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Modeling the pedestrian's movement and simulating evacuation dynamics on stairs

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This paper presents an enhanced social force model to describe the pedestrian's movement and evacuation dynamics on stairs. Compared with original models that described the pedestrian's planar motion, our model introduces some mechanisms of the staircase movement, such as the influence of staircase geometry, the restriction of the step size and the optimal velocity selection. The body shape of each pedestrian is regarded as a set of three circles to precisely quantify the movement. In addition, the rotation dynamics are included into the model to describe the congestion effect. The improved model can obtain individual velocity under different staircase geometries and the flow characteristics of the evacuation dynamics. Some empirical data and a series of observations captured in two subway stations in Beijing are applied to study the characteristics and further validate the model. The results show that our model performs well consistent with the observed data. At last, simulations are implemented to find the solutions of estimating the evacuation time and evaluating the capacity of stair.

1. Introduction

Stairs are widely used in all kinds of buildings, especially in large scale public places, i.e., subway stations, shopping malls and office buildings. Walking on stairs is very common and important in our daily lives, and scientific design and effective utilization of stairs are urgently needed for designers and managers (Peacock et al., 2009). In emergency, such as power failure, fire, earthquake or other hazards, the elevators may be out of commission, and the stairs become the primary escape routes. If there are too many people crowded on stairs, they will pack closer together or even lead to some dangerous situations (Shields and Boyce, 2009). Knowing the flow characteristics and predicting the egress time are the key points to grasp the evacuation dynamics and make emergency response plans on stairs (Graat et al., 1999; Oven and Cakici, 2009).

The characteristics of pedestrian staircase movement are determined by organizational, constructional and behavioral factors: the organizational factors, i.e., preparation for emergencies; the constructional factors, i.e., the staircase geometry including riser height, tread depth and step width (Graat et al., 1999; Fujiyama and Tyler, 2010); the behavioral factors, i.e., responses and movement characteristics of pedestrians (Yang et al., 2012; Ma et al., 2012). The study of the staircase movement is an interdisciplinary field with different focuses, such as biomechanics, physics, physiology, phycology, computer science, safety science (i.e., Hankin and Wright, 1958; Fruin, 1971; Predtechenskii and Milinskii, 1978; Templer, 1992; Batty, 1997; Helbing et al., 2000; Hase and Yamazaki, 2002; Nelson et al., 2002; Hoskin, 2004; Pauls, 2005; Trew, 2005; Casburn et al., 2007; Hostikka et al., 2007; Galea et al., 2008; Kretz et al., 2008; Seer, 2008; Xu and Song, 2009; Fujiyama and Tyler, 2010; Galea et al., 2010; Hoskins, 2011; Halsey et al., 2012; Yang et al., 2012; Peacock et al., 2012; Burghardt et al., 2013). To make quantitative analyses and detailed descriptions of staircase movement, many researches have carried out a lot of surveys, experiments and evacuation drills on stairs, and have collected large amounts of experimental and observational data of staircase movement (please see Table 1 for details). In these studies, the flow characteristics of staircase movement are described in individual level and collective level. Pedestrian flow in low densities reflects the characteristics in the individual level, and walking speed is influenced by physiological feature and body function, such as gender, age, height, weight, heart rate, rate of oxygen consumption and rate of energy expenditure (Irvine et al., 1990; Teh and Aziz, 2002; Halsey et al., 2012). It is also influenced by stairway geometries and movement direction. Pedestrian flow in high densities reflects the characteristics in the collective level. The collective behaviors include pedestrians' self-organized behaviors and optimal route choice behaviors (i.e., Helbing et al., 2000, 2005; Moussaid et al., 2011). The researches of pedestrian flow in the collective level focus on three aspects, (1) evaluating evacuation time, (2) reproducing

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Table 1
The state-of-the-art of staircase movement.

