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Effect of a static pedestrian as an exit obstacle on evacuation

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Building exit as a bottleneck structure is the last and the most congested stage in building evacuation. It is well known that obstacles at the exit affect the evacuation process, but few researchers pay attention to the effect of stationary pedestrians (the elderly with slow speed, the injured, and the static evacuation guide) as obstacles at the exit on the evacuation process. This paper explores the influence of the presence of a stationary pedestrian as an obstacle at the exit on the evacuation from experiments and simulations. We use a software, Pathfinder, based on the agent-based model to study the effect of ratios of exit width (D) to distance (d) between the static pedestrian and the exit, the asymmetric structure by shifting the static pedestrian upward, and types of obstacles on evacuation. Results show that the evacuation time of scenes with a static pedestrian is longer than that of scenes with an obstacle due to the unexpected hindering effect of the static pedestrian. Different ratios of D/d have different effects on evacuation efficiency. Among the five D/d ratios in this paper, the evacuation efficiency is the largest when d is equal to $0.75D$, and the existence of the static pedestrian has a positive impact on evacuation in this condition. The influence of the asymmetric structure of the static pedestrian on evacuation efficiency is affected by D/d. This study can provide a theoretical basis for crowd management and evacuation plan near the exit of complex buildings and facilities.

Keywords: evacuation, exit obstacle, static pedestrian, pathfinder simulation

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1. Introduction

With the increase of the urban population and the rapid development of science and technology, modern urban buildings have the characteristics of structural complexity and functional diversity. Meanwhile, building fire accidents occurred frequently (19 people dead and 63 people injured in Bronx apartment building fire in January 2022, 19 people injured in a 30-storey building fire in Abu Dhabi in June 2022, 5 people dead and 44 people injured in a South Korea's hospital building fire in August 2022), When emergencies such as fire accidents occur, it is great challenges to evacuate crowds from complex buildings efficiently. It is pointed out that failure to evacuate in time was the main cause of casualties in fire accidents.[1] Therefore, how to improve the efficiency of building evacuation has attracted the attention of researchers and managers, such as modifying evacuation strategy,[2] optimizing building structure,[3,4] analyzing pedestrian behaviors,[5,6] *etc*. Building exits restrict pedestrian movement during evacuation as the bottleneck structure and have a significant impact on evacuation efficiency.[7] Interestingly, some researchers have proposed that the reasonable setting of obstacles at the exit can have a positive impact on the evacuation process.[1,8]

Researchers have studied the effect of obstacles at the exit on evacuation through experiments and simulations. In terms of experimental research, researchers demonstrated that the positive or negative impact of obstacles on evacuation depends on obstacle sizes,[9] obstacle shapes,[10] the distance between obstacles and the exit,[9] and the height[11] of obstacles and so on. On the one hand, it is found that the reasonable setting of obstacles at the exit can improve evacuation efficiency. For example, Helbing *et al.* placed a board-shaped obstacle in front of the exit in a controlled experiment and found that the presence of obstacles can reduce the clogging effect at the exit and increase the escape rate.[12] Yanagisawa *et al.* investigated the effect of exit obstacles on frictional and turning functions on pedestrian outflow through experiments and simulations. Results show that the presence of the obstacle can reduce the number of conflicting pedestrians at the exit. They suggested that placing an obstacle at the exit can improve pedestrian flow.[13] Zhao *et al.* studied the impact of exit obstacles on evacuation by varying obstacle numbers, obstacle shapes and distances of obstacle-exit during the experiment. They found that evacuation efficiency can be improved when obstacles are placed in a proper position. The presence of obstacles reduces the density of congested areas by separating space effectively. Compared to a pillar-shaped obstacle, the panel-shaped and

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double pillar-shaped obstacles have a better effect on improving evacuation efficiency.[10] Shi *et al.* carried out experiments to investigate the effect of exit obstacles on evacuation efficiency by varying obstacle sizes (0.6 m, 1.0 m), the distance of obstacle exit (0.6 m, 0.8 m, 1.0 m), and locations of the exit (corner, middle). They find that evacuation efficiency can be improved by setting appropriate obstacle size and position of obstacle.[9] On the other hand, some studies indicated that the existence of obstacles has a negative effect on evacuation. Ding *et al.* conducted experiments to study the impact of a bar-shaped obstacle with different heights and obstacle-exit distances on room evacuation. Results show that evacuation time is longer in the presence of an obstacle than in the absence of an obstacle. The obstacle-exit distance and height of the obstacle affect evacuation efficiency.[11] Jia *et al.* from experiments found that two different trends of egress time with the increase of obstacle size can be observed. When the obstacle is close to the exit, the variation of obstacles does not affect the egress time. When the obstacle is far away from the exit, evacuation time increases with obstacle size. This is mainly due to the influence of the obstacle on the frequency of changing lanes behavior, thus influencing evacuation efficiency.[14] In addition, some researchers pointed out that although the existence of obstacles at the exit can not reduce the evacuation time, obstacles can reduce the development of collective transversal rushes,[15] alleviate the pressure at the exit[16] and stabilize longitudinal crowd waves,[17] which could be as crucial as reducing the evacuation time.

In terms of the simulation aspect, researchers have reached inconsistent conclusions about the impact of obstacles on evacuation efficiency. Some researchers suggested that the presence of obstacles has a positive effect on evacuation. For example, Helbing *et al.* found that placing columns asymmetrically in front of the exit can improve outflows and prevent the accumulation of fatal pressures based on a social force model.[18] Yanagisawa *et al.* investigated the effect of conflicts and turning of exit obstacles on outflow by a floor field model. They found that when congestions appear at the exit, the presence of obstacles has a positive effect on evacuation because the number of conflicts is reduced by obstacles.[19] Jiang *et al.* found that placing pillar-shaped obstacles on both sides of the exit can reduce the tangential momentum and increase the escape speed, so as to maximize the evacuation efficiency by using a social force-based genetic algorithm and experiments.[20] Wang *et al.* investigated the effect of exit locations, bottleneck lengths, and exit obstacles on pedestrian egress by a modified social force model. Results show that placing obstacles (a barricade obstacle and two-pillar obstacles) near the exit does not increase the evacuation time, but improves the evacuation efficiency. The parameters of obstacles play a decisive role in evacuation efficiency. However, there is no consistent conclusion on which shape of the obstacle is better.[8] Xu *et al.* studied the effect of a moving obstacle on the evacuation of a single exit room. They found that a moving obstacle can improve evacuation efficiency at different desired velocities. The presence of the moving obstacle increases the pedestrian velocity toward the exit and reduces the crowd density near the exit.[21] On the other hand, some studies indicated that the impact of exit obstacles on evacuation depends on the experimental settings and the attributes of obstacles. For instance, Frank *et al.* investigated the impact of obstacle shapes, obstacle locations, and pedestrians' capacity to avoid obstacles on evacuation efficiency. They suggested that the positive or negative impact of obstacles on evacuation is related to the desired velocity of pedestrians.[22] Yano used a toy model to study the effect of obstacle shapes on evacuation time. It is found that evacuation time is affected by the shape of obstacles. The evacuation time is the shortest in the presence of a circular cylinder obstacle.[23] Zhao *et al.* optimized the setting of exit obstacles based on a social model for panic evacuation. The simulation results show that the presence of obstacles can reduce the high density area near the exit and improve evacuation efficiency. The panel-shaped obstacle is more robust to increase evacuation efficiency than the pillar-shaped obstacle.[24] Wang *et al.* also obtained similar conclusions through experiments and simulations, and the positive effect of obstacles on evacuation depends on obstacle size and distance from the exit. Through sensitive analysis, they found that the influence of distance between obstacle and exit, length and width of the obstacle on evacuation gradually decreased.[1] Li *et al.* studied the influence of incomplete informed pedestrians on evacuation in the presence of obstacles in room evacuation based on an improved social force model. The positive effect of obstacles on evacuation is related to obstacle sizes, offset distances, and the desired velocity. The presence of obstacles does not reduce evacuation time when pedestrians are not fully aware of the evacuation information.[25]

