Study on the Impact of Heavy Rain on the Evacuation Safety of Pedestrians Inside Subway Stations

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Abstract. In recent years, rapid urbanization has led to frequent occurrences of extreme weather conditions. As a vital component of urban transportation networks, subway lines often face flooding disasters. Due to the unique spatial characteristics of subway facilities, flooding incidents can easily lead to inefficient evacuation of passengers within the stations, trapping them in high-risk areas and endangering their lives. Therefore, it is crucial to study the hazards of evacuation within subway stations under different rainfall conditions. Revealing these patterns can assist professionals involved in evacuation safety in improving existing evacuation plans. Utilizing different evacuation strategies under varying rainfall conditions can mitigate the risk of passengers being stranded inside subway stations, enhance evacuation efficiency, and thereby safeguard lives and property.

Keywords: extreme weather, underground space,evacuation, fluid simulation.

1 Introduction

The urbanization process in China has been steadily increasing year by year, leading to the formation of national-level urban clusters such as the Beijing-Tianjin-Hebei region, the Yangtze River Delta, the Guangdong-Hong Kong-Macao Greater Bay Area, the Central Yangtze River Region, and the Central Plains [1]. The rapid pace of urbanization is driven by the increasing human activities. As a consequence, global warming trends have intensified, resulting in an increase in atmospheric moisture content. The increased moisture in the atmosphere raises the probability of extremely heavy rainfall events, leading to both external flooding and internal waterlogging in urban environments [2]. Therefore, while urbanization is advancing rapidly, the associated risk of urban flood disasters is also on the rise.

In recent years, extreme rainfall disasters have been frequent, severely impacting the safety of underground spaces in cities, especially the operation of large cities’ subway lines. These subway lines are densely populated and located underground or in semi-enclosed spaces, making it challenging for passengers to evacuate during extreme rainfall events. The investigation report on the “7·20” severe rainstorm disaster in Zhengzhou, Henan, China, specifically highlighted casualties that occurred in urban

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underground spaces such as subways and tunnels [3].Research in related areas in China has been slow to initiate, primarily focused on theoretical research and analysis of the current situation.According to Xu Jie [4], some underground spaces in China have entrances and exits set at a height approximately 40 cm to 50 cm higher than the road level, yet the appropriateness of this configuration remains unverified.Based on various relevant domestic and international cases, Liu Shuguang et al. [5] contend that urban underground spaces are highly susceptible during urban flooding disasters.The research on flood disaster prevention and control in underground spaces in China is still in its nascent stage, in contrast to other disasters, such as earthquakes and fires.The primary challenge stems from inherent flaws in underground spaces, specifically the imprudent selection of locations.According to Chen Feng et al. [6], most underground spaces in China, based on collected samples, are predominantly situated in flood-prone and low-lying areas.Moreover, there is inadequate flexibility in water-blocking standards across different regions, with notable variations in local requirements. Additionally, the drainage facilities are insufficient, and the comprehensive drainage capacity of underground spaces has not been taken into account in the norms and design, particularly when confronted with high volumes of floodwater.

Research on underground space evacuation has been approached from various perspectives. Huang Cong et al. [7] conducted physical modeling simulations and discovered that an increase in water inflow hampers the efficiency of personnel evacuation. Additionally, the positioning of water inlets also affects evacuation efficiency. Mo Weili [8] employed numerical simulation methods to determine underground space evacuation time by analyzing the relationship between surface water depth and underground space infiltration flow, drawing on the theory of underground space water intrusion escape in Japan. Lou Xia [9] observed and compared the geometric structures of straight and L-shaped staircases, studying their impact on evacuation. The findings revealed that L-shaped staircases, by mitigating fluid kinetic energy at the corners, offer higher safety than straight staircases. Jiang Lijie [10] conducted experiments with human body models and measured the threshold critical stress for safe evacuation to be approximately 42.4N.

