ANALYSIS OF CLOGGING IN EVACUATION USING A MULTI-GRID MODEL

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ABSTRACT

Some collective behavior during escape panic such as the ‘faster-is-slower effect’ and the irregular outflow are associated with clogging. The reasons for clogging appearance are investigated with a multi-grid model which is presented in previous work. The model implements finer discretization which leads to clogging effects in the dynamics. The effects of the exit width and the interactions caused by overlapping grid on clogging are analyzed by a simulation that pedestrians evacuate from a room with one door. The influences of different maximum numbers of overlapping grid are also investigated.

KEYWORDS: Multi-gird model, Clogging, Overlapping

INTRODUCTION

Recently, pedestrian dynamics have attracted increasing attention of researchers. The cellular automata (CA) model, a discrete model in which the time, space and state variables are discrete, has been widely used in this field. Approaches based on CA model have been suggested [1-21] and some experimental results have also been presented to support the results [9,11,12,22-24]. Social force model [25], a successional model, can reproduce many collective behaviours such as arching and clogging at a bottleneck and faster-is-slower observed in pedestrian dynamics. As the movement of pedestrians is described by the dynamical equation of motion in social force model, many statistic and analytical investigations have been studied based on this model [24,26-28]. Other models [17,29-34], for instance, bionics-inspired cellular automaton model and centrifugal force model, which can be regarded as the extension of the two above models, have been proposed to study the features of pedestrian dynamics at the same time.

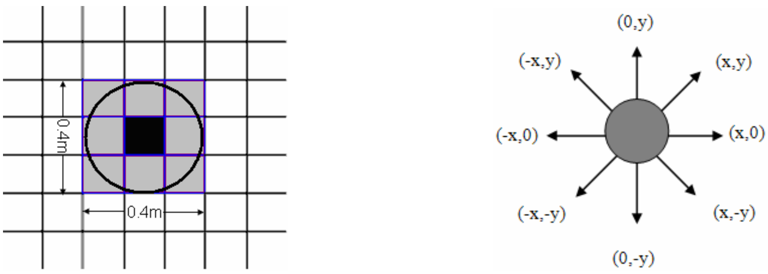
In most discrete model, the space discretization has been chosen in the simplest way that a pedestrian is allowed to occupy only one cell. However, it is necessary to implement a finer discretization of space to study the pedestrian dynamics for some applications. Weng et al.[35] have investigated the effect of different walking speeds on an evacuation scenario where a pedestrian occupies more than one grid. Kirchneret al. [14] have studied discretization effects in CA model for pedestrian dynamics by reducing the cell size. The multi-grid model[36] in our work adopts the same concept to study the interaction forces among pedestrians. However, the understanding of non-local conflict that is contacted with overlapping grids is not enough and requires further investigation.

The local interaction among pedestrians and those between pedestrian and environment plays a crucial role in pedestrian dynamics especially in the case where locally high density regions occur, e.g. in panic situations. It can have a strong impact on global behaviours of pedestrians through its local influence. Since the movement of pedestrians in social force model is based on Newton’s laws of motion, the expression of the interaction force in this continuous model is precise and reasonable. This model is particularly suited to describe many characteristic features in pedestrian dynamics, however, it is ineffective on computation. As a classic discrete model, CA model is mainly used in the study of pedestrian dynamics for its high computational efficiency. The basic principle in traditional CA model is that the space is discretized into small cells which can either be empty or occupied by exactly one pedestrian. Thus, interactions among pedestrians are represented simply by excluded-volume effect. Some important characters of human behaviors especially in high density situations miss as a result of lacking for the consideration of interactions in this model. It is remarkable that the interaction concept has been implemented in some extendible CA models. Kirchner et al.[31] extended CA model by introducing the friction parameter μ which is interpreted as a kind of an internal local pressure among pedestrians. When two or more pedestrians try to enter the same space at one time step, conflict occurs. Then the movements of all pedestrians involved are controlled by a certain probability according to the friction parameter. It is shown that these conflicts are important for a correct description of the pedestrian dynamics. In fact, the so-called ‘‘friction’’ in this model can be treated as repulsion among pedestrians. Based on the same concept, Song et al.[17-18] have present a new CA model entitled cellular automata with forces essentials (CAFE). In this model, interactions are classified into three types: attraction, repulsion and friction. The model proposed a series of formulas which determine the transition of the pedestrians in different situations including conflict. They reproduced arching, clogging and faster-is-slower phenomena and the relative results were compared in detail with those obtained by the social force model.

