WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2024.151877

ARCHIVES OF CIVIL ENGINEERING

Vol. LXX ISSUE 4 2024

pp. 29 –42

Research paper

Building pedestrian simulation and channel design simulation technology based on virtual reality technology

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Abstract: In recent years, virtual reality technology has been widely applied and researched in various fields. In digital architectural design and simulation, it has gradually become an important tool. For the evacuation of commercial buildings, virtual reality technology is introduced and a digital building evacuation simulation model based on panic emotions is proposed. Meanwhile, based on this model, the behavior and distribution of pedestrians are simulated, targeted evacuation design schemes are proposed, and the spatial evacuation congestion situation of each scheme is evaluated. These results confirm that in digital commercial building simulation design, the visibility loop rate of the strip path model is as high as 71.25%, which is 8.93% and 11.35% higher than that of the circular path and radiation path, respectively. Meanwhile, the reachability loop back rate of this model is as high as 76.39%. In addition, when the horizontal spacing is 2.5 m, the time for the group to complete evacuation is the shortest, only 180 seconds. And its evacuation rate reached a maximum of 0.4. When the horizontal spacing increases to 4.5 meters, the evacuation time and efficiency are close to the barrier free situation, and obstacles have little effect on reducing congestion. The adoption of the proposed method can help designers develop reasonable evacuation strategies more efficiently and safely, providing strong technical support for the field of architectural design.

Keywords: Arch effect, digital architecture, evacuation simulation, improve particle swarm optimization algorithm, panic emotions, simulation design, VR

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1. Introduction

Commercial buildings are iconic products of urban modernization, typically located in the center of commerce and in places with extremely dense pedestrian and vehicular traffic. Commercial buildings are constantly developing towards larger volumes, more complex structures, and more comprehensive functions in the new environment. At the same time, the number of people admitted is gradually increasing, with some urban complexes reaching a peak of hundreds of thousands of customers. Once a fire occurs, it is extremely difficult to evacuate personnel, which can easily cause major accidents such as casualties and property losses [1]. In order to reduce the casualties caused by fires and other accidents in urban complexes, and ensure the safety of personnel evacuation, it is necessary to organize crowd evacuation reasonably and efficiently in emergency situations. The traditional evacuation design methods are largely based on experience and norms, which may be sufficient to deal with emergency situations in simple building spaces. However, the spatial design of modern commercial buildings tends to be diversified, and the division of functional areas presents a high degree of complexity. This makes it difficult for people to quickly find a safe escape route in emergency situations [2]. Secondly, the personnel composition in modern commercial buildings is also more complex, including different roles such as employees and customers, who may exhibit different behavioral characteristics in emergency situations [3]. In recent years, the development of Virtual Reality (VR) technology has provided new solutions for building evacuation design. This technology can simulate the real building environment, allowing people to experience the interior of the building firsthand and immerse themselves in it. In building evacuation design, VR can simulate various scenarios inside buildings, such as emergencies such as fires and earthquakes. Therefore, the study introduces VR and proposes a Digital Architecture (DA) evacuation simulation model based on panic emotions, which is jointly applied to building evacuation design. The contribution of the research lies in the introduction of VR and DA evacuation simulation models based on panic emotions. This can help designers intuitively understand the spatial structure and facility layout inside the building, as well as the behavioral characteristics of people in emergency situations, which helps optimize the design of the building.

The research content includes four parts. Firstly, a review is conducted on VR and building evacuation design. Secondly, the evacuation design and simulation of digital commercial buildings based on VR are introduced. The first section introduces VR, followed by the introduction of the DA evacuation simulation model, and then the evacuation design of DA is carried out. The third part conducts simulation experiments to verify the optimization design based on VR. Finally, the research results are summarized and discussed, and future prospects are proposed.

2. Related works

In architecture, VR is gradually becoming a powerful tool. Wang et al. proposed a three-dimensional visualization based urban landscape planning method to address the shortcomings of traditional urban landscape planning and design methods. These results confirm that this technology can provide timely information through intelligent drawing, improving design efficiency and quality [4]. Safikhani et al. found that the construction, engineering, and construction industries were relatively slow to adopt VR. So they proposed a method of conducting two rounds of surveys and analyzing feedback from industry experts and researchers. These results confirm that the use of VR is expected to steadily increase within 5 to 10 years [5]. Rafsanjani and Nabizadeh proposed a VR-based university architecture VR system to address the issues of single teaching methods and insufficient remote teaching capabilities in university architecture teaching. These results confirm that this technology provides an effective teaching method for architecture courses [6].

