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Influence of Staircase Design on Flood Characteristics in Underground Spaces

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Abstract

Underground flooding events are intensifying due to the rapid expansion of urban underground spaces and frequent extreme precipitation events caused by climate change. Due to the vulnerability of urban underground spaces to such flooding events and the fact that access to underground spaces is generally in the form of staircases, it is of both academic and practical value to explore the evolution of flooding on underground staircases. This work investigates the flood dynamics characterized by water depth and flow velocity on different types of staircases in underground spaces. A numerical model based on the two-dimensional (2D) shallow water equations (SWEs) is established to simulate flooding on staircases of different designs. Results show that shorter or higher steps lead to shallower water depths and higher flow velocities, with step length exerting a greater impact on flood dynamics than step height. For the staircase with junction, the branch line experiences significantly lower water depths and flow velocities compared to the main line.

Keywords: Underground flooding; Staircase; 2D shallow water equations

1. INTRODUCTION

Urban flooding has enormous negative socio-economic impacts including significant economic losses and socio-environmental damage (Hall et al., 2005; Salman and Li, 2018; Khajehei et al., 2020) and can lead to the breakdown of urban services (e.g., transportation, sewage, communication, and power supply) and damage to urban infrastructure (Ashley et al., 2005; Miller and Hutchins, 2017; Chakraborty et al., 2020). In recent decades, with the rapid development of urbanization, cities around the world have expanded not only horizontally but also vertically through the large-scale construction of underground spaces, such as underground tunnels, underground car parks, underground metro stations and underground shopping plazas, etc. (Park and Won, 2019; Tanir et al., 2021). However, due to their low-lying feature, underground spaces are very vulnerable to flood disasters, which cause floods intrude into the underground spaces and pose a threat to people's lives and property (Forero-Ortiz et al., 2020).

To date, work on underground flooding around the world has been conducted primarily from two perspectives: the first one is to study the propagation characteristics of floods throughout the entire underground spaces (Hashimoto and Park, 2010; Ozaki et al., 2014; Hamaguchi et al., 2016; Li et al., 2018; Lyu et al., 2019). Since underground spaces are typically accessed via staircases which serve as crucial escape routes for pedestrians during flood events, the second perspective for studying underground flooding is to focus on the entrance of the underground space, i.e., the staircases. Therefore, more emphasis is placed on the water flow state and characteristics on the staircases, as well as the potential threat to the safety of pedestrians on the stairways. Currently, research in this area is relatively limited, with existing studies mainly conducted through physical and numerical experiments. For physical experiments, the most conventional and fundamental staircase configuration, namely, straight-run staircase with successive steps has been predominantly employed. For example, Ishigaki et al. (2006) and Kim and Lee (2018) designed real-scaled models of such staircases connecting to the underground shopping mall or metro station to test different evacuation routes from underground spaces and defined the critical water depth for safety evacuation index on the staircases. Shao et al. (2014) introduced an intermediate rest platform into the staircase model and conducted experiments to investigate the characteristics of flooding flow on such underground staircases. For numerical experiments, several studies have focused on predicting and analyzing the processes and behavior of the water flow over flooded staircases (Yoneyama et al., 2009; Shao et al., 2015; Hou et al., 2022; Li et al., 2022). In addition, more attention has been placed on investigating the mixing and interaction of flow and air by combining the volume of fluid (VOF) method with turbulence models, such as the k–ε turbulence model (Shao et al., 2015; Bentalha and Habi, 2019; Hou et al., 2022) and the large eddy simulation model (Li et al., 2022). Moreover, the 2D shallow water equations (SWE) model also shows promising accuracy in hydrodynamic simulations, but its application on stepped terrain, particularly on staircases, remains limited due to their discontinuous and abrupt nature. It is of great significance to investigate the feasibility of utilizing the 2D SWEs model for simulating water flow over underground staircases, and evaluating its potential for achieving high accuracy and reliability. It is also noted that the majority of the literature reviewed above rarely address the influence of different step designs. The aforementioned gap in the literature provides the motivation for the current work. Consequently, this study aims to investigate the relation between staircase designs and flow characteristics over the staircase.

