Influence of pre-bottleneck diversion devices on pedestrian flow

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Abstract. The existence of bottlenecks often leads to the stagnation of pedestrian gatherings, which seriously affects the efficiency of traffic and reduces the flow of pedestrians. Some studies have shown that setting devices in front of bottlenecks can promote pedestrian evacuation under certain conditions. In this paper, the effect of setting diversion devices in front of the exit on pedestrian flow is studied. From our observation, these diversion devices can form a buffer zone before the exit and affect pedestrian behaviors. The evacuation times are found to decrease as the devices become farther away from the exit. In our experiments, it is found that the effect of shunt piles on evacuation is better than in the case of safety barriers and without device conditions. Under the condition of setting up safety barriers approximately 1 m and 3 m in front of the exit, the evacuation times are extended by 0.88\% and 2.67\%. For shunt piles, the evacuation times are 11.53\% and 14.96\% shorter than that of those without a device regarding the different distances to exit (1 m and 3 m, respectively). In addition, setting up shunt piles reduces the time interval between two consecutive pedestrians. To sum up, in our experimental settings, the diversion devices can effectively improve the average speed ahead of the exit and promote evacuation to become more orderly, which reduces the congestion in the later period of evacuation. In other words, this study demonstrates that a reasonable layout of facilities can not only meet the daily functional requirements but also improve the efficient
use of space in emergencies, reducing the probability of crowd conventions and jams.

**Keywords:** bottleneck, diversion devices, buffer zone, pedestrian, evacuation

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### 1. Introduction

Bottlenecks are construction facilities (e.g. exits) that limit the movement of people. When the crowd density is high, the traffic flow will be limited by the bottleneck structure, leading to the decline of evacuation efficiency, and further bringing congestion and even stampede accidents. In order to reduce the risk of accidents at the bottleneck, many scholars [1–3] have conducted many experiments and simulations related to the bottleneck. Generally, many kinds of research mainly focus on the impact of evacuation by changing the types of bottlenecks. For example, in [4–11], they study how the width, length, and other parameters of bottleneck influence evacuation efficiency, which find that some self-organizing phenomena, such as lane formation, zipper effect, faster-is-slower effect and so on, are highly correlated to the above factors. Besides, under the condition of crowd competition, the frequency of congestion increases with...
the decrease in bottleneck width [12]. When the bottleneck width is small, the competitive behavior will reduce the evacuation efficiency [13]. In order to further match the real situation, some researchers [14–17] add the extra factors of the proportion of different ages, genders, special people, etc.

In order to explore the influence of obstacles on bottleneck flow, a series of experimental [18–24] and simulation [25–29] studies have been carried out. In terms of model simulation, scholars mostly try to find the optimal distance and arrangement of obstacles in specific scenes. Wang et al [25] study the influence of human-obstacle interaction on evacuation in classrooms based on the cellular automata model. Two types of obstacles are considered, including the passing-over-obstacles and the pushing obstacles. The results show that this method has a good application prospect. Obstacle-jumping behavior is conducive to the improvement of evacuation efficiency. In addition, the impact of obstacles [28] is studied by analyzing conflicts. This suggests that barriers reduce the number of pedestrians involved in conflicts at the exit. Haghani et al [27] use a social force model to perform extensive simulations to find the optimal parameters of the model and fit the relationship between pedestrian evacuation speed and time to derive quantitative results between the two. Echeverría and Zuriguel [26] perform numerical simulations of an asymmetric spherical column system. When the distance between the obstacle and the wall is smaller than the width of the exit, the evacuation time is prolonged; by increasing the distance from the obstacle to the exit, the blockage can be reduced, and the optimal obstacle location can be obtained. Zhao et al [30] simulate the effects of different shapes of obstacles through a social force model and analyze the density map, velocity map, flow map, and spatiotemporal pressure map of placing obstacles at the exit. They conclude that placing obstacles at the exit can effectively reduce the crowd density, reduce the blockage effect at the exit bottleneck, and improve evacuation efficiency. The robustness and stability of plate-shaped obstacles are better than column-shaped obstacles in complex scenarios, while the crowd evacuation efficiency is found to be greatly influenced by the geometric parameters of the obstacles. Varas et al [29] use the cellular automata model to conduct pedestrian evacuation simulation experiments under obstacles and find that there is an optimal distance between obstacles and exits. If they exceed this distance, the existence of obstacles will have adverse effects on pedestrians.

