MODELING OF THE INFLOW BEHAVIOR OF EVACUATING CROWD INTO A STAIRWAY

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ABSTRACT

A series of experiments have been conducted on the inflow behavior of evacuating crowd into a stairway using 50 subjects to clarify principles dictating the directions and the speed of evacuees in a dense crowd. Through analysis of the bird’s-eye video images throughout each experiment, it has been found that there is a general tendency that individuals in a crowd try to follow antecessors rather than proceed simply toward the goal. General rules for the way-finding behaviour of individuals and the walking velocity dependence on the distance to antecessor have been proposed on the basis of these analyses.

KEYWORDS: Evacuation, Walking behavior, Opening inflow, Evacuation crowds

INTRODUCTION

Because of the lack of data on the walking behavior of evacuating crowd in weakly confined space, there are difficulties in the engineering assessment of evacuation safety in large facilities such as underground arcades, stadiums, and exhibition halls. In numbers of past disasters in such facilities, secondary disasters such as fall or pressure at the entrance to stairways due to the local excessive number of evacuees frequently occurred. In this study, experiments have been conducted to reproduce the inflow behavior of a highly dense crowd of evacuees into a stairway to clarify the general principles for the walking behavior in such configuration.

THE EXPERIMENT

A 1.5 m wide stairway of a high-rise apartment building was used for the ease of the bird’s-eye view observation of the behavior of the subjects flowing into the entrance to the stairway. The stairway was essentially designed and installed for evacuation according to the current Japanese evacuation regulations. Video cameras were installed at almost the top of the stairway for the visual record of the movement of the subjects. 50 subjects first stood in a grid in front of the stairway entrance and started to “escape” toward the entrance and then walked upward the stairway (Fig. 1). Three different proportions of grid, nearly square arrangement, 1:2 and 2:1 rectangular ones, as shown in Fig. 2 were tested to examine the effect of the depth and width of a crowd on the formation of local congestion near the entrance. Adhesive tapes were pasted on the paved ground for the exact measurement of the location of each subject. No congestion was observed on the stairway in any of the experiments.

The subjects were indicated to flow into an opening from free walking route, not to prohibit passing particularly. All the subjects are physically unimpaired students and wore caps with ID numbers for the ease of identification from the video taken from the top of the stairway. Trajectory of each subject was reproduced by the analysis of the bird’s-eye video record.

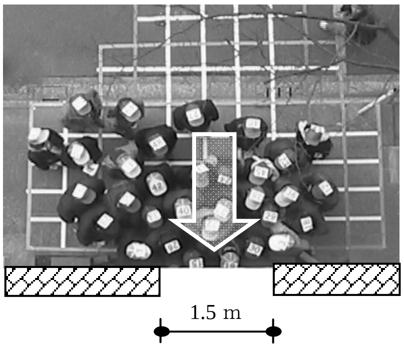


FIGURE 1. The experimental circumstance

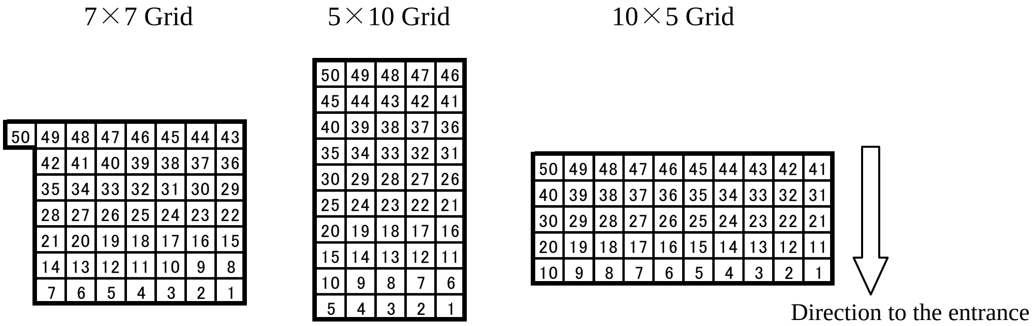


FIGURE 2. Grid patterns of subjects

RESULTS AND DISCUSSION

Tendency of Walking Behavior and "Dependence Walking"

From the video record of each experiment, movement of each subject was traced and the velocity vector of each subject at every time step was obtained. Fig. 3 is an example of the location and the velocity vector of each subject. One of the most interesting features found from this analysis is that the velocity vectors of relatively large numbers of the subjects are not directed to the entrance. Fig. 4 is a summary of the proportion of the subjects whose velocity vectors are directed to the stairway entrance. It reveals that 20 to 30 % of the subjects do not face the entrance until they come very close to the entrance. This unexpected tendency is particularly pronounced in a vertically long crowd.