In previous work[36], we have developed a new discrete model entitled *multi-gird model* in which finer lattice is used, namely, each pedestrian occupies 3 × 3 grids instead of one. On the one hand, the movement of pedestrians is more accurate because the update timescale is one-third of that in general CA model. On the other hand, the interaction forces among pedestrians or those among pedestrians and constructions can be calculated quantitatively by the number and position of the overlapping grids. The interaction consists of extrusion, repulsion and friction, and is expressed in the form of probability which is consistent with the movement rule of the model. We have shown the dependence of the evacuation time on the system parameters by an evacuation simulation of a room with one door. In this paper, we analyze the effects of different maximum numbers of overlapping grid and the interactions caused by pedestrians on evacuation time steps in the same scenario. We except to investigate the reasons for clogging by the use of multi-grid model.

MULTI-GRID MODEL

The pedestrian is assumed to occupy only one cell and the size of which is 40cm×40cm in the conventional discrete model. This is the typical space occupied by a person in a dense crowd. We divide the occupied space of a pedestrian into 3×3 small grids in the multi-grid model. As shown in Fig. 1(a), black grid denotes the center of the pedestrian which is forbidden to be occupied by others(hard core exclusion), and red ones can be overlapped. Considering that the compressibility of a pedestrian is limited, we assume that at most three grids are allowed to be overlapped with other pedestrians or constructions. This is the *conflict rule* of the model. Each pedestrian can move to one of the eight neighboring grids based on transition probabilities per time step (see Fig. 1(b)).



(a) (b)

FIGURE 1. Schematic illustration of a pedestrian. (a) Black grid denotes the center of the pedestrian which is forbidden to be occupied by others, and gray ones can be overlapped. (b) Possible transition directions for a pedestrian.

The transition probability that a pedestrian move to site(i,j) is given by:

$$P_{i,j} = N\delta_{i,j}I_{i,j}\left(\frac{1-D}{\sum \delta_{i,j}} + D_{i,j} + \sum_{P} f_{i,j} + \sum_{W} f_{i,j}\right)$$

We assume that the preferential direction of each pedestrian points to the site to which the distance from exit is shortest. Then, drift D represents the intensity that a pedestrian moves in preferential direction. $D_{i,j}$ are transition probabilities of the preferential direction and of which two closest directions. The distribution of $D_{i,j}$ depends on the configuration. Fig. 2 shows all the possible configurations of a pedestrian whose preferential direction is (x,0). $D_{i,j}$ corresponding to each configuration are given by the following: $D_{x,0} = D, D_{x,y} = D_{x,-y} = 0$ for configurations (a),(c),(e), $D_{x,0} = 0, D_{x,y} = \frac{2}{3}D, D_{x,-y} = \frac{1}{3}D$ for configuration(b), $D_{x,0} = D_{x,y} = 0, D_{x,-y} = D$ for configuration(d) and $D_{x,0} = D_{x,y} = D_{x,-y} = 0$ for configuration(f). Note that $D_{x,y} = \frac{2}{3}D$ and $D_{x,-y} = \frac{1}{3}D$ is based on the assumption that site(x,y) is closer to the exit than site(x,-y). δ denotes whether the pedestrian is allowed to move to site (i, j), i.e., δ =1 if the approach is available and δ =0 if it is unavailable.

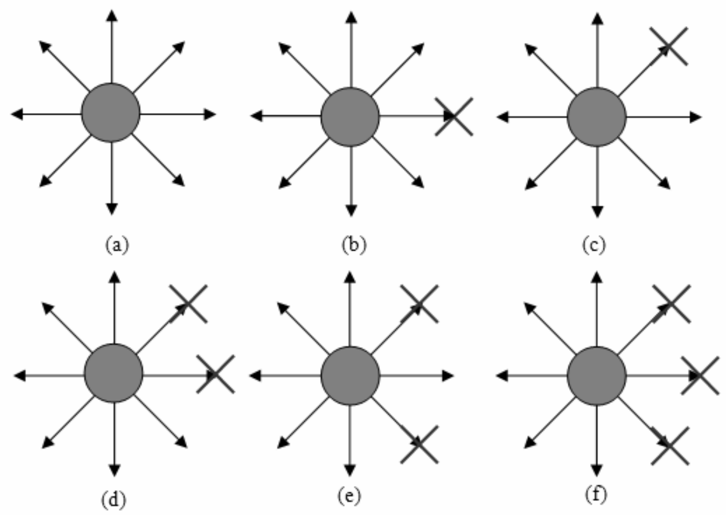


FIGURE 2. All the possible configurations of a pedestrian whose preferential direction is (x,0). The cross represents that the pedestrian can not move to the site according to the conflict rule of the model