As for the experiments, the majority of scholars have favored that the pre-exit device can have a positive effect on pedestrian evacuation. Helbing et al [18] study the effect of adding obstacles in front of exits on the evacuation effect. They design an experiment on the evacuation of pedestrians in a room with an 82 cm wide door and place a wooden board with a width of 45 cm as an obstacle near the exit. The results show that the obstacle increased the flow of pedestrians in the room by approximately 30% compared to no obstacle, and the time interval between two consecutive pedestrians leaving the room become shorter. Yanagisawa et al [28] study the effect of obstacles in front of the exit in NHK television studio in Japan. A 20 cm diameter post is placed in front of the 50 cm wide outlet. It is found that participants have a greater outflow (approximately 7% increment) when the barrier is in front of the exit compared to normal evacuation. Wang et al [19] find that setting railings in front of the exit to form a buffer zone can improve evacuation efficiency, effectively reduce the crowd density at the exit, alleviate
the inrush of density waves in the crowd, and thus reduce the risk of crowd extrusion and stampede. In addition, when the desired speed is high, the longer the buffer, the faster the pedestrian evacuation speed. Jiang et al [20] conduct experiments on 76 college students (aged 21–25 years) to study the influence of obstacles near exits. One obstacle, two obstacles, and no obstacle are set before the exit of the experiment. It turns out that there are two barriers near the exit that work best.

But not all experiments have shown that placing barriers in front of exits has a positive effect. Ding et al [31] study the influence of obstacle height on pedestrian evacuation efficiency, and find that when the distance between the obstacle and exit is relatively close, the obstacle effect on pedestrians that can be crossed over fixed obstacles is less than that that cannot be crossed over fixed obstacles. Their experimental result is that fixed obstacles hinder pedestrian evacuation. Garcimartín et al [22, 23] vary the degree of emergency (as reflected by different desired pedestrian speeds) to study the effect of barriers. The results show that the effect of barriers is negative in low as well as high competing pressures, inhibiting pedestrian evacuation and prolonging the overall time. Liu [21]'s experiment shows that under normal walking and jogging conditions, placing cylindrical barriers in front of the safety exit would reduce the evacuation efficiency, but the obstacles would eliminate the gathering phenomenon of pedestrians. Chattaraj et al [24] investigate the effect of the presence of strip space barriers in pedestrian walkways on the local speed and density of pedestrians and conclude that the placement of strip barriers along the walking direction of pedestrians in the walkway will reduce the evacuation efficiency of pedestrian flow. In summary, the effect of obstacles on evacuation efficiency is related to their size, location, material, and experimental conditions, and the experimental results may differ in different cases.

At present, the most commonly used pedestrian dispersal measures in public spaces with large numbers of people and crowded areas and their internal ‘bottleneck’ areas are to change the distribution of pedestrians in the passage. To maintain a safe flow of passenger traffic by controlling pedestrian routes at appropriate times [32]. The most commonly used methods are batch release, flow control at entrances and exits, channel space flow separation, etc. Adding barriers such as separation rails in front of channel exits, usually by setting flow restriction rails to slow down passenger flow, can effectively improve the orderliness and stability of passenger queues [33] and facilitate on-site staff to maintain order.

However, there is a lack of research on whether safety barriers are the best choice, in which position they have the best evacuation effect, and whether they will have a negative impact when an emergency occurs. Therefore, this paper carried out a series of pedestrian evacuation experiments. By setting different types of diversion devices in the experimental scene and changing the distance between them and the exit, so explore the influence of the diversion devices on the pedestrian movement law.

