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Modified two-layer social force model for emergency earthquake evacuation

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HIGHLIGHTS

- A two-layer social force model is proposed in this paper.
- Group organization pattern study is extended from a lower to a higher density.
- It proposed an algorithm to reach a dynamic group partition.
- The modified model maximizes the role of group leaders.
- The paper simulates a grouping process according to a real-life earthquake evacuation.

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ABSTRACT

Studies of crowd behavior with related research on computer simulation provide an effective basis for architectural design and effective crowd management. Based on low-density group organization patterns, a modified two-layer social force model is proposed in this paper to simulate and reproduce a group gathering process. First, this paper studies evacuation videos from the Luan'xian earthquake in 2012, and extends the study of group organization patterns to a higher density. Furthermore, taking full advantage of the strength in crowd gathering simulations, a new method on grouping and guidance is proposed while using crowd dynamics. Second, a real-life grouping situation in earthquake evacuation is simulated and reproduced. Comparing with the fundamental social force model and existing guided crowd model, the modified model reduces congestion time and truly reflects group behaviors. Furthermore, the experiment result also shows that a stable group pattern and a suitable leader could decrease collision and allow a safer evacuation process.

1. Introduction

Research interest in pedestrian dynamics for emergency evacuations has increased significantly, especially in some disciplines, such as traffic science and safety engineering [1]. An evacuation system is an important component in the management of public places. One such system is the foundation assembly occupancy risk management, which aims to contain serious calamities.

In an actual situation, not all pedestrians in a crowd evacuation know the exact evacuation route. Therefore, their behaviors are based on their self-organization and individual behaviors, and may also be influenced by other pedestrians

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around them. Often, their own judgment and behavior are in accordance with public behaviors. Hence, they become willing to walk together due to conformist mentality. Moreover, only a few pedestrians move independently. In the process of a guided emergency evacuation for pedestrians, people become more willing to evacuate in a tight group. Therefore, crowd simulation studies should have a deeper understanding of the features and mechanisms of group evacuation due to conformist mentality, which can theoretically support group behaviors in a crowd evacuation simulation. Based on existing research, this paper presents a guided crowd evacuation simulation model and grouping algorithm. The fundamental social force model (FSFM) has also been modified in this paper. The main contributions are listed below.

(1) A modified two-layer social force model is proposed in this paper.
(2) The study of group organization patterns is extended from a lower to a higher density.
(3) After considering the disorganized pedestrians, this paper proposed an algorithm to reach a dynamic group partition.
(4) The modified two-layer social force model maximizes the role of group leaders, while simulating a grouping process according to a real-life earthquake evacuation.

Based on the aforementioned points, the modified two-layer social force model (MTSFM) proposes group evacuation and builds a guided crowd dynamic by using our MTSFM. This paper then simulates group behavior in crowd simulation based on the SFM, individual characteristics, and group evacuation behavior features. In addition, a series of simulation experiments are carried out to clearly present social phenomena, such as gathering, balance, and conflict, further verifying the effectiveness and efficiency of the proposed modeling method. Results provide theoretical support for engineers and architects in their respective fields of building design and maximizing safety during emergency evacuations.

This paper is organized as follows. Section 2 mainly introduces past works related to the FSFM. Section 3 introduces the FSFM and the MTSFM. Section 4 provides simulation experiments that demonstrate the efficiency of the method proposed in this paper. The conclusion and future research topics are described in Section 5.

2. Related works

A strong interest in pedestrian dynamics for emergency evacuations emerged in the early 1990s, and thus far, two types of crowd evacuation models have been proposed [2]. These models, namely, macro and microscopic models [3–5], can effectively simulate several dynamic features for pedestrian evacuation, such as clogging effect and stop and go waves [6]. Numerous classical macroscopic models, such as fluid dynamics [7], can be used to describe trends in crowd movement although they have not fully considered detailed behaviors and interactions among pedestrians. In comparison, microscopic models fully consider the interactions of detailed behaviors. Representative models include social force model (SFM) [8–10], cellular automata model [11,12], and lattice gas model [13–15].

SFM is a classic continuous space microscopic model that can qualitatively reproduce many self-organizing phenomena like lane formation and arching. This model allows pedestrians to move continuously within a predefined place by defining forces, i.e., desired force. The two factors allow the models to continually improve. Ref. [16], proposed an attraction model (ATM) based FSFM, which can observe obvious group phenomena by adding gravitation into SFM. Meanwhile, past studies have attempted to reduce unrealistic collision behaviors in the model [17–19]. Han et al. proposed an extended route choice model based on an available evacuation route [20]. Li simulated classroom evacuation in the Ya'an earthquake last 2013 in China by parameter calibration and social force model optimization [21]. Kretz demonstrated that approaching another person depends on parameters and that oscillations can be avoided [22].

Numerous studies on pedestrian evacuation simulation in emergency situations have been published, whereas only few have investigated crowd movements, especially during evacuation efforts in large-scale public places [23]. With the proposed group dynamics, the characteristics of groups, such as aggregation, conflict, and balance, have been fully expressed in group evacuation [24]. Loscos et al. showed the importance of group behavior in a realistic crowd simulation [25]. Another study [26] implemented several crowd behavior scenarios with the existence of individual or grouped pedestrians. Moussaïd et al. added the "small group" phenomenon into the SFM [27]. Wang Lei simulated the phenomenon of gathering and grouping people by adding attraction force [28]. Hou Lei improved the social force model by setting the same number of leaders and exports, and then conducted a series of analysis regarding the impact of number and the leader's position on the evacuation [29]. Yang proposed a modified guided model (GM) that can be used for guided crowd dynamics in large-scale public places [30]. Fasheng Qiu presented a unified and well defined framework for modeling the structural aspect of various groups in pedestrian crowds [31]. Qingge Ji proposed a dynamic grouping algorithm based on A*Algorithm to simulate a grouping phenomenon with a number of leaders [32].

