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Evacuation simulation considering action of guard in artificial attack*

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To investigate the evacuation behaviors of pedestrians considering the action of guards and to develop an effective evacuation strategy in an artificial attack, an extended floor field model is proposed. In this model, the artificial attacker's assault on pedestrians, the death of pedestrians, and the guard's capture are involved simultaneously. An alternative evacuation strategy which can largely reduce the number of casualties is developed and the effects of several key parameters such as the deterrence radius and capture distance on evacuation dynamics are studied. The results show that congestion near the exit has dual effects. More specifically, the guard can catch all attackers in a short time because the artificial attackers have a more concentrated distribution, but more casualties can occur because it is hard for pedestrians to escape the assault due to congestion. In contrast, when pedestrians have more preference of approaching the guard, although the guard will take more time to capture the attackers resulting from the dispersion of the attackers, the death toll will decrease. One of the reasons is the dispersal of the crowd, and the decrease in congestion is beneficial for escape. The other is that the attackers will be caught before launching the attack on the people who are around the guard, in other words, the guard protects a large number of pedestrians from being killed. Moreover, increasing capture distance of the guard can effectively reduce the casualties and the catch time. As the deterrence radius reflecting the tendency of escaping from the guard for attackers rises, it becomes more difficult for the guard to catch the attackers and more casualties are caused. However, when the deterrence radius reaches a certain level, the number of deaths is reduced because the attackers prefer to stay as far away as possible from the guard rather than occupy a position where they could assault more people.

Keywords: evacuation behavior, artificial attack, floor field model

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1. Introduction

In recent years, pedestrian evacuation under artificial attacks has attracted much attention due to many real events. For example, a knife attack was carried out by a 35-year-old man with a personal grievance in a busy shopping mall in Beijing on February 11, 2018, leading to 1 death, 12 injuries; and the deadly mass attack by knife-wielding men at a railway station in Kunming in south-west China on March 1, 2014 led to at least 29 deaths and more than 130 injuries. Due to the threat of artificial attacks, it is necessary to understand the pedestrian dynamics in this situation for developing effective evacuation schemes.

During the last decades, various simulation models have been established to investigate pedestrian evacuation processes,[1] and there have been two fundamentally different ways of representing people in these models, namely, macroscopic model and microscopic model.[2] According to the macroscopic model, pedestrians are represented as an analogy to fluid flow with a specific density which corresponds to people density and velocity.[3] In contrast, each pedestrian in a microscopic model would be treated as a self-driving particle with certain properties.[4] Therefore, these models could consider the heterogeneities of the pedestrians, thus they are more similar to reality and have become the most common way of modeling pedestrian dynamics.[5] Particularly, the floor field model,[6] one of the most important microscopic models, is a well-studied pedestrian model using cellular automata.[7] Due to its flexibility and extensibility,[8] the floor field model has been extensively used and could successfully reproduce realistic pedestrian behavior and self-organization encounters in pedestrians dynamics, such as clogging,[9] exit selection strategy,[10] leading[11] and group behavior[12] conflicts at the exit,[13] crowd flow through multiple bottlenecks,[14] and oscillation at the bottleneck.[15,16]

Pedestrian flow exhibits variable patterns of behavior in the artificial attack scenario, and the most important reason is the complex interactions involved in this case, such as pedestrian-to-pedestrian, pedestrian-to-environment, attacker-to-pedestrian, and pedestrian-to-attacker interactions. Each interaction can be described as a floor field in the floor field model where individuals make their decision according to the so-called transition probabilities modified by different floor fields. Chen[17] studied the pedestrian dynamics by an extended floor field model and found the rolling behavior and along-the-wall motion of the crowd with aggravating extent of the influence of attackers on pedestrians. Li[18] proposed a three-stage model to reproduce a series of complex behaviors and decision-making processes at the onset of an attack, and

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the influence of the terrorist attack on pedestrian dynamics has been well-studied. Liu[19] developed a social force model to study the crowd evacuation when a terrorist attack occurs in a public place and the effects of the initial positions of terrorists, the number of terrorists, and the emergency exit choice strategy on crowd evacuation have been studied.

However, fewer researchers have focused on pedestrian evacuation involving the artificial attacker and the guard simultaneously. In reality, there are always guards with protection function in public areas and the guards would have a positive effect on pedestrian but a negative effect on the attackers, which makes pedestrian dynamics different and more complicated. It should be studied for reducing the death toll and developing effective evacuation strategy.

In this paper, an extended floor field model is proposed to investigate evacuation behaviors of pedestrians in an artificial attack considering the guard; the the movement of the pedestrian, guard, and attacker, the attacker's assault, and the guard's capture are involved simultaneously. The rest of this paper is organized as follows. The proposed model considering the interactions among the attacker, guard, and pedestrian is introduced in Section 2. In Section 3, the comparison of two evacuation strategies and the effects of several key parameters on pedestrian evacuation are discussed. In Section 4, some conclusions are drawn from the present study, finally.

