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Study on Efficiency of Evacuation with an Obstacle on Hexagonal Cell Space

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Abstract : The authors of this paper have found that putting an obstacle in front of an exit in a congested situation increases the pedestrian outflow, which is the number of pedestrians going through an exit with a unit width in a unit time, from their experiments. In this paper, the effects of conflicts and turning, which affect the pedestrian outflow significantly, are introduced by the frictional and turning functions to analyze the effect of an obstacle. They clearly explain the mechanism of the effect of an obstacle, i.e., it blocks a pedestrian moving to the exit and decreases the average number of pedestrians involved in the conflict. The authors have also studied when an obstacle contributes to ease the congestion most effectively. The results of their simulation indicate that its maximum efficacy is achieved at the point where the cluster of pedestrians is started to form. The mean traveling time of pedestrians becomes a quarter if an obstacle is set up since it prevents the formation of the cluster against increase of the inflow by reducing the impact of conflicts.

Key Words : frictional function, turning function, evacuation, jamology, cellular automata.

1. Introduction

Pedestrian dynamics has been studied vigorously over last decades [1],[2], and the behavior of pedestrians at an exit is focused on by many researchers in physics since it greatly affects the total evacuation time in an emergency situation [3]–[6]. Researchers of multi-robot systems are also interested in this theme [7].

In Ref. [8], it is indicated that we can evacuate faster when an obstacle is put in front of an exit. The authors have verified this phenomenon by experiments and investigated it by their model, which includes two important factors of pedestrian dynamics at an exit. One is *conflict* and the other is *turning*. In the floor field (FF) model, which is a pedestrian dynamics model using stochastic cellular automata, conflicts are taken into account by the friction parameter. Since the friction parameter is constant, the strength of a conflict does not depend on the number of pedestrians involved in the conflict. In reality, however, it is more difficult to avoid a conflict when three pedestrians move to the same place at the same time than two pedestrians move to the same place at the same time. Furthermore, the decrease in walking speed by turning has not been considered in the previous model.

Therefore, we introduce the *frictional function* and the *turning function*, which make it possible to describe the pedestrian behavior around an exit more precisely and realistically, and analyze the mechanism of the effect of an obstacle. The effect of an obstacle against various inflows is also studied by our simulation.

2. Floor Field Model

2.1 Advantages of Discretization

Since FF model is an extension of a two dimensional stochastic cellular automata, the space in the model is discretized into cells as in Fig. 1 (a). A pedestrian at the cell A cannot move to its upper cell even if he/she chooses there since each cell contains only one pedestrian at most. A conflict will occur at the cell B if the two pedestrians move there at the next time step. Although detailed movements of pedestrians are prevented, there are many advantages of discretization of both space and time. First, it is feasible to introduce *probability* and additional *rules* to the movement of pedestrians, thus, variation and complexity of the movement is simply reproduced despite the approximated space. Second, the excluded-volume effect of pedestrians, which is important to consider physical inter-

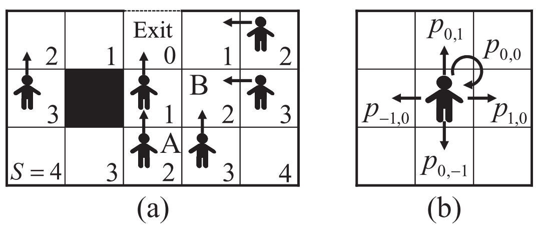

Fig. 1 (a) Schematic view of an evacuation simulation by the FF model. (b) Target cells for a pedestrian at the next time step.

