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Simulation of high-rise building evacuation considering fatigue factor based on cellular automata: A case study in China

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Abstract

Stair evacuation plays a crucial role in building evacuation since stairs are generally the only means to evacuate high-rises on fire. To ensure safety stair design, the Life Safety Code suggests using a performance-based design approach, which requires evacuation simulations. Most of existing simulations, however, do not consider the structure of stairs and fatigue of evacuees, and these simulations are not validated by real emergency events or experiments. This paper is on improving the simulation of pedestrian flow in the stairs of high-rises by addressing these issues. A new Cellular Automata simulation model is developed where the simulation map is divided into zones based on the stair structure, and the rule of evacuees' movement for each zone is appropriately defined to simulate turning behavior. To validate the simulation, a fire drill was held in two high-rise buildings. In this drill, evacuees felt tired after a walk. The simulation results demonstrate that, compared with the simulation without fatigue factor, our simulation can predict the evacuation time more accurately. Building designers can make evacuation plans and strategies based on the new simulation.

Keywords

stair simulation,
high-rise evacuation,
cellular automata,
fatigue

Article History

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1 Introduction

Stair evacuation plays an important role in building evacuation since stairs are usually the only way to evacuate of high-rises on fire. There are many factors that influence the evacuation pedestrian flow in stairs, such as the structure of stairs (Ronchi and Nilsson 2013) and fatigue factor (Pelechano and Malkawi 2008). The structure of stairs makes the evacuees' movements on stairs different from that in corridors. In stairs, people will be affected by the treads and they will change their directions at the interface (landing). As a result, the structural design of stairs is currently reflected in several building codes, such as NFPA101 (NFPA 2012) and International Building Code (2009). Fatigue is another important factor which is reported in WTC 9/11 (Galea et al. 2009), and it is always observed in high-rise evacuation. People, who feel fatigue, will slow down or even stop in stairs (Ronchi and Nilsson 2013). They may become "obstacles" to others and cause additional delay to the pedestrian flow and evacuation process.

To get better safety stair design considering these factors, the Life Safety Code (NFPA 2012) suggests using performance-based design approach, and such approach requires the use of simulations. However, the most of existing pedestrian flow simulations do not consider the structure of stairs and fatigue of evacuees, and these simulations are not validated by real emergency events or experiments. As a result, how to improve the simulation of pedestrian flow in stairs during high-rises evacuation considering fatigue factor is an important problem.

To simulate pedestrian flow in stairs, microscopic simulation models are commonly used (Pelechano and Malkawi 2008; Fang et al. 2012) because such models can better characterize interactions among evacuees. Among these models, Cellular Automata (CA) models (Wolfram et al. 1983; Varas et al. 2007; Yamamoto et al. 2007; Nguyen et al. 2013; Ding et al. 2015; Li et al. 2016) are well accepted because such type of models is fit for a large-scale evacuation because

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of the discrete simulation space. There is usually one transition rule (determines the movement of evacuees) in most of the existing CA simulation model. When considering the structure of stairs, one transition rule cannot demonstrate the pedestrian flow well on both treads and landings at the same time. To simulate fatigue factor in CA model, variable speeds are required (Galea et al. 2009; Heyes and Spearpoint 2012; Koo et al. 2014). The system should shorten the time interval, and evacuees can move during several intervals (Johnson 2005). However, it will increase computational complexity if all the evacuees update their positions at each interval.

In this paper, a new CA stair simulation model is established in Section 3, and the structure of stairs and fatigue of evacuees are considered in the simulation. To simulate the pedestrian flow well on both treads and landings, the simulation map of each floor is divided into zones, and the transition rule for each zone is defined separately. This new kind of grid map and transition rules can simulate the evacuees' movements and turning behaviors on treads and landings well at the same time. To reduce computational complexity, the concept of basic update time is introduced, and evacuees only update the positions at an integer multiple of this basic update time. After the simulation model is established, it is important to validate this simulation. However, validation is difficult because it is hard to get stair evacuation data or hold drills in high-rise buildings (Hostikka et al. 2007), especially fatigue factor should be involved in stair evacuations or drills. Real emergency events such as WTC 9/11 had been studied and plentiful results were discussed (Johnson 2005), but these data cannot be used to validate microscopic simulation since these events were not fully video recorded. The detailed information which is needed in simulations cannot be collected because of the lack of video record. As a result, we held a fire drill in a high-rise buildings in Tsinghua University. In order to bridge the gap between the fire drill and stair evacuations, harmless smoke was released during evacuation. The validation and simulation in Sections 4 and 5 demonstrate that, compared with the simulation without fatigue factor, our simulation can predict the evacuation time more accurately.

2 Literature review

2.1 Fatigue of evacuees in high-rises

As high-rise buildings dramatically change the skylines in major cities, fire in high-rises happened more frequently than that in the last decades. For example, terrorist attacks to World Trade Center (WTC) in 2001 (Corley 2002; Galea et al. 2009), Deutsche Bank building fire in New York City in 2007, big fire in a high-rise apartment in Shanghai in 2010 (Yuan and Wen 2012). These events highlight the severity of evacuating a large number of evacuees in a short period of time. As reported in WTC 9/11 evacuation, several survivors said they need to stop because of fatigue or their companions need to take a rest: slow down or stop (Averill et al. 2005). About 20% of the survivors said they feel tired during the evacuation, and half of them stopped to take a rest after travelling about thirty floors. Some survivors claimed that they slow down because of people with low speed. Although the ratio of tired people is not large, they influenced the pedestrian flow and led to bottleneck. It is found that the evacuees' speeds are low to 0.22 m/s in crush condition in WTC 9/11 (Galea et al. 2009).

In 2010, fifty-eight people died in the big fire in Shanghai. The fire building is an apartment with twenty-eight floors, and the fire floors were between 10th and 12th floor. Our team interviewed forty-two survivors (Yuan and Wen 2012), and it is found that more than half of them were over fifty years old at that time. Among these survivors, 47.6% of them said that they moved slowly during evacuation for two reasons: (1) some people were easy to get tired because of age and illness, and (2) several evacuees needed to move together with their families who walked slowly. Overall, fatigue factor influences the pedestrian flow during evacuation.

