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Simulation of pedestrian evacuation in stampedes based on a cellular automaton model

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ABSTRACT

Human stampedes have been identified as a major hazard that could occur during pedestrian evacuations around the world. This paper establishes an extended floor field model to study the pedestrian evacuation dynamics during stampedes. The event floor field and a tumble factor are elaborated to describe the influence of stampedes. Different evacuation strategies are proposed to represent the behavioral differences in pedestrians: staying away from the stampede location (S1), following the movement direction of the majority within the perception range (S2), and walking along a wall (S3). We perform numerical simulations to discuss pedestrian evacuation in stampedes. The effects of the pedestrian density, event floor field, stampede location, evacuation strategy, stampede occurrence time and chaos duration on the evacuation efficiency and the number of casualties are analyzed in detail. Our results can provide reference and guidance for developing evacuation strategies for stampedes and reducing casualties.

1. Introduction

Numerous stampede events that have led to casualties during pedestrian evacuation are reported each year and have received worldwide attention from both scientific research and planning perspectives. Generally, stampedes occur during religious festivals, political demonstrations, sporting events, concerts, or other unplanned events. According to reports, a total of 215 human stampedes occurred from 1980 to 2007, resulting in 7069 deaths and at least 14,078 injuries [1]. In 2010, the stampede that occurred at Ram Janki Temple on March 4 killed 63 people [2], and the severe crowd disaster that occurred during Love Parade on July 24 caused more than 500 casualties [3]. The frequent occurrence of stampedes not only directly endangers the lives of people but also leads to substantial economic losses. Hence, determining how to reduce casualties during stampedes has become an important issue that has attracted considerable attention.

To explore the pedestrian evacuation dynamics in stampedes, researchers have conducted in-depth investigations and analyses [4–7]. Helbing et al. [8] presented a high-performance video analysis of the crowd disaster that occurred during Muslim pilgrimage in Mina/Makkah and noted that the subsequent transition to turbulent flow led to falling and trampling of people. Illiya et al. [9] reviewed stampede data from religious festivals over the past five decades in India to structure an effective risk reduction framework for events. We theorize that the fatal consequences of stampedes can be classified into two types according to the above literature: pedestrians are trampled to death, and pedestrians die of asphyxiation [3,4]. Our paper proposes a simplified pedestrian evacuation model to simulate the first type of casualty.

Various models have been applied to simulate pedestrian evacuation in recent years. The most common models are the lattice gas

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model [10–13], social force model [14–18], cellular automata model [19–27] and agent-based model [28–31]. The cellular automata model is a discrete model based on updating rules that has been widely used in the simulation of pedestrian flows due to its simple and efficient computations. Many researchers have used the floor field cellular automaton (FFCA) model to calculate the pedestrian transition probability [32–35]. Compared with other microscopic models, the FFCA model has advantages in its flexibility, extendibility, and relatively low computational cost by transforming long-range interactions into local interactions; additionally, its feasibility to implement provides efficient simulations of large crowd scenarios. Specifically, the model can reproduce some typical evacuation phenomena, such as jamming, clogging, herding, and lane formation [36–38].

Generally, evacuation cases can be divided into two types: normal evacuation and emergency evacuation. In normal evacuation, people leave a public location in a certain order, and no casualties occur. Varas et al. [39] simulated the process of pedestrian evacuation from a room with obstacles and considered the exit types of a single door and double doors. Tang et al. [40–43] modeled and simulated pedestrian flows in university cafeterias and school classrooms, and evacuation strategies were discussed based on the simulation results. Zhou et al. [44] introduced a multithreading mechanism into the simulation updating rules to consider different speeds and fields of view of pedestrians in an evacuation space.

Emergency evacuation studies consider the injuries or fatalities caused by fires, earthquakes, floods or other external hazard events. For example, Yuan and Tan [45] considered that the smoke concentration produced by a fire is not constant, and the vision range of pedestrians changes over time due to the influence of smoke. Wang et al. [46] proposed a new agent-based model that accounted for panic to simulate the emergency evacuation of pedestrians in public places. Zheng et al. [47,48] established an extended floor field model to study pedestrian evacuation behavior under the influence of fire and smoke diffusion while dividing pedestrian movement behavior into three stages. Lu et al. [49] described the group behavior of pedestrians in the process of emergency evacuation and formulated movement rules for leaders and followers. Zheng et al. [50] proposed a modified FFCA model considering the flood spreading process and discussed the pedestrian evacuation dynamics in underground flood situations.

However, previous works seldom introduced stampedes during the pedestrian evacuation process, merely treating fallen pedestrians as normal pedestrians or ordinary obstacles. In fact, the evacuation patterns of normal evacuees will be disrupted due to avoiding injured or dead pedestrians [9,51]. When pedestrians are influenced by a stampede, they lose concern for their surroundings and respond irrationally for self-protection. Thus, evacuees have a certain probability of being tripped and getting hurt or dying during the evacuation process [4]. According to these characteristics of pedestrian psychology and behavior, we simulate pedestrian evacuation in a stampede using an extended FFCA model and combine this approach with a multiagent system method to define different evacuation strategies for pedestrians.

The remainder of this paper is organized as follows. Section 2 introduces the improved FFCA model and pedestrian evacuation strategies. Section 3 analyzes the simulation results. Finally, the conclusions are presented in Section 4.

2. Model

2.1. Model assumptions

A stampede during pedestrian evacuation process is complex for the following reasons: (1) a stampede is sudden and uncontrollable [15], and the fall of the first pedestrian will quickly affect the evacuation behavior of the surrounding pedestrians. A stampede can be controlled after a short period of time [52]. (2) Our simulation experiments and previous studies indicated that the number, time and location of the initial fallen pedestrians influence the severity of the stampede [53]. (3) The occurrence of the first fallen pedestrian is extremely complicated and can be caused by a combination of factors [54]. (4) Pedestrians will pile up when they are tripped [52]. Therefore, to establish a practical model that is as close to reality as possible, a few assumptions are made as follows:

- This paper proposes the chaos duration of a stampede for realistic simulation;
- We artificially set the time and location of the initial fallen pedestrian, which reflects the occurrence of a stampede;
- We assume that there is a probability that fallen pedestrians will get up again [3];
- Normally, a new fallen pedestrian occupies two cells. In this paper, we assume that one is his/her original cell and one is the cell of a fallen pedestrian who tripped him/her because his/her target cell is occupied by that fallen pedestrian; and
- We consider only casualties caused by tripping over existing fallen pedestrians and not other factors.

2.2. Model description

In this paper, we distinguish fallen pedestrians from normal pedestrians or obstacles. When a normal pedestrian chooses a cell occupied by a fallen pedestrian as the target cell to move, he/she will trip over this fallen pedestrian, thus creating a new fallen pedestrian who occupies two cells (mentioned in Section 2.1). Hence, the area of fallen pedestrians increases over time [8,55].