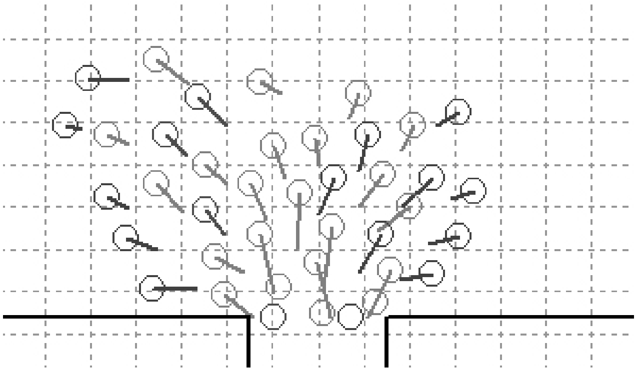


FIGURE 3. Example of the location and velocity vector of each subject

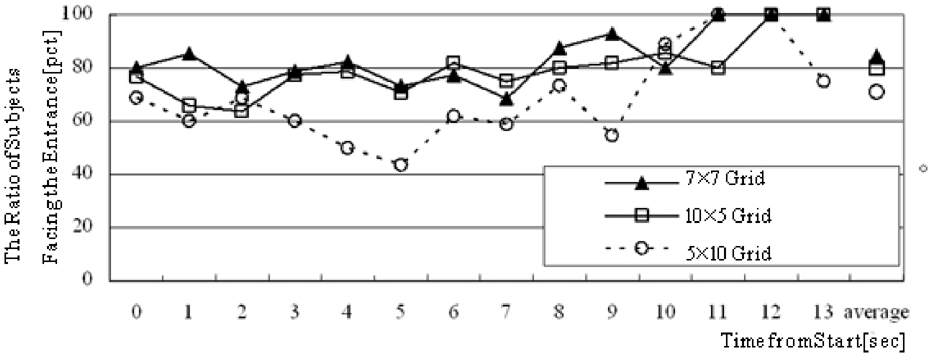


FIGURE 4. The ratio of subjects facing the stairway entrance

This is believed to represent a characteristic feature of group evacuation of a highly dense crowd, in which considerable people have to coordinate their direction-finding with the movement of the surrounding crowd. According to the analysis of the video records, the behavior of each subject during group evacuation seemed to be dominated by the pressure from others, by intention to overtake or follow the antecessor, or by apathy about finding their own directions. Fig. 5 is a summary of the classification of the deemed causes for particular movement of the subjects.

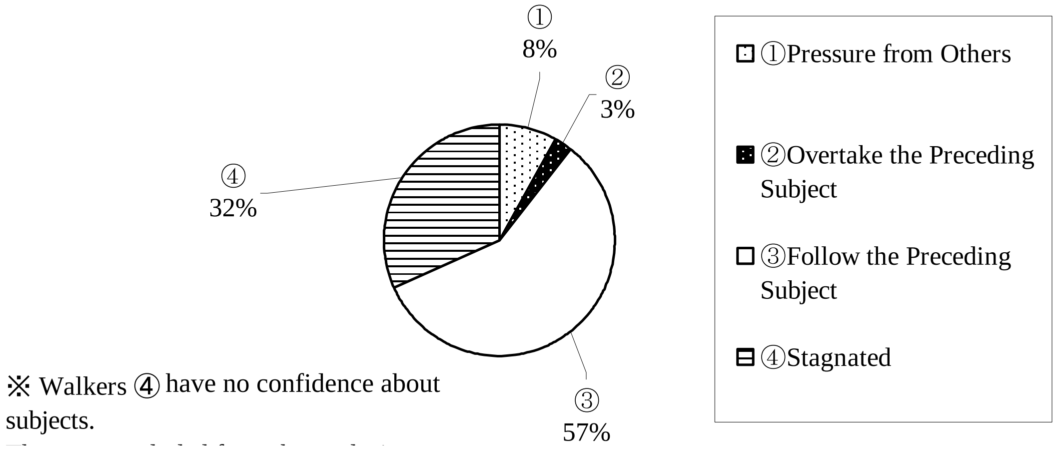


FIGURE 5. Estimated causes for the deviation of velocity vectors from the entrance

Velocity vector of the majority of subjects not facing the entrance were found to be directed to any of other subjects slightly closer to the entrance. Such deviation of the velocity vectors from the ultimate goal is believed to be a result of the intention to follow antecessor. Fig. 6 is a typical example of time series of the images capturing the walking behavior trying to follow the antecessor. The subject “A” was facing the entrance at the beginning, but once the gap to surrounding subjects was almost lost his velocity vector began to deviate from the entrance and directed to the back of the preceding subject “B”.