Author(s)	Year	Method	Model	Evacuation process		Walking speed		Note
				Dynamics	FD	Geometry	Direction	
Hankin and Wright	1958	Data analysis	–	○	●	○	●	–
Fruin	1971	Data analysis	–	○	●	○	○	Planning method
Predtechenskii and Milinskii	1978	Data analysis	Planning model	○	●	○	○	Planning method
Tanaboriboon et al.	1986	Macro	Linear function	○	●	○	○	Fundamental diagram
Weidmann	1993	Macro	Non-linear function	○	●	●	●	–
Frantzich	1996	Data analysis	–	○	●	●	●	–
Graat et al.	1999	Data analysis	–	○	●	○	○	Capacity estimation
Lam and Cheung	2000	Macro	BPR function	○	●	●	●	Fundamental diagram, capacity estimation
Proulx et al.	2002	Data analysis	Non-linear function	●	●	○	○	SFPE
Nelson and Mowrer	2002	Data analysis	Non-linear function	●	●	○	○	SFPE
Hoskin	2004	Software simulation	Coordinate-based model	●	●	●	●	Simulex32
Pauls	2005	Data analysis	–	●	○	○	○	–
Hostikka et al.	2007	Data analysis	–	●	●	○	○	–
Kretz et al.	2008	Data analysis	–	○	●	●	●	Pedestrian movement on long stairs
Seer et al.	2008	Data analysis	–	●	●	○	○	Flow characteristics
Pelechano and Malkawi	2008	Software simulation	Grid based model	●	○	○	○	Literature review (STEPS, EXODUS)
Galea et al.	2008	Software	Evacuation model	●	○	○	○	Merging behavior at interactions
Xu and Song	2009	Micro	Multi-grid model	●	○	○	○	Flow characteristics, such as in and out flow
Fujiyama and Tyler	2010	Macro	Linear function	○	○	●	●	Individual walking speed
Galea et al.	2010	Data analysis	–	●	●	○	○	Evacuation software
Hoskins	2011	Macro	Linear function	●	●	●	●	Fundamental diagram
Yang et al.	2012	Data analysis	–	●	●	●	○	Evacuation drill
Lei et al.	2012	Software simulation	–	●	○	○	○	Software (FDS, EVAC)
Hoskins and Milke	2012	Data analysis	–	○	●	○	○	NIST
Peacock	2012	Data analysis	–	●	●	●	○	NIST, different measurement methods
Ma et al.	2012	Data analysis	CA	●	○	○	○	Simulation
Burghardt et al.	2013	Data analysis	–	○	●	○	○	Fundamental diagram

● Represents the factor is included and ○ represents the factor is not included.

fundamental diagram, and (3) describing flow characteristics, i.e., inflow, outflow, capacity.

Staircase movement is a complicated three-dimensional movement, and modeling the movement is a quite challenging work. Nowadays, researches have integrated behavioral and constructional factors, and have established many models to analyze the flow characteristics and simulate evacuation processes in both single-story and multi-story buildings (Table 1). In our work, we mainly focus on the case of single-story staircases. These models are classified into two categories: macroscopic model and microscopic model (Zheng et al., 2009). The macroscopic models regard the crowd as a single entity, and focus on fitting the expression of fundamental diagram. Linear, piecewise linear and non-linear functions (i.e., Fruin, 1971; Warren, 1984; Tanaboriboon et al., 1986; Weidmann, 1993; Lam and Cheung, 2000; Proulx, 2002; Peacock et al., 2012; Hoskins and Milke, 2012) have been applied to describe relationship between velocity and density under different stair geometries.

Compared with macroscopic models, the microscopic models are able to precisely describe the individual behavior, qualitatively explain the evacuation dynamics and reproduce some self-organized phenomena (Helbing et al., 2000). These microscopic models are spatial-discrete models (cellular automation model, i.e., Kirchner et al., 2004; Huang and Guo, 2008; Schadschneider and Seyfried, 2009) and spatial-continuous models (social force model, i.e., Helbing et al., 2000). These models have been applied to reveal two-dimensional planar movement, but few of them have described the three-dimensional staircase movement (Song et al., 2006; Pelechano and Malkawi, 2008; Xu and Song, 2009; Ma et al., 2012). In addition, the spatial-discrete models are some restricted to describe the staircase movement, such as grid size, fatigue factor, route selection, and uneven use of stairs (Pelechano and Malkawi, 2008). Although the spatial-continuous models are advantageous to solve most of the aforementioned problems, these models are quite rare.

Social force model (Helbing and Molnar, 1995) is a well-known spatial-continuous model in the field of pedestrian flow. The model can reproduce several self-organized phenomena, such as lane forming, arching queue, shock waves and clogging effects (Helbing et al., 2005, 2007). Moussaid et al. (2011) have proposed a heuristics-based model to replace the social force with a heuristics intelligent optimum function. Based on the heuristic social force model, this paper introduced some special rules and established an enhanced model to describe the mechanisms of pedestrian movement and evacuation dynamics on stairs. Firstly, the body shape of each pedestrian is regarded as a set of three circles (Thompson and Marchant, 1995). Compared with traditional single-circle shape (i.e., Helbing et al., 2000), the three-circle shape precisely represents the projection of human body and describes the rotation movement when two pedestrians collide with others. Secondly, pedestrians usually walk more carefully on stairs than on planar, so two 'safety rules' are proposed to describe staircase movement behavior. The first rule is that a pedestrian wants to walk upstairs/downstairs with integral steps at a time, and the step-size is restricted by the staircase geometry, such as tread depth, riser height and step width. The second rule is that a pedestrian tends to walk along the sides, i.e., holding handrails, propping up against walls. Thirdly, the relaxation time is extended to a variable in our model. The relaxation time is defined that a pedestrian tends to correspondingly adapt his/her actual velocity to desired velocity with a certain characteristic time τ (i.e., Helbing et al., 2000; Moussaid et al., 2011). The relaxation time is mostly