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Numerical Computation of Underground Inundation in Multiple Layers Using the Adaptive Transfer Method

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Abstract: Extreme rainfall causes surface runoff to flow towards lowlands and subterranean facilities, such as subway stations and buildings with underground spaces in densely packed urban areas. These facilities and areas are therefore vulnerable to catastrophic submergence. However, flood modeling of underground space has not yet been adequately studied because there are difficulties in reproducing the associated multiple horizontal layers connected with staircases or elevators. This study proposes a convenient approach to simulate underground inundation when two layers are connected. The main facet of this approach is to compute the flow flux passing through staircases in an upper layer and to transfer the equivalent quantity to a lower layer. This is defined as the 'adaptive transfer method'. This method overcomes the limitations of 2D modeling by introducing layers connecting concepts to prevent large variations in mesh sizes caused by complicated underlying obstacles or local details. Consequently, this study aims to contribute to the numerical analysis of flow in inundated underground spaces with multiple floors.

Keywords: underground inundation; flood modeling; adaptive transfer method; layer connection

1. Introduction

1.1. Significance of Underground Inundation Analysis

Examination of the flood disaster damage data for 2000 to 2010, taken from the international disaster data server EM-DAT in the CRED (Center for Research on the Epidemiology of Disaster), shows that Asia is a region vulnerable to flood disasters, with 70% of the global casualties (3949 per year) and 50% of the global economic damage ($1 billion USD per year). These conditions also apply to the Republic of Korea: major cities are experiencing increased localized heavy rainfall, and the effective rainfall is not completely contained by the sewage collection system. This causes pluvial urban flooding. The risk of flood damage has increased because of intensive urbanization and associated densification of infrastructure [1]. Consequently, the risk of underground flood damage has increased because the number and diversity of underground facilities that can be damaged in urban areas has also increased.

In recent years, underground space utilization has increased because it provides a solution to the lack of available land for construction in built-up metropolitan areas. Currently, 1170 buildings in Republic of Korea are connected to underground tunnel ways or metro facilities. In the Republic of Korea, underground buildings that have at least 11 floors or a personnel capacity of 5000 are known as underground connected complex buildings. Urban underground spaces have many high density operating facilities, such as subways, underground passages, markets, parking lots, and underground substations. These underground spaces are closed from the open air. Increases in the frequency, duration, and scale of rainfall events have the potential to create a dysfunctional city with complex logistical problems and physical damage. Rainfall in urban areas flows underground as a result of gravity; rainwater on the streets reaches underground spaces by various routes. Rainfall entering underground stairways, in particular, may cause flood damage because it has a rapid velocity even at shallow depths, and therefore its excessive pressure and momentum may cause harm to people and damage to property.

In the case of extreme rainfall, the surface runoff flows toward lowlands, and subterranean facilities are vulnerable to catastrophic submergence. In addition, the basements of skyscrapers generally contain shopping centers, electrical power systems, garages, or warehouses. During floods, the infrastructure inside buildings in lowlands can be severely damaged. The floods frequently paralyze transportation networks, submerge automobiles under water, damage property, and cause breakdowns in the electrical power grid. The typical recovery time for normal operations to resume after a flood disaster can vary between a few weeks and several months. This leads to considerable financial losses and significant budgets are required for reconstruction, which, in turn, have serious economic and social consequences.

1.2. Previous Studies and Selection of Model Dimension

Existing research concerned with urban flooding has usually been at the basin scale [2] and usually involved: inundation analysis targeting province [3], sewer network analysis [4], and impact evaluation of flood prevention measures [5]. Recently, various models and techniques were applied to predict flooding, inundation, and its vulnerability in advanced approaches [6–9]. However, there is a lack of hydrodynamic-based modeling that analyzes, in detail, the flow through underground access stairways or the flow characteristics through underground structures that link upper and lower layers in complex underground areas.

Although many numerical models have been developed and successfully applied to reproduce flood inundation, most of the models only address overland flow or urban sewer systems. In these contexts, flood modeling of underground space was not adequately studied because there were difficulties in reproducing the associated multiple horizontal floors connected by staircases or elevators. The flood inundation of complex buildings with underground connections can be accurately analyzed using 3D numerical modeling. However, the application of 3D models that describe changes that occur over all three spatial dimensions is very costly. Furthermore, the modeling of inundation areas spanning upper and lower levels with steep elevation differences using a 3D model may require high density grids that will result in high computation costs and/or lengthy computation times. Therefore, to the best of the authors' knowledge, there is no literature analyzing the underground inundation with full-3D model. In addition, most of the engineers, designers or policy makers are concerned with representative behavior of the flooding. In these situations, 2D flow modeling with layer connections (Figure 1) is a favorable option because of its efficiency and reasonable predictability.

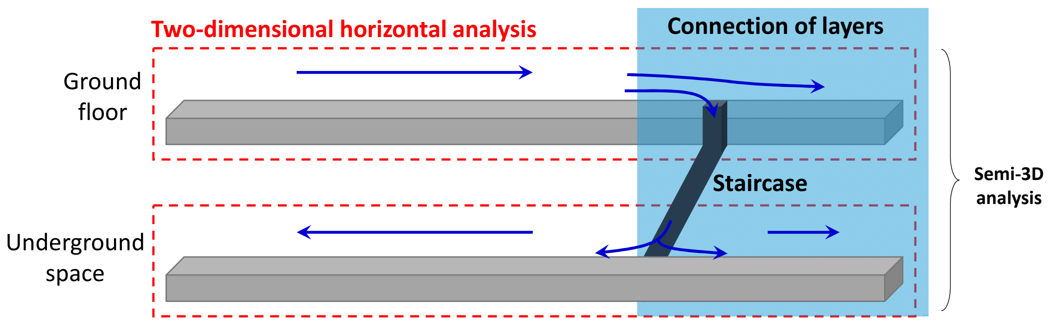


Figure 1. Inundation analysis in two layers.