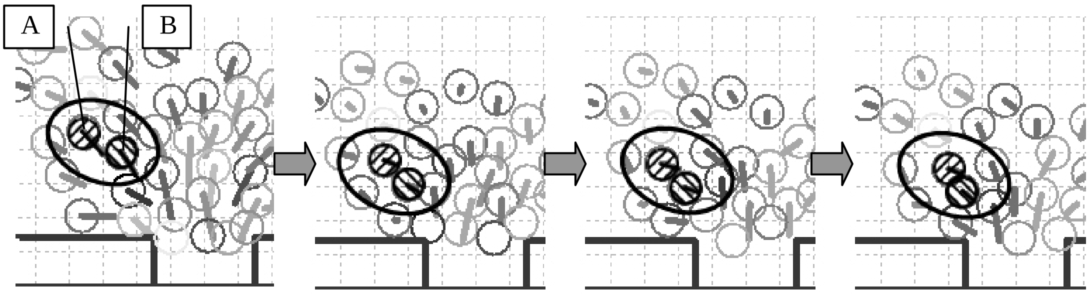


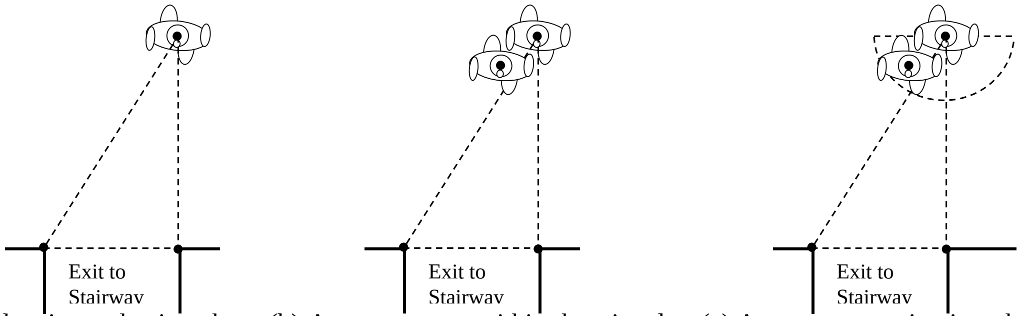
FIGURE 6. Typical dependent behavior

As seen in this example, deviation of the velocity vector from the final goal seems to occur when the crowd becomes extremely dense. In this particular experiment, the density reached as much as 5.0 persons/m^2, which is larger than any anticipation in normal evacuation planning for buildings. The most significant impediment against free walking in a highly dense crowd is the difficulty in finding a space on the ground to get one step further. The “chasing behavior” seen in Fig. 4 should be the result of the successive movement of the “chasing” pedestrian taking steps to the small space hardly generated by the advancement of his/her antecessor. Taking this behavior as a typical mode of individual walking behavior in a highly dense crowd, such behavior is referred to as “dependent walk” and the evacuees walking this way as “dependents”. The dependents are assumed to try to reach the final goal through finding space to move closer by intentionally depending on any of the preceding evacuees walking directly or diagonally in front of the dependent. For this reason a dependent generally does not try to overtake the antecessor and the dependent’s velocity vector is dominated essentially by the antecessor. In such sense, the one whose behavior results in dictating the dependent’s evacuation is referred to as the “host”. In contrast with the dependents, walking behavior apparently not affected by others could be defined as “free walking”. According to the analysis of the bird’s-eye images, it has been found that there are considerable numbers of subjects walking not exactly behind anyone else but still dominated by anyone slightly closer to the entrance. In order to study more carefully this mode, dependent walking following diagonally in front of the dependent is referred to as “slant dependent walk” while “direct dependent walk” applies to those whose trajectories nearly overlap.

Host Finding Principles

While a pedestrian can be assumed to try to walk freely toward the ultimate goal at his/her favorite velocity, the walking mode must move to the dependent mode as he/she begins to experience difficulty in finding the right space to proceed. The first thing that the pedestrian should do is to find a right host. As the pedestrian is facing the final goal at the very beginning of this move, it is naturally believed that he/she seeks candidates of the host from the semicircle of a certain radius toward the goal. Fig. 7 stands for this situation.

Because no one must stand between the host and the dependent, it can be naturally assumed that anyone closest to the dependent within the semicircle is selected as the host if he/she tries to change the mode. Then the central problem in modeling the host finding according to this scenario is to identify the radius of the semicircle, because large radius of the semicircle directly means the increase of the freedom of the pedestrian in finding the location to advance and may no longer force him/her to be dependent. The appropriate radius of the semicircle is sought by measuring the host-dependent intervals for all the subjects judged as dependent walkers. Fig. 8 is a summary of the radius and the ratio covering the experimental host-dependent intervals. It was found that the ratio becomes nearly saturated at 0.7 to 1.0 m head-to-head distance, and this distance can still exclude free walking relations. In further discussions for the modeling, 1.0 m is taken as the radius of this territory not to miss the right host candidates.



(a) Pedestrian and exit make a triangle.

(b) Antecessor not within the triangle does not make a host-dependent relationship.

(c) Antecessor coming into the semicircle and the triangle makes a host-dependent relationship.

FIGURE 7. General condition for making a host-dependent relation

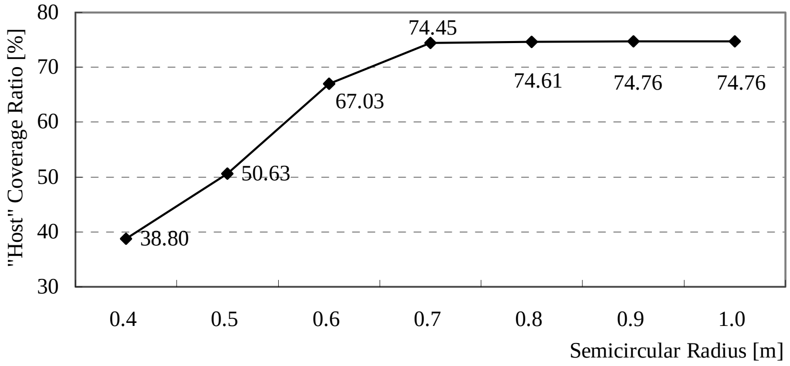


FIGURE 8. Selected semicircle radius vs host coverage ratio

Velocity Vector of "*Dependents*"

Figs. 9 and 10 are time histories of the two modes of dependent walk, direct and slant dependent walks. Fig. 9 demonstrates a typical direct dependent walk, and it can be seen that the subject "C" is always directly facing the subject "D", while there is notable change of the direction of the velocity vectors of both subjects. On the other hand, in Fig. 10, the subject "E" walks almost parallel to the slant preceding subject "F" at the beginning but when approaching the entrance he gradually changes the direction toward the subject "F". The slant dependent walk at the beginning could be because the subjects are still rather far from the entrance and facing originally the goal. The move to the direct dependent walk mode in the vicinity of the entrance is probably because of the higher density near the entrance. Fig. 11 captures the moment of transfer of the mode from the slant dependent walk to the direct dependent walk.

In Fig. 11, the subject "G" slightly behind the subject "H" is walking nearly parallel at the beginning, but the subject "H" gradually changes his direction toward the subject "H" as they come closer to the entrance and finally nearby the entrance that he walks behind the subject "H". This action of subject "G" is interpreted as that when approaching the entrance and with increase in density and the deviation of his direction from the entrance he begins to feel difficult in continuing the slant dependent relation. It indicates that pedestrians in a dense crowd may change their mode according to the deviation of his/her direction from the final goal and the change of the density.