As mentioned above, people will slow down when they feel tired. The deceleration rates of evacuees' speeds over travel distances are shown in Table 1. The data are captured from several experiments which are focused on people's moving speeds (Denny 2008). The participants in the experiments are all in good physical conditions. If people are overweighed or disabled, the rate of speed decreasing will be larger. Issues of fatigue are complex since different people have different personal factors such as the state of health and fitness (Koo et al. 2013, 2014; Choi et al. 2014).

2.2 Stair simulation

Many simulation models are established for building safety design (Tavares 2009; Ronchi and Nilsson 2014). These

Table 1 Deceleration rates of evacuation speed over travel distances (Denny 2008)

Distance (m)	Ratio of current speed over original speed (%)
Up to 100	100.00
101 to 200	99.85
201 to 400	89.42
401 to 800	75.80
801 to 1500	69.82
1501 to 3000	65.72

models can be classified into two kinds (Pelechano and Malkawi 2008): macroscopic models and microscopic models. Macroscopic models are developed to simulate the evacuation process as a whole. However, interactions among evacuees and human behaviors are not well considered in such kind of models. To better characterize interactions among pedestrians, microscopic models are widely used. Among microscopic simulation models, social force models and cellular automata models are well accepted. Social force model (Helbing and Molnár 1995; Helbing et al. 2002) is a continuous model which is effective at simulating the evacuation process in a room or a corridor considering evacuees' psychological status, such as nervousness (Helbing et al. 2000), but it is not appropriate for simulating a large-scale evacuation because of time consuming when calculating complicate social force equations. Different from social force model, CA model is a kind of discrete model. Such kind of model divides the building space into a grid map (Wolfram 1983). Each agent evacuee moves on this map at a certain time interval. CA models (Yamamoto et al. 2007; Feng et al. 2013; Nguyen et al. 2013; Ding et al. 2015) are fit for both small-scale and large scale evacuation according to the discrete simulation space. As a result, stair simulation is based on CA model.

Wąs' group uses CA model (Wąs 2005) and Agent-based model (Wąs and Lubaś 2014) to simulate crowd dynamics in both normal and emergency conditions. They consider strategic as well as tactical and operational levels of the decision-making process. Their model can run large-scale simulation, such as a football stadium. Sirakoulis' group use CA model (Giitsidis and Sirakoulis 2014) to simulate the evacuation process in aircraft, and the effect of carrying baggage is considered in their simulation. Compared with existing aircraft evacuation simulation, the evacuation time of their simulation is more accurate to real experiments. In order to speed up the simulation process for real-time system, they use Field Programmable Gate Array (FPGA) device to run their simulation.

However, in most of existing CA simulation models, the stair structure and fatigue of evacuees are ignored (Pelechano and Malkawi 2008). In stairs, people need to change their directions frequently (turning behavior). To simulate turning behavior, a common idea is adding more parameters to the transition rule, such as add a "turning point" (Xu and Song 2009), and people will change their directions at this point. However, most of existing models cannot simulate human behaviors and pedestrian flow well on both treads and landings at the same time. Fatigue of evacuees will also influence the prediction of evacuation time based on simulation. The latest study (Koo et al. 2014) on the simulation considering fatigue factor shows how the people with low speeds influence other people with high speeds, and the mechanism of speeds changing is based on runners who are in good physical conditions (Denny 2008). As a result, more data about fatigue factor is needed.

3 The model

A new CA model for stair evacuation in high-rise buildings is established in this section. To improve the basic structure of the CA model, the simulation map between two floors is divided into zones based on the structure of stairs in Section 3.1. In Section 3.2, the rule of how evacuees move on each zone is appropriately defined. To reduce computational complexity, the concept of basic update rule is introduced in Section 3.3. In Section 3.4, the influence of fatigue will be modeled.

3.1 Grid map

CA model is a kind of discrete model where the simulation space is discrete. The simulation space is called grid map in CA models, and the grid map is composed by cells. In most of existing CA models, the cell is a fixed square, e.g., the cell size is 0.5 m × 0.5 m (Lord et al. 2005; Ma et al. 2012; Li et al. 2016) or 0.4 m ×0.4 m (Varas et al. 2007). However, these cell sizes are also used in the stair simulation where the stair structure (tread and landing) is ignored (Pelechano and Malkawi 2008). As a result, such models are not good at demonstrating the interaction among individuals.

In our simulation model, a new grid map is established to reflect stair structure including treads and landings. The cell sizes are defined according to two different parts: treads and landings. For the tread part, the cell size is the width of shoulder × the depth of tread since one pedestrian can only occupy one tread (Ding et al. 2013). Most of the depths of tread are among 0.27 m – 0.3 m, and it should be no less than 0.22 m referring to the China National Standard Design Code for Residential Buildings (MOHURD 1999). Landings are the connection of two tread parts, and the cell size of landings is the width of shoulder × the width of shoulder. As the joint cell size is the width of shoulder, the cells on the landings and steps can be connected. The structure of a stair and the six zones are shown in Fig. 1.

For evacuees in stairs, they may have different moving directions. To distinguish evacuees with directions, the whole stair between two floors is divided into six zones: zones a–f. As is shown in Fig. 2, movements of evacuees in these zones are also different based on their moving directions. Movements of evacuees are also influenced by their environment including: emergency situations and interactions among evacuees. Emergency situations, such as fire and smoke, will influence evacuees' behaviors during evacuation, and their desired speeds will increase. Evacuees

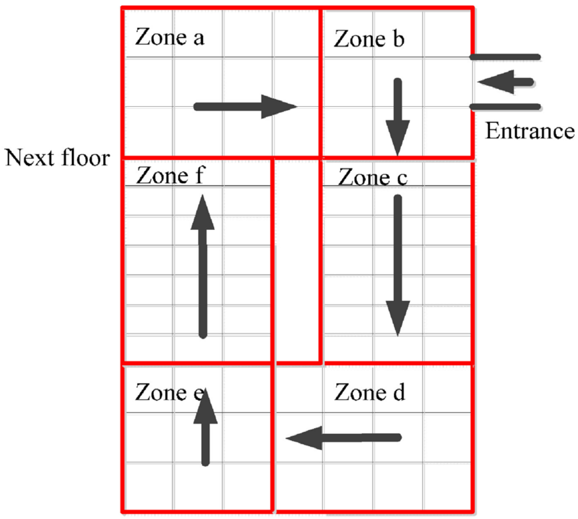


Fig. 1 Grid map and six zones

will also be influenced by their neighbors, which are defined as the cells around one target cell. The neighborhood in the new CA model is a typical Moore neighborhood (Pelechano and Malkawi 2008).