2. Model description

In the proposed model, the space is represented by two-dimensional foursquare cells. Each cell is an identical square of 0.4 m$\times$ 0.4 m[20] and can be either empty or occupied by an obstacle, a pedestrian, a guard, or an attacker. In each discrete time step, they can move one step by corresponding principles. More specially, the attackers aim is to kill more people so they are attracted by the crowd and move towards the desired direction according to the calculated attractive force. However, once the distance from the guard is small enough, the attackers have to run away from the guard as far as possible to avoid being caught. On the other hand, the guard chases the nearest attackers and can catch them in a capture distance by the prey–predator model. Meanwhile, the pedestrian will die with a certain probability when attacked by the attacker and the movement of pedestrians is based on the extended floor field model where individuals make their decision according to the so-called transition probabilities modified by the exit, attack threat, and the guard floor field. Three different kinds of actions are involved in this model and their detailed expressions are modeled as follows.

2.1. Action of attacker

In general, the artificial attackers aim to attack more people and create as much panic as possible, thus the attackers do not have clear targets and are assumed to be attracted by pedestrians and move towards the direction of the larger population. However, the attacker can run away from the guard to avoid being attacked if the guard is getting very close to the attacker. Therefore, a new parameter R_{D} named deterrence radius is introduced to represent the critical distance that the attackers have to escape from the guard, which can be viewed as a measure of the tendency of the attackers to avoid the guard while they are chasing the crowd. In other words, the attackers will run away from the guard when the distance between the attackers and the guard is less than the deterrence radius, otherwise, the attackers will chase and attack the crowd. It should be noted that the attacker will also attack the pedestrian in this escape process. Accordingly, either the intensity to move towards the crowd or the repulsion between the attacker and the guard is imposed on the attacker, and an analogical formulation taking reference of the physical mechanics is introduced. And a detailed expression for the above forces is modeled as shown in Fig. 1

$$\boldsymbol{f} = \begin{cases} \dfrac{\sum\limits_{i=1}^{n} \boldsymbol{f}_{\mathrm{p}i}}{\left|\sum\limits_{i=1}^{n} \boldsymbol{f}_{\mathrm{p}i}\right|}, & d_{\mathrm{ag}} > R_{\mathrm{D}}, \\ \dfrac{\boldsymbol{f}_{\mathrm{ag}}}{|\boldsymbol{f}_{\mathrm{ag}}|}, & d_{\mathrm{ag}} \leq R_{\mathrm{D}}, \end{cases} \tag{1}$$

where $\boldsymbol{f}$ is the resultant force on the attacker, n is the number of pedestrians within the attacker's sighting range, $\boldsymbol{f}_{\mathrm{p}i}$ is the single attractive force of the i^{th} pedestrian to the attacker, $\sum_{i=1}^{n} \boldsymbol{f}_{\mathrm{p}i}$ is the intensity to move towards the crowd, $\boldsymbol{f}_{\mathrm{ag}}$ is the repulsion between the attacker and the guard, d_{ag} is the distance between the attacker and the guard, and R_{D} is the deterrence radius.

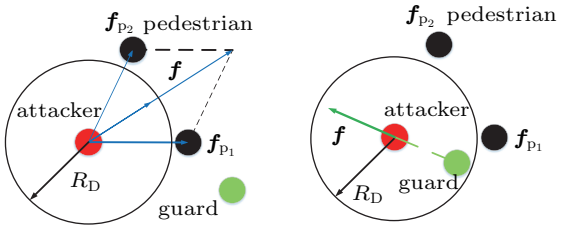


Fig. 1. Diagram of force acting on attacker when $n = 2$.

In Fig. 1, the red solid circle represents the attacker, the black one is the pedestrian, and the green one is the guard. Each pedestrian has a single attractive force to the attacker. The $\boldsymbol{f}$ denotes the force on the attacker and R_{D} is the deterrence radius. In the first case, $\boldsymbol{f}$ is calculated by the attractive resultant force from the crowd because the distance between the attacker and the guard is bigger than the deterrence radius and the attacker will chase the crowd. While in the other case, $\boldsymbol{f}$ is calculated by the repulsion from the guard which results from the fact that the distance between the attacker and the

guard is smaller than the deterrence radius and the attacker has to get away from the attacker to avoid being attacked.

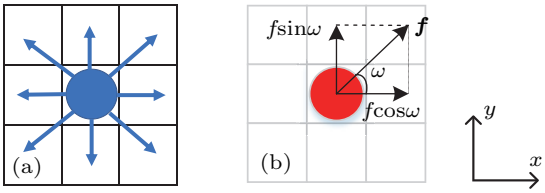


Fig. 2. (a) Possible movement directions of attacker and (b) component forces of $\boldsymbol{f}$ in x and y directions.