To sum up, the positive or negative impact of exit obstacles on evacuation mainly depends on the attributes of the obstacles and the distance of the obstacle-exit. The size of obstacles in the previous research is usually larger than the size of the human body, and their appearances are significantly different from pedestrians. However, in real life, the standing evacuation guides, the elderly at slow speed, injured pedestrians, and pedestrians who stop to look for something (for example: looking for ID cards at the gate, *etc.*) may act as obstacles near the exit to affect the evacuation process. Compared with non-living obstacles, the repulsion and unpredictability of pedestrian obstacles by other pedestrians may affect the evacuation process. Research on pedestrians acting as obstacles is insufficient. In this paper, the effect of a static pedestrian as an exit obstacle on building evacuation efficiency under emergency is studied from experiment and simulation. The influence of a static pedestrian on evacuation was studied by varying exit widths, distances between the static pedestrian and the exit, offset distances, and types of obstacles. The structure of this paper is as follows: In Section 2, the experiment settings and experiment results are studied. Software introduction, simulation scenario setup, and simulation results are discussed in Section 3. The conclusions are summarized in Section 4.

2. Experiment

This paper focuses on analyzing the dynamic characteristics of pedestrians near the exit. In order to obtain the dynamic characteristics of pedestrians in emergency situations as simulation parameters, we specially carry out experimental research on the area near the exit. Many middle school students were invited to participate in the Activities for Popular Science of a university. Therefore, except for the static pedestrian (an adult with 0.4-m shoulder width), volunteers participating in the experiment were junior school students (with 0.38-m shoulder width) aged 14–16. During the experiment, no volunteers presented or reported physical disabilities. The sketch map of the experiment scenario is shown in Fig. 1(a). Pedestrians were asked to evacuate from a 3.9 m×3.9 m square room with two openings, a one-way entrance and a one-way exit. The entrance was located at the upper boundary of the room and the exit was located in the middle of the left boundary of the room. Before the experiment, all the volunteers entered the room through the entrance. During the experiment, only the exit can be used to leave the room. A static pedestrian acted as an obstacle standing in the front of the exit. The distance between the static pedestrian and the exit (d) is 0.8 m. During the experiment, volunteers were asked to leave the room as soon as possible, assuming that there was a fire accident. In order to encourage volunteers to evacuate the room as quickly as possible, a reward plan was carried out. The top three volunteers who left the room in the experiment can get a gift. Therefore, our experiment can be regarded as room evacuation in an emergency. During the experiment, a digital camera was used to record the whole process. Fig. 1(b) is a screenshot of the experimental video. The frame rate of the video is 25 frames per second.

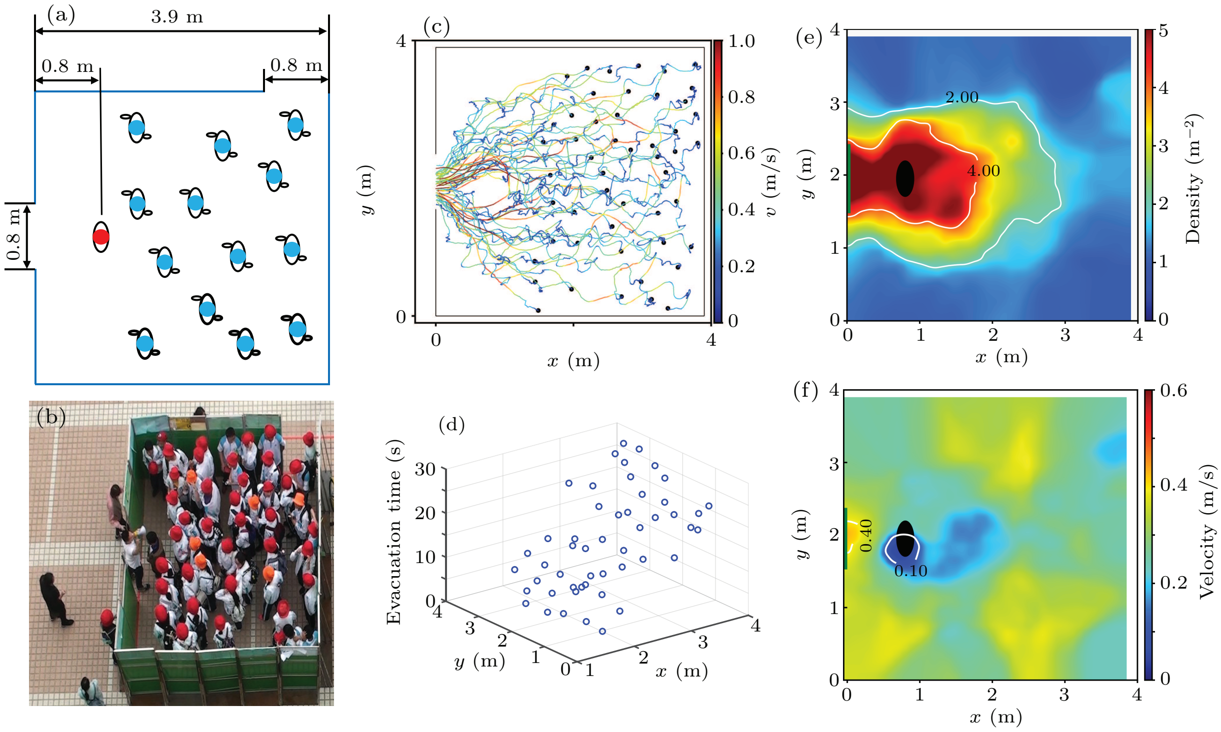

Fig. 1. Details of experiment scenario and results: (a) sketch map of experiment scenario, (b) a video screenshot of experiment scenario, (c) trajectories with the speed of pedestrians, (d) evacuation time of each pedestrian with their initial positions, (e) density profile of experiment, (f) velocity profile of experiment.