Based on the analysis above, we improve the FFCA model, and the Moore neighborhood is adopted, as shown in Fig. 1. The event floor field F_{ij} is introduced to reflect stampede avoidance behavior for some pedestrians. A tumble factor α_{ij} is defined to indicate whether a cell is occupied by a fallen pedestrian. The pedestrian moves to a neighboring cell according to the transition probability p_{ij}, which is calculated by the following equations:

$$p_{ij} = NI_{ine}\cdot\exp(k_S S_{ij} + k_D D_{ij} + k_F F_{ij})\cdot(1 - n_{ij})\xi_{ij}\alpha_{ij} \tag{1}$$

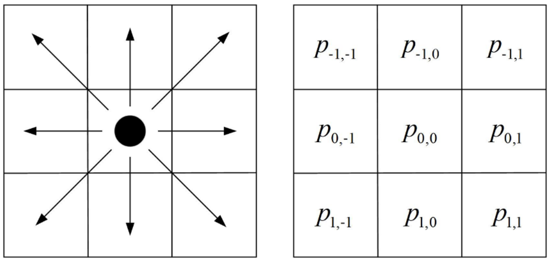

Fig. 1. Moore neighborhood.

$$N = \sum p_{ij}^{-1} \tag{2}$$

$$n_{ij} = \begin{cases} 1, & \text{the cell } (i, j) \text{ is occupied by a normal pedestrain} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

$$\xi_{ij} = \begin{cases} 0, & \text{the cell } (i, j) \text{ is occupied by a wall or obstacle} \\ 1, & \text{otherwise} \end{cases} \tag{4}$$

where S_{ij}, D_{ij}, and F_{ij} represent the static, dynamic and event floor fields, respectively. k_S, k_D, and k_F are the sensitivity parameters. N is a normalization factor to ensure that $\sum p_{ij} = 1$. I_{ine} is an inertial parameter: $I_{ine} = 1.2$ when the direction is the same as the movement direction at the previous time step; otherwise, $I_{ine} = 1$. n_{ij} is a parameter used to indicate whether a cell is occupied by a normal pedestrian. ξ_{ij} is a parameter that indicates whether a cell is occupied by a wall or obstacle.

The static floor field S_{ij} describes the pedestrian behavior of finding the shortest path to the exit during the evacuation process. Since the remaining normal evacuating pedestrians regard fallen pedestrians as obstacles after the chaos duration, the calculation steps of $S_{ij}$are as follows according to the previous study of Varas et al. [39]:

The exit cells are assigned a value of "1″, and a large number is assigned to cells occupied by obstacles, fallen pedestrians (after the chaos duration), and walls to indicate that pedestrians will not choose to move to these cells; a value of "500″ is assigned in this paper.

All cells assigned at the previous time step are identified, and the adjacent cells are assigned according to the following rules: if the cell has value "n", then the adjacent cells in the vertical or horizontal directions are assigned a value "$n + 1$" and adjacent cells in the diagonal directions are assigned a value "$n + \mu$". $\mu > 1$ indicates that the distance between the cell and the diagonal cells is slightly larger than the distance between the cell and the horizontal or vertical cells. In this paper, $\mu = 1.5$.

If there are conflicts in the assignment of a value to a cell, the minimum value is taken as the final value.

Repeat steps (2) and (3) until all cells are evaluated.

S_{ij}^0 denotes the assigned value of cell (i, j). Assuming Γ represents the set of cells that are not occupied by obstacles, fallen pedestrians (after the chaos duration) or walls, the final value of the static floor field is calculated as follows:

$$S_{ij} = \max_{(i,j)\in\Gamma} (S_{ij}^0) - S_{ij}^0 \tag{5}$$

The dynamic floor field D_{ij} represents the interactions among pedestrians in the evacuation process, which involves diffusion and decay dynamics and is represented by the diffusion probability α and the decay probability δ. At the initial time step, the dynamic floor field of all cells is 0. Whenever someone passes through cell (i, j), $D_{ij} = D_{ij} + 1$. The dynamic floor field diffuses or decays over time and is calculated as follows:

$$\begin{aligned} D_{ij}^t &= (1-\alpha)(1-\beta)D_{ij}^{t-1} + \tfrac{\alpha(1-\beta)}{8}(D_{i-1,j-1}^{t-1} + D_{i-1,j}^{t-1} + D_{i-1,j+1}^{t-1} \\ &+ D_{i,j-1}^{t-1} + D_{i,j+1}^{t-1} + D_{i+1,j-1}^{t-1} + D_{i+1,j}^{t-1} + D_{i+1,j+1}^{t-1}) \end{aligned} \tag{6}$$

The event floor field F_{ij} reflects that some pedestrians intend to escape from the stampede location when they are affected by the stampede. The field is related to the distance between the cell and the stampede, and the corresponding formula is as follows:

$$F_{ij} = \begin{cases} -\exp(1/d_{ij}), \ d_{ij} \le d_0 \\ 0, \ d_{ij} > d_0 \end{cases} \tag{7}$$

$$d_{ij} = \min_{(k',l')\in\Omega} \left(\sqrt{(i-k')^2 + (j-l')^2}\right) \tag{8}$$

where Ω represents the set of grid coordinates of all fallen pedestrians, d_{ij} represents the shortest distance from cell (i, j) to the stampede, and (k', l') represents the positions of fallen pedestrians. $d_0$is the influence scope of the stampede, set as 8 cells around a fallen pedestrian in this paper [47].

The tumble factor α_{ij} is related to the risk floor field A_{ij} and the surrounding pedestrian density ρ_0 of the center cell [4][5]. A_{ij}depicts that the pedestrian movement direction affects the risk of being tripped.$\rho_0$reflects the congestion degree around the center

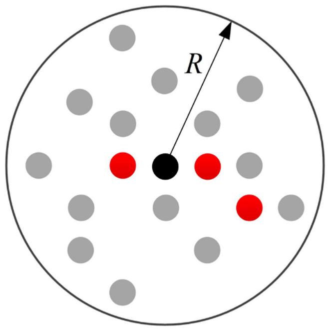

Fig. 2. Perception range of a pedestrian. Here, black represents the central pedestrian, red represents fallen pedestrians, and gray represents normal pedestrians.

cell. $\alpha_{ij}$is calculated as follows:

$$\alpha_{ij} = \begin{cases} k_c \varepsilon \rho_0 \cdot \exp(k_A A_{ij}), & \text{the cell } (i, j) \text{ is occupied by a fallen pedestrian} \\ 1, \text{ otherwise} \end{cases} \tag{9}$$

$$\rho_0 = \frac{\sum_{(x', y') \in U_0} f(x', y')}{|U_0|} \tag{10}$$

$$f(x', y') = \begin{cases} 1, \text{ the cell } (x', y') \text{ is not empty} \\ 0, \text{ otherwise} \end{cases} \tag{11}$$

$$A_{ij} = \cos\theta - 1, \theta \in [0, 180°] \tag{12}$$

where U_0 is the grid coordinate set of cells within the perception range of the center cell. k_c and k_A are the sensitivity parameters. The perception range of a pedestrian is a circular area centered on himself/herself with a radius of R, as shown in Fig. 2. The critical density for trampling is 4 ped/m^2 in this paper according to the value used in a previous study [53]. If the density is less than four persons per 1 m^2 ($\rho_0 < 0.64$ according to the simulation settings in Section 3), $\varepsilon = 0$; otherwise, $\varepsilon = 1.\theta$ is the angle between the movement direction $\mathbf{e}_0$ in the previous time step of the central pedestrian and the normal vector$\mathbf{n}_0$ point from the center cell to cell (i, j), as shown in Fig. 3.