The theoretical framework for researching foreign countries is relatively well- developed, with an emphasis on the practical application of theory. Scholar Yasuyuki BABA conducted a study exploring the correlation between flood depth and the difficulty of evacuation [11]. According to BABA, males require a critical depth of about 0.4m for safe evacuation, while females require a depth of approximately 0.3m.In a separate study, Dias and Charitha [12] conducted experiments using a channel model with water flow impact. Their study involved one hundred volunteers. They discovered that as the water level rises, people's stride length decreases, and individuals tend to sway from side to side to create more lateral space. This behavior is aimed at reducing the impact of fluid resistance during movement. However, this movement style poses a higher risk of evacuation in relatively narrow underground passages.On the other hand, Bernardini and Gabriele [13] investigated more extreme flood situations. They found that when the depth of the flood increases to 40-60cm, the resistance of the flood flow significantly hampers the evacuation speed of the crowd. Additionally, some researchers have focused on the impact of individual characteristics on evacuation capabilities. For example, Hamilton observed that children, who have lower individual abilities, are greatly influenced by their familiarity with the environment during emergency evacuations [14]. In flood conditions, when the surfaces of buildings are covered with sewage, individuals' decision-making abilities and subsequent evacuation efforts can be severely compromised.

Subway stations are relatively enclosed spaces with only a few entrances and exits directly connected to the outside. During extreme rainfall, the water level inside the station rises more rapidly than on the city streets. The relatively closed visibility within subway stations makes it difficult for management personnel to make informed decisions in the event of an emergency. Heavy rain can lead to congestion and an increased risk of slipping inside the station, further hindering the evacuation process. Studying this impact can help improve the safety of subway stations. Different rainfall conditions present varying evacuation difficulties for the people inside. This study focuses on China’s commonly used two-level island-type stations and uses Fluent fluid simulation software to simulate different flooding conditions. Hazard levels are used to describe the difficulty of pedestrian evacuation. The hazard growth curve under different flooding conditions can provide reference advice for management personnel to improve evacuation plans. When facing severe rainstorms, advance evacuation arrangements can be made for the crowd, effectively improving evacuation efficiency, reducing the difficulty of evacuation for individuals, and preventing passengers from being trapped in the station, thus ensuring the safety of evacuees to the greatest extent.

2 Hazard Calculation Formulas

The formula for calculating urban surface water depth is as follows:

$$h = v_t t \quad (\mathrm{m}) \tag{1}$$

Where vt is the rate of urban surface water rise, m/s.

Based on experiments conducted by the Japanese scholar Shitan Taisuke on the physical model of stairs, the method for calculating the water depth at the entrance to underground spaces and the flow rate of water infiltrating underground spaces is as follows [15]:

$$q = 1.98h^{1.621} \tag{2}$$

Where q represents the single-width flow rate at the entrance to the underground space, m3/s/m, and h denotes the water depth at the entrance to the underground space.

Therefore, the total amount of floodwater infiltrating the underground space at t seconds can be calculated as follows:

$$V(t) = \int_0^t 1.98Bh(t)^{1.621}dt = 1.98B\frac{v_t^{1.621}}{2.621A_S}T^{2.621} \quad (\mathrm{m}^3) \tag{3}$$

Where B indicates the width of the underground entrance stairs, m, and As refers to the underground space area, m2.

Then, the water depth in the underground space at t seconds is:

$$h_u = \frac{V(t)}{A_s} = 1.98B\frac{v_t^{1.621}}{2.621A_S}t^{2.621} \quad \text{(m)} \tag{4}$$

According to the hazard calculation formula [16]:

$$f = v^2 * h_u \quad (\mathrm{m}^3/\mathrm{s}^2) \tag{5}$$

Where v stands for the fluid velocity at the measurement point, m/s.

From the above equations, the hazard calculation formula for a certain point in this model at t seconds is:

$$f = \frac{qB}{2.621As}\mathrm{v}^2\mathrm{t} \quad (\mathrm{m}^3/\mathrm{s}^2) \tag{6}$$

3 Research Methodology

3.1 Subway Station Pedestrian Flow Model

This study is based on commonly used two-level island-type subway stations. Firstly, the AnyLogic pedestrian flow simulation software is employed for modeling the subway station. Rational pedestrian movement logic is designed to closely mimic the daily operations of real subway stations. The software's density statistics feature is used to highlight high-density areas on different floors, which serve as critical points for assessing hazard levels during evacuations.The simulation of crowd density is depicted in Figure 1 and Figure 2. Figure 1 illustrates the density of the crowd at the concourse level, while Figure 2 portrays the density of the crowd at the platform level. High-density areas were identified and designated as critical monitoring points for fluid velocity.