Pedestrian trajectories with speed are shown in Fig. 1(c). The color of trajectory indicates the speed of pedestrians. The black dot is the initial position of each pedestrian. It can be seen that the presence of the static pedestrian influences the movement of other pedestrians. Pedestrians make a detour to pass the static pedestrian to reach the exit and the movement speed of pedestrians around the static pedestrian decreases. Figure 1(d) shows the evacuation time of pedestrians at different initial positions. It can be seen that the evacuation time of pedestrians is positively correlated with the x-coordinate of the initial position. That is, the farther away from the exit, the evacuation time the longer. The relationship between the evacuation time and the y-coordinate of its initial position is not obvious. Figures 1(e) and 1(f) are the average density profile and average velocity profile in 5 s–15 s of the experiment, it can be seen that high-density areas appear around the exit and the static pedestrian, the existence of obstacles elongates the congested area at the exit. It can be seen from the velocity profile that a low-speed area is formed behind the obstacle pedestrian. However, there is no low-speed area in the high-density area at the exit. This also shows that the existence of the static pedestrian affects the pedestrian dynamic near the exit, then we propose the following assumptions: when the distance between the static pedestrian and the exit is in a certain range, the static pedestrian can alleviate the congestion at the exit, and most pedestrians are congested around the static pedestrian so that the congestion at the exit can be alleviated and the evacuation time can be reduced. When the static pedestrian is too close to the exit, the congestion at the exit overlaps with the congestion around the static pedestrian, which fails to alleviate the congestion at the exit. When the static pedestrian is far away from the exit, two congestion areas will be formed, and the static pedestrians cannot share the congestion at the exit. Whether the static pedestrian can alleviate the congestion at the exit and play an active role in evacuation depends on the distance between the static pedestrian and the exit. We will systematically investigate the effect of this distance on evacuation efficiency in the simulation section.

3. Simulation

3.1. Software introduction

In the field of pedestrian dynamics, researchers have developed much software to simulate the movement of large-scale crowds, evaluate the fire safety of buildings, and provide the basis for evacuation plans. For example, MassMotion[26] is based on the social force model, STEPS[27] is based on the cellular automata model, and Pathfinder[28] is based on the agent-based model, *etc*. Among them, agent-based models have received extensive attention due to their ability to simulate pedestrian behaviors at the micro level, such as interactions between pedestrians and the environment, and the synthesis of collective behaviors and individual behaviors. In this paper, Pathfinder software was employed. Pathfinder evacuation simulation software is developed by Thunderhead engineering and is an agent-based evacuation simulator.[28] The default movement mode of Pathfinder is steering mode. Steering mode combines path planning, and guidance mechanism and avoids collisions allowing more complex pedestrian behaviors. The steering model is used in this paper. Pathfinder software has been used to simulate pedestrian behaviors in a variety of scenarios, such as fire emergency evacuation in a subway station,[29] evacuation model combined with reversal guidance, collision handling and path planning of a commercial center,[30] the effect of stairs wide, landing on the evacuation of a school,[31] optimized evacuation strategy in high-rise buildings.[32]

3.2. Simulation scenario setup

We built the same scenario as experiments on the Pathfinder as shown in Fig. 2(a). Cylinders are used to represent pedestrians of 1.65 m in height. The initial setting of simulation scenarios is consistent with experiments, that is, the distance of obstacle-exit and the initial distribution of pedestrians. In addition to shoulder width and walking speed (except for the static pedestrian, who was an adult, all the volunteers were middle school students), the parameters of the static pedestrian are the same as those of other pedestrians. Since the emergency is simulated in our experiment, the values of parameters are adjusted according to the experimental data and literature.[33] The results of the simulation are in good agreement with the experimental results as shown in Fig. 2(b) (Mann–Whitney U test, evacuation time, experiment *versus* simulation: $p = 0.6172 > 0.05$). The model parameters are shown in Table 1.

Table 1. Model parameters.

Parameters	The static pedestrian	Other pedestrians
Shoulder width (m)	0.4	0.38
Speed (m/s)	0	2
Acceleration time (s)	0.45	0.45
Reduction factor	0.7	0.7
Persist time (s)	0.5	0.5
Collision response time (s)	1.0	1.0
Slow factor	0.05	0.05
Wall boundary layer (m)	0.15	0.15
Comfort distance (m)	0.05	0.05

After obtaining the parameter values, we built a room with 3.9 m×3.9 m as shown in Fig. 2(c), which is the same size as the experimental scenario. Pedestrians are evenly distributed in the room except for the static pedestrian. We study the impact of the static obstacles on evacuation efficiency by considering the following scenes: (i) based on the experiment scenario, studying the influence of different obstacle-exit distances on evacuation efficiency. Details of parameters are shown in Table 2; (ii) considering different ratios of exit width (D) to distance (d); (iii) considering the asymmetry location of the static pedestrian with different offset distances (O) and distances (d); (iv) the difference of the obstacle (First, a regular dodecagonal small room is established at the position of the static obstacle. The distance between any two vertices of the small room is the same as the diameter of the static pedestrian (0.4 m), and the shape is similar to a circle. Secondly, the small room is deleted so that an obstacle is generated at the position where the static pedestrian was originally located) and the static pedestrian. The time when all pedestrians leave the room is defined as evacuation time to indicate evacuation efficiency. Figure 2(d) shows a screenshot of the simulation scenario when $D = 0.8$ m, $d = 1.5$ m, $O = 0.2$ m, pedestrian number = 40.