In an actual situation, not all pedestrians during crowd evacuation know the exact evacuation route. Therefore, their behaviors are not only based on their self-organization, but also influenced by people around them. Their own judgments and actions are easily influenced by public behaviors. Only a small number of pedestrians move independently, and most are willing to walk along with others due to conformist mentality. People are more willing to evacuate in a tight group, especially during the mobilization of pedestrians for guided emergency evacuation. Therefore, crowd simulation studies should have a deeper understanding of the features and mechanisms of group evacuation due to conformist mentality, which theoretically support group behaviors in crowd evacuation simulations. However, pedestrians are restricted by attraction, which increases the computational complexity in these SFMs. Entire moving teams are disorganized, and it often takes a long time for pedestrians to gather. Furthermore, leaders and group members are fundamentally the same, and the existing modified SFMs do not reflect the particularity of its leaders.

3. Modification of the social force model

3.1. Social force model

SFM, first proposed by Helbing et al. in 2000 [33], which represents pedestrians' motions using the combination of physical and psychological forces. According to Newton's second law of motion, the change of pedestrian's velocity in time t is then given by the acceleration equation

$$m_i \frac{d\vec{v_i}(t)}{dt} = \vec{f_i^0} + \sum_{j(\neq i)} \vec{f_{ij}} + \sum_{w} \vec{f_{iw}}, \tag{1}$$

where the pedestrians are driven by three forces: desired force $\vec{f_i^0}$, which shows the destination of pedestrians; the interaction force $\vec{f_{ij}}$ between pedestrians i and j, which prevents the collision of pedestrians; and the interaction force $\vec{f_{iw}}$ between pedestrians and walls, which is added into the model to keep pedestrians away from walls.

The corresponding mathematical expression of the three forces can be expressed as follow.

$$\vec{f_i^o} = m_i \frac{v_i^0(t)\vec{e_i^0} - \vec{v_i}(t)}{\tau_i}, \tag{2}$$

where m is the pedestrian mass, desired direction $\vec{e_i^0}$ determines the direction of pedestrian i moving in the desired velocity $\vec{v_i^0}$, d_{ij} is the distance between pedestrian i and j, and τ_i is a time constant related to the relaxation time of the pedestrian i to achieve $\vec{v_i}$.

$$\vec{f_{ij}} = A_i \exp[(r_{ij} - d_{ij})/B_i] + kg(r_{ij} - d_{ij})\vec{n_{ij}} + \kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t \vec{t_{ij}}, \tag{3}$$

$$\vec{f_{iw}} = A_i \exp[(r_i - d_{iw})/B_i] + kg(r_i - d_{iw})\vec{n_{iw}} + \kappa g(r_r - d_{iw})(\vec{v_i}\vec{t_{iw}})\vec{t_{iw}}, \tag{4}$$

where $\vec{f_{ij}}$ illustrates the interaction forces from pedestrian i and pedestrian j, $\vec{f_{ij}}$ consists of $\vec{f_{ij}^{psy}}$ and $\vec{f_{ij}^{phy}}$. The psychological force $\vec{f_{ij}^{psy}}$ is mainly determined by the distance between pedestrians, which is shown as the first term on the right side of Eq. (3). Other terms of the right side of Eq. (3) show physical force $\vec{f_{ij}^{phy}}$, which calculates body compression and sliding friction. Here, r_{ij} is the sum of r_i and r_j, d_{ij} is the distance between the centers of mass of the pedestrians, n_{ij} is the normalized vector pointing from j to i, t_{ij} shows the tangential direction, and Δv_{ji}^t shows tangential velocity difference. The interaction with the walls is treated analogously. In Eq. (4), d_{iw} is the distance to the wall W, n_{iw} is the direction perpendicular to W, and t_{iw} shows the direction that is tangential to the wall.

3.2. Modified social force model

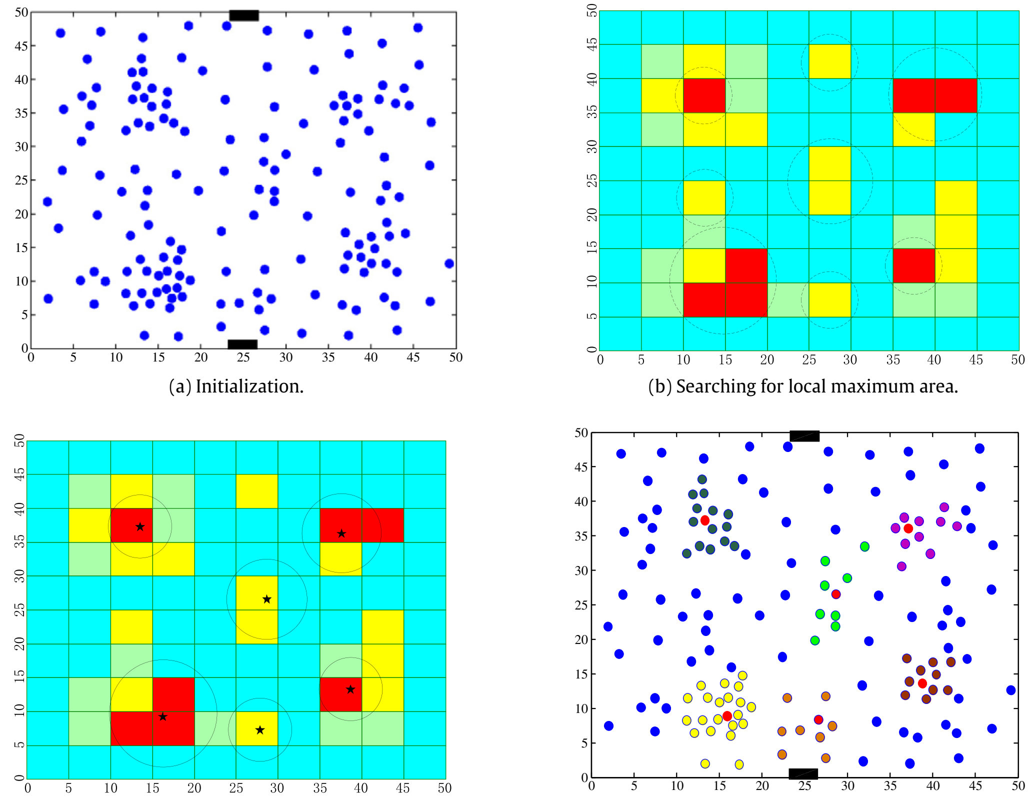
Some self-organization phenomena, such as lane formation and arching, can be simulated by the SFM easily, including the pedestrians' detailed behaviors. However, this model still has its limitations. People are complicated beings, and as such, we tend to adjust ourselves according to the pedestrians around us during an evacuation. We follow what others do and tend to move together with those around us. However, since its conception, the model has been extended to include group behaviors, e.g., a crowd evacuation model based on grouping or one based on guidance.

