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Research Article

Study of Split-Flow Wall Located at Exit

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Congestion is the major cause of crowd stampede-trampling and crushing incidents. To alleviate the phenomenon of congestion in the process of evacuation, theory of split-flow wall is put forward to optimize the evacuation and the principle of it is analyzed. Based on the occupant evacuation software of buildingEXODUS, the set parameters of the split-flow wall are studied, and we find that the best range of shunt wall length is 1.5–2 times the export width and the best position of the split-flow wall is 0.5 to 0.75 times the export width far from the exit. Shunt wall can effectively alleviate and even eliminate the congestion in the process of evacuation and will not affect safe evacuation when crowd density is low.

1. Introduction

Along with the fast development of the economy, the business center, shopping plaza, large market, and comprehensive malls emerge endlessly. Their generation and progress are common product of the city, society, science and technology, finance, and other fields actually. The appearance and development of public buildings bring convenience to our life; at the same time, this kind of building with complex space structure, luxurious decoration, big fire load, big traffic, and complicated composition has brought great challenge for fire-fighting and evacuation.

In order to ensure that the people in public buildings in an emergency evacuate effectively and safely, some scholars abroad such as Kretz et al. have carried out a series of experiments on the through characteristic of bottleneck and got the relationship between export density and width of bottleneck [1]; Helbing et al., according to the mechanics model of society, found that placing a cylinder in front of the exit can reduce the evacuation crowd density near the exit and alleviate stranded phenomenon caused by excessive congestion [2]; Yanagisawa et al. found that setting obstacles in front of security exit can reduce the number of conflicts before the exit and increase number of people fleeing out of the building [3]; Kirchner et al., based on the simulation research of cellular automata model, found that the distance between small cylinder and the exit is an important factor affecting safety evacuation time [4].

Some domestic scholars have done a lot of research. Based on cellular automata model, they studied the evacuation problems of crowd in multiexport room and analyzed the influence of rationality degree and the sensitivity coefficient to the evacuation process; Huili got a function relation between exit width and evacuation time [5]; Chen did more detailed research on critical jam density of the people stream evacuating in cross channel [6]. In recent years, in addition, some domestic researchers are also beginning to study the evacuation and diversion facilities of shunt wall; for example, Jinjing introduced a conflict function into cellular automata model and researched the set parameters of shunt wall [7].

In order to prevent the occurrence of crowd trample in the evacuation process, ensure the safe and effective evacuation of the crowd, we must reduce the population density of the bottleneck. For this purpose, we can widen the export [8], but the effect is not obvious. In view of this, it is an effective measure to improve the safety of evacuation by setting up the shunt wall at the bottleneck of evacuation. Shunt wall is usually set near the exit of the building with high-density crowd such as Movie theater and shopping center, in emergency cases which can play an important role in alleviating stranded phenomenon near the exit and ensure the safety evacuation of the crowd.

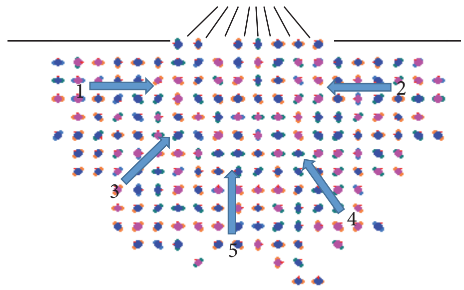

Figure 1: Evacuation without shunt wall.

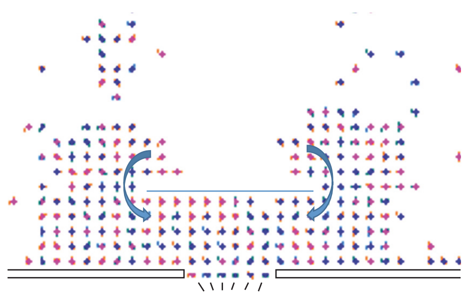

Figure 2: Evacuation with shunt wall.

2. Analysis of Shunt Wall

Because of the herd mentality of crowd in the process of evacuation, especially in the case of an emergency such as fire, coupled with the surrounding environment, is unfamiliar, concentrating on minority evacuation passageway, congestion, and the arching phenomenon (as shown in Figure 1) is bound to appear in the process of evacuation, which would reduce the evacuation efficiency.