Evacuation design is a crucial research direction in architecture, which involves the safety of personnel and the protection of life and property. Bina and Moghadas proposed a method based on agent modeling using BIM software and human behavior simulation engine to simulate the emergency evacuation of 177 representatives from the conference hall. These results confirm that placing two symmetrical exit doors on both sides of the conference hall can provide the most effective evacuation mode [7]. Wang et al. proposed using a new discrete molecular dynamics technique to simulate personnel evacuation in panic situations for emergency evacuation in buildings. These results confirm that adaptive geometric configurations can improve safety and efficiency during emergency evacuation, and dynamic wall modeling can improve crowd flow and reduce spill over rates [8]. Song et al. proposed a dynamic exit decision-making model to solve the problem of multi-exit layout in buildings, integrating exit selection strategies and social force models. These results confirm that the layout of two parallel exits is the most effective, with a distance between exits that is too large or too small increasing evacuation time. A uniform and symmetrical layout is more effective [9].

In summary, domestic and foreign researchers have conducted extensive research on VR and building evacuation design, and have achieved certain results. But few studies have introduced VR into the evacuation design of DA. Therefore, the study adopts VR combined with a fear based evacuation simulation model to jointly apply to building design to achieve more accurate and effective building evacuation design.

3. Digital building evacuation design and simulation model design based on VR technology

To achieve more efficient DA evacuation design, this chapter first introduces VR for DA evacuation design and analyzes the role of this technology in the design. Subsequently, a DA evacuation simulation model based on panic emotions is proposed, analyzing the speed adjustment between ordinary individuals and leaders. Finally, the proposed method is used to optimize the design work for the research case.

3.1. Digital building evacuation design and simulation model design based on VR technology

In today's complex environment, evacuation simulation has become an indispensable tool for decision-makers to evaluate the evacuation and safety performance of buildings and public places. VR is a computer technology that can create and experience virtual worlds. By simulating human auditory, visual, and tactile senses, it allows users to immerse themselves in a highly realistic three-dimensional virtual environment [10]. In the evacuation simulation of urban commercial buildings, using VR for evacuation simulation can help decision-makers comprehensively understand various possible situations during the evacuation process [11]. Through simulation, decision-makers can accurately evaluate the length, width, and accessibility of evacuation routes, as well as determine whether exits or signage need to be added. By observing the response and action characteristics of the population in emergency situations, decision-makers can determine whether measures need to be taken to optimize the evacuation process. VR can also simulate people escaping from different floors or areas, helping decision-makers better understand the flow of people and areas where congestion may occur.. In addition, VR can be used to evaluate the selection of safe shelters. By simulating the evacuation process in emergency situations, decision-makers can evaluate the location, capacity, and accessibility of shelters to ensure safe evacuation for personnel in emergency situations. And it is possible to observe the reactions and movement speed of different groups of people when searching for shelters, and determine whether it is necessary to add shelters or optimize their positions. Figure 1 shows the functional architecture of VR.