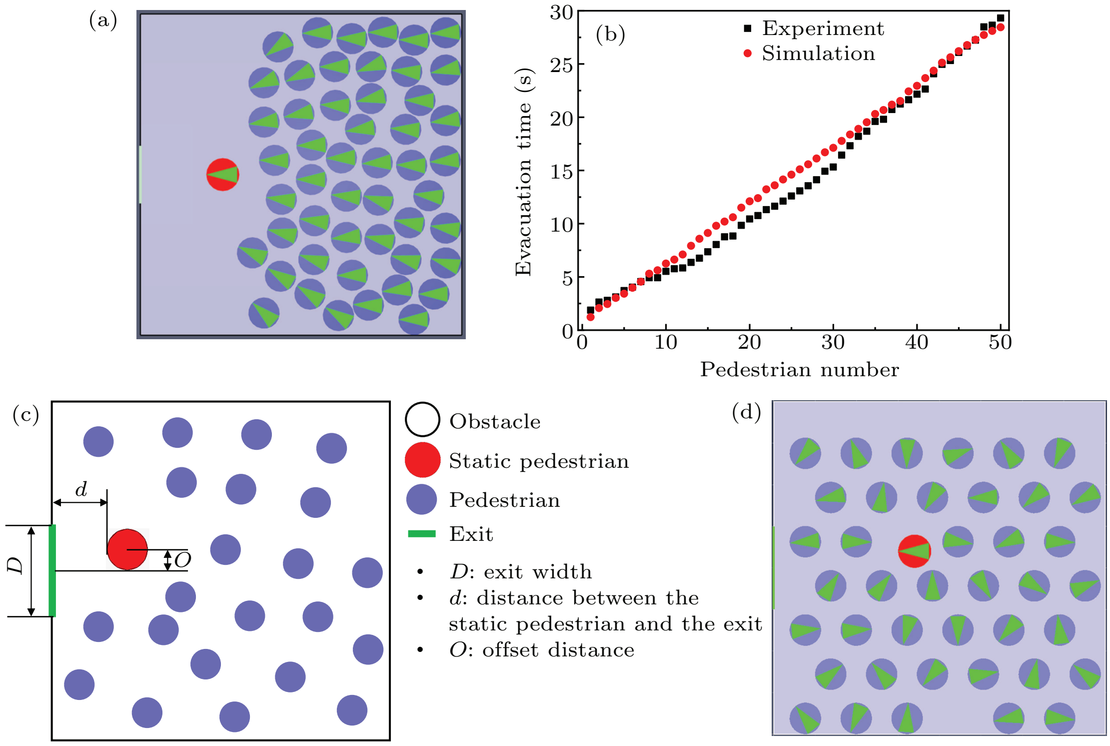

Fig. 2. Simulation scenario setup: (a) experiment scenario in simulation, (b) evacuation time of experiment and simulation, (c) sketch map of simulation scenarios, (d) a screenshot of one simulation scenario.

Table 2. Details of parameters in simulation scenes.

Scenario A	
D (m)	0.8
Pedestrian number	20, 40, 60
d (m)	0.5, 0.6, 0.7, 0.8, 0.9, 1.0
Scenario B	
D (m)	0.8, 0.9, 1.0, 1.1, 1.2
Pedestrian number	40
d (m)	$0.5D$, $0.75D$, $1D$, $1.25D$, $1.5D$
Scenario C	
D (m)	1.0
Pedestrian number	40
d (m)	0.5, 0.75, 1.0, 1.25, 1.5
O (m)	0.1, 0.2, 0.3, 0.4, 0.5
Scenario D	
D (m)	1.0
Pedestrian number	40
d (m)	0.5, 0.75, 1.0, 1.25, 1.5

4. Simulation results

From previous studies, we know that the distance from the obstacle to the exit affects evacuation efficiency.[22,34] Therefore, in our model, the effect of different distances between the static pedestrian and the exit on evacuation efficiency under different global densities were investigated. The evacuation time of different d is shown in Fig. 3. In addition, the condition without a static pedestrian in the front of the exit (hereafter referred to as no-static-pedestrian) was simulated as the baseline. The evacuation time in the condition of no-static-pedestrian under different global densities is 9.53, 20.18, and 31.08 s respectively, which is shown as the dashed line in Fig. 3.

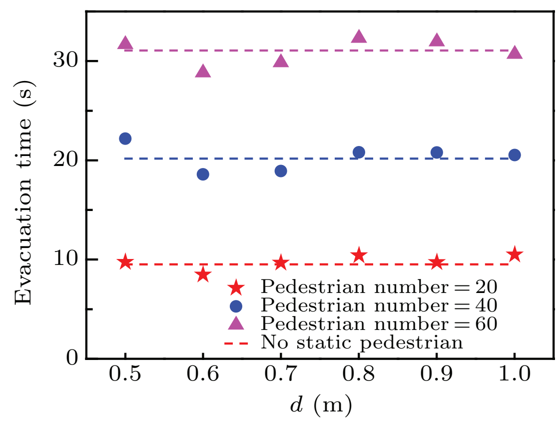

Fig. 3. Difference in evacuation time in scenario A.

When the static pedestrian is too close to the exit, other pedestrians cannot leave the room, so the minimum distance in scenario A is set to 0.5 m. Overall, the evacuation time increases with the number of pedestrians in the room. It can be seen that when there is a static pedestrian as an obstacle in the front of the exit, the evacuation time is affected by the distance between the static pedestrian to the exit (d). With the increase of d, the evacuation time first decreases and then increases. When d is equal to 0.6 m, the static pedestrian has a positive effect on evacuation efficiency. When the distance is too small ($d = 0.5$ m) or too large ($d = 0.8$, 0.9, 1.0 m), the static pedestrian has a negative impact on evacuation efficiency and increases the overall evacuation time. In this paper, when d

is equal to 0.6 m ($d = 0.75D$), the evacuation efficiency is the highest.

In order to study the coupling effect of exit width (D) and distance (d) on evacuation efficiency, simulation parameters were selected according to scenario B in Table 2. When $D = 0.8$ m and $d = 0.5D = 0.4$ m, the distance (d) and exit width (D) is relatively small, and other pedestrians get stuck around the exit and cannot complete the evacuation. On this occasion, d was set to 0.5 m and $d = 0.625D$. Figure 4 shows the relation between the number of evacuees and evacuation time (N–T) and flow rate with different ratios of D/d.

The N–T relation can reflect the evolution of evacuation efficiency with time. As shown in Figs. 4(a)–4(e), the evacuation time was the shortest when $d = 0.75D$ regardless of the exit width, under the same evacuation time, more pedestrians can be evacuated when the static pedestrian stands at the distance of $d = 0.75D$ from the exit. Figure 4(e) shows the flow rate (number of pedestrians/evacuation time) with different D and d. It can be seen that the flow rate increases with the increase of the exit width as a whole. In different exit widths, when $d = 0.75D$, the flow rate is the largest and the evacuation efficiency is the highest. Compared with the no-static-pedestrian condition with the same exit width, when $d = 0.75D$, the flow rate increases by 8.6%, 7.6%, 1.3%, 5.4%, and 4.4% from exit width = 0.8 to 1.2 m. When $d = 1.25D$, the flow rate is the lowest, and at this time, the static pedestrian has the greatest negative effect on the evacuation. Only when the exit width is small (0.8 m) and $d = 0.5D$, the minimum flow rate occurs. At this time, $d = 0.5$ m, and the exit width is 0.8 m, which greatly limits the available exit width to other pedestrians, thus reducing the movement efficiency at the exit, increasing the density around the static pedestrian and reducing the overall flow rate. When $d = 1.5D$, there is little difference in flow rate compared with the no-static-pedestrian condition.

