Modeling the capability of penetrating a jammed crowd to eliminate freezing transition

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Frozen state from jammed state is one of the most interesting aspects produced when simulating the multidirectional pedestrian flow of high density crowds. Cases of real life situations for such a phenomenon are not exhaustively treated. Our observations in the Hajj crowd show that freezing transition does not occur very often. On the contrary, penetrating a jammed crowd is a common aspect. We believe the kindness of pedestrians facing others whose walking is blocked is a main factor in eliminating the frozen state as well as in relieving the jammed state. We refine the social force model by incorporating a new social force to enable the simulated pedestrians to mimic the real behavior observed in the Hajj area. Simulations are performed to validate the work qualitatively.

Keywords: multidirectional flow, jamming transition, pedestrian behavior, social force

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1. Introduction

Organizing safer mass event is a great challenge to the specialists and authorities in various countries. In critical situations, massive congestion has resulted in disasters, crowd stampedes, serious injuries, and loss of lives.[1–4] Although authorities make careful, well-planned arrangements for offering better pedestrian facilities to ensure the safety of mass crowds, fatal accidents in open areas keep recurring.[5,6] Inappropriate crowd behavior in critical areas in multidirectional flow has been identified as a main reason why such accidents take place. For example, there have been many serious incidents in open areas and multidirectional walkways in Mina during the Hajj, where more than two million Muslims annually perform the stoning rituals.[4] Although Saudi authorities have deployed a considerable amount of effort for improving the Jamarat bridge and the surrounding area in Mina in order to ensure a smooth flow of pilgrims, crowd stampede has occurred recently.[5,6] To recognize the critical crowd behaviors and eliminate the undesirable ones, researchers have been provoked to understand the behaviors of pedestrian traffic flow in multidirectional walkways. Collecting relevant real-life data from empirical studies has become a major concern for analysis and prediction of the crowd behaviors.[4,7] However, there is a lack of resources to provide researchers with such data, which is also limited by photographs and videos. Alternatively, conducting series of experimental studies to explore the aspects of the multidirectional flow has become a big concern. The factors dominating these aspects have been taken in detail in a considerable number of studies, such as the bi-directional flow distributions,[8] avoidance maneuver,[9] the dependence of the arrival time on the density,[10] the effect of look-ahead behavior on the velocity as well as the traffic flow,[11] the effects of the speed variability on the stability of the traffic structure,[12] the order of counter flows on the speed-flow-density relations[13] and the pedestrian flow in multi-intersecting areas.[14] However, for ethical reasons and other difficulties, critical situations which could result in an extreme state (e.g., extreme crowd flow at entrance[3] or stop and go waves[4]) could not be set up.

For this reason, researchers have been motivated to improve simulation models to help simulate the aspects of the multidirectional pedestrian flow and correspondingly examine the solutions for better crowd behavior and environmental design. For the purpose of validation, the simulation models are essentially required to mimic the real aspects of the multidirectional flow behavior and reproduce its characteristics accurately as well. Subjected to this requirement, a variety of simulation models have been developed to reproduce the pedestrian flow aspects.[15–25] The problematic issue to be treated in this article is that the simulation models have produced a freezing transition from the jammed state[26–30] which contradicts our observations from the Hajj crowd (see Figs. 1 and 2). Figure 1 shows that a single lane is penetrating a jammed crowd (where the crowd density could exceed 5 m^{-2}) moving in the opposite direction of the lane.

This real observation does not resemble oscillatory flow phenomenon at bottleneck,[31,32] where the penetrating process in the latter phenomenon is due to the pressure from the flow performing the penetration. Moreover, no spatial separation rule as suggested in Ref. [32] was provided for the pilgrims to constitute the lane opposing the counter flow shown in Fig. 1. On the other hand, freezing transition has not been reproduced in the empirical and experimental studies,[5,6,14] in which local density could approximately reach 10 m^{-2}. The

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empirical study in Ref. [4] showed turbulent transition from a moving extreme crowd which resulted in the falling and trampling of people.

Thus, the existing crowd dynamics models do not represent some crowds' behaviors similar to what happens in real life situations. Our simulation based on the social force model introduced freezing transition as introduced by Helbing *et al.*[26] We refer the freezing transition to shortcoming from the simulated pedestrians located in a jammed crowd who cannot penetrate the high density crowd in front as well as from the opposing simulated pedestrians who lack the kindness behavior as a social characteristic to make a way for the others who directly face them. The remaining part of this paper is organized as follows. In Section 2, we introduce the social force model. In Section 3, we address the issue of how the penetration process could eliminate freezing transition, and then we propose a refinement of the social force model to enable the penetrating process in jammed crowds. Finally, the relevant simulations to demonstrate the results of our work are performed.