In addition, models need to be at least 2D to predict the flooding patterns of underground areas because of the need to calculate the propagation of longitudinal and transverse flow with submerged depth. Accordingly, by considering highly variable flow fields in a horizontal plane with moderate inundation depths, urban flooding can be well predicted by shallow water flow modeling.

1.3. Research Objectives

In this study, an adaptive transfer method (ATM) is newly proposed to analyze sequential inundation phenomena occurring in two floors inside a building. This method overcomes the limitation of 2D modeling by introducing the layer connecting concept to prevent large variations in mesh sizes caused by complicated underlying obstacles or local details. Consequently, this study aims to contribute to the numerical analysis of flow routing of inundated underground spaces with multiple floors. The approach employed in this study can be helpful in designing realistic and effective flood management strategies or mitigating flood damage (see [10–13] for previous studies on mitigating flood damages in-house scale).

This study is organized in the following order. Section 2 provides the fundamental concept of ATM, and its procedure. Section 3 contains the validation of inundation analysis model by comparing with the experimental data set in previous literature. In Section 4, the validated numerical model is applied to a mid-size building with underground space. Section 5 addresses the conclusions and future studies.

2. Connection of Underground Inundation in Two Layers

This study proposes a practical approach for simulating underground inundation occurring in two layers in a connective way. As shown in Figure 2, the main modelling concept used is to compute the flow flux passing through staircases in an upper floor and then to transfer the equivalent quantity to the lower floor. This is defined as the ATM in this study. The detailed ATM procedures are: (1) Complete the hydrodynamic modeling in ground floor by assigning appropriate initial/boundary conditions for flooding; (2) Based on the numerical results for velocity and flow depth at each node, evaluate the water discharge passing through a specific domain where staircases or elevators are located. Flow flux can be obtained by multiplying the discharge by the water density; (3) The flow flux is transported to the lower layer by an interlayer connection structure, which provides a discharge source that spreads out; and (4) Apply two sets of governing equations selectively to underground space. If water inflows from an interlayer connection structure, then shallow water equations with adaptive transfer terms (Equations (1) and (2)) should be employed for those elements. Otherwise, solve the general equations (Equations (1) and (2) without last terms).

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + h\frac{\partial u}{\partial x} + v\frac{\partial h}{\partial y} + h\frac{\partial v}{\partial y} = Eh\sqrt{u_j u_j} \quad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -g\frac{\partial (H+h)}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\frac{\partial u_i}{\partial x_j}\right) - gn^2\frac{u_i\sqrt{u_j u_j}}{h^{4/3}} - Eu_j u_j \quad (2)$$

where h is the flow depth; u and v are the depth-averaged velocities in x- and y-direction, respectively; E is the transfer coefficient adjusting the magnitude of the flow moving to downstairs; H is a bottom elevation measured from datum; ν is the kinematic eddy viscosity; and n is the roughness coefficient.

The developed inundation model has its origins in river flow analysis models [14,15] that have been adapted for various situations [16–18].

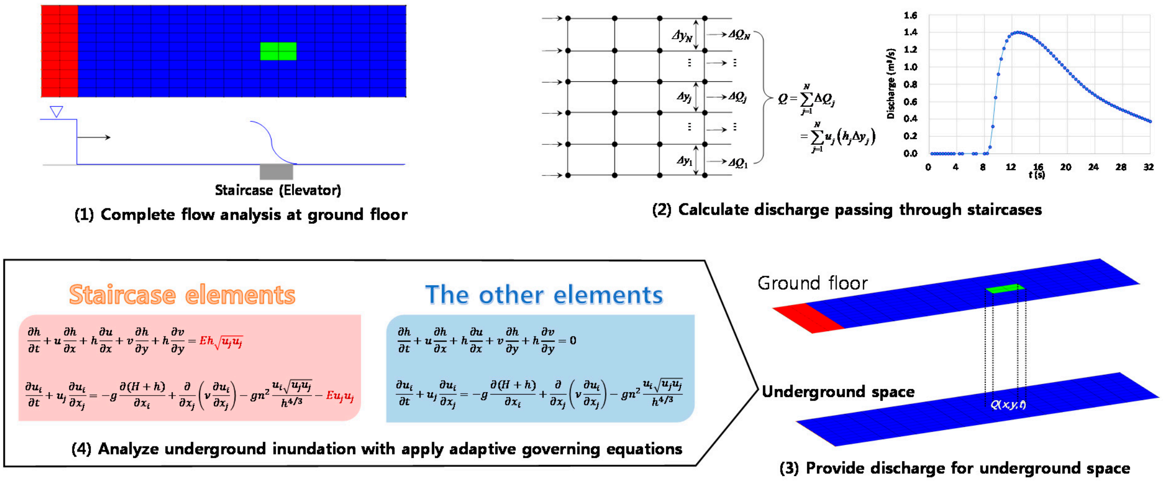


Figure 2. Representation of the ATM.

3. Inundation Analysis Model

Buildings and underground spaces in urban areas are vulnerable to flooding by torrential rain. To validate the performance of the numerical model mentioned in previous section, the experimental data set provided by Smith et al. [19] was used. They constructed a physical model (12.5 m long by 5 m wide) to reproduce the historical flood event that occurred in 2007 at the Morgan–Selwyn floodway in Merewether, Newcastle, Australia, and used hydraulic flume tests and Froude scaling relationships to determine the urban overland flow path for the extreme flood event. They recorded the model topography, water level, and velocity data at various survey points. Figure 3 shows the mesh layout and bathymetry contours. The holes in the mesh represent buildings which are treated as impermeable obstacles. As pointed out by Smith et al. [19], predicting flood flow characteristics in an urban environment can be complicated because buildings and other obstacles in the urban landscape significantly influence local flood properties. These flood properties include depths, flood surface gradients, the distribution of flood flows, and the magnitude of flood velocities. The complex conditions can be seen in Figure 3.