3.2 Movements of evacuees

To describe the movements of evacuees, transition rules are introduced into CA models. As mentioned in Section 3.1, moving directions of evacuees are different in zones a–f (shown in Fig. 2, index a–f of the figure is corresponding to zones a–f).

To measure the probabilities of the pedestrians' movement, a benefit matrix $\boldsymbol{B}$ is introduced with the elements b_{ij}, $i, j = -1, 0, 1$. The benefit value of moving forward equals 1. On the contrary, the benefit value of moving backward is -1. If one of the neighbor cells is occupied by others, the value of this cell is -1. When going downstairs, people want to go along the route with shortest distance. For example, in the stair shown in Fig. 1, evacuees intend to go along the inside of the stair. Parameter d, with $0 < d < 1$, is introduced to demonstrate this preference and is added into the benefit matrix. As most people intend to go along the shortest route in evacuation events, d equals 0.9 in this paper. As is shown in Fig. 3 (no other evacuees around the agent in the middle), the benefit value of each zone (a–f) is given according to evacuees' moving directions.

The probabilities of evacuees' movements are as follows:

$$b'_{ij} = \begin{cases} c & b_{ij} = 0 \\ 0 & b_{ij} < 0 \\ b_{ij} & b_{ij} > 0 \end{cases} \tag{1}$$

$$P_{ij} = \frac{b'_{ij}}{\sum\limits_{i,j=-1,0,1} b'_{ij}} \tag{2}$$

where b'_{ij} is the positive conversion value for benefit value b_{ij}, c is a positive and small enough number with $0 < c < 1$, and c can insure that if the forward directions are occupied by others, pedestrians can stay where he/she is; P_{ij} is the probability of the evacuee moving to the cell with position i and j, and (0, 0) is the position of the target cell which is shown in Fig. 4.

3.3 Variable speed

To address the issue of fatigue in the simulation, variable speeds are required. However, traditional CA models only have a unique speed level. The system should shorten the time interval, and evacuees can move during several intervals (Johnson 2005). However, it will increase computational

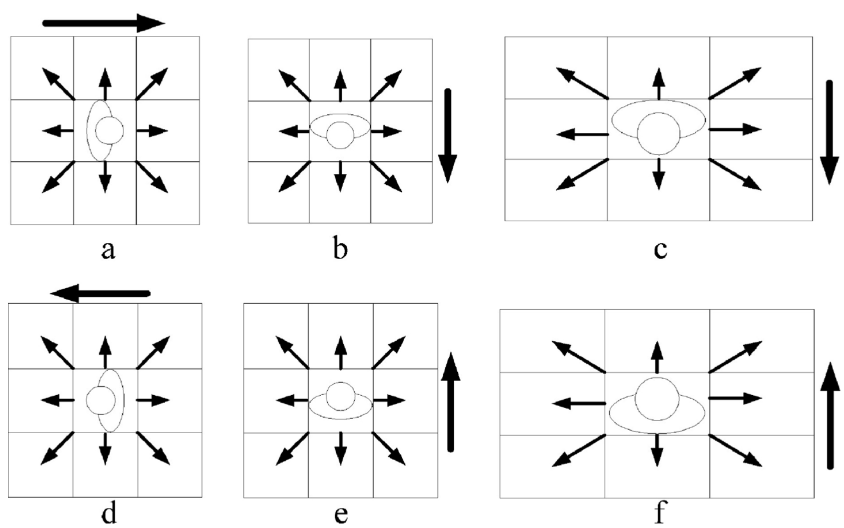


Fig. 2 Moving directions on each zone

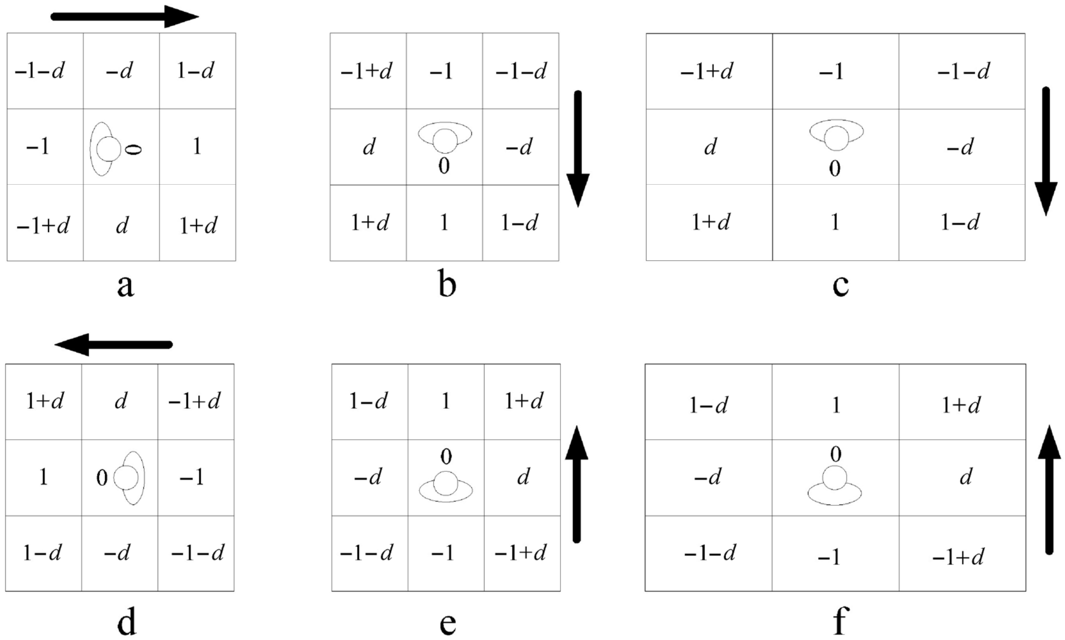


Fig. 3 Benefit matrix for each zone

$P_{1,-1}$	$P_{1,0}$	$P_{1,1}$
$P_{0,-1}$	$P_{0,0}$	$P_{0,1}$
$P_{-1,-1}$	$P_{-1,0}$	$P_{-1,1}$

Fig. 4 Positions of cells

complexity if all the evacuees update their positions at each interval. To solve this difficulty, the concept of basic update time is introduced, and an evacuee's movement is updated at an integer multiple of this basic update time instead of every system time step. An evacuee's integer multiple of basic update time can be changed according to his/her environment and fatigue which are shown in Fig. 5. In our simulation, evacuees' speeds should be input into the system, and then decides whether this evacuee will fatigue or not based on Section 3.4 below. A "fatigue" evacuee will slow down after travelling a certain distance, and other evacuees can keep their desired speeds during the whole evacuation process.