2. Experiment setup

To investigate the effect of the above diversion devices on pedestrian evacuation efficiency, we design an experimental scenario, as shown in table 1(a). The experimental scenario is a closed structure with a one-way through lane, the pedestrian waiting area
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Table 1. Experimental walking condition table.

| Index | Device     | Size | Distance from exit | Amount |
|-------|------------|------|--------------------|--------|
| B-1   | Safety barriers | 1.5 m | 1.0 m | 1.5 m |
| B-3   | Safety barriers | 1.5 m | 3.0 m | 1.5 m |
| P-1   | Shunt piles   | 0.1 m | 1.0 m | 1.5 m |
| P-3   | Shunt piles   | 0.1 m | 3.0 m | 1.5 m |
| N-0   | No device    | –    | –     | –     |

* Where the safety barriers are indicated by B, the shunt piles are indicated by P, and no device is indicated by N; the control devices in this thesis are of the same length of 1.5 m, and the number after the letter represents the distance from the device to the exit.

Figure 1. Video screenshot of the experimental scenario and mapping of the scenario. Eighty-seven adults (21–25 years old) initially stood in the waiting area with the device placed $x$ meters in front of the exit. The buffer zone is the orange area where the device is placed in front of the bottleneck.

is delineated on the left side of the scenario, and the bottleneck is set on the opposite side of the waiting area with a width of 0.6 m, which meets the minimum width of single passenger flow at the safety exit. Before the start of the experiment, participants are required to stay in a row in the waiting area, and after hearing the instructions, all participants have to quickly move through the closed area towards the bottleneck and leave the experimental area.

To simulate the possible scene distribution, in reality, we chose to use six shunt piles as well as safety barriers as diversion devices (D) and set them at 1 m and 3 m from the bottleneck, where the shunt pile has a radius of 0.1 m and a height of 0.8 m, and the safety barrier is 1.5 m long and 1.0 m high, all of which are conventional dimensions, all pedestrians did not cross the device during the experiment. Through several experiments, the device type, as well as the distance to the bottleneck, were changed to obtain experimental data under different walking conditions, and all the experimental conditions are shown in table 1. The experiment was conducted in September 2021 in Hefei, Anhui Province, China, as shown in figure 1(b). Eighty-seven student volunteers with an average age of $23 \pm 3$ years (20–26 years) and an average height of 170.2 cm (155–185 cm) joined the experiment. Each volunteer was asked to wear a colored hat (red, orange, and blue) during the experiment, which was recorded by two digital cameras (model: https://doi.org/10.1088/1742-5468/acb42c
3. Spatial distribution characteristics

In this chapter, we analyze the above-mentioned experimental data by using JPSReport [35] and Python processing. In section 3.1.1, we firstly conduct an overall cross-sectional comparison of all walking conditions to analyze the effect of different walking conditions on pedestrian evacuation time. To further investigate the pattern, we plot the pedestrian trajectories for different walking conditions in section 3.2 to observe the effect of the device on the pedestrian movement patterns.

3.1. Time analysis

3.1.1. Evacuation time. In table 2, we list the average evacuation time for each condition. To ensure the fairness of the comparison, the average evacuation time is taken as the average of three repeated experiments. To eliminate errors, the first 5 people and the last 5 people in each run are removed to avoid the transient state. As seen in table 2, the evacuation time always decreases with increasing distance between the diversion devices and the exit, regardless of the type of diversion devices used. When we consider the type of diversion devices, it can be found that the evacuation times of safety barriers are all longer than that of no device, increasing by 1.28 s and 0.42 s, respectively (evacuation efficiency decreases by 2.67% and 0.88%), while shunt piles facilitate evacuation, reducing the overall evacuation time by 5.52 s and 7.16 s, respectively (evacuation efficiency increases by 11.53% and 14.96%). Therefore, we believe that when the distance between the diversion devices and the exit is short, the use of safety barriers as a diversion device is not recommended.