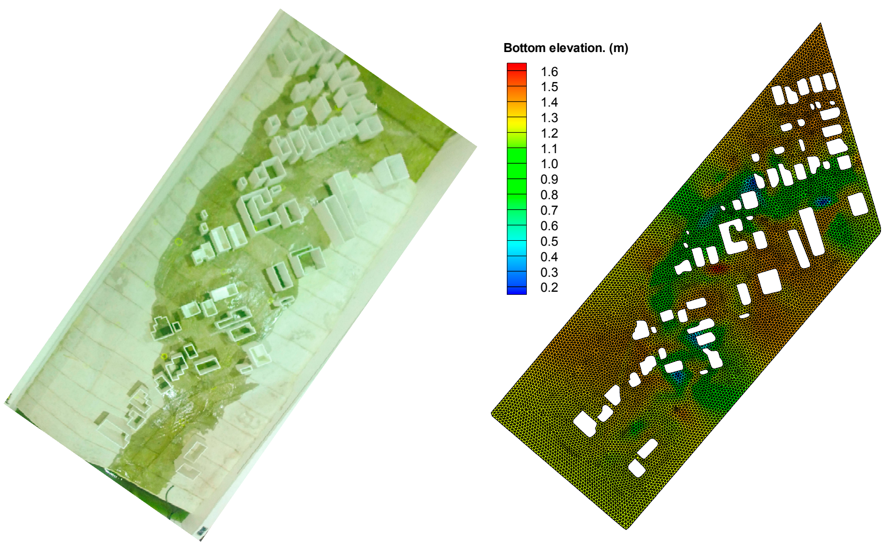


Figure 3. Model construction and configuration for analyzing urban inundation (**left**: experimental flume; **right**: FE mesh layout).

The roughness coefficient and the model run conditions (e.g., flow rate) were set to identical values used by Smith et al. [19]. As was discussed in Smith et al. [19], the inflow boundary condition was assigned as constant discharge of peak flow rate (19.7 m^3/s). The outflow section and two boundaries surrounding the flooded area had transmissive conditions, imposing free outflow conditions. The initial condition was dry bottom with zero velocity at every node. The model was run until it reached a steady state with those initial and boundary conditions.

A comparison of the modelled and measured flow depths at 22 points (solid dots in Figure 4a) are given in Figure 4b. Figure 4c illustrates the numerical results for the velocity vector. It was clearly found that buildings acted as obstacles to flow, and considerably affected the velocity configuration. Fast flow occurred along the distant side of a crowded building. The nine solid points in Figure 5a were used for velocity validation and the comparison results are plotted in Figure 4d. The results showed a reasonable match, and the average depth difference between the numerical and measured values was 6.2 mm. The relative error between measured and predicted velocity results was 3.34%, which indicated a reasonable agreement.

