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Analyzing floor-stair merging flow based on experiments and simulation

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Analyzing floor-stair merging flow based on experiments and simulation*

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In most situations, staircase is the only egress to evacuate from high-rise buildings. The merging flow on the stair landing has a great influence on the evacuation efficiency. In this paper, we develop an improved cellular automaton model to describe the merging behavior, and the model is validated by a series of real experiments. It is found that the flow rate of simulation results is similar to the drills, which means that the improved model is reasonable and can be used to describe the merging behavior on stairs. Furthermore, some scenarios with different door locations and building floor numbers are simulated by the model. The results show that (i) the best door location is next to the upward staircase; (ii) the total evacuation time and the building floor number are linearly related to each other; (iii) the pedestrians on upper floors have a negative influence on the evacuation flow rate.

Keywords: evacuation dynamics, merging flow, stair simulation, cellular automaton, high-rise buildings

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1. Introduction

In many countries, staircase is the only way to evacuate from a multi-story building when a fire or other emergency occurs.[1] All the upper stories share the lower stairs, which leads to a natural merging behavior in the stair landing and the sharply increasing density will slower the evacuees' velocity and the flow rate. Understanding the rules of merging will help improve the high-rise buildings' evacuation strategies. In recent years, more and more scholars have paid attention to the merging behavior and conducted many valuable researches.

Pedestrian merging behavior can be divided into two parts, merging on the ground or merging along the vertical direction. Craesmeyer and Schadschneider developed a floor field model to describe the dynamics at T-junctions and compared the fundamental diagram with experiments.[2] Cuesta *et al.* have built an experimental data-set about the passing time cost in various combinations of door weight, corridor weight, and the height differential at the junction.[3] Aghabayk *et al.* have done some real merging experiments to compare the flow rates among the cases of different merging angles (60°, 90°, and 120°) at different walking velocities (1.5 m/s and 3 m/s).[4] Analogously, Shi *et al.* conducted a series of controlled experiments considering symmetrical 60°, 90°, 180° merging angles and found that as the merging angle increases, mean velocity and mean flow in the measuring region decrease.[5] Lian *et al.* analyzed a university-students' experiment and studied the relationship between branch width and the flow rate.[6] Chen *et al.* built a bidirectional pedestrian flow merging model based on social force model to simulate the merging behavior at a T-junction.[7]

As for the merging behavior in stairs, as early as 2008, Galea *et al.* developed a C++ software including Occupant, Movement, Behavior, Toxicity, and Hazard sub-models. Conflict behavior was introduced to describe the merging behavior.[9] Ding *et al.* investigated a computer simulation model to describe the merging behavior at the floor–stair interface and four different door positions were discussed. The results show that the door which is on the opposite side of the landing to the incoming stair is the best situation.[10] Boyce *et al.* analyzed three evacuation drills in university and health center and the people's merging behavior was described in detail.[11] Xu and Song modeled the staircase evacuation with multi-grid CA model considering the turning behavior, and compared the simulation results with an egress drill.[8] Huo *et al.* extended the original lattice gas model by considering inner-side walk preference, turning behavior, and different desired speeds. The simulation results had the same tendency as the empirical data.[12] After that, Huo *et al.* conducted two different experimental scenarios. The speed of participants walking through two adjacent floors and the space–time distribution were discussed.[13] Sano *et al.* put forward a simplified mathematical model for calculating the evacuation time

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from a multi-story building. In this model, the merging rate is continuous and the merging ratio is equal for all the stories. The result was compared with a simulation model using SimTread.[14]

Summarizing the current models, it can be found that when the people come into the landing, the merging behavior occurs naturally. However, in our real life, when the pedestrian faces a crowded staircase, he prefers to await for a certain amount of time to avoid congestion rather than to walk into the landing directly. To describe the procession of stair evacuation, the waiting time and policy should be considered in the models. As a consequence, a series of low-density merging experiments are conducted in this paper. Waiting policy considering the influence of crowd density is involved in the improved cellular automaton model to simulate the merging behavior on stairs.

The rest of this paper is organized as follows. In Section 2, the experimental procedure is introduced. In Section 3 the change of the model is presented. The drills and simulations are compared in Section 4 and expansion simulation is conducted in Section 5. Finally, the conclusions and disscusion about the experiments and the model are given in Section 6 and Section 7 respectively.