As is shown in Fig. 5, evacuees with different fatigue can update their positions. As mentioned above, the pedestrians' speeds are not unique in our CA model. The concept of basic update time is introduced into the simulation model, and an evacuee's movement is updated at an integer multiple of this basic update time instead of every system time step. Give evacuee i a update time UT_i based on Table 2 (for example, UT_i =5), if system time $t\%UT_i$==0 (t is divisible by UT_i), update i's position. The basic update time is 0.05 s, and the cell size is 0.5 m × 0.275 m on the tread (the length of the tread is assumed as 0.275 m), and then the speed is 0.55 m/s if the update interval is 0.5 s (ten multiple of basic update time). There are ten speed levels in the simulation, and 0.55 m/s is the speed level 4 which is shown in Table 2. If a pedestrian feel fatigue, the speed should decrease. In other words, the UT value should become larger, so the update duration is larger. The update sequence is from the lower floor to the higher floor in a building, and from forward to backward in a floor. In high-density situation, the update sequence is similar to the pedestrians' movement in stairs since people should follow the one in the front in congested stairwell.

3.4 Fatigue

Multiple floors of high-rise buildings create the cumulative effect of requiring evacuees to travel a long distance in stairs for evacuation. The physical demands made on evacuees often exceed their capabilities, and they will feel fatigue and slow down or even stop to take a rest. In an experiment (Ma et al. 2012), several participants go downstairs from floor 101 to the ground floor in normal conditions. It is found that the evacuees cost about 2000 s to move down about 460 m to the ground. These participants feel fatigue during evacuation and their legs ache slightly the day after the experiments. Whether evacuees feel fatigue depends on their Body Mass Index (BMI) and their health conditions (Spearpoint and MacLennan 2012). In our investigation to a high-rise apartment building

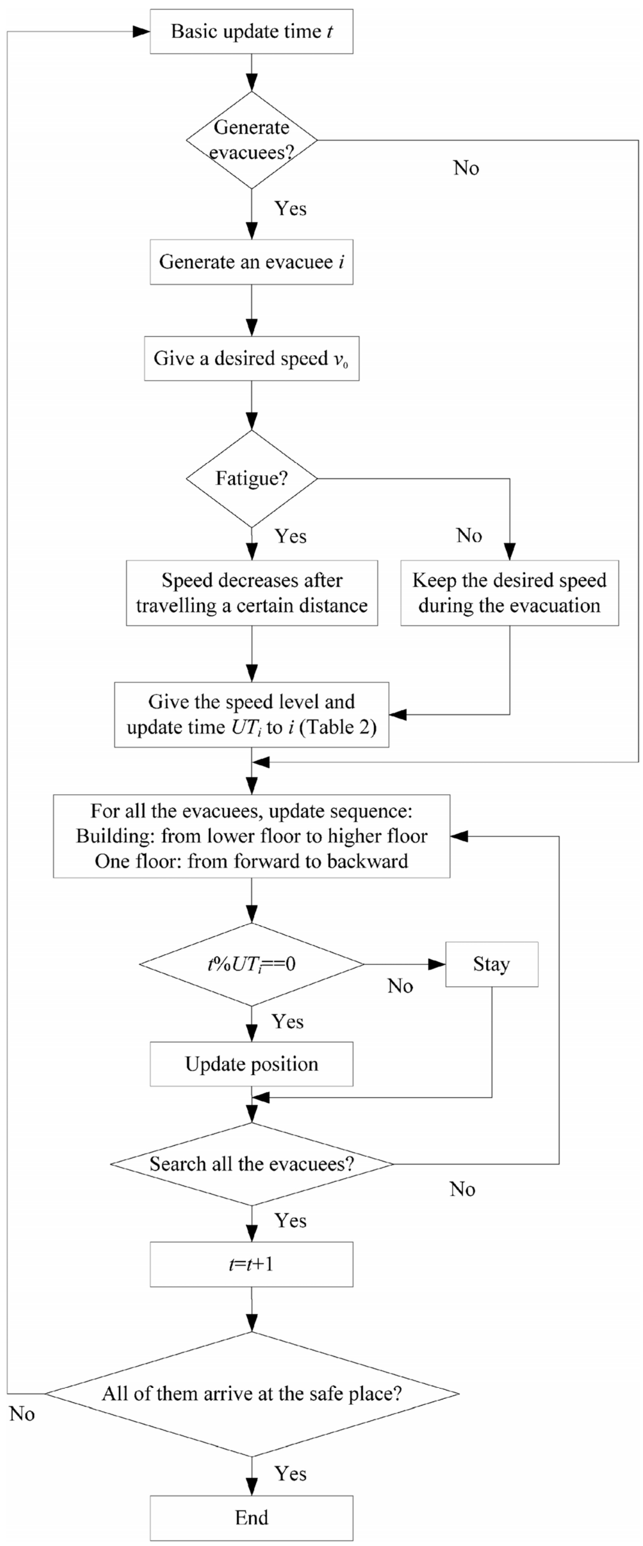


Fig. 5 Flowchart of the simulation

(15 floors) with the occupants who are all female Ph.D. student (which will be presented in Section 4), only 12.2% of the participants in a fire drill said they feel fatigue and slow down during evacuation. This ratio is similar to that of the data from a report of WTC 9/11 (20% of 124 survivors felt fatigue during evacuation) (Averill et al. 2005; Galea et al. 2009). It is noteworthy that these fatigue evacuees are all from the middle or high floors. In the model, evacuees may decrease their speeds or stop based on certain probabilities, and the people who stop because of fatigue will become “obstacles” to the pedestrian flow.

