A numerical study of contact force in competitive evacuation*

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Crowd force by the pushing or crushing of people has resulted in a number of accidents in recent decades. The aftermath investigations have shown that the physical interaction of a highly competitive crowd could produce dangerous pressure up to 4500 N/m, which leads to compressive asphyxia or even death. In this paper, a numerical model based on discrete element method (DEM) as referenced from granular flow was proposed to model the evacuation process of a group of highly competitive people, in which the movement of people follows Newton's second law and the body deformation due to compression follows Hertz contact model. The study shows that the clogs occur periodically and flow rate fluctuates greatly if all people strive to pass through a narrow exit at high enough desired velocity. Two types of contact forces acting on people are studied. The first one, i.e., vector contact force, accounts for the movement of the people following Newton's second law. The second one, i.e., scale contact force, accounts for the physical deformation of the human body following the contact law. Simulation shows that the forces chain in crowd flow is turbulent and fragile. A few narrow zones with intense forces are observed in the force field, which is similar to the strain localization observed in granular flow. The force acting on a person could be as high as 4500 N due to force localization, which may be the root cause of compressive asphyxia of people in many crowd incidents.

Keywords: crowd flow, discrete element method (DEM), contact force, force localization

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1. Introduction

Major events, such as the Olympic Games, the World Expo, rock concerts, and large religious events, etc., can attract more than 5×10^5 people. A proper crowd control and management strategy is essential for the safety of the people. In general conditions, a large population gathering should pose no serious problem. However, a combination of inadequate facilities and deficient crowd management may cause chaos or even catastrophe. Crowd disasters happen in different areas across the globe almost every year and take approximately 2000 lives per year on average.[1,2] These crowd accidents within recent decades have evoked a lot of scientific interest in the study of crowd flow. Crowd simulation models included macroscopic models, cellular automata, social force models, velocity-based models, continuum models, hybrid models, behavioral models, and network models. Macroscopic models describe the movement of pedestrians at a high level of aggregation as flow, whilst microscopic models describe the behavior of each individual and their interactions in detail. Lachapelle and Wolfram[3] presented a crowd model based on the mean field games theory. This macroscopic approach is based on a microscopic model, which considers smart pedestrians who rationally interact and anticipate the future. Based on concepts from the kinetic theory for active particles Dogbe[4] developed a model, in which pedestrians are regarded as entities whose microscopic states include a geometric variable, a mechanical variable, and a variable to describe the rate of development of individual strategies that influence the collective dynamics. Zhang *et al.*[5] numerically studied the pedestrian push-force in evacuation with arched congestion before an exit based on cell automata.

Helbing *et al.*[6–9] proposed a social force model and the movement of people is simplified as a kind of self-driven particle in which the driving force is not external, but from each particle itself and used a computer model to quantitatively explain the behavior of panicking individuals. They created a generalized force model using Newton's formula, force equals mass multiplied by acceleration. The social force model has been widely adopted to study the evacuation behavior. In Refs. [9] and [10] based on suitable video recordings of interactive pedestrian motion and improved tracking software, the authors proposed an evolutionary optimization algorithm to determine optimal parameter specifications for the social force model. The calibrated model is then used for large-scale pedestrian simulations of evacuation scenarios, pilgrimage, and urban environments. They found the phenomenon of intermittent flows and stop-and-go wave in crowd flow at extreme high densities. This crowd dynamics is dangerous and it

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may cause people to fall. It is noted that the reaction of pedestrians to what happens in front of them is much stronger than to what happens behind them and a centrifugal social force model[11,12] was proposed by taking into account the distance between pedestrians as well as their relative velocities. Wang *et al.*[13] improved the social force model by considering the impacts of interaction among companions and further developed a comprehensive model by combining that with a multi-exit utility function. Guo *et al.*[14] extended the original cost potential field cellular automata to study more general evacuation scenarios. Tang *et al.*[15] adopted a cellular automaton (CA) model to study the passengers' motion at the hall of HSR station during the check-in process.