2. Experiment

The experiments were conducted in the 4-story simulation building. The structures of the building stairs are shown in Fig. 1. All the participants were college students from two classes of the same department. There were 33 students in class one and 29 students in class two. Besides, there are 2 guide students in each experiment. The students starting from floor 3 were regarded to wear blue hat and those from floor 2 wore red hats, so it was easy for us to distinguish the different crowds in merging areas.

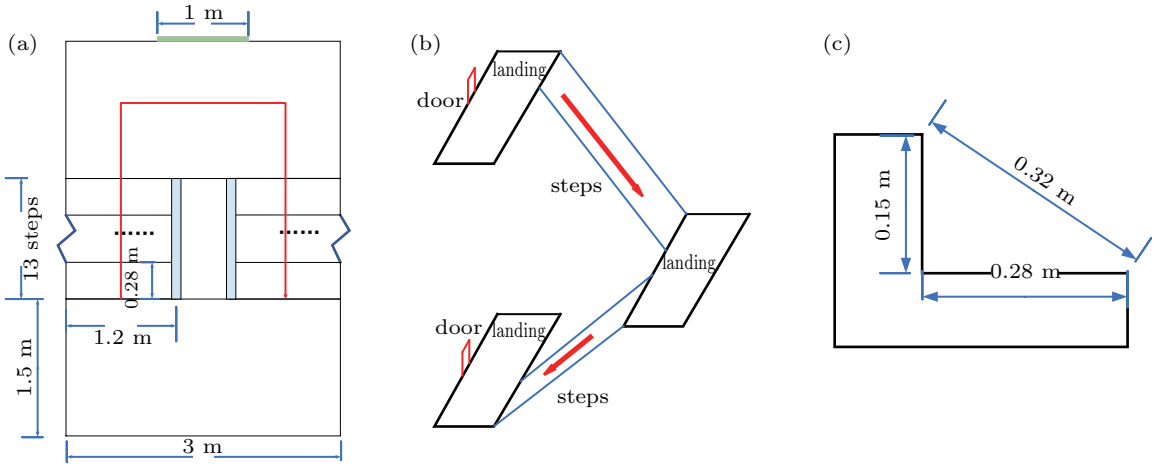


Fig. 1. Structures of building stairs: (a) structure of the stairs between the 3rd floor and the 1st floor; (b) stereogram of stairs; (c) stair tread.



Fig. 2. Lines of students on (a) floor 2 and (b) floor 3 about to start experiment.

At the beginning of the drills, the participants were divided into 2 parts randomly. They were arranged in a single line behind the door on floor 2 and floor 3 respectively. The two guide students were assigned to be the heads of the two lines respectively. The participants in the two lines were required to "try to merge into one line when going downstairs". After hearing the order "Go!", the guide student on floor 3 began to walk into the stair landing and went downstairs first. Other students on floor 3 followedthe guide. To extend the merging time period, the students on floor 2 were regarded as starting to participate in the experiment after the first floor 3 student had come into the downward staircase of floor 2. The drills ended after all the students had passed through the door of floor 1. The same procedure was repeated separately by class one, class two and the two class together. Figure 2 shows the beginning lines and figure 3 shows the merging behavior and leaving behavior.

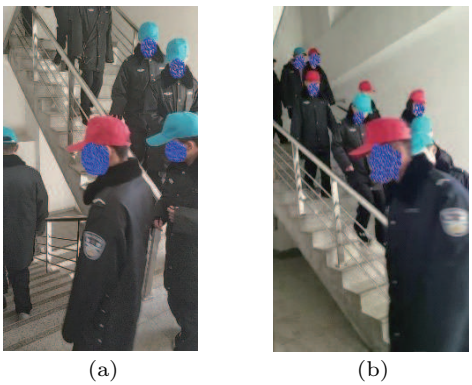


Fig. 3. (a) Merging on floor-2 landing, where the red hat tries to merge into the two blue hats, and (b) leaving on floor 1.