2. Methodology

2.1 Model description

A 2D SWEs-based hydrodynamic model is adopted to simulate flow dynamics on the underground staircases (Guan et al., 2016). The equations in vector form are expressed below:

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}}{\partial x}+\frac{\partial \mathbf{G}}{\partial y}=\mathbf{S} \quad [1]$$

$$\mathbf{U}=\begin{bmatrix} h \\ hu \\ hv \end{bmatrix}, \quad \mathbf{F}=\begin{bmatrix} hu \\ hu^2+\frac{1}{2}gh^2 \\ huv \end{bmatrix}, \quad \mathbf{G}=\begin{bmatrix} hv \\ huv \\ hu^2+\frac{1}{2}gh^2 \end{bmatrix}, \quad \mathbf{S}=\begin{bmatrix} 0 \\ gh(S_{bx}-S_{fx}) \\ gh(S_{by}-S_{fy}) \end{bmatrix} \quad [2]$$

where x and y are the two directions of a two-dimensional Cartesian system, t is time, h is the water depth, u and v are components of the flow velocity along x and y respectively, and g is the acceleration of gravity. Consider the bed slope terms in the x and y directions, denoted as S_{bx} and S_{by}, respectively, and the friction source terms in the same directions, denoted as S_{fx} and S_{fy}, respectively. They are defined by

$$S_{bx}=-\frac{\partial z_b}{\partial x}, \quad S_{by}=-\frac{\partial z_b}{\partial y} \quad [3]$$

$$S_{fx}=\frac{n^2u\sqrt{u^2+v^2}}{h^{4/3}}, \quad S_{fy}=\frac{n^2v\sqrt{u^2+v^2}}{h^{4/3}} \quad [4]$$

where z_b is the bed elevation, S_{fx} and S_{fy} are defined by the Manning's roughness coefficient n.

It is worth noting that the presence of staircase will cause sudden changes in bed elevation. Therefore, a well-balanced bed source term treatment is crucial for well capture of flow dynamics on staircases. Here we used the surface reconstructure approach proposed by Xia et al. (2017) to address bed slope term S_b to prevent excessive flow velocity at locations where the bed elevation changes abruptly.

2.2 Simulation scenarios

The simulation scenarios are shown in Table 1. To validate the model, we employ the same staircase design and inflow conditions consistent with the experiments conducted by Ishigaki et al. (2006) at Tokyo university, as shown in Fig.1. The whole equipment consists of a water tank, a pump, a 2.5m long platform, and a 6m long, 1m wide, and 3m high staircase composed of 20 small steps of 0.3m length and 0.15m height. The water on the platform is provided by the tank, while the initial water depth and flow velocity are controlled by the pump to facilitate the simulation of different inflow conditions. The water then flows from the platform to the staircases. In the subsequent study, the step parameters are modified based on the staircase design used in the validation. To investigate the impact of step length, the step height-to-length ratio is maintained at 1:2, and the step length is systematically adjusted in the range of 0.3m to 0.5m, while the height varies from 0.15m to 0.25m. Additionally, in order to examine the influence of step height, a fixed step length of 0.3m is maintained, while the heights are systematically adjusted in the range of 0.15m to 0.21m, with the corresponding step slopes being modified accordingly.

For the overall configuration of staircases, the present study introduces a staircase design that merges the straight-run and L-shaped structures, incorporating a junction, as depicted in Fig. 2. The total length of the staircase is 6 m, with a rest platform of 1m length located halfway along the main line staircase. This platform serves as a junction where the branch staircase runs perpendicular to the main line. The branch line of the staircase has an equivalent number of steps to the downstream of the platform on the main line, and the individual steps have uniform design specifications (length and height) for both directions. The step size in this design is consistent with that in the validation, with a length of 0.3 m and a height of 0.15 m. For all scenarios, the flood depth at the staircase entrance ranges from 0.1m to 0.9m. The corresponding input discharge values are calculated using the following formula summarized by Ishigaki et al. (2006):

$$q = 1.980h^{1.621} \tag{8}$$

Where h is the flood depth at the staircase entrance, q represents the flow rate supplied by the tank, which is equivalent to the flow rate delivered to the staircase.