Aftermath investigations have shown that the physical interactions in the crowd add up and cause dangerous pressures up to 4500 N/m, which leads to compressive asphyxia of people. Death occurred 15 seconds after a load of 6227 N was applied or 4 min–6 min after a load of 1112 N was applied;[16] a force of 3×10^3 N can break the ribs of a human from medical bone fracture analysis.[17] The interaction forces of human bodies play a dominant role in resulting in the death of people in these accidents. However, little work has been conducted on how the forces acting on people spread in the crowd flow and why such deadly forces arise. Lee and Hughes[18] studied data on accidents in human crowds that occurred over the past decade showing that one of the fatal consequences of crowding was asphyxia, that is by crushing, by utilizing the standard forward–backward autoregressive modeling techniques for spectral analysis of a measured signal to predict pressures generated by very high densities of pedestrians. It is difficult to directly measure the contact forces in crowd flow, particular in extremely high densities. Discrete element method (DEM)[19–22] is a numerical method for computing the motion and effect of a large number of particles. It can provide the local information (particle position and velocity, inter-particle contact forces) needed to investigate the relationship between microscopic and macroscopic behavior. The forces acting on each particle are calculated and force balance is integrated explicitly and acceleration velocity, velocity, and the coordinate at each time step are deduced accordingly by applying Newton's second law. Lin *et al.*[20,23] proposed a discrete element method to study the crowd through an exit at different desired velocities and found that clogging occurs more easily and the exit may be totally blocked (i.e., deadlock situation) when the desired velocity is high enough. Lin *et al.*[24,25] also conducted a series of experiments by using mice driven by a varying number of joss sticks and the experiment found that the escape times significantly increased with the increased levels of stimulus.

Discrete element method is adopted to study the contact force in crowd flow passing through a bottleneck. This paper is structured as follows. The next section details the formulation of the proposed DEM model. In Section 3 and Section 4, the contact forces in crowd flow at a desired velocity of 1.5 m/s and 2.5 m/s are studied respectively and the characteristics of the contact forces are discussed. The conclusions are drawn in Section 5.

2. Discrete element method for the movement of a crowd

2.1. Governing equations for the movement of a crowd

In DEM simulation,[17–20] a granular material is modeled based on a finite number of discrete, semi-rigid, spherical particles interacting by means of contact or non-contact forces, and the translational and rotational motions of every single particle are described by Newton's laws of motion. Lin *et al.*[20,23] proposed a discrete element method (DEM) to study the crowd through an exit. In DEM, the human body is modeled based on a finite number of discrete, soft, spherical particles interacting by means of contact or non-contact forces. The differences of the proposed DEM model with the social force[6–9] are in the three aspects: (i) Hertz contact model is incorporated and the normal push-back force for two overlapping particles is proportional to the area of the overlapped two particles, and is thus a nonlinear function of overlapped distance; (ii) an anisotropic social force model is proposed; and (iii) both translational movement and rotational movement are considered. A detailed description of the proposed DEM model is included in Refs. [20] and [23].

The translational and rotational motions of each person are described by Newton's laws of motion. The dynamical movement of people is time-dependent and can be described as follows:

$$m_i \frac{\mathrm{d}^2 x_i}{\mathrm{d}t^2} = F_i, \tag{1}$$

$$I_i \frac{\mathrm{d}\omega_i}{\mathrm{d}t} = T_i. \tag{2}$$

With a person i with mass m_i at his/her position x_i, F_i is the sum of forces acting on him/her, I_i is the moment of inertia , ω_i is the angular velocity, and T_i is the total torque.