3. Model

The cellular automaton (CA) model has been widely-used in many fields, such as pedestrian simulation in buildings,[15–23] crossing streets,[24] choosing exits,[25–27] the interaction among pedestrians and vehicles,[28,29] the self-organized phenomenon,[30] *etc*. Especially, because the space in a CA model is discrete and the same as that in a staircase, it is also used to simulate the pedestrian flow in stairs or escalators.[21,31,32]

This improved CA model is based on the one considering evacuee's walk preferences of Ding *et al.*[33,34] The cell size in the landing is 0.5 m×0.5 m and that in the steps is 0.5 m×0.28 m. From the experiment video data, it is found that there is one or two evacuees' lines in the step because the number of evacuees is not so large, which means that the extra 20-cm step width has no influence on the model. That is to say, the 1.2-m width step can be replaced with 2 cells. In the experiment, evacuees are regarded as leaving the door in a single line, so the door can be represented by one cell but not two cells. The landing and the staircase are divided into 6 parts just as shown in Fig. 4. The moving direction depends on the location area. On the red line, the pedestrian transfers to another floor in the model.

The model details are as follows.

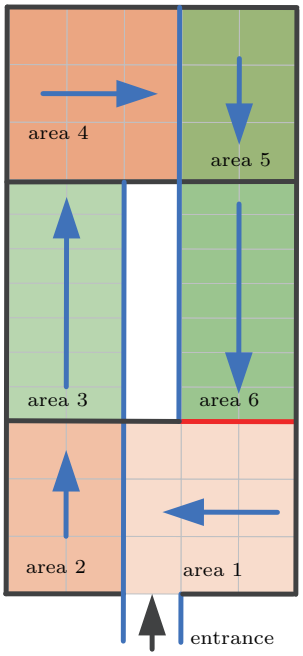


Fig. 4. Model area setting and moving direction.

3.1. Walk preference

In the Ding's model[34] evacuees' desiring to keep distance with others is introduced and the neighborhood around a pedestrian with two situations is defined. In this experiment, some new characteristics are found.

When the evacuees are in lower density situation, for example, only the students from floor 3 walking on the treads, the distance between two pedestrians is 2 steps. After students from floor 2 come into the stream, the distance becomes 1 step. As the evacuees on the treads accumulate, the distance turns into 0 step. The distance between the evacuees in the experiment video snapshot is shown in Fig. 3. As a result, the neighborhood of a pedestrian on the step is changed as shown in Fig. 6, while the neighborhood types on the landings are consistent with each other.

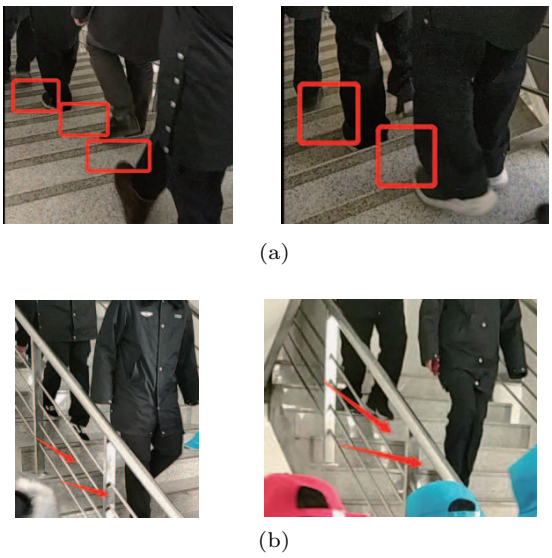


Fig. 5. Video snapshot of experiment, showing (a) 1-step distance in higher density; (b) 2-step distance in lower density.

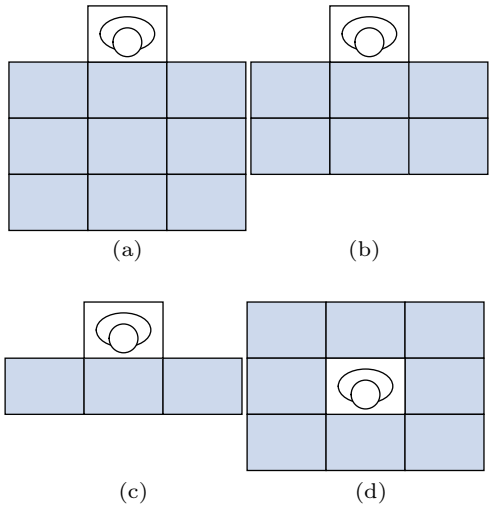


Fig. 6. Neighborhoods in different condition for (a) low step density, (b) medium step density, (c) high step density, and (d) landing neighborhood with no change.

3.2. Merging policy

While the pedestrians on the upper floor walk through the front landing, the students will make a decision about whether to merge into the flow considering the landing density and their own patience of waiting. If the landing density is considered as being high by the pedestrian, he/she will await for a moment until the density becomes bearable. With the waiting time accumulating, the endurance to high landing density increases and the desired density advances, too.