Shunt wall was able to optimize evacuation, on the one hand, because shunt wall can split the stream of crowd; if there is shunt wall near the exit, the crowd would be diverted and they would evacuate along the shunt wall to the exit; as a result, the personnel density near the export is reduced, the phenomenon of congestion is alleviated, and, to some certain extent, shunt wall can also improve the efficiency of evacuation; on the other hand, in the process of crowd evacuating out of the door, there is a change in the direction of walking at the end of shunt wall, the situation where people coming from all directions flock to the core of export at the same time is changed, as shown in Figures 1 and 2, which can avoid the appearance of arch structure with balance force [9] and reduce probability of crowded stampede due to the collapsing of arch structure equilibrium state.

In addition, width of building export is constant, the evacuation capability is certain, phenomenon of congestion appears when the number of people arriving at the exports is greater than that of the largest evacuation capacity, and crowded time is t. If there is a shunt wall, the evacuation route will change and the evacuation distance will increase; extension distance is ΔL. At the same time, due to the change of path, crowd will slow down; moreover, when the crowd encounter the shunt wall in process of evacuation, they will spend some time to choose evacuation path, thus delaying the evacuees arriving near the exit of the building; the delay time is ΔT, which is shown in (1), so that shunt wall can effectively relieve the congestion.

Table 1: Personnel composition.

Personnel type	Adult man	Adult woman	Children	Elders
Ratio	40%	40%	10%	10%

$$\Delta T = \Delta T_1 + \Delta T_2 + \Delta T_3, \tag{1}$$

where $\Delta T_1 = \Delta L/V$, caused by the extension distance, ΔT_2 is caused by slow speed, and ΔT_3 is the time spent during the choice of the path. The degree of congestion is expressed by η, which is shown in

$$\eta = \frac{t - \Delta T}{T}, \tag{2}$$

where T is the evacuation time and ΔT_1, ΔT_2, and ΔT_3 are directly affected by the D, L of shunt wall, which is shown in

$$\eta = f(D, L). \tag{3}$$

The influence of shunt wall is different to the people at different direction of the door. Just as Figure 1 shows, the crowd can be divided into 5 parts, the path of parts 1 and 2 would not change, the value of ΔT_1 and ΔT_3 will be 0, and ΔT contains ΔT_2 only because people from other parts would occupy the way which belongs to parts 1 and 2 only when there is no shunt wall, so that the shunt wall affects parts 1 and 2 slightly. While the influence on parts 3 and 4 is serious compared to that of parts 1 and 2, because ΔT of parts 3 and 4 contains the three parts all, the influence to part 5 is more serious than that of parts 3 and 4, because the extension distance ΔL of part 5 is longer than that of parts 3 and 4. The shunt wall can delay people arriving at the export in different degree and vary the situation of the people crowding into exit at the same time. The theory of using shunt wall to optimize evacuation is setting up shunt wall with reasonable parameters of D and L, making η as small as possible; at the same, the evacuation time cannot be lengthened a lot.

3. Optimization of Shunt Wall Set Parameters

Because the pretty penny of traditional full-scale evacuation experiments is prone to accidents, when determining the optimum setting parameters of the shunt wall, the evacuation experiments in this paper are conducted by the software of buildingEXODUS and take η and T as two evacuation parameters as the judgment, hoping to obtain the best setting parameter of shunt wall. Experimental design is shown in Figure 3; it is a 31×16 m square room shown in Figure 3, with exit 1, 4 m wide, and exits 2 and 3, 2 m wide. Based on the current international practical public personnel composition used in the commercial complex, the composition of evacuees of this paper is shown in Table 1. The location of the people is random. There is big difference in walking speed of evacuees

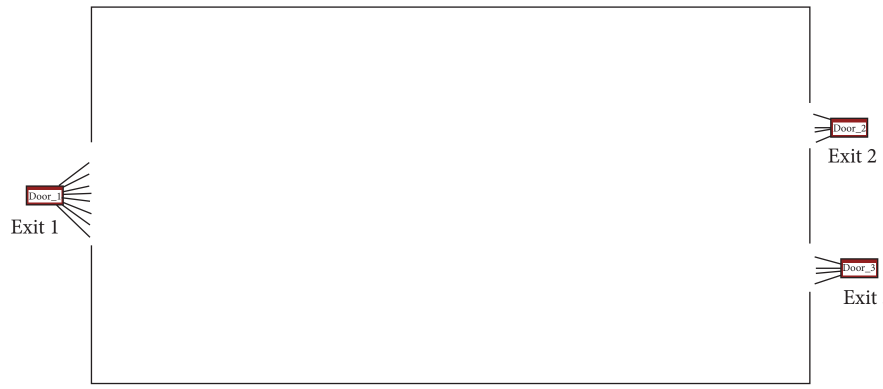

Figure 3: Experimental model.