The sum of force F_i is expressed as:

$$F_i = F_{\text{self-driven force}} + F_{\text{social force}} + F_{\text{contact force}}, \tag{3}$$

$F_{\text{self-driven force}}$ is the force to drive the person to move forward for a specific object, e.g., getting out as quickly as possible and Helbing *et al.*[6–9] proposed to represent it as:

$$F_{\text{self-driven force}} = m_i \times (V_{\text{desired velocity of person } i} - V_{\text{actual velocity of person } i})/\tau, \tag{4}$$

where $V_{\text{desired velocity of person } i}$ is the desired velocity for the person i to achieve in each time step and it can be used to represent the mental state of a person during movement. τ is

the reaction time and $\tau = 0.5$ s. During the movement, a person adjusts his/her desired direction of movement θ targeting at the exit at each time step. A parameter ε is introduced as he/she cannot accurately locate his/her coordination and ε is taken as a random value ranging from -0.03θ to 0.03θ. ε is beneficial to recirculate the flow when a deadlock occurs at the exit. Therefore, X and Y components of the desired velocity can be expressed as:

$$\begin{aligned} &VX_{\text{desired velocity of person } i} \\ &= |V_{\text{desired velocity of person } i}|\cos(\theta+\varepsilon), \end{aligned} \tag{5}$$

$$\begin{aligned} &VY_{\text{desired velocity of person } i} \\ &= |V_{\text{desired velocity of person } i}|\sin(\theta+\varepsilon). \end{aligned} \tag{6}$$

$F_{\text{contact force}}$ is the force on the person only when he/she is in physical contact with others or wall/boundary. An anisotropic social force model $F_{\text{social force}}$ is proposed. A detailed discussion on $F_{\text{contact force}}$ and $F_{\text{social force}}$ is included in Ref. [23]. For simplicity, the present study is limited to granular systems only composed of spherical particles. The movement of people is restricted in two directions, i.e., x and y. The position in z direction is a constant. The rotational movement is restricted in z direction only and the rotation in x and y is set to zero. Based on Taylor expansion and velocity verlet integration, the position and velocity at each time step can be updated and the time step is 0.001 s.[23]

2.2. Contact force acting on the human body

The sum of the contact forces which act on a person and lead to the deformation of his body is called the composition of contact forces. The composition of contact forces, coupling the self-driven force and the social force, provides the particle with the acceleration velocity following Newton's second law of motion. It is a vector quantity with a magnitude and a direction. The composition contact force on each person by its neighboring people due to physical deformation is expressed as:

$$F_x^i = \sum_1^{N_c} f_x \quad \text{and} \quad F_y^i = \sum_1^{N_c} f_y, \tag{7}$$

where N_c is the number of contacted persons. f_x and f_y are the contact forces acting on the person i exerted by the contacted person a (or b) in x direction and y direction respectively as shown in Fig. 1. The sum of the vector contact forces can be expressed as:

$$F_{\text{I}}^i = \sqrt{F_x^2 + F_y^2}, \quad \theta = \arctan\frac{F_x^i}{F_y^i}, \tag{8}$$

where θ is the angle of the vector contact force. The vector contact force is one of the key factors contributing to the acceleration of the human body.

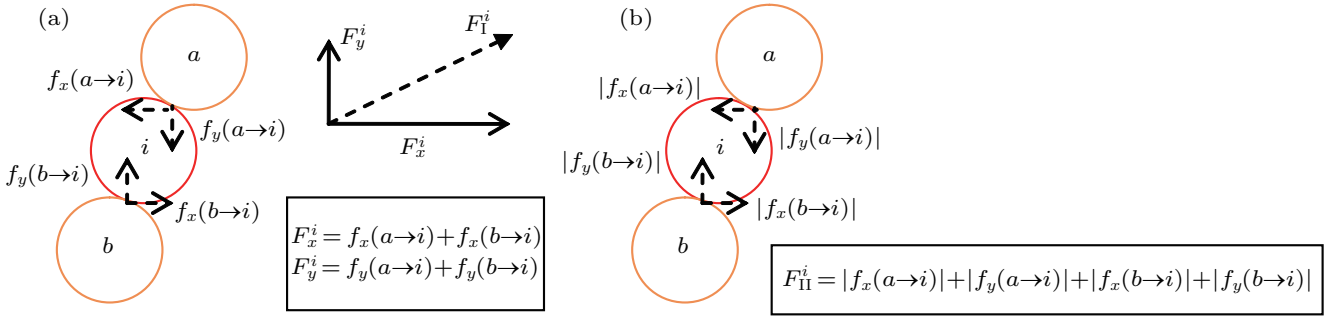


Fig. 1. (color online) Illustration of the vector contact force and scalar contact force: (a) vector contact force and (b) scalar contact force.