What is more, if a large number of people come into the landing in a few seconds, that is to say, the landing density is foreseen to be higher, the endurance will increase.

According to the experiment videos, the desired landing density in the new model is divided into three states: low density (landing people number is less than 3), medium density (landing people number is between 4 and 6), high density (landing people number is more than 6). At the beginning of the experiment, the desired density is low density. The desired density will increase one level after every 4-s waiting (it takes 4 s for someone to walk through half the floor staircase in the experiments). Meanwhile, if the number of people on the last 3 steps of the upward stairs is more than 5, the desired density will also increase one level. In one computation step, the desired density is changed as shown in Table 1.

Table 1. Desired density changing situation.

Original state	Waiting time	Upper number	Summary	Final state
Low	<4 s	<5.5	$+0$	low
		>5.5	$+1$	medium
	$4\text{ s}<8\text{ s}$	<5.5	$+1$	
		>5.5	$+2$	high
	>8 s	<5.5	$+2$	
		>5.5	$+3$	

3.3. Right priority

The right preference is considered by several models.[8,33] In Ding's model, high probability rightward is considered, which may cause an unreasonable phenomenon during evacuation simulation. For example, when someone occupies a landing cell next to the staircase, it is possible that the pedestrian walks back to the tread in the simulation. Consequently, the right preference is changed at the particular positions. For pedestrians in the landing cells next to the staircase, the staircase side is not considered no matter wherher the cell is occupied. An example is demonstrated in Fig. 7.

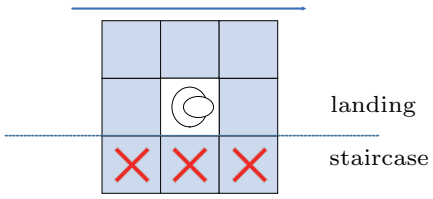


Fig. 7. Special neighborhood.

4. Validation

4.1. Drill 1

There are 16 students on floor 3 and 19 students on floor 2 in drill 1. The experimental flow and the simulation flow are shown in Fig. 8. To describe the difference between the simulations and experiment results, the mean-square error (MSE) value of the leaving time is calculated from the following formula:

$$\mathrm{MSE}=\sum_{i=1}^{N}\left(Simu_LT_i-XExperiment_LT_i\right)^2/N=0.66.$$

Meanwhile, the leaving times of the evacuees are compared as shown in Fig. 9. The absolute values of all the results are less than 1.5 s. The average speed is represented with the time taken by a student going through one floor and the boxplot. Figure 10 shows the results. The simulation average time is 0.2 s faster than the leaving time in drill, and the relative error is 2.13%.

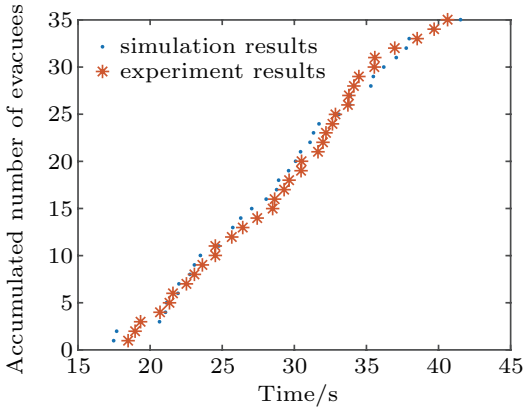


Fig. 8. Flow rate of drill 1 and simulation results.

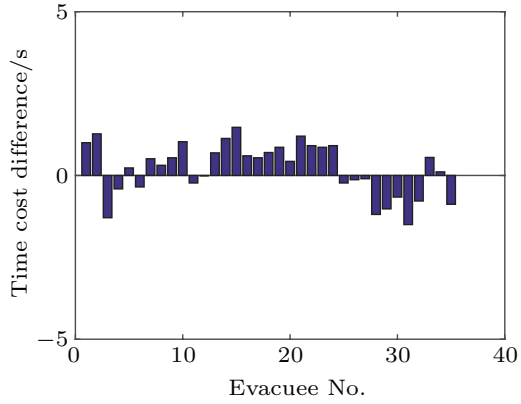


Fig. 9. Difference in leaving time between simulation and drill 1.