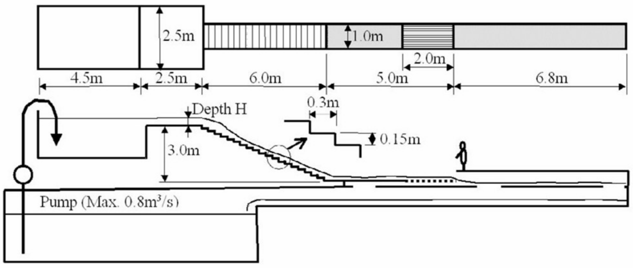

Figure 1. The sketch of experimental setting (Ishigaki et al., 2006).

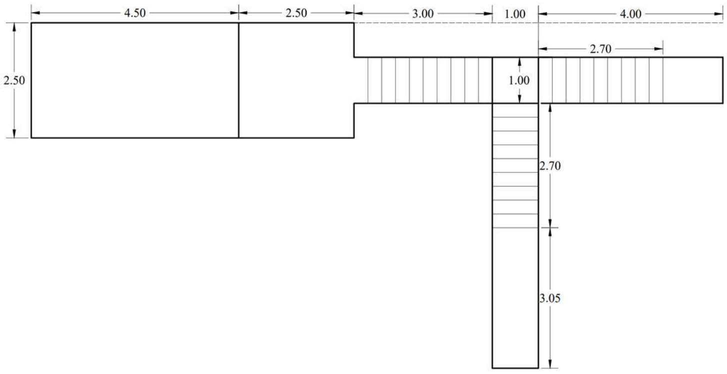

Figure 2. The sketch of staircase with junction.

Table 1. Summary of design scenarios.

		Step length (m)	Step height (m)
Staircase design	Validation	0.3	0.15
	Step length	0.3 - 0.5	0.15 - 0.25
	Step height	0.3	0.15 - 0.21
	Staircase with junction	0.3	0.15
Flooding depth (m)		0.1 - 0.9	

3. Results and Discussion

3.1 Model validation

We validate the capability of the 2D hydrodynamic model in simulating floodwater over stepped staircases by reproducing the experimental events by Ishigaki et al., (2006). Figure 3 plots the comparison of the simulated and measured water depths (h), flow velocities (v) and the safety indexes (v^2h) when floodwaters with varying depths flash into the staircases. (H=0.1m, 0.2m, 0.3m, 0.4m). It shows that the model reproduces both water depth and flow velocity on staircases under various flow conditions reasonably well with marginal discrepancies. For various initial water depths, the simulated flooding depth on the steps gradually decreases along the staircase and almost coincides with the experimental results. The simulated flow velocity is also observed to be in line with the experimental measurements. In accordance with the principle of water conservation, the flow velocity gradually increases along the steps. Given that the safety index v^2h is a second-order parameter of flow velocity, its value experiences a concurrent increase with the flow velocity over the staircase. Since the last step's location is x = 6m, beyond which lies a flat ground, it is observed that when the value of x exceeds 6m, the flow velocity, together with the safety index decreases while the water depth increases slightly.