The scalar contact forces, i.e., the sum of absolute value of the contact forces acting on a person i in all directions, is defined. The scalar contact forces represent the degree of body deformation due to external forces and it is expressed as:

$$F_{\text{II}}^i = \sum_1^{N_c} |f_x| + \sum_1^{N_c} |f_y|, \tag{9}$$

where N_c is the number of contacted persons. f_x and f_y are the contact forces acting on the person i exerted by the contacted person a (or b) in x direction and y direction respectively.

A comparison of the two contact forces is shown in Fig. 1. The person i has two contacted persons, namely person a and person b. The force acting on i from person a in the x direction is expressed as

$$F_x^i(a \to i) = 200 \text{ N}$$

and the force in the y direction $F_y^i(a \to i) = -400$ N. Similarly, $F_x^i(b \to i) = 200$ N and $F_y^i(b \to i) = 400$ N are the forces from person b in two x and y directions respectively. The sum of the contact forces in the x direction is $F_x^i = 0$ and the sum of the forces in the y direction is $F_y^i = 0$. Therefore, the sum of the vector contact forces $F_{\text{I}}^i = 0$, which means that the contact forces do not contribute to the acceleration of people i. However, the sum of the scalar force II

$$\begin{aligned} F_{\text{II}}^i &= |F_x^i(a \to i)| + |F_y^i(a \to i)| \\ &\quad + |F_x^i(b \to i)| + |F_y^i(b \to i)| = 1200 \text{ N}, \end{aligned}$$

which means that the person i has to withstand the physical force of 1200 N from the two persons contacted.

3. Contact force acting on human at a desired velocity of 1.5 m/s

Studies are conducted for 300 people getting out of a room with an exit of 1-m wide as shown in Fig. 2. A detailed description of the parameters adopted in the simulation are included in Ref. [23]. Figure 3 shows the flow process of 300 people at a desired velocity of 1.5 m/s. Generally speaking, a desired velocity of 1.5 m/s represents an evacuation of medium competition.

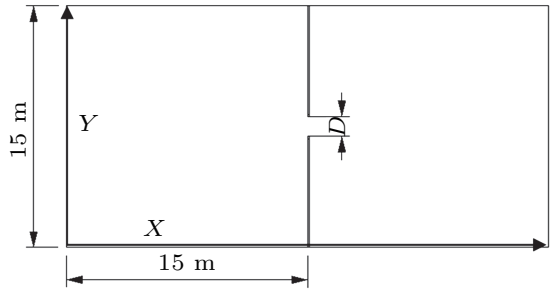


Fig. 2. Layout of room for numerical simulation ($D = 1$ m).

The flow is continuous in the first 50 seconds and it clogs from 50 s to 120 s and the throughput is zero. From 120 seconds, the flow resumes until all the people get out. The flow rate is shown in Fig. 4 and the flow rate fluctuates from 0 to 2 persons per second. The intermittent flow through a bottleneck due to the interaction of human bodies leads to the spontaneous development of clogs and arches close to the exit.

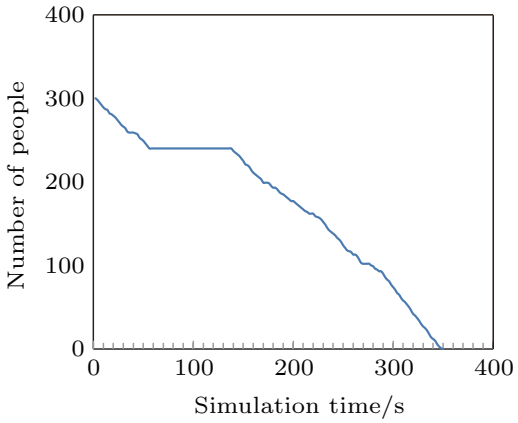


Fig. 3. (color online) Evacuation process at a desired velocity of 1.5 m/s.