3.1.2. Time interval. The former studies in [36, 37] show that the shorter the time interval between two consecutive pedestrians leaving the exit is, the smoother the pedestrian leaves the bottleneck. Referring to [36], we study the variation of the time interval $\Delta t$ based on the Clauset–Shalizi–Newman method, and the formula is as follows:

$$\Delta t = t_i - t_{i-1}$$

(1)

where the time interval $\Delta t$ is defined as the time elapsed between two consecutive pedestrians passing through the bottleneck. To eliminate the experimental error, we delete the data of the first five pedestrians and the last five pedestrians in each experiment because they all represent transients and have large randomness. In general, the $p(\Delta t)$ distribution conforms to the power-law distribution formula $p(\Delta t) \sim \Delta t^{-\alpha}$, while the exponent $\alpha$ can be used to characterize dynamic measurement parameters of the exit.
Table 2. Overall evacuation time of pedestrians under different walking conditions.

| Distance to exit | 0 m  | 1 m  | Improvement  | 3 m  | Improvement  |
|------------------|------|------|--------------|------|--------------|
| Safety barriers  | 47.88 s | 49.16 s | −2.67%      | 48.30 s | −0.88%      |
| Shunt piles      | 42.36 s | 40.72 s | +11.53%     | 40.72 s | +14.96%     |

* In ‘Improvement’, ‘+’ means that the evacuation time is improved compared with no device; ‘−’ represents reduced evacuation time compared to no device efficiency.

Figure 2. Cumulative probability of the time interval $\Delta t$.

Table 3. The exponent $\alpha$ obtained from the power-law analysis with $x_{\text{min}} = 0.5$.

| Index | $\alpha$ | $\Delta \bar{t}$ | $k$   |
|-------|----------|------------------|-------|
| N-0   | 2.31     | 0.58             | −1.29 |
| B-1   | 2.27     | 0.55             | −1.54 |
| B-3   | 2.32     | 0.57             | −1.38 |
| P-1   | 2.37     | 0.51             | −1.69 |
| P-3   | 2.43     | 0.48             | −1.75 |

Therefore, according to this function, the diagram of complementary of the cumulative distribution function (CDF) of different walking conditions is drawn, as shown in figure 2.

In table 3 we counted the average evacuation time $\Delta \bar{t}$. We also calculate the $\alpha$ and the slope of the curve $k$ (from the beginning of the descent to the end) under each walking condition. As seen in table 3 we can find that the slope $k$ of the curve
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Figure 3. Trajectory diagram of pedestrians under different walking conditions.

is highly related to the size of the block at the exit: the larger the slope, the longer the tail of the curve, which means the longer the stagnation time [39]. The greater the \( \alpha \) value represents the smaller the possibility of blocking. Under the walking condition of the shunt piles, the value of \( \alpha \) increases and the slope of \( k \) decreases, indicating that a reasonable diversion device can promote the continuity of pedestrian outflow at the exit. Moreover, the average time interval \( \bar{\Delta t} \) between two consecutive pedestrians passing through the exit is significantly shortened, which makes the flow of people pass through the exit more effectively.

3.2. Pedestrian trajectories

To investigate the intrinsic reasons for the influence of device type and placement distance on pedestrian movement characteristics, we plotted the pedestrian trajectories in different scenarios, as shown in figure 3. Different colors represent the different speeds of movement of pedestrians. Experimental video can be found that almost all scenarios follow the phenomenon that when the evacuation starts, people in the front row of the queue move rapidly toward the exit, and since the population density is still relatively low at this time, they can proceed almost unimpeded. After a few seconds, as the density near the exit increases, blocking begins to form in front of the exit. By comparing the shape of the trajectory, we find that there are differences in whether the shunt piles
or safety barriers have an impact on the movement trajectory of pedestrians, as shown by the different positions of pedestrians contracting toward the exit.