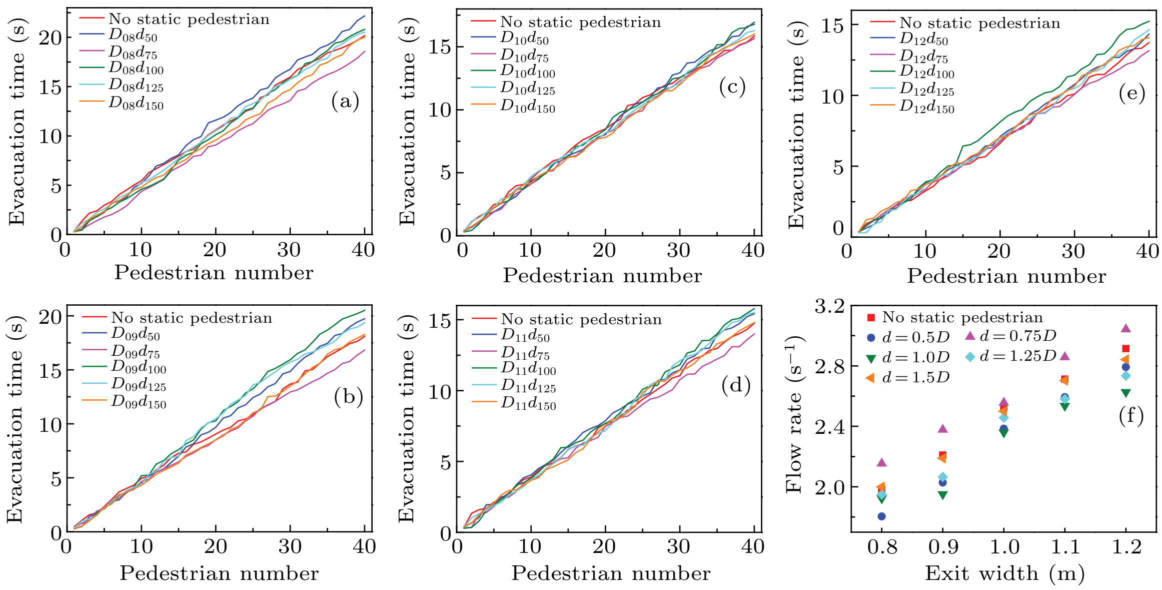

Fig. 4. The N–T relations with different exit widths and flow rate: (a) exit width = 0.8 m (in $D_{08}d_{50}$, $d = 0.5$ m, $d = 0.625D$); (b) exit width = 0.9 m; (c) exit width = 1.0 m; (d) exit width = 1.1 m; (e) exit width = 1.2 m; (f) flow rate with different ratios of D/d.

We summarize the impact of obstacle position and size on evacuation in previous research in Table A1. It can be seen from the table that except for conditions in index 1 and index 2, the size of obstacles is much larger than that of pedestrians which makes it difficult to compare with this study. The result in index 1 is the closest to that in this paper, that is, when the obstacle diameter = 0.6 m and $d = 0.83D$, the flow at the exit is the largest. In addition, we also found that it is difficult to compare these papers due to the difference in experiment setting, but in general, they concluded that evacuation efficiency can be increased when the size and position of obstacles are reasonably set.

In the pedestrian field, researchers have spent a lot of time on the influence of asymmetric structure on pedestrian movement, such as space configuration on dynamics of two merging flows,[35] the effect of symmetry exits layout on evaluation efficiency,[36,37] *etc*. Similarly, it is found that the asymmetric structure of obstacles in the front of the exit affects the overall evacuation efficiency, such as reducing conflicts at the exit,[38] increasing the escape speed (reducing the tangential momentum),[20] and blocking pedestrians moving.[39] In simulation scenario C, we investigate the effect of the symmetrical structures of the static pedestrian on evacuation efficiency. By shifting the static pedestrian vertically upward, different offset distances (hereafter referred to as O) from 0.1 to 0.5 m were obtained. In order to test that the direction of shift does not affect the evacuation efficiency, the evacuation time of shift the static pedestrian vertically downward by 0.1 m ($O = -0.1$ m, $d = 1.0$ m) was collected. Mann–Whitney U test was used to test the statistical difference in evacuation time between conditions of $O = 0.1$ m and $O = -0.1$ m. The null hypothesis of evacuation times composed of these two conditions are samples from continuous distributions with equal medians. The results (Mann–Whitney U test, $p = 0.8663 > 0.05$) indicate that there is not enough evidence to reject the null hypothesis and conclude that the shift direction does not affect the evacuation time at the default 5% significance level. The evacuation time in different O and d is shown in Fig. 5.

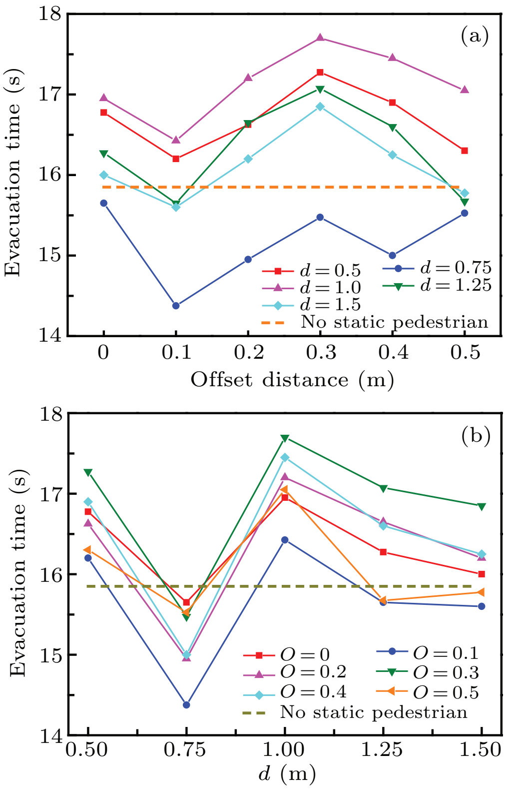

Fig. 5. Evacuation time with different offset distances.

It can be seen from Fig. 5 that the effect of the asymmetry structure of the static pedestrian on evacuation depends on d and O. In Fig. 5(a), compared with the evacuation time under the no-static-pedestrian condition (The orange dashed line), the positive or negative effects of different O on evacuation time are mainly related to d. When $d = 0.75D$, regardless the changes of O, the evacuation time at this time is lower than the evacuation time under the condition of no-static-pedestrian, and the static pedestrian plays an active role in the evacuation process. Compared with the evacuation time under the symmetrical structure of the static pedestrian ($O = 0$ m), when $O = 0.1$ m, the evacuation time is reduced; as O continues to increase ($O = 0.2$, 0.3 m), the existence of the static pedestrian has no positive effect on the evacuation; when shifting the static pedestrian upward and out of the exit area ($O = 0.4$, 0.5 m), the influence of the static pedestrian on the evacuation gradually decreases, and the evacuation time is closer to the evacuation time under the condition of no-static-pedestrian. This indicates that a small offset distance can improve evacuation efficiency. The conclusion of our simulation is consistent with that in Ref. [38], that is, the small offset distance has a positive effect on evacuation. By comparing Fig. 5(a) and Fig. 6(b), it can be seen that with the change of the horizontal axis, the change of the vertical axis in Fig. 5(a) is not as big as that in Fig. 5(b). That is, the change of the evacuation time in the same d and different O is smaller than that in the same O and different d. In general, variable d has a greater impact on evacuation time than variable O.