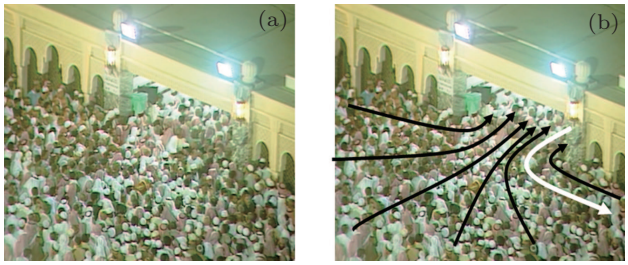


Fig. 1. (color online) (a) Muslim pilgrims are going outside the Sanctuary Mosque in Makkah after performing their prayers. In the meantime, a one-pedestrian width lane opposing the flow of the people is recognized. This aspect, in the case of highly dense crowd, could not be represented in simulation models. (b) The leaving pilgrims' directions and the opposing lane's direction are illustrated.

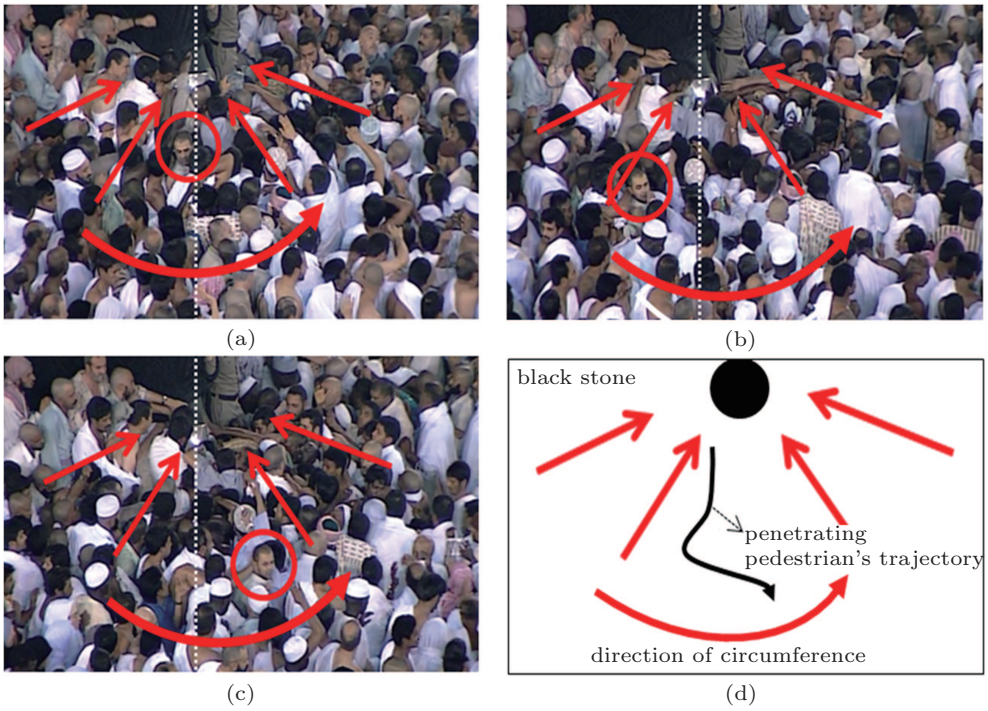


Fig. 2. (color online) Muslim pilgrims perform circular movement around the Kaaba as a part of the Tawaf ritual during the Hajj. Many try to reach the Kaaba to touch the Black Stone, and then return to continue their Tawaf. (a) The pilgrim indicated by the circle is trying to return to continue his Tawaf. (b) This pilgrim is continuing penetrating the opposing pilgrims. (c) The pilgrims are about to join the others performing the circular movement. (d) The pilgrim's trajectory is illustrated.

2. Social force model

The social force model (SFM) is a continuous-space microscopic simulation model that has been considered as the most realistic model to express the motivations of pedestrians to act as forces. The motion of each simulated pedestrian is subject to a semi-Newtonian equation, where the simulated pedestrian has an acceleration $\mathrm{d}\boldsymbol{v}_i/\mathrm{d}t$ that results from the sum of forces exerted by the surrounding pedestrians and obstacles

$$\frac{\mathrm{d}\boldsymbol{x}_i(t)}{\mathrm{d}t} = \boldsymbol{v}_i(t), \tag{1}$$

$$m_i \frac{\mathrm{d}\boldsymbol{v}_i}{\mathrm{d}t}(t) = \boldsymbol{f}_i^{\mathrm{social}}(t) + \boldsymbol{f}_i^{\mathrm{physical}}(t) + \varepsilon_i(t), \tag{2}$$

where ε_i is a source of fluctuation of the pedestrian's acceleration. The social forces $\boldsymbol{f}_i^{\mathrm{social}}$ are represented as