As shown in Fig. 2(a), for the attacker, other than keeping unmoved, there are eight possible movable directions at the next time step, but which direction the cell will move in is dependent on the resultant force indicated by Eq. (1). As illustrated in Fig. 2(b), $\boldsymbol{f}$ denotes the resultant force on the attacker hypothetically, and the component forces of $\boldsymbol{f}$ in the x and y directions can be expressed as $f\cos\omega$ and $f\sin\omega$, respectively, and the movable direction of the attacker at the next time step can be determined by the relative magnitude between $f\cos\omega$ and $f\sin\omega$. When pedestrian n is assumed to be located at the position (i, j), the relationship of the relative magnitude between $f\cos\omega$ and $f\sin\omega$ with the rule of movable direction for pedestrian n at the next step is tabulated in Table 1.

The assault of the attackers is considered in this model. The attacker will launch an attack on the pedestrian when the distance between the attacker and the pedestrian is small enough, and the pedestrian will die with a certain probability when assaulted by the attacker. And the attacker can just attack once at each time step and the probability of the pedestrian being killed is set to be 0.7[19] in this model.

2.2. Action of guard

The interaction between the guard and attackers is a pursuit-and-evasion problem and can be modeled by the prey–predator model,[21] which is extensively used to study the collective motion of living organisms and can reproduce many self-organization phenomena.[22] In this model, the guard can be regarded as the predator and the attacker is the prey, and the guard will be assumed to have more force advantages than the attackers thus the guard cannot be defeated. The guard will chase the nearest attacker and catch him if their distance is no more than the capture distance of the guard, then the caught attacker will be removed. The attacker will move according to the resultant forces as mentioned before while the guard will follow the simplest principle, that is, preference to the location which has a shorter distance to the attacker.

The guard movement rules are defined as follows. a) Calculate respectively the distance between the guard and each attacker from

$$d_{\mathrm{ag}} = \sqrt{\left(x_{\mathrm{a}} - x_{\mathrm{g}}\right)^2 + \left(y_{\mathrm{a}} - y_{\mathrm{g}}\right)^2}, \tag{2}$$

where d_{ag} denotes the distance between the guard and the attacker, x_{a} and y_{a} represent the coordinates of the attacker, and x_{g} and y_{g} represent the coordinates of the guard. And find out the location of the nearest attacker. b) Determine all available positions for the guard, an available position means a location unoccupied by obstacles, pedestrians, or the attacker. c) Calculate respectively the distance between the nearest attacker and each available position. d) Move into the location which has the shortest distance to the nearest attacker at the next time step. Note that the guard will select randomly any of them when two or more positions have the same priority and will not move when all neighborhood positions have been occupied. e) Catch the attacker once the attacker is within the capture distance of the guard.

2.3. Action of pedestrian

The interactions of pedestrians with evacuation scenario, the guard, and the attackers must be considered when simulating the movement of people. In this model, pedestrian dynamics is described by the extended floor field model where individuals make their decision according to the so-called transition probabilities modified by several floor fields. We employ Moore neighborhood, composed of a central cell and its eight surrounding cells, as the pedestrian moving method. Therefore, a 3×3 matrix of preferences p_{ij}, as shown in Fig. 3, is constructed which contains the transition probabilities of its neighbors for cell (i, j). Note that the transition probabilities mean that the individual would prefer to move in an optimal direction of higher fields rather than move in a direction probabilistically.[23]

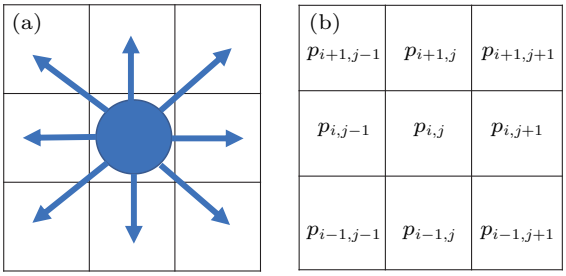


Fig. 3. (a) Possible movement directions of the pedestrian and (b) the transition probability p_{ij}.

The transition probability p_{ij} of cell (i, j) is expressed as

$$p_{ij} = N \exp\left(\left(k_{\mathrm{s}} S_{ij} + k_{\mathrm{t}} T_{ij} + k_{\mathrm{g}} G_{ij}\right)\left(1 - n_{ij}\right)\right), \tag{3}$$

where N is a normalization factor, S_{ij}, T_{ij}, and G_{ij}, denote the static floor field, attack threat, and the guard floor field of the cell (i, j), respectively. And the corresponding sensitivity coefficients are k_{s}, k_{t}, and k_{g}, which determine the weight of each floor field and theoretically range from 0 to 1. If the coefficient is 0, it implies that the corresponding floor field has no effect on the pedestrian, and if the coefficient is 1, it means that

the individual motion is completely determined by the corresponding floor field. In addition, n_{ij} denotes the occupation number of cell (i, j) and $n_{ij} = 1$ if the cell is occupied by a pedestrian, otherwise $n_{ij} = 0$.