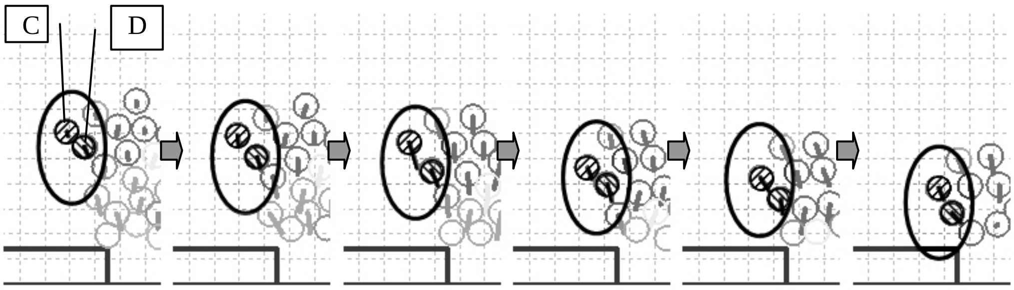


FIGURE 9. Progressive summary of a typical direct dependent relationship

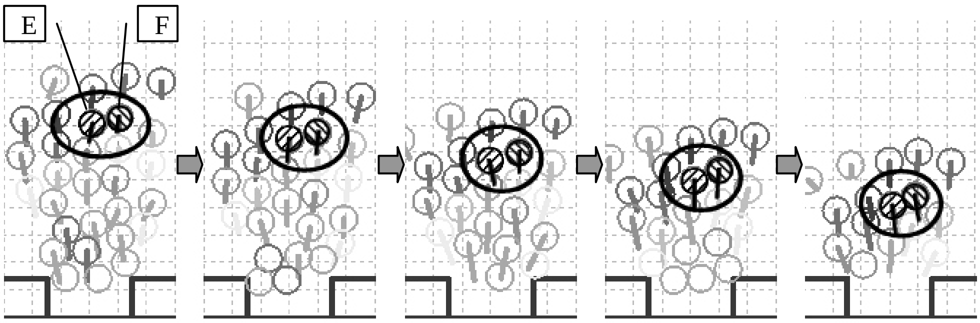


FIGURE 10. Progressive summary of a typical slant dependent relationship

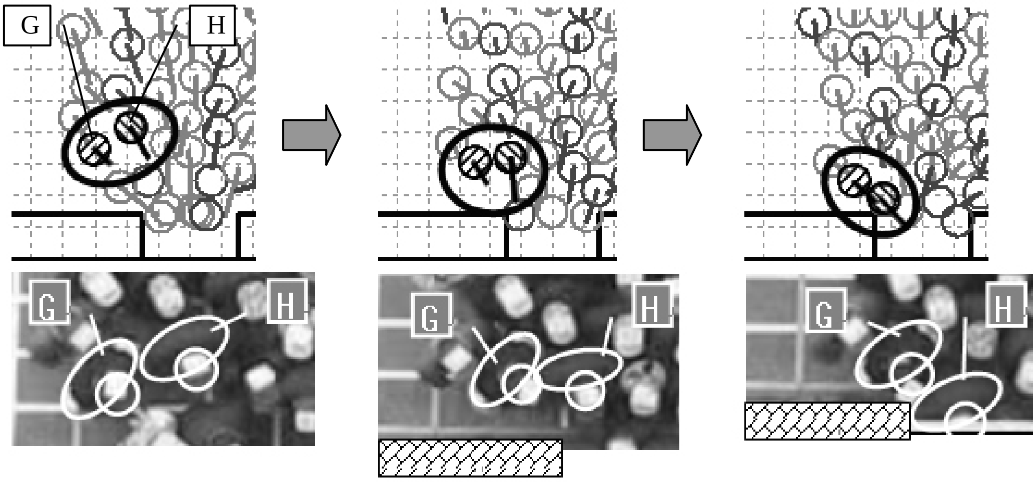


FIGURE 11. Change of slant dependent mode to direct dependent mode in front of the goal

Then, under what condition does a pedestrian change his/her direction? Assuming the deviation angle of the velocity vector from the direction to the final goal as the primary control parameter, correlation between the distance from the entrance and the deviation angle of each subject was summarized as shown in Fig. 12. The deviation angle is generally within 40^{o} and the maximum deviation angle increases with distance for $L < 3.0$ m and can be described as:

$$\theta\ \mathrm{max} = 20.8L - 19.5 \quad (0 \leqq \theta\ \mathrm{max}) \qquad [1]$$

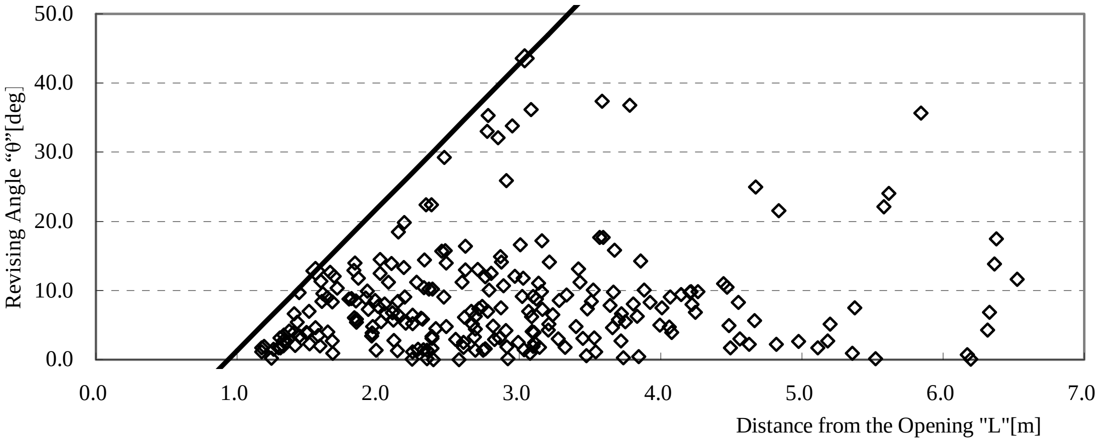
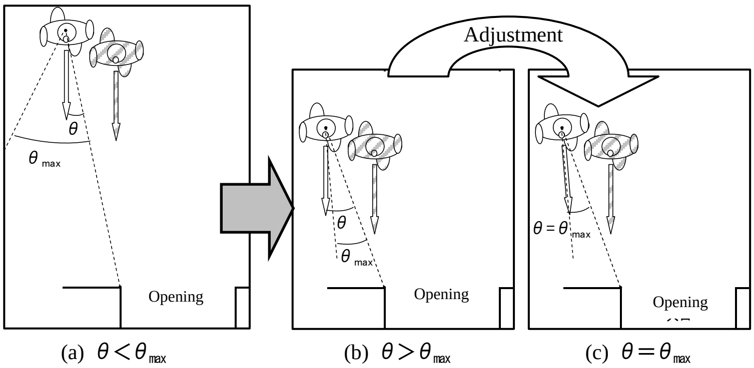