Table 2 Example of various speeds

Speed level	Update interval (s)	Speed (m/s)
1	1.00	0.28
2	0.70	0.39
3	0.60	0.46
4	0.55	0.50
5	0.50	0.55
6	0.45	0.61
7	0.40	0.69
8	0.35	0.79
9	0.30	0.92
10	0.25	1.10

To demonstrate the probability of decreasing speed, P_f is introduced. After travelling several floors, people start to feel fatigue. The longer they travel, the higher probability will be given to the evacuees to slow down at one speed level.

$$P_f = \begin{cases} 0 & x < N_{fd} \\ P_0 + (x - N_{fd})P_{plus} & N_{fd} \le x < N_{fs} \\ P_{max} & x \ge N_{fs} \end{cases} \tag{3}$$

where P_f is the probability of evacuees who feel fatigue, x is the number of floors where people locate, people start to feel fatigue after travel N_{fd} floors, P_0 is the basic probability when people get tired, P_{plus} is the cumulative probability when people travel more than N_{fd} floors, $N_{fs} = N_{fd} + (P_{max} - P_0)/P_{plus}$. Not all the evacuees feel fatigue during evacuation, so the maximum probability of decreasing speed is set to be P_{max} which is smaller than 1.

The mechanism of evacuees feel fatigue and reduce their speeds in the simulation are shown in Fig. 6. Based on the floor level of evacuees, the probability of fatigue can be given based on Eq. (3). According to the probability P_f, select the evacuees who will feel fatigue during their evacuation process. These selected evacuees will reduce their speed to a lower level (based on Table 2) during their travelling. It is worth to be mentioned that character N_{fd}, N_{fs}, P_{plus}, P_{max} and P_0 should be calibrated according to the situation of a building (The data in Table 1 are not from the evacuation in stairs). The experiment data in this paper (Section 4.1) cannot be used to all buildings in various countries, and more experiments are needed to calibrate there characters.

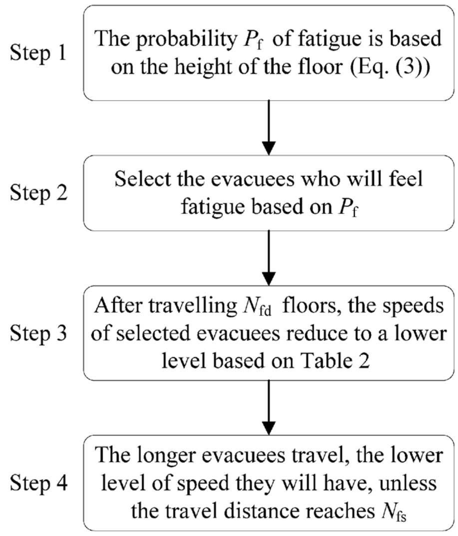


Fig. 6 Flowchart of fatigue in the simulation

It is reported in WTC 9/11 report that fatigue evacuees may stop and take a rest during evacuation. In order to simulate this behavior, a number of s is added to parameter c in Eq. (1) to increase the probability of stopping, and the new one is shown in Eq. (4). According to the WTC 9/11 report (Galea et al. 2009; Ma et al. 2012), the value s is 0.3–0.5.

$$b'_{ij} = \begin{cases} c+s & b_{ij}=0 \\ 0 & b_{ij}<0 \\ b_{ij} & b_{ij}>0 \end{cases} \tag{4}$$

4 Fire drill and model validation

To validate our simulation model, a fire drill was video recorded. The data of the fire drill will be shown in Section 4.1. Then a simulation is carried out according to the fire drill data based on our model. The total evacuation time and the evacuation times between two floors in the simulation are compared with those in the fire drill in Sections 4.2 and 4.3.

4.1 Fire drill

The fire drill was held in a high-rise building with harmless smoke, which makes the environment close to real events. The visibility is more than 10 m in stairs and more than 5 m in the lobby. This drill is an announced drill, but we only told the occupants that we would start the drill in the morning instead of a specific time. Participants were observed to slow down according to the video, and some of them stated that they feel tired based on the after-drill survey questionnaire. The fire drill was held in a high-rise apartment building with fifteen floors (the lobby is on floor zero, and it is the highest building in the campus with 42 m in height) in Tsinghua University, and the residents are all female Ph.D. students. There are fifteen floors and three stairs in the building, and the building layout is shown in Fig. 7. We recorded the right stair exit at the bottom by videos. Harmless smoke was released on the fourth floor and in the lobby (floor 0) to simulate real fire scenario.

When the smoke in the stair was generated, nearly every evacuee covered a towel on her nose. Videos were set on the first floor, the third floor, the fifth floor, the seventh floor, the ninth floor, the eleventh floor, the thirteenth floor and in the lobby, because we did not have enough equipment to record all the floors and all the staircases. The structure of stairs and the position of the video on each floor are shown in Fig. 8.

In this drill, totally sixty-three students used the stair with video record. The results are shown in Table 3, and the time when the first student appeared in the stair is set to be 0 s, and the total evacuation time is 477 s. Floor

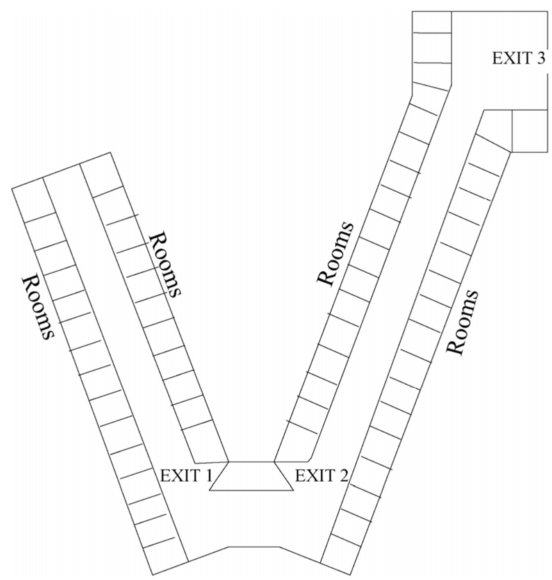


Fig. 7 Positions of exits on each floor

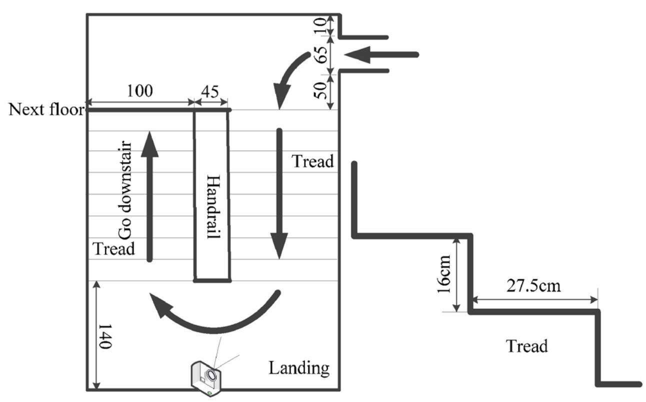


Fig. 8 Structure of staircase, size of tread, and the position of video (the unit of the numbers is centimeter)