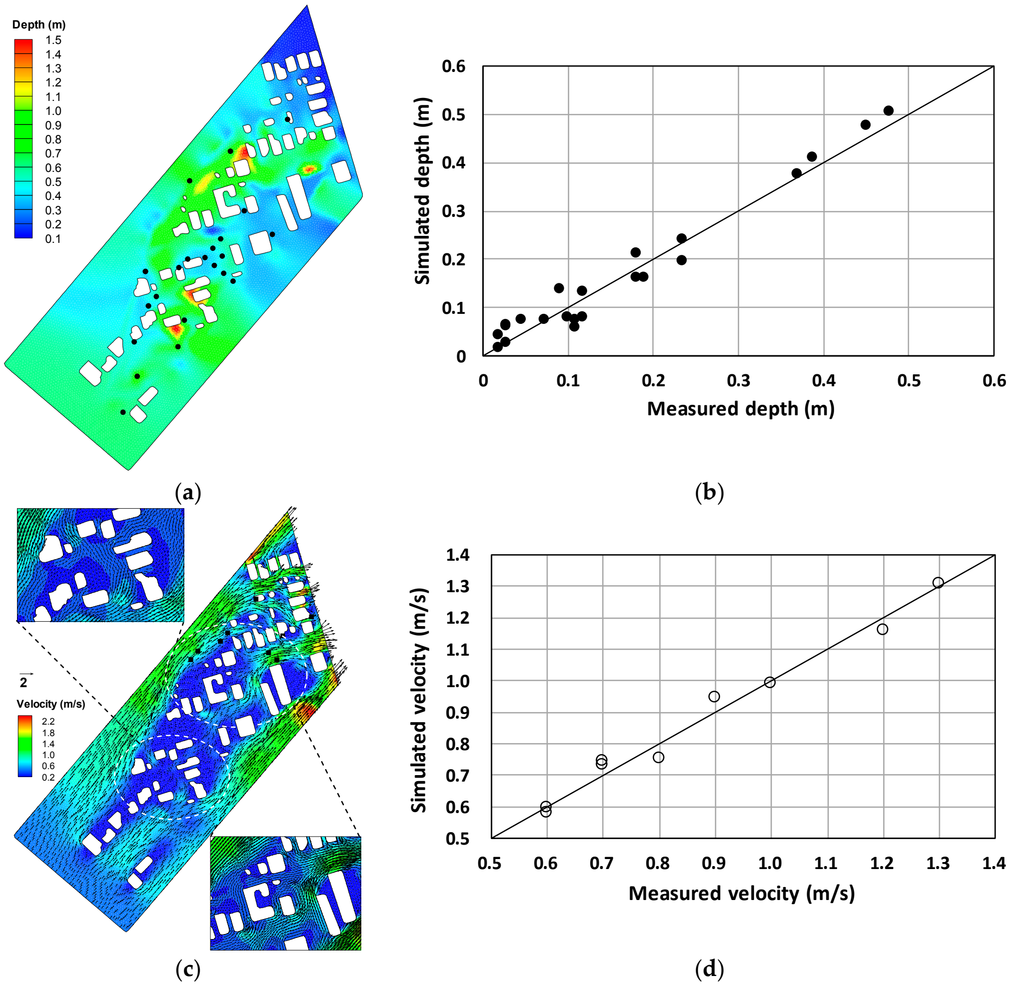
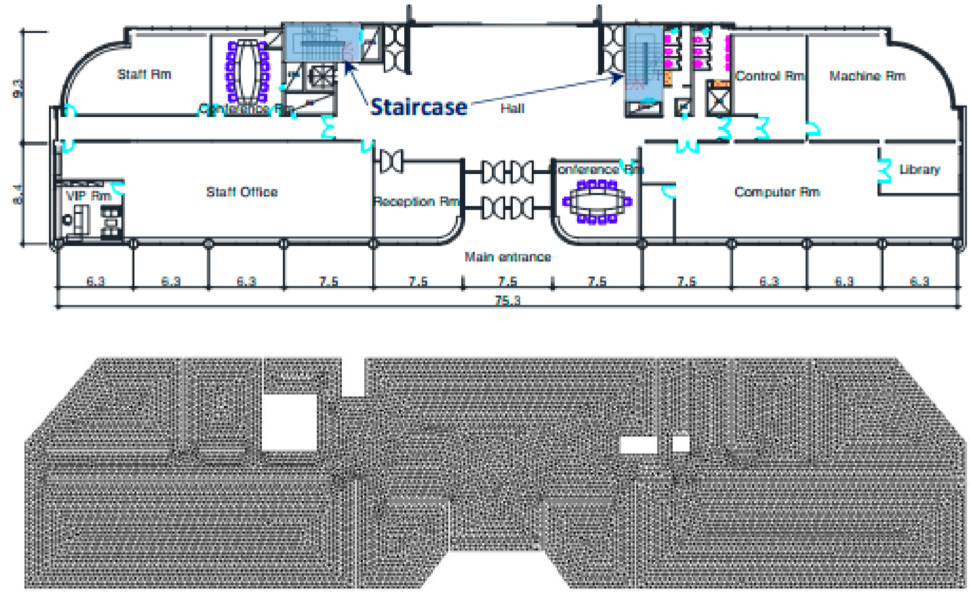
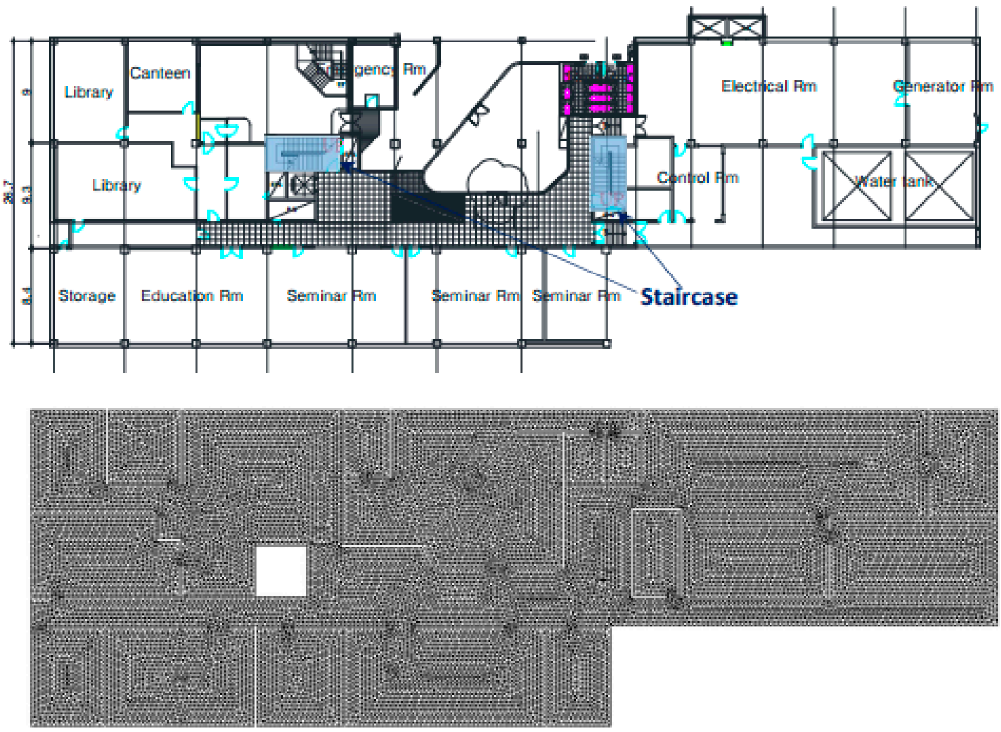


Figure 4. Comparison of inundation characteristics: (**a**) depth and comparison points; (**b**) scatter plot for depth comparison; (**c**) velocity vector; (**d**) scatter plot for velocity comparison.

The available data set or documentations to verify the performance of the ATM is very difficult to obtain. However, because the primary objective of present study is to propose an inundation analysis method which associates the ground floor and underground space, the applicability of the ATM approach was tested in a single building with two layers. Instead, the model performance of reproducing the flow over staircase was checked in previous study [20] by comparing the numerical results with experimental values and empirical equation.



(**a**)



(**b**)

Figure 5. Application site containing two layers: (**a**) ground floor (above: architectural design plan; below: mesh layout); (**b**) underground space (above: architectural design plan; below: mesh layout).

After confirming the feasibility of the model's performance for inundation prediction, we extended the application to multiple floor inundation through interlayer connection structures. The results are in the following section.

4. Underground Inundation in Two Layers by the ATM

The model developed was applied to the main building of the Korea Institute of Civil Engineering and Building Technology, located in Ilsan, Gyeonggi-do, Republic of Korea. This building is of moderate dimensions, has underground space with a number of separated rooms, and can therefore properly represent mid-size buildings with underground space. The architectural design plans for the ground and base floor are given in Figure 5, and the layouts of the triangular finite elements for inundation analysis are provided below.

In general, the shallow water flow model includes two adjustable coefficients of roughness and eddy viscosity. Because the surface material of the building floor was smooth concrete, the roughness coefficient was assigned as 0.011 [21]. According to the Smagorinsky model [22], the eddy viscosity was determined at each node using velocity gradient.