3.2.1. Differences in space utilization. By comparing these pedestrian trajectories, we find that the diversion devices have an impact on the trajectory of the pedestrians on the outer lanes, which mainly affects the timing of crowd contraction before the exit. It determines the difference in space utilization before the exit and is also a key factor affecting evacuation. Therefore, we extracted the movement trajectory of the outermost 10 pedestrians (5 on each side). The scatter plot of the average trajectory can be obtained by calculating the mean \( y \) under the same \( x \) coordinate, as shown in figure 4. By using the piecewise linear fitting method, we can obtain the location of the inflection point where the pedestrian trajectory turns, as shown in table 4. As seen from the table, under the condition of shunting piles with the same device distance, the position of pedestrian contraction always occurs earlier than that of safety barriers. When the devices are 1 m away from the exit, the pedestrian starts to adjust the direction to approach the exit at about 20–30 cm from the end of the safety barriers (B-1), while it is approximately 50–60 cm in the case of shunt piles (P-1). This indicates that pedestrians may be more inclined to maintain a certain distance from the safety barriers arranged in the passage. From the evacuation time of section 3.1.1, it can be seen that the shorter the evacuation time, the earlier the inflection point of the pedestrian trajectory It may be that the sooner the outside pedestrians approached the exit, the less likely it was to create blocking at the exit, and our suspicions can be confirmed in the video. It can also be seen in the table that the device appears earlier at the inflection point at 3 m (B-3, P-3) than at 1 m (B-1, P-1), and the evacuation time at 3 m is shorter than that at 1 m.

3.2.2. The width of the crowd. Through the change of inflection point, we find that as the distance from the device to the exit gradually increases, the possibility of pedestrian contact with the walls on both sides of the exit decreases, and the track contour formed at the exit will shrink in advance, slowly showing the same teardrop distribution as without the device (such as figures 3(b) and (d)). However, although these walking
Table 4. Coordinates of the outermost pedestrian inflection point under different walking conditions and linear fit correlation.

| Index | Inflection point 1 | $R^2$ | Inflection point 2 | $R^2$ |
|-------|-------------------|-------|-------------------|-------|
| N-0   | (4.84, 0.37)      | 0.94  | (4.61, 3.05)      | 0.92  |
| B-1   | (5.82, 0.36)      | 0.95  | (5.72, 3.13)      | 0.93  |
| B-3   | (5.16, 0.38)      | 0.96  | (4.88, 3.06)      | 0.96  |
| P-1   | (5.49, 0.35)      | 0.85  | (5.35, 3.09)      | 0.86  |
| P-3   | (4.71, 0.35)      | 0.97  | (4.06, 3.10)      | 0.99  |

Figure 5. Trajectory diagram of pedestrians under different walking conditions.

Thus, we select the earliest point $x(x = 4.06)$ that starts to shrink to study the behavior of the crowd after the team shrinking. It mainly analyzes the changes in the width of the crowded queue, which is defined as the length of the crowded queue in the ordinate direction in the coordinates of the experimental scene. Figure 5 records...
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Table 5. Pedestrian lane change behavior statistics.

| Index | 0–2 m | 2–4 m | 4–6 m | 6–7 m | total |
|-------|-------|-------|-------|-------|-------|
| B-1   | 3     | 5     | −     | 0     | 8     |
| B-3   | 5     | −     | 5     | 0     | 10    |
| P-1   | 3     | 3     | 9     | 0     | 15    |
| P-3   | 5     | 10    | 3     | 0     | 18    |

the variation in the width of the crowd in different scenarios (figures 5(a) and (b)) and the difference between the width of the crowd line relative to the deviceless situation (figure 5(c)). When the safety barriers (B-1) are placed 1 m in front of the exit, the width of the crowd in the buffer area is higher, especially before reaching the devices. Pedestrians begin to consciously increase the distance between each other to enter the buffer area, and the width gradually rises to a peak after 5 leaving the buffer area. In contrast, the difference between the width of the crowd of the diversion safety barriers placed at 1 m and the width of the crowd without the device is not as significant as that of the shunt piles (P-1). When the shunting device is placed 3 m in front of the exit, the width of the crowd of the safety barriers (B-3) is still higher than that without the device for most of the time, while the shunt piles (P-3) show a shrinking phenomenon.

In [40], the author believes that the crowd edge contraction when pedestrians near the bottleneck can reduce the walking distance, make pedestrians move more directly to the exit, and improve the evacuation efficiency. Therefore, we speculate that in the walking condition in this paper, the width of the crowd before the exit is one of the important factors affecting the time interval for continuous pedestrians to leave the exit, and this variable will also indirectly affect the overall evacuation efficiency.