Once a grid of the pedestrian is overlapped with other pedestrians or constructions, he receives forces at this direction. The interaction forces, including extrusion, repulsion and friction among pedestrians and those among pedestrians and constructions, are translated into probabilities $\sum_P f_{i,j}$ and $\sum_W f_{i,j}$ respectively. We do not give a full definition of $f_{i,j}$, which can be found in Ref.36 and the meanings of other parameters have been explained in Ref.36, too.

SIMULATION AND RESULTS

We carry out a computer simulation that 200 pedestrians leave a hall with length × width of 16 m × 16 m and the exit width is W. Initially, pedestrians are distributed randomly in the hall. Each pedestrian is updated at every time step in a random sequential way. When a pedestrian goes out of the system, he is removed from the system. The procedure repeats until all the pedestrians leave the hall. We set the friction coefficient μ and inertia I as constant, 0.2 and 1.2, respectively. The exit width W represents the grid number of the exit.

The assumption that a pedestrian occupies only one cell in many discrete models is not adequate to describe physics of crowd dynamics. Pedestrians have to compress their spaces occupied in a normal case in high density situations, e.g. during evacuation processes. Hereby, we implement a finer discretization of space in the model where at most three grids occupied by a pedestrian can be overlapped with other pedestrians or constructions to study the evacuation process.

We investigate the effect of different numbers of overlapping grid on evacuation times. The interaction forces are not taken into account since we focus on the influence of overlapping. Fig. 3 shows the relation of evacuation time steps against maximum number of overlapping grid for different values of drift. The movement is more effective when more grids of pedestrians are allowed to be overlapped with others. The overlapping grid reflects that pedestrians give their space to others partially, which makes for they passing through a bottleneck simultaneously. The drift D which has been discussed in previous work represents the intensity that a pedestrian who walks in the direction closest to the exit. A large value of drift indicates that the pedestrian moves toward the exit definitely instead of moving in chaos. Hereby, the evacuation time step decreases with the increase of drift.

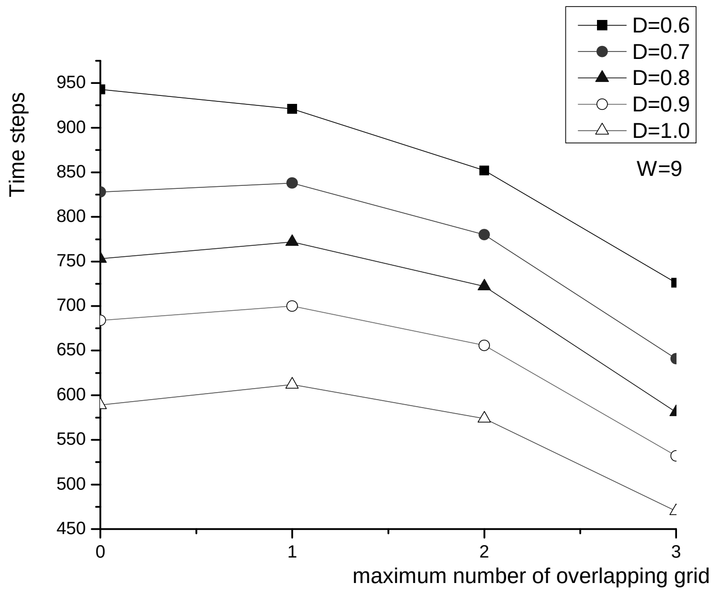


FIGURE 3. Relation of evacuation time steps against maximum number of overlapping grid