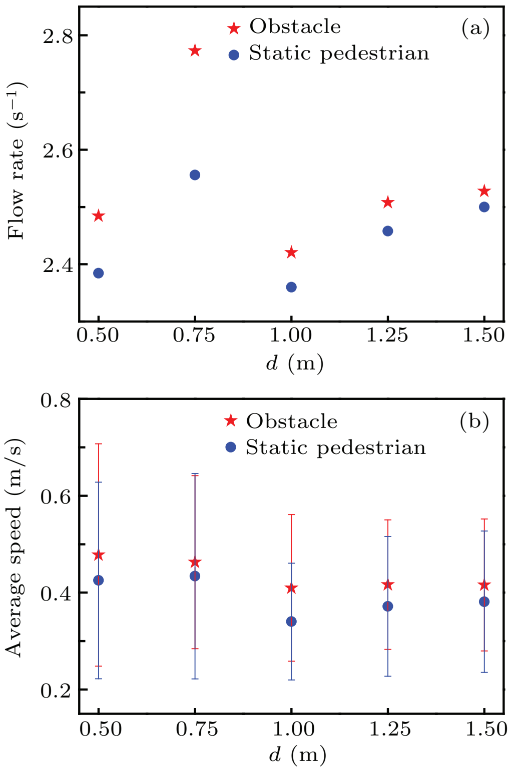

Fig. 6. Difference between the obstacle and the static pedestrian on (a) flow rate, (b) average speed.

Figure A1 is the average density profile of 1 s–10 s during the evacuation process when offset distances are 0 m (the left column), 0.1 m (the middle column), and 0.3 m (the right column). By comparing these figures, on the whole, when $O = 0.3$ m, the area of high-density (dark red) is the largest, and when $O = 0.1$ m, the area of high-density area is the smallest. It can be seen that when $O = 0.1$ m, the static pedestrian restrains the movement of the pedestrians on the upper side in the figure, and pedestrians on the other side (lower side of the static pedestrian) can leave more quickly and smoothly (The density is greater in the lower side of the static pedestrian than the upper side due to more pedestrians passing by). In order to confirm that a small offset distance can make pedestrians leave the room more smoothly, we calculate the time headway of pedestrians leaving the exit under different d and O conditions. Time headway is defined as the time interval between two consecutive pedestrians passing through the entrance or exit. The shorter the time headway, the smoother the pedestrian's movement at the exit or entrance. The boxplot of time headway is shown in Fig. A2, the triangle in the box plot is the mean value of time headway. It can be seen that the average time headway under $O = 0.1$ m conditions is the smallest and under $O = 0.3$ m conditions is the largest, which means that a small offset distance can make pedestrians leave the exit more smoothly. In general, the effect of offset on evacuation mainly depends on d, and a small O can play a positive role in evacuation.

Previous studies have found that the shape of the obstacles (pillar, panel, triangle, *etc*.) affects the evacuation efficiency.[22,24,40] It is found that pedestrians keep a certain distance from the obstacle in the experiment.[9] However, for static pedestrians, there are no significant differences in appearance between them and other pedestrians. That is to say, other pedestrians may not keep far away from the static pedestrian and can not predict the blocking effect of the static pedestrians. We investigate whether the impact of the static pedestrian with the same attribute on evacuation is the same as that of non-living obstacles. We study the difference in the influence of an obstacle and a static pedestrian on evacuation in scenario D. We create a regular dodecagonal obstacle (the distance between the two opposite corners of the regular dodecagon is 0.4 m) similar to the shape of the static pedestrian in Pathfinder. Flow rate and average speed under the impact of the obstacle and the static pedestrian are shown in Fig. 6.

It can be seen that the flow rate under the obstacle conditions is significantly larger than that of the static pedestrian conditions. When $d = 0.75D$, the flow rate is the highest in these two cases, and this conclusion is consistent with the previous conclusion, that is, the positive effect of the static pedestrian on evacuation is the greatest at this time. A possible reason for this is that pedestrians know the existence of the obstacle in advance during the evacuation, and they plan their route in advance to avoid the obstacle, leading to a lower congestion level around the obstacle. We calculate the average speed (movement distance/movement time) under the obstacle and the static pedestrian conditions, as shown in Fig. 6(b). Similarly, we find that the average speed of pedestrians under the obstacle condition is larger than that of the static pedestrian condition. When d gradually increased (from 0.5 m to 1.5 m), the average speed under the obstacle condition is 12.4%, 6.7%, 20.4%, 12.1%, 9.1% larger than the average speed of the static pedestrians (Mann-Whitney U test, $d = 0.5$ m: $p = 0.3481 > 0.05$; $d = 0.75$ m: $p = 0.0448 < 0.05$; $d = 1.0$ m: $p = 0.0055 < 0.05$; $d = 1.25$ m: $p = 0.0147 < 0.05$; $d = 1.5$ m: $p = 0.0266 < 0.05$). This shows that the presence of the obstacle at the exit is more conducive to evacuation than that of the static pedestrian because pedestrians know the existence of the obstacle and plan their routes in advance. Therefore, the impact of the static pedestrian as obstacles and the non-living obstacle on evacuation efficiency is different and needs to be treated separately. For example, in order to prevent the negative impact of static guides or slow-moving people during evacuation time, we can set up obvious signs or warning sounds to warn pedestrians of the existence of obstacles, so as not to hinder the evacuation.

5. Conclusion

As the last and most important state of a building evacuation, pedestrian movement at the building exit has attracted attention from researchers. Investigating pedestrian dynamics near the exit can help improve the building evacuation efficiency. For a long time, researchers have mainly focused on the effect of obstacles near the exit on evacuation while ignoring the effect of the stationary pedestrians. However, in the process of leaving or evacuating from buildings, there are slow-moving pedestrians, injured pedestrians, pedestrians who stop to look for something, or guide who act as obstacles during the evacuation process, these static pedestrians may have an impact on the evacuation process. Therefore, we investigated the effect of a static pedestrian on building evacuation through experiments and simulations. Firstly, to obtain simulation parameters, we conducted an experiment in which a static pedestrian was set as an obstacle at the exit. By analyzing the experimental trajectory, evacuation time and density–velocity profiles, it was found that the presence of the static pedestrian has an impact on the movement of other pedestrians and affects the density and velocity distribution in the exit area. Secondly, the simulation parameters were obtained based on experimental data. Simulations were conducted by varying exit width, the distance between the static pedestrian and the exit, offset distance, and types of obstacles. Simulation results show that a static pedestrian and an obstacle have different effects on evacuation. Compared with the presence of the static pedestrian, the flow rate under the obstacle condition is larger. This is because other pedestrians know the existence of the obstacle and make a detour in advance instead of forming congestions around the static pedestrian. Among the five different ratios of D/d, the evacuation efficiency is the highest when d is equal to $0.75D$, and the presence of the static pedestrian has a positive effect on evacuation at this point. The effect of offset distance (the asymmetric structure) on evacuation efficiency is affected by the distance between the static pedestrian and the exit (d). Compared with the symmetry structure of the static pedestrian, the small offset distance is helpful for evacuation. Therefore, we suggest that when there are static pedestrians near the exit, they need to be treated differently from obstacles. When setting up the evacuation guide, to reduce the negative impact on evacuation, the location of the evacuation guide needs to take into account the exit width and the distance of the evacuation guide to the exit. At the same time, when someone falls or there is a stationary pedestrian near the exit, other pedestrians can be prompted by obvious signs and sounds. This study can be used for the development of evacuation strategies and crowd management in the presence of static pedestrians near building exits.