$$\boldsymbol{f}_i^{\mathrm{social}}(t) = \boldsymbol{f}_i^{\mathrm{pref}}(t) + \sum_j \boldsymbol{f}_{ij}^{\mathrm{rep}}(t), \tag{3}$$

where the preferred force $\boldsymbol{f}_i^{\text{pref}}$ is modeled to adapt the pedestrian's actual velocity $\boldsymbol{v}_i$ to reach his preferred velocity $v_i^0 \boldsymbol{e}_i^0$ at which he prefers to walk as follows (we use the pronoun he to refer to both male and female pedestrians or pilgrims):

$$\boldsymbol{f}_i^{\text{pref}}(t) = \gamma_i \left(v_i^0 \boldsymbol{e}_i^0(t) - \boldsymbol{v}_i(t) \right), \tag{4}$$

where the social repulsive force $\boldsymbol{f}_{ij}^{\text{rep}}$ is modeled on the assumption that the pedestrian i is motivated to avoid potential collisions with the surrounding objects $j's$ located within his perception (see Fig. 3). This process allocates each pedestrian to his personal area that should not be transgressed by others. It was proposed in Ref. [20] with an exponential form

$$\boldsymbol{f}_{ij}^{\text{rep}}(t) = -A^{\text{rep}} \mathrm{e}^{(R_{ij} - d_{ij}(t))/B^{\text{rep}}} \boldsymbol{n}_{ij}(t) W\left(\phi_{ij}(t)\right), \tag{5}$$

where

$$W(\phi_{ij}(t)) = \left(\lambda_i + (1-\lambda_i) \frac{1+\cos(\phi_{ij}(t))}{2} \right), \tag{6}$$

where A^{rep} and B^{rep} are constant parameters denoting the strength and the repulsive distance range of the corresponding force; the normalized vector $\boldsymbol{n}_{ij}$ points from the object i to the pedestrian j; R_{ij} and d_{ij} are the sum of the radii of i and j and the distance between the centers of i and j, respectively. The weight function $W(\phi_{ij})$ is proposed to take into account the effect of the anisotropic perception of object j, where ϕ_{ij} denotes the angle between the direction of motion $\boldsymbol{e}_i = \boldsymbol{v}_i / \|\boldsymbol{v}_i\|$ and the direction $\boldsymbol{n}_{ij}$, (i.e., $\cos\phi_{ij} = -\boldsymbol{n}_{ij}.\boldsymbol{e}_i$); the angular perception parameter λ_i determines the effect of the perception of pedestrian i to those who are behind him on the magnitude of the force.

The physical forces $\boldsymbol{f}_{ij}^{\text{push}}$ and $\boldsymbol{f}_{ij}^{\text{friction}}$ as illustrated in Fig. 3 were modeled as linear functions[21] in an analogy with the granular forces

$$\boldsymbol{f}_i^{\text{physical}}(t) = \sum_j \boldsymbol{f}_{ij}^{\text{push}}(t) + \sum_j \boldsymbol{f}_{ij}^{\text{friction}}(t). \tag{7}$$

The forces of the SFM are characterized with parameters capable of being formulated to accommodate enormous aspects of crowd dynamics to introduce self-organization phenomena and to reproduce real life data as well.[24,31–34] In Ref. [34], the repulsive distance range B^{rep} was modeled in terms of local density, by reproducing the fundamental diagram conforming to experimental data produced in Ref. [35]

$$\begin{aligned} B_i^{\text{rep}}(\rho_i) \;=\; & -0.003\rho_i^4 + 0.011\rho_i^3 + 0.062\rho_i^2 \\ & - 0.34\rho_i + 0.538. \end{aligned} \tag{8}$$

Analogously, the parameter λ_i was formulated in Ref. [24] in terms of the pedestrian's local density, based on reproducing realistic flow rate within the range stated in experimental studies as follows:

$$\begin{aligned} \lambda(\rho_i) \;=\; & -0.00058\rho_i^6 + 0.01\rho_i^5 - 0.076\rho_i^4 + 0.3\rho_i^3 \\ & - 0.72\rho_i^2 + 1.1\rho_i - 0.024. \end{aligned} \tag{9}$$

The essential force plays a main role, and for collision avoidance, is the social repulsive force (see Fig. 3). In the case of a high density crowd, overtaking facing pedestrians becomes hard because of the size of the personal area. According to Eq. (8), the radius of the personal area decreases with the increase of the local density which enables the pedestrian to further push his way through the crowd, and accordingly reduces the opportunity of jamming transition. However, in a jammed crowd, the simulated pedestrians are in contact and pushing their way through the jammed crowd is unachievable. Freezing transition is most likely to occur.