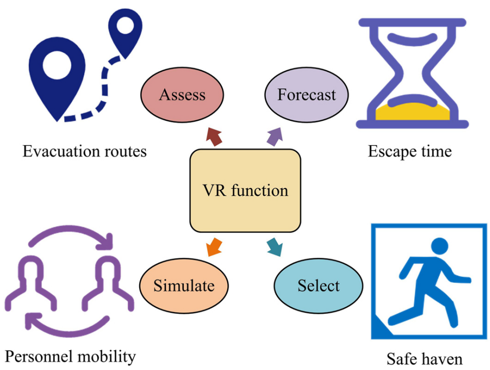

Fig. 1. The functional architecture of VR

3.2. Digital building evacuation simulation model based on panic emotions

A DA evacuation simulation model based on panic emotions is proposed for the design of pedestrian flow evacuation in urban commercial buildings, which covers three stages [12]. In the perception stage, a continuous evacuation scene model is constructed using VR to simulate the evacuation process in indoor environments. Ordinary individuals are abstracted as agents and multiple type attributes of agents are defined, including leaders and conservative, stable, and sensitive ordinary individuals. Leaders have familiarity with evacuation scenarios and evacuation skills, such as shopping mall guides or security guards. In the decision-making stage, each agent will use VR to make evacuation decisions from a first person perspective, taking into account their own abilities and surrounding environmental conditions, and following the principle of the fastest evacuation. For leaders, their evacuation decision is to move towards the nearest exit. Meanwhile, if there are ordinary individuals following, they will cooperate with the follower's speed. In the evacuation decision of ordinary individuals, if they discover an exit, they move directly towards the exit. If people can see the leader, they follow the leader to move. If people cannot see either the exit or the leader, they choose to follow other ordinary individuals within their field of vision. If no one is visible in the field of vision, randomly choose a direction to move. During the action phase, each agent moves based on the evacuation decision made during the decision-making phase. Through VR, users can observe the agent's movement trajectory and evacuation process in real time, and interact with the virtual environment [13]. For leaders and ordinary individuals, Figure 2 shows their speed update steps.

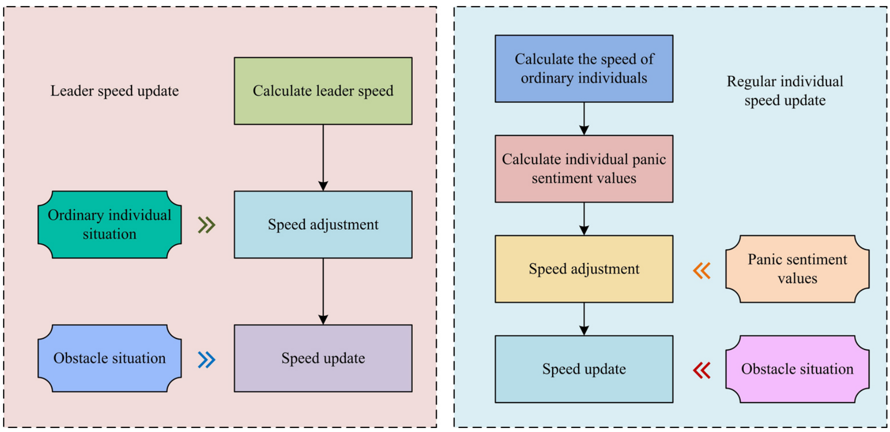

Fig. 2. Steps for Speed Update between Leaders and Ordinary Individuals

In order to better solve the problem of finding the optimal solution for the model, particle swarm optimization algorithm was introduced in the study. Aiming at the problem of classical particle swarm optimization algorithms easily falling into local optima and reducing particle population diversity in the later stages of iteration, this study combines genetic operations in genetic algorithms with dynamic parameter particle swarm optimization algorithms and proposes an improved particle swarm optimization algorithm. This algorithm mainly updates the spatial position of the current particle swarm through cross factors, which generates a new particle swarm that is more in line with the objective optimization function, can obtain better fitness, and thus improve the local search ability of classical particle swarm algorithms. The leader speed calculated iteratively using the improved particle swarm optimization algorithm is represented by Equation (3.1).

$$\vec{v}_l(t+1) = w \cdot \vec{v}_l(t) + c_1 r_1(\text{Pbest}_l(t) - x_l(t) + c_2 r_2(x_{exit} - x_l(t)) + \frac{1}{m_l}\sum_{j\subset\Omega_l} \vec{f}_{lj} \cdot \mathrm{d}t \tag{3.1}$$

In Equation (3.1), t represents the time step. w represents the inertia weight. Pbest_l is the best position in the history of leaders. $x_l(t)$ represents the position of the leader. x_{exit} represents the exit location. c_1 and c_2 represent the partial weights of historical optimal solutions for individuals and groups, respectively. r_1 and r_2 are random numbers between [0,1]. m_l represents the quality of the leader. Ω_l represents the leader neighborhood. $\vec{f}_{lj}$ represents the interaction force between the leader and the neighboring individual j. If ordinary individuals can see a nearby exit, their speed is represented by Equation (3.2).

$$\vec{v}_l(t+1) = w \cdot \vec{v}_l(t) + c_1 r_1(\text{Pbest}_l(t) - x_l(t)) + c_2 r_2(x_{exit} - x_l(t)) + \frac{1}{m_l}\sum_{j\subset\Omega_l} \vec{f}_{lj}\mathrm{d}t \tag{3.2}$$

If ordinary individuals can only see the leader, their speed is represented by Equation (3.3).