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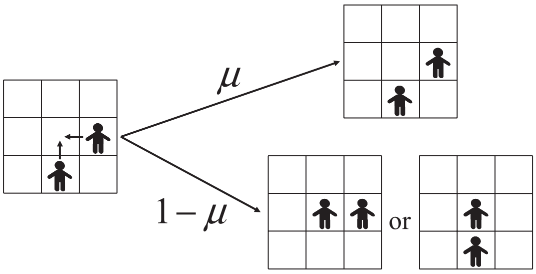


Fig. 2 Schematic view of an conflict in the FF model.

action between them, is also simply introduced by limiting the maximum number of pedestrians in a cell to one. [1] Third, computational efficiency is high since there is no restriction on the length of one time step in the numerical simulation. The numerical error does not also accumulative in long simulation. [2] Finally, theoretical analysis is achieved by applying the calculative method in stochastic process.

2.2 Static Floor Field and Transition Probability

We briefly review FF model by considering an evacuation situation, which every pedestrian in a room moves to the same exit as in Fig. 1 (a), as an example. Man shaped silhouettes and the black cell represent pedestrians and an obstacle cell, respectively. Numbers in the figure denote the *static floor field* (SFF), which is the L^1 norm from the exit cell. Note that SFF is also represented by the Euclidean distance [11]; however, we adopt the simpler version here. Each cell contains only a single pedestrian at most [3] and the parallel update rule is adopted.

Every time step pedestrians choose which cell to move from the five cells for simplicity: a cell which the pedestrian stands now $[(i, j) = (0, 0)]$ and the Neumann neighboring cells $[(i, j) = (0, 1), (0, -1), (1, 0), (-1, 0)]$ (Fig. 1 (b)). SFF determines the transition probability p_{ij} for a move to a neighboring cell (i, j) as follows:

$$p_{ij} = N\xi_{ij} \exp(-k_s S_{ij}). \tag{1}$$

Here the values of SFF S_{ij} at a cell (i, j) is weighted by the sensitivity parameter k_s with the normalization N, and ξ_{ij} returns 0 for obstacle, wall, and occupied cells, and returns 1 for other kinds of cells. Several other important FFs are developed in Ref. [12],[13]; however, we consider only SFF in this paper since we consider normal evacuation situation where pedestrians clearly know the position of the exit and do not aggressively press others.

When pedestrians reach the exit cell, they leave the room with the probability $\alpha \in [0, 1]$ and stay there with the probability $1 - \alpha$. Note that the exit cell itself is one of the component cells of the room, and one edge of the exit cell represents an *exit* or an *exit door*.

2.3 Friction Parameter

Due to the use of parallel dynamics, it happens that two or more pedestrians choose the same target cell in the update procedure as at the cell B in Fig. 1 (a). In this paper, such situation is called *conflict*. It is modeled by the *friction parameter* μ, which describes clogging and sticking effects between the pedestrians, in Ref. [14]. When we denote the number of pedestrians moving to the same cell at the same time as $k_e \in \mathbb{N}$, the friction parameter is not used in $k_e = 1$, but applied in $k_e \geq 2$ as follows:

$$\phi_\mu(k_e) = \begin{cases} 0 & (k_e = 1), \\ \mu & (k_e \geq 2), \end{cases} \tag{2}$$

where ϕ_μ is the probability that all the pedestrians involved in the conflict remain at their cell. $\phi_\mu(1) = 0$ since there is no conflict in $k_e = 1$. In $k_e \geq 2$, the movement of *all* involved pedestrians is denied with probability μ; therefore, the conflict is solved with probability $1 - \mu$, and one of the pedestrians is allowed to move to the desired cell with equal probability as in Fig. 2. In a situation with large μ, pedestrians are competitive and do not give way to others, while in a situation with small μ they give way and cooperate each other.

