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An extended model for describing pedestrian evacuation under the threat of artificial attack

Changkun Chen [a,*], Yunhe Tong [a], Congling Shi [b,*], Wenlong Qin [a]

[a] Institute of Disaster Prevention Science & Safety Technology, Central South University, Changsha, 410075, PR China
[b] Beijing Key Laboratory of Metro Fire and Passenger Transportation Safety, China Academy of Safety Science and Technology, Beijing 100012, PR China

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ABSTRACT

An extended floor field model was proposed to investigate evacuation behaviors of pedestrians under the threat of artificial attack. In this model, pedestrian movement governed by the static and dynamic floor field, and the motion and assault of artificial attacker were involved simultaneously. Further, injuries with lower velocity and deaths of pedestrians caused by the attacker during evacuation were considered. And a new parameter k_t was introduced. It is the sensitivity coefficient of attack threat floor field and could reflect quantitatively the extent of effect of attack threat on the decision-making of the individual. Moreover, effects of several key parameters such as the sensitivity coefficient, assault intensity and pedestrian density on evacuation dynamics were studied. Results show that pedestrian evacuation would display interesting phenomena transiting from rolling behavior to along-the-wall motion with aggravating extent of the impact of attackers on pedestrians, which refers k_t in the model varying from 0.5 to 0.8. As assault intensity increases, more casualties would be caused and the available evacuation time would decrease, which means people have to flee the room in a shorter time period for survival. When the pedestrian density increases, more clogging at the exit would be generated and pedestrians would be more difficult to evacuate due to the limited capacity of egress and the reduction in the average speed of pedestrian flow caused by the injured. And the injured with limited motion capacity could hardly complete the evacuation owing to that they need more evacuation time and would retard the speed of the pedestrian flow.

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1. Introduction

Artificial attacks, such as antisocial attack, terrorist attack and so on, commonly occur in crowded public areas with difficulty in evacuation and result in a large number of casualties. For example, in 2016, there were 25673 deaths caused by terrorism according to the report [1], which caused a huge psychological panic to the public. As an effective means of reducing disaster losses, emergency evacuation, especially in the context of artificial attacks, should be paid more attention to.

Previous research focused on pedestrian dynamics in general walking situation and many models that could reproduce realistic pedestrian behavior have been proposed. These models can be classified into two categories – macroscopic and microscopic. Macroscopic models treat the crowd as a flowing continuum and describe pedestrian movements by hydrodynamics method [2]. While microscopic models, such as Cellular Automata [3], floor field model [4] and social force model [5], would consider each pedestrian as a self-driving particle and take the decision of the individual and interaction among pedestrians into consideration. Particularly, floor field model, where individuals make their decision according to the so-called transition probabilities modified by the static and dynamic floor field, is a well-studied pedestrian model using cellular automata. Due to its flexibility and extendibility [6], floor field model is extensively used and could successfully model evacuation behavior and self-organization encounter in pedestrians dynamics, such as clogging [7], pedestrian flow through multiple bottlenecks [8], oscillation at the bottleneck [9] and conflicts at the exit [10].

Generally speaking, interactions between pedestrian and pedestrian or environment are two main factors studied in pedestrian dynamics. And interactions among pedestrians are repulsive generally because one likes to keep a minimal distance to others in order to avoid bumping into them. While in certain situations,

* Corresponding authors.
E-mail addresses: cckchen@csu.edu.cn (C.K. Chen), shicl@chinasafety.ac.cn (C.L. Shi).

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pedestrians are likely to be attracted by relatives [11], guides [12] or the crowd in view of herding effect [13]. Indeed, complex collective behaviors originate from elementary individual interactions [14]. The dynamic features of pedestrian evacuation such as stop and go waves [15], self-slowing behavior [16], faster-is-slower effect [17], paired effect [18] and collision avoidance [19] have been observed. Meanwhile, surroundings of pedestrians during evacuation affect crowd flow greatly. Pedestrian behavior in exit [20], competitive room [21], the bottleneck [22] and T-shaped intersection [23] have been well-studied and many significant and valuable results were obtained.

However, pedestrian dynamics would be more complicated and unpredictable when people are under the imminent threat of attackers, because it involves interaction between pedestrian and other pedestrians, environment or the attacker simultaneously in this situation. Additionally, autonomous attackers will assault people on the basis of some principles and change their motions according to pedestrian flow. On the other hand, the individual assaulted by attackers will die, or lose the ability to move due to injury. Henein [24] studied crowd forces and associated injuries by Kirchner's field model including the force and the pedestrian who experience excessive accumulated force would be injured and lose the individual control, which is different from the pedestrian who would suffer the outbreak of violence caused by the attacker. Kamimura [25] researched collective motion of particles with pursuit-and-escape interactions, which is similar to the attack scenario that one chaser pursues the crowd. Also, there are some recent studies on pedestrian dynamics in the context of artificial attacks. In 2017, Li [26] proposes a three-stage model to reproduce a series of complex behaviors and decision-making processes at the onset of an attack, and the impact of the terrorist attack on pedestrian dynamics has been well-studied. Recently, pedestrian dynamics in the context of artificial attacks has received attention. Nonetheless, fewer researchers focus on the pedestrian evacuation that involves the attacker affected by crowd flow and pedestrian under the threat of artificial attack concurrently.