Three assumptions were made in the implementation of the numerical simulations: (1) water inflows from the main entrance at a constant depth of 1 m; (2) every door inside the building is open; and (3) water passing through the staircases from the first floor moves down to the basement.

Figure 6 shows the inundation depth contours. After the intrusion of water through the main entrance, the water fanned out in response to the two walls located nearby (Figure 6a). At t = 12 s, the flooded water collided with the opposite wall, bounced off it, and spread out in the room between the walls (Figure 6b). The inflowing water filled the hall for 24 s and rose up to 1 m (Figure 6d). At around 10 s, the ground floor water reached the staircases, and descended to the underground floor.

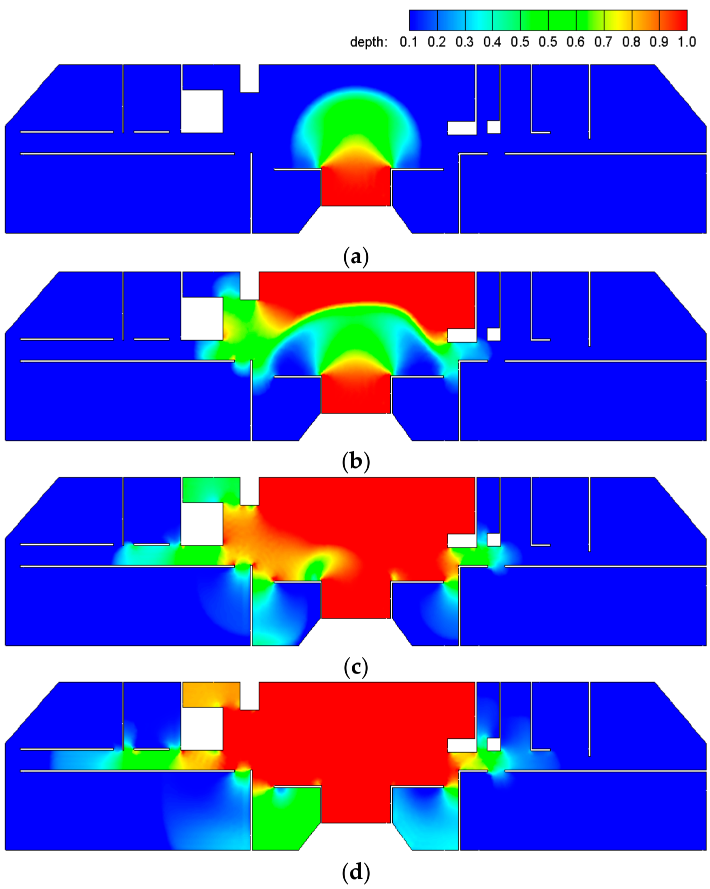


Figure 6. Configurations of inundation depth for the ground floor (unit of contour legend: m); (**a**) t = 4 s; (**b**) t = 12 s; (**c**) t = 18 s; (**d**) t = 24 s.

The velocity is formed in line with the configuration of inundation depth as illustrated in Figure 7. In the initial period, a maximum velocity exceeding 3.0 m/s was predicted in the vicinity of the main entrance, and propagated over the empty space. In Figure 7c,d, it can be clearly seen that the velocity in the gap (representing an open door) was significantly faster than in other areas.

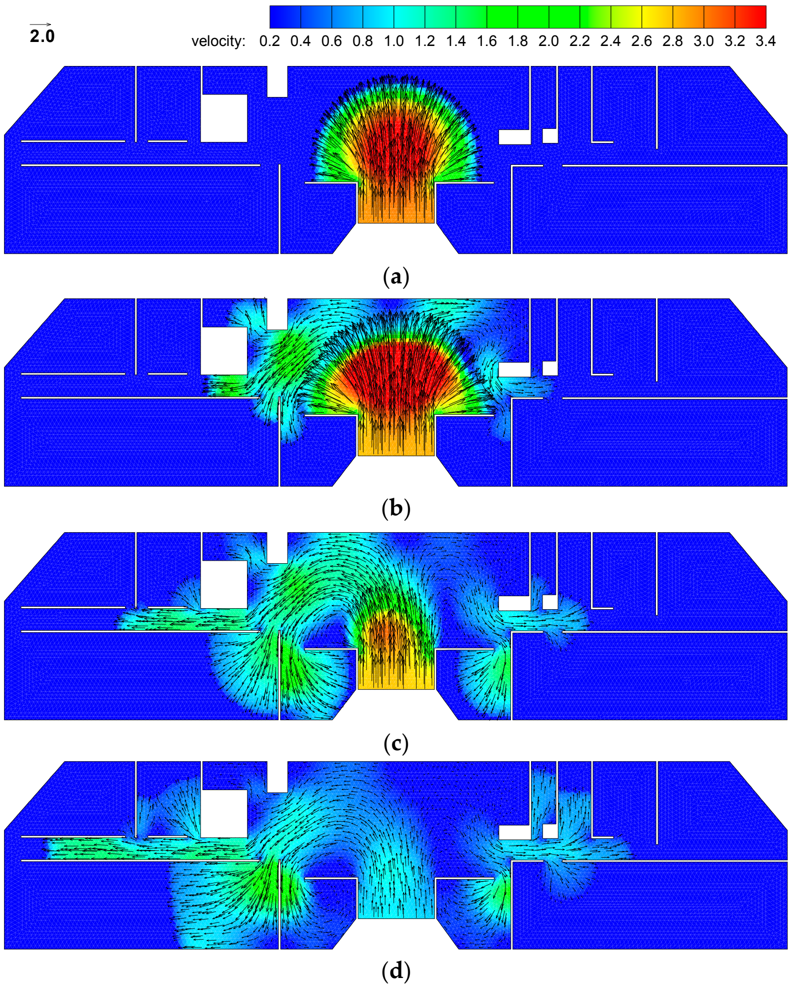


Figure 7. Configurations of velocity for the ground floor (unit of contour legend: m/s); (**a**) t = 4 s; (**b**) t = 12 s; (**c**) t = 18 s; (**d**) t = 24 s.

