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Geometric constraint based pedestrian movement model on stairways

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HIGHLIGHTS

- Pedestrian Footstep Model is put forward to simulate pedestrian movement on stairways.
- The model is verified and validated by a well-structured single-file pedestrian movement results.
- Combined effects of riser height and tread depth are discussed.
- Dynamics of pedestrian movement on stairways are investigated.

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ABSTRACT

Stairways connect different levels of ground and serve as the only means of escape in case of fire in most buildings. Thus pedestrian movement dynamics on stairways has attracted researchers from different disciplines. As a result of the geometric constraints of the stairs, pedestrian movement features on stairways are different from level ambulation. However, most current modeling pedestrian models for stairway movement have not taken into account the constraints of stairs. In the present study, a computer simulation model named Pedestrian Footstep Model is formulated. In this model, the tread depth and riser height together determine a pedestrian's footstep length, which finally affects the actual movement speed that a pedestrian can achieve. In this way, the model cannot only simulate pedestrian movement on stairs but also on horizontal ground. Dynamics of pedestrian crowd movement process are explored considering different stair geometry features, floor height and flow situations.

1. Introduction

Over the past decades, most pedestrian flow models have been established to simulate two-dimensional pedestrian level ground movement, such as social force model [1], cellular automata model [2], lattice gas model [3] and agent-based model [4]. Actually, there exist a large number of three-dimensional staircases, which are critical vertical circulations that link different floors or levels and thus play an important role during evacuation in various built facilities. Compared with horizontal motion, pedestrian movement characteristics on stairways are very different due to the constraints of staircase

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geometry as well as the influence of pedestrian gravity. Although some models have been proposed to investigate the flow characteristics and pedestrian movement on stairs, these models have essentially treated staircases as two-dimensional spaces. For example, a fatigue-motivation model was presented [5] to investigate the impact of fatigue on speed of evacuees during evacuation from staircases. Xu and Song [6] proposed a multi-grid model for staircase evacuation by considering factors including rectangular body shape, pedestrian turning behavior and various walking speeds in different densities. Then Huo et al. [7] improved the above model to investigate the pedestrian merging behavior at the floor-stair interface. More recently, two other models have reported that they were able to simulate three-dimensional evacuation process in multi-floor buildings [8,9]. However, they only employed two-dimensional social force model by projecting all stair surfaces as horizontal planes. In general, these two-dimensional models lead to the deviation of simulation from actual situations as they cannot represent the unneglectable influence of the three-dimensional staircase geometry on pedestrian movement features.

Despite the challenge and complexity of three-dimensional models, researchers have still been paying more attention to investigate features of pedestrians moving upstairs and downstairs. Some of the studies have mainly focused on the biomechanics attribute of gait adaptations [10], while only a few models have concentrated on pedestrian movement behaviors on staircases or complex terrains. For example, a prediction model was developed to calculate the walking speed of a pedestrian on stairs by taking into consideration stair gradient and leg extensor power of a pedestrian [11]. Wang et al. [12] combined the topographic characteristics of the environment with calculation of pedestrian varying speed in a three-dimensional surface and proposed a cellular automata model to simulate residents' evacuation in a mountain area in China. Wei et al. [13] proposed a three-dimensional cellular automaton to depict the characteristics of bi-directional pedestrian flow on a channel containing two stairs at both ends. You et al. [14] and Hu et al. [15] put forward two similar three-dimensional cellular automata models to analyze the evacuation movement from a stepped classroom with dynamic variation of the exit width, and the transition probability in their models was calculated based on the combination of the attraction, exit congestion degree, repulsive force and friction force. It should be pointed out that both the above models suffer from unrealistic assumptions because of the space discretization. In their model, uniform cubic cells with side lengths equal to 0.3 or 0.4 m were used. The speed setup of walking upstairs and downstairs was faster than on level ground, which is also unrealistic.

In addition, social force model has been improved to depict pedestrians' movement and evacuation on stairs. Based on the heuristic social force model proposed in Ref. [16], Qu et al. [17] established an enhanced model by introducing special rules, which include three aspects: (1) representing the body of each pedestrian as a set of three circles; (2) pedestrians moving forward with integer steps; and (3) using a variable relaxation time. The combination of these three rules resulted in (i) the improvement on rotation movement representation when two pedestrians collide with each other; and (ii) the modifications on optimal direction calculations. The authors reported that this model can describe heterogeneous individual velocities and mechanisms of pedestrian movement under different staircase geometries. However, it should be noted that increasing relaxation time in the simulation would result in unreliable pedestrian movement features. Wang and Weng [18] improved the original social force model through the introduction of gravity and the modification of main parameter values, to simulate three-dimensional stairway evacuation. This method works, however, it is hard to find a direct relation between the slope value and the parameter which quantifies the influence of gravity.

To sum up, the existing three-dimensional models have made much progress in terms of authenticity of simulation of pedestrians moving on staircases. However, they also have some limitations. For example, discrete models may be subject to inaccurate discretization of staircase geometry and unreal descending and ascending speeds. Although the force-based methods may, to some extent, overcome the restraints of the aforementioned problems in discrete models, such models are quite rare.

Thus, to bridge pedestrian movement features with stairway geometry features, a Pedestrian Footstep Model is established that takes into account stair constraints in this paper. The rest of this paper is organized as follows. In Section 2, we introduce the geometry constrained pedestrian model. In Section 3, the model was verified and validated with the data from a recent experiment and a field survey. In Section 4 simulation studies on pedestrian movement on stairs with different dimension features were conducted. Section 5 draws conclusions of this paper.

2. Geometry constrained pedestrian model

Pedestrian movement on stairways is a 3-dimensional movement, which can be projected onto horizontal and vertical planes. To model pedestrian movement on stairway, we mainly consider the projected pedestrian horizontal movement on stairway. For the reason that quite a few models have been established for pedestrian movement on level ground, these models can serve as a foundation when modeling the horizontal projection of pedestrian staircase movement. In the following subsections, we first discuss the constraints of stairs, show how the geometric features affect pedestrian movement and finally introduce the model.

2.1. Footstep length

It was found that when moving on level ground, the next position of a pedestrian has to be on the footstep circle around him/her [19]. However, when walking on stairs, pedestrian footstep feature is different because the friction demand on stairs