In general, the static floor field is related to the evacuation scenario such as the size of the room and the location of the exit. In this model, the static floor field S_{ij} is set to be inversely proportional to the distance from the exit and can easily specify the regions of the room which are more attractive, which is calculated as follows:

$$S_{ij} = N \max_{(i,j)} \left(\min_{e_m} \sqrt{\left(x_{e_l} - x_{ij}\right)^2 + \left(y_{e_l} - y_{ij}\right)^2} \right) - \min_{e_m} \sqrt{\left(x_{e_l} - x_{ij}\right)^2 + \left(y_{e_l} - y_{ij}\right)^2}, \quad (4)$$

where m is the number of exits, e_l represents the l^{th} exit, x_{e_l} and y_{e_l} represent the coordinates of the l^{th} exit, and x_{ij} and y_{ij} represent the coordinates of cell (i, j).

In contrast, the attack threat and the guard floor field will evolve with time steps and be modified by other individuals. It is certain that the pedestrian will be more willing to try to get away from the attackers and prefer a location with as long distance to the attacker as possible, thus attack threat T_{ij} is set to

$$T_{ij} = N \sqrt{\left(x_{\text{Q}} - x_{ij}\right)^2 + \left(y_{\text{Q}} - y_{ij}\right)^2} \quad (5)$$

to ensure that the location far away from the attacker has a higher field and is more attractive to pedestrians, where x_{Q} and y_{Q} represent the coordinates of the attacker. Moreover, some pedestrians might be likely to move closer to the guard for survival due to panic when they are chased by the attacker, so the guard floor field T_{ij} can be set to

$$G_{ij} = -N \sqrt{\left(x_{\text{g}} - x_{ij}\right)^2 + \left(y_{\text{g}} - y_{ij}\right)^2} \quad (6)$$

to make sure that the position with short distance from the guard will be more attractive to the pedestrian and has a higher field, where x_{g} and y_{g} represent the coordinates of the guard.

2.4. Determination of parameter

The k_{s}, k_{t}, and k_{g} are three key parameters reflecting to what extent the corresponding factor affects the individual, and they should be determined prior to the simulation. Naturally, the sum of these parameters is 1, as shown by

$$k_{\text{s}} + k_{\text{t}} + k_{\text{g}} = 1, \quad (7)$$

because the pedestrian movement is just totally affected by these floor fields in this model.

Several critical cases are taken into account to study relations between these parameters. As shown in Fig. 4(a), when the attacker, exit, and guard on the same x or y axis, the pedestrian will move far away from the attacker due to the threat, rather than head for the exit even though there is the attractive force from the exit and the guard.[19] Therefore, the relation among these parameters can be described as follows:

$$k_{\text{t}} \geq k_{\text{s}} + k_{\text{g}}. \quad (8)$$

Another critical case where a pedestrian is located in the middle of the exit and the guard as shown in Fig. 5(b) is investigated. In this condition, most of people would prefer the exit for survival while some might be more willing to get close to the guard to avoid the attack due to panic. Actually, the latter would consider the high preference of approaching the guard but the former would not, and the two conditions will be studied and compared below.

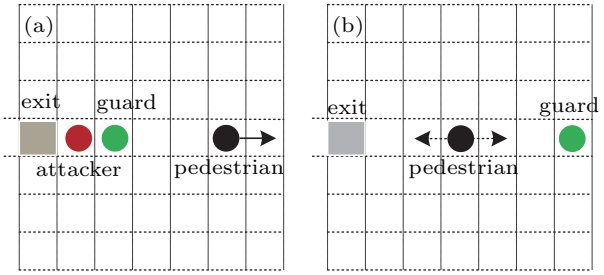


Fig. 4. Diagram of two critical situations. The red solid circle represents the attacker, the green one is the pedestrian, the black one is the pedestrian, and the grey one is the exit.

Combining Eq. (7) with Eq. (8), these parameters could be obtained as follows:

$$0.5 < k_{\text{t}} \leq 1, \quad (9)$$

$$0 < k_{\text{s}} \leq 0.5, \quad (10)$$

$$0 < k_{\text{g}} \leq 0.5. \quad (11)$$

3. Results and discussion

As shown in Fig. 5, the proposed model is tested in a cellular space of 35×35 cells and the pedestrians are initially distributed randomly and attempt to escape from the room with one exit. The guard is located in the center of the room at first while the initial positions of the attackers are in the corners of the room. The number of attackers is set to be four in this scenario for a better comparison. When the simulation starts, the attacker is attracted by pedestrians and moves towards the desired direction according to the attractive force. Meanwhile, the guard chases the nearest attacker, and the pedestrian escapes according to the transition probabilities and will die when assaulted by the attacker. According to the above analysis, the parameters in the simulation are set as follows: $k_{\text{t}} = 0.5$, $k_{\text{s}} = 0.4$, and $k_{\text{g}} = 0.1$ for the case of low preference of approaching the guard in which the pedestrians would be less affected by the guard and $k_{\text{t}} = 0.5$, $k_{\text{s}} = 0.1$, and $k_{\text{g}} = 0.4$ for the case of high preference of approaching the guard in which the pedestrians prefer to move closer to the

guard for survival. In the following, the pedestrian behavior in two strategies and effects of several key parameters on the pedestrian flow are investigated.