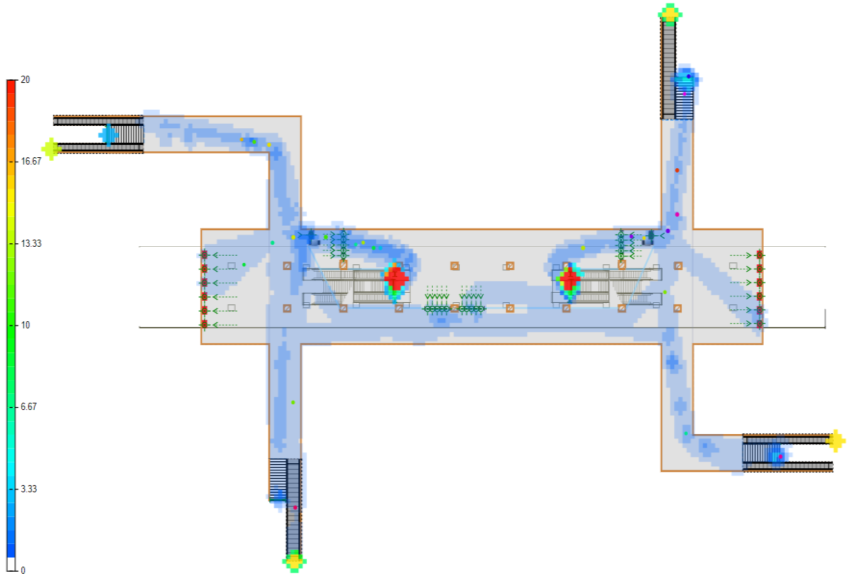

Fig. 1. Pedestrian Density Map of the Concourse Level

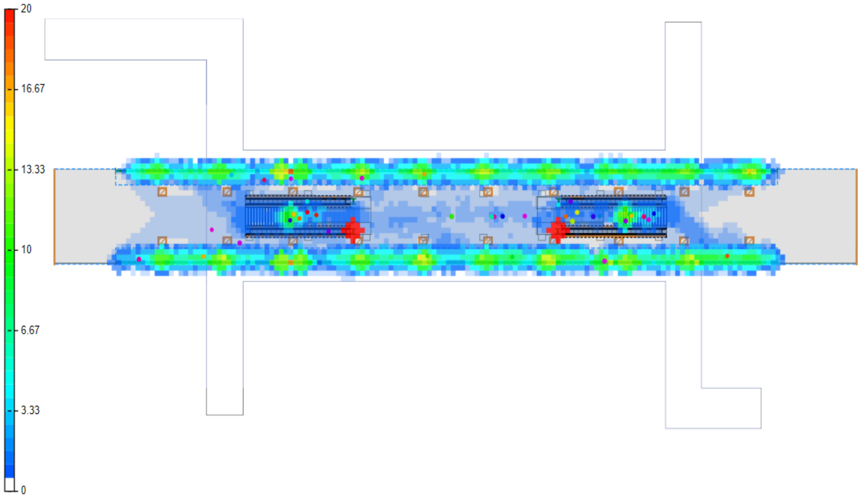

Fig. 2. Pedestrian Density Map of the Platform Level

3.2 Fluid Simulation Model

Based on the established two-level island-type subway station model, we used Fluent fluid simulation software to perform simulations using the Volume of Fluid (VOF) model for two-phase flow. Our focus was on the variation in fluid velocity in the designated areas, and we recorded velocity change graphs at six different monitoring points (including four on the concourse level and two on the platform level).We applied the implicit time differencing method to test three different single-width flow rate conditions,The data presented in Figure 3 indicates a flow rate of 0.05m^3/s/m, while Figure 4 displays a higher flow rate of 0.16m^3/s/m. Moreover, Figure 5 exhibits the highest flow rate among the three, measuring 0.28m^3/s/m.