2.3. Evacuation strategy

In the model, pedestrians can be regarded as agents who are able to take different actions according to their own traits and the nearby environment, especially when a stampede occurs. They will make movement decisions according to the transition probability and evacuation strategy.

When unaffected pedestrians are first within the influence range of the stampede, they will transform to affected pedestrians until the chaos duration is over. In this paper, the occurrence time of the stampede and the chaos duration of the stampede are set as T_s and T_c, respectively. Based on videos and photos of stampede events (as shown in Fig. 4), as well as analyses in the literature [3,45,56–58], pedestrians apply dissimilar evacuation strategies during stampedes because they have distinct physical and psychological characteristics. Hence, we propose three different evacuation strategies: S1, S2, and S3:

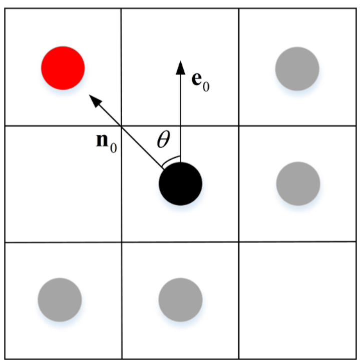

Fig. 3. The angle θ. Here, black represents the central pedestrian, red represents a fallen pedestrian, and gray represents normal pedestrians.

Fig. 4. Illustration of human behaviors during stampedes: (a) A stampede in China; (b) A stampede in India; (c) A stampede in Iraq.

(1) Strategy S1: Pedestrian attempts to stay away from the stampede location. The transition probability is calculated based on Eq. (1).
(2) Strategy S2: Pedestrian loses reasonable judgment of the ideal evacuation path and chooses to follow the movement direction of neighbors, and his/her movement direction $\mathbf{e}_{S2}$is determined as:

$$\mathbf{e}_{S2} = \mathbf{e}_{\max} \tag{13}$$

where $\mathbf{e}_{\max}$ indicates the movement direction of most pedestrians within the perception range of this affected pedestrian.

(1) Strategy S3: Pedestrian preserves the movement direction of the last time step until he/she reaches a wall and then evacuates along the wall clockwise or anticlockwise. Thus, a pedestrian choosing strategy S3 has the desired movement direction in his/her own mind. His/her movement direction $\mathbf{e}_{S3}$ is determined as:

$$\mathbf{e}_{S3} = \mathbf{e}_{\text{desired}} \tag{14}$$

where $\mathbf{e}_{\text{desired}}$ indicates the desired movement direction of this affected pedestrian. Moreover, when a pedestrian stays in the same cell for over 5 time steps, he/she will change the desired direction randomly.

2.4. Pedestrian movement behavior

During the entire evacuation process, a pedestrian state can transform in the range of set $S = \{U_e, U_n, A_e, A_n, C\}$, where

U_e: an unaffected pedestrian who can perceive the exit;
U_n: an unaffected pedestrian who cannot perceive the exit;
A_e: an affected pedestrian who can perceive the exit;
A_n: an affected pedestrian who cannot perceive the exit; and
C: a fallen pedestrian.

There are three situations in which pedestrians are in state U_e or U_n: 1) The stampede has not yet occurred, 2) The chaos duration of the stampede is over, or 3) Pedestrians have not been affected by the stampede. It should be noted that evacuees regard fallen pedestrians as normal obstacles, and they will not become injured in these situations.

We give a detailed description of the distinct movement behavior in these states as follows.

- Pedestrians in state U_e are in the vicinity of the exit and can perceive the exit. Therefore, they ignore the influence of other factors and evacuate through the exit as soon as possible. In this case, the pedestrian transition probability is calculated as follows:

$$p_{ij} = NI_{ine}\cdot\exp(k_S S_{ij})\cdot(1 - n_{ij})\xi_{ij} \tag{15}$$

- Pedestrians in state U_n have an approximate view of the environment and evacuate toward the exit; their transition probability is calculated as follows:

$$p_{ij} = NI_{ine}\cdot\exp(k_S S_{ij} + k_D D_{ij})\cdot(1 - n_{ij})\xi_{ij} \tag{16}$$

- Pedestrians in state A_e intend to leave the room as quickly as possible but still have the possibility of being tripped. The transition probability in this case is calculated as follows:

$$p_{ij} = NI_{ine}\cdot\exp(k_S S_{ij})\cdot(1 - n_{ij})\xi_{ij}\alpha_{ij} \tag{17}$$

- For the pedestrians in state A_n, the three strategies mentioned in Section 2.3 will be implemented. Note that affected pedestrians who choose strategy S3 will move along a wall until they leave the room, and other pedestrians can return to normal after the chaos duration $T_c$is over.
- For the pedestrians in state C, if they are not pinned under others, they can get up and continue to evacuate. In this paper, the

probability of a fallen pedestrian getting up again is related to the duration of the time spent on the ground, and this probability obeys a Poisson distribution with λ=1.

2.5. Update rules

The specific simulation update rules of this model are structured as follows.

(1) Step 1: Generate pedestrians and populate them randomly into the cells inside the room.
(2) Step 2: In each time step, calculate the static floor field S_{ij}, the dynamic floor field D_{ij} and the event floor field F_{ij} according to Section 2.2.
(3) Step 3: For each pedestrian, determine his/her state and make a decision regarding movement behavior. If the pedestrian is in state U_e,U_n or A_e, calculate the transition probability according to Eqs. (15)–(17), respectively. If the pedestrian is in state A_n, he/she chooses one of the strategies S1, S2 or S3 to evacuate. If the pedestrian is in state C, calculate the probability of him/her getting up again.
(4) Step 4: Each pedestrian moves to his/her target cell. If the pedestrian chooses a target cell that is occupied by a fallen pedestrian, he/she will be tripped and become a new fallen pedestrian.
(5) Step 5: If the chaos duration is over, uninjured pedestrians regard fallen pedestrians as obstacles and conduct a normal evacuation. There will be no more new fallen pedestrians.
(6) Step 6: When multiple pedestrians choose to move to the same target, one pedestrian is randomly selected with equal probability to move to the target cell, and other pedestrians remain in their original cells.
(7) Step 7: Determine whether the evacuation is over. If there are still uninjured pedestrians in the room, return to step 2 and repeat the simulation process until all the uninjured pedestrians evacuate from the room.