The existing model based on grouping takes a long time for pedestrians in the same group to gather together; at the same time, a group is restricted by adding attraction into the model, thus making the whole moving team disorganized. On the one based on guidance, the function of the guide has not been maximized, and the guide is considered as having the same position as others in the crowd. Therefore, a MTSFM is proposed in this paper.

3.2.1. Group partition and the selection of leaders

A leader knows more about the exact information associated with exports as well as the best routes to the target compared with group members. In an actual situation, the selection of leader is guided by the following rules:

(1) Leaders should stand in the center of the group, which makes it easier for group members to gather at the beginning of an evacuation.
(2) Leaders should walk in front of the group to make it convenient for group members to follow during the process of evacuation.



(a) Initialization. (b) Searching for local maximum area.

(c) The selection of leaders. (d) Group partition.

Fig. 1. Group partition and the selection of leaders.

In the paper, we divided the scene into grids, and we calculated the population density of each grid, and then searched for the local maximum density regions in the scene. In order to reduce the error of the grid partition, we selected the maximum fitness function $Fit(x)$ value within each region's minimum enclosing circle. The pedestrian who gain the max $Fit(x)$ value would be endowed as leader. His or her corresponding group is the circle area with a radius of minimum enclosing circle's radius.

However, if leader's local density is smaller than the average density of the whole scene, the group would be discarded. In special cases, as for multi-room scene, if the single room is small, such as the school classroom and office room, the pedestrians who stay in the same room are divided into the same group. Moreover, in specific cases, for example, teachers often play a role of leader. As a result, leader identity can be directly endowed to the teachers. Considering the above points, the leader fitness function $Fit(x)$ is determined as follows,

$$Fit(\mathrm{X}) = \begin{cases} count[N]/\Omega & \text{, normal cases} \\ 1 & \text{, have obvious feature of leader} \\ 0 & \text{, others} \end{cases}, \tag{5}$$

In order to have a more intuitive observation, the process of group partition and the selection of leaders is show in Fig. 1.

3.2.2. Modeling for leaders and group members

While leaders move as normal pedestrian in SFM. Using the leaders as the base, a MTSFM is mainly used to describe the relationship between the lead and group members. In the model, leaders act as the ligament that connects the export and group members. Furthermore, using the advantages of SFM in gathering, group members move directly to their respective leaders. Changing the velocity of pedestrians at time t is described by the acceleration equation

$$m_i \frac{d\vec{v_i}(t)}{dt} = \vec{f_{il}^0} + \sum_{j \neq i} \vec{f_{ij}} + \sum_{w} \vec{f_{iw}}. \tag{6}$$

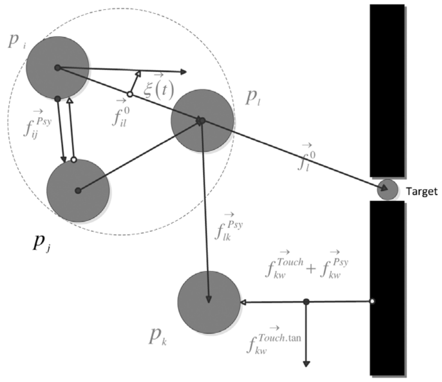


Fig. 2. Force illustration in MTSFM.

Eq. (6) is similar with the FSFM based on Newton's second law of motion. Furthermore, on the basis of the FSFM, $\vec{f}_{il}^{0}$ is determined as

$$\vec{f}_{il}^{0} = m_i \frac{v_{il}^{0}(t)\vec{e}_{il}^{0} - \vec{v_i}(t)}{\tau_i}. \tag{7}$$

Where $\vec{e}_{il}^{0}$ refers to the export of the scene in the existing models, and is the direction pointing to the position of leader. Group members ignore the impact of target while retaining former forces. To present a more intuitive description of pedestrian movement driven by the MTSFM, the illustration of force is shown in Fig. 2.

In Fig. 2, p_l plays the role of leader moving towards the target as in the FSFM, p_i and p_j are the two group members of leader p_l, and p_k is a pedestrian who serves as the leader of another group. The modified $\vec{f}_{il}^{0}$ drives p_i to move towards p_j instead of the final target compared with the fundamental model. Due to the psychological force $\vec{f}_{ij}^{psy}$, they move directly towards the leader at a corresponding angle $\vec{\xi}(\mathrm{t})$, and only the necessary collision avoidance force is maintained between leader and other pedestrians around him/her. Ordered group phenomena are typically observed during evacuations. However, several optimum algorithms are added into the proposed model.