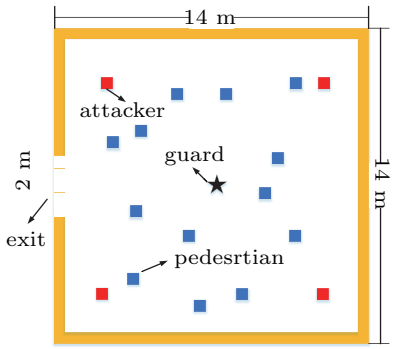


Fig. 5. Schematic illustration of room, where each cell is an identical square area of 0.4 m× 0.4 m.

3.1. Effect of guard on evacuation

Figure 6 indicates how the k_g value affects the evacuation process. It can be found in Fig. 6 that as the k_g value rises, the number of casualties will decrease but the evacuation time will increase. There are two main reasons for the decrease in death toll as k_g rises. One is that a larger k_g value means that the guard has a greater influence on the decision-making of the individual and the pedestrian prefers to get close to the guard for survival. Therefore, a certain number of people would stay around the guard to avoid being attacked. Another reason is that the less congestion near the exit reduces the threat of the pedestrian being attacked. More specially, when the k_g value is large, many people would stay around the guard and less congestion near the exit will be generated, and this means that the pedestrian has more time to escape from the attacker rather than gather around the exit where it is are hard to move due to congestion, which leads to a lower death toll. Moreover, the evacuation time increases as k_g rises, and it is because a larger k_g value means that the pedestrian would prefer to get close to the guard rather than the exit for survival, which would largely delay the evacuation process.

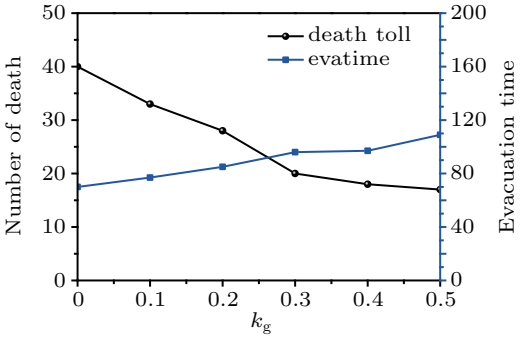


Fig. 6. Evacuation time and death toll against k_g.

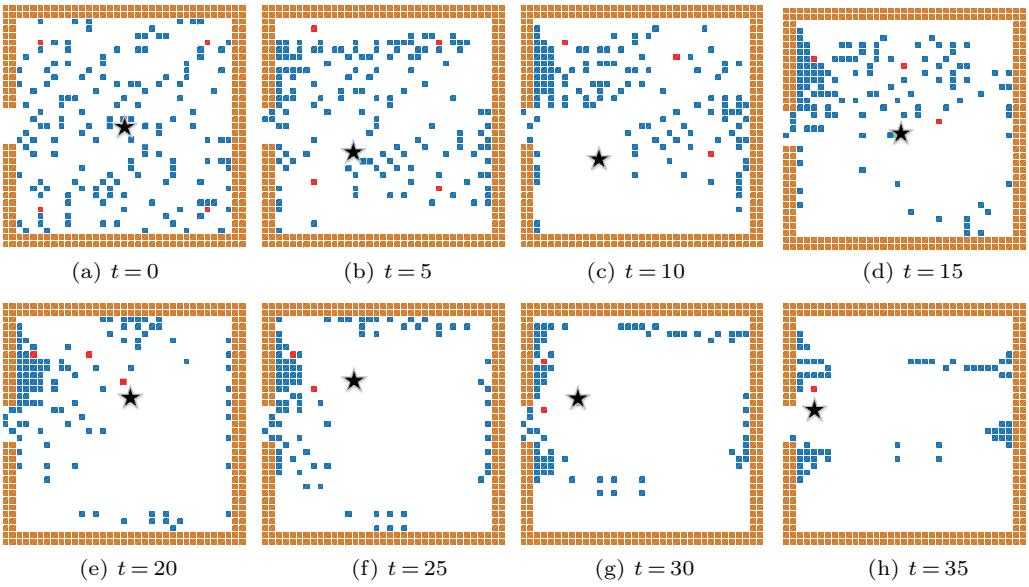


Fig. 7. (a)–(h) Snapshots at different time steps in low preference of approaching guard situation. Black pentagram represents the guard, the red square is the attacker, and the blue one is the pedestrian.