The framework of pedestrian behavior decisions is shown in Fig. 5.

3. Simulation results

3.1. Evacuation scenario and parameter values

The simulations are conducted in an empty room (12 m × 12 m) with a single exit in the middle of the left wall, and the exit width is 1.6 m. We define two areas, namely, the exit-perceived area and exit-unperceived area, as shown in Fig. 6. The radius of the perception range is R, so the exit-perceived area consists of two 1/4 circles with a radius of R and a rectangle ($R \times W$). The length and width of each cell are 0.4 m, and the room is 30 cells × 30 cells. Each time step corresponds to 0.3 s, which implies a walking speed of approximately 1.33 m/s [22]. Pedestrians can move at most one cell in each time step.

Pedestrians are distributed randomly in the room initially, and the number of pedestrians is denoted as N. The simulation process terminates after all the uninjured pedestrians leave the room. The fallen pedestrians who did not successfully evacuate from the room are casualties.

We analyzed the initial stampede location in three cases [47]: (1) Case I: in the left part of the room, namely, cell (16, 4); 2) Case II: in the middle part of the room, namely, cell (16, 16); and 3) Case III: in the right part of the room, namely, cell (16, 26).

Systematic experimental studies of stampedes remain a challenging problem for ethical reasons, which has led to a serious lack of experimental data. According to other works with environments similar to that considered in our study [22,50,51], we adjust the fixed parameters to k_S=5, k_D=1, $k_A = 1$, $k_c = 0.5$, $\alpha = 0.3$, $\delta = 0.3$, and R=5 cells. The percentages of affected pedestrians who choose strategies S1, S2, and S3 are 50%, 30%, and 20%, respectively, unless otherwise noted. The calibration of parameters in the proposed model should be further considered in the future.

Fig. 7 gives the average evacuation times and the number of casualties in different simulation scenarios. Notably, the outcome stabilizes as the number of simulation runs increases. The fluctuations are acceptable when the number of runs is larger than thirty. Therefore, each scenario is run 30 times, and the average of the outcomes is used in the following analysis.

3.2. Simulation of evacuation process

Fig. 8 shows scenarios of the evacuation process at different time steps (t = 0, 20, 40, 60, 80, 100). Fig. 8(a) and 8(b) shows that there are no fallen pedestrians when $t < T_s$. At t = 40, the initial fallen pedestrian appeared and the stampede has occurred, the affected pedestrians choose different strategies to evacuate from the room, and we can observe some adjacent fallen pedestrians in Fig. 8(c), 8(d) and 8(e). The chaos duration of the stampede is over at t = 80, pedestrians who choose Strategy S3 continue to evacuate along a wall, while other pedestrians regard fallen pedestrians as obstacles and bypass them to evacuate. There are no new fallen pedestrians, as shown in Fig. 8(f).

3.3. The effect of pedestrian density

Fig. 9 displays the number of pedestrians in the room as a function of the time step for different pedestrian densities N = 100, 200, 300, 400, 500, 600. One can see that the number of pedestrians in the room decreases with the time step at any density.

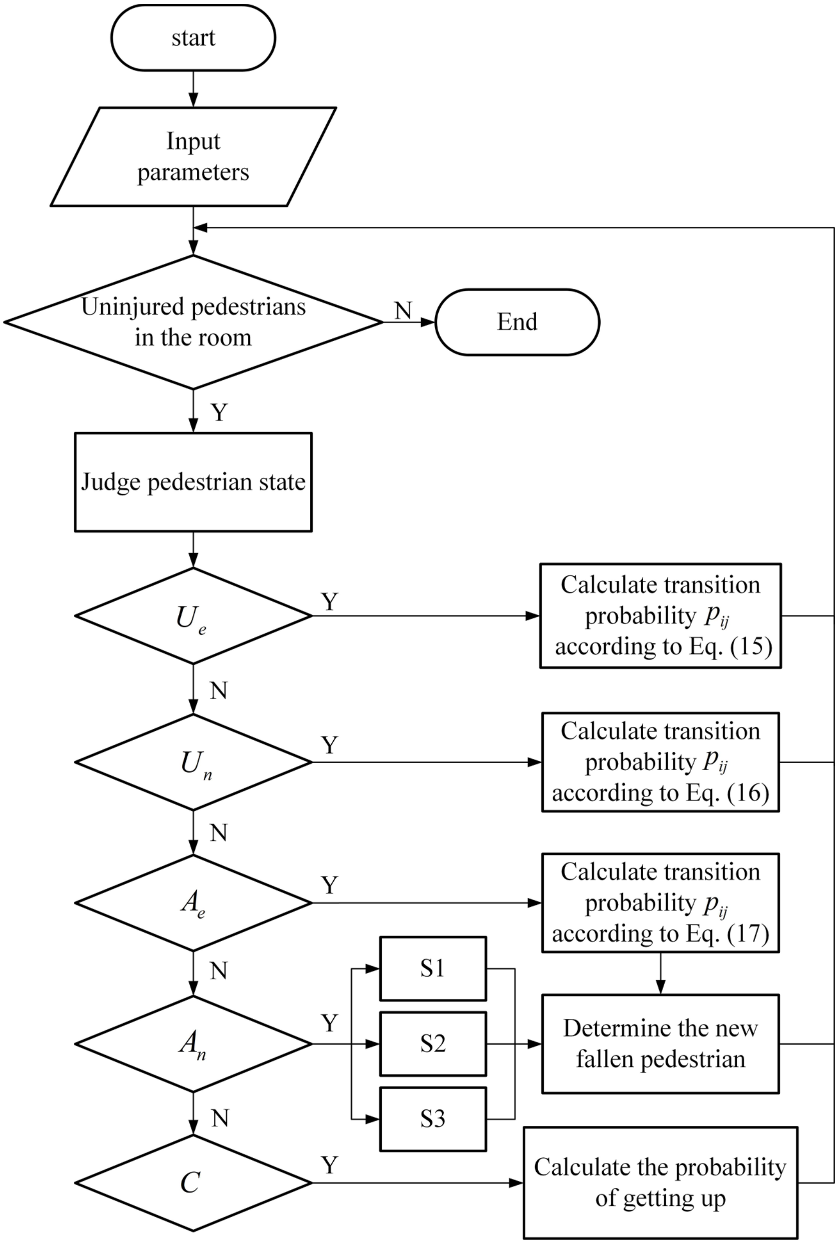

Fig. 5. The framework of pedestrian behavior decisions.

When the density is small, all pedestrians can evacuate from the room successfully. As the density becomes larger, casualties occur and the number of casualties increases. Limited by the chaos duration T_c, the number of casualties tends to remain the same when the density is high rather than increasing rapidly.