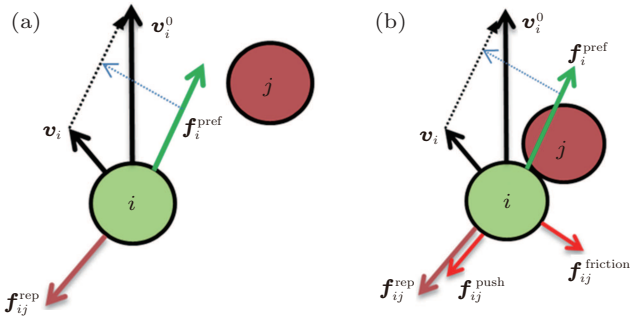


Fig. 3. (color online) (a) The social forces exerted by an object j on pedestrian i are illustrated. (b) The physical forces appear because of the physical contact between pedestrian i and object j.

Strategies of collision avoidance have been incorporated into the social force model by modifying the preferred velocity such as in Ref. [36], adding new forces in Ref. [37] or directing the instantaneous motion toward immediate blank spaces in Ref. [25]. However, these strategies do not play an effective role in the jammed state because of the lack of blank spaces. Therefore, freezing transition could emerge quickly.

3. Modeling the capability of penetrating a jammed crowd

Based on the implementation of simulation models, it is observed that the frozen state starts with a small cluster of jammed pedestrians, and consequently the walking of a few of them becomes blocked. With time going by, the cluster becomes large due to extreme jamming and the flow becomes frozen. In our real observations, the single lane in Fig. 1 is most likely to be constituted by a penetrating pilgrim and other pilgrims following him. This lane becomes an attractive object for stuck pedestrians walking in the same direction. Penetrating the counter flow is an essential process for them to join the lane. In Fig. 2, the pilgrims who go to touch the stone are able to return back to continue their circular movements-Tawaf. Generally speaking, pedestrians walking in a local jammed crowd are highly motivated to penetrate the crowd to join attractive areas located within their sights. In light of

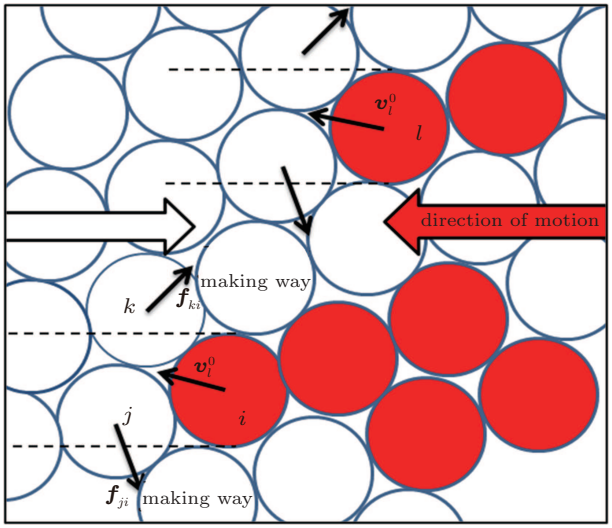


Fig. 4. (color online) Physical contact between the penetrating pedestrians i and l and their facing pedestrians.

these observations, initiative elimination of blocked walking when jamming is confined in local areas is an essential means to prevent frozen state. However, the penetration process does not guarantee that it will eliminate the freezing transition in all conceivable cases. It is worth noting here that a stuck pedestrian cannot penetrate a jammed crowd without kindness from the opposing pedestrians constituting this crowd. Kindness behavior is expected as long as the penetration behavior is socially justified and does not threaten their safety. Hence, we exclude handling cases of an extreme jammed crowd where pushing often causes harm for others and therefore causes the kindness behavior to transform into a wild one. To our experience, kindness behavior is confirmed in the Hajj area where the majority of pilgrims are in spiritual submission and try to avoid what deforms their religious rituals (the authors have gone through the Hajj experience many times).

Theoretically, in the SFM, the freezing transition could occur when simulated pedestrians have not appreciated values of forces to penetrate the front of the jammed crowd. Their preferred forces are completely vanished by the numerous encountering forces. The proposed model in this section provides the simulated pedestrians with blocked walking ability of penetrating a jammed crowd and provides his opposing pedestrians with kindness behavior to allow such a penetration. To each stuck pedestrian i we give the notion of his facing pedestrians as the pedestrians opposing him, intersecting his rectangular path along his direction toward his destination, and are in contact. They are almost two, j and k, with respect to pedestrian i as illustrated in Fig. 4. In the case of three opposing pedestrians, we ignore the one with the least intersection.