In this study, the staircase is the only conduit that allows the transfer of the water into the lower layer. The flow rates at the staircases were calculated from the numerical results (Figure 8). There are two staircases on the ground floor, as shown in Figure 5a, and by using the results of the flow depth at these locations, the step-flow formula gave the discharges that were transmitted to the underground space [23–25].

$$Q = 0.544A\sqrt{2gh_s} \tag{3}$$

where Q is the volumetric flow rate over the stair; A is the cross-sectional area of the flow; and h_s is the water depth measured from the bottom to the water surface. The step-flow formula can be regarded as a kind of weir equation that describes water discharge surpassing over a structure with specific depth.

The flooded water came from the main entrance and filled the ground floor as time elapsed. During its propagation, it collided with walls and constricted or expanded into smaller or larger rooms. As shown in Figure 5a, two staircases are located beside the hall and after experiencing irregular flow pattern at initial period, the discharge flowing into staircases became constant after 50 s as shown in middle panel of Figure 8. The discharges produced at the right and left staircases approached 0.81 m^3/s and 0.74 m^3/s, respectively. These discharges describe the water source in the lower floor, and can be used as the basis for inundation analysis in the underground space.

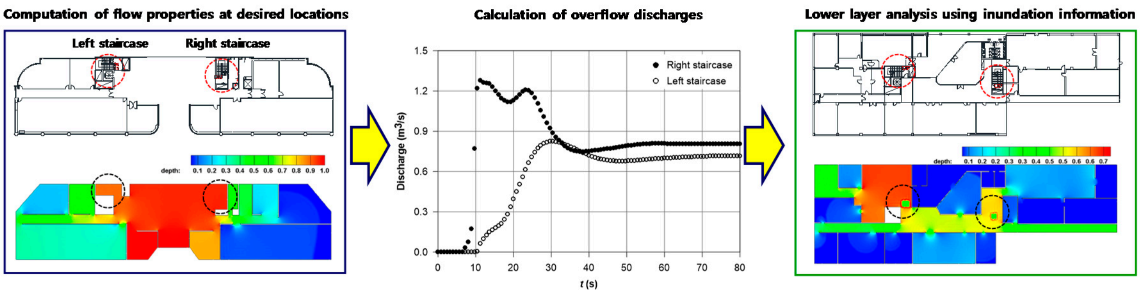


Figure 8. Analysis procedure for connecting inundation in two layers.

Figures 9 and 10 denote how the inundation depth and velocity evolves in the underground space. It is clearly shown in Figure 10a that the submergence by flooded water evolved in a radial direction from the staircases. As time progressed, a larger space (including the corridor and adjacent rooms) was inundated. As shown in Figure 9d, the inundation depth at the left side of the underground space was higher than on the right side. This was because the right side had more empty space to flood compared with the left side.

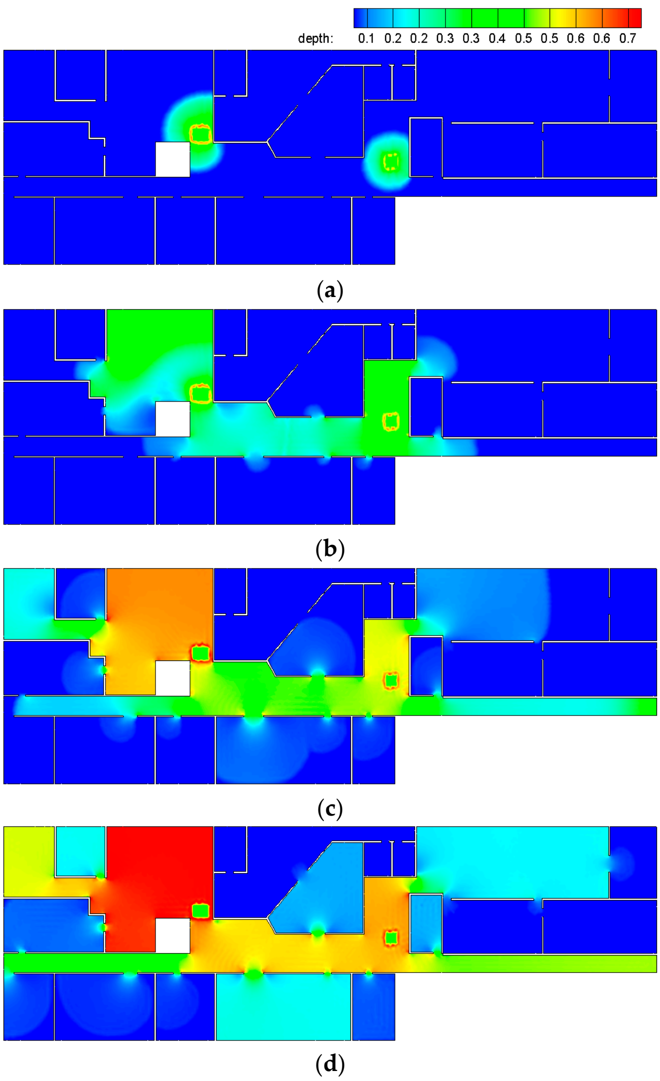


Figure 9. Inundation depth in the underground space (unit of contour legend: m); (**a**) $t = 15$ s; (**b**) $t = 30$ s; (**c**) $t = 60$ s; (**d**) $t = 100$ s.

The velocity contour and vector for the same times (Figure 9) are provided in Figure 10. Because the strength and power of the flood water became weaker as it passed from the ground floor, the maximum magnitude of the velocity was reduced from 3.4 m/s to 1.8 m/s. In Figure 10c,d, a velocity of 0.8 m/s was observed at narrow gaps (doors or hallway).