3.2.3. Differences in lane change behavior. Unlike the case without the device, the pedestrian trajectories under shunt devices conditions automatically form four lanes (before reaching the device placement area) from the state of dispersion (before reaching the device placement area, hereafter referred to as the buffer zone), thus creating a stratification phenomenon [41, 42]. Since shunt piles have greater flexibility compared to safety barriers, it is easier for pedestrians to change their routes under this device. Therefore, we consider that changing lanes can improve evacuation efficiency due eliminating the speed impact of queuing and achieving more flexible space selection.

To prove our conjecture, we calculate the number of lane changes that occur at different channel interval, namely $x = 0–2$ m, $x = 2–4$ m, $x = 4–6$ m, $x = 6–7$ m. Where $x = 0–2.5$ m represents the front of the device, $2.5–4$ m and $4–6$ m represent the two different placement positions of devices, $6–7$ m is the behind of the device. The statistical results are shown in table 5. It can be seen in table 5 that their lane change behaviors are similar before the device area. However, pedestrians are more likely to change lanes frequently in shunt piles, leading to better space utilization and flexible action, while safety barriers limit this behavior. In particular, most pedestrians changed lanes within the shunt piles installation area, while in safety barrier conditions, pedestrians cannot even change lanes the where device install. There are no lane change behaviors within
1 m before the exit due to the crowding of pedestrians. On top of that, lane change behavior was more obvious when devices are set at 3 m before the exit, no matter in shunt piles and safety barriers. Overall, we think that lane change behavior is proportional to evacuation efficiency, where the potential reason may be lane changing reduce the waiting time and make out-of-exit time faster.

4. Characteristic analysis of evacuation motions

In this section, we first analyze the various characteristics of movement quantities in section 4.1, such as pedestrian density, in section 4.2 to investigate the congestion level of pedestrian movement.

4.1. Pedestrian density and motion characteristics

To further quantify the effect of the diversion device on pedestrian motion characteristics, we calculate the velocity variation of pedestrians in the measurement area over time from the trajectory data and obtained the global density variation utilizing Voronoi diagrams \[43\]. Note that due to the limited number of experiments, there is a process of density map variation at the beginning and end of the experiment. This is shown in figure 6, we refer to the selection of the steady state of the velocity density in the case of accessibility by using the modified cumulative and control chart algorithm CUSUM calculation \[44\]: two vertical lines represent the beginning and end time points of the selected relative steady state, and the period between the two vertical lines is the data analysis of the selected steady state. The data analysis in section 4.1.1 takes the steady-state interval of each operating condition for calculation.

4.1.1. Density variation. Figure 7 plots the density variation curves over time for different device settings. It can be seen that the pedestrian density at 4–6 m has been maintained at a high level without barriers of approximately 2.45 pm\(^{-2}\). The overall average density decreases after the installation of safety barriers or shunt stakes, approximately 2.04 pm\(^{-2}\) and 2.13 pm\(^{-2}\), respectively. In particular, we can see a clear peak at the end of the safety barriers when the safety barriers are installed. Comparing figures 7(a) and (b) and the corresponding evacuation time, we find that if the safety barriers (B-1) are set at a place closer to the exit, it tends to cause the crowd density to be too high and gather at the exit location, thus reducing the evacuation efficiency, compared to setting it at a place farther away from the exit, which can effectively alleviate this phenomenon. In the case of setting up shunt piles, the density fluctuation after leaving the barrier is less obvious and the overall density is reduced, which indicates that setting up shunt stakes has a positive effect on the enhancement of the evacuation process.

4.1.2. Walk-stop ratio. As the density before the exit increases, pedestrians appear to switch between waiting and walking alternatively, which is called the walk-stop phenomenon. Helbing et al \[45\] analyzes videos of the pilgrimage stampede in Mecca and found that the flow of pedestrians developed from laminar to ‘stop-and-go’, eventually
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Figure 6. Steady-state phase selection (no device steady-state selection process as an example; other cases are selected according to this method).

Figure 7. Distribution of the effect of different devices on pedestrian density (where the safety barriers are indicated by B, the shunt piles are indicated by P, and no device is indicated by N; the number represents the distance to the exit; the black box represents the peak population density of the safety barriers).