3.1. Kindness factor

Basically, we assume that all simulated pedestrians are kind. The stuck pedestrians who are opposing enormous

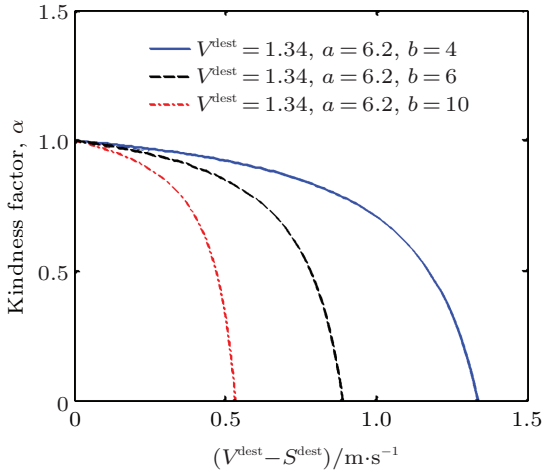


Fig. 5. (color online) Different values for the parameters in Eq. (11) to show its effect on the curvature of the curves.

counter flow would lose their respect to the personal areas of the facing pedestrians. The kindness factor $\alpha^{\rm kindness}$ is incorporated into Eq. (5) to help the stuck pedestrians to some extent ignore the effect of the socially repulsive forces exerted by the facing pedestrians, and on the contrary the facing pedestrians keep their repulsive motivations toward them as a kindness behavior

$$\begin{aligned}&\boldsymbol{f}_{ij}^{\rm rep}(t)\\&=\alpha_i^{\rm kindness}\left(-A^{\rm rep}\,{\rm e}^{(R_{ij}-d_{ij}(t))/B^{\rm rep}}\boldsymbol{n}_{ij}(t)W\left(\phi_{ij}(t)\right)\right).\end{aligned}\tag{10}$$

The factor $\alpha^{\rm kindness}$ could be influenced by personal, cultural, or environmental factors. In this work, it is proposed as follows. The factor $\alpha^{\rm kindness}$ equals one for the kind pedestrian, it would slightly decrease for the stuck pedestrian with the decrease in his actual speed $S^{\rm dest}$ toward his destination, and it would considerably fall to approximately zero when $S^{\rm dest}$ goes below a threshold value to represent complete loss of patience. The model of $\alpha^{\rm kindness}$ for all pedestrians is introduced in the following form:

$$\alpha_i^{\rm kindness}(t)=\begin{cases}1-c_i, & S_i^{\rm dest}(t)<0,\\ 1-c_i\left(\dfrac{1}{a-b\left(V_i^{\rm dest}-S_i^{\rm dest}(t)\right)}-\dfrac{1}{a}\right), & 0\le S_i^{\rm dest}(t)\le V_i^{\rm dest},\\ 1, & S_i^{\rm dest}(t)>V_i^{\rm dest},\end{cases}\tag{11}$$

where the parameter c has value one for the stuck pedestrians and zero otherwise, $V_i^{\rm dest}$ is the initial preferred speed toward the destination, $S_i^{\rm dest}(t)$ is equal to $v_i(t)\,e_i^{\rm dest}(t)$, and $e_i^{\rm dest}$ is the preferred direction toward the destination. The threshold value for losing patience is not involved in Eq. (11) because of the lack of relevant psycho-social studies. However, the parameters a and b are to govern the response of losing patience and to determine the range of $S^{\rm dest}$ in which the high deceleration starts (see Fig. 5).

3.2. Incorporating making way force

Naturally, making way behavior is a moral response by the kind pedestrians to the voice or bodily cues or pushing from the stuck pedestrian who tries to penetrate the front of the jammed crowd, e.g., declaratively asking way or transgressive walking. Such a behavior is common in areas where religious rituals are performed, for example the Hajj crowd (as illustrated in Fig. 2). The pedestrian who decides to penetrate the front of a jammed crowd is named here the penetrating pedestrian. The penetrating pedestrians for each local jammed crowd are the stuck pedestrians who do not face the back of other stuck pedestrians. Accordingly, the stuck pedestrian who leads a flow is a penetrating pedestrian. Besides, the stuck pedestrian not in contact with another pedestrian moving in the same direction is also a penetrating pedestrian.

The penetrating pedestrians are specified with a value one for the penetration parameter P_i. The parameter P_i equals zero for the remaining pedestrians. For the penetration process, firstly, we propose that the penetrating pedestrian strengthens his preferred force by increasing his preferred speed and directing his motion toward the weakest point in the front of the jammed crowd to be penetrated, namely, the point of contact between the facing pedestrians j and k (see Fig. 4). The model of the preferred speed and direction for the simulated pedestrians are as follows:

$$\begin{aligned} v_i^0(t) &= (1-P_i)\,V_i^{\text{dest}} \\ &\quad + P_i\left[\alpha_i(t)\,V_i^{\text{dest}} + (1-\alpha_i(t))\,V_i^{\max}\right], \qquad (12) \\ \boldsymbol{e}_i^0(t) &= (1-P_i)\,\boldsymbol{e}_i^{\text{dest}}(t) \\ &\quad + P_i\Bigg[\alpha_i(t)\,\boldsymbol{e}_i^{\text{dest}}(t) \\ &\quad + (1-\alpha_i(t))\,\frac{\boldsymbol{n}_{ij}(t)+\boldsymbol{n}_{ik}(t)}{\left\|\boldsymbol{n}_{ij}(t)+\boldsymbol{n}_{ik}(t)\right\|}\Bigg], \qquad (13) \end{aligned}$$