This study investigates the effect of a static pedestrian on the evacuation process through Pathfinder. It is important to state the limitations of our work. (i) In this paper, only the pedestrian attributes of middle school students, such as movement speed, acceleration and body size, are considered. (ii) The size of the static pedestrian is based on the adult obstacle pedestrian in the experiment. Different obstacle sizes may have different effects on evacuation with small exit width and a small distance between the static pedestrian and the exit. (iii) In the future, relevant validation experiments should be carried out and the impact of the static pedestrian on the entry process should be studied. This study preliminarily studied the impact of the static pedestrian on the evacuation process, especially the different positions and offset distances. We believe that this study provides a theoretical basis for future experimental research and crowd management.

Appendix A

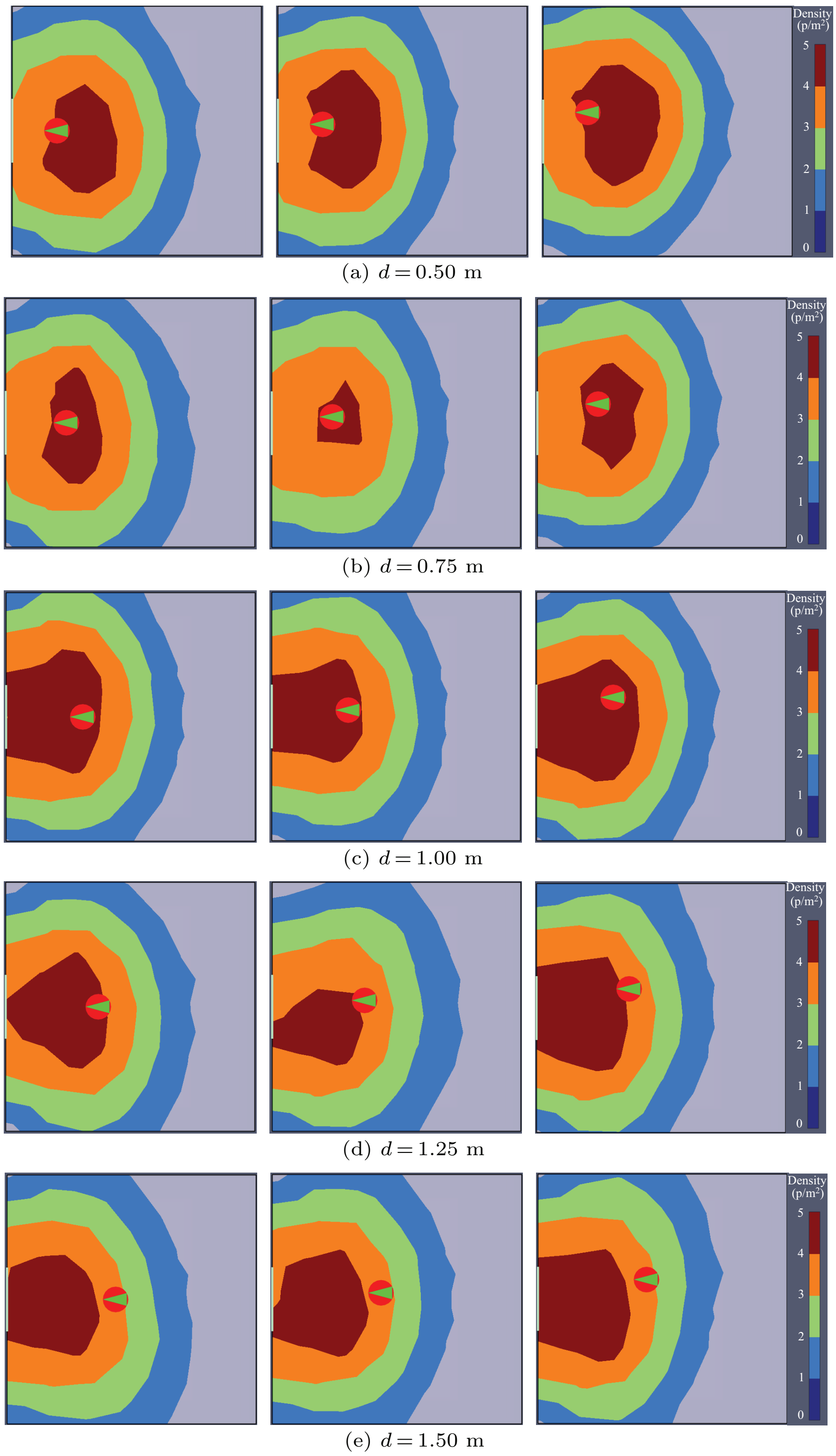

Fig. A1. Density profiles with different d and O. the left column: $O = 0$ m; the middle column: $O = 0.1$ m; the right column: $O = 0.3$ m.

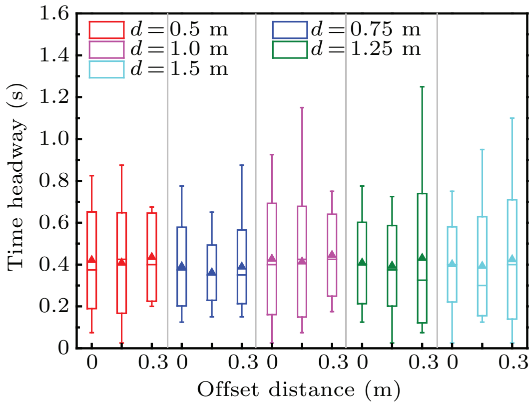

Fig. A2. Time headway with different d and O.

Table A1. Relevant research about obstacle size and position.