Table 3 Fire drill data

Floor	Number of students	Floor evacuation time range (s)	Evacuate time range (s)
13	15	125–311	235–477
11	7	164–298	269–365
9	7	134–289	224–382
7	8	140–224	192–292
5	16	86–340	137–404
3	10	0–330	22–361

evacuation time can be defined as the time when a pedestrian showed in the stairwell and vertical evacuation gets started. In this evacuation, only a few evacuees started to evacuate before 125 s because they knew there would be a drill and went out early in case of congestion. The maximum and minimum average speeds among these participants are 1.03 m/s and 0.44 m/s (horizontal speed), respectively. To the people who travelled more than ten floors (including ten floors, the slope distance of ten floors is about 100 m), it is found that the average speed of evacuees reduced (from 0.73 m/s to 0.62 m/s) when they travel to lower floors.

In this fire drill, several phenomena reported in other studies (Fruin 1971; Proulx 1995; Helbing et al. 2000; Peacock et al. 2010, 2012) are also observed. One phenomenon is that the speeds of some students were faster than others, and they will overtake others to finish evacuation as soon as possible. Another one is that most of the students took the inner side route of the stair as the shortcut when they are going downstairs.

4.2 Total evacuation time

To validate the simulation, all the parameters are setup based on the fire drill, such as the number of students on each floor, their speeds, and their floor evacuation times are the same to those in the fire drill. As the students wore thick clothes in winter, the width of the shoulder is 0.5 m. Then the cell size on tread is 0.5 m × 0.275 m and the cell size of landing is 0.5 m × 0.5 m. The width of exit and handrail are set to be the width of one cell as 0.5 m. As mentioned in Section 3, parameter d equals 1 because evacuees incline to go along the shortest route in stairs. Parameter c is a positive small number, so let c = 0.001. After travel N_{fd} floor, evacuees start to get tired, and N_{fd} = 10, F_{max} = 0.9, the probability P_{plus} = 0.02 and s = 0.3 according to the survey in Section 3. Two kinds of simulation are run: all the evacuees have the same speed (average horizontal speed 0.71 m/s, and the average vertical speed is 0.26 m/s in the fire drill) without fatigue (simulation 1 for short) and the evacuees have variable speeds (agents from different floors will have different speeds according to the speeds of evacuees in the fire drill) considering fatigue (simulation 2 for short). In simulation 2, evacuees may change their speeds because of fatigue.

Both of simulation 1 and simulation 2 are run based on Matlab 7.8.0 on an Intel Core i3 + 2.3 GHz Windows PC with 2 GB RAM. There are uncertainties in our simulations, and we run each simulation many times to get the average value of evacuation time. To decrease the impact of uncertainties, functional analysis is used based on Euclidean Relative Difference (ERD) (Ronchi and Nilsson 2014). As the total evacuation time (TET) is the most important result in our simulation, we compare the results of TET based on ERD. If the simulation is run for n times, the average value of TET (Ronchi and Nilsson 2014) is

$$\mathrm{TET}_{\mathrm{avn}} = \frac{1}{n}\sum_{i=1}^{n}\mathrm{TET}_i \tag{5}$$

where i is the i-th run. The convergence of two consecutive mean is

$$\mathrm{TET}_{\mathrm{convn}} = \left|\frac{\mathrm{TET}_{\mathrm{avn}} - \mathrm{TET}_{\mathrm{avn}-1}}{\mathrm{TET}_{\mathrm{avn}}}\right| \tag{6}$$

where $\mathrm{TET}_{\mathrm{avn}-1}$ is the average TET of $n-1$ runs. In (Peacock et al. 2010), the $\mathrm{TET}_{\mathrm{convn}}$ should be smaller than a constant (usually around 1%). In our paper, the average TET is 477 s, and the difference of different simulations of the same scenarios is around 10 s. It is very easy that the $\mathrm{TET}_{\mathrm{convn}}$ is smaller than 1%. In this paper, we use 0.001% as our criterion. The results show that the $\mathrm{TET}_{\mathrm{convn}}$ is 0.00067% at the 35th time. Then we choose fifty runs as our simulation times. The average CPU time is 5.48 s (simulation 1) and 5.61 s (simulation 2). We also test the CPU time without considering the concept of basic update time mentioned in Section 3, and the CPU time is 9.35 s (simulation 1) and 9.68 s (simulation 2). Take simulation 2 for example, the CPU time can be reduced by 42% when considering basic update time. Then we use IBM SPSS Statistics 19 to analyze the simulation data.

The evacuation times of the fire drill data and the simulation results are shown in Fig. 9. The evacuation time

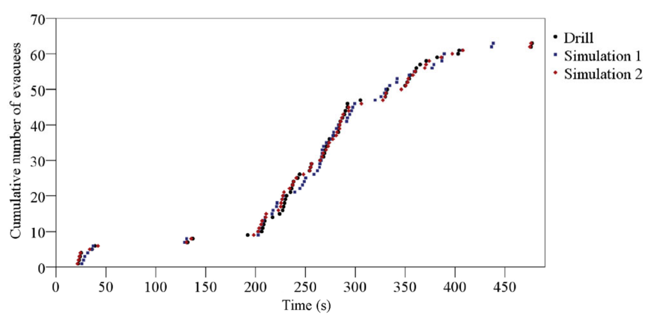
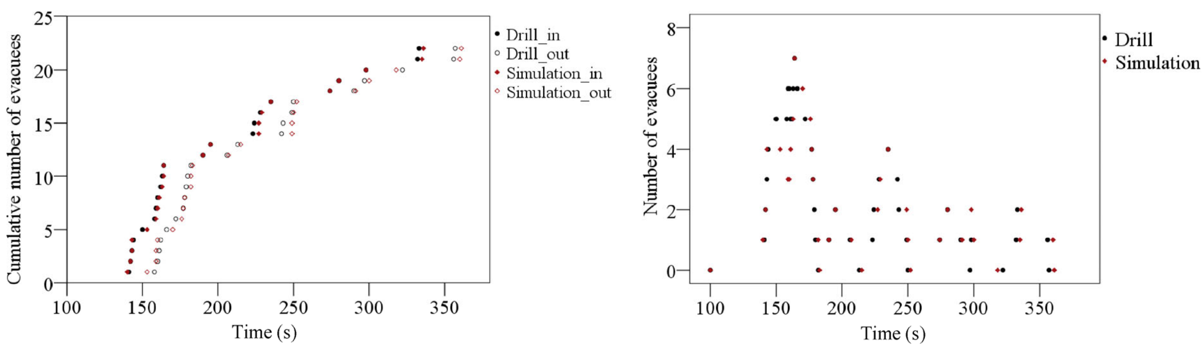