3. Extended Floor Field Model at an Exit

3.1 Hexagonal Cells and Bottleneck Parameter

Although the FF model is successfully applied to evacuation simulations, it is not specified for analyzing pedestrian dynamics at an exit, thus we have extended it to obtain the more realistic model and also simplified to analyze theoretically. Figure 3 shows the extended floor field model at an exit. Hexagonal cells are used to construct the field around the exit since pedestrians often stand between the two former pedestrians to see their way clear between the two heads in the congested evacuation situation. Result of the evacuation experiment also supports this extension [15]. In this model, we focus on the exit cell and its four neighboring cells, and consider a situation that a cluster of pedestrians is formed at the exit. Thus, pedestrians come into the cell 1, 2, 3, and 4 with the probability 1, when they are empty. Pedestrians who are very near to an exit do not detour or move backward, but directly move there in an evacuation situation since they want to evacuate from a room as soon as possible. Therefore, we simplified the transition probabilities as follows. Each pedestrian at the four neighboring cells try to move to the exit cell with the probability $\beta \in [0, 1]$ (bottleneck parameter [3]) and get out from the room with the probability α. This simplification enables us to analyze theoretically.

3.2 Frictional Function

In this model conflict among two to four pedestrians is possible to occur at the exit cell. The strength of clogging and sticking should depend on the number of pedestrians involved in the conflict; however, the friction parameter is constant in $k_e \geq 2$, where k_e is the number of conflicting pedestrians. Therefore, we introduce the *frictional function* $\phi_\zeta \in [0, 1]$, which is a function of k_e as follows:

$$\phi_\zeta(k_e) = 1 - (1 - \zeta)^{k_e} - k_e\zeta(1 - \zeta)^{k_e - 1} \qquad (k_e \geq 1). \tag{3}$$

ϕ_ζ represents the probability of the unsolved conflict and is defined by considering the psychological effect of pedestrians. The movement of all pedestrians is denied with the probability ϕ_ζ and one of them randomly move to the exit cell with the

[1] If the space is continuous, the excluded volume effect is introduced by an inequality, which increase complexity of the simulation.

[2] In coupled differential equations models such as the social force model [9], the length of one time step in the numerical simulation has to be infinitesimal to improve the accuracy of the simulation [10].

[3] Thus, the size of a cell is the approximate size of one pedestrian.

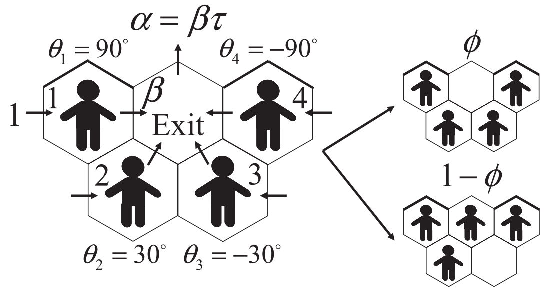


Fig. 3 Schematic view of the extended FF model at an exit.

probability $1 - \phi_\zeta$ as in Fig. 3. $\zeta \in [0, 1]$ is the probability of not giving way to others when more than one pedestrian move to the same cell at the same time. The term $(1 - \zeta)^{k_e}$ in the expression (3) is the probability that all pedestrians involved in the conflict try to give way to others. The term $k_e\zeta(1 - \zeta)^{k_e-1}$ is the probability that only one pedestrian does not give way to others while the others do. By subtracting the two terms, which are the probabilities of resolving the conflict, from 1, we obtain the frictional function ϕ_ζ. Therefore, ϕ_ζ includes the effect of motivations of pedestrians. Note that the frictional function monotonically increases as k_e and ζ increase.

3.3 Turning Function

Since pedestrians have inertia, their walking speeds decrease when they turn and change their headings. Thus, we have introduced the turning function $\tau \in (0, 1]$, which represents the decrease in walking speed by turning. After the pedestrians at the four neighboring cells have moved to the exit cell with the probability β, their transition probability getting out from the room decreases by turning. Therefore, α is improved by the turning function τ as follows:

$$\alpha(\theta_m) = \beta\tau(\theta_m), \qquad (\tau(\theta_m) = \exp(-\eta|\theta_m|)), \tag{4}$$

where $\eta \geq 0$ is the inertia coefficient in turning, which represent the strength of the inertia, and $\theta_m \in [-\pi, \pi]$ $(m \in \mathbb{N})$ is the incident angle for the pedestrian who move from cell m to the exit cell (Fig. 3). Since an exponential function is greatly used in the FF model for simplicity [8], the form of the turning function is decided as above. Note that the turning function monotonically decreases as $|\theta_m|$ and η increase.