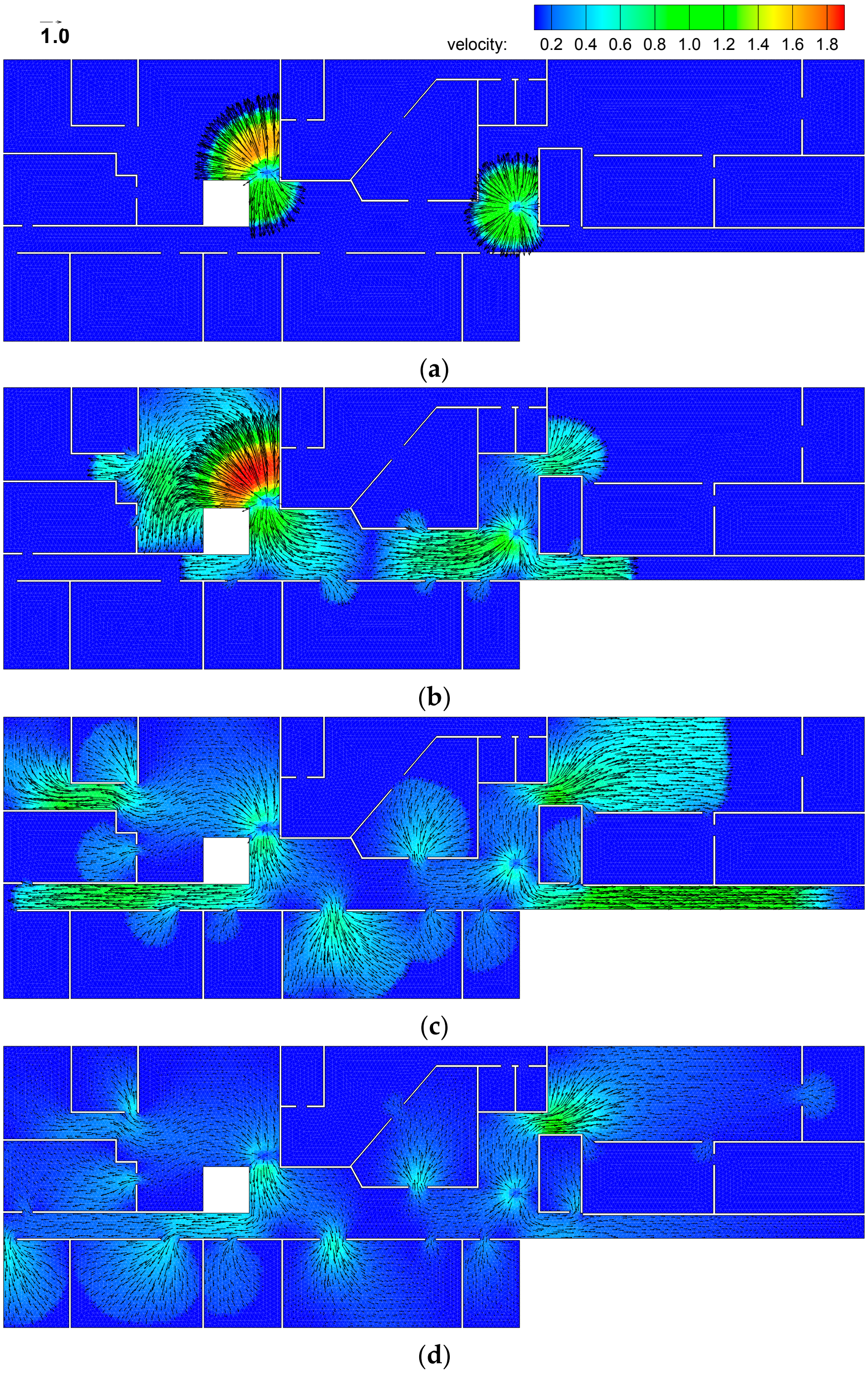


Figure 10. Velocities in the underground space (unit of contour legend: m/s); (**a**) t = 15 s; (**b**) t = 30 s; (**c**) t = 60 s; (**d**) t = 100 s.

5. Summary and Conclusions

Rainfall in urban region flows to underground areas under the effect of gravity. During floods, the infrastructure inside buildings constructed on lowlands can be severely damaged. The floods frequently paralyze transportation networks, submerge automobiles under water, damage property, and cause the electrical power grid to break down. In this study, a new ATM was proposed that could be used to design a realistic and effective flood management strategy or mitigate flood damage. This method overcomes the limitation of previous 2D modeling by introducing the layer connecting concept so that it prevents large variations in mesh sizes resulting from complicated underlying obstacles or local details.

The model was applied to a building in Korea with moderate dimensions, underground space, and a number of separated rooms. This building can therefore fairly represent mid-size buildings with underground space. Staircases were assumed to be the only conduits that transfer the water mass into lower layers. The flow rates at the staircases were calculated from numerical results. From the results of the moving flow depth on the staircases, the step-flow formula was used to give discharges that were transmitted to the underground space. These discharges act as a water source in the lower floor, and can be used as the basis for inundation analysis in the underground space. The detailed sequence of the flood water colliding with the opposite wall, bouncing off it, and spreading out in the room between the walls was clearly represented. The velocity of the water passing through door gaps was significantly faster than for other areas.

The present study aims for a conceptual application of the ATM approach in a simple way. In the near future, we will extend the application to several buildings with complex underground spaces.