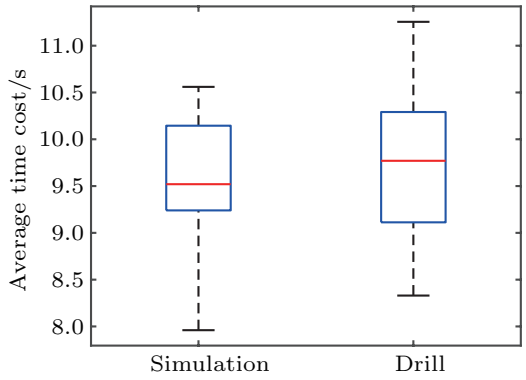


Fig. 10. Average time of simulation and drill 1.

Besides the evacuation flow, evacuation consequence is also an important indicator to evaluate the model. The data of drill 1 are extracted to compare the accumulation number of evacuees with the increase of evacuation people. The evacuees from floor 2 are compared in Fig. 11. Obviously, the simulation results are similar to the experiment results. To explain it more clearly, the simulation results and experimental results are compared as shown in Fig. 12, and the two series of data fit well within the root mean square error (RMSE) 0.6066.

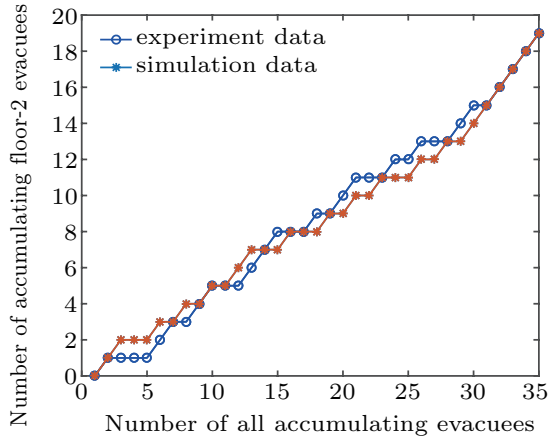


Fig. 11. Comparison between experimental and simulation result for the number of evacuees accumulating on floor 2 *versus* the number of all accumulation evacuees.

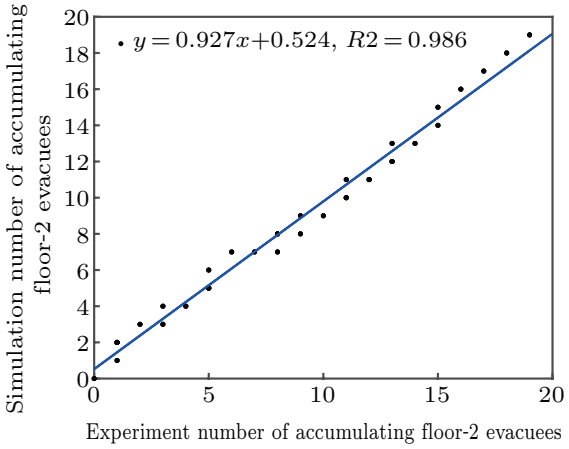


Fig. 12. Simulation result *versus* experimental results for the number of evacuees accumulating on floor 2.

On the other hand, due to $N_{\text{all}} = N_{\text{f2_accu}} + N_{\text{f3_accu}}$. ($N_{\text{all}}$ denotes the total accumulation number, $N_{f2/3_\text{accu}}$ the accumulation number of evacuees on floor 2 and floor 3), the absolute value of the difference between simulation and experiment for floor 2 and floor 3 are the same.

4.2. Drill 2

In drill 2, the students of class 2 replace those of class 1. There are 10 students on floor 3 and 21 on floor 2. The experiment procedure is the same as that in drill 1. The flow rate comparison is shown in Fig. 13 and MSE is 0.60.

Figures 14 and 15 display the leaving time simulation error and the average costing time. The difference in maximum leaving time is 2.08 s. The average time of simulation is 0.59 s slower than that in drill 2 and the relative error is 6.54%.

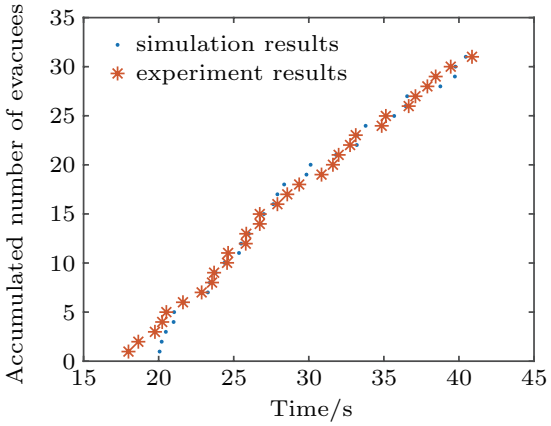


Fig. 13. Comparison between experimental and simulation result of flow rate in drill 2.