α becomes small for the pedestrians who move to the exit cell from the cell 1 and 4, since they have to turn $\pm 90^\circ$ at the exit cell, while pedestrians who move to the exit cell from the cell 2 and 3 get out from the room smoothly, since they need to turn only $\pm 30^\circ$ (Fig. 3).

3.4 Theoretical Pedestrian Outflow

In this section, we calculate the theoretical pedestrian outflow for general $n_e \in \mathbb{Z}_{\geq 0}$, which is the number of the neighboring cells of the exit cell. The case $n_e = 4$ is depicted in Fig. 3. Pedestrian outflow is the number of pedestrians who go through an exit with unit width in unit time and one of the important factors in evacuation designing since the total evacuation time is estimated from it [16].

The probability of $k_e \in \mathbb{N}$ pedestrians trying to move to the exit cell at the same time is described as

$$b(k_e) = \begin{pmatrix} n_e \\ k_e \end{pmatrix} \beta^{k_e}(1 - \beta)^{n_e - k_e}. \tag{5}$$

Then, the probability that one pedestrian succeeds to move to the exit cell is obtained as

$$r(n_e) = \sum_{k_e=1}^{n_e} [\{1 - \phi(k_e)\} b(k_e)], \tag{6}$$

where ϕ is ϕ_μ or ϕ_ζ given by (2) or (3), respectively. We define $\pi_t(0)$ as the probability that a pedestrian is not at the exit cell at time step t and $\pi_t(m)$ $(m \in [1, n_e])$ as the probability that a pedestrian who was at the neighboring cell m is at the exit cell. The master equation of $\Pi_t = [\pi_t(0), \ldots, \pi_t(n_e)]^T$ is described as follows:

$$\Pi_{t+1} = \begin{bmatrix} 1 - r(n_e) & \alpha(\theta_1) & \ldots & \alpha(\theta_{n_e}) \\ r(n_e)/n_e & 1 - \alpha(\theta_1) & & \text{\huge 0} \\ \vdots & & \ddots & \\ r(n_e)/n_e & \text{\huge 0} & & 1 - \alpha(\theta_{n_e}) \end{bmatrix} \Pi_t. \tag{7}$$

By using (7) with the normalization condition $\sum_{m=0}^{n_e} \pi_t(m) = 1$, we obtain the stationary $(t \to \infty)$ solution

$$\begin{cases} \pi_\infty(0) = \left[1 + \dfrac{r(n_e)}{n_e} \displaystyle\sum_{\acute{m}=1}^{n_e} \dfrac{1}{\alpha(\theta_{\acute{m}})}\right]^{-1}, \\ \pi_\infty(m) = \dfrac{r(n_e)}{n_e\alpha(\theta_m)}\pi_\infty(0) \qquad (m \in [1, n_e]). \end{cases} \tag{8}$$

Thus, the average pedestrian outflow is described as

$$\begin{aligned} \langle q_{\text{theo}}(n_e, \theta_1, \ldots, \theta_{n_e}) \rangle &= \sum_{m=1}^{n_e} \alpha(\theta_m)\pi_\infty(m) \\ &= r(n_e)\pi_\infty(0), \end{aligned} \tag{9}$$

where $\langle x \rangle$ represents the sample average of x.

4. Evacuation through an Exit with an Obstacle

4.1 Experiment

The effect of an obstacle put in front of an exit is studied in this section. As we have briefly described in Ref. [15], evacuation experiment has been performed at the NHK TV studio in Japan. Two large walls were set up in the studio, and the width of the exit is set as 50 [cm] by adjusting them. The participants of the experiment were fifty women, who were their thirties and forties. We have performed three kinds of experiments: (a) normal evacuation (Fig. 4 (a)), (b) evacuation through the exit with an obstacle (Fig. 4 (b)), and (c) evacuation in one line (Fig. 4 (c)). In the case (b), pedestrians evacuated as normally as in the case (a); however, the pole, whose diameter was 20 [cm], was set up. Its center was 75 [cm] far from the exit and shifted 25 [cm] from the center of the exit. In the case (c), pedestrians formed a line and evacuated one by one. No conflict occurs in this case since the sequence of the evacuation is determined *a priori*. The case (a) and (b) were performed six times, and the case (c) was performed three times.