During the turbulence phase, the crowd gradually loses control, pedestrians are wrapped up in the crowd and move back and forth, and stampede accidents occur. Stop-and-go behavior is an intermediate stage in the development of pedestrian flow from laminar flow to turbulence, which may be a sign of the danger of pedestrian flow. Thus, we have counted the stop-and-go phenomenon in various situations, and quantitatively expressed the stop-and-go behavior of pedestrians during the movement with the waiting ratio. The waiting ratio is calculated as shown in equation (2).

\[ R_W = \frac{\sum_{i=1}^{N} t_{wi}}{\sum_{i=1}^{N} T_{mi}} \]  

where \( t_{wi} \) is the waiting time of each pedestrian, \( T_{mi} \) is the movement time of each person, the numerator represents the sum of the waiting time of all pedestrians in the
same working condition, and the denominator represents the sum of the walking time of all pedestrians in the same working condition. Combined with the method used by [46–48] to calculate the walk-stop ratio, we select the duration of each pedestrian at a speed below the critical speed state as the waiting time. Referring to other studies in [47] that the pedestrian is stopping when the speed is below 0.1 m s$^{-1}$, the critical speed is set to 0.1 m s$^{-1}$ in this paper. According to the processing method in section 3.1.1, in order to avoid the influence of several people at the beginning and the end of the experiment, the first five people and the last five people are deleted. The results are shown in the figure below.

As shown in figure 8, when the device is set at the same location, the effect on pedestrian movement is different. When set at 1 m from the exit, the waiting ratio is higher than without the device because the density of pedestrians in front of the exit increases in the case of the device, and more pedestrians wait, resulting in more walk-stop phenomenon; thus, the waiting ratio increases. When the device is moved back to 3 m from the exit, the waiting ratio is lower than when the device is set at 1 m. These results show that in the process of moving towards the exit, reasonable setting of the device position can make the crowd waiting for phenomenon less, the movement is more smooth, and the shunt piles can reduce the waiting ratio before the exit.

4.2. Congestion level

Due to the limited exit width, most pedestrians in all conditions will stall in front of the exit, and excessive crowd density will cause congestion. Evacuation behavior is limited if measured only by density, so we calculated the congestion level here. Referring to [49], the curl of the discrete velocity field in each time interval can be calculated as follows:

$$R(x, y) = \nabla \times \mathbf{v}(x) = \left( \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} \right) \cdot k$$ (3)
where $v(x)$ represents the velocity in the grid, $\frac{\partial v}{\partial x}$ and $\frac{\partial v}{\partial y}$ represent the gradient of the velocity in the direction $x$ and $y$ respectively, and $k$ is a unit vector perpendicular to the plane. So the congestion level can be calculated as:

$$Cl = \frac{\text{max} R(x_i) - \text{min} R(x_j)}{|v(x)|}$$

(4)

where $\text{max} R(x_i)$ and $\text{min} R(x_j)$ are the maximum and minimum values belonging to the region of $x^1$. We will call this local region the region of interest (ROI). $|v(x)|$ represents modulus of average speed in each grid. Following [49], we set 2.5 s as our sampling time interval. As for grid size, we find that 0.3–0.5 m is an appropriate interval, beyond this interval the distribution of data points is relatively discrete (especially in the case of less than 0.3 m, there are a lot of zero values). As our scene is relatively small and pedestrians are dense, the ROI of 3–5 is a more suitable value. Finally, we set grid size as 0.3 m and ROI as 3 in our subsequent analysis, the congestion level with time can be seen in figure 9.

As seen from the figure 9, the congestion level is in an upward trend in the early stage and enters a stable fluctuation stage after reaching the peak. At around 20 s, most pedestrians gather in front of the exit and wait, and the average speed of pedestrians changes little. Therefore, the determining factor is mainly pedestrians’ walking direction changes. When the device is at 3 m, it is obvious from figure 9(b) that the congestion level without devices fluctuates more, and there is already a decreasing trend in approximately 30 s with devices, when pedestrians are mostly in the device area, forming a queue before the exit, and the distribution is relatively neat. Without the devices, there is a smaller peak of pedestrians in the 40 s, because the pedestrians are scattered and disordered before the exit. And the speed direction changes more, so the congestion level still shows an increasing trend.