FIGURE 12. Distance from goal vs deviation angle from the goal

From this relation, it can be concluded that dependents may keep the dependency mode as long as the deviation angle remains within this limit, but must change the mode if the deviation angle exceeds the limit. As long as a pedestrian walks in the normal direction to the entrance line toward the entrance, his/her deviation angle to the final goal must increase by getting closer to the entrance. The intercept of the limit line at L = 1.0 m suggests that the pedestrian must try to coordinate his/her direction toward the entrance if he/she approaches as near as roughly 1.0 m from the final goal. Fig. 13 explains the transfer of the mode from independent walk or slant dependent walk to direct dependent walk with the deviation angle as the critical condition.



(a) $\theta < \theta_{max}$ (b) $\theta > \theta_{max}$ (c) $\theta = \theta_{max}$

FIGURE 13. Walking mode transfer and the deviation angle from the goal

Switch of Host

There were considerable subjects who seemed to change the host during the dependent walk. Fig. 14 demonstrates a typical example. In this particular case, the subject "I" is walking behind the subject "K" but in the third frame of Fig. 14 he gets behind leaving a small room behind the subject "K". The subject "J" who is walking nearby the subjects "I" and "K" interposes to this room and finally the subject "I" begins dependence on the subject "J" rather than the subject "K". The interruption is obviously the result of the failure of the subject "I" in advancing to the room behind the host, but more essential background for the switch should be the high density in front of the final goal.

The process can be demonstrated more schematically in Fig. 15. The pedestrian "M" is walking behind the subject "N", but once other pedestrian interposes into the triangle toward the opening width, the new preceding pedestrian can become the new host.

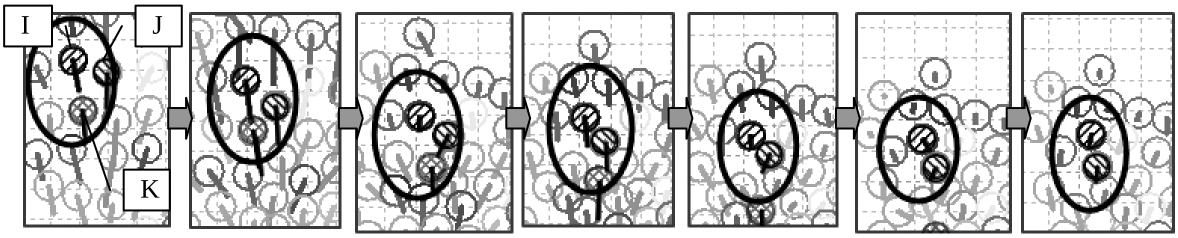


FIGURE 14. Process example of the change of host

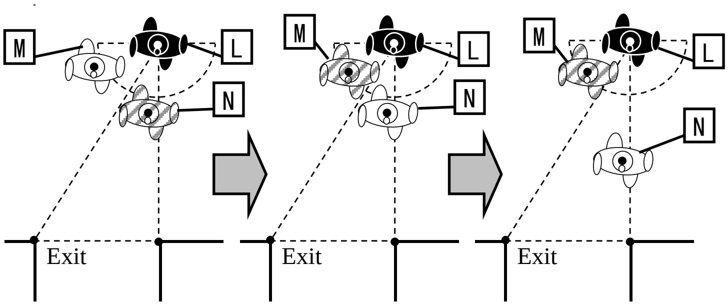


FIGURE 15. Model for the change of host

Such interruption occurs essentially because the entrance is notably narrower than the crowd width and as the crowd come close to the entrance the rows become close to each other so that interactions could occur easier.

The opening width is narrower than the crowd width, the crowd comes at the center, a distance between lines is near. As different lines join together, the crowd arrangement falls into disorder. As the crowd come near the opening, the number of lines decrease. And when the lines are joining repeatedly, a "dependence walker" changes the "depended walker" when another walker breaks between the "depended walker". Thus, it is thought that a walker advance towards the opening while repeating the cycle such as Fig. 16.