The experimental pedestrian outflows are calculated as

$$\langle q_{\exp} \rangle = \frac{j - i}{w(t_j - t_i)}, \tag{10}$$

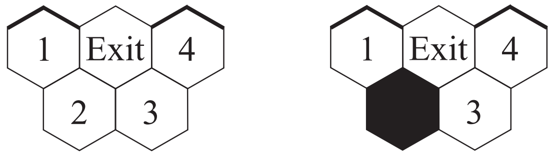
where i and j are the orders of the first and the last pedestrian used to calculate the pedestrian outflows, and t_i and t_j are the evacuation times of the i th pedestrian and the j th one, respectively. w represents the width of the exit. We decide $i = 1$, $j = 47$ for the case (a) and (b), and $i = 4$, $j = 50$ for

(a) Normal

(b) With an Obstacle

(c) One Line

Fig. 4 Snap shots of the evacuation experiments taken from an angle, where the exit is at the bottom center of each figure.



(a) (b)

Fig. 5 Schematic views of the exit conditions.

the case (c). In the former cases, the number of pedestrians decreases and the interaction among more than two pedestrians is hardly observed in the end of the evacuation, and the situations become totally different from the stationary state. Therefore, we use the evacuation time of first forty-seven pedestrians for the calculation. By contrast, in the latter case, pedestrians move very fast at the starting time since there is no one ahead of the first pedestrian and the density is very low. Thus, we need to wait for the stationary state.

The experimental average pedestrian outflows of the three cases are

$$\langle q_{\mathrm{exp}} \rangle = \begin{cases} 2.80 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (a))}, \\ 2.92 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (b))}, \\ 3.23 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (c))}. \end{cases} \quad (11)$$

The outflow in the case (c) is the largest, since there was no conflict. Comparing the result of the experiment (a) and (b), we surprisingly find that the outflow of the experiment (b), i.e., the experiment where we put the obstacle in front of the exit, is larger than that of the experiment (a), which is a normal evacuation.

4.2 Theoretical Analysis

We explain this phenomenon by our theoretical calculation. In Ref. [15], it is verified that there are approximately four pedestrians move to the exit at the same time, i.e., $n_e = 4$, in the normal evacuation (case (a)) as in Fig. 3. Thus, the exit in the case (a) is modeled as in Fig. 5 (a). Watching the video of the experiment, we see that the obstacle blocks the pedestrians moving to the exit. Thus, we assume that the number of the neighboring cells of the exit cell decreases by one because of the obstacle. Therefore, we have modeled it by blocking the cell 2 in Fig. 3 and consider that $n_e = 3$ in the case (b) as in Fig. 5 (b). Note that we set $n_e = 1$ and $\theta_1 = 0°$ in the case (c).

We consider two kinds of theoretical pedestrian outflows. One is $\langle q_{\mu 0} \rangle$, which adopts friction parameter for modeling conflict and neglects the effect of turning. The other is $\langle q_{\zeta\eta} \rangle$, which includes the effect of both the frictional and turning functions. We have determined the length between two hexagonal cells as 50 [cm] [4] and the unit time step as 0.3 [sec], and calculated the parameter β from the result of the experiment (a) as

[4] Here, the size of one hexagonal cell is the approximate size of one pedestrian.

$$\beta = 0.97. \quad (12)$$

The other parameters are obtained by the method of the least squares as

$$\begin{cases} \mu = 0.23, \\ \zeta = 0.22, \\ \eta = 0.09. \end{cases} \quad (13)$$