3.2.3. Modeling for disorganized pedestrians

In this paper, as for those disorganized pedestrians, if there are groups existing in their horizon, they tend to move towards groups due to herd mentality, and then gather into groups dynamically. The movement of disorganized pedestrians can be described by the following equation,

$$m_i \frac{d\vec{v}_i(t)}{dt} = (1-\beta_i)\vec{f}_i^{0} + \beta_i \sum_{g \in G_i} \xi(\mathrm{g})\vec{f}_{ig}^{0} + \sum_{j \neq i} \vec{f}_{ij} + \sum_{w} \vec{f}_{iw}. \tag{8}$$

Where parameter $\xi(\mathrm{g})$, β_i is determined as follow,

$$\xi(\mathrm{g}) = \frac{count[N_{ig}]}{\sum_{g \in G_i} count[N_{ig}]}, \tag{9}$$

$$\beta_i = \begin{cases} 0 & , exit_i \in \Omega_i \\ \dfrac{\sum_{g \in G_i} count[\mathrm{N}_{ig}]}{count[\mathrm{N}_i]} & , exit_i \notin \Omega_i \end{cases}, \tag{10}$$

where Ω_i is the range of disorganized pedestrian i's vision, radius of visual field is *sight*, the angle of visual field is θ, $exit_i$ is the exit that i chooses, G_i is the aggregation of groups within the range of i's vision, N_i is the aggregation of pedestrians within the range of i's vision, N_{ig} is the aggregation of group g within the range of i's vision, $count[N_{ig}]$ is the amount of N_{ig}, $\vec{f}_{ig}^{0}$ refer to the closest group members in group g.

The illustration of force is shown in Fig. 3. As we can see from Fig. 3, however, disorganized pedestrian i is still more willing to move towards group g_2 under the influence of the other two groups.

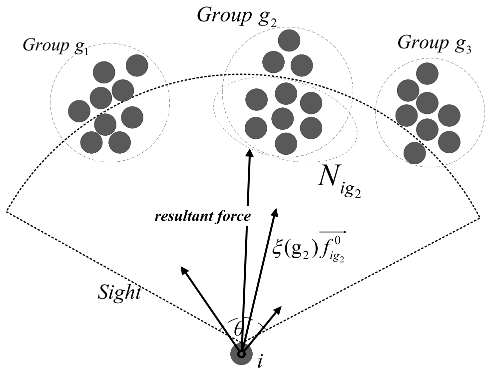


Fig. 3. Force illustration of disorganized person.

3.2.4. Identity switch process

The SFM has its own defects, which make it difficult to solve the multi-room evacuation problem. There is a serious problem faced by Yang's model in the multi-room scene that the group member can not decide whom to follow with the absence of the former leader. The identity switch process is proposed to solve the problem. The main steps are given below.

Step 1: Initialization of pedestrians.
Step 2: Select leaders referring to Eq. (5).
Step 3: The leader moves to the center and lead group members towards the target.
Step 4: If leaders move out of the former room, run Step 5; else rerun Step 3.
Step 5: Select a new suitable leader who is closest to the exit in the former room, and transmit information on exports and path to the new leader.
Step 6: All pedestrians evacuated from the previous room.

As we can see from the process, leaders play an important role in leading the group members. In a multi-room situation, when the former leaders move out of the room, the whole group is then divided into two parts; one in the former room and the other out of the former room. The flowchart shows that group members who are out of the former room still follow their old leaders, where those who stay in the former room are treated as a temporary group. And then the temporary group selects a temporary leader who can lead the temporary group. In some scenarios with narrow space especially in some crowded exports, people need not think more about evacuate rotes, the crowded pedestrian flow causes sight blockage. Meanwhile, group members in the same group gather closely due to the crowed pedestrian flow, the selection strategy of the temporary group's new leader would not bring great shock to the group's movement.

4. Simulation results

This paper creates a crowd evacuation simulation system using Visual Studio 2012 as a platform. In order to analyze and search for the influences of the MTSFM on organized evacuation, a series of experiments are carried out using different models. In this section, the MTSFM is validated by four examples and then compared with the literature and real evacuation scenarios (i.e., the evacuation video of the 4.8 Luan'xian earthquake in 2012). On the basis of a past study [27], the first example further studies the related patterns of organization in a high-density situation and recreates the group that is organized in an emergency guided evacuation. Then, the degree of group polymerization is studied and compared with the ATM. The second example features a simple scene to observe the effect of Section 3.2.3. The MTSFM is validated by experimental data through comparing with the ATM and GM proposed in the literature [30] and [16]. In a multi-room office scene, the process proposed in Section 3.2.4 has been proven effective using the third example. The last example illustrates that MTSFM is more effective in complex scenes, especially in the obstacle scene.

The simulation parameters in the paper are as follows: individual radius ($r = 0.25$ m), individual quality ($m = 80$ kg), angle of visual field ($\theta = 120^\circ$), radius of visual field ($R = 20$ m), and the constants of the SFM ($k = 1.2 \times 10^5$ kg $\cdot$ s^{-2}, $\kappa = 2.4 \times 10^5$kg $\cdot$ m^{-1} $\cdot$ s^{-1}, $A = 2,000$ N, $B = 0.08$ m, $C = 2,000$ N, $D = 0.05$ m, $E = 2,000$ N).