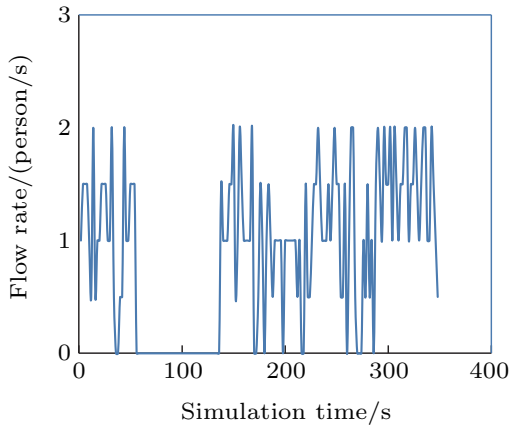


Fig. 4. (color online) Flow rate per second.

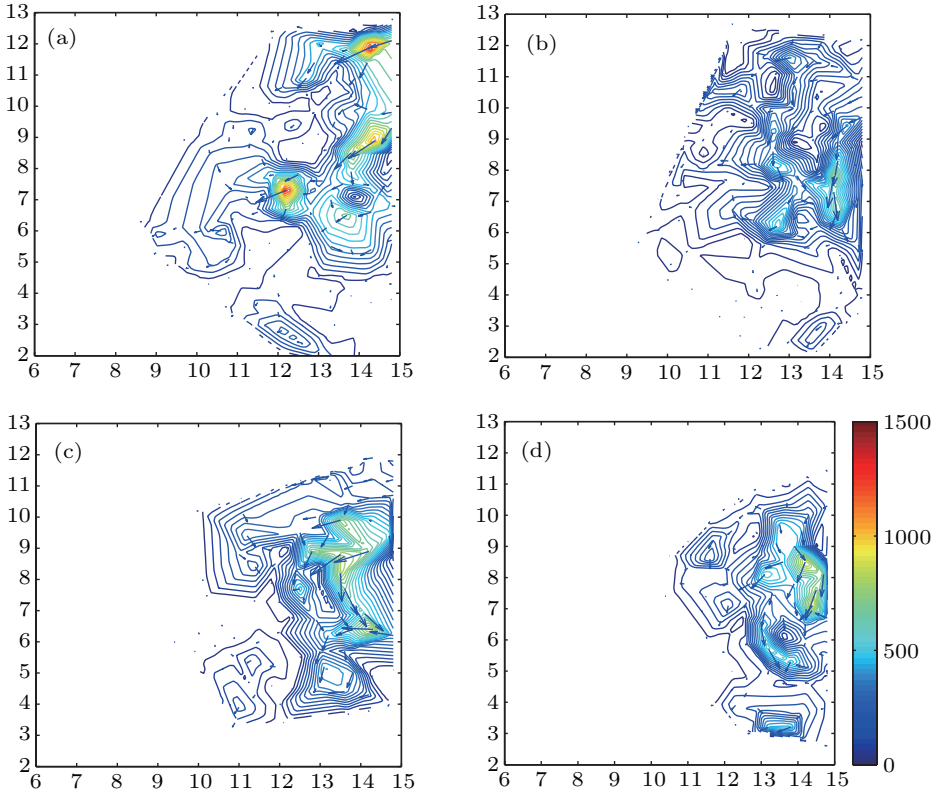


Fig. 5. (color online) Vector contact force and the scalar contact force at a desired velocity of 1.5/s at time (a) 30 s, (b) 40 s, (c) 160 s, and (d) 180 s respectively (the arrow is the vector contact forces and the contour is the scalar contact forces.