Table 2: Evacuation speed V.

Function of building	Walking speed (m/s)		
	The ramp and stair		Shops, horizontal corridors, inward, and outward
	Up	Down	
Adult man	0.5	0.7	1.2
Adult woman	0.43	0.6	1.02
Children	0.33	0.46	0.79
Elders	0.3	0.42	0.71

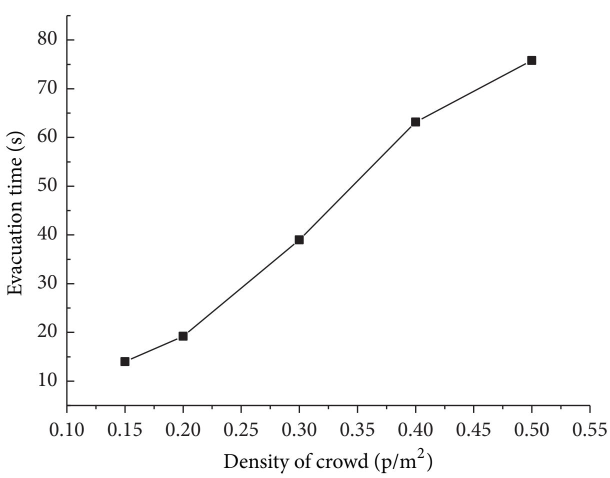

Figure 4: Evacuation time without shunt wall.

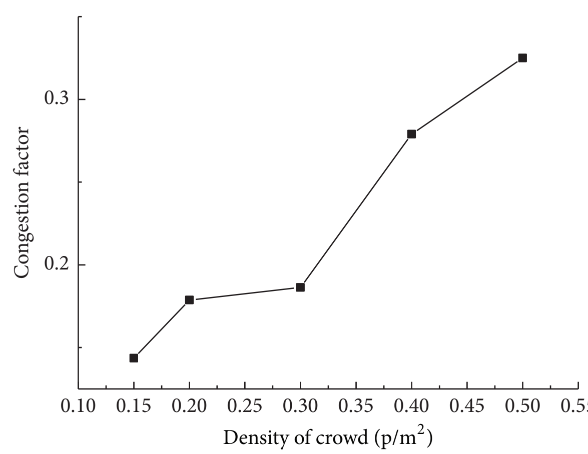

Figure 5: Congestion factor without shunt wall.

in different age and sex and different way. The project of University of Edinburgh, Scotland, mainly researched on the speed of people with different age, sex, and so on [10, 11]. The speed of evacuees in this paper is shown in Table 2. In this article, the authors views the crowd density (ρ) [12–15], length (L), and location (D) of the shunt wall and conducts comprehensive simulation experiment.

4. Analysis of Experimental Results

When there is no shunt wall, results of evacuation simulation experiment are shown in Figures 4 and 5; the figures show that, with the increasing of population density, congestion factor increases obviously, and congestion becomes more serious with the increases of density. When population density is 0.5, η reaches 0.8. There is a great change in evacuation time too; the evacuation time changes from 15 s when the density of crowd is 0.15 p/m^2 to 35 s when the density of crowd is 0.5 p/m^2.

Figures 6 and 7 are variation of the evacuation parameters with the change of shunt wall length, when the density of crowd is 0.3 p/m^2 and the position of the shunt wall is 0.5. As we can see from the figures, shunt wall affects η mainly, and with the increase of shunt wall length, η reduces and the speed of η reducing increases. When the range of the shunt

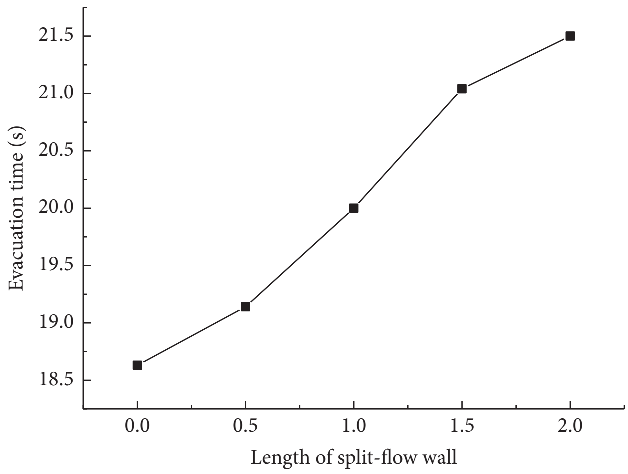

Figure 6: Evacuation time when $D = 0.5$, $\rho = 0.3$.