4.1. Average patterns of organization

This paper studies the related patterns of organization. In the ATM shown in Fig. 4, when the population density is low, groups are easily organized in a row, when there is a higher density, group members bunch up easily leading to a group square formation which is rare in emergency evacuations. In the MTSFM, when the density is low, the group members stand

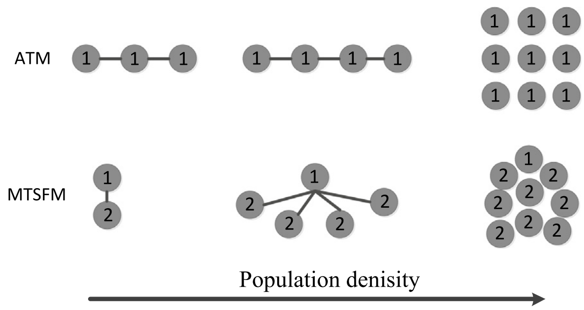
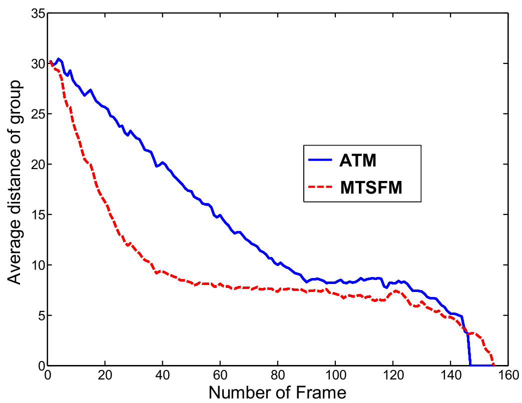


Fig. 4. Average patterns of organization.

(a) The process of grouping.

(b) Grouping patterns in simulation.



(c) Degree of group polymerization.

Fig. 5. Analysis of different grouping patterns.

in line. With the increase of density, the linear walking formation is bent forward and transforms into a V-like pattern. The MTSFM then fans the group into a two- or three-column formation when the density is much higher, which is closer to what happens in actual emergency evacuations.

In order to verify the authenticity of the model, we select an image from a real emergency school evacuation video during an earthquake and choose simulation results under realistic platforms. The comparison chart is shown in Fig. 5. Fig. 5(a) presents an emergency evacuation shot that occurs in a real earthquake scene. The evacuation process shows that the group members follow their leader and the group presents a fan-like formation. Fig. 5(b) is in the simulation scenario, which is completed by the MTSFM and restores the group movement as much as possible.

In order to reduce the interference of other conditions, the scale of the population is set 300, and the average size of each group is set 50. The average distance between the same groups was used as the criterion to evaluate the degree of aggregation. The change of group polymerization is shown in Fig. 5(c), which indicates that pedestrians in the MTSFM gather together in

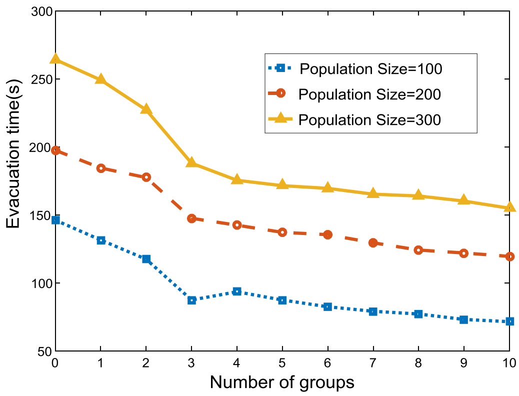
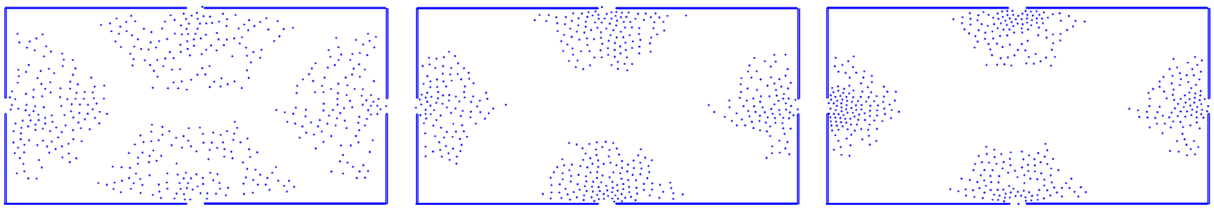
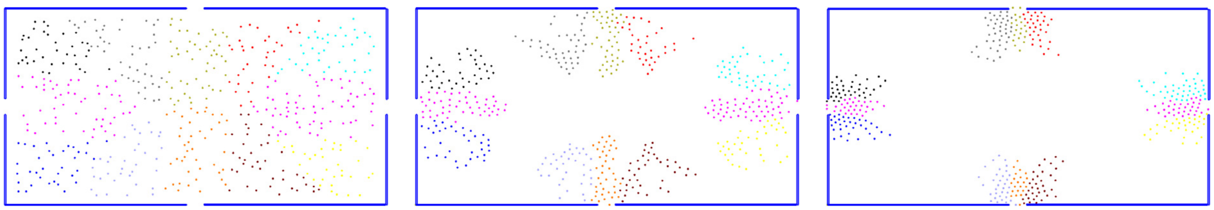


Fig. 6. Evacuation time against the number of leaders.



(a) Initialization. (b) Snapshots at $t = 8$ s. (c) Snapshots at $t = 27$ s.

Fig. 7. Snapshots generated by the FSFM.



(a) Initialization. (b) Snapshots at $t = 8$ s. (c) Snapshots at $t = 25$ s.

Fig. 8. Snapshots generated by the MTSFM.