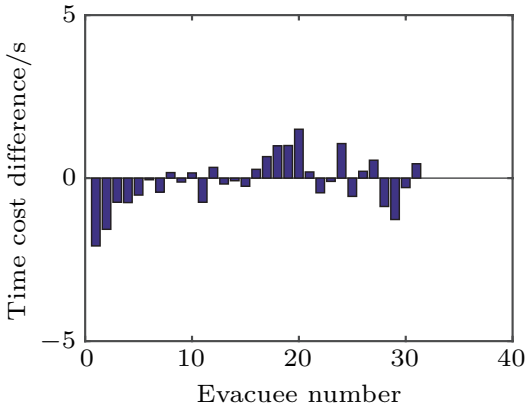


Fig. 14. Leaving time difference between simulation and drill 2. Calculation method is the same as that in Fig. 9.

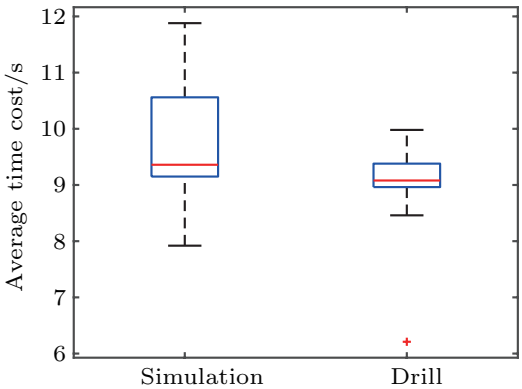


Fig. 15. Average time cost of simulation and drill 2.

4.3. Drill 3

In drill 3, the students of both the two classes are required to participant in the experiment. There are 25 students on floor 3 and 39 students on floor 2. Figure 16 shows the comparison of flow rates.

All the comparison results indicate that this improved CA model is reasonable and able to simulate the staircase evacuation behavior.

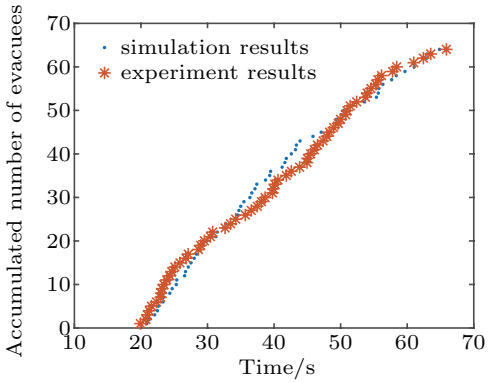


Fig. 16. Comparison between experimental and simulation result of flow rate in drill 3.

5. Simulation

5.1. Floor number

The experiment is limited by the crowd number and the building floor number and only 3 floors are involved. To simulate the evacuation from high-rise building, various floor number scenarios are conducted. In the simulations, there are 30, 40, 50 up to 90 evacuees on each floor respectively and the total evacuation time is shown in Fig. 17. Analyzing the total time cost, it is easy to find its linear relationship with floor number. All the regression R^2 is over 0.9996 which is similar to the simulation result of Ding *et al.*[10] In addition, the slope of the regression line increases with the evacuee number increasing, demonstrating that the increasing of evacuee number slowers the efficiency of evacuation.

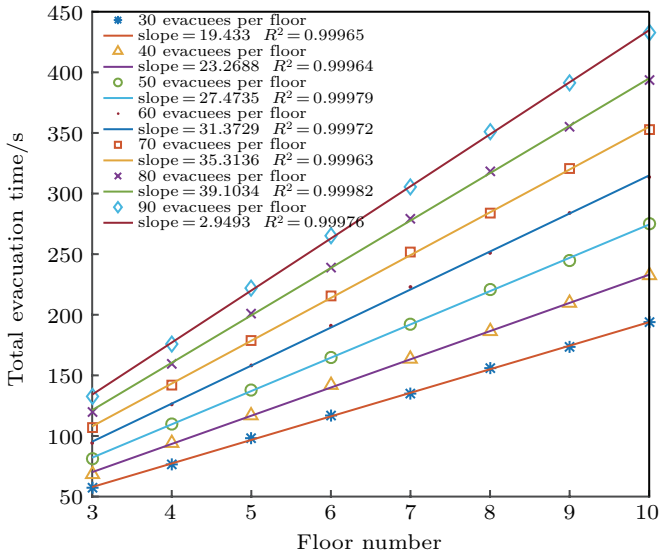


Fig. 17. Total evacuation time changing with floor number and evacuee number for various cases.