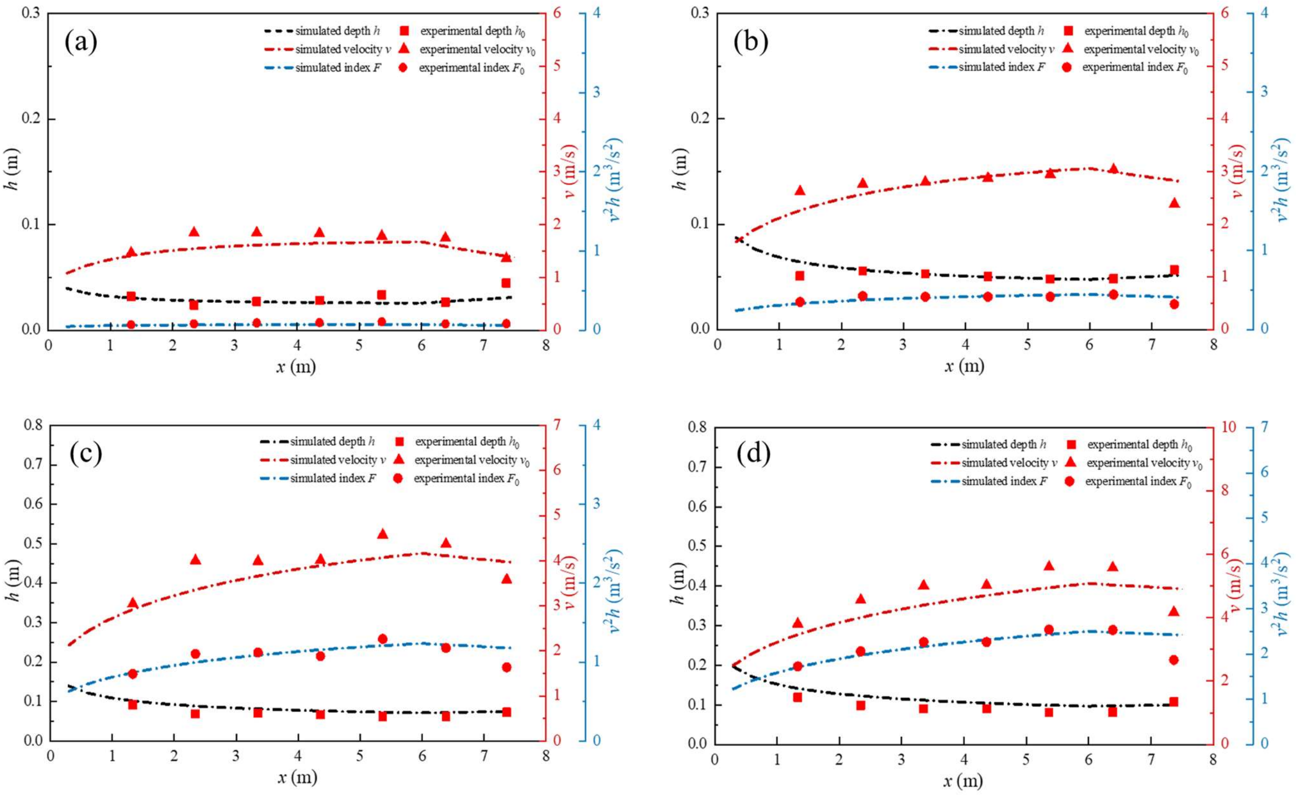

Figure 3. A comparison of water depth, velocity and safety index v2h between numerical simulation and experiment when (a) H=0.1m, (b) H=0.2m, (c) H=0.3m, (d) H=0.4m. Note: x=0 for the first step of the staircase.

3.2 The flow characteristics over different designs of staircases

3.2.1 Step length

To investigate the impact of individual step design on the water flow characteristics over flooded staircases, we adjust the step length *l* to 0.3m, 0.4m, and 0.5m and examine the water depth *h* and flow velocity *v* over staircases at different initial flood depths, as shown in Figure 4. It is important to note that our analysis focuses solely on the step portion of the staircase, excluding the flat portions before and after the steps. Figure 4 indicates that the flow velocity gradually increases as the water flows over the steps primarily due to the height difference between the upstream and downstream steps. From the point of view of energy conservation, during the water flow, a portion of the gravitational potential energy converts into kinetic energy, leading to an increase in water flow velocity (Hou et al, 2021). Due to mass conservation, the product of the water velocity and the cross-sectional area of the flow channel remains unchanged, resulting in a gradual decrease in the flooding depth along the staircase.