Index	Experiment/simulation	Scenario geometry	Conclusions
1[9]	experiment	room size: 8 m×8 m; door width: 1.2 m; size of the column-obstacle: diameter = 0.6, 1.0 m; d = 0.6, 0.8, 1.0 m;	influenced factors: exit location, obstacle size, d the minimum evacuation time: exit location = corner, the column obstacle size = 0.6 m, d = 1.0 m
2[34]	simulation lattice game model	room size: 4 m×4 m door width: 1.2 m pedestrian size: 4×4 cells (0.4 m×0.4 m)	influenced factors: density, obstacle size, d. the minimum evacuation time: density = 0.3: obstacle size 3×4 cells, d = 2.8 m; density = 0.5: 3×2 cells, d = 2.4; density = 0.8: 3×6 cells, d = 1.6 m
3[25]	simulation social force model	room size: 20 m×15 m; door width: 1 m; pedestrian size: R = 0.6 m; obstacle size: $L \times 0.2$ m (panel-shaped); d = 1.2 m	influenced factors: desired speed, obstacle length (L), O the minimum evacuation time: V_desired = 1.5 m/s, L = 4 m, O = 3.5 m
5[24]	simulation social force model	room size: 20 m×15 m; door width: 1 m; pedestrian size: R = 0.6 m; the pillar-like obstacle: radius r the panel-like obstacle: $0.2 \times L$	influenced factors: shapes of obstacle (pillar-like/panel-like), d, O the minimum evacuation time: the pillar-like obstacle: d = 0.97 m, O = 1.2 m, r = 1.38; the panel-like obstacle: d = 1.08 m, $O = -0.15$ m, L = 11.68 m
6[8]	simulation social force model	room size: 8.4 m×7.8 m; door width: 0.8 m; pedestrian size: radius = 0.22 m; two cubic-like obstacles: 1 m×1 m the panel-like obstacle: L	influenced factors: obstacle shape (panel-like, cubic-like), obstacle length, d. the minimum evacuation time: the panel-like obstacle: d = 1 m, L = 8 m; two cubic-like obstacles: d = 1 m, interval-distance = 1 m
7[14]	experiment	corridor size: 3 m×8 m; door width: 0.7 m; obstacle size: $0.62 \times L$; L = 0.42, 0.84, 1.26, 1.68 m; d = 1.6, 4.0 m;	influenced factors: L, d; the minimum evacuation time: L = 1.26, d = 1.6 m;
8[10]	experiment	room size: 7.8 m×8.4 m; door width: 1.0 m; the pillar-like obstacle: 1.2 m×1.2 m; the panel-like obstacle: 0.2 m×L (3, 4.8 m) d = 1.2, 1.8, 2.4 m;	influenced factors: L, d, number of obstacles, the distance between two pillar-like obstacles (g); the minimum evacuation time: two pillar-like obstacles: g = 1.2, d = 1.2

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References

[1] Wang J H, Li J C, Li J, Feng J J, Xu S Y, Liu J and Wang Y 2022 *J. Build. Eng.* **45** 103658

[2] Yang X X, Jiang H L, Kang Y L, Yang Y, Li Y X and Yu C 2022 *Chin. Phys. B* **31** 078901

[3] Wang W L, Wan F F and Lo S M 2020 *Chin. Phys. B* **29** 084502

[4] Gao Q F, Tao Y Z, Wei Y F, Wu C and Dong L Y 2020 *Chin. Phys. B* **29** 034501

[5] Ma Y P and Zhang H 2020 *Chin. Phys. B* **29** 038901

[6] Wang G N, Chen T, Chen J W, Deng K F and Wang R D 2022 *Chin. Phys. B* **31** 060402

[7] Li J, Wang J H, Xu S Y, Feng J J, Li J C, Wang Z R and Wang Y 2022 *Build. Simul.* **15** 659

[8] Wang J Y, Sarvi M, Ma J, Haghani M, Alhawsawi A, Chen J and Lin P 2022 *Build. Simul.* **15** 631

[9] Shi X M, Ye Z R, Shiwakoti N, Tang D N and Lin J K 2019 *Physica A* **522** 350

[10] Zhao Y X, Lu T T, Fu L B, Wu P and Li M F 2020 *Saf. Sci.* **122** 104517

[11] Ding Z J, Shen Z W, Guo N, Zhu K J and Long J C 2020 *J. Stat. Mech.-Theory Exp.* **2020** 023404

[12] Helbing D, Buzna L, Johansson A and Werner T 2005 *Transp. Sci.* **39** 1

[13] Yanagisawa D, Kimura A, Tomoeda A, Nishi R, Suma Y and Ohtsuka K and Nishinari K 2009 *Phys. Rev. E* **80** 036110

[14] Jia X L, Murakami H, Feliciani C, Yanagisawa D and Nishinari K 2021 *Saf. Sci.* **144** 105455

[15] Garcimartín A, Maza D, Pastor J M, Parisi D R, Martín-Gómez C and Zuriguel I 2018 *New J. Phys.* **20** 123025

[16] Zuriguel I, Echeverría I, Maza D, Hidalgo R C, Martín-Gómez C and Garcimartín A 2020 *Saf. Sci.* **121** 394

[17] Feliciani C, Zuriguel I, Garcimartín A, Maza D and Nihinari K 2020 *Sci. Rep.* **10** 15947

[18] Helbing D, Farkas I and Vicsek T 2000 *Nature* **407** 487

[19] Yanagisawa D, Nishi R, Tomoeda A, Ohtsuka K, Kimura A, Suma Y and Nishinari K 2010 *SICE JCMSI* **3** 395

[20] Jiang L, Li J Y, Shen C, Yang S C and Han Z G 2014 *PLoS One* **9** e115463

[21] Xu H, Zhang J, Song W G, Hu Y H, Li X D, Ren X X, Yang L N, Yu H and Jiang K C 2022 *J. Stat. Mech.-Theory Exp.* **2022** 023407

[22] Frank G A and Dorso C O 2011 *Physica A* **390** 2135

[23] Yano R 2018 *Phys. Rev. E* **97** 032319

[24] Zhao Y X, Li M F, Lu X, Tian L J, Yu Z Y, Huang K, Wang Y N and Li T 2017 *Physica A* **465** 175

[25] Li Q R, Gao Y C, Chen L and Kang Z X 2019 *Physica A* **533** 122068

[26] Massmotion User Manual 2019 *MassMotion Help Guide*

[27] Wall J and Waterson N 2002 *Fire Command Studies* **1** 151

[28] Thornton C, O'Konski R, Hardeman B and Swenson D 2011 *Proceedings of the International Conference on Pedestrian and Evacuation Dynamics*, Boston, pp. 889–892

[29] Qin J W, Liu C C and Huang Q 2020 *Case Stud. Therm. Eng.* **21** 100677

[30] Wang H R, Chen Q G, Yan J B, Yuan Z and Liang D 2014 *Proceedings of the 7th International Conference on Intelligent Computation Technology and Automation*, Washington, pp. 226–230

[31] Rostami R and Alaghmandan M 2021 *J. Build. Eng.* **33** 101598

[32] Ronchi E and Nilsson D 2014 *Build. Simul.* **7** 73

[33] Zhou R, Cui Y K, Wang Y and Jiang J C 2021 *Tunn. Undergr. Space Technol.* **110** 103837

[34] Wei Y F, Shi W and Song T 2012 *Procedia Eng.* **31** 1077

[35] Shahhoseini Z and Sarvi M 2018 *Transp. Res. Record* **2672** 121

[36] Yue H, Guan H Z, Shao C F and Zhang X 2011 *Physica A* **390** 198

[37] Delcea C, Cotfas L A, Bradea I A, Boloş M I and Ferruzzi G 2020 *Symmetry* **12** 627

[38] Kirchner A, Nishinari K and Schadschneider A 2003 *Phys. Rev. E* **67** 056122

[39] Yanagisawa D, Kimura A, Tomoeda A, Nishi R, Suma Y, Ohtsuka K and Nishinari K 2009 *Proceedings of the 2009 ICCAS-SICE*, Fukuoka, pp. 5040–5045

[40] Escobar R and La Rosa A D 2003 *Proceedings of the European Conference on Artificial Life*, Berlin, pp. 97–106