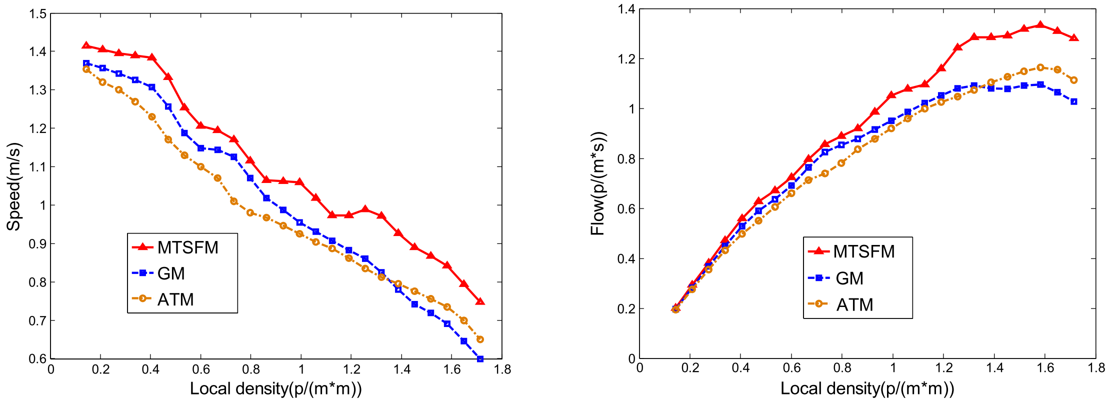
a short time, and that the group organization is more stable. At the same time, the aggregation speed of ATM is slower, and frequent shocks can be observed in ATM. The experiment results indicate that the MTSFM is more suitable for simulating an organized evacuation process.

In order to analyze the evacuation time against the number of leaders, we continuously increase the number of leaders from 0 to 10 in single-exit scene, and the result is shown in Fig. 6. In the MTSFM, the more leaders exist in the system, the less evacuation time is. However, as the number of leaders increases to a large number, the reduction of evacuation time would be little, and thus, we argue that, about 3 leaders for one exit is enough efficiently accelerate the evacuation.

4.2. Simulation results in a simple scene

In order to observe the group behavior for disorganized pedestrians, the paper generates several snapshots referring to different time points. The snapshots generated by the FSFM are shown in Fig. 7, whereas those generated by the MTSFM are shown in Fig. 8. According to the results in Fig. 6, each exit has no more than 3 groups in the experiments of this section.

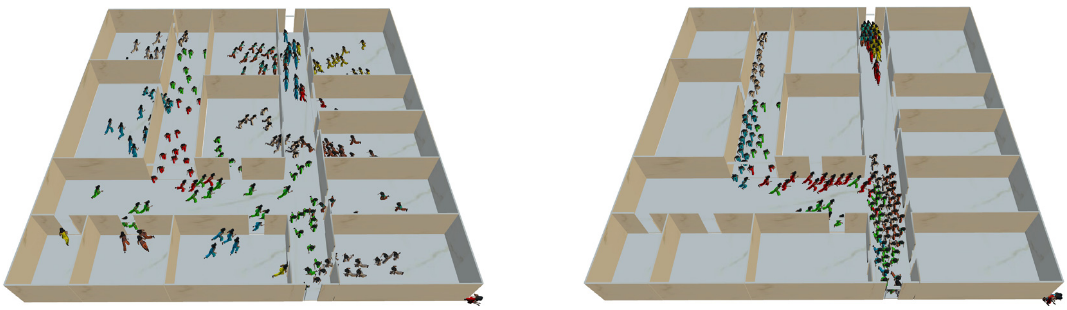
In the snapshots shown in Figs. 7 and 8, different colors represent different groups, and each point is a pedestrian in the scene. The initialization snapshots are shown in Figs. 7(a) and 8(a). Figs. 7(b) and 8(b) are the graphs of the pedestrians evacuating at $t = 8$ s. In Fig. 7(b), the whole moving team is disorganized, and the group members gather together. In Fig. 8(b), group members who walk behind their leaders form a tight group. In Fig. 7(c), when $t = 25$ s, pedestrians are mostly in front of the export, clogging can be observed and serves as the major impediment preventing pedestrians from



(a) Speed as a function of local density.

(b) Flow as a function of local density.

Fig. 9. Comparison diagram.



(a) The process of grouping.

(b) The evacuation in corridors.

Fig. 10. Simulation using the existing GM.

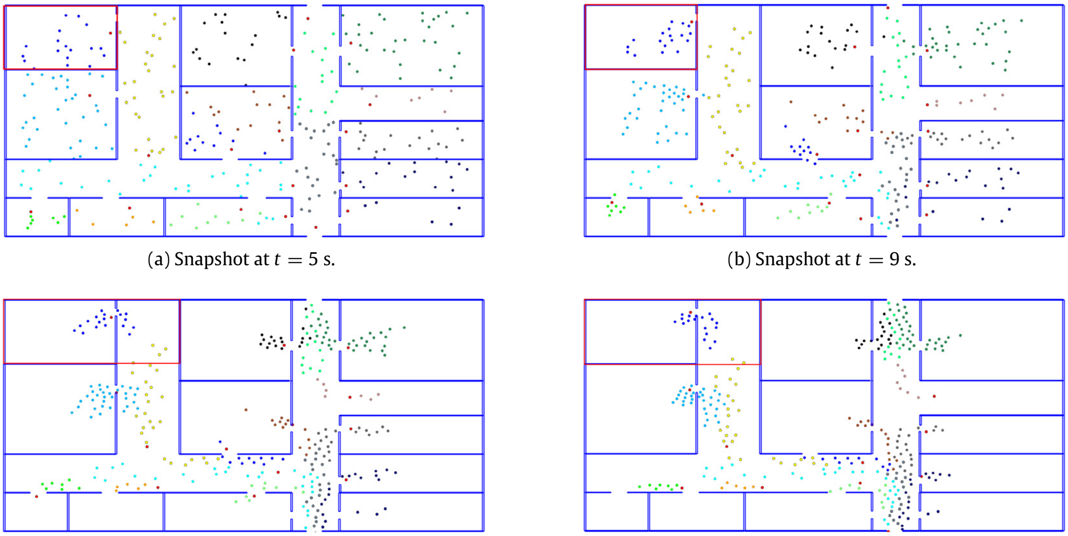
evacuating efficiently. As shown in the figures, when using the FSFM, arches form easily at the exits due to the congestion among pedestrians, thus leading to a bottleneck that affects the speed of evacuation. In comparison, when using the MTSFM, the evacuation efficiency is improved. As shown in Fig. 8(c), fewer people are left in the room unlike those shown in Fig. 7. Under the guidance of a leader, people in the same group are organized and can decrease the bad influence of bottleneck problem at the exit points, thus improving the efficiency of the evacuation.