$$\vec{v}_i(t+1) = w \cdot \vec{v}_l(t) + c_2 r_2(x_l(t) - x_i(t)) + \frac{1}{m_i}\sum_{j\subset\Omega_l} \vec{f}_{lj}\mathrm{d}t \tag{3.3}$$

In Equation (3.3), m_i represents the mass of an ordinary individual. If ordinary individuals can only see nearby ordinary individuals, their speed is represented by Equation (3.4).

$$\vec{v}_i(t+1) = w \cdot \vec{v}_l(t) + \frac{1}{m_l}(\text{herd}\, c_2 r_2 \sum\nolimits_{j\subset\Omega_i} \vec{f}_{ij}^{\text{attr}} + \sum\nolimits_{j\subset\Omega_i} \vec{f}_{ij})\mathrm{d}t \tag{3.4}$$

In Equation (3.4), herd represents the conformity coefficient. $\vec{f}_{ij}^{\text{attr}}$ represents the attraction between ordinary individuals. $\vec{f}_{ij}$ represents the interaction force between ordinary individuals. If ordinary individuals cannot see any individual, their speed is represented by Equation (3.5).

$$\vec{v}_i(t+1) = w \cdot \vec{v}_l(t) + (x_{\text{rand}} - x_i(t)) \tag{3.5}$$

In equation (3.5), x_{rand} represents any position in the environment. Considering the surrounding obstacles and the impact of panic values, it is necessary to adjust the leader's speed, represented by Equation (3.6).

$$\vec{v}_i(t) = \begin{cases} \min(\vec{v}_l(t), i \in \Omega_i), & |\Omega_i| \neq 0 \\ \vec{v}_i^0(t), & |\Omega_i| = 0 \end{cases} \tag{3.6}$$

In Equation (3.6), Ω_i represents the neighborhood of an ordinary individual. The interaction force between people and obstacles is represented by Equation (3.7).

$$f_{io} = \left\{A_i \exp\left[\frac{r_i - d_{io}}{B_i}\right] + kg(r_{ij} - d_{io})\right\} + kg(r_i - d_{io})(v_i \cdot t_{io})t_{io} \tag{3.7}$$

In Equation (3.7), A_i represents the coefficient of psychological repulsion. B_i represents the distance coefficient. r_{ij} is the sum of radii for ordinary individuals. r_i is the model radius size for the ordinary individual i. d_{io} is the distance from the average individual i to the obstacle o. t_{io} represents the tangent direction vector. k represents the elastic coefficient of compression. $g(x)$ is a piecewise function, represented by Equation (3.8).

$$g(x) = \begin{cases} 0, & x \leqslant 0 \\ x, & x > 0 \end{cases} \tag{3.8}$$

After considering obstacles, the speed of ordinary individuals is represented by Equation (3.9).

$$\vec{v}_i(t) = \vec{v}_{\mathrm{APSO}} + \sum_{w \subset \Omega_i} \frac{1}{m_i} \vec{f}_{iw} \mathrm{d}t \tag{3.9}$$

In Equation (3.9), $\vec{v}_{\mathrm{APSO}}$ represents the adjusted Agent speed. $\vec{f}_{iw}$ represents the force exerted by adjacent ordinary individuals. The panic value is represented by Equation (3.10).

$$\mathrm{panic}_i = e_1 q_i^{\mathrm{PS-Durupinar}} + e_2(v_i^0 - v_i) + e_3 Q + e_4 \tag{3.10}$$

In Equation (3.10), e_1, e_2, e_3, and e_4 represent proportional constants. $q_i^{\mathrm{PS-Durupinar}}$ represents emotional value. Q represents the cumulative panic value. The speed of ordinary individuals in a state of panic is represented by Equation (3.11).

$$v_i(t) = (1 - \mathrm{panic}_i) v_i^0 + \mathrm{panic}_i \cdot v_{\max} \tag{3.11}$$

In Equation (3.11), $v_{\max}$ represents the maximum speed. The emotional values of ordinary individuals are represented by Equation (3.12).

$$Q(i) = \sum_{j \subset \Omega_l} q_j \tag{3.12}$$

If the individual is conservative, the emotional value is represented by Equation (3.13).

$$q(t) = \mathrm{rand}\,(0, 0.4) \tag{3.13}$$

If the individual is sedate, the emotional value is represented by Equation (3.14).

$$q(t) = \mathrm{rand}\,(0.4, 0.8) \tag{3.14}$$

If the individual is sensitive, the emotional value is represented by Equation (3.15).