The vector contact force field at different time is shown in Fig. 5. Most of the contact forces acting on people are relatively low most of the time. The contact forces are more prominent close to the exit, and their directions are predominately against the direction of movement. A few contact forces are as high as 1000 N and the force fluctuates in the magnitude and direction. As for the scalar force field as shown in Fig. 5, from 0 s∼ 50 s, the flow runs intermittently and the force pattern varies greatly in each step as the circulation of crowd flow leads to the continuous reconstruction and deconstruction of the force network, e.g., at 30 s, three spikes with a force of 1500 N are observed. At 40 s, the spikes are relocated. The force field is characterized as a narrow zone of intense force across the force field. The phenomenon called strain localization in granular flow is observed in crowd flow. From 50 s∼ 140 s, the crowd flow is clogged at the exit due to the competitiveness. From 140 s∼ 300 s, the crowd flow resumes and the flow goes out intermittently. The force pattern varies greatly in each step. Force localization is observed and the spike force is around 1500 N as represented in Fig. 5. The contact forces acting on an individual during evacuation process are studied as shown in Fig. 6. The contact forces are turbulent and fluctuate greatly during the process. The vector contact force varies from 0 N∼ 1000 N, whilst the scalar contact force varies from 0 N∼ 1500 N.

The strain localization due to nonhomogeneous deformation of elastoplastic materials is observed on a wide class of engineering material in soils and rocks. In this study, the particles of movement are the self-driven people with a desired velocity of 1.5 m/s. The actual velocity ranges from 0 m/s to 0.1 m/s as observed in the simulation. The self-driven force of a person is around 180 N∼ 240 N, i.e., approximately 3 times the mass of the person. The forces from an assembly of people are accumulated and concentrated through the interactions of particles, and a spike force of 1500 N is observed at critical zones, where people should endure higher pressure and are more vulnerable to compressive asphyxia.

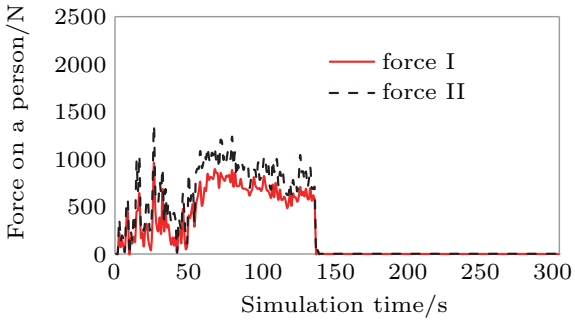


Fig. 6. (color online) Historical contact forces of a person at desired velocity of 1.5 m/s (force I is the vector contact forces and force II is the scalar contact force).

4. Contact force acting on a human at a desired velocity of 2.5 m/s

The desired velocity is an important parameter to represent the mental state of the crowd during an evacuation. Further study is conducted for 300 people getting out at a higher desired velocity, i.e., 2.5 m/s, which represents an evacuation of high competition. The increase in the desired velocity leads to stronger interactions of human bodies. Figures 7 and 8 show that the flow is highly intermittent. The clogs at the exit last for a few seconds to several minutes. The clogs and avalanches occur by turns. The high desired velocity of people leads to the frozen crowd flow at the exit.



Fig. 7. Snapshot of the escape process at a desired velocity of 2.5 m/s at different times (from left to right $t = 52$ s, 60 s, 90 s, 100 s, and 120 s).

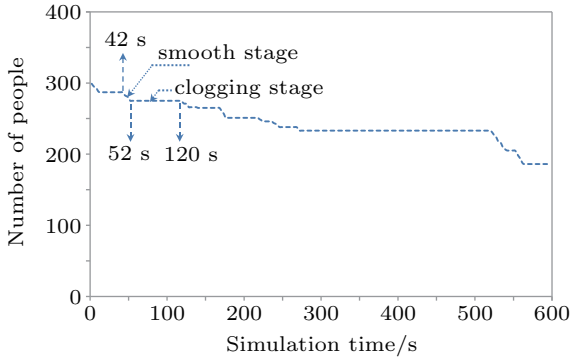


Fig. 8. (color online) Evacuation process at a desired velocity of 2.5 m/s. The flow is smooth during 42 s∼ 52 s and it is clogging during time 52 s–120 s.

Figure 9 shows the scalar contact force during flow circulation stage whilst figure 10 shows the scalar contact force during flow clogging stage. No discernable difference on the characteristic of contact force is observed for the two stages. The force field fluctuates even though the flow is clogged at the exit. More prominent force localization results in a contact force as high as 4500 N. The contact forces between self-driven particles are distributed homogeneously in space. The magnitude of the force varies greatly from contact to contact. The non-uniform distribution of the contact force in the crowd lead to the forces concentrating on a few people, who are exposed to the force as high as 4500 N.

