Research on the Impact of Obstacles at Bottlenecks on the Efficiency of Crowd Evacuation

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Abstract: With economic development and pandemic relief, crowd gatherings have become a focal point. Despite academic interest in crowd evacuation due to sudden events, the influence of exit obstacles has been neglected. This paper builds on prior research, presenting a social force model for emergency crowd evacuation under obstacle diversion. It explores the diverse effects of various obstacles on evacuation efficiency through experiments, mathematical modeling, and simulations. The study aims to offer scientific insights for urban planning based on the analysis of evacuation outcomes under different obstacle configurations.

Keywords: Evacuation of Crowds; Obstacles; Evacuation Efficiency; Exit Planning; Social Force Model

1. Introduction

With economic development, the surge in crowd gatherings is a notable social phenomenon. This has sparked academic interest in crowd evacuation during sudden events like earthquakes, fires, and terrorist attacks. Existing research predominantly focuses on crowd characteristics, interactions, and exit choices, neglecting the impact of exit obstacles on evacuation.

Some scholars have explored methods to enhance evacuation efficiency by manipulating obstacle settings through experiments and simulations [1–3]. For instance, Zhao et al. found that a single square obstacle had minimal effect on evacuation time, while two square obstacles or a rectangular barrier significantly reduced evacuation time, improving efficiency [1]. Wang et al. influenced crowd density distribution in bottleneck areas by placing isolation barriers at exits, enhancing evacuation efficiency by weakening internal interactions within the crowd [2]. However, past studies often overlooked the impact of differences between obstacles, such as shapes, quantities, and layouts.

In this context, this paper extends previous research by proposing a social force model for emergency crowd evacuation with exit obstacles. The objective is to explore the impact of obstacles on evacuation efficiency and the microscopic mechanisms alleviating congestion. Through a systematic examination of obstacle settings, we emphasize the importance of factors like shapes, quantities, and layouts. This research contributes to understanding crowd evacuation behavior, enhancing urban safety, and optimizing emergency plans. Combining empirical research and theoretical models, we aim to offer accurate guidance for future urban planning and public safety management.

2. Model Framework

2.1 Simulation Scenario

For result consistency, the simulation scenario is a closed area of 8m × 10m with a single 1m-width exit, aligning with safety standards. Various obstacles, including single or symmetrically distributed pairs of circular, square, and trapezoidal columns, are placed near the exit to study the impact of different shapes and quantities on crowd evacuation efficiency.

When setting obstacles, it is vital to make their areas nearly equal for consistent variables. To simplify calculations, set the areas of different obstacles to approximately 2m2 each. For instance, the circular obstacle has a radius of 0.798m, the square obstacle can be 1.4m × 1.4m, and the trapezoidal obstacle has upper and lower base lengths of 1.5m and 3.5m, with a height of 0.8m.

2.2 Evolution Rules of the Model

In 1995, German scholar Helbing[3,4], based on Newton's Second Law, integrated and supplemented the forces acting on pedestrians during walking, proposing the Social Force Model. The dynamic equation of the model is as follows:

$$m_i \frac{dv_i(t)}{dt} = f_i^0 + \sum_{j(\neq i)} f_{ij} + \sum_{w} f_{iw} \qquad (2-1)$$

In equation (2-1), Helbing categorizes forces during walking into three types: self-propulsion force f_i^0, interaction force between pedestrians f_{ij}, and interaction force between pedestrians and the environment f_{iw}. Here, m_i is the pedestrian's mass, and $\frac{dv_i(t)}{dt}$ is the pedestrian's acceleration. This paper extends Helbing's Social Force Model by including interaction forces between pedestrians and exit obstacles, aiming to realistically capture pedestrians' movements when detouring around obstacles. The dynamic equation is as follows:

$$m_i \frac{dv_i(t)}{dt} = f_i^0 + \sum_{j(\neq i)} f_{ij} + \sum_{w} f_{iw} + \sum_{o} f_{io} \qquad (2-2)$$

In equation (2-2), the interaction force between pedestrians and exit obstacles is denoted as f_{io} and its expression is given by:

$$f_{io} = \left\{ Aexp\left[\frac{r - d_{io}}{B}\right] \right\} n_{io} + K\Theta(r - d_{io})(v_i \cdot t_{io}) t_{io} \qquad (2-3)$$

In equation (2-3), d_{io} is the distance from pedestrian *i* to the center of the obstacle. For a circular obstacle, $r = r_i + r_o$, where r_i and r_O are the radius of pedestrian *i* and the obstacle, respectively. For square r trapezoidal obstacles, $r = r_i$ and the interaction force between pedestrian *i* and the obstacle is the vector sum of the forces exerted by the pedestrian on each boundary of the obstacle. $\Theta(x)$ is a piecewise function used to determine contact between pedestrians: $\Theta(x) = x$ if $x > 0$ (contact) and $\Theta(x) = 0$ if $x \leq 0$ (no contact).

3. Simulation Analysis and Discussion

3.1 Impact of Obstacles on Crowd Evacuation Efficiency

We experimentally vary the distance (d) from obstacles to the exit to investigate if obstacle presence reduces evacuation time and enhances efficiency. Figure 4.1 displays numerical simulation results for a scenario with two obstacles. Each data point represents the average of multiple samples, mitigating the impact of initial pedestrian distribution before evacuation.