$$q(t) = \mathrm{rand}\,(0.8, 1.0) \tag{3.15}$$

3.3. Design of digital building evacuation optimization

Based on the evacuation simulation model, this study evaluates the spatial evacuation congestion situation of various schemes by simulating the behavior and distribution of pedestrians in various schemes to obtain targeted design schemes [14]. The main factors affecting evacuation efficiency include path form and width, exit and location, etc. During the evacuation process, the movement of pedestrians will form a zipper phenomenon, which has a significant impact on the speed of pedestrian movement. The zipper effect is a phenomenon of pedestrian self-organization, which refers to the macro phenomenon of pedestrian flow generated by pedestrians based on their own factors and spontaneous organization without external force guidance. During walking in the same direction, the positional relationship between two adjacent pedestrians can be divided into three types: side by side, diagonal, and straight. Figure 3 shows the manifestation of pedestrian zipper phenomenon.

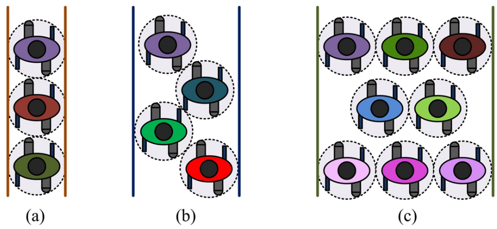

Fig. 3. Pedestrian zipper phenomenon expression form; (a) Inline form, (b) Oblique form, (c) Multiple column by side form

Through simulation experiments and analysis, when the channel width only allows one pedestrian to pass through, pedestrians will maintain a straight line arrangement. When the width of the passage cannot accommodate two people standing side by side, pedestrians will maintain a straight or diagonal arrangement. When the actual channel width can accommodate multiple pedestrians passing side by side, the three arrangement modes of side by side, diagonal, and straight will all occur. To ensure emergency evacuation in commercial buildings, setting the path width to 4.8 meters can ensure a balance between economy and evacuation. In addition, in VR based evacuation simulations, congestion at entrances and exits is more severe due to the concentration of people, and there is an arch effect. People instinctively face towards the exit, forming a shape similar to an arch. The research mainly aims to reduce congestion by adjusting the arch effect's position. When the arch is located on the outside, the congestion in the area below the arch will be significantly reduced, and the pedestrian congestion in that area will also decrease accordingly. Therefore, the study sets the lower side of the arch as a protected area, mainly relying on setting obstacles near the exit area to achieve this goal. In the initial stage, obstacles are determined based on the width of the exit. The horizontal spacing is the same as the exit width, and the vertical spacing is about 1/3 of the horizontal spacing. The side length data of obstacles is set to the corresponding horizontal spacing of 1/2. To minimize congestion in commercial buildings, the study selects obstacles with a horizontal spacing of 2.5 meters and a vertical spacing of 1.0 meters and adopts a symmetrical obstacle setting mode.

4. Simulation experiment analysis of digital building evacuation design based on VR

This chapter validated the building strategy designed for VR and DA evacuation simulation models and verified the effectiveness of the proposed design scheme through simulation experiments. Firstly, different path forms and width designs were verified, and then the impact of obstacle settings on building evacuation was verified.

4.1. Analysis of the impact of path form and width design on building evacuation

To verify the effectiveness of VR based DA evacuation design, a simulation was conducted using VR under the same conditions. The simulation platform uses Anylogic, which has a variety of modeling elements and intelligent agent libraries inside, and has high visibility. Meanwhile, a fixed number of 1000 people were selected for the experiment. Table 1 shows the proportion of participants with different attributes in the experiment.

Table 1. Member proportions for the different attributes

Basic attributes	**Personnel ratio (%)**
Juvenile	0.1
Youth	0.6
Old age	0.3
Masculine	0.43
Leadership oriented	0.08
Conservative type	0.24
Stable and heavy	0.4
Sensitive type	0.28

The study first verified the effectiveness of the designed strip path and compared it with circular and radial paths. Visibility loop rate and accessibility loop rate were used as evaluation indicators for evacuation efficiency. Simultaneously, 10 experiments were conducted on models with different path forms, and the average value was taken as the final experimental result. Figure 4 shows the reachability loop rate and visibility loop rate of different path features. The various indicators of the strip path were superior to the other two forms. In Figure 4(a), the visibility loop rate of the strip path model was 71.25%, which was 8.93% and 11.35% higher than the other two forms, respectively. In Figure 4(b), the reachability loop rate of the strip path model was 76.39%, which was 5.93% and 9.05% higher than other forms, respectively. The research indicates that the designed strip path can provide better evacuation effects.