When comparing the results of different step lengths under four sets of initial water depths, it can be observed that the water flow velocity is comparatively higher on the shorter steps, while the water depth is relatively shallower. This can be attributed to the preferential energy conversion facilitated by shorter steps, as water flowing over shorter steps tends to flow preferentially toward the next step, converting gravitational potential energy into kinetic energy more efficiently than when flowing over longer steps. As water progresses downstream, the velocity difference between steps accumulates over multiple steps, leading to a greater flow velocity disparity on downstream steps. Additionally, the step can be regarded as a small-sized platform, which has an impact similar to the backwater effect on the water flowing down the step. Hence, longer steps exert a more significant backwater effect, resulting in a greater water depth compared to shorter ones. It is worth noting that longer steps are designed with greater height to maintain a consistent sloping, leading to a relatively higher potential energy conversion of water when falling from such steps. Nonetheless, the preferential energy conversion facilitated by shorter steps still dominates.

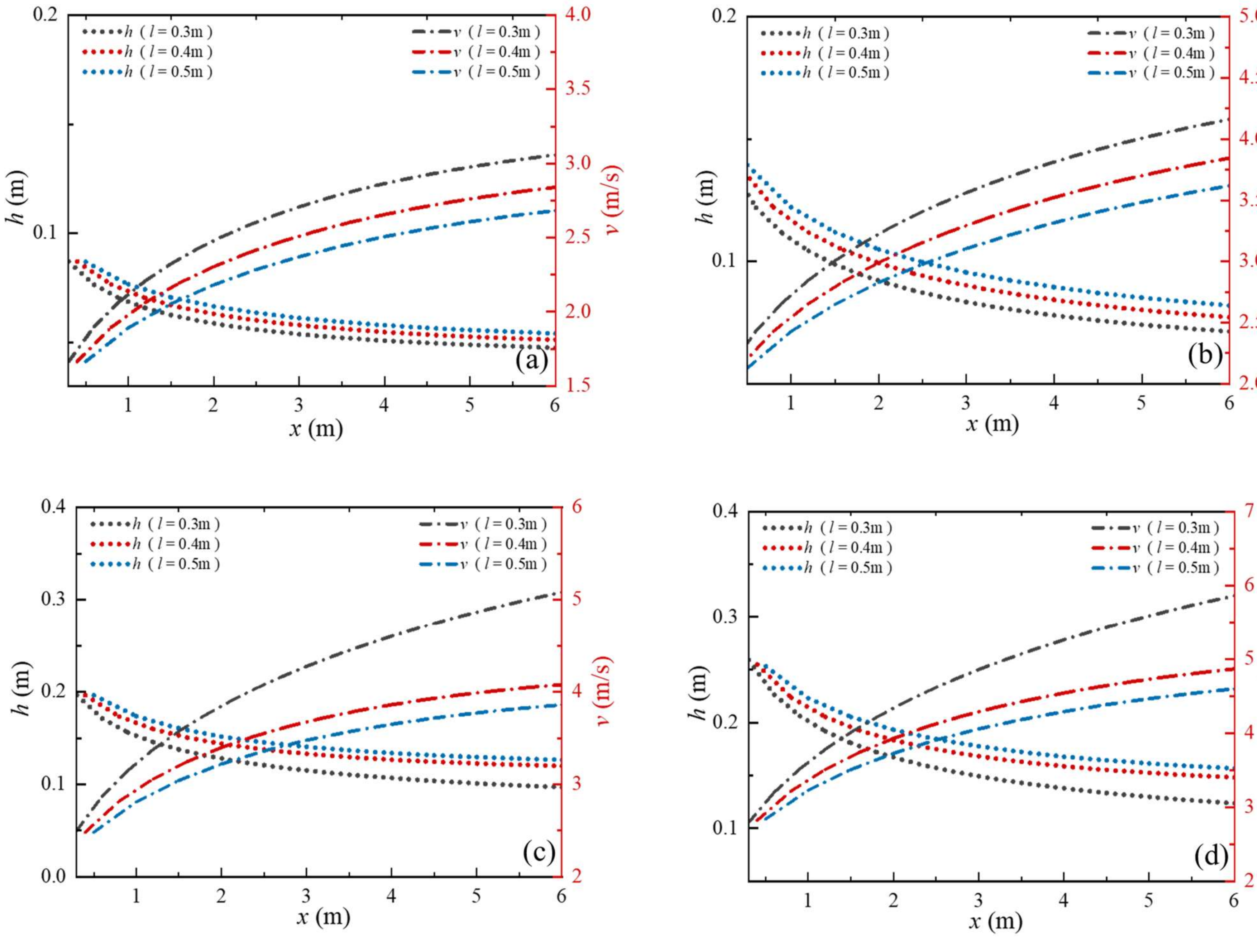

Figure 4. Water depth and velocity when (a) H=0.2m, (b) H=0.3m, (c) H=0.4m, (d) H=0.5m.