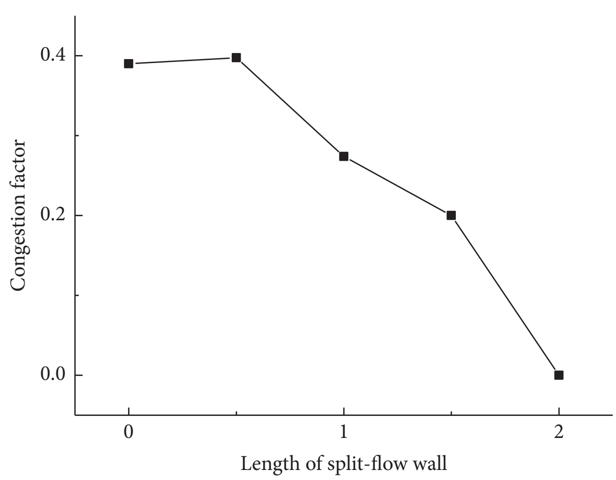

Figure 7: Congestion factor when $D = 0.5$, $\rho = 0.3$.

wall length is 1.5 to 2, the speed of η reducing is the fastest; when the shunt wall length is 2, η reduces to 0. In addition, as we can see from Figure 6, as the increase of the shunt wall length, evacuation time increases, and when the shunt wall length is 1.5 to 2 times the width of the exports long, the speed of evacuation time increasing slows down.

Figures 8 and 9 are evacuation parameters along with changes of the length of the wall when the population density is $0.5\,\text{p/m}^2$ and the position of the shunt wall is 0.5. We can see from the comparison of Figures 6 and 8 that shunt wall affects the evacuation parameters more significantly when the population density is low. Figure 8 displays that shunt wall affects η mainly, and with the increase of shunt wall length, the speed of η reducing increases. When the range of the shunt wall length is 1.5 to 2, the speed of η reducing is the fastest, and η changes from 0.72 when the length of shunt wall is 1.5 to 0.61 with the length of shunt wall being 2. In addition, as Figure 8 shows, evacuation time increases with the growth of length of the shunt wall, and when shunt wall length is 1.5 to 2, the evacuation time slightly reduces.

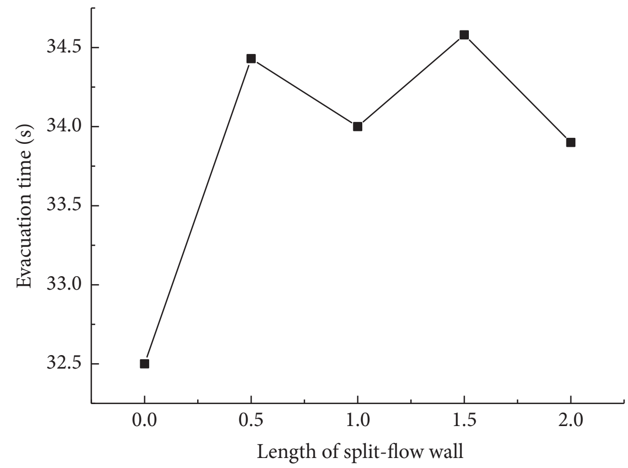

Figure 8: Evacuation time when $D = 0.5$, $\rho = 0.5$.

Consider Figures 6, 7, 8, and 9 together; with increase of shunt wall length, crowded parameter reduces. It is because when we lengthen the shunt wall, the extension distance ΔL becomes longer, and the shunt wall can interlace the arrival time of each part shown in Figure 1. But the length of shunt wall cannot be too long, because it is unrealistic and the evacuation time would become too long if the shunt wall is very long, just as Figures 7 and 9 show. And from Figures 7 and 9, we can know that, when shunt wall length increases, evacuation time grows slightly; when the crowd density is $0.3\,\text{p/m}^2$, evacuation time grows by 6%; when the crowd density is $0.5\,\text{p/m}^2$, evacuation time grows by 1.5%, which indicates that the increase in evacuation time due to shunt wall has little effect on evacuation. Consider η and T together; the most suitable length of shunt wall is 1.5–2.