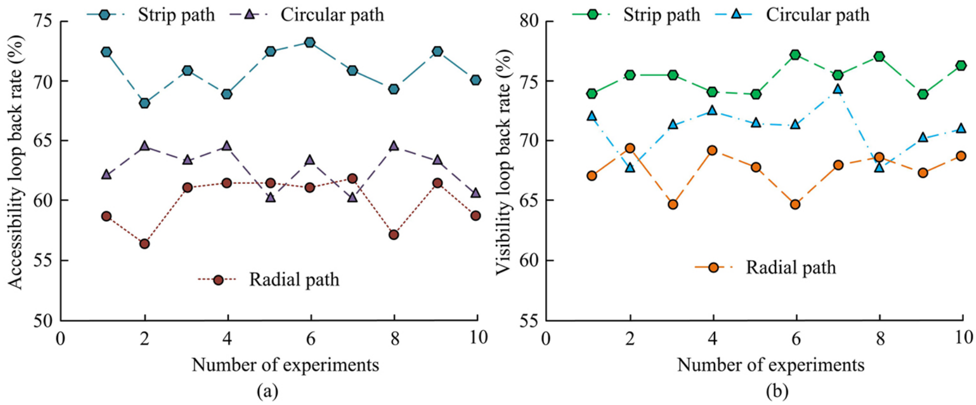

Fig. 4. Accessibility loop rate (a) and visibility loop rate (b) of different path form

The study continued to explore the impact of different entrance and exit widths on evacuation time. Under various width conditions, 10 simulation runs were conducted, and the average value was taken as the evacuation time at the corresponding width. Figure 5 shows the evacuation time under different width conditions. In Figure 5(a), when the width of the entrance and exit was set to 4.8 meters, the simulated evacuation time was only 170 seconds. When the width of the entrance and exit was set to 2.4 meters, the simulated evacuation time was 360 seconds, an increase of 190 seconds compared to 4.8 meters. When the width of the entrance and exit was set to 3.6 meters, the simulated evacuation time was 220 seconds. In Figure 5(b), when the path width was higher than 4.8 meters, the growth rate of the number of evacuees slowed down with the increase of evacuation time. When the width of the entrance and exit was set to 8.4 meters, the evacuation rate was highest before 93 seconds. The main reason is that the wider the entrance and exit in the early stage of evacuation, the higher the carrying capacity, and the higher the evacuation efficiency. The subsequent evacuation time depends on the minimum speed of the evacuees and is not related to the width of the entrance and exit.

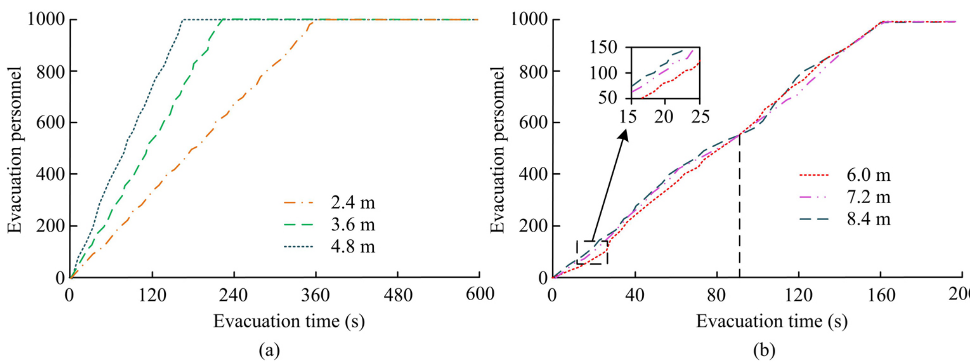

Fig. 5. Evacuation time for different widths of entrances and exits; (a) Evacuation time when the exit width is less than 4.8 m, (b) Evacuation time when the exit width is greater than 4.8 m