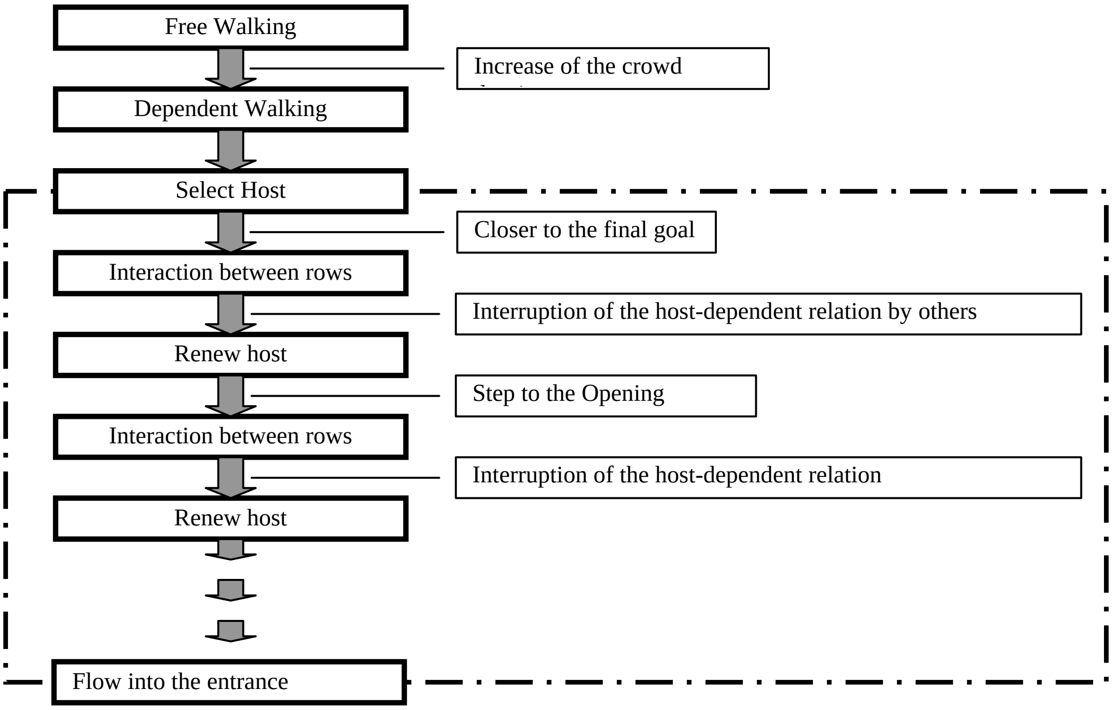


FIGURE 16. Schematic of way-finding behavior in crowd evacuation

Walking Velocity Correlations

The image analysis of the subjects suggests that the walking behavior of "dependents" should be highly dictated by the behavior of their antecessors. In order to verify this assumption more quantitatively, walking velocity of each subject and the head-to-head distance to the antecessor is correlated. Fig. 17 is the summary.

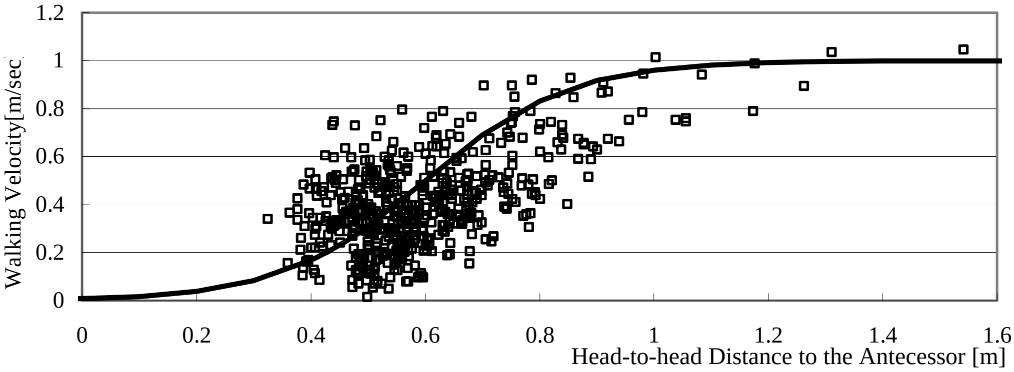


FIGURE 17. Individual walking velocity and the head-to-head distance to antecessor

As seen in Fig. 17, the walking velocity approaches roughly 1.0 m/s as the distance becomes around 1.0 m, the radius of the territory of the pedestrian estimated in section 3.2. The asymptotic walking velocity, 1.0 m/s is close to the typical free walking velocity, so this result is considered to endorse the suitability of the assumption for the territory radius, and indicates the reduction of walking velocity by the presence of predecessor within this territory. Naturally there is the lower limit for the head-to-head distance around 0.3 m; no data exist for the minimum head-to-head distance. For further modeling of the walking behavior of dense crowd, the walking velocity and the distance correlation is represented by a hyperbolic function:

$$V_{\ell} = \mathrm{TAN\ h}\{(\ell - 0.65)\times 3\}\times 0.5 + 0.5 \qquad [2]$$

where V_{ℓ} is the walking velocity in a crowd [m/s], and ℓ is the distance between walkers [m].

Influence of the Walking Velocity of Antecessor to the Walking Behavior of Dependents

Another element that should dominate the walking behavior of dependents is the walking velocity of the antecessor. This is believed to be the reason for the wide scattering of the data at around $V_{\ell} = 0.4 – 0.8$ in Fig. 16. In order to assess the significance of the influence of the walking velocity of the predecessor, the walking velocities of a subject and his/her subsequent subject are correlated. As seen in Fig. 17, the walking velocity of the followers is generally slower than the antecessors but it is obvious that the walking velocity of a pedestrian is dependent on that of the antecessor within the tested distance range. It is noteworthy that the walking velocity of any subject is close to that of the antecessor for the distance not larger than 0.5 m. Scattering is found to grow generally with increase of the distance. As seen already in Fig. 18, the distance to the antecessor will become more important for the determination of the walking velocity of a pedestrian in a dense crowd with the increase of the distance.

From these observations, it can be concluded that if the pedestrian-to-pedestrian distance is very small, the walking velocity of a pedestrian is likely to be dictated mainly by that of the antecessor, while the distance will become more dominant with the increase in distance.