In order to verify the evacuation efficiency of the MTSFM, quantitative analyses of different scenarios are carried out. We compared MTSFM with some models, such as GM and ATM. In the current work, we made the following experiments in the aforementioned experiment environments. Speed as a function of local density is given in Fig. 9(a), and flow as a function of local density is given in Fig. 9(b). As shown in Fig. 9(a), the MTSFM has a higher speed than the other models in the same density, and the speed tends to decrease with the density increase. In Fig. 9(b), we can see a higher flow in the MTSFM. The results obtained from this study show that an efficient grouping method proposed in our paper can realize a larger number of evacuations in the same density, thus demonstrating the effectiveness of the proposed method.

4.3. Simulation results in an office scenario

To verify the effectiveness of the proposed model in complex and actual environments, we built an office scenario, which has 11 rooms and 4 corridors, and each room have at least one export. We can see the simulation using the existing GM in Fig. 10. In the figures, people initialized in the same outlet room are divided into the same group, and those who stay in the room that has more than one exit select the export according to the distance between people and exports. Meanwhile, people in different groups use different character models. However, after leaders come out of the former room, the evacuation in the former door becomes relatively chaotic, and the aggregation of groups becomes less obvious.

To conduct a more intuitive evaluation of the MTSFM with the process proposed in Section 3.2.4, several snapshots referring to different time points in an office scenario are generated. We use Matlab to generate the snapshots at different time points; different colors mean different groups, as shown in Fig. 11. For the purpose of telling the differences between leaders and group members, leaders are painted red, and one group is framed in a red line. When $t = 5$ s, leaders move almost



(a) Snapshot at $t = 5$ s.

(b) Snapshot at $t = 9$ s.

(c) Snapshot at $t = 18$ s.

(d) Snapshot at $t = 22$ s.

Fig. 11. Snapshots generated by the MTSFM. A representative group is marked with red lines, leaders are pained in red and all the other pedestrians are pained in different colors representing different groups.

in front of the exit, as shown in Fig. 11(a). During this time, group members gather around leaders, as shown in Fig. 11(b). Meanwhile, disorganized pedestrians move towards leaders using the method in Section 3.2.3. The identity switch method mentioned in Section 3.2.4 can be seen. From Figs. 11(b) to (c) and from Figs. 11(c) to (d), previous leaders transmit the identity of the leader to others who still stay in the former room. A new leader then leads the group and acts as the gather target for group members; at the same time, the group members who have already left the previous room select the most suitable leader of the present group. The simulation result shows that the method improves the sense of reality in crowd evacuation simulation, thus verifying the effectiveness of the MTSFM in a complex environment.

To conduct a more intuitive simulation according to earthquake evacuation, we built a more realistic scene. In Fig. 12(a), students running on the corridor are the group members who come out of the former room. We can see the former leader who is in the corridor still leads the temporary group outside, as shown in Fig. 12(c). In Fig. 12(b), students who remain in the former room follow the student who is nearest to the door. Therefore, the walking formation of all students in the room is bent forward, creating a long V-like pattern. The shape of the group resembles two columns represented in Fig. 12(d).

4.4. Simulation in an obstacle scene

To further analyze the significance of a guided model in crowd evacuation, several experiments are conducted by taking the stress conditions as the standard.

In Fig. 13, different gray values show different situations of force level; a higher gray value means greater pressure. Figs. 13(a) and (b) show that pedestrians cause a massive congestion, thus serving as obstacles that lead to the accumulation of people at the entrance. Meanwhile, the extrusion pressure among pedestrians becomes too large, such that people become more susceptible to be knocked down and trampled underfoot. In Figs. 13(c) and (d), consensus is hard to reach on path selection for the group members in ATM, which leads to more collisions. In Figs. 13(e) and (f), it is obvious that the collisions among pedestrians have been reduced during the whole evacuation process, we can also see the groups make the process of evacuation much more smooth.

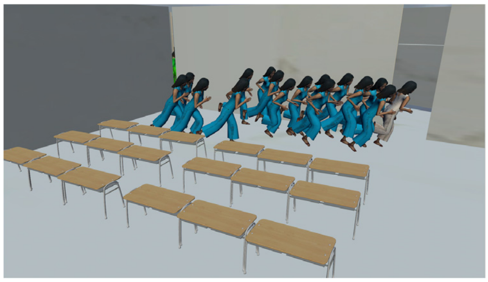
In order to further analyze the significance of improving crowd evacuation in obstacle scenes and comparing the differences on pedestrian force, this paper use the distance between each pedestrian as the collision standard. The force difference of group members is reflected as the pedestrian collision time. Table 1 presents the results of 50 experiments carried out to illustrate the differences among the FSFM, ATM, GM and MTSFM. The statistics are shown in Table 1.

In the same population scale, the MTSFM completes evacuation at a faster speed than the other models; hence, evacuation efficiency of MTSFM is improved. As for GM, both the number of collision and evacuation time are significantly reduced comparing with ATM and FSFM, which states that a suitable leader could promote the evacuation efficiency and reduce the collision in evacuation. Furthermore, in the experiments using the MTSFM, both numbers of collision and collision peak times of each frame are drastically reduced. The number of collisions reached 11.3845/100 people in the FSFM, whereas the number is only 2.0605/100 people in the modified model. However, in the ATM, the model always add new force to the social force models to generate groups, which makes the force between pedestrians more complicated. This results in

(a) Students in the corridor.