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Author Contributions: Hyung-Jun Kim designed this study and provided main idea. Dong Sop Rhee analyzed the results of hydrodynamic simulations. Chang Geun Song developed ATM approach and performed hydrodynamic simulations. Also, all authors wrote this paper together.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Song, C.G.; Ku, Y.H.; Kim, Y.D.; Park, Y.S. Stability Analysis of Riverfront Facility on Inundated Floodplain Based on Flow Characteristic. *J. Flood Risk Manag.* **2016**, *9*. [CrossRef]
2. Ahmadisharaf, E.; Kalyanapu, A.J.; Chung, E.S. Sustainability-Based Flood Hazard Mapping of the Swannanoa River Watershed. *Sustainability* **2017**, *9*, 1735. [CrossRef]
3. Liu, Y.; Yuan, X.; Guo, L.; Huang, Y.; Zhang, X. Driving Force Analysis of the Temporal and Spatial Distribution of Flash Floods in Sichuan Province. *Sustainability* **2017**, *9*, 1527. [CrossRef]
4. Zhang, C.; Wang, Y.; Li, Y.; Ding, W. Vulnerability Analysis of Urban Drainage Systems: Tree vs. Loop Networks. *Sustainability* **2017**, *9*, 397. [CrossRef]
5. Son, C.H.; Baek, J.I.; Ban, Y.U.; Ha, S.R. The Effects of Mitigation Measures on Flood Damage Prevention in Korea. *Sustainability* **2015**, *7*, 16866–16884. [CrossRef]
6. Ishigaki, T.; Kawanaka, R.; Ozaki, T.; Toda, K. Vulnerability to Underground Inundation and Evacuation in Densely Urbanized Area. *J. Disaster Res.* **2016**, *11*, 298–305. [CrossRef]
7. Bermudez, M.; Neal, J.C.; Bates, P.; Coxon, G.; Freer, J.; Cea, L.; Puertas, J. Quantifying Local Rainfall Dynamics and Uncertain Boundary Conditions into a Nested Regional-local Flood Modeling System. *Water Resour. Res.* **2017**, *53*, 2770–2785. [CrossRef]
8. Schubert, J.E.; Sanders, B.F. Building Treatments for Urban Flood Inundation Models and Implications for Predictive Skill and Modeling Efficiency. *Adv. Water Resour.* **2012**, *41*, 49–64. [CrossRef]
9. Zhang, T.; Feng, P.; Maksimovic, C.; Bates, P. Application of a Three-Dimensional Unstructured-Mesh Finite-Element Flooding Model and Comparison with Two-Dimensional Approaches. *Water Resour. Manag.* **2016**, *30*, 823–841. [CrossRef]
10. Choi, J.H.; Hwang, S.H.; Kim, J.S.; Moon, Y.I. Inundation Analysis of Ground and Underground Spaces in Urban Areas. *J. Korean Soc. Hazard Mitig.* **2015**, *15*, 109–117. (In Korean) [CrossRef]

11. Joo, J.S.; Kim, T.H. An Experimental Study on Evacuation Ability during Underground Space Inundation. *J. Korean Soc. Hazard Mitig.* **2015**, *15*, 189–196. (In Korean) [CrossRef]
12. Toda, K.; Kawaike, K.; Yoneyama, N.; Fukakusa, S.; Yamamoto, D. Underground Inundation Analysis by Integrated Urban Flood Model. In *Advances in Water Resources and Hydraulic Engineering*; Springer: Berlin/Heidelberg, Germany, 2009.
13. Toda, K.; Inoue, K.; Oyagi, R.; Nakai, T.; Takemura, N. Hydraulic Model Test of Inundation Water Intrusion into Complicated Underground Space. *J. Hydrosci. Hydraul. Eng.* **2005**, *23*, 13–25. [CrossRef]
14. Song, C.G.; Seo, I.W.; Kim, Y.D. Analysis of Secondary Current Effect in the Modeling of Shallow Flow in Open Channels. *Adv. Water Resour.* **2012**, *41*, 29–48. [CrossRef]
15. Seo, I.W.; Kim, Y.D.; Song, C.G. Analysis of Flow Characteristics around Islands due to Semi-Diurnal Currents in the Han River, Korea. *J. Korean Soc. Civ. Eng. KSCE* **2015**, *19*, 1905–1915. [CrossRef]
16. Song, C.G.; Oh, T.K. Transient SU/PG Modelling of Discontinuous Wave Propagation. *Prog. Comput. Fluid Dyn. Int. J.* **2016**, *16*, 146–162. [CrossRef]
17. Park, I.H.; Seo, I.W.; Kim, Y.D.; Song, C.G. Flow and Dispersion Analysis of Shallow Water Problems with Froude Number Variation. *Environ. Earth Sci.* **2016**, *75*, 120. [CrossRef]
18. Song, C.G.; Ku, T.G.; Kim, Y.D.; Park, Y.S. Floodplain Stability Indices for Sustainable Waterfront Development by Spatial Identification of Erosion and Deposition. *Sustainability* **2017**, *9*, 735. [CrossRef]
19. Smith, G.; Wasko, C.; Miller, B. Modelling the Influence of Buildings on Flood Flow. In Proceedings of the 52th Floodplain Management Association Conference, Batemans Bay, NSW, Australia, 21–24 February 2012.
20. Rhee, D.S.; Kim, H.J.; Song, C.G. Inundation Simulation of Underground Space using Critical Dry Depth Scheme. *J. Korean Soc. Saf.* **2015**, *30*, 63–69. (In Korean) [CrossRef]
21. Chow, V.T. *Open-Channel Hydraulics*; McGraw-Hill: New York, NY, USA, 1959.
22. Smagorinsky, J. General Circulation Experiments with the Primitive equations: I. The basic experiment. *Mon. Weather Rev.* **1963**, *91*, 99–105. [CrossRef]
23. Inoue, K. Study on its Application to Water Engineering and Numerical Analysis of Open Channel Unsteady Flow. Ph.D. Thesis, Kyoto University, Kyoto, Japan, 1986.
24. Ishigaki, T.; Toda, K.; Baba, Y.; Inoue, K.; Nakagawa, H. Experimental Study on Evacuation from Underground Space by Using Real Size Models. *Proc. Hydraul. Eng. JSCE* **2006**, *50*, 583–588. [CrossRef]
25. Ko, D.W. Mitigation Effects on Urban Flood by Installing an Underground Storage Box. Ph.D. Thesis, Kyoto University, Kyoto, Japan, 2015.