where $V_i^{\max}$ is the maximum speed at which the pedestrian i can walk. Secondly, the social forces $\boldsymbol{f}_{ji}^{\text{MakingWay}}$ and $\boldsymbol{f}_{ki}^{\text{MakingWay}}$ exerted by the penetrating pedestrian i on each facing pedestrian j and k are proposed. The force $\boldsymbol{f}_{ji}^{\text{MakingWay}}$ represents the motivation of pedestrian j to make way to pedestrian i and modeled as a perpendicular vector on the vector $\boldsymbol{n}_{ji}$, opposite to the direction of $\boldsymbol{f}_{ji}^{\text{friction}}$, and with magnitude directly proportional to $\left\|\boldsymbol{f}_{ji}^{\text{push}}\right\|$

$$\boldsymbol{f}_{ji}^{\text{MakingWay}} = P_i(1-P_j)\,F\left\|\boldsymbol{f}_{ji}^{\text{push}}\right\|\boldsymbol{n}_{ji}^{\perp}, \qquad (14)$$

where the parameter F is a constant of proportionality, and $\boldsymbol{n}_{ji}^{\perp}$ is a unit vector orthogonal to $\boldsymbol{n}_{ji}$. The model of $\boldsymbol{f}_{ki}^{\text{MakingWay}}$ is similar to $\boldsymbol{f}_{ji}^{\text{MakingWay}}$. According to the factor $P_i(1-P_j)$, the penetrating pedestrian j in $\boldsymbol{f}_{ji}^{\text{MakingWay}}$ will not make way for his facing pedestrians, and the kind pedestrian j in $\boldsymbol{f}_{ji}^{\text{MakingWay}}$ will make way only for the penetrating pedestrian facing him.

Finally, equation (3) is introduced for all pedestrians as follows:

$$\boldsymbol{f}_i^{\text{social}}(t) = \boldsymbol{f}_i^{\text{pref}}(t) + \sum_j \boldsymbol{f}_{ij}^{\text{rep}}(t) + \sum_j \boldsymbol{f}_{ij}^{\text{MakingWay}}(t). \qquad (15)$$

4. Simulation results and discussion

Two scenarios are set up in this section to validate the work of this article. The first scenario is the conduction of simulations to exhibit the ability to simulate pedestrians for penetrating the jammed crowd in normal situations, and the second scenario is an implementation of our work to show its effect on forming lanes.

4.1. Scenario 1: Penetrating a jammed crowd

The setup of the physical environment depicted in Fig. 6 is a large room, on the right side with an exit to a straight corridor with widths of 3 m. The positions of the simulated pedestrians in the room and the corridor are initialized randomly, and their initial preferred speeds are Gaussian distributed,[38] with mean equal to 1.34 m/s and standard deviation equal to 0.26 m/s. The aim of the simulated pedestrians in the corridor is to enter the room. They are considered as stuck pedestrians, $c_i = 1$. The pedestrian parameters and the SFM parameters are shown in Table 1.

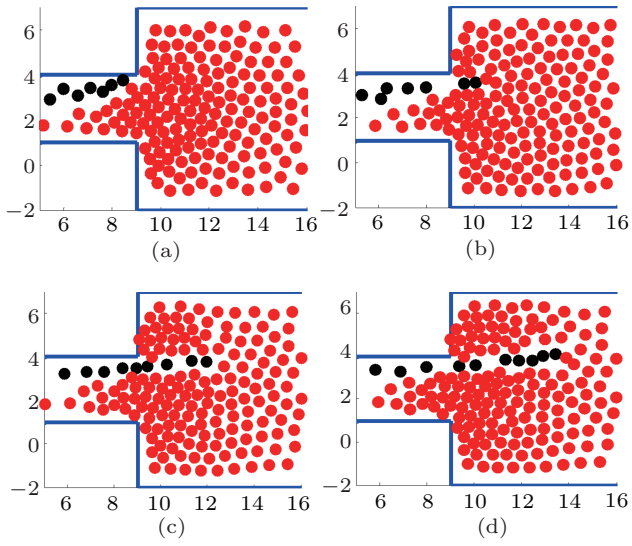


Fig. 6. (color online) Snapshots (a)–(d) have chronologically been taken, to capture the penetration of jammed crowd exiting a room.

We choose $a = 6.2$ and $b = 4$ based on the obtained $\alpha^{\text{kindness}} = 0$ when the actual velocity of a penetrating pedestrian approaches to zero (see Fig. 5).