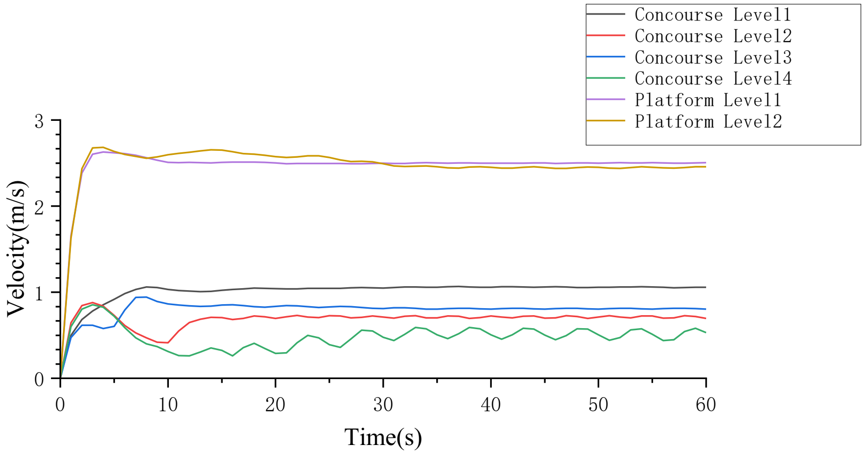

Fig. 3. Velocity-Time Graphs for Monitoring Points under Condition 1

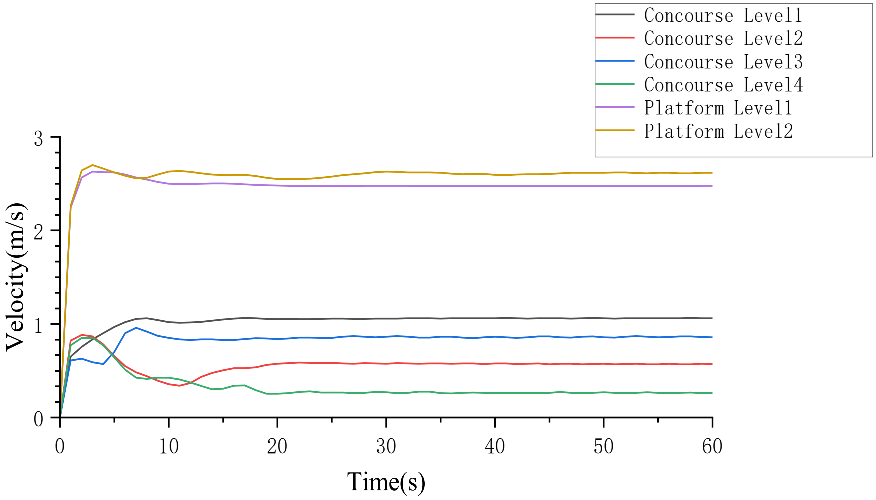

Fig. 4. Velocity-Time Graphs for Monitoring Points under Condition 2

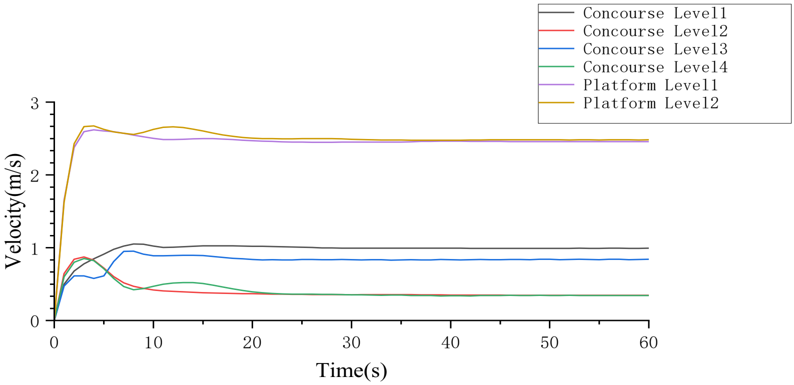

Fig. 5. Velocity-Time Graphs for Monitoring Points under Condition 3

4 Research Results

Based on the plotted velocity-time curves for each condition and in conjunction with the hazard calculation formula (2.26) in our model, we created hazard-time curves for each monitoring point. Subsequently, we selected the monitoring point with the highest average hazard as the basis for evaluating the evacuation hazard on the respective floor. According to relevant literature, the critical safety thresholds for hazard are defined as f=1.2 (m^3/s^2)[17] and f=1.5 (m^3/s^2)[18]. These thresholds can be used to distinguish high-risk areas. When f is less than 1.2 (m^3/s^2), it indicates a low-risk area; when f exceeds 1.5 (m^3/s^2), it signifies a high-risk area.