Setting the evacuee number on each floor to be 30, the flow rate and total evacuation time for various cases are displayed in Table 2. In this paper, flow rate is calculated from equation $F = N/(t_2 - t_1)$, where F denotes the flow rate, N the pedestrian number, t_2 the leaving time of the last pedestrian, and t_1 the leaving time of the first pedestrian. The flow rate represents the average number of evacuees succeeding in evacuating per second.

As to each floor evacuation rate, the rate descends with the floor number increasing, that is to say, the bigger the upper floor number, the slower the pedestrians evacuate. And in one experiment, the flow rate increases with floor number increasing.

Table 2. Simulation results in different floor number scenarios.

Total time/s	Flow rate of each floor/(p/s)								
	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
57.31	0.80	1.10							
76.62	0.61	0.76	0.95						
98.09	0.49	0.62	0.72	0.88					
116.76	0.41	0.48	0.59	0.67	0.81				
135.04	0.35	0.39	0.45	0.48	0.59	0.64			
156.03	0.31	0.35	0.37	0.42	0.45	0.55	0.51		
173.35	0.28	0.30	0.32	0.35	0.37	0.40	0.47	0.52	
193.97	0.25	0.27	0.29	0.30	0.33	0.33	0.39	0.42	0.40

5.2. Egress position

A series of simulations with 30 pedestrians on each floor and with 90 pedestrians on each floor are conducted and the door position is diverse as demonstrated in Fig. 18. The average flow rates are compared among different simulations. The results are recorded in Fig. 19. All the simulations are repeated 15 times and the data in chart is the average value.

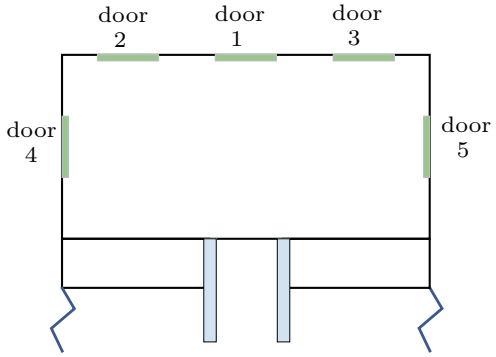


Fig. 18. Various door positions.

It is found clearly that the flow rates of the selected door with different evacuee numbers fluctuate in a small range. What is more, the rate of door 5 is fastest and that of door 4 is slowest. Doors 2, 3, and 1 have similar evacuation flow rates. The best position of stairwell door is next to the downward staircase and the opposite is the worst position, which is the same as the conclusion of Pathfinder simulation.[10]

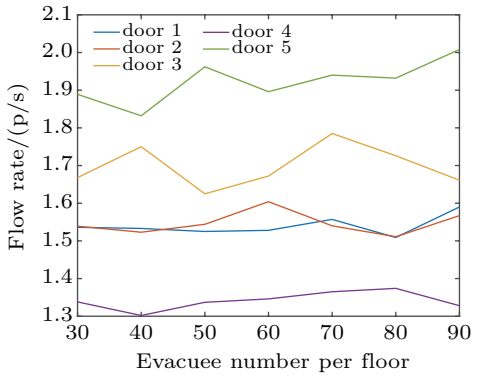


Fig. 19. Comparison of flow rate among different evacuee numbers and different door locations.

6. Discussion

It should be noted that participants are all college students aged from 20 to 24. Consequently, the features in this paper cannot represent the general characteristics of old people or children. Moreover, the floor number involved in the experiment is limited and the fatigue is not considered in the model. Besides, the experiments and the simulations are all for normal environment. It will be very different in emergency due to panic emotion. However, the model introduces high landing density endurance (in Subsection 3.2) to describe the merging decision. High endurance may be useful for panic evacuation simulation, which needs further research.