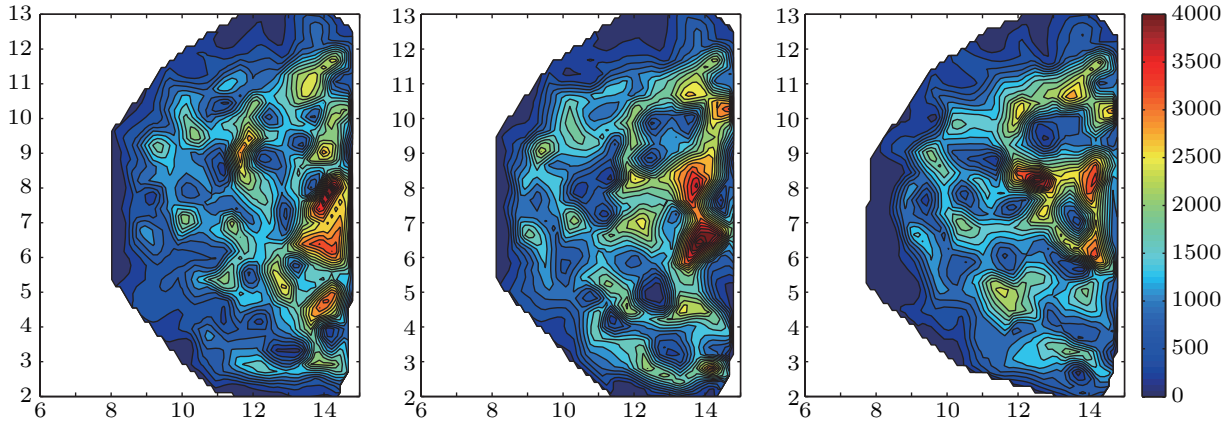


Fig. 9. (color online) Scalar contact force at smooth flow stage (from left to right 42 s, 45 s, and 50 s).

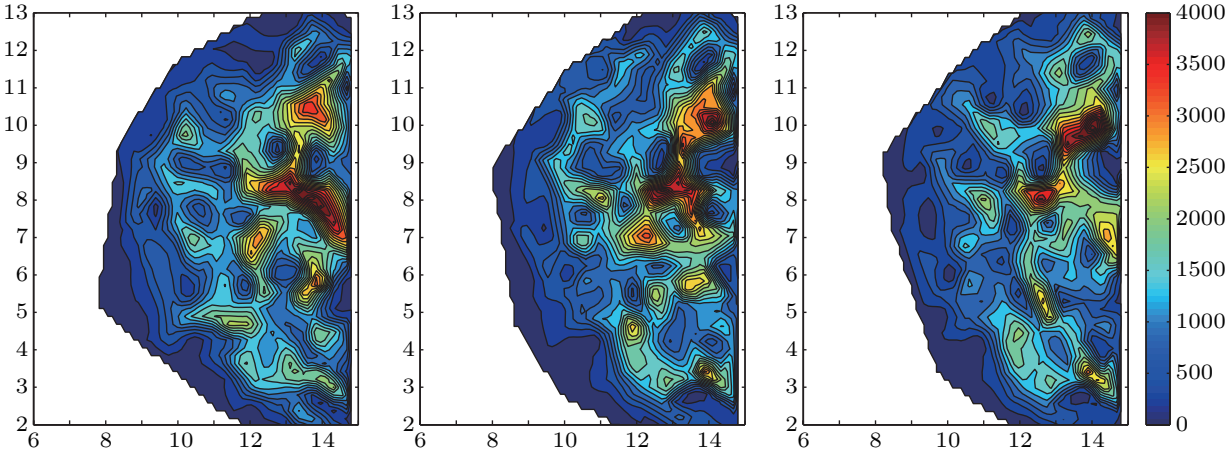


Fig. 10. (color online) Scalar contact force at clogging flow stage (from left to right 60 s, 90 s, and 120 s).