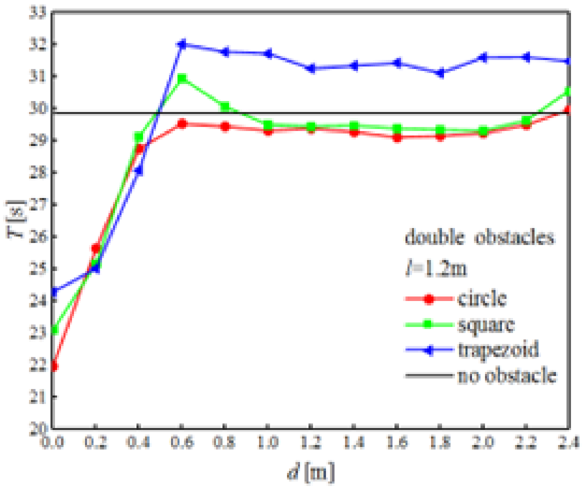

Figure 3.1 Diagram of the relationship between evacuation time T and the distance d from obstacles to the exit

Figure 3.1 compares evacuation times with and without obstacles symmetrically placed in front of the exit. Notably, when two obstacles are symmetrically positioned near exit walls (d=0m), all three obstacle shapes significantly reduce evacuation time, demonstrating higher efficiency than without obstacles. The experiments affirm that strategically placing dual obstacles positively alleviates bottleneck issues at evacuation exits, enhancing evacuation efficiency.

Furthermore, when $0 < d < 0.6$m, the evacuation time gradually increases with the increase of *d*, and the contribution of obstacles to improving evacuation efficiency decreases as the distance from obstacles to the exit increases. When $d > 0.6$m, the time required for evacuation remains almost constant with increasing *d*.

3.2 Mechanism Analysis of Obstacle Alleviating Arching Effect

Figure 3.2 illustrates the spatiotemporal evolution pattern during crowd evacuation to further explore how obstacles alleviate congestion bottlenecks. Pedestrians are color-coded based on the magnitude of the squeezing force (f_{push}) they experience, with darker colors indicating higher forces.

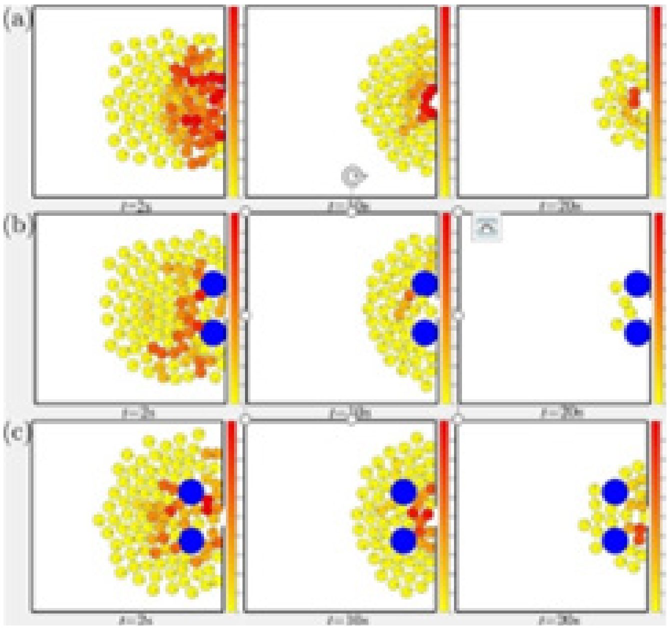

Figure 3.2 Temporal and spatial patterns of crowd evacuation process under different distances from obstacles to exits. (a) No obstacle; (b) D=0m; (c)D=1m.

In Figure 3.2 (a), during the initial evacuation stage, the crowd quickly gathers toward the safe exit. However, without exit obstacles, a wide congestion area forms, causing significant squeezing forces (f_{push}) and the development of an arching effect. This impedes quick pedestrian escape and, in severe cases, may lead to stampede incidents, posing life-threatening risks. The bottleneck induced by the arching effect takes a long time to dissipate, resulting in prolonged evacuation times.

Contrastingly, Figure 4.2 (b) depicts the scenario with symmetrically placed obstacles near the exit. Initially, the crowd gathers near the exit, but the obstacles effectively separate them, reducing the probability of contact and squeezing. The obstacles act as a buffer, slowing down pedestrians behind them, creating an arching effect that shifts the occurrence to behind the obstacles. This minimizes direct contact between pedestrians, resulting in a low number and proportion of collisions in the critical area in front of the exit. Consequently, this configuration allows for a rapid escape, improving evacuation efficiency. When two circular obstacles are symmetrically placed away from the exit (d=1m) (as shown in Figure 4.2(c)), evacuation blockage occurs earlier, increasing the distance for pedestrians to reach the safety exit. Simultaneously, pedestrians on either side of the obstacles converge towards the exit through the space between the obstacles and the wall, creating strong mutual squeezing forces. This results in a reduced efficiency of crowd passage at the exit, leading to a longer evacuation time.

4. Article Summary

This study focuses on addressing congestion bottlenecks to minimize evacuation time and ensure personal safety in scenarios with obstacles at exits. We present a social force model for crowd emergency evacuation, exploring the impact of obstacles with different shapes, quantities, and layouts on evacuation efficiency.

After a thorough investigation, key conclusions reveal that symmetrically placing two obstacles near exit walls with a wide gap, whether circular, square, or trapezoidal, effectively reduces evacuation time. Circular obstacles show a more significant improvement in efficiency.

In summary, this study offers valuable insights for designing and optimizing exits in crowded locations. Understanding how obstacle shapes, quantities, and layouts affect evacuation efficiency provides a scientific basis for future planning, contributing practically to enhancing urban safety and optimizing emergency management strategies.

References

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