3.4. The effect of event floor field

Fig. 10 shows the number of casualties as a function of different values of event floor field k_F. We study the scenarios with $N = 300$ and $N = 500$. When the event floor field is small, pedestrians' willingness to stay away from the stampede location is not high, and the gathering of pedestrians at the stampede location leads to more casualties. With the increment of the event floor field, more affected pedestrians tend to move to the cells that are farther away from the stampede, which results in fewer casualties. When the event floor field increases to a certain value, the impact on the number of casualties gradually stabilizes due to the limited influence scope of the stampede.

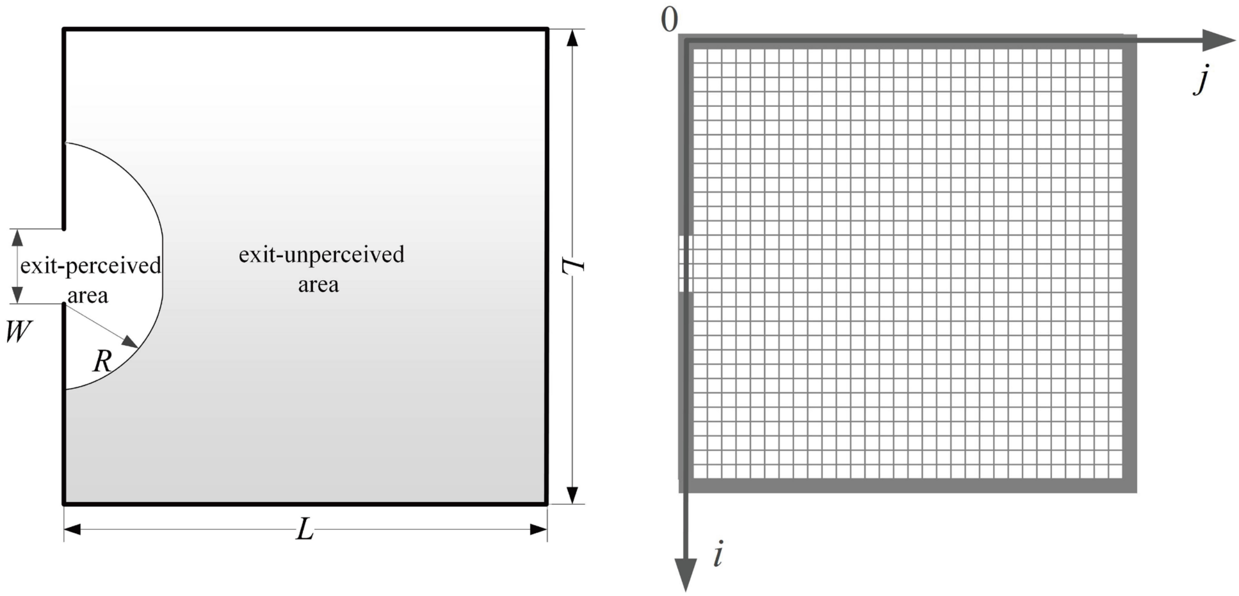

Fig. 6. Illustration of an evacuation scenario. *L*is the room length, and *W* is the exit width.

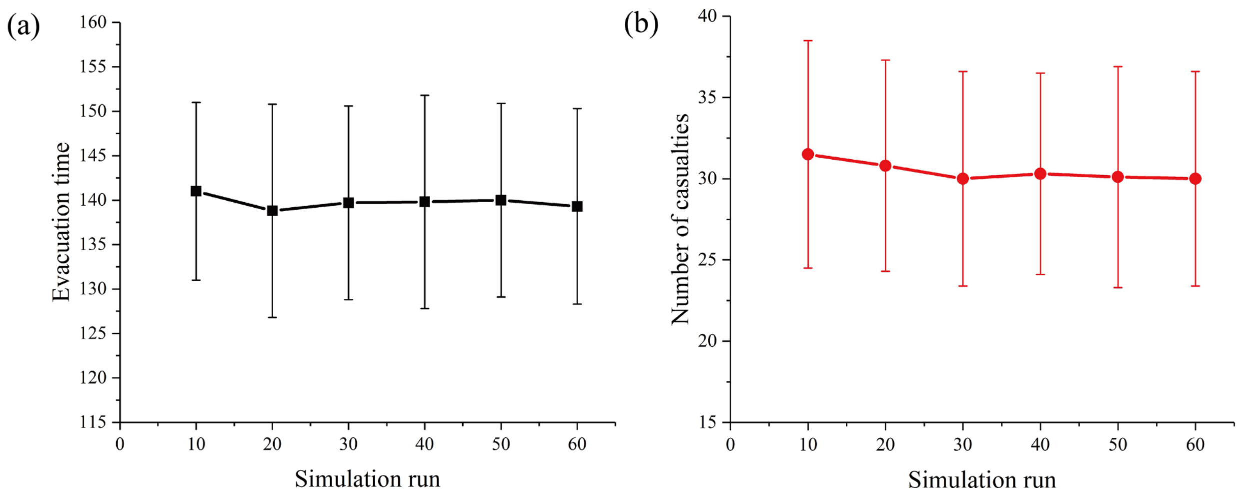

Fig. 7. Evacuation time (time steps) and the number of casualties for different simulation runs. The stampede location is that in Case I, and the parameters are $N = 300$, $k_F = 2$, $T_s = 30$th time step, and $T_c = 50$ time steps. (a) Evacuation time, (b) Number of casualties.

3.5. The effect of stampede location

We studied three typical locations in this paper: the stampede occurs in the left part of the room (near the exit, cell (16, 4)), in the middle part of the room (cell (16, 16)), and in the right part of the room (far from the exit, cell (16, 26)). Fig. 11 indicates the number of pedestrians in the room as a function of the time step for different stampede locations. As shown in Fig. 11(a), all the pedestrians can evacuate from the room successfully when the density is low, and the stampede location has little effect on the evacuation efficiency. When the pedestrian density increases, the effect on the evacuation becomes larger as the distance between the stampede location and the exit decreases (see Fig. 11(b), (c), and (d)). This is understandable that pedestrians would gather at the exit during the evacuation process, and the stampede location that is closer to the exit can affect more people and cause more casualties. In addition, when a stampede occurs in the right part of the room, there is no mass gathering of pedestrians around the stampede location. Thus, few casualties occur, even at high pedestrian densities.