Figures 10 and 11 are evacuation parameters varying with the shunt wall location when the population density is $0.3\,\text{p/m}^2$ and length of shunt wall is 1.5. Figure 10 shows that, with the distance between shunt wall and export lengthening, congestion factor increases; when the location of the shunt wall is 0.5, η is the minimum. Figure 10 shows that, with the increase of the distance between shunt wall and export, evacuation time reduces slightly.

Figures 12 and 13 are evacuate parameters vary with the shunt wall location when the population density is $0.5\,\text{p/m}^2$ and length of shunt wall is 2. Figure 12 shows that, with the distance between shunt wall and export lengthening, the value of congestion factor grows, congestion factor is the smallest when the location of the shunt wall is 0.5. Figure 13 shows that, with the increase of the distance between shunt wall and export, evacuation time reduces slightly.

Consider Figures 10, 11, 12, and 13 together; with shunt wall becoming far away from export, congestion factor grows. The reason is that if the distance between shunt wall and the export is too long, the area beside the door is big enough to form congestion again after people bypass the shunt wall. Figures 11 and 13 show that, with the increase of the distance between export and shunt wall, evacuation time reduces slightly, because with shunt wall being far away from the export, the extension distance ΔL becomes longer and it is

Table 3: Set parameters of shunt wall.

Case	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ρ (p/m^2)	0.15	0.15	0.15	0.15	0.15	0.2	0.2	0.2	0.2	0.2
D	0	0.5	0.75	0.5	0.75	0	0.5	0.75	0.5	0.75
L	0	1.5	1.5	2	2	0	1.5	1.5	2	2

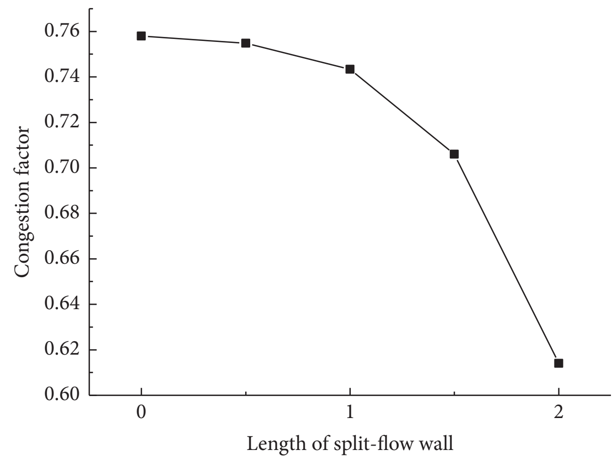

Figure 9: Congestion factor when $D = 0.5$, $\rho = 0.5$.

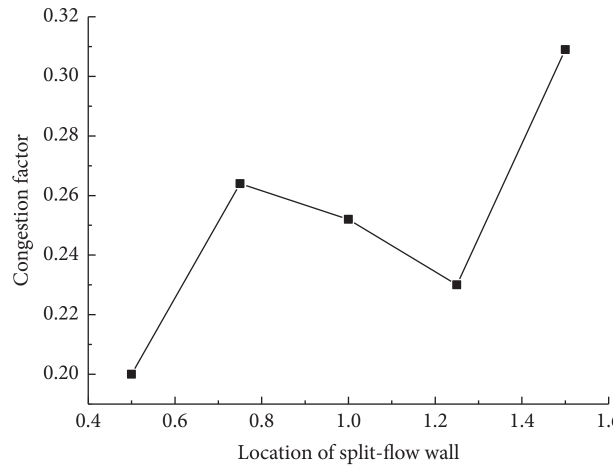

Figure 11: Congestion factor when $L = 1.5$, $\rho = 0.3$.

