SUBGRID SCALE MODELING OF STORM SURGE INUNDATION IN COASTAL URBAN AREA CONSIDERING VOLUME OF BUILDINGS

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INTRODUCTION

The increasing intensity of typhoons associated with climate change is projected leading to a higher risk of coastal inundation in Japan's three major metropolitan areas. Therefore, assessing the long-term risk of the coastal urban flooding and its impact on human lives and assets has become a significant challenge in Japan's coastal hazard mitigation. Therefore, it is essential to understand the fluid dynamic characteristics during inundation using numerical models. In recent years, numerical modeling has been performed using high-resolution topography data of less than 10 m resolving buildings (e.g., Takagi et al., 2016). However, inundation simulations at resolutions of O(10) to O(100) m are still important from a computational load perspective. Fukui et al. (2022) have developed an urban inundation model using a subgrid model of iDFM (individual Drag Force Model) to represent buildings within grid cells and provide feedback on the drag force of building groups to the fluid flow. They conducted flood simulations at resolutions ranging from 20 m to 50 m. However, addressing the consideration of building volumes in the mass conservation equation remains a challenge, which is the aim of this study.

COMPUTATIONAL METHOD

The storm surge model, SuWAT (Kim et al., 2015), based on the depth-averaged shallow water equations, is used for the numerical model of storm surge inundation. In the momentum conservation, the original iDFM (iDFM-v1) model considers buildings using drag force as following equation (1);

$$F_D^x = N_b \times \frac{1}{2}\rho C_D \bar{A}_x \frac{M\sqrt{M^2+N^2}}{D^2}\frac{d}{D}\frac{1}{\Delta x \Delta y} \tag{1}$$

where N_b and $\bar{A}_x$ are the number of buildings in a grid cell and characteristic projected area as subgrid-scale parameters, and C_D, ρ, D, M, N, Δx, Δy and d are the drag coefficient, water density, total water depth, discharge fluxs in x- and y-directions, computational grid size in x- and y-directions, and effective depth which is the height of water column applying drag force, respectively. In this study, the new iDFM (iDFM-v2) is developed based on the sophistication of mass conservation as follows;

$$\phi\frac{\partial \eta}{\partial t} + \frac{\partial \phi M}{\partial x} + \frac{\partial \phi N}{\partial y} = 0 \tag{2}$$

where η and t are the water surface elevation and elapsed time. The wet fraction ϕ is calculated as a ratio of the water volume to water and building volume in every time step using high-resolution topography given by

$$\phi = \frac{1}{\Delta x \Delta y D_{i,j}} \sum_{ii,jj} D_{ii,jj}^{SG} \Delta x^{SG} \Delta y^{SG} \tag{3}$$

where

$$D_{ii,jj}^{SG} = \begin{cases} h_{ii,jj}^{SG} + \eta_{i,j} & (h_{ii,jj}^{SG} + \eta_{i,j} > 0) \\ 0 & (h_{ii,jj}^{SG} + \eta_{i,j} \le 0) \end{cases} \tag{4}$$

Here, $h_{ii,jj}^{SG}$ and $D_{ii,jj}^{SG}$ are the still and total water depths at ii-th and jj-th subgrid cells, and $h_{ii,jj}^{SG}$ includes the topography information, including building height. Also, $D_{i,j}$ and $\eta_{i,j}$ denote the total water depth and water surface elevation at the computational grid cell. The increase of the water surface and inundation depth is expected by this sophistication since water volume exclusion by buildings can be considered.

NUMERICAL SETUP OF TOKYO BAY CASE

This study presents a performance test applying the iDFM-v2, v1, and conventional regional roughness model based on land usage categories. Figure 2 shows the coastal urban area of Tokyo Bay, the computational domain, and the 3D city view of PLATEAU.

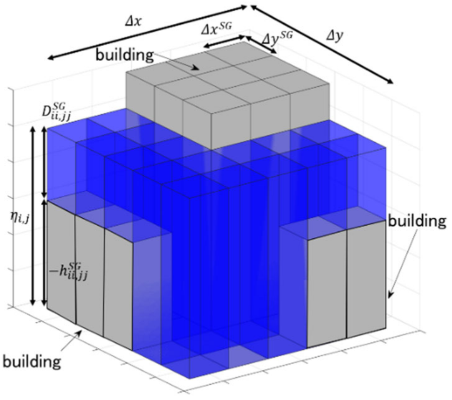

Figure 1 - Schematic view of a subgrid variable to calculate the wet fraction

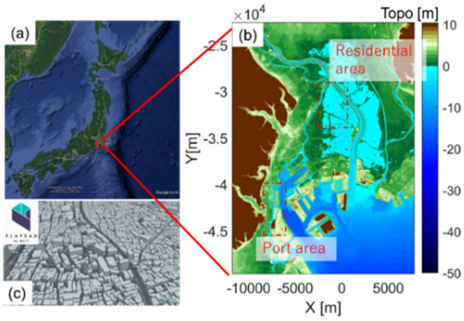

Figure 2 - Location of Tokyo Bay (a), computational domain (b), and view of the 3D city model PLATEAU (c)

The result of the pseudo-global warming simulation of typhoon Hagibis by Kawase et al. (2021) is used as a meteorological field. The horizontal resolution Δx of SuWAT is from 2430 m (D1) to 30 m (D5) using a topography dataset from the Central Disaster Management Council of the Cabinet Office. The computational time step (Δt) was set to 1 sec. The subgrid-scale parameters of buildings, $\bar{A}_x$, N_b, etc., are preliminarily calculated using the 3D building shape data based on PLATEAU (see Figure 2c).