3.6. The effect of evacuation strategy

In this section, all affected pedestrians selected the same evacuation strategy, and we studied the impact of different strategies. Fig. 12 indicates the number of casualties as a function of evacuation strategy with different densities $N = 300$ and $N = 500$. As shown

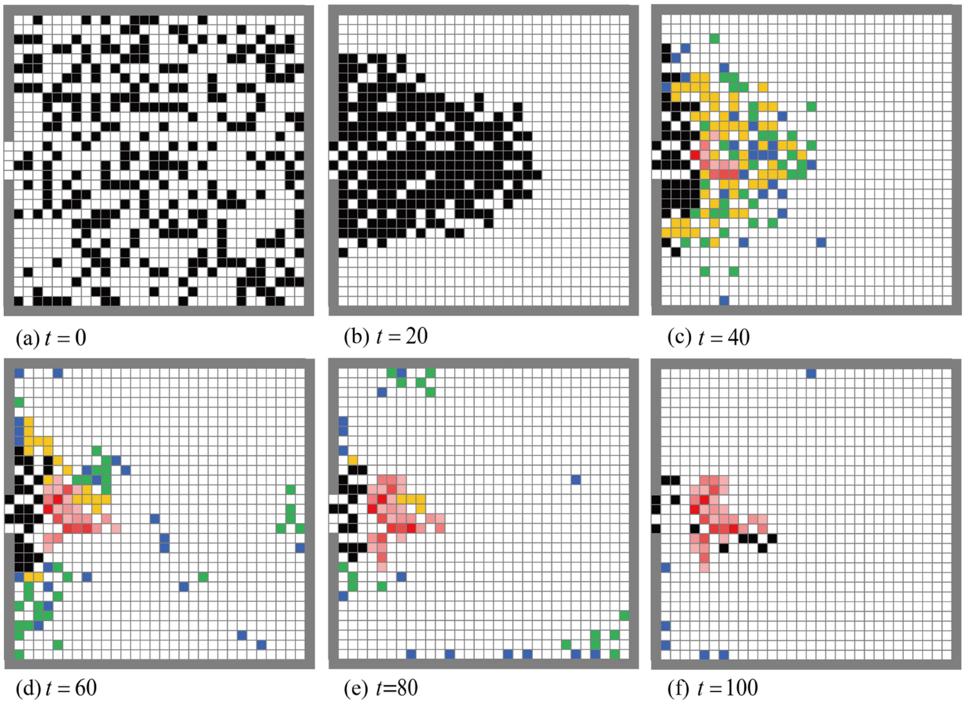

Fig. 8. Snapshots of evacuation. The stampede location is that in Case I. The scenarios are shown at time steps (a)t = 0, (b) t = 20, (c) t = 40, (d) t = 60, (e) t = 80, (f) t = 100. Here, yellow indicates pedestrians who choose strategy S1, green indicates pedestrians who choose strategy S2, blue indicates pedestrians who choose strategy S3, red indicates fallen pedestrians, and black indicates other pedestrians. The darker the red color is, the greater the number of fallen pedestrians in that area. The parameters are N = 300, k_F = 2, T_s = 30th time step, and T_c = 30 time steps.

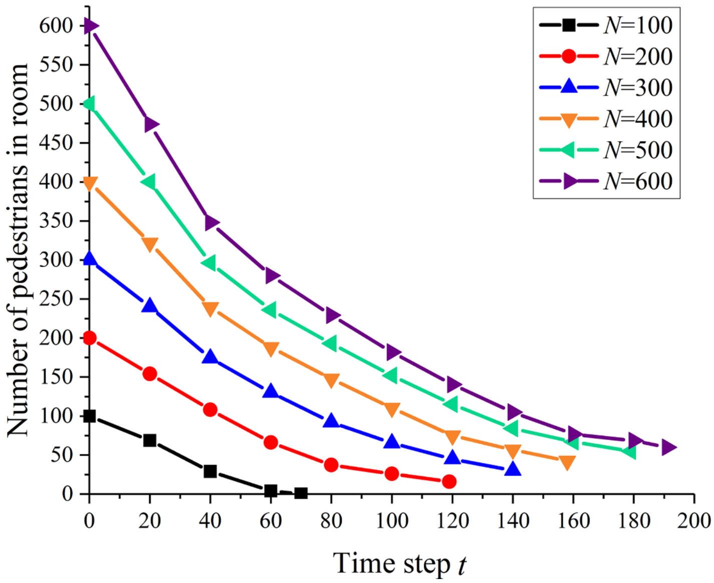

Fig. 9. The number of pedestrians in room as a function of time step for different pedestrian densities. The stampede location is that in Case I, and the parameters are k_F = 2, T_s = 30th time step, and T_c = 50time steps.

in Fig. 12(a), when the stampede occurs near the exit, strategy S2 causes the fewest number of casualties. The reason is that when pedestrians choose strategy S2, they follow the movement direction of most pedestrians within the perception range, some of whom are in the exit-perceived area and move toward the exit. Therefore, strategy S2 can guide pedestrians in the right direction.

As shown in Fig. 12(b), when the stampede occurs in the middle of the room, strategy S1 can minimize the number of casualties. Pedestrians can appropriately stay away from the stampede location and find a more suitable path to evacuate, instead of gathering there. In Case II, the blindly following behavior of pedestrians can lead to serious casualties.

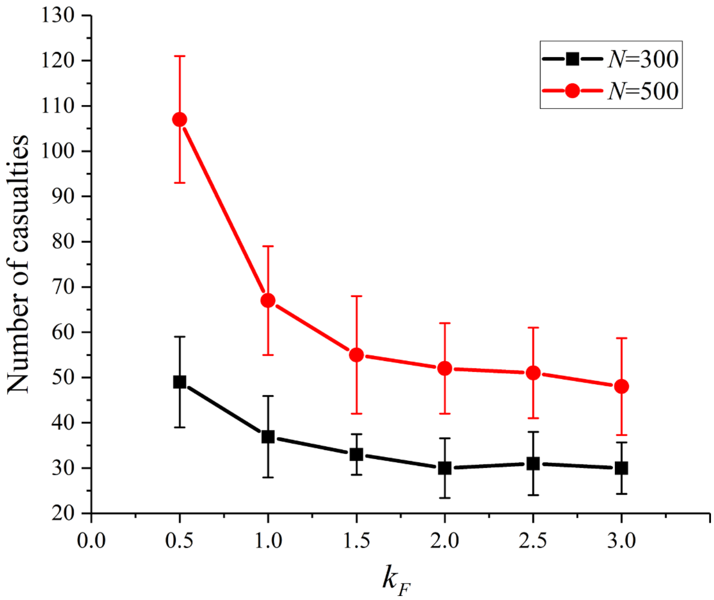

Fig. 10. The number of casualties as a function of different values of k_F. The stampede location is that in Case I, and the parameters are T_s = 30th time step and T_c = 50 time steps.

Based on the simulation results, we observe that different strategies can lead to the unequal number of casualties in the same scenario. Furthermore, the same strategy presents distinct effects in different scenarios.

3.7. The effect of stampede occurrence time

Fig. 13 indicates the number of casualties as a function of different stampede occurrence times T_s with different densities N = 300 and N = 500. One can see that the number of casualties gradually declines as the stampede occurrence time increases in both Case I and Case II, because the later the stampede occurs, the fewer the number of pedestrians remain in the room, which can reduce the casualties. The results reveal stampedes that occur in the early stage of evacuation lead to the higher number of casualties, so the relevant personnel of public places should observe the pedestrian evacuation dynamics at all times and guide evacuees in a timely manner.