In order to further analyze the distinction of congestion level in different scenarios, we divide the whole evacuation process into early stage and late stage, which represent the common rising and falling process of congestion level respectively in all scenarios. We take 17.5 s when the congestion level begins to stabilize as the start time of the early stage.
Figure 10. Congestion level of different devices before/after the experiment (the left part is the comparison diagram between the without device and the devices placed 1 m away from the exit, and the right part is the comparison diagram between the without the device and the devices placed 3 m away).

Stage, 30 s is the start time of the late evacuation period. The boxplots before and after the congestion level in figure 10. From the box line plot, we can observe the quartiles, whiskers, and outliers of the congestion level data. From the bottom to the top of the vertical box line plot, each horizontal line represents the lower whisker, lower quartile (Q1, 25), median (50), upper quartile (Q3, 75), upper whisker, and mean (marked by black dots in the box), respectively.

It can be found in figure 10 that in the early stage, the average line of the boxplot presents an inverted V shape. The safety barriers significantly increase the congestion level of pedestrians, and the congestion level of the shunt piles are a little lower than that without the device. But in the later stage, we can see significant differences. In particular, in the case of setting diversion devices, the congestion level is much lower than the condition of no device, and the diversion devices increase with the distance to the export decline.

When the diversion devices are set to 1 m, the congestion level of the safety barriers and shunt piles decreases by 10.24% and 22.29%, respectively. When set to 3 m, the congestion level of the safety barriers and shunt piles decreases by 20.48% and 36.14%, respectively. Therefore, it can be concluded that setting the diversion devices at a specific distance before the outlet can effectively suppress the outlet congestion level, and the shunt piles have a stronger inhibitory effect on the congestion level. There may be an optimal distance to make its inhibition more pronounced, which we will continue to explore in future experiments. It can be proven that the placement of shunt piles leads to the reduction of the congestion level in the later stage of evacuation: the shunt piles set at a specific distance before the exit can effectively guide pedestrians to move in a favorable direction to improve the efficiency of pedestrian evacuation.

5. Conclusion

In this work, we study the characteristics of pedestrian evacuation in emergencies and the differences between pedestrian evacuation by different diversion devices through...
experiments with diversion devices placed in front of a narrow exit. By studying the influence of the devices on the motion characteristics of pedestrians in terms of density, speed, congestion, and direction of movement, the main conclusions are as follows:

- As the distance between the devices and the exit increases, the overall evacuation time shows a decreasing trend. The experimental results show that the devices can reduce the congestion level of the late evacuation by 17.59%, improve the order degree of pedestrians, shorten the overall evacuation time by 14.96%, and improve the evacuation efficiency under the best condition of the experiment.

- The experimental data show that the devices at 3 m can prompt the pedestrian to adjust the direction of movement in advance and shrink toward the exit than the devices at 1 m, and the position of the pedestrian on both sides is different. Shunt piles can reduce the proportion of the walk-stop phenomenon. In the best case, the time interval between consecutive pedestrians in front of the exit is reduced by 17.24%, making the evacuation process smoother.

- From the results, we can see that the average density varies throughout the space, with roughly the same trend in different scenarios. The peak density of the devices at 1 m from the exit appears in front of the exit. The back of the devices can drive the density peak in front of the exit into a rapid decline in density.

By comparing the two kinds of diversion devices, it is found that the shunt piles are better than the safety barriers in all aspects. In actual life, shunt piles occupy a small area, are easy to move, and have the least negative impact on pedestrians while improving evacuation efficiency, so they can be applied in mass activities.

The analysis in this paper enriches the empirical data on pedestrian evacuation at bottlenecks and demonstrates that the type and distance of pre-exit devices can have different effects on pedestrian evacuation. However, the above conclusions are only based on experimental devices at two different distances. In future work, we will continue to refine the effects of devices on pedestrian evacuation at multiple distances and strengthen theoretical and modeling aspects to draw more comprehensive conclusions.

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