Physica A 465 (2017) 175–194

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Optimal layout design of obstacles for panic evacuation using differential evolution

Yongxiang Zhao [a,b], Meifang Li [a,*], Xin Lu [c], Lijun Tian [a], Zhiyong Yu [d], Kai Huang [a], Yana Wang [a], Ting Li [a]

[a] School of Economics and Management, Fuzhou University, Fuzhou 350108, China
[b] Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, USA
[c] College of Information System and Management, National University of Defense Technology, Changsha 410073, China
[d] College of Mathematics and Computer Science, Fuzhou University, Fuzhou 350108, China

HIGHLIGHTS

- Differential evolution is used to optimize the geometrical parameters of obstacles.
- Profiles of density, velocity, specific flow as well as crowd pressure are analyzed.
- Placing an obstacle in panic situations promotes the pressure to a much higher level.
- Physical mechanism of efficiency enhancement is a reduction of high density region.
- Panel is more robust than pillar to guarantee the enhancement of pedestrian outflow.

ARTICLE INFO

Article history:
Received 13 April 2016
Received in revised form 5 July 2016
Available online 20 August 2016

Keywords:
Panic evacuation
Social force model
Obstacle optimization
Pedestrian outflow
Differential evolution
Crowd pressure

ABSTRACT

To improve the pedestrian outflow in panic situations by suitably placing an obstacle in front of the exit, it is vital to understand the physical mechanism behind the evacuation efficiency enhancement. In this paper, a robust differential evolution is firstly employed to optimize the geometrical parameters of different shaped obstacles in order to achieve an optimal evacuation efficiency. Moreover, it is found that all the geometrical parameters of obstacles could markedly influence the evacuation efficiency of pedestrians, and the best way for achieving an optimal pedestrian outflow is to slightly shift the obstacle from the center of the exit which is consistent with findings of extant literature. Most importantly, by analyzing the profiles of density, velocity and specific flow, as well as the spatial distribution of crowd pressure, we have proven that placing an obstacle in panic situations does not reduce or absorb the pressure in the region of exit, on the contrary, promotes the pressure to a much higher level, hence the physical mechanism behind the evacuation efficiency enhancement is not a pressure decrease in the region of exit, but a significant reduction of high density region by effective separation in space which finally causes the increasing of escape speed and evacuation outflow. Finally, it is clearly demonstrated that the panel-like obstacle is considerably more robust and stable than the pillar-like obstacle to guarantee the enhancement of evacuation efficiency under different initial pedestrian distributions, different initial crowd densities as well as different desired velocities.

* Corresponding author.
E-mail address: limeifang@fzu.edu.cn (M. Li).

http://dx.doi.org/10.1016/j.physa.2016.08.021

1. Introduction

In recent years, pedestrian evacuation in case of emergencies, such as fire, earthquake, tsunamis, or a terrorist attack, has attracted considerate attention. Traffic behaviors have been successfully reproduced by statistical physics models including social force model [1–3], cellular automation models [4–6], lattice gas models [7–10] and queueing-based models [11] proposed by MacGregor Smith and Cruz [11]. These models provide important design guidelines for transportation and building environment [12–15], as well as offering strategies for emergency evacuation in all kinds of natural or man-made disasters [16–18].

In panic situations, where people push each other to get out of a room, it is possible to increase the outflow by suitably placing an obstacle in front of the exit [1,19–24]. Obstacles may enhance pedestrian flow by more than 30% and even double the flow that would occur without the obstacle [25]. However, the obstacle's size and placement should be properly tuned in order to obtain an optimal improvement in the evacuation time. When these geometrical parameters of obstacles are unsuitable, the area near the exit may become more crowded which will slow down the outflow rather than increase it. For instance, it will become harmful and inefficient for obstacles placed symmetrically near the exit door. Therefore, the best way for achieving an optimal evacuation outflow is to shift the obstacle slightly from the center of the exit [26,27].

