Physics Letters A 381 (2017) 435–439

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Dual effects of pedestrian density on emergency evacuation

Yi Ma [a,b,*], Eric Wai Ming Lee [b], Richard Kwok Kit Yuen [b]

[a] School of Transportation and Logistics, Southwest Jiaotong University, Chengdu, China
[b] Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong

ARTICLE INFO

Article history:
Received 2 October 2016
Received in revised form 29 November 2016
Accepted 29 November 2016
Available online 2 December 2016
Communicated by C.R. Doering

Keywords:
Pedestrian evacuation
Visibility
Exit
Pedestrian density

ABSTRACT

This paper investigates the effect of the pedestrian density in building on the evacuation dynamic with simulation method. In the simulations, both the visibility in building and the exit limit of building are taken into account. The simulation results show that the effect of the pedestrian density in building on the evacuation dynamics is dual. On the one hand, when the visibility in building is very large, the increased pedestrian density plays a negative effect. On the other hand, when the visibility in building is very small, the increased pedestrian density can play a positive effect. The simulation results also show that when both the exit width and visibility are very small, the varying of evacuation time with regard to the pedestrian density is non-monotonous and presents a U-shaped tendency. That is, in this case, too large or too small pedestrian density in building is disadvantageous to the evacuation process. Our findings provide a new insight about the effect of the pedestrian density in building on the evacuation dynamic.

1. Introduction

Pedestrian evacuation under emergency in buildings has been recognized as an important but challenging issue, which has attracted considerable attention in the fields of engineering and physical science over the last decades. Currently, experiment and simulation are mainly means for the study of pedestrian evacuation. On the one hand, many experimental studies have been carried out to understand the pedestrian individual and collective behaviors, the self-organized phenomena, and the dynamical features of evacuation. On the other hand, many pedestrian evacuation simulation models have been developed, such as the social force model [1], the cellular automaton model [2–4], the lattice gas model [5,6], the agent-based model [7], and the animal dynamics-based model [8,9]. Many typical collective behaviors and self-organized phenomena, such as herding behavior, clogging and arching phenomena, and "faster is slower" effect can be reproduced by these simulation models [1].

For the pedestrian evacuation in buildings, the exit of building is critical, especially, for the pedestrian evacuation in the building with large population. In this case, evacuation is usually delayed as the pedestrian flow exceeds the capacity of the exit. Up to now, many studies have been conducted to address the relation between the evacuation dynamics and the placement, the number, the width of exits. For example, Nagai et al. [10] found that the evacuation time decreases as the number of exits increases, and the evacuation time of two exits is about one-half of that of the single exit. Zhao et al. [11] addressed how the exit width and the door separation influence the evacuation time. They found that the exit width should be bigger than a critical value, and the door separation should be neither too small nor too big. Lei et al. [12,13] studied the effect of exit width on evacuation time and maximum flow rate. Their study results also revealed the existence of the critical value of exit width. Furthermore, Yue et al. [14] conducted simulation study of evacuation in the room with asymmetrical exits layout. Nagai et al. [6] investigated the evacuation processes of walkers and crawlers under different exit widths.

In many cases, such as fire accident and earthquake, the visibility in building can be usually reduced by the consequent smoke or the blackout. Evacuation may be delayed by the reduced visibility. Up to now, pedestrian evacuation under limited visibility have been investigated by various simulation models, such as, the social force model [15], the cellular automaton model [16], the floor field model [17], and the agent-based model [18]. Also, there have been many experimental studies conducted in different scenarios addressed how the visibility influences pedestrian evacuation dynamics [10,19–23].

It is widely understood and recognized that when the visibility is very good, more people in building usually means more evacuation time because of the limited capacity of the exit. That is to say, the higher the pedestrian density in building, the more the

* Corresponding author at: Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong.
E-mail address: yima23-c@my.cityu.edu.hk (Y. Ma).

http://dx.doi.org/10.1016/j.physleta.2016.11.043
0375-9601/

evacuation time needed. However, it may be not the case for the pedestrian evacuation under limited visibility. In order to address this question, we conduct the pedestrian evacuation simulation study based on the extended social force model. In the simulation study, both the visibility and exit conditions are taken into account. We attempt to reveal that how the pedestrian density in building influences the evacuation dynamic in the cases of different visibilities and different exit widths.