Some specific details are shown in Fig. 7, which presents snapshots at different time steps when the pedestrians are less affected by the guard. As shown in Fig. 7, the pedestrians have to avoid the attack and try to move to the exit, thus a large number of pedestrians move toward the exit and congestion would be formed quickly. For the gathered people, it would be difficult to escape the assault due to the congestion, for example, at $t = 15$. And when the attackers reach the exit, they do not need to spend more time chasing because of the high-density of pedestrians, which means that the attackers could launch the attack each time step and thus a higher pedestrian death toll is caused. Meanwhile, because of the clustered pedestrians near the exit, most of the attackers would move to the exit so that the guard does not need too much extra time to chase another after capturing one attacker, which could greatly reduce the total catch time. In addition, when all the attackers are caught,

the pedestrians could complete the evacuation in a short time because most of the people are around the exit.

The crowd presents different dynamic characteristics when the pedestrian is greatly affected by the guard, that is, the pedestrian prefers to get close to the guard for survival. First, there is still congestion at the exit, but it is significantly reduced, and the overall pedestrian distribution becomes more dispersed because most of pedestrians move according to the movement of the attackers and guards instead of gathering near the exit. Second, the dispersion of the crowd also leads to the dispersion of the attackers due to the fact that the attackers chase the crowd. Therefore, the guard has to spend more time on catching all attackers. For example, there is only one attacker alive in Fig. 7 while at $t = 35$ there are two attacker alive in Fig. 8. It also implies that the attackers have more time to attack people but it does not cause a greater death toll, because there are always a large number of people close to the guard and these people would be less likely to be attacked because the attacker who tries to attack these people will be caught by the guard. Finally, the pedestrians have to take more time to finish the evacuation when the attack threats have been eliminated by the guard due to the scattered pedestrians.

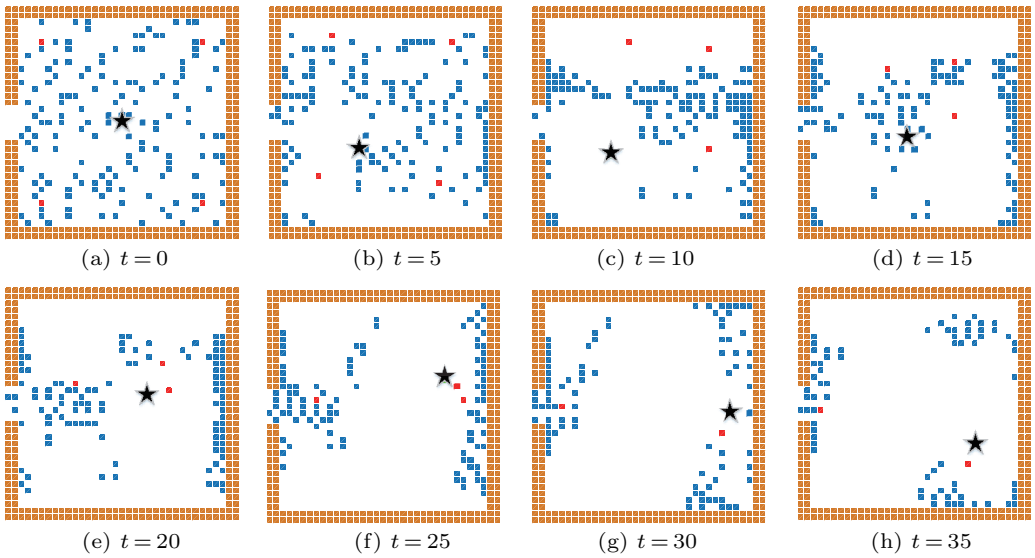


Fig. 8. Snapshots at different time steps in high preference of approaching the guard situation. The black pentagram represents the guard, the red square is the attacker, and the blue one is a pedestrian.

3.2. Effect of deterrence radius on evacuation

The deterrence radius represents the critical distance that the attackers have to escape from the guard. Figure 9 shows the plots of catch time against deterrence radius in two cases. And the catch time is defined as the total time taken for the guard to successfully capture all the attackers. It can be seen that the catch time shows significant increasing tendency as the deterrence radius rises in both cases. When the deterrence radius is large, the attackers run away from the guard earlier and the guard has to take more time to catch these attackers, which results in the increase in catch time. Moreover, the catch time in the high preference of approaching the guard situation is always higher than that in the low preference situation. In the low preference, the pedestrian prefers to get close to the exit for survival thus a considerable number of pedestrians would stay around the exit, which will make congestion generated near the exit. And the attackers will be attracted by these people and chase them when the distance from the guard is less than the deterrence radius, and it means that the guard who just captured one attacker will take less time to catch another, which leads to a decrease in catch time.

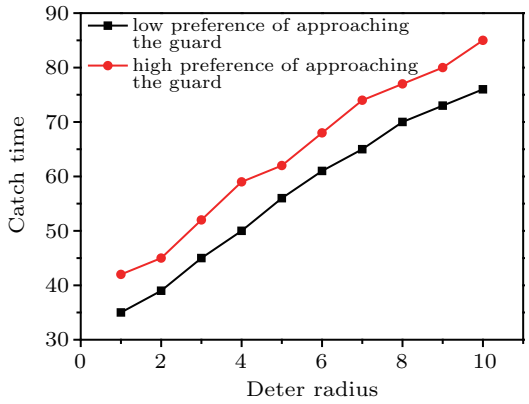


Fig. 9. Plots of catch time against deterrence radius.