Although a significant amount of researches have already been performed on how to control the pedestrian outflow and to maximize the escape velocity in panic situations, there is no very simple but effective approach to obtain the optimal geometrical parameters of obstacles, including the optimal size of obstacle, the optimal obstacle–door gap and asymmetric offset distance of obstacle to the center of the exit. Recently, genetic algorithm was used to provide the layout design of the obstacles that can reduce the tangential momentum and increase the escape speed [20]. However, in their works, only pillar-like obstacles were considered. In fact other shaped obstacle such as a thin flat panel also has ability to enhance the outflow efficiency. G.A. Frank et al. investigated the impact of human behavior on an escaping situation, obstructed by a pillar and a panel close to the door [19]. Although their papers showed clearly that both pillar and panel are simple and effective shapes of obstacle, they did not tell us what is the optimal layout for pillar-like obstacle and panel-like obstacle. Therefore, the main objective of our paper is to find an optimal tuning on obstacle size and placement in order to achieve a minimum leaving time for all the pedestrians in the room, and a differential evolution will be used to provide the optimal layout design of pillar-like and panel-like obstacles.

Moreover, Kirchner et al. proposed that placing an obstacle in panic situations might avoid clogging near the exit by absorbing pressure, and consequently, the clogging effects translate to an early stage [26]. Helbing et al. suggested that the obstacle may behave like a wave breaker to absorb the pressure in the crowd and to reduce it to a subcritical level [25]. Zuriguel et al. also agreed that the physical mechanism behind the clogging reduction while placing an obstacle is a pressure decrease in the region of arch formation [23]. However, to our knowledge, the spatial distribution of pedestrian pressures are rarely directly compared among the different shaped obstacles. Therefore, in this paper, we will further calculate the maximum pressure, the average pressure, and the spatial distribution of pedestrian pressures among no obstacle, pillar-like obstacle and panel-like obstacle in order to prove that placing an obstacle can reduce the pressure in the region of exit or, on the contrary, increase the pressure to a more dangerous level.

The paper is then organized as follows. Firstly, a robust differential evolution (DE) is employed to optimize the geometrical parameters of different shaped obstacles in order to achieve a minimum leaving time for all the pedestrians in the room. Then the effects of these geometrical parameters of obstacles on evacuation time have been further analyzed respectively, including the size of obstacle, the obstacle–door gap and the offset distance of obstacle to the center of the exit. Moreover, to uncover the essence of evacuation performance enhancement, the profiles of density, velocity and specific flow for no obstacle, pillar-like obstacle and panel-like obstacle are compared based on the Voronoi method, and the panel-like obstacle can significantly decrease the high crowd density near the area of exit which leads to the remarkable enhancement of escape speed and pedestrian outflow. Especially, the maximum pressure, average pressure, and the spatial distribution of pedestrian pressures among no obstacle, pillar-like obstacle and panel-like obstacle are analyzed, and it is clearly demonstrated that placing an obstacle surprisingly increases the average crowd pressures in the region of exit which is markedly different from the hypothesis of existing literature. Finally, to further verify the robustness and universality of evacuation performance for different shaped obstacles, we have compared the evacuation time among no obstacle, pillar-like obstacle and panel-like obstacle under different initial pedestrian distributions, different initial crowd density, and different desired velocities of escape.

2. DE-based geometrical parameters optimization of obstacles

2.1. Social force model

The social force model [1–3] is a pedestrian behavior model based on socio-psychological and physical forces. It assumes that each pedestrian meets the laws of motion as a particle, and uses force vectors to describe the real force and the intrinsic motivation. Each of N pedestrians i of mass M_i likes to move with a certain desired speed v_i^0 in a certain direction e_i^0, and thus tends to adapt his or her actual velocity v_i with a certain characteristic time τ. Simultaneously, pedestrians i will try to keep a distance from other pedestrians j and walls w by the interaction forces f_{ij} and f_{iw} respectively. Therefore, the velocity