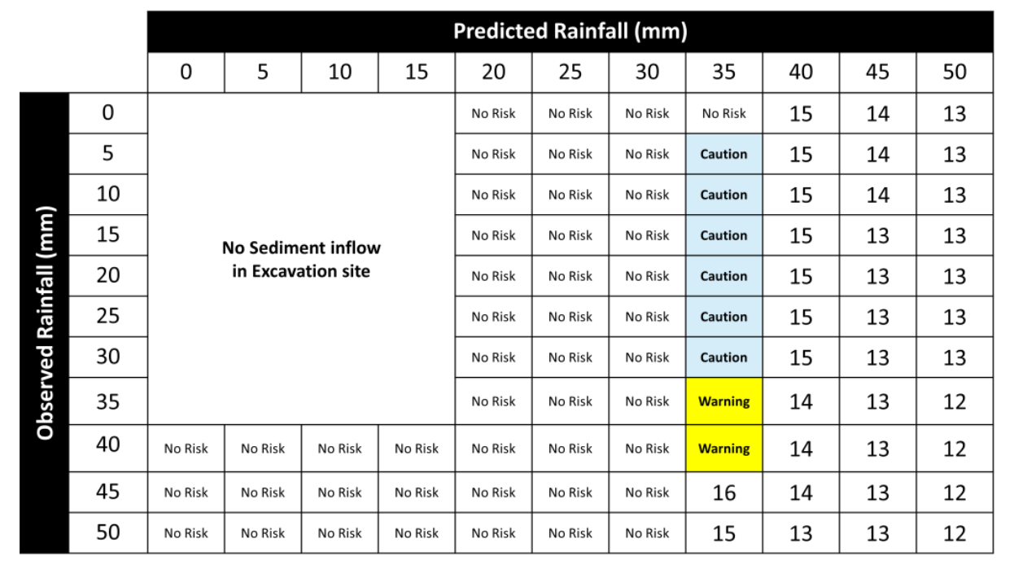

Fig. 7 Nomograph reflecting Safety Factor

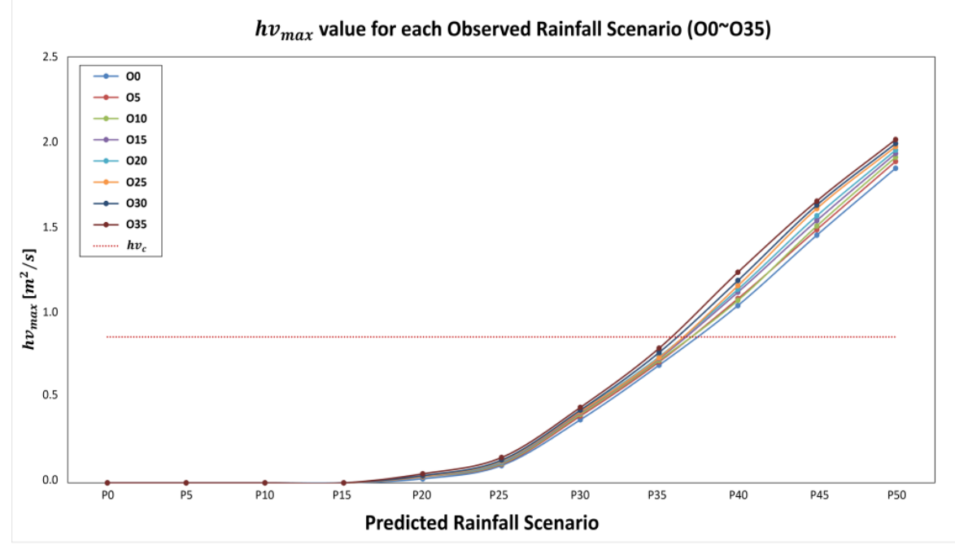

Fig. 8 hv_{max} value for O0~O35 scenario

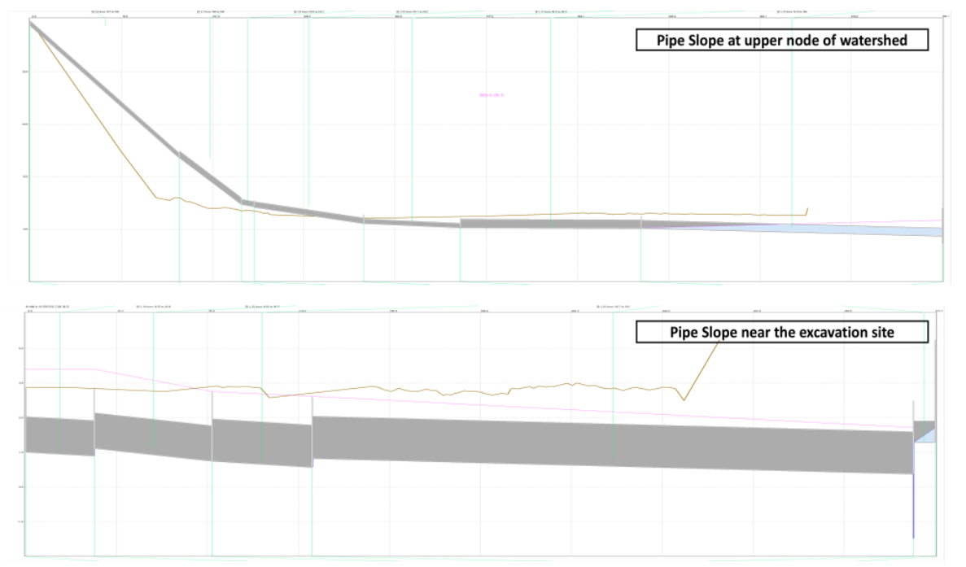

Fig. 9 Comparison of pipe slope

Conclusion

- The nomograph developed in this study enables pre-identification of risk occurrence time along evacuation routes for each rainfall scenario, securing lead time for worker evacuation
- Distributing the nomograph to on-site managers allows real-time risk assessment based on minute-level variations in rainfall during extreme events
- Risk occurrence times and hv values for each scenario may vary significantly depending on terrain characteristics and overflow node behavior within the target watershed
- To improve accuracy, 2D hydraulic analysis results should be combined with topographic and surface flow analyses tailored to the specific watershed where the construction site is located

Acknowledgement

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