Then, we obtain

$$\langle q_{\mu 0} \rangle = \begin{cases} 2.86 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (a))}, \\ 2.86 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (b))}, \\ 3.23 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (c))}; \end{cases} \quad (14)$$

and

$$\langle q_{\zeta\eta} \rangle = \begin{cases} 2.80 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (a))}, \\ 2.92 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (b))}, \\ 3.23 \text{ [persons / (m} \cdot \text{sec)]} & \text{(case (c))}. \end{cases} \quad (15)$$

The well correspondence between the experimental outflow and $\langle q_{\zeta\eta} \rangle$ is observed; however, $\langle q_{\mu 0} \rangle$ is almost same for the case (a) and (b), and does not agree with the experimental results.

The friction parameter does not change the strength of the clogging against n_e; therefore, the difference of the outflow in the case (a) and (b) is not appropriately reproduced. On the contrary, the frictional function can adjust the strength of clogging adequately, thus, the result of the experiment is obtained if it is used with the turning function. This result also verify the importance of the frictional function and justifies our assumption that the obstacle increases the pedestrian outflow since it decreases n_e, so that the number of pedestrians moving to the exit at the same time becomes small. The turning function plays an important role to represent the position of the obstacle. It enables us to distinguish which cell is blocked by the obstacle, the cell whose incident angle is $\pm 30°$ or $\pm 90°$.

5. Variation in Traveling Time against Various Inflow

5.1 Conditions for Simulation

As we have seen in the former section, the pedestrian outflow increases if an obstacle is set up at the proper position in a congested evacuation situation, which is achieved by the large pedestrian inflow, i.e., the number of pedestrians coming into the room in unit time step. The effect of the position and the size of an obstacle in a congested situation is studied in Ref. [15],[17]. Therefore, we consider how the effect of an obstacle varies with the situation around an exit by controlling the pedestrian inflow.

We combine the normal FF model described in Sec. 2 and the extended one in Sec. 3 and construct a room by hexagonal cells as in Fig. 6. The depth and the width of the room are 9 and 10 cells, respectively. Pedestrians in the room except at the exit cell, its four neighbors (the cell 1, 2, 3, and 4), and the edge cells can move to their six neighboring cells in this model.

SFF is represented by the number of the cells in the shortest way to the exit cell as parenthetic numbers in the figure. Each time step the position of the entering cell is randomly chosen from the ten edge cells at the bottom of the room in the figure, and one pedestrian enters in the room with the probability $\lambda \in [0, 1]$ if the entering cell is vacant. Large λ corresponds to the large inflow. The pedestrians in the room proceed to the four neighboring cells of the exit cell according to SFF, move to the exit cell with the probability β, and evacuate from the room with the probability $\alpha = \beta\tau$ (Eq. (4)). If conflicts occur, they are solved by using the frictional function ϕ_ζ. Their transition probability is given as

$$p_x = N\xi_x \exp(-k_s S_x), \tag{16}$$

where x represents either one of the six neighboring cells or the cell where the pedestrian is standing. We would like to mention that the turning function is applied only at the exit cell and neglected in the other cells since the turning at the exit cell is the important factor observed in the experiment, whereas the turning at the other cells is artificial phenomena due to the hexagonal cells.

We have performed evacuation simulations with two kinds of exit conditions [5], which are introduced in Sec. 4: (a) exit with no obstacle (normal evacuation), (b) exit with an obstacle set up at the cell 2 as shown in Fig. 5. The parameter β, ζ, and η are set as same as in Sec. 4.2. Since we consider the situation where the all pedestrians know the position of the exit well and try to evacuate from the room as soon as possible, we determine the sensitivity parameter $k_s = 10$, which is large enough for pedestrians to move to the exit cell directly without going out of their way. The entering probability λ is executed from 0.05 to 1 by 0.05 except between 0.4 to 0.5, where the increment is 0.005 for detailed analysis. Each case is run for 101,000 time steps, and the traveling time of each pedestrian, which is a time step between the arrival at the room and the leaving from the exit, after 1,001 time step are recorded.