Fig. 9 Evacuation time of both fire drill and simulation

of the fire drill is 477 s, and the result of simulation 1 is 438 s, which is 39 s smaller than the fire drill data. It is believed that if the building has more floors, the difference between the fire drill and the simulation without considering fatigue of evacuees will be larger. The evacuation time of the simulation 2 is 476 s, which is only 1 s smaller than the evacuation time in the fire drill. After the comparison, we find that simulation 2 is better than simulation 1. To further validate simulation 2 (the new simulation in this paper), evacuation time on each floor will be compared in the next subsection.

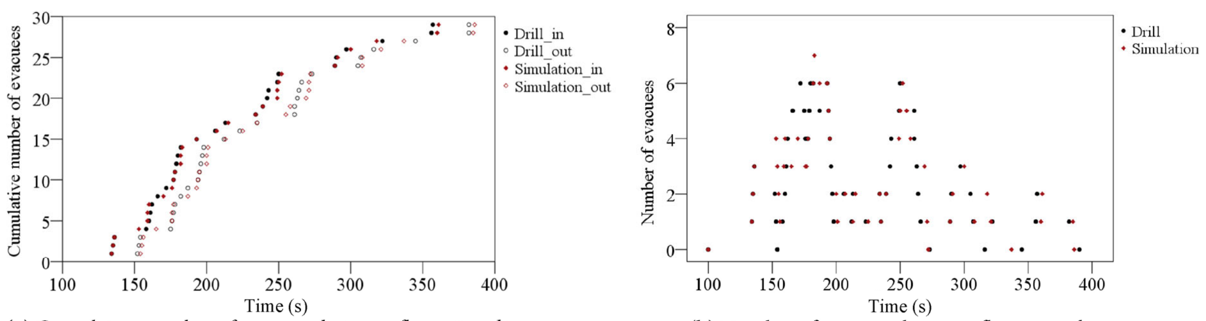
4.3 Evacuation time between two floors

To further validate the simulation model, the evacuation time between two floors of simulation 2 is compared with that in the fire drill. Different from the total evacuation time in Section 4.2, the evacuation times on certain floors have two parts including the time when evacuees enter in and evacuate out. "In" means the time of a pedestrian enters in a certain floor range, and "out" means the time of a pedestrian leaves a certain floor range. For example, floor range is 7–5, in and out means a pedestrian enter in 7th floor and leave 5th floor. The data of floors between 11 and 9 (Fig. 10), 9 and 7 (Fig. 11), 7 and 5 (Fig. 12), 5 and 3 (Fig. 13) are compared. Evacuees in a floor range containing all the evacuees pass through these floors. Floors 5 to 3 containing all the evacuees from 5th floor or higher floors (11, 9, 7). To validate the simulation in detail, the number of evacuees between two floors is also compared.



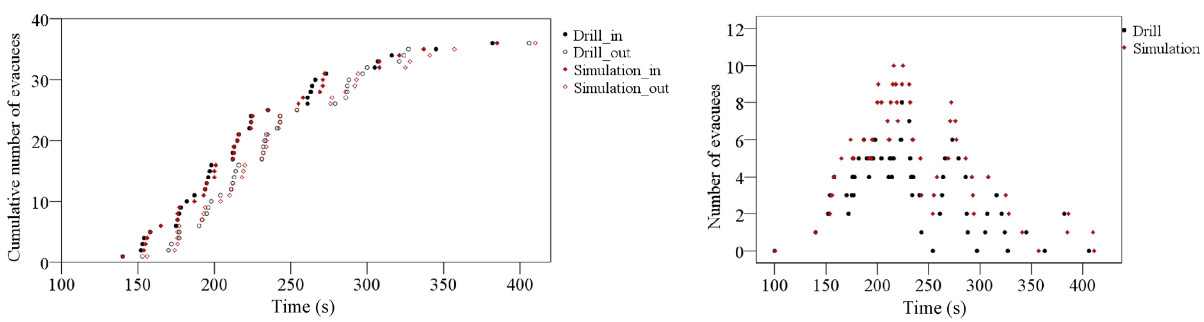
(a) Cumulative number of evacuees between floors 11 and 9 (b) Number of evacuees between floors 11 and 9

Fig. 10 Drill and simulation data between floors 11 and 9



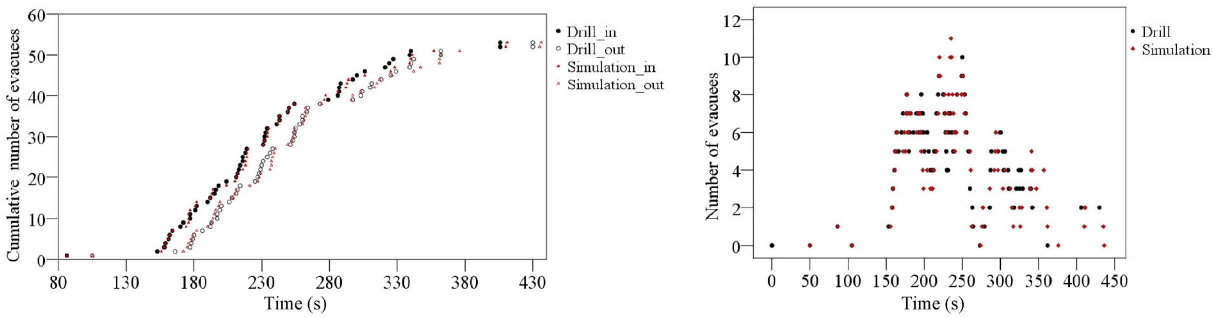
(a) Cumulative number of evacuees between floors 9 and 7 (b) Number of evacuees between floors 9 and 7

Fig. 11 Drill and simulation data between floors 9 and 7



(a) Cumulative number of evacuees between floors 7 and 5 (b) Number of evacuees between floors 7 and 5

Fig. 12 Drill and simulation data between floors 7 and 5



(a) Cumulative number of evacuees between floors 5 and 3 (b) Number of evacuees between floors 5 and 3

Fig. 13 Drill and simulation data between floors 5 and 3

As are shown in Figs. 9–12, the evacuation times in simulation of both in and out are similar to that in the drill. When evacuees travel a long distance, the uncertainties will become larger. The evacuation times of both drill and simulation are shown in Table 4, and the differences between evacuation time in the drill and evacuation time in simulation 2 are small.