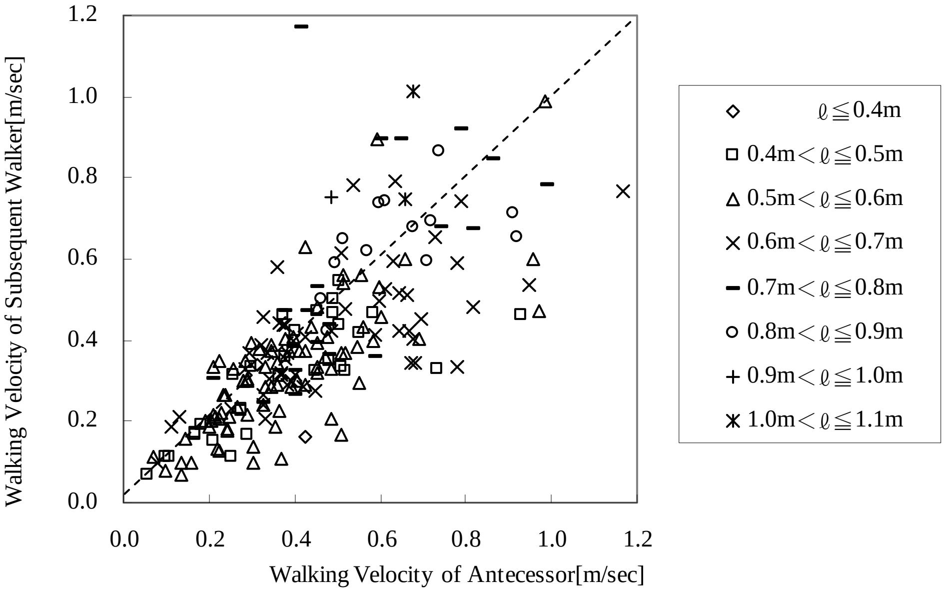


FIGURE 18. Correlation between walking velocities of antecessor and subsequent walker

Formulation of the Walking Velocity in a Dense Crowd

In this section, the walking velocity of individuals in a dense crowd directed toward a relatively limited goal is formulated according to the above observations taking account of the influences of the walking velocity of the antecessor and that of the pedestrian-to-pedestrian distances. The influence of the walking velocity of the antecessor must decrease with pedestrian-to-pedestrian distance and is assumed to be represented by a hyperbolic function as:

$$P_{v'} = -\mathrm{TAN\ h}\{(\ell - 0.8)\times 4\}\times 0.5+0.5 \qquad [3]$$

where $P_{v'}$ is the contribution ratio of the walking velocity of antecessor, and ℓ is the distance to antecessor [m].

On the other hand, the contribution of the pedestrian-to-pedestrian distance is assumed to be:

$$P_{\ell} = \mathrm{TAN\ h}\{(\ell - 0.8)\times 4\}\times 0.5+0.5 \qquad [4]$$

where P_{ℓ} is the contribution ratio of the pedestrian-to-pedestrian distance.

These relative influences are depicted as shown in the curves in Fig. 19.

The walking velocity of a pedestrian in a crowd is then represented as a weighted average of these elements. It may be represented as:

$$\begin{aligned} V &= V'\times P_{v'} + V_{\ell}\times P_{\ell} \qquad [5] \\ &= V'\times〔-\mathrm{TAN\ h}\{(\ell - 0.8)\times 4\}\times 0.5+0.5〕 \\ &\quad +〔\mathrm{TAN\ h}\{(\ell - 0.65)\times 3\}\times 0.5+0.5〕\times〔\mathrm{TAN\ h}\{(\ell - 0.8)\times 4\}\times 0.5+0.5〕 \end{aligned}$$

where V is the walking velocity[m/s], V’ is the walking velocity of antecessor [m/s], and V_{ℓ} is the walking velocity obtained from equation [3] [m/s].

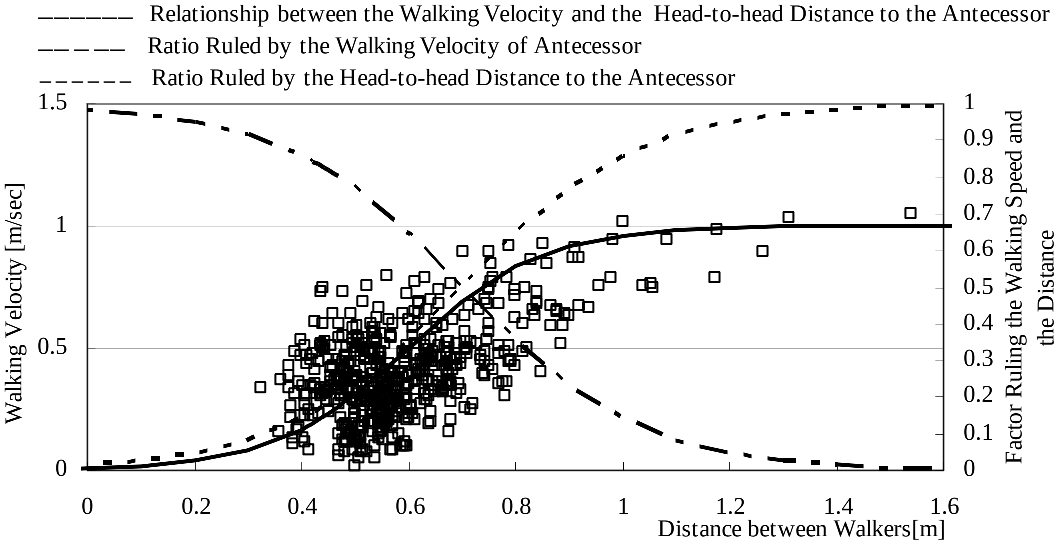


FIGURE 19. Representation of the relative significance of the influences of pedestrian-to-pedestrian distances and the walking velocity of antecessors in the walking velocity of individuals

Fig. 20 is the summary of the relation between the walking velocities of individuals of the reported experiments and those calculated from equation [5]. The model seems to give a practically acceptable agreement with the experiments.