4.2. Analysis of the impact of obstacle setting on building evacuation

A comparative study was conducted to analyze the impact of different horizontal distances between obstacles on alleviating congestion. The horizontal distances between obstacles were set to 1.5 m, 2.5 m, 3.5 m, and 4.5 m, respectively. In the data comparison, the impact of different distances on evacuation was analyzed using obstacle free conditions as a reference. Figure 6 shows the evacuation efficiency of different horizontal distances between obstacles. As the spacing increased, the level of pedestrian congestion within the protected area gradually increased. In Figure 6(a), when the horizontal spacing was 1.5 meters, the group completed evacuation for the longest time, up to 270 seconds, exceeding the situation of obstacle free. Meanwhile, its evacuation rate was the lowest, with a maximum of only 0.76. In Figure 6(b), when the horizontal spacing was 2.5 meters, the time for the group to complete evacuation was the shortest, only 180 seconds. And its evacuation rate reached a maximum of 0.4. In Figure 6(c), when the lateral spacing increased to 3.5 meters, the time for the group to complete evacuation was 225 seconds. In Figure 6(d), when the lateral spacing increased to 4.5 meters, the evacuation time and efficiency were close to the unobstructed situation, and obstacles had little effect on reducing congestion. It indicated the optimal lateral distance between obstacles was 2.5 meters.

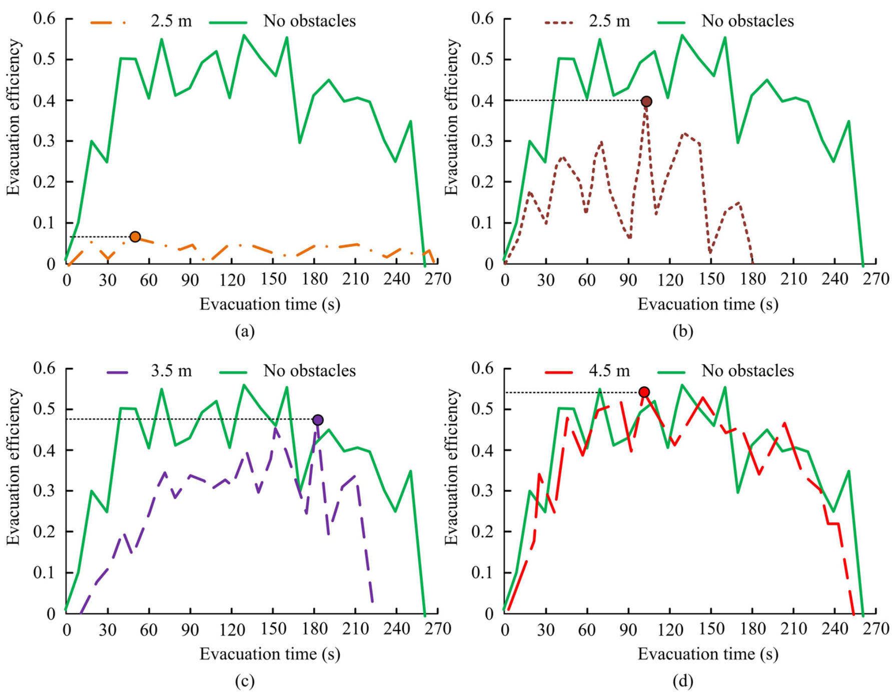

Fig. 6. Evacuation efficiency of different horizontal distances between obstacles; (a) Evacuation efficiency of 1.5 m obstacle lateral spacing, (b) Evacuation efficiency of 2.5 m obstacle lateral spacing, (c) Evacuation efficiency of 3.5 m obstacle lateral spacing, (d) Evacuation efficiency of 4.5 m obstacle lateral spacing

The study continued to explore the impact of different longitudinal spacing of obstacles on evacuation efficiency, with longitudinal spacing of obstacles set at 0.5 m, 1.0 m, 1.5 m, and 2.0 m, respectively. Meanwhile, the obstacle free condition was set as the reference group. Figure 7 shows the experimental results. When the longitudinal distance between obstacles was 1.0 m, the evacuation efficiency was highest, and the evacuation time was only 182 seconds. When the longitudinal spacing was 0.5 m, the evacuation efficiency was the lowest, with an evacuation time of up to 268 seconds. When the longitudinal spacing was 2.0 meters, the evacuation efficiency was close to the unobstructed situation, and obstacles have little effect on evacuation. It indicated the optimal longitudinal distance between obstacles was 1.0 m.