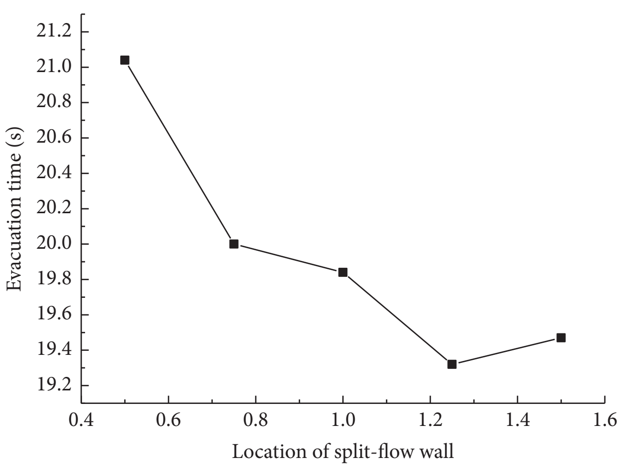

Figure 10: Evacuation time when $L = 1.5$, $\rho = 0.3$.

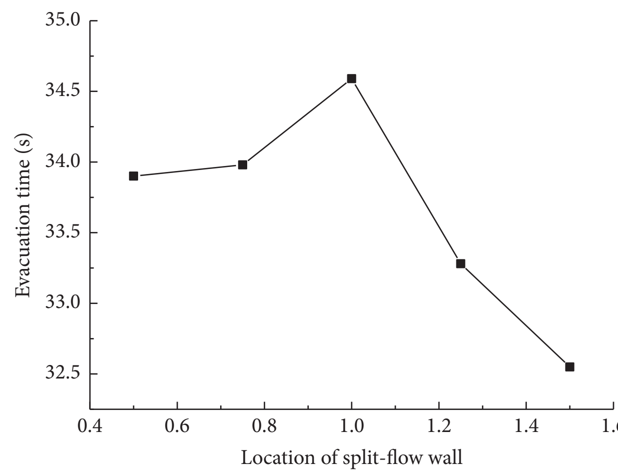

Figure 12: Evacuation time when $L = 2$, $\rho = 0.5$.

more easy to walk out of the building. But evacuation time is longer than the case without shunt wall; when the crowd density is 0.3 p/m^2, evacuation time grows by 8.6%; when crowd density is 0.5 p/m^2, evacuation time grows by 4.6%. The reason is that, when there is a shunt wall, the evacuation distance becomes longer than that of the case without shunt wall. But the increase evacuation time due to shunt wall has little effect on evacuation. According to η and T, the best location of the shunt wall is 0.5–0.75.

Figures 14 and 15 are the evacuation time when the density of the crowd is 0.15 p/m^2 and 0.2 p/m^2, respectively; the information of the shunt wall is shown in Table 3. As the figure shows, evacuation time is longer than that when there is no shunt wall. The values of evacuation time increasing due to shunt wall are 3 s and 2 s when the crowd density is 0.15 p/m^2 and 2 p/m^2, respectively.

When the crowd density is 0.15 p/m^2, the value of congestion factor is 0 in any case shown in Table 3. When the crowd density is 0.2 p/m^2, the value of η is 0.27 with no shunt wall and 0.098 with shunt wall length of 1.5, position of shunt wall is 0.5, and η of another case is 0. It can be seen that the evacuation time of the low-density crowd increases, but it will not affect the safety of the evacuation because the evacuation time of the low density of population is short. In a word, the increasing of evacuation time due to shunt wall will not affect the safe evacuation; at the same time, shunt wall can effectively relieve congestion.

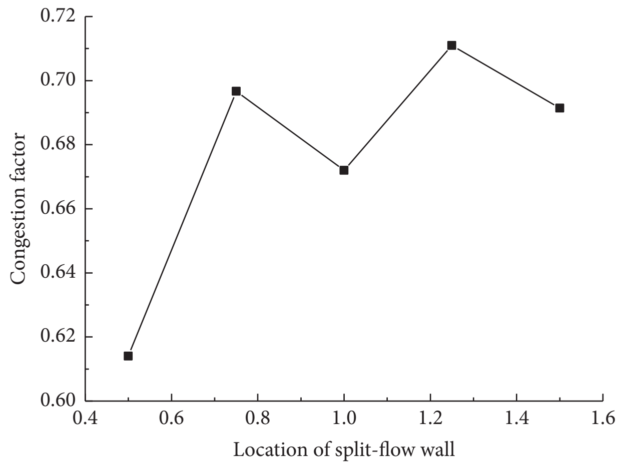

FIGURE 13: Congestion factor when $L = 2$, $\rho = 0.5$.