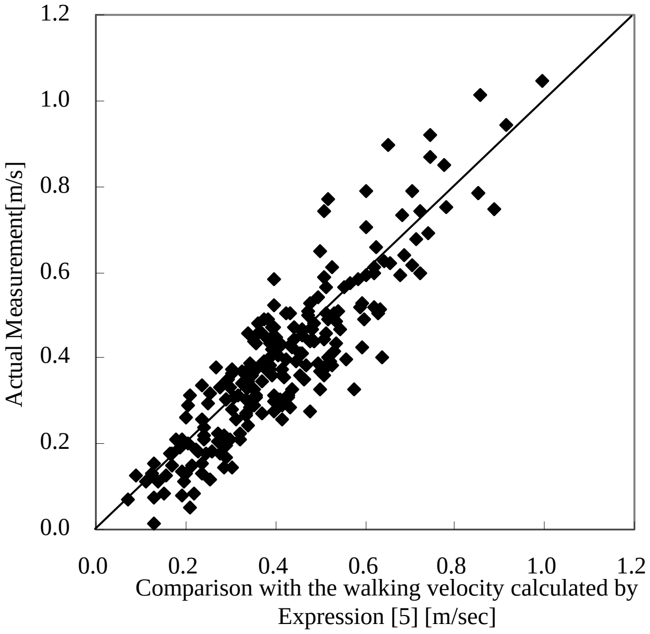
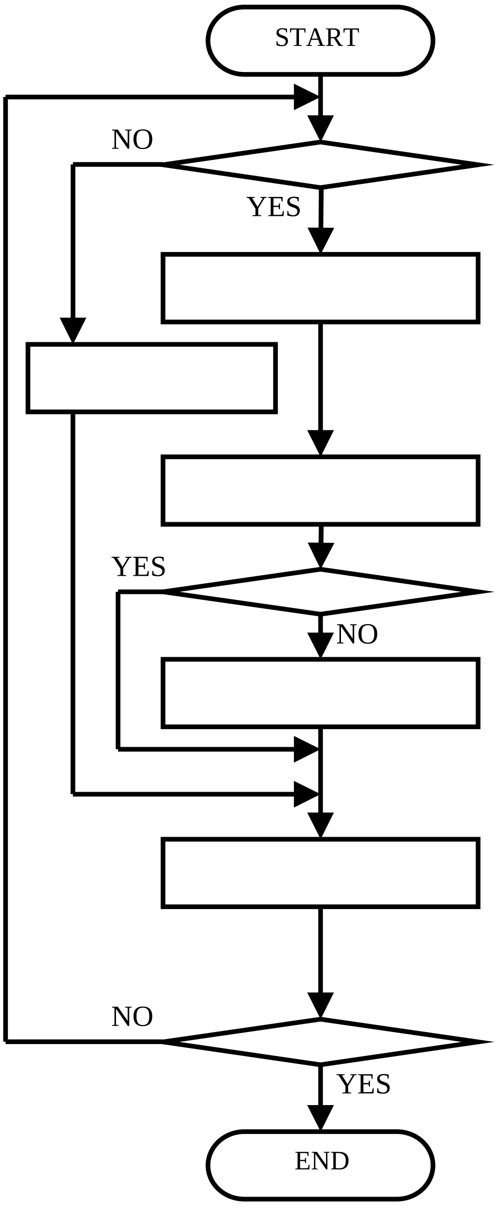


FIGURE 20. Comparison with the walking velocity calculated by Expression [5] and the actual measurement

CONCLUSIONS

Field experiments with 50 subjects using an external stairway actually installed for emergency have yielded the identification of different modes of walking behavior of individuals in a dense crowd flowing into an entrance to an evacuation facility. Especially general principles dictating the dependent walk that a pedestrian tries to follow another preceding one have been derived. For further quantification of the findings and development of predictive models for group evacuation, mathematical expressions are given for the representation of the walking velocity of an individual in a dense crowd as a function of such parameters as pedestrian-to-pedestrian distances and the walking velocity of antecessor. Fig. 21 is a summary of the general flow for calculating the whole history of the crowd behavior flowing into the exit of a space.



Range to Find Host

Determine the Triangle from the location of pedestrian and the dimension of the goal
Draw the semicircle with 1.0 m radius

Any pedestrian in the semicircle?

Select the pedestrian nearest within the semicircle(referred to as “X_t”).

Proceed toward the goal.

Turn the Vector to the Angle that the Position Relations with X_{t+1} sy Time “t+1” and the Position Relations with X_{t+} in the Time of “t” are Same.

$0 \leqq \theta \leqq 20.8L - 19.5$ (L: Distance from the Opening)
Deviation Angle from the Opening is θ.

$\theta = 20.8L - 19.5$ (L: Distance from the Opening)
Turn the Direction to adjust the angle.

$$v_t = v'_t \times [-\mathrm{TANh}\{(\ell_t - 0.8) \times 4\} \times 0.5 + 0.5] + [\mathrm{TANh}\{(\ell_t - 0.65) \times 3\} \times 0.5 + 0.5] \times [\mathrm{TANh}\{(\ell_t - 0.8) \times 4\} \times 0.5 + 0.5]$$

v_t: Walking Velocity at the time “t”[m/sec]
v'_t : Walking Velocity of X_t at time “t”[m/s]
ℓ_t : Distance to X_t at time “t”[m]

Walking Velocity is V_t.

Flow into Exit.

FIGURE 21. The model of walking behavior of an opening flow