3.2.1 Step length (slope)

In this subsection, in order to investigate the impact of individual step height/ slope on flow characteristics over flooded staircases, we keep the step length constant while adjusting the step heights to 0.15m, 0.18m, and 0.21m, respectively, and the step slope varies accordingly from 26.56° to 34.99°. Figure 5 depicts that greater step height or steeper slope correlates with higher water velocity and shallower water depth. This is because, as the step length remains constant, higher steps result in a greater drop in potential energy of the water flow and this portion of the potential energy converts into more kinetic energy, resulting in faster flow velocity and shallower water depth.

Upon comparison of the simulation results under varying initial flooding depth conditions, it is evident that the difference in results for varying step heights increases with greater initial flooding depth. As presented in Figure 5, when the initial water depth increases to 0.5m, 0.7m, and 0.9m, the difference in simulation results for varying step heights are more discernible. This is attributed to the fact that with greater water volume inflow, more gravitational potential energy converts to kinetic energy as the water flows down the steps, leading to faster flow velocity. In the previous subsection, significant differences in simulation results for varying step lengths were observed in the case of very shallow initial water depths (H = 0.2m). However, in this subsection, it is only when the initial water depth is relatively much deeper (H = 0.5m) that the noticeable differences in results for different step heights start to appear. Compared to the backwater effect of the horizontal step length, the impact of changes in step height on water flow properties is relatively weak. The slight influence of step height is only amplified and manifested when the gravitational force of the water body itself is significant. Hence, it can be inferred that the hydrodynamic properties are more sensitive to variations in step length than step height.