5.2 Traveling Time and Traveling Time Ratio

We describe the mean traveling time in the case (a) and (b) as T_a and T_b, respectively. They are shown in Fig. 7 against λ. When λ is small, pedestrian come into and get out from the room smoothly, so that both T_a and T_b are small. In contrast, both T_a and T_b are large when λ is large since the cluster of pedestrians is formed at the exit. It is also observed that the traveling times greatly increase around $\lambda = 0.4 \sim 0.5$.

We would like to focus on the difference of the mean traveling time between the case (a) and (b); therefore, the ratio T_b/T_a is plotted against the entering probability λ as in Fig. 8. In the following we divide both Figs. 7 and 8 into three part and analyze them in detail.

Left part ($\lambda = 0.05 \sim 0.4$) Firstly, we would like to focus on the left part of the figures, where the inflow and the mean traveling time are small in both the case (a) and (b) (Fig. 7).

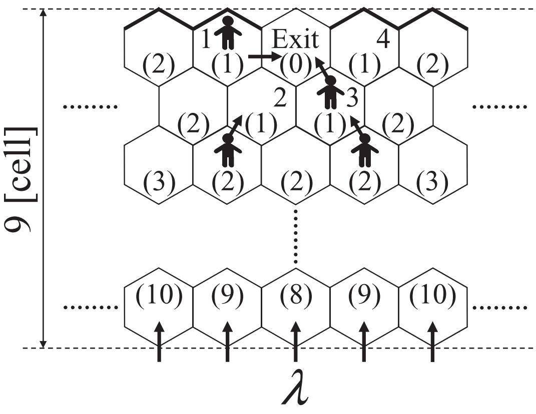


Fig. 6 Schematic view of an evacuation simulation by FF model with hexagonal cells, where the numbers in the four neighboring cells are the cell number, and those in parentheses represent SFF.

We see that the ratio T_b/T_a is slightly larger than 1 from Fig. 8 and confirm that the pedestrian cluster is not formed at the exit from our simulation. When there is no cluster at the exit, most pedestrians move to the exit from the cell 2 and 3 in the case (a), thus, they do not greatly decrease their walking speeds by 90°-turning and evacuate from the room smoothly. However, the cell 2 is blocked by an obstacle in the case (b), so that some pedestrians proceed to the exit cell from the cell 1 or 4 and their walking speeds decrease by 90°-turning. Furthermore, going around the obstacle does not only decrease the walking speeds of pedestrians, but also increases the walking distance. Thus, the traveling time becomes a little longer in the case (b) than in the case (a).

Middle part ($\lambda = 0.4 \sim 0.5$) Secondly, in the middle part, we surprisingly observe that the ratio becomes dramatically small in Fig. 8. This is because the congestion around the exit is started to observe at the smaller λ in the case (a) than in the case (b). As λ increases, conflicts between four and three pedestrians occur at the exit cell in the case (a) and (b), respectively. Since the strength of sticking and clogging becomes strong according to the number of pedestrians involved in the conflict, the cluster of pedestrians is first formed in the case (a). Thus, the traveling time of pedestrians also greatly increases first in the case (a) as in Fig. 7, so that the ratio T_b/T_a temporally decreases, and when the cluster is also started to form in the case (b) as the λ increases, the ratio increases.

Right part ($\lambda = 0.5 \sim 1$) Finally, the ratio becomes smaller than 1 in the right part, where the inflow is large and the area around the exit is congested, as in Fig. 8. This is easy to understand since the pedestrian outflow in the case (b) is larger than that in the case (a) in a congested situation as we have seen in Sec. 4.