RESULTS AND DISCUSSIONS

The model difference of the maximum inundation depths is first described. Figure 3 shows the relative difference between the maximum inundation depths of iDFM-v2 to iDFM-v1 in the port and residential areas. In both areas, the inundation depth in iDFM-v2 tends to increase, with an average increase of 15.3% and 104.4% for the port and residential areas, respectively. When calculating the water level in the mass conservation (Eq. (2)), the inverse of the wet fraction ϕ (>1) is multiplied, and then the water level becomes larger at the next time step. This process represents that the water level rises due to the buildings.

The characteristic of the relative difference in inundation depth varies with the region. Figure 4 shows the cross-sectional distribution of inundation depths, maximum momentum fluxes, and elevations for CS1 (Port area) and CS2 (Residential area). Here, CNTL denotes the regional roughness model case as a reference run. In CS1 (port), the elevation increases abruptly when the run-up distance exceeds 500 m. The results show that the flooding depths in the models are insignificant.

On the other hand, the differences in momentum flux show a trend of CNTL>iDFM-v2> iDFM-v1: the average of the momentum flux in the iDFM-v2 is 43% larger than that in iDFM-v1. The discharge flux calculated in the momentum conservation is found to be proportional to the inverse of the wet fraction ϕ in the momentum conservation law. In CS2, located in a low-lying area, the difference in the inundation depths is relatively more significant than that in CS1. The inundation depth in the iDFM-v2 model is an average of 60.8% and 76.7% larger than those in iDFM-v1 and CNTL. Also, the momentum flux in the iDFM-v2 model is more significant than that in iDFM-v1, the same as CS1. These two cross-sections show that inundation depths in iDFM-v2 tend to be largely calculated compared to those in iDFM-v1. As a result, such characteristic is clarified when the area with low ground elevation is widely inundated.

CONCLUSION

This study presented the newly developed subgrid model of storm surge inundation in a coastal urban area considering the building volume. The wet fraction updated the mass conservation in a grid cell. The performance test shows that iDFM-v2 has a common tendency to model larger inundation depths than iDFM-v1 and that the increase depends on the topography. Therefore, optimizing the drag coefficient according to the target area ,building shape characteristics, and improving the method of giving the wet fraction are recommended. Further validation using building-resolving simulations using high-resolution topography will be presented at the conference.

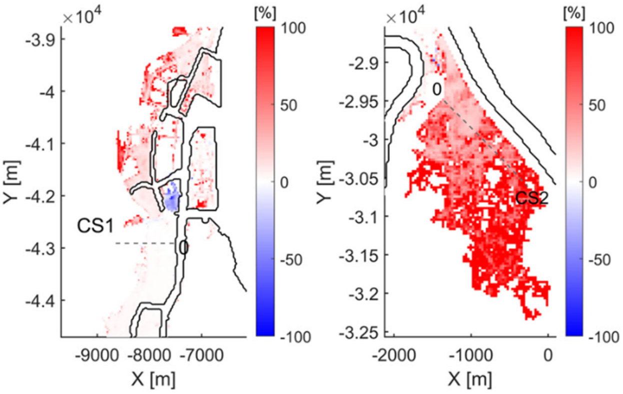

Figure 3 - Relative difference of the inundation depth between iDFM-v1 and v2; (v2 - v1)/v1 in the port area (left) and residential area (right)

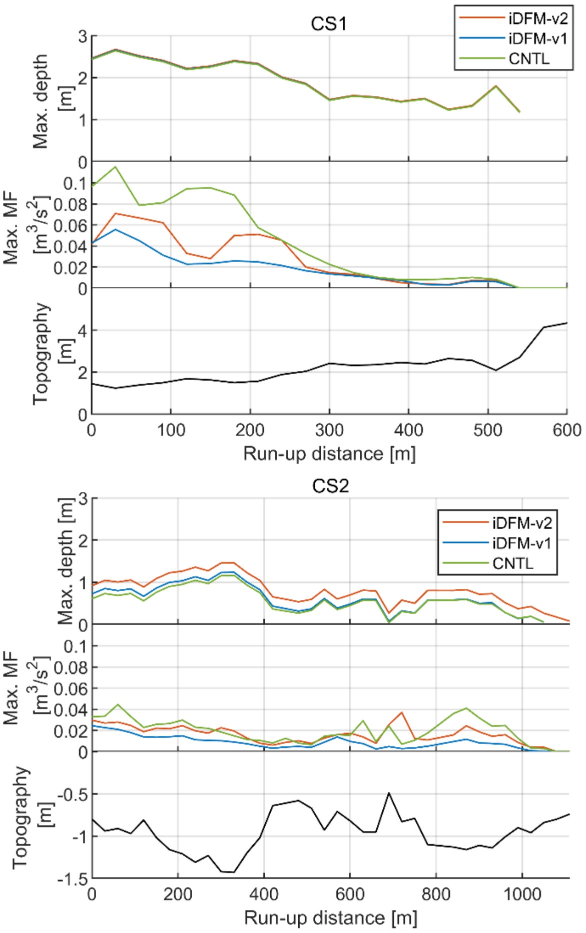

Figure 4 - Spatial distribution of maximum values, inundation depth (top) and momentum flux (middle), and topography (bottom) along CS1 and 2

REFERENCES

Fukui, N., Mori, N., Miyashita, T., Shimura, T., Goda, K. (2022) Coastal Engineering, ELSEVIER, vol. 177, 104175.