In the traditional discrete model such as cellular automata model, the exit width is always an integer multiple of a grid size which is as large as one pedestrian. Hereby, all the pedestrians can go through the exit successfully. In fact, it is observed in practice that when several pedestrians reach the bottleneck at the same time, their mutual blockage may lead to a deadlock that none of them can pass through the bottleneck. This is the typical clogging phenomenon at the bottleneck. Fig.4(a) is a snapshot of a blockage where two pedestrians block each other. The clogging is more or less stable and can freeze the system. It is found that there are different critical values of exit width for clogging according to maximum number of overlapping grid. Clogging occurs more frequently when the exit width is under the critical value but never appears when the exit width is greater than or equals to the critical value in our simulations. The critical value is 5,7,7,9 corresponding that the maximum number of overlapping grid is 0,1,2,3 respectively. Fig. 4(b) is a snapshot of a blockage where four pedestrians mutually block each other's motion(the maximum number of overlapping grid is two). Fig. 4(c) is a snapshot of a blockage where the maximum number of overlapping grid is three. Note that the situation shown in Fig. 4(c) occurs infrequently in our simulations because the door width is sufficient for nearly three pedestrians passing through the exit simultaneously. Furthermore, the larger the allowed number of overlapping grid is, the larger the critical value is. It can be explained that because the movement of a pedestrian is restricted to others partially when his inherent space is occupied with others, clogging occurs more easily when the allowed number of overlapping grid is larger. Therefore, we conclude that exit width and overlapping are two important conditions for the occurrence of clogging.

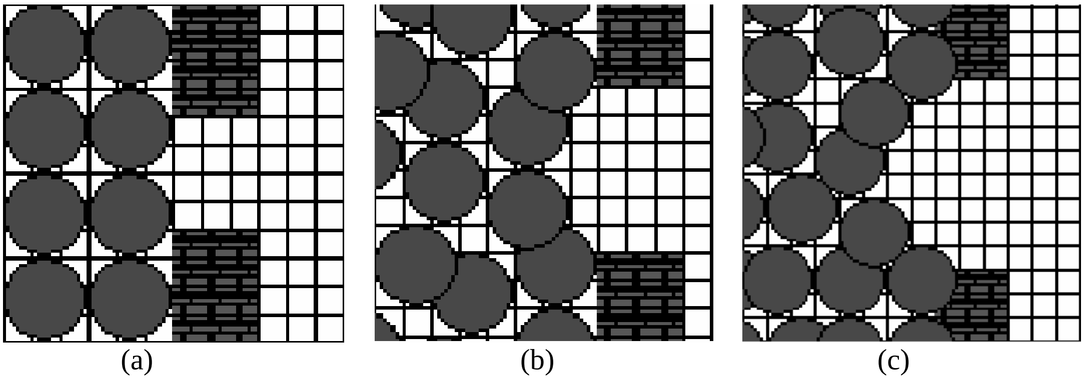


FIGURE 4. Blockage at the bottleneck. The maximum number of overlapping grid is 0,2,3 corresponding to (a),(b),(c) respectively.

In contrast to the above discussion, we investigate the influence of different numbers of overlapping grid with interactions in the following section. The interaction force including extrusion, repulsion and friction is expressed by parameter *F*. The evacuation time increases with increasing *F*, which has been investigated in Ref. 36. Fig. 5 gives the evacuation time steps as a function of interaction forces for different maximum numbers of overlapping grid. With the increase of *F*, pedestrians overlapped with others are no longer access the target cell easily and directly but have to choose other directions or even stop because of the large interactions from others. The interactions become larger with increasing the number of overlapping grid because the interactions are superposed when more grids are overlapped. Therefore, there is a turning point of evacuation times with increasing the number of overlapping grid (see Fig. 6). The vertical coordinate is the absolute time step difference between different maximum numbers of overlapping grid. It indicates that there are two consequences of using a finer discretization. On the one hand, evacuation time steps decrease because pedestrians can move to the available space that is less than their own size. On the other hand, the forces caused by overlapping weaken the control of pedestrians moving in desired direction.

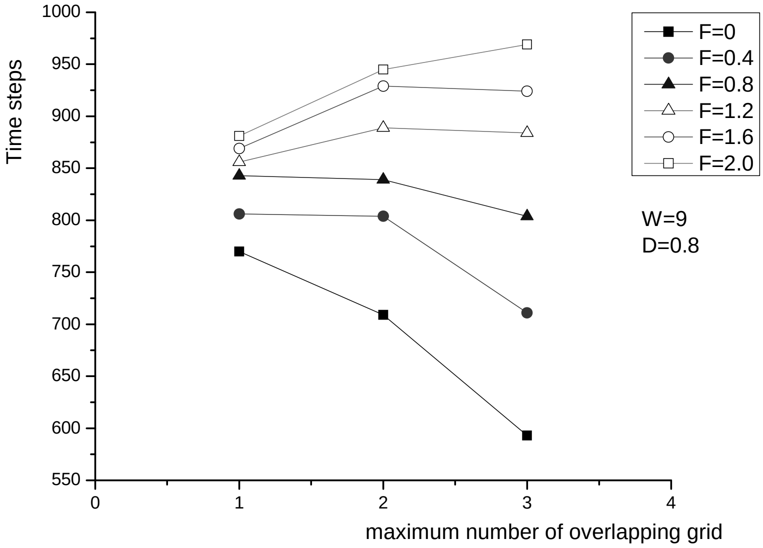


FIGURE 5. Evacuation time steps as a function of interaction forces for different maximum numbers of overlapping grid