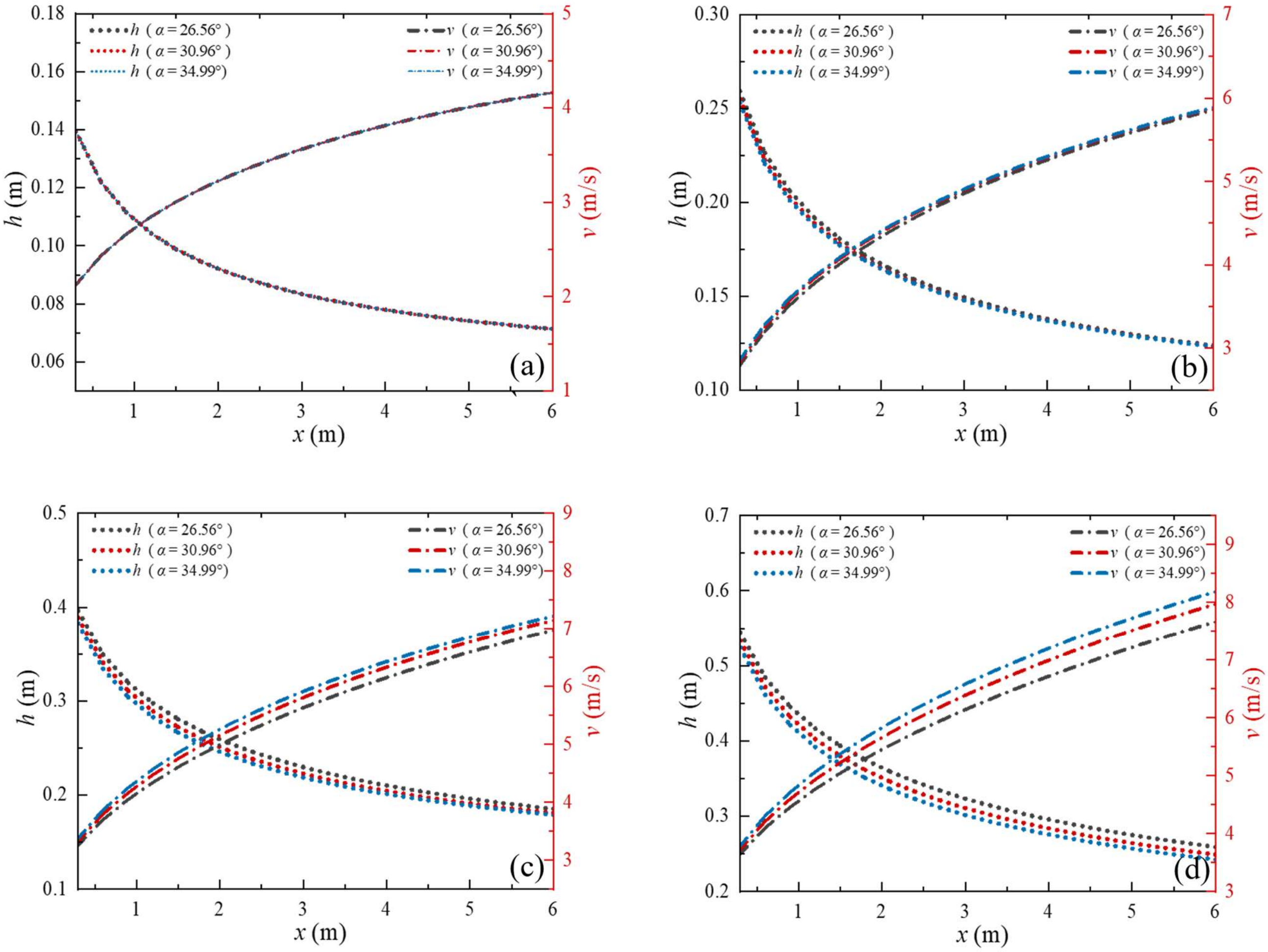

Figure 5. Water depth and velocity when (a) H=0.3m, (b) H=0.5m, (c) H=0.7m, (d) H=0.9m.

3.2.1 Staircase with junction

The flow direction of people in a large underground area can be complex, leading to the use of different types of staircase configurations. In this subsection, we focus on the study of staircase with junctions formed by L-shaped and straight-run staircases. The presence of branch lines in the staircase with junction leads to non-uniform flow along its width, which is different from the straight-run staircase. Therefore, we selected the depth and flow velocity on the central line of the main and branch stairs as representatives. Figure 6 presents the floodwater depth and velocity on the conventional straight-run staircase and the branch line and mainline of the staircase with junction. Overall, the water depth on the mainline of the staircase increases slightly at the junction (x = 3m), exceeding the water depth at the same location on the conventional straight-run staircase, and then gradually decreases after the junction. Nonetheless, as analyzed in the previous subsections, the steps - acting as small platforms - can hinder the water flow. Given that the length of the platform at the junction is considerably longer than the length of the steps, the backwater effect at the platform hence results in a slight increase in the water depth, even if the branch stairs divert a portion of the water flow. On the other hand, the water depth on the branch line is considerably lower than that on the main line. This is mainly due to the junction being located in the middle of the entire staircase. As a result of inertia, the majority of the flood water continues to flow in the previous direction after passing the upstream steps. In terms of flow velocity, the combined effect of water volume conservation and the backwater effect of the steps results in a slightly lower flow velocity on the main line at the junction. However, after passing the platform, the flow velocity gradually increases and the slope of the flow velocity increase is almost identical to that before the junction. In other words, the effect of the platform on the flow velocity is limited to the platform's vicinity. As the step design upstream and downstream of the main line remains unchanged, the slope of the velocity change will gradually return to the same as upstream after the water flow passes the platform.