The contact forces acting on an individual person during evacuation process at a desired velocity of 2.5 m/s are shown in Fig. 11. Both the contact forces fluctuate greatly. The vector contact force varies from 0 N$\sim$ 3000 N, whilst the scalar contact force varies from 0 N$\sim$ 4500 N. At a desired velocity of 2.5 m/s, the self-driven force of a person is around 300 N$\sim$ 400 N. The resultant sum of vector forces with a desired velocity is as high as 3000 N. Even discounting the social force and self-driven force, the contact force alone could produce an acceleration velocity of around 50 m/s^2 which is around 5 times of gravity acceleration velocity. Few people could control the balance of his body under such a high acceleration velocity and mostly likely they will lose balance and fall down. Furthermore, the sum of scalar contact force is as high as 4500 N. Researchers showed that death could occurred at a load of 6227 N lasting for 15 seconds and a load of 1112 N lasting for 4 min–6 min. For the selected person as shown in Fig. 10, the person could withstand a force of more than 4000 N. It is believed that the person could lose consciousness or compression to death. The combination of high acceleration velocity and compressive asphyxia is lethal to the people at the critical zones with force localization.

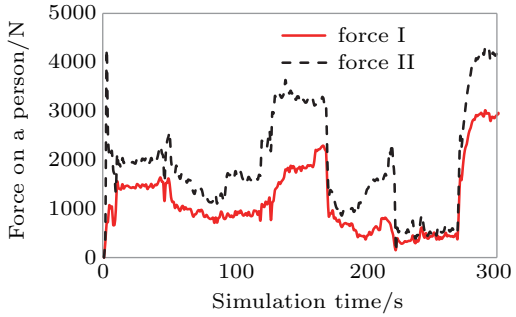


Fig. 11. (color online) Historical contact forces of a person at a desired velocity of 2.5 m/s (force I is the vector contact forces and force II is the scalar contact force).

5. Discussions and conclusions

In this work, we study crowd flow by using the theory from granular dynamic. The human body is treated as a granular particle and dynamical movement of people is studied by applying Newton's second law. Hertz's contact model is incorporated to describe the forces among human bodies when they are physically contacted. The velocity of desired (VOD) represents the mental state of crowd. The larger the VOD, the higher degree of aggression to move forward, which results in the flow rate fluctuating greatly and the total freezing of the

crowd at the bottleneck.

Force localization due to nonhomogeneous deformation of elastoplastic materials is observed on a wide class of engineering material in soils and rocks. For the self-driven human bodies with high densities, forces are predominately the result of bodies' contact mechanics and the contact force is inherently fragile and susceptible to reorganization. The force is localized to narrow domains called force localization. People at the zone of high force endure a higher pressure and are more prone to compressive asphyxia if the pressure continually lasts for a few minutes.

At a desired velocity of 1.5 m/s, a spike force of 1000 N could be incurred. At a desired velocity of 2.5 m/s, a spike of 4500 N could be incurred. It is noted that a desired velocity of 2.5 m/s is only slightly higher than normal walking velocity and it can hardly be defined as a panic velocity. However, it could produce an alarming force of 4500 N and cause people to lose consciousness or be compressed to death. Clearly, the nonhomogeneous deformation of an assembly of human bodies leads to the force localization and concentration, which results in a number of critical zones with extremely high force.

After the study of the crowd incident in the love parade on 24th July 2010 in Duisburg, Germany, Helbing[9,10] concluded that there was no sign of panic in the crowd flow during the incident and the crowd turbulence was the cause of the loss of 21 lives in the tragedy. The trivial behaviors of people interactions, e.g., rushing, pushing, could lead to the generation of turbulent flow, whilst the force localization leads to forces at some areas being uncontrollable and unbearable. The force localization could be the root cause of compressive asphyxia of people in many crowd incidents. Further study of the characteristics of the contact forces in the crowd flow (e.g., the magnitudes and their frequency) will be conducted and further compared with the results in gravity-driven silo flow.

Acknowledgments

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