(b) Students who stay in the room.

(c) The temporary group staying outside.



(d) The temporary group staying inside.

Fig. 12. An actual multi-room evacuation simulation.

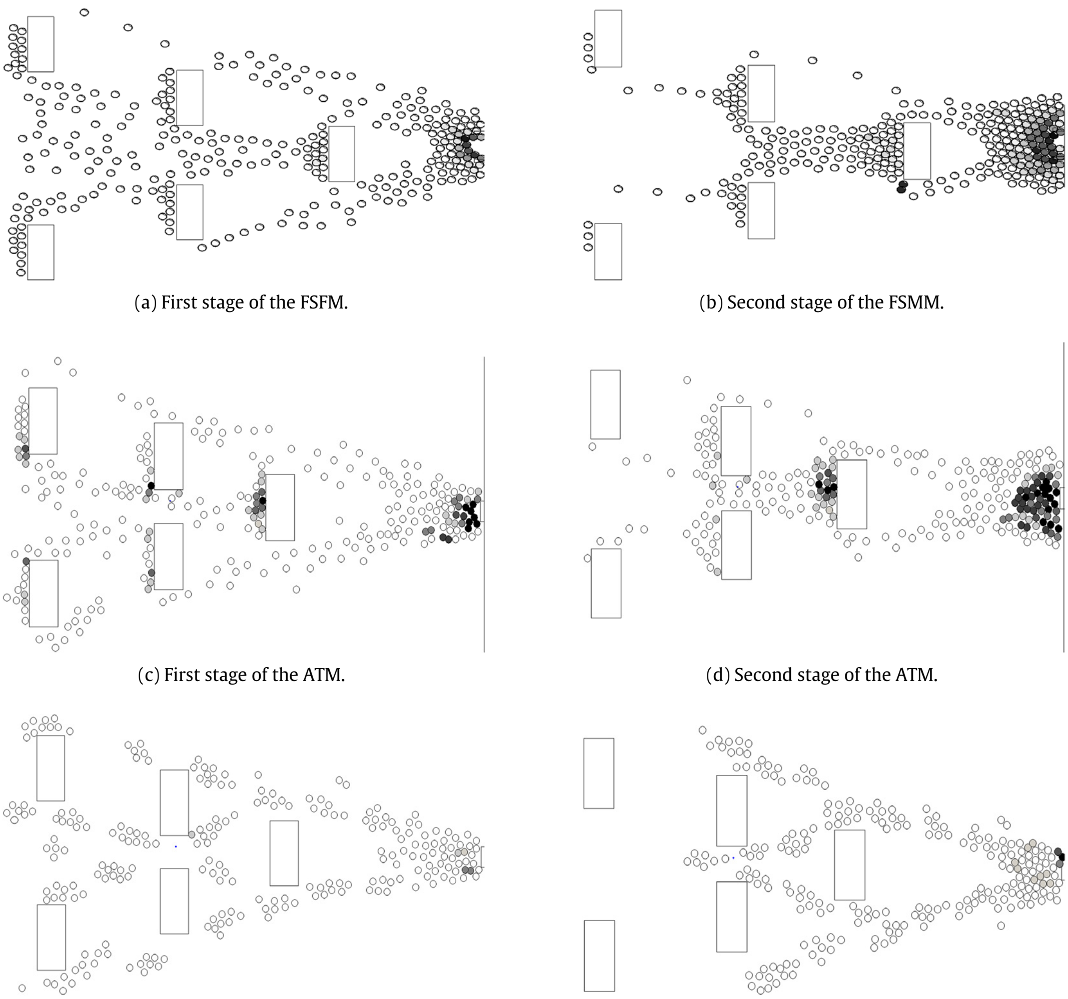
Table 1
Statistical comparison of force.

Model	FSFM	ATM	GM	MTSFM
Total number	250	250	250	250
Average number of frames	358.02	294.7	282.4	276.1
Max. collision times	63	57	27	14
Average collision times per experiment	10189.76	8473.58	3531.40	1573.48
Collision times/100 people	11.3845	11.50	5.3057	2.3113

a statistic of 11.50 crowd collisions/100 people, which is even higher than that using the fundamental social force model. The experiments in the obstacle scene show that stable group patterns and suitable leaders could lead to the realization of a large crowd evacuation with safety and security in less time.

5. Conclusion

A modified two-layer social force model is proposed, and a guided crowd dynamic is created using the modified two-layer social force model. To improve applicability in complex situations, modification and method are added into the modified two-layer social force model. A series of experiments are carried out using different models to search for and analyze the influences of the modified model. First, the paper studies the evacuation video of the Luan'xian earthquake in 2012, and extends the study of group organization patterns from a lower density to a higher one. Second, group organizations in real-life situations are recreated. Comparing the group polymerization with the attraction model, the modified model has a more stable group organization and fewer shocks. Moreover, the experiments compared with the existing guided model and attraction model show that an efficient grouping method can realize better evacuation in the same density. Then, in a multi-room office scenario, evacuation in real-life situations is simulated and reproduced using the modified model. Finally, the experiments in the obstacle scene show that stable group patterns and a suitable leader could lead to the realization of a large crowd evacuation with safety and security in less time. Future research will continue to the investigation of crowd dynamics together with the study of group behaviors. At the same time, we aim to seek for the possibility of combining other efficient algorithms into crowd evacuation [34], e.g. a crowd simulation combining neural networks [35] and Markov model [36], and then develop a computer evacuation system which may simulate more real group behaviors with less cost.



(a) First stage of the FSFM. (b) Second stage of the FSMM.

(c) First stage of the ATM. (d) Second stage of the ATM.

(e) First stage of the MTSFM. (f) Second stage of the MTSFM.

Fig. 13. Obstacle scene simulations.

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