In this paper, an extended floor field model is established to investigate evacuation behaviors of pedestrians under the threat of artificial attack. And the pedestrian movement, the attacker's motion and assault are involved. Further, injuries with limited motion capacity and deaths of pedestrians assaulted by the attacker were considered. The rest of this paper is organized as follows: An extended floor-field model, considering the interaction between the attacker and pedestrian is introduced in section 2. In section 3, effects of several key parameters on pedestrian evacuation are surveyed and simulation results are discussed. In section 4, the conclusion is made and the paper is closed.

2. Model description

This model is extended on the basis of floor field model [4], where individuals make their decision according to the so-called transition probabilities modified by the static and dynamic floor field. In the proposed model, the space is represented with two-dimensional foursquare cells. Each cell is an identical square area of 0.4 m × 0.4 m [27] and can either be empty or occupied by an obstacle, a pedestrian or an attacker. In each discrete time step, pedestrians move one size to his neighborhoods or remain unmoved according to the transition probabilities. Meanwhile, the attacker would aim to kill more people, so the attacker is attracted to the crowd and move toward the corresponding direction according to the calculated attractive resultant. Furthermore, the attacker would assault pedestrians by the proposed assault model, and the assaulted person would be injured. It is certain that the motion capacity of the injured would be degraded and the pedestrian might be killed when assaulted by the attacker for many times. Based

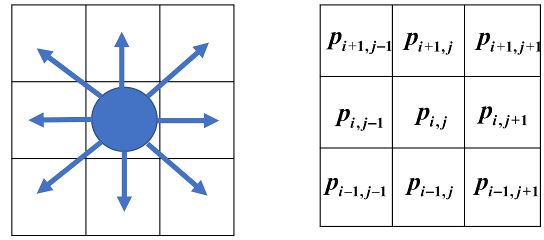

Fig. 1. Possible movement directions of the pedestrian and the transition probabilities p_{ij}.

on these factors, in this model, the pedestrian would be injured and half the speed when assaulted by the attackers for the first time, and the injured pedestrian would die when attacked again. Moreover, a direct algorithm for multi-velocity in cellular-automata model [28] is used in our model. It would be more simple when there are only two different velocities. The evacuation time is divided into two sub-time steps Δt_{sub}, and the locations of all occupants will be updated at every time increment Δt_{sub}. However, the injured with half speed only moves one cell distance for every two sub-time steps, and therefore the injured will be waiting for his turn to move until the sequence number of sub-time step is $2, 4, 6, \ldots$. That is, at the same time, the uninjured with normal speed will move once in every sub-time steps.

2.1. Pedestrian movement

At every time step, the pedestrian must decide where to move or stay still. In this model, pedestrians would consider evacuation scenario, attack threat, and influence of other pedestrians, so as to make the optimal decision. Pedestrian movement is governed by the transition probabilities [4], expressed as Equation (1), given by the interaction with the static and dynamic floor field which will be described below. And the Moore neighborhood [29], composed of a central cell and its eight surrounding cells, is used in this model. Consequently, a 3×3 matrix of preferences p_{ij}, as shown in Fig. 1, is constructed which contains the transition probabilities of its neighbors for cell (i, j). However, it should be noted that the transition probabilities mean the pedestrian prefer an optimal direction of higher fields, rather than move in a direction probabilistically.

$$p_{ij} = N\left[\exp(k_s S_{ij} + k_i I_{ij} + k_t T_{ij})(1 - n_{ij})\right] \quad (1)$$

Equation (1) describes the transition probabilities p_{ij} of cell (i, j), where N is a normalization factor calculated by Min–max normalization theory [30] which is devoted to linear normalizing the origin data, ensuring the result fall in the $[0, 1]$ interval, and the N is expressed as Equation (2).

$$N = \frac{p' - \min(p'_{\text{moore}})}{p'(\max(p'_{\text{moore}}) - \min(p'_{\text{moore}}))} \quad (2)$$

where p'_{moore} is the original matrix that has not been standardized and p' is the element of p'_{moore}.

In Equation (1), S_{ij}, T_{ij} and I_{ij} denote the static floor field, attack threat, and interactions among pedestrians floor field of cell (i, j), and their corresponding sensitivity coefficients are k_s, k_t and k_i, respectively. These coefficients determine the weight of each floor field and theoretically range from 0 to 1. When the coefficient is 0, it means the corresponding floor field has no effect on individuals, and when its value is 1, it implies the individual motion is completely determined by the corresponding floor field. It should be noted that the value of k_t should be greater than 0.5 to ensure that the attack threat floor field would have more weight than the

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