As shown in Fig. 6, the pedestrians in the corridor are able to penetrate the jammed crowd clogging the exit. The leader

of the lane entering the room is the only one whose penetration parameter keeps equal to one.

Table 1. Simulation parameters.

Variable	Parameter	Simulation value
m	range of pedestrians' mass	[77–83] kg
r	range of pedestrians' radius	[0.25–0.27] m
A^{rep}	strength of the repulsive social force	2000 N
B^{rep}	repulsive distance parameter as a function of density, see Eq. (8).	$B^{\text{rep}}(\rho)$
λ	angular parameter as a function of density, see Eq. (9)	$\lambda(\rho)$
ε	range of fluctuation source of the pedestrian's acceleration, which is randomly assigned to each individual.	$[0,(0.1)v^0]$

It is worth noting here that this penetration process is different from the oscillation phenomenon at a bottleneck, as stated in Ref. [31]. In the latter, the increase in the pressure from the blocked pedestrians can result in the change of the flow direction. However, this is not a matter of pressure; it is a kindness behavior from the pedestrians exiting the room.

To investigate the dependence of the average time for penetrating the jammed crowd on coefficient F, we chose different values of F for the values $a = 6.2$, $b = 4$, and $V_i^{\max} = 1.6$ m/s. At each value of F, we perform ten simulations and calculate the mean and the standard deviation of the average time for the penetrating pedestrian (the leader) entering the room 1 m away from the exit. As shown from the error bar curve in Fig. 7, the average time decreases with increasing value of F.

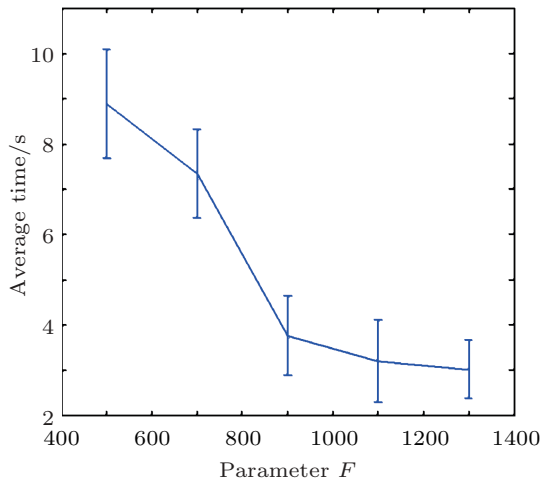


Fig. 7. (color online) Error bars show the means and deviations of the average time plotted as a function of the magnitude of parameter F.

However, this decrease is not significant for values higher than 900. The last behavior is natural because making way for the penetrating pedestrians is limited to the lack of spaces among the clogging pedestrians. Similarly, we chose different values of $V_i^{\max}$ for $F = 900$ and obtain an error bar curve which has a similar curvature to the previous one (see Fig. 8). However, the simulation results show that high values of $V_i^{\max}$ which exceed 2 m/s result in physical pushing to the facing pedestrians, leading to significant negative motion with respect to their preferred velocities.

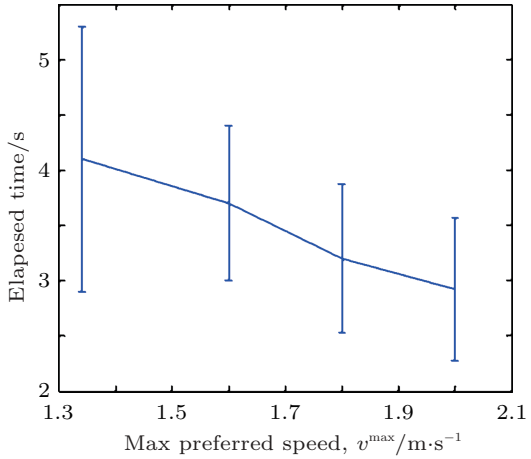


Fig. 8. (color online) Error bars show the means and deviations of the average time as a function of the magnitude of parameter $V^{\max}$.

4.2. Scenario 2: Joining lanes

In this subsection, the simulations to exhibit the pedestrian ability to join the lanes are conducted. Investigating the flow of lanes is an intelligent capability proposed in Ref. [39]. The simulated area of the current simulations is a straight walkway (see Fig. 9) with functionality as a racetrack. That is, when the perception area possessed by the simulated pedestrian i (the blue circle located on the left side of the walkway in Fig. 9(a)) walking toward the left exceeds the left boundary of the walkway, it is automatically computed to be on the right part of the walkway as illustrated in Fig. 9(a). Therefore, the simulated pedestrians inside the right circle are considered as pedestrians located within the perception of pedestrian i, and accordingly they exert social forces on pedestrian i. Subsequently, when the pedestrian i exceeds the end on the left side of the walkway, he is regenerated on the right side with identical y-component of his previous location and identical actual velocity and forces exerted by his followers. Invariably, pedestrian i keeps following their motion inside the walkway from the right side again as though he is in a closed walkway. Thus, the walkway is considered to be a closed loop, with regards to the implementation.