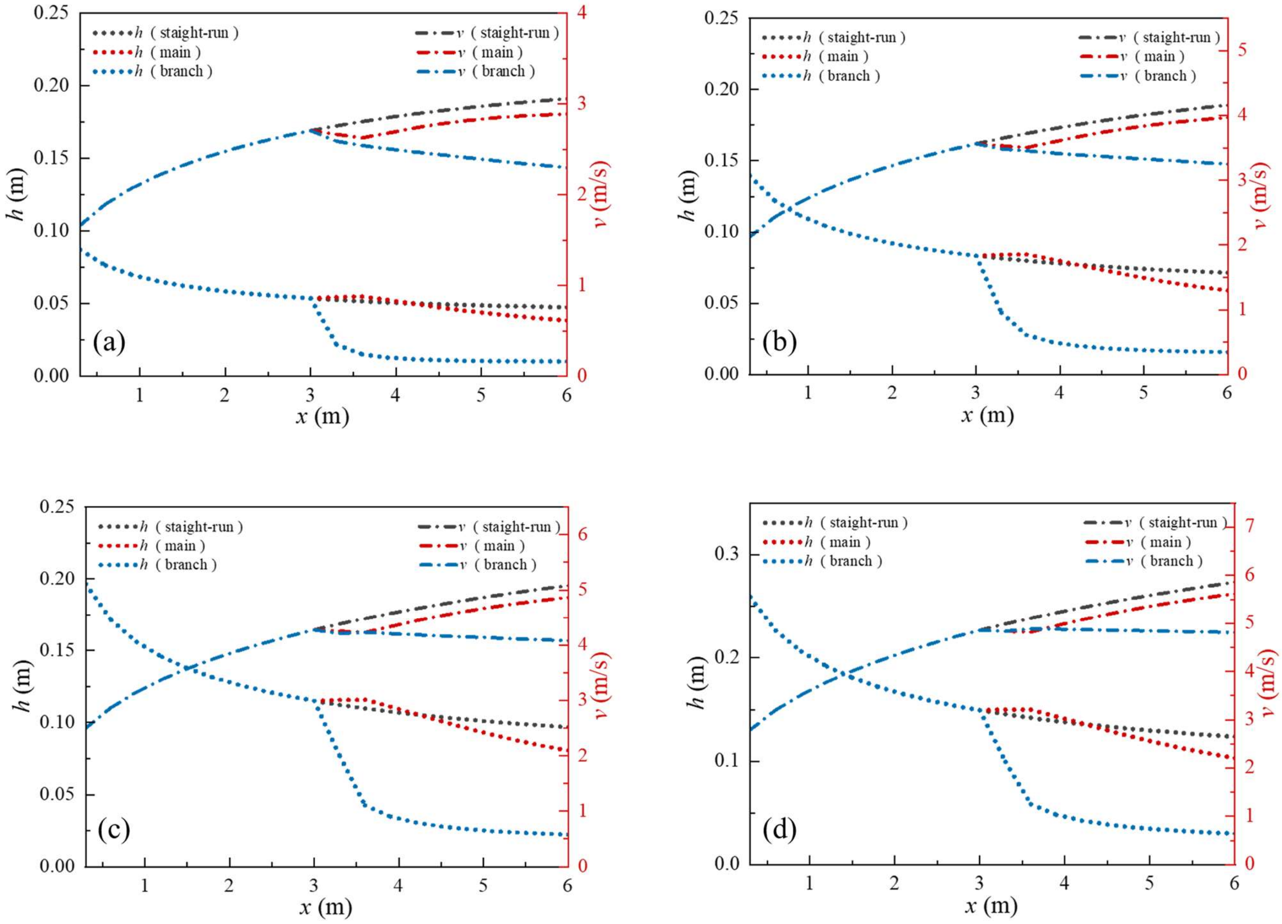

Figure 6. Water depth and velocity when (a) H=0.2m, (b) H=0.3m, (c) H=0.4m, (d) H=0.5m.

4. CONCLUSIONS

This study numerically investigates the flood dynamics characterized by water depth and flow velocity over various types of staircases in underground spaces. It is found that shorter or higher steps result in shallower water depths and higher flow velocities at the same location on the staircases, and the difference in floodwater characteristics over steps with various designs is further intensified by the initial flooding depth. Flood characteristics are less sensitive to the change of step height than the step length. For the staircase with junction, the water depth and flow velocity on the branch line are considerably lower than those observed on the main line.

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