Discussion When the inflow is small and the cluster of pedestrians is not formed at an exit, an obstacle does not work effectively; on the contrary, it may slightly increase the traveling time for each pedestrian by blocking the way for them. However, it enables us to achieve smooth flow in a congested situation as we have also verified by the experiments in Sec. 4 since it weakens the impact of conflicts. Its maximum efficacy is achieved at the point where the cluster of pedestrians is started

[5] We would like to focus on the effect of an obstacle, so that the conditions (a) and (b) are investigated in this section. If we compare the case (c) (one line) with the other two cases by the simulation, the entering process should be modified since the number of candidates for the entering cell is one in the case (c) while it is ten in the other cases.

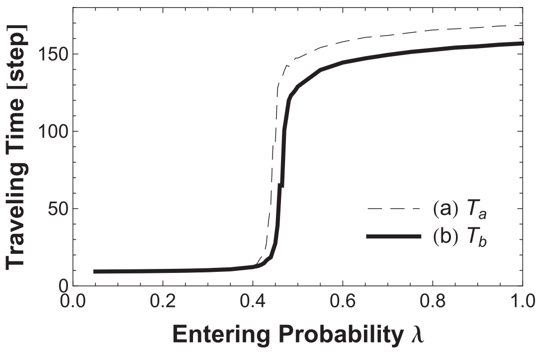


Fig. 7 Mean traveling time against the entering probability λ.

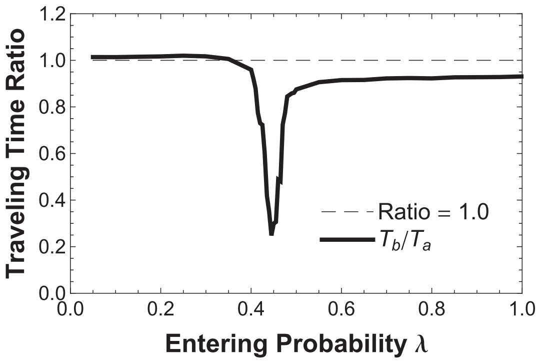


Fig. 8 Mean traveling time ratio T_b/T_a against the entering probability λ.

to form, and the mean traveling time becomes a quarter of that in the case (a), i.e., the evacuation without an obstacle. By reducing the strength of conflicts, an obstacle delays the formation of the cluster against the increase in the inflow, so that T_b starts to increase after T_a starts to increase as in Fig. 7.

Therefore, we should consider setting up an obstacle as one option to ease congestion if the cluster of pedestrians is often formed at an exit. An obstacle makes the pedestrian flow smoother when the area around an exit is congested and prevents the formation of the cluster even if the inflow is large and an exit without an obstacle start to be congested.

We would also like to mention that Fig. 8 is a new type of diagram, which clearly indicates the quantitative difference between the two traveling times. Although we can see $T_a > T_b$ from Fig. 7, the quantitative difference is difficult to be verified at a glance when $\lambda = 0.4 \sim 0.5$. Thus, Fig. 8 is useful to design an exit and decide whether to consider setting up an obstacle or not.

6. Conclusion

We have introduced the frictional and turning functions to investigate the phenomenon that the pedestrian outflow increases when we put an obstacle at an exit. The frictional function explains that an obstacle blocks pedestrians' movement and decrease the number of pedestrians involved in a conflict, so that the pedestrian outflow increases. We have also discovered that the smooth evacuation is achieved by an obstacle in a congested situation. By contrast, when the cluster is not formed, traveling time of each pedestrian slightly increases since the pedestrians are forced to turn at the exit. Our numerical simulation also indicates for the first time that the value of the inflow where the pedestrian cluster is started to form becomes large when an obstacle is set up. Thus, an obstacle exhibits its maximum performance at the inflow where an exit without an obstacle starts to be congested, while an exit with it is not.

Since the position of an obstacle is fixed as in Fig. 5 (b) in the evacuation simulation in this paper, we would also like to investigate how an obstacle at different position affect pedestrian outflow in both small and large inflow cases in the future. The work will improve our understanding on an obstacle in more detail and contribute to achieve smoother pedestrian flow.

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