3.8. The effect of chaos duration

Fig. 14 displays the number of casualties as a function of different chaos durations T_c with different densities N = 300 and N = 500. We find that the number of casualties grows as the chaos duration T_s becomes longer in both Case I and Case II. Evacuees cannot safely avoid fallen pedestrians to find a safe route during the chaos duration, the increasing chaos duration causes more pedestrians to change their evacuation behavior and increases the risk of casualties. In an actual emergency evacuation, the chaos duration of a stampede needs to be controlled through guidance in both physical and psychological ways.

4. Conclusion

This paper presents an extended floor field model to study the pedestrian evacuation dynamics during stampedes. Pedestrians' stampede avoidance behavior and the probability of being tripped are considered in the model. In addition, three evacuation strategies are also proposed to describe the behavioral differences in pedestrians. The impacts of the pedestrian density, event floor field, stampede location, evacuation strategy, stampede occurrence time and chaos duration on evacuation dynamics are analyzed. The results are summarized as follows:

(1) The pedestrians' behavior change caused by the stampede seriously affects the evacuation efficiency and results in casualties. Moreover, the evacuation becomes harder and the number of casualties becomes larger with the increase in pedestrian density.
(2) When the event floor field increases, pedestrians' behavior of avoiding the stampede becomes prominent. More pedestrians can evacuate from the room successfully, and the number of casualties decreases.
(3) As the distance between the stampede location and the exit increases, the effect of the stampede location on the evacuation becomes smaller, and the number of casualties declines.
(4) The effectiveness of evacuation strategies is closely related to stampede location. Strategy S2 is more efficient when the stampede occurs near the exit, while the performance of strategy S1 is better when the stampede occurs in the middle of the room.

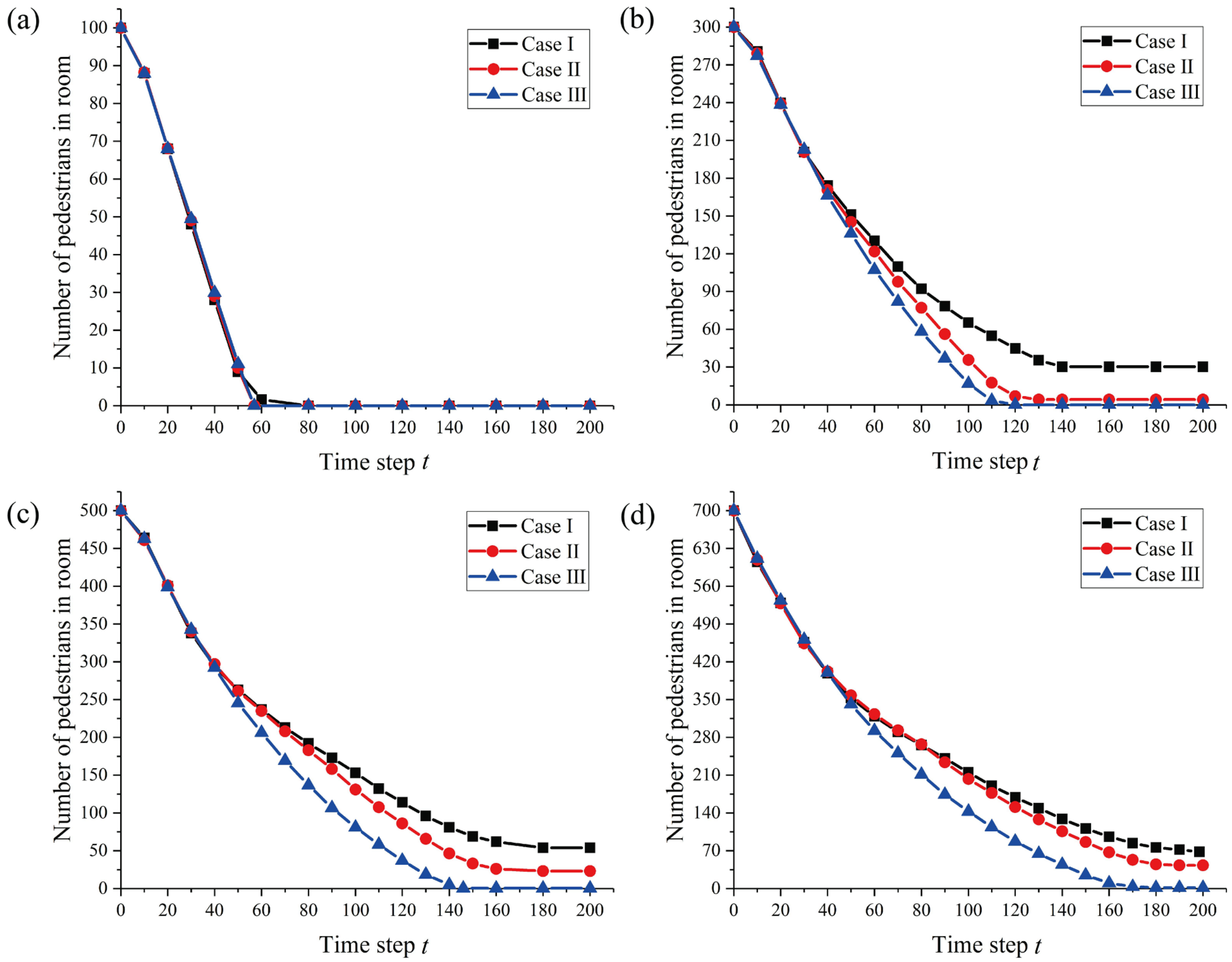

Fig. 11. The number of pedestrians in room as a function of time step for different stampede locations. The parameters are $k_F = 2$, $T_s = 30$th time step, and $T_c = 50$ time steps. (a) $N = 100$, (b) $N = 300$, (c) $N = 500$, and (d) $N = 700$.