Figure 10 shows how the deterrence radius affects the death toll in the two cases. As the deterrence radius rises, the death toll first increases and then decreases whether the preference of approaching the guard is low or high. The reason for the increase is that when the deterrence radius is high, the attackers are more difficult to catch and it will take more time for the guard to grab all attackers as analyzed before. It also means that the attackers have more time to chase and attack people, which will cause more casualties in this process. In contrast, when the deterrence radius is large enough, the at-

tackers will be largely affected by the guard and try to avoid being caught as much as possible. As a result, the attackers have to escape from the guard earlier and move to the position far away from the guard instead of the position where they could attack more people. Therefore, less pedestrians can be attacked in the escape process of the attacker and the attackers might be forced to move to the corner of the room with a few people, which leads to a lower death toll. Moreover, more casualties will occur in the low preference of approaching the guard situation than in the high preference situation. This is because in the high preference situation, the pedestrians prefer to stay around the guard for survival and the attackers are caught before they can attack the people who stay around the guard. In contrast, in the low preference situation, there is more congestion and the crowd clustered near the exit is hard to evacuate and thus the attackers can assault a considerable number of pedestrians in a short time.

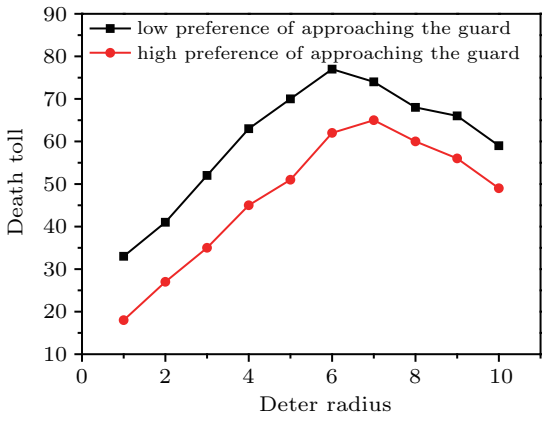


Fig. 10. Plots of death toll against deterrence radius.

3.3. Effect of capture distance on evacuation

The capture distance is the distance that the guard could catch the attackers. Figure 11 indicates the effect of the capture distance on the catch time. It can be seen that the catch time always decreases with capture distance increasing whether the preference of approaching the guard is low or high. When the capture distance is large, the guard could catch the attackers in a long distance thus the catch time would decrease. It should be noted that the catch time in the high preference is always higher than that in the low preference. As mentioned before, in the low preference situation, the pedestrians are more likely to be assembled near the exit due to the tendency of moving towards to the exit. Then the attacker can be attracted by these people and get more close to each other on the distance, and the guard will spend less time on capturing these attackers.

Figure 12 shows how the capture distance affects the death toll. It is obvious that less pedestrians die as the capture distance increases. When the capture distance is large, the catch time decreases due to the fact that the guard can catch the attackers over a long distance. Therefore, the attackers do not have much time to chase and assault pedestrians and the casualties are reduced. Furthermore, more casualties can occur in the low preference situation. The reason for this is, in the high preference, the pedestrians prefer to get close the guard for survival, and the attacker would be hard to assault these people because the attacker can be caught before launching the attack. In contrast, in the low preference situation, more congestion can be generated and the attackers do not need much time to chase pedestrians due to the high-density targets near the exit, which means that the attackers can assault more people in a quite short time. The two reasons together lead to the decrease in the death toll in the high preference situation.

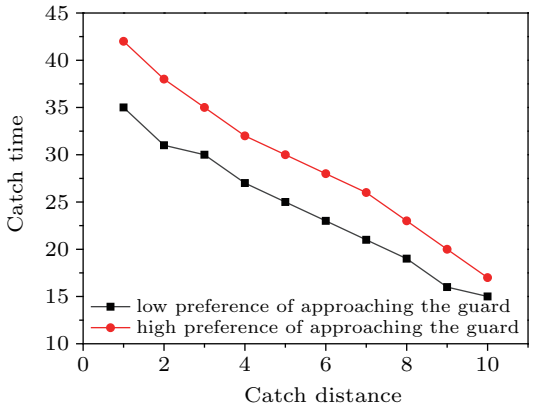


Fig. 11. Plots of capture time against capture distance.