As there are uncertainties, such as evacuees' speeds, happened in our drill, the evacuation times of different drills are not the same. To use our simulation effectively, the emergency scenario information, such as evacuees' speeds, floor evacuation time, etc., should be used to calibrate the parameters in the simulation. Although we use a fire drill to validate our simulation, the model is partial validated.

5 Simulation

Several cases are carried out in this section. Case 1 shows that the model can demonstrate certain human behaviors and phenomena observed in both of stair evacuations and drills. To study the effective width of a stair, case 2 is carried out. Case 3 shows how the simulation can help building designer improve emergency guidance plans. These cases were also run based on Matlab 7.8.0 on an Intel Core i3 + 2.3 GHz Windows PC with 2 GB RAM. The case contains three sub-cases to demonstrate evacuee's trajectory on the landing, overtake phenomenon, and how evacuees with low speed affect pedestrian flow.

Case 1 Trajectory on the landing
In this case, the simulation happens in a building with only two floors, and there is only one evacuee from floor 2. We run the simulation several times, and most of the evacuees' trajectories are the same. As is shown in Fig. 14, the trajectory of most evacuees in our simulation is reasonable. As mentioned above, the movement of evacuees is based on probability, so not all trajectories are the same as Fig. 14.

Table 4 Evacuation time of drill and simulation on each floor

Floor	Evacuation time (s)	
	Drill	Simulation
11 to 9	357	361
9 to 7	382	386
7 to 5	406	410
5 to 3	430	436

Case 2 Overtake
Overtake, which is one of the most important behaviors in stair evacuation and was also observed in the fire drill presented in Section 4.1, can be demonstrated in our simulation. In this case, a building with five floors (floors 1 to 5) is tested. There are two evacuees with high speed on floor 5 and one evacuee with low speed on floor 4, and their speeds and evacuation times are shown in Table 5. The overtake behavior occurs between floors 2 and 3, with evacuees from the higher floor arrived at the lobby early. This demonstrates that the simulation can better capture the interactions among evacuees.

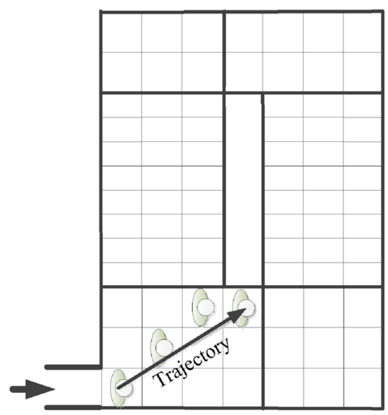


Fig. 14 Evacuee's trajectory on the landing

Table 5 Evacuees' speed and evacuation time of case 2

Floor	Evacuee's No.	Speed (m/s)	Evacuation time (s)
4	1	0.56	35
5	2	1.1	24
	3	1.1	26

Case 3 People with low speed

It is reported in WTC 9/11 (Galea et al. 2009) that evacuation flows are affected by evacuees with low speeds, and some survivors claimed that they had to slow down to wait for slow people in front of them. To demonstrate this, a building with four floors (floors 1 to 4) is simulated, and two sub-cases are considered. A snapshot is shown in Fig. 15. In case 3.1, evacuees are all at the same speed of 1.1 m/s. In case 3.2, 80% of the evacuees are at the speed of 1.1 m/s, and others are at the low speed of 0.56 m/s. There are thirty evacuees on each floor, and the entering interval between two evacuees is 1 s. Cumulative numbers of evacuees of two sub-cases are shown in Fig. 16, and the total evacuation time of case 3.1 is 58 s, which is 12 s smaller than 70 s in case 3.2. In a building with only 4 floors, the low speed pedestrians can decrease the total evacuation time by 20%.

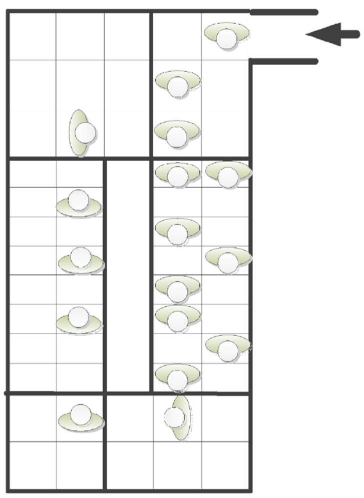


Fig. 15 A snapshot of the simulation

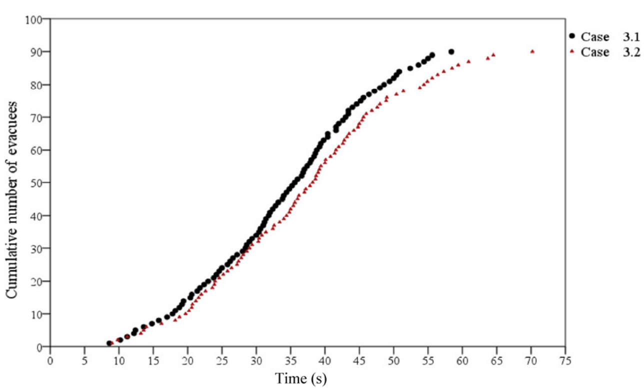


Fig. 16 Cumulative evacuees of case 3.1 and case 3.2

6 Conclusions

This paper improves the stair evacuation simulation problem in high-rise buildings considering fatigue of evacuees, and three aspects of work are involved: simulation modeling, simulation validation, and case study. Fatigue factor is investigated based on the data analysis on the real evacuation events (such as WTC 9/11), fire drills, and after-drill questionnaire. A new CA simulation model is developed, and the basic structure is improved. A key concept of basic update time is introduced in the model to reduce the computer complexity. After the validation, it is found that the simulation results and the drills data have no significant difference. Finally, the simulation is used to improve the emergency guidance plan in a high-rise building.

In order to evaluate and improve our existing work, evacuation guidance should be studied based on the new simulation in the future.

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