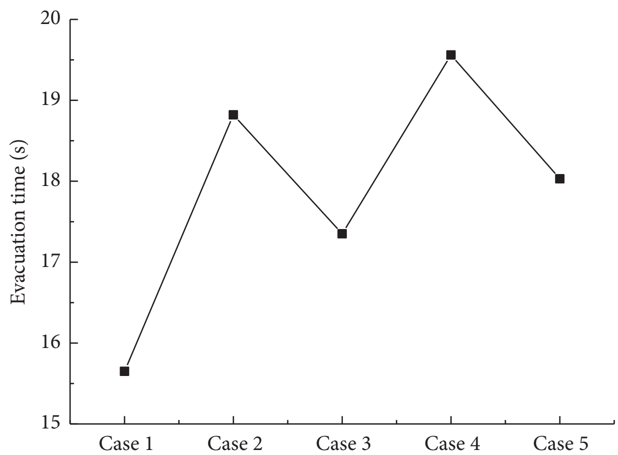

FIGURE 14: Evacuation time when $D = 2$, $L = 1.5$.

Above all, the best length of shunt wall is 1.5 to 2 times as long as the export, and the best set position is 0.5 to 0.75 times the export width far away from the exit. Shunt wall can effectively alleviate and even eliminate the congestion in the process of evacuation.

5. Conclusions and Suggestions

5.1. Conclusions. According to the statement of the simulation results, we can get the following conclusions:

(1) Shunt wall plays a significant role in alleviating the congestion, especially when the density of population is lower than 0.5 p/m^2.

(2) The best length of shunt wall is 1.5 to 2 times as long as the export, and the best set position is 0.5 to 0.75 times the export width far away from the exit.

(3) Setting the shunt wall with relatively high-density crowd evacuation process can effectively alleviate the evacuation congestion; when the crowd density is low, shunt wall will not affect the safety evacuation.

5.2. Suggestions. It is important to ensure that the people evacuate out of the building in emergency, information of

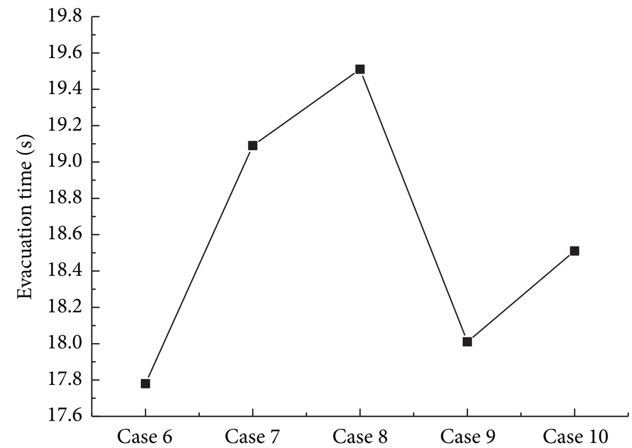

FIGURE 15: Evacuation time when $D = 2$, $L = 1.5$.

pedestrian about evacuation routes plays an important role in the evacuation, and the effect of the obstacles before export has been recognised by many researchers. Shunt wall with reasonable set parameters can improve the safety of the evacuation and improve the efficiency of evacuation effectively. But shunt wall in front of the export keeps the door out of the sight of people to a certain extent; therefore, shunt wall should be used combined with evacuation marks to achieve good effect of evacuation. In addition, there are two cases where the length of shunt wall is more than 2 times as long as the export width and the distance between the shunt wall and export is less than 0.5 times as far as the export width is not involved in this article; the main reason is that it is unrealistic in the practical buildings when the shunt wall is too long, and it is equal to the set obstacles among exports, indirectly reducing the export width, when the distance between shunt wall and export is less than 0.5 times the width and goes against the starting point of setting shunt wall to improve the evacuation safety and efficiency.

Symbols

ΔT: Delay time caused by shunt wall
t: Crowded time
ΔL: Extension distance due to the shunt wall
V: Walking speed of evacuees
T: Time from the beginning of the evacuation to the last trapped person leaving the building
η: Dimensionless quantity, crowded degree of evacuation bottleneck with the most serious congestion throughout the evacuation area, expressed by a percentage of the evacuation time being in crowded station
D: Dimensionless quantity, the position of the shunt wall which is the distance between the export and the shunt wall, expressed by the ratio of the distance and width of export
L: Dimensionless quantity, the length of the shunt wall, expressed by the ratio of the actual length of the shunt wall and width of export.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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