The specification of the simulated pedestrians and their motion are as follows: up to 400 simulated pedestrians are initialized in the walkway and divided into two groups. The positions of the first group of pedestrians were initialized randomly in the walkway simultaneously and their motion instan-

taneously is directed rightward. The second group is directed to the opposite side; a few of them are initialized in the right-up corner of the walkway randomly and considered as stuck pedestrians, $c_i = 1$, and the remaining pedestrians are initialized as a lane in the lower part.

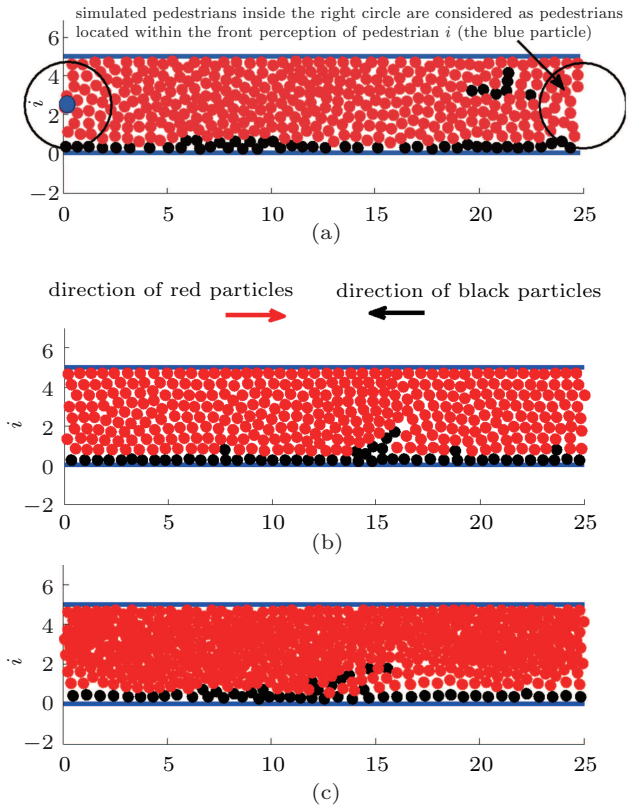


Fig. 9. (color online) Joining lane behavior by a group of pedestrians in bidirectional pedestrian flow is examined. (a) The initialization of the simulated pedestrians is performed. (b) A small lane is formed, while crossing the counter flow and joining the lower lane. (c) Similar behavior is performed, while penetrating local density exceeding 5 m^{-1} .

All simulated pedestrians prefer velocities with a mean of 1.34 m/s and standard deviation of 0.26 m/s. The criterion to validate the above work is the occurrence of joining lanes in jammed situations; that is, the stuck pedestrians from the second group changes their direction and intersects the opposing flow to join the lane below. As shown in Fig. 9(b), penetrating jammed crowd capability is essential for crossing the counter flow and joining the lane. The stuck pedestrians are able to penetrate high density areas with a local density of approximately 5 m^{-1}. A small lane is often formed as a result of penetrating and following behavior. However, in simulations with 500 simulated pedestrians to obtain local density exceeding 5 m^{-1}, the joining behavior is established but most often during larger time interval and scattered pedestrians (see Fig. 9(c)). The stuck pedestrians in the last case are forced to be dispersed because of the intense head of conflicts. Such a formation is commonly apparent in real life situations, such as in the Hajj crowd when the pilgrims leave the Tawaf ritual to perform the Sa'ee ritual.

5. Conclusions

In this article, penetrating a jammed crowd as a critical crowd behavior is recognized in multidirectional walkways. It is simulated in the social force model by enabling the stuck pedestrians to penetrate the front of a jammed crowd. Kindness behavior (such as making way) from the facing pedestrians toward the stuck pedestrian is an essential factor for the penetration process. With this representation, freezing transition introduced by many simulation models can be eliminated. The representation of real behavior observed in the Hajj crowd is used as a qualitative validation of this work. The result is consistent with the experimental studies which handle multidirectional flow aspects.

The contribution in this article gives researchers an insight into the crowd behavior, which helps eliminate the undesirable ones. It can be easily extended to many aspects of pedestrian flow by considering different orderings of multidirectional flow and incorporating some aspects involving physical characteristics such as obstacles and walls. Having techniques that can offer a nearly optimal parameter value is necessary. We recommend devoting more effort to the development and the implementation of these techniques for the calibration of our proposed model.

It is hoped that this work will be of particular benefit to those who are involved in the applications of organizing safer mass events such as the Hajj crowd.

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