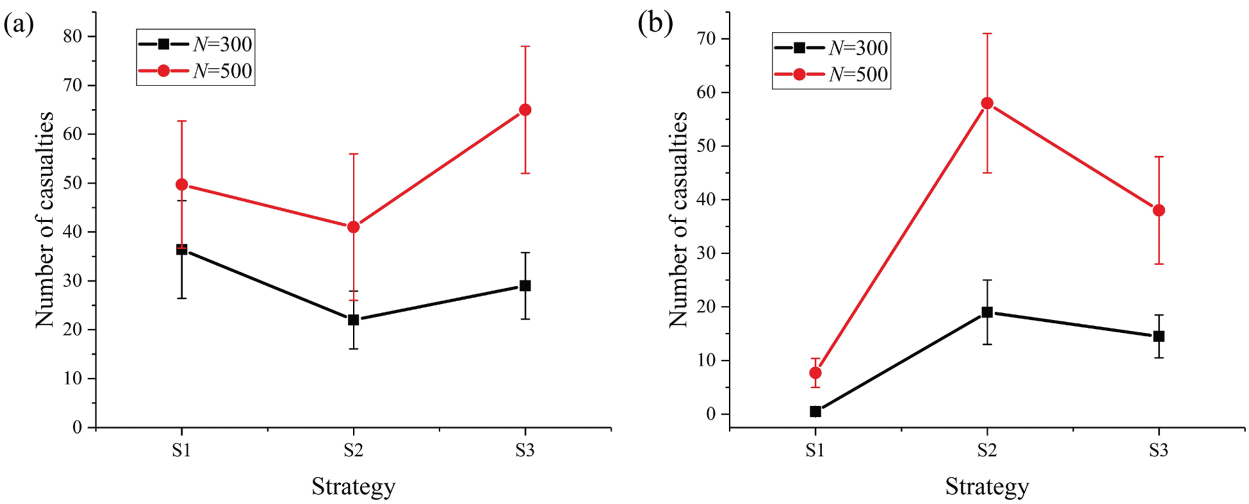

Fig. 12. The number of casualties as a function of different evacuation strategies. The parameters are $k_F = 2$, $T_s = 30$th time step, and $T_c = 50$ time steps. (a) Case I, (b) Case II.

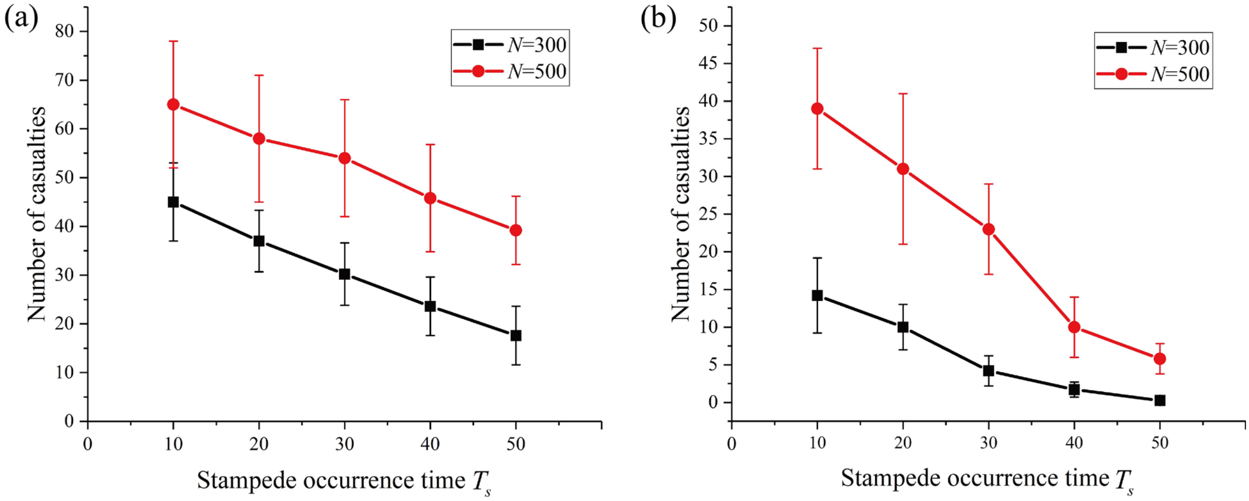

Fig. 13. The number of casualties as a function of different stampede occurrence times T_s (time step). The parameters are k_F = 2 and T_c = 50 time steps. (a) Case I, (b) Case II.

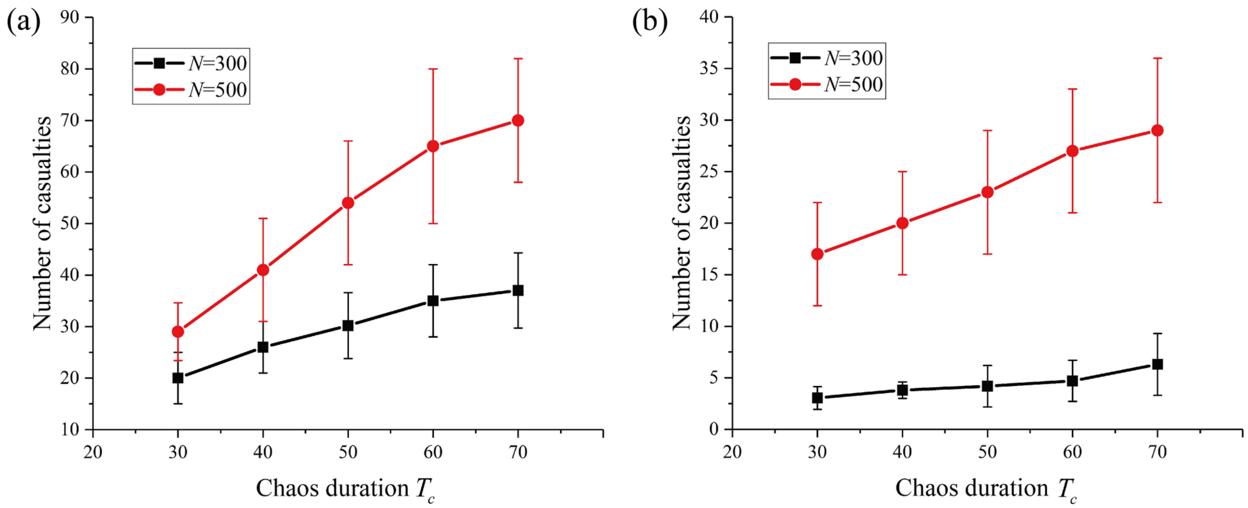

Fig. 14. The number of casualties as a function of different chaos durations T_c (time steps). The parameters are k_F = 2 and T_s = 30thtime step. (a) Case I, (b) Case II.

Appropriate evacuation strategies should be developed and adopted based on different evacuation scenarios.

(5) The stampede occurrence time and chaos duration both have obvious influences on evacuation. The later the stampede occurs, the fewer the number of casualties. Additionally, the longer the chaos duration becomes, the greater the number of casualties. Pedestrians should be guided in a timely manner to delay the stampede occurrence time and shorten the chaos duration.

Our paper attempts to study pedestrian evacuation in stampedes with a simplified model based on realistic situations and existing theory. The research results provide reference for planning evacuation strategies and establishing emergency management. In future work, more complex stampede scenarios could be described, and pedestrians' group behavior and helping behavior should also be considered.

CRediT authorship contribution statement

Jiaxuan Yi: Investigation, Formal analysis, Writing - original draft. **Shuangli Pan:** Investigation, Formal analysis. **Qun Chen:** Conceptualization, Methodology, Writing - review & editing.

Declaration of Competing Interest

None.

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