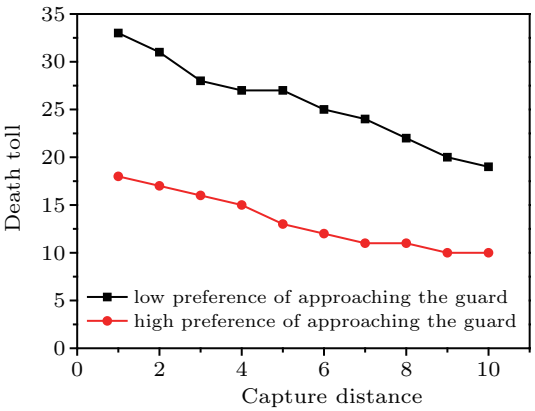


Fig. 12. Plots of death toll against capture distance.

3.4. Conclusions

This work aims to study the pedestrian dynamics considering the action of the guard in the context of artificial attacks. And two different strategies are compared and the effects of deterrence radius and capture distance on the pedestrian dynamic are studied.

The sensitivity coefficient k_g reflecting the extent of the effect of the guard on the decision-making of pedestrians is investigated. As the k_g value rises, the pedestrian is more likely to get close to the guard for survival, thus more people will stay around the guard, which can reduce the death

toll of pedestrians. Moreover, when the k_g value is large, the pedestrian prefers the guard to the exit for survival, which will greatly delay the evacuation process and cause a longer evacuation time.

Two different evacuation strategies of low and high preference of approaching the guard are compared. The guard always takes more time to capture all the artificial attackers and a lower death toll can be caused in the high preference situation than in the low preference situation.

The deterrence radius is defined as the critical distance that the attackers have to escape from the guard. As the deterrence radius rises, the attackers run away from the guard earlier and the guard has to take more time to catch these attackers. Further, the death toll first increases then decreases. Moreover, as the distance that the guard can catch the attackers rises, it will take much less time for the guard to capture all the attackers.

This study is expected to provide a valuable insight into optimizing evacuation strategy. While in reality, the dynamics of pedestrians, the attacker, and the guard are more complex, thus certain reasonable simplifications and assumptions have to be made, and some factors such as the attackers' initial distribution and number can affect the pedestrian dynamics and should be studied in depth in the future.

Appendix A: attacker movement update rules

Table 1 gives the attacker movement update rules at each time step for the attacker at (i, j). The attack selects one position which has not been occupied according to the priority position sequence to move. The attacker selects randomly any of them when two positions have the same priority and stay unmoved when all priority positions have been occupied.

Table 1. Attacker movement update rules at each time step for attacker at (i, j).

Step 1	Step 2	Step 3	Priority position sequence
		if $= a_t \sin\omega_a > a_t \cos\omega_a$	$(i-1,j+1) > (i-1,j) > (i,j+1)$
	if $a_t \cos\omega_a > 0$	if $= a_t \sin\omega_a = a_t \cos\omega_a$	$(i-1,j+1) > (i-1,j) = (i,j+1)$
		if $= a_t \sin\omega_a < a_t \cos\omega_a$	$(i-1,j+1) > (i,j+1) > (i-1,j)$
If $a_t \sin\omega_a > 0$	if $a_t \cos\omega_a = 0$	–	$(i-1,j) > (i-1,j+1) = (i-1,j-1)$
		if $= a_t \sin\omega_a > a_t \cos\omega_a$	$(i-1,j-1) > (i-1,j) > (i,j-1)$
	f $a_t \cos\omega_a < 0$	if $= a_t \sin\omega_a = a_t \cos\omega_a$	$(i-1,j-1) > (i-1,j) = (i,j-1)$
		if $= a_t \sin\omega_a < a_t \cos\omega_a$	$(i-1,j-1) > (i,j-1) > (i-1,j)$
	if $a_t \cos\omega_a > 0$	–	$(i,j+1) > (i-1,j+1) = (i+1,j+1)$
If $a_t \sin\omega_a = 0$	if $a_t \cos\omega_a = 0$	–	$(i,j) = (i,j)$
	if $a_t \cos\omega_a < 0$	–	$(i,j-1) > (i-1,j-1) = (i+1,j-1)$
		if $= a_t \sin\omega_a > a_t \cos\omega_a$	$(i+1,j+1) > (i+1,j) > (i,j+1)$
	if $a_t \cos\omega_a > 0$	if $= a_t \sin\omega_a = a_t \cos\omega_a$	$(i+1,j+1) > (i+1,j) = (i,j+1)$
		if $= a_t \sin\omega_a < a_t \cos\omega_a$	$(i+1,j+1) > (i,j+1) > (i+1,j)$
If $a_t \sin\omega_a < 0$	if $a_t \cos\omega_a = 0$	–	$(i-1,j+1) > (i-1,j) > (i,j+1)$
		if $= a_t \sin\omega_a > a_t \cos\omega_a$	$i+1,j-1) > (i+1,j) > (i,j-1)$
	if $a_t \cos\omega_a < 0$	if $= a_t \sin\omega_a = a_t \cos\omega_a$	$(i+1,j-1) > (i+1,j) = (i,j-1)$
		if $= a_t \sin\omega_a < a_t \cos\omega_a$	$(i+1,j-1) > (i,j-1) > (i+1,j)$

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