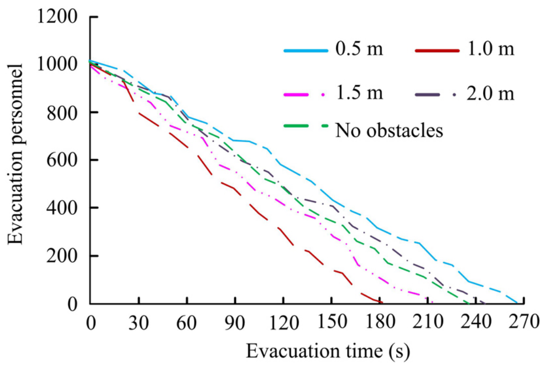

Fig. 7. Evacuation efficiency of different longitudinal spacing

The study continued to explore the effects of asymmetric and symmetric obstacles on evacuation efficiency. Figure 8 shows the impact of obstacles in different modes on evacuation efficiency. Both types of obstacle designs could be used to regulate specific arch effects. In

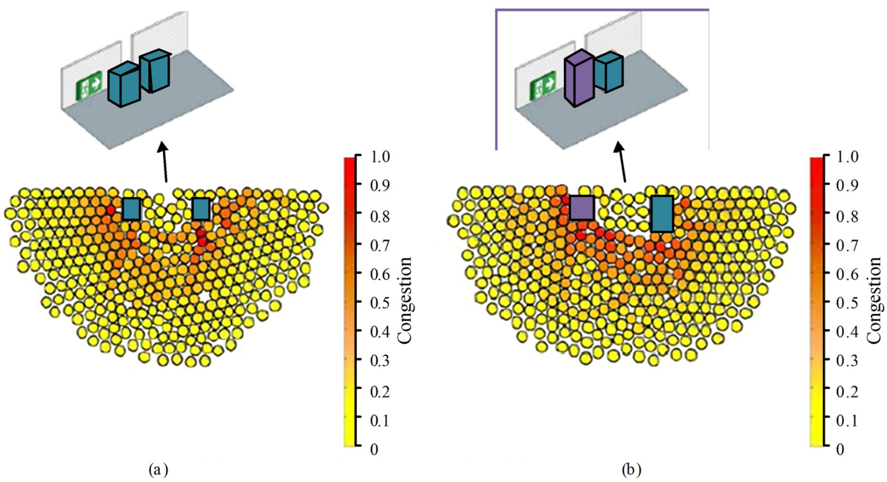

Fig. 8. Results of different modes of obstacles on evacuation efficiency; (a) Design of symmetrical obstacle evacuation mode, (b) Design of asymmetrical obstacle evacuation mode

Figure 8, the crowding degree of the arches on both sides of the symmetrical obstacle was equivalent, with only a few points having higher crowding degree. In Figure 8(b), the right arch foot of the asymmetric obstacle led to higher crowding, thus increasing the probability of encountering danger. In the case of setting asymmetric obstacles, there was a significant fluctuation in the crowding level, and the evacuation time was longer. Therefore, using symmetrical obstacles to alleviate congestion is a more effective choice.

5. Conclusions

In commercial buildings, pedestrian evacuation is an important safety consideration. In response to the problem of digital commercial building design, VR has been introduced in this study, and corresponding optimization designs have been carried out in combination with DA evacuation simulation models. These results confirm that when the width of the entrance and exit is set to 4.8 meters, the simulated evacuation time is only 170 seconds. When the width of the entrance and exit is set to 2.4 meters, the simulated evacuation time is 360 seconds, an increase of 190 seconds compared to 4.8 meters. When the width of the entrance and exit is set to 3.6 meters, the simulated evacuation time is 220 seconds. When the width of the entrance and exit is set to 8.4 meters, the evacuation rate is highest before 93 seconds. And when the longitudinal distance between obstacles is 1.0 m, the evacuation efficiency is highest, and the evacuation time is only 182 seconds. When the horizontal spacing is reduced to 0.5 m, the evacuation efficiency is the lowest, and the evacuation time is 268 seconds. However, when the lateral spacing increases to 2.0 meters, the evacuation efficiency is close to the unobstructed situation, and obstacles have almost no impact on evacuation. In addition, the crowding degree of the arches on both sides of the symmetrical obstacle is equivalent, with only a few points having a high degree of crowding. The right arch foot of the asymmetric obstacle leads to higher crowding. These indicate that the optimized design based on the method proposed in the study has significant advantages. However, the study does not consider the relevant design of the corridor and store layout, which is also an important influencing factor for pedestrian evacuation. Further research can be conducted.

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Received: 2024-01-12, Revised: 2024-03-12