2. Model and methods

The social force model [1] is adopted to simulate basic pedestrian evacuation movement. The social force model is one of the most well-known pedestrian evacuation simulation models. In the model, each pedestrian i of mass m attempts to move with a certainly desired speed v_i^0 in a desired direction $\mathbf{e}_i$ by adjusting its actual velocity $\mathbf{v}_i$ within a certain characteristic time τ for reaching the target (e.g., exits). Meanwhile, the pedestrian i will try to keep a distance from other pedestrians j and walls w for avoiding the potential collision. In mathematical terms, the change of velocity at time t is given by equation (1).

$$M_i \frac{\mathrm{d}\mathbf{v}_i(t)}{\mathrm{d}t} = M_i \frac{v_i^0 \mathbf{e}_i - \mathbf{v}_i(t-\tau)}{\tau} + \sum_{j(\neq i)} \mathbf{f}_{ij}(t) + \sum_{W} \mathbf{f}_{iw}(t) \tag{1}$$

The interaction force $\mathbf{f}_{ij}$ between pedestrian i and j is calculated by:

$$\mathbf{f}_{ij} = A_i \exp[(r_{ij} - d_{ij})/B_i]\mathbf{n}_{ij} + kg(r_{ij} - d_{ij})\mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t \mathbf{t}_{ij} \tag{2}$$

where, the term $A_i \exp[(r_{ij} - d_{ij})/B_i]\mathbf{n}_{ij}$ represents the psychological tendency between pedestrian i and j to stay away from each other. A_i and B_i are constants, r_{ij} is the sum of the body radius of pedestrian i and j. $d_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$ is the distance of centers of mass between pedestrian i and j. $\mathbf{n}_{ij} = (n_{ij}^1, n_{ij}^2) = (\mathbf{r}_i - \mathbf{r}_j)/d_{ij}$ is the normalized vector pointing from pedestrian j to i. The terms $kg(r_{ij} - d_{ij})\mathbf{n}_{ij}$ and $\kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t \mathbf{t}_{ij}$ are referred as "body force" and "sliding friction force", respectively. They will arise when pedestrian i and j touch each other (i.e., $d_{ij} < r_{ij}$). $g(x)$ equals to x only when $d_{ij} < r_{ij}$, otherwise equals to zero. k and κ are large constants. The vector $\mathbf{t}_{ij} = (-n_{ij}^2, n_{ij}^1)$ represents the tangential direction. $\Delta v_{ji}^t = (\mathbf{v}_j - \mathbf{v}_i)$. $\mathbf{t}_{ij}$ represents the tangential velocity difference.

Similarly, if d_{iw} corresponds to the distance between the pedestrian i and the wall w, $\mathbf{n}_{iw}$ corresponds to the perpendicular direction to the wall, and $\mathbf{t}_{iw}$ corresponds to tangential direction. The interaction force $\mathbf{f}_{iw}$ between the pedestrian i and the wall w can be given by:

$$\mathbf{f}_{iw} = A_i \exp[(r_i - d_{iw})/B_i]\mathbf{n}_{iw} + kg(r_i - d_{iw})\mathbf{n}_{iw} + \kappa g(r_i - d_{iw})(\mathbf{v}_i.\mathbf{t}_{iw})\mathbf{t}_{iw} \tag{3}$$