7. Conclusions

In this work, an improved CA model describing the merging behavior in the stairwell landings is presented and validated experimentally. This paper focuses on studying the factors influencing the evacuation from high-rise building, such as the floor number, evacuee number, and door location. The results show that the door located next to the downward staircase leads to fastest evacuation and the total time ascends linearly with the floor number increasing. Additionally, the pedestrians on upper floors have a negative influence on evacuation flow rate.

In conclusion, the improved CA model is good for describing the merging behavior and can extend to other high-rise building staircase evacuation scenarios.

References

[1] Ronchi E and Nilsson D 2013 *Fire Sci. Rev.* **2** 7
[2] Craesmeyer M and Schadschneider A 2014 *Transp. Res. Procedia* **2** 406
[3] Cuesta A, Abreu O, Balboa A and Alvear D 2017 *Tunnelling Underground Space Technol.* **70** 155
[4] Aghabayk K, Ejtemai O, Sarvi M and Sobhani A 2014 *Transp. Res. Procedia* **2** 768
[5] Shi X, Ye Z, Shiwakoti N, Tang D, Wang C and Wang W 2016 *Accid. Anal. Prev.* **95** 405
[6] Lian L, Mai X, Song W, Richard Y K K, Rui Y and Jin S 2017 *Fire Saf. J.* **91** 918
[7] Chen M M, Wang J H, Zhi Y R and Gao L J 2018 *Procedia Eng.* **211** 70
[8] Xu X and Song W 2009 *Build. Environ.* **44** 1039
[9] Galea E R, Sharp G and Lawrence P J 2008 *J. Fire Prot. Eng.* **18** 291
[10] Ding Y, Yang L and Rao P 2013 *Procedia Eng.* **62** 463
[11] Boyce K E, Purser D A and Shields T J 2012 *Fire Mater.* **36** 383
[12] Huo F, Song W, Lv W and Liew K M 2014 *Simulation* **90** 501
[13] Huo F, Song W, Chen L, Liu C and Liew K M 2016 *Saf. Sci.* **86** 165
[14] Sano T, Ronchi E, Minegishi Y and Nilsson D 2017 *Fire Saf. J.* **89** 77
[15] Yang L Z, Zhao D L, Li J and Fang T Y 2005 *Build. Environ.* **40** 411
[16] Weng W G, Chen T, Yuan H Y and Fan W C 2006 *Phys. Rev. E* **74** 036102
[17] Qiu G, Song R, He S and Yin W 2018 *Phys. A: Stat. Mech. Its Appl.* **508** 199
[18] Shi M, Lee E W M and Ma Y 2018 *Phys. A: Stat. Mech. Its Appl.* **497** 198
[19] Zhao D L, Li J, Zhu Y and Zou L 2008 *Build. Environ.* **43** 518
[20] Zheng X P, Zhong T K and Liu M T 2009 *Build. Environ.* **44** 437
[21] Yue F R, Chen J, Ma J, Song W G and Lo S M 2018 *Chin. Phys. B* **27** 124501
[22] Chen Y Z, Li M, Jiang R and Hu M B 2018 *Chin. Phys. B* **27** 088901
[23] Chen R, Li X and Dong L Y 2012 *Acta Phys. Sin.* **61** 144502 (in Chinese)
[24] Feng S M, Ding N, Chen T and Zhang H 2013 *Physica A* **392** 2847
[25] Xu Y, Huang H J and Yong G 2012 *Chin. Phys. Lett.* **29** 080502
[26] Lin P, Ma J and Lo S 2016 *Chin. Phys. B* **25** 034501
[27] Hu J and You L 2014 *Acta Phys. Sin.* **63** 080507 (in Chinese)
[28] Sun Z, Jia B and Li X G 2012 *Acta Phys. Sin.* **61** 100508 (in Chinese)
[29] Li W J and Nie L 2018 *Chin. Phys. B* **27** 070204
[30] Dong L Y, Lan D K and Li X 2016 *Chin. Phys. B* **25** 098901
[31] Ding N, Chen T and Zhang H 2017 *Building Simul.* **10** 407
[32] Jin H and Guo R Y 2019 *Acta Phys. Sin.* **68** 020501 (in Chinese)
[33] Ning D, Hui Z, Tao C and Luh P B 2015 *Chin. Phys. B* **24** 068801
[34] Ding N, Chen T, Zhang H and Luh P B 2014 *Traffic and Granular Flow '13* pp. 145–153