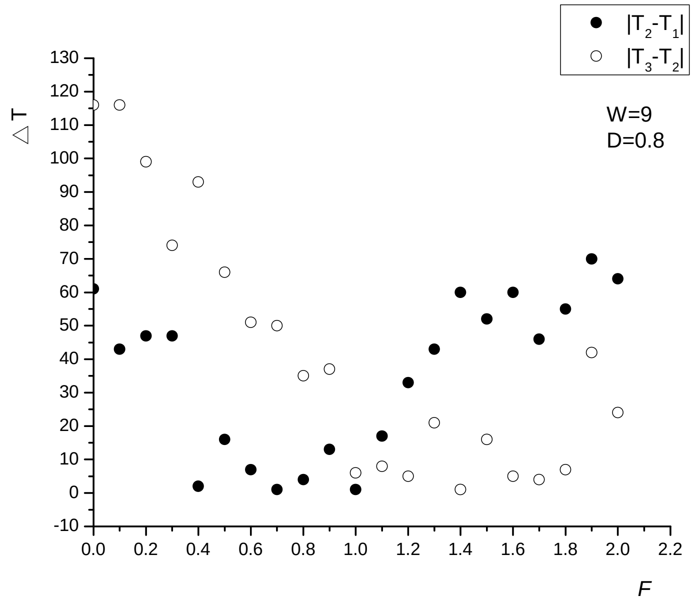


FIGURE 6. Relation of absolute time step difference between different maximum numbers of overlapping grid against F

When the self-driven ability of a pedestrian is not enough to overcome the resistance, the pedestrian will go backward or stop at the current position. The stop behaviour may lead to clogging at the bottleneck. This is illustrated for a typical situation in Fig. 7. The direction of the black particles is available in this situation. However, the forces from pedestrians or walls are large enough to prevent them from moving. Then, all the six pedestrians closest to the exit can not move at all, that is to say, clogging occurs. It demonstrates that the large interaction force is another reason for clogging.

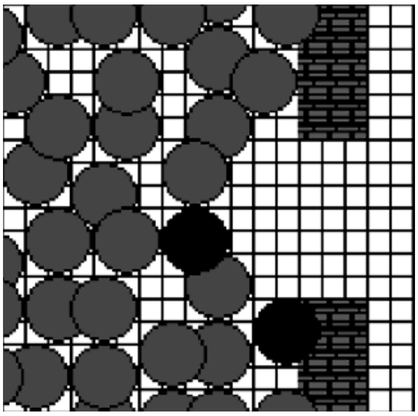


FIGURE 7. The maximum number of overlapping equals to three. It is available for the two black particles to move, but the forces from pedestrians or walls are large enough to prevent both of them from moving

CONCLUSIONS

We have investigated the reasons for clogging phenomena during evacuation by multi-grid model. The model adopts a finer spatial deiscretization and the interactions are introduced by overlapping grids. It is found that two consequences of using a finer discretization. On the one hand, the evacuation is more effective because pedestrians can move to the available space that is less than their own size. On the other hand, the pedestrians can block each other more frequently due to overlapping. Clogging can be observed in our model when the deadlock occurs at bottleneck. There are different critical values of exit width for clogging according to maximum number of overlapping grid. The larger the allowed number of overlapping grid is, the larger the critical value is. The movement of a pedestrian is restricted to others partially when his inherent space is occupied with others, so clogging occurs more easily when the allowed number of overlapping grid is larger. The interaction force can have a strong impact on global behaviours of pedestrians through its local influence. It may change the pedestrian's direction or even prevent pedestrians from moving ahead. When the self-driven ability of a pedestrian is not enough to overcome the resistance, the pedestrian will go backward or stop at the current position. The stop behaviour may lead to clogging at the bottleneck.

Summarizing, the multi-grid model is able to solve the conflict due to overlapping grids and quantify the interaction forces. Using this model, we investigate the clogging phenomena during evacuation in this paper. The results indicate that the finer discretization, overlapping and interaction forces are three important reasons for clogging at bottleneck.

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