Finally, the change of position $\mathbf{r}_i(t)$ is given by:

$$\frac{\mathrm{d}\mathbf{r}_i}{\mathrm{d}t} = \mathbf{v}_i(t) \tag{4}$$

The visibility condition of scenario is taken into account. It is assumed that pedestrians can only see the things within the visual range of radius η due to visibility limitation. For the pedestrians who can see the exit, normally, they tend to move toward the exit directly, therefore, the desired directions $\mathbf{e}_i$ of them are set to point from their current positions to the exit. For the pedestrians who cannot see the exit, normally, these aimless pedestrians tend to follow the neighbors group detected within the visual field. During the process of following, on the one hand, they may move toward the central position of the neighbors group to avoid being isolated. Correspondingly, in the model, the desired directions $\mathbf{e}_i$ of them can be given by equation (5):

$$\mathbf{e}_i^{\alpha}(t+1) = \frac{\sum \mathbf{r}_j(t)/n - \mathbf{r}_i(t)}{|\sum \mathbf{r}_j(t)/n - \mathbf{r}_i(t)|} \tag{5}$$

where, n represents the number of neighbors within the visual range, including itself. The variable $\mathbf{r}_j(t)$ represents the position of each neighbor. On the other hand, they may attempt to align with the neighbors group due to herding effect. Correspondingly, in the model, the desired directions $\mathbf{e}_i$ of them can be given by equation (6)

$$\mathbf{e}_i^{\beta}(t+1) = \frac{\sum \mathbf{v}_j(t)/|\mathbf{v}_j(t)|}{|\sum \mathbf{v}_j(t)/|\mathbf{v}_j(t)||} \tag{6}$$

where, the vector $\mathbf{v}_j(t)$ denotes the moving direction of the neighbor j, including itself. In the model, we couple isolation avoidance behavior and herding behavior as given in equation (7):

$$\mathbf{e}_i(t+1) = \frac{\omega \mathbf{e}_i^{\beta}(t+1) + (1-\omega)\mathbf{e}_i^{\alpha}(t+1)}{|\omega \mathbf{e}_i^{\beta}(t+1) + (1-\omega)\mathbf{e}_i^{\alpha}(t+1)|} \tag{7}$$

where the weighting term $\omega = \exp(\lambda - d_{ic})$. d_{ic} is the distance between pedestrian i and the central position of neighbors. λ is the psychological safety value of pedestrian i for the distance d_{ic}. Here, the value of λ is assumed to be 0. When d_{ic} goes to 0, the value of ω will converge to 1, and $\mathbf{e}_i(t+1)$ will equal to $\mathbf{e}_i^{\beta}(t+1)$. That is, when the pedestrian i is already located at the center of the neighbors group, the behavior of "align with the neighbors group" will dominate. On the contrary, when d_{ic} is very large, $\mathbf{e}_i(t+1)$ will equal to $\mathbf{e}_i^{\alpha}(t+1)$. That is, when pedestrian i is very far from the center of the neighbors, the behavior of "move toward the central position of the neighbors group" will dominate.

Also, it is possible that pedestrians cannot see anything, including exit, neighbor. These isolated pedestrians are set to be move randomly.

Furthermore, the model parameters are specified as follows: for each pedestrian, the body radius $r = 0.3$ m, the mass $m = 80$ kg, the characteristic time $\tau = 0.2$ s, the desired speed $v_i^0 = 0.7$ m/s, the constants $k = 20000$ kg/s^2, $\kappa = 30000$ kg/s^2, $A = 2000$ N, $B = 0.08$ m.

3. Simulations and results

The simulations are conducted using above model. Simulation scenario is set to be an $L \times L$ squared room with an exit of width s at the middle of the right wall, where L is 15 m. Initially, pedestrians numbered from 1 to N are assumed to be distributed randomly with the random directions in the scenario. Under above scenario settings, the simulations are conducted with different visibilities η, different exit widths s and different pedestrian densities ρ. Furthermore, the evacuation is considered to be failed, if there is still pedestrian in the room after 100 s.

Fig. 1 gives the plots of the evacuation time T against the pedestrian density ρ for different visibilities $\eta = 1$ m, 2 m, 3 m, 4 m, 5 m, 6 m, 7 m, and 8 m in the cases of different exit widths $s = 1$ m, 2 m, 3 m, 4 m, 5 m, and 6 m.

From Fig. 1, we can see the evacuation time can always decrease with the increase in the visibility or the exit width for the certain pedestrian density. This finding is not expected. The similar result can be also seen in other literatures such as Refs. [11,15]. The underlying reason is that, generally, the evacuation time of pedestrians under the certain pedestrian density is mainly dependent on two factors: the congestion at the exit and the navigational