Figure 6 illustrates the findings, it is evident that overall, the platform level exhibits much higher hazard levels than the concourse level, rapidly reaching the high-risk zone. In underground space disasters, areas located at lower elevations usually pose greater risks. Under Condition 3, the platform level enters the high-risk zone in just 28 seconds, and even under Condition 1, with lower single-width flow rates, the platform level reaches the high-risk zone in 53 seconds. Therefore, in the event of a subway station flooding disaster, individuals should evacuate the platform level as a priority to reduce evacuation risks. According to China’s current “Subway Design Code” (GB50157-2003), in the event of a disaster during peak hours with high passenger flow, all passengers inside the train and waiting passengers, as well as staff, should evacuate the platform within 6 minutes.

Facing rare extreme rainfall conditions, such as Condition 3, the increase in hazard levels on the concourse level should not be overlooked. At 60 seconds, the hazard level reaches its maximum in the low-risk zone. However, under Conditions 1 and 2, with smaller single-width flow rates, the hazard level on the concourse level increases slowly. Therefore, during the evacuation process in flooding disasters, when facing a relatively small influx of floodwater, it is advisable to prioritize the transfer of platform-level passengers to the concourse level as a buffer zone and then gradually evacuate them outward, to avoid overcrowding and the risk of secondary stampede accidents.

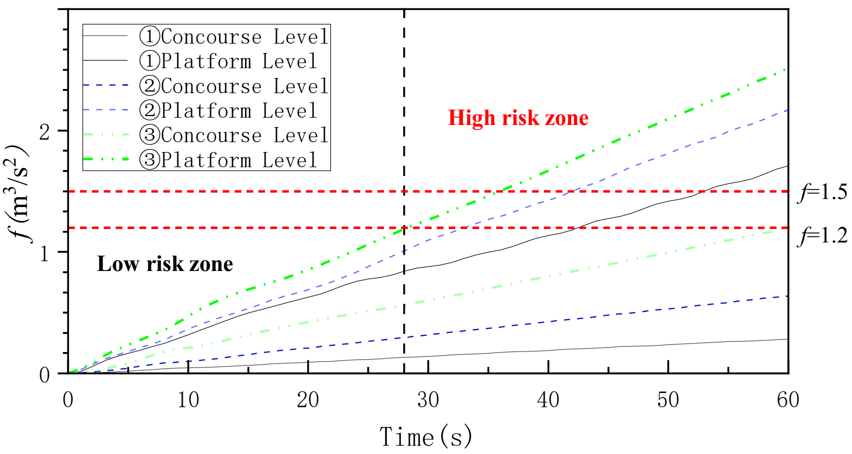

Fig. 6. Hazard-Time Graphs for Different Floors under Three Conditions

5 Conclusion

In the face of increasingly frequent extreme weather conditions, the probability of subway stations encountering high-volume floodwater infiltration due to extremely heavy rainfall is on the rise. Subway stations are characterized by a large flow of people, which poses significant risks. The research results indicate that when subway stations face flooding disasters, the risk is higher for evacuating individuals on the platform level, and this risk increases rapidly over time. Failure to evacuate in a timely manner could result in individuals being stranded on the platform level, endangering their lives. Conversely, in the absence of extremely heavy rainfall, the concourse level is typically considered low-risk and can serve as a temporary evacuation point. According to the research findings, in the event of emergencies, emergency evacuation management personnel should prioritize evacuating passengers and staff on the platform level, which is at a lower elevation, to increase safety. Additionally, the concourse level can serve as an evacuation buffer zone, offering a larger surface area, more entrances and exits, and lower hazard levels, thus preventing overcrowding and the risk of secondary stampede accidents. Furthermore, it is essential to logically distribute evacuation routes for platform-level evacuees, avoiding congestion at evacuation exits, enhancing evacuation efficiency, reducing evacuation time, and improving overall evacuation safety as much as possible. Finally, based on the hazard-time variation graphs for different floors under various conditions, adjustments can be made to the start times and monitoring thresholds of different drainage equipment in a targeted manner. This helps reduce equipment operating costs while maximizing evacuation safety for passengers.

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