SIMULATION OF EVACUATION BEHAVIOR FROM AN UNDERGROUND PASSAGEWAY DURING AN EARTHQUAKE

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SUMMARY

The Distinct Element Method (DEM) was used to simulate evacuation behavior during a disaster. This is a numerical analysis method that can compute the position of each element by solving the equation of motion step by step. We propose a calculation algorithm in which elements can avoid and pass each other naturally. Experiments were done to estimate the spring constant and driving force of the human body. The DEM parameters were determined from the results of these experiments. We simulated an emergency evacuation from a confined space representing an underground shopping center and paths. Evacuation behavior and time needed to evacuate were estimated quantitatively.

INTRODUCTION

People tend to gather in underground constructions such as shopping centers, stations, and public roads that are part of the development of urban areas because they are very convenient for obtaining the necessities of daily life and as places of amusement during all type of weather. If an earthquake occurs, people who are caught in such areas encounter dangerous situations. For a disaster prevention plan to be established, such a situation has to be fully considered and dangerous factors eliminated in advance. Computer simulation provides a powerful tool by which to estimate the evacuation behavior of people in such underground spaces.

Evacuation simulations for an earthquake or a fire mainly has been done to check the position of emergency exits, the widths of such exits, the time needed for evacuation and the distance to an exit. No quantification of mental factors has been incorporated in this kind of simulation. Even were quantification possible, the forces that act on a person can not be fully assessed, and studies these forces in terms of human evacuation behavior are rare [Kiyono et al., 1995]. If the action force when people concentrate at an exit can be estimated, danger in the situation can be predicted in advance and the results can be integrated in the plan of construction plans for underground spaces.

We simulated an emergency evacuation from a confined space representing an underground shopping center and paths. Evacuation behavior, and time needed to evacuate are estimated quantitatively.

Many evacuation models have been proposed. Modeling with respect to the area concerned is of two types; evacuation from a wide area in a disaster such as widespread fire [Okada, 1981] and flooding, and evacuation from a limited area such as a building. There are network, mesh, potential and coordinate models representing the space model in which evacuees move around. The units of the evacuees with which the models deal are a group and an individual. The group model is used when the movement of the people is considered a flow. The history of this group model is long and the merit of the model is that the entire tendency is easily understood. The individual model can take into account the personal characteristics such as walking speed, recognition of space, and information exchange. Decisions on the behavior pattern with these models are based on the diverse theories from such fields as automaton theory [Iki, 1980], potential theory [Yokoyama et al., 1993], magnetic theory [Okazaki, 1979], flow theory [Togawa,1954], and dynamics theory [Hirai and Nishida, 1977].

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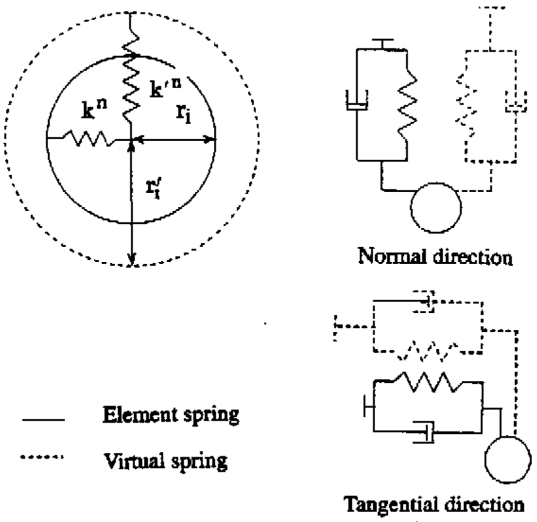


Figure 1: The human body as modeled by the distinct element method with spring and dashpot

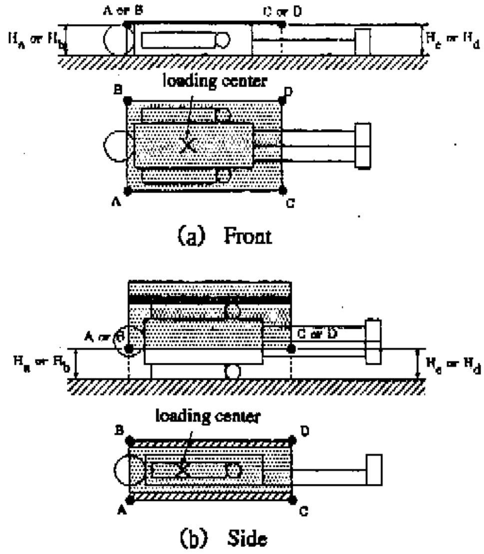


Figure 2: Compression experiment on the human body

On the basis of the above classifications, the model we propose deals with the evacuation from the confined area of an underground shopping mall and is of the coordinate and individual type. The movement of persons obeys dynamics theory. As the person is modeled as a distinct element, the Distinct Element Method (DEM) [Cundall, 1971] is used to simulate evacuation behavior during a disaster. The movement of each element is determined by solving the equation of motion.

OUTLINE OF DEM MODEL

The DEM is a numerical analysis method that can compute the position of each element by solving the equation of motion step by step. We propose a calculation algorithm in which elements can avoid and pass each other naturally. Human body size is modeled as a circular element with a radius is 0.295m because Furin [1974] proposed that the area of the cross section of the human body as $0.21m^2$. The weight per unit volume is assumed to be $1.69x10^3 N/m^3$ and the mass per unit height 36.2kg.

Psychologically people tend to keep a constant distance from each other when they walk or run. We here call this psychological distance the virtual radius of the human body. When others approach on the virtual radius, a rejection force acts on their bodies. Each human body is called an element, and each element has a spring and dashpot in its normal and tangential direction when it comes in contact with others. In terms of the virtual radius, the spring and dashpot appear when others come into contact with the virtual circle (Figure 1).

The equation of motion is

$$m_i \ddot{x}_i(t) = f_i^x(t) \tag{1}$$

$$m_i \ddot{y}_i(t) = f_i^y(t) \tag{2}$$

in which m_i, x_i and y_i, fix and f_{iy} are the mass, displacements, and combined forces in the x- and y-direction for the i-th element in the a group. As we deal with human behavior, rotation of the element is restricted. The combined force is expressed as the sum of various forces;

$$f_i^j(t) = f_k + f_c + f_k' + f_c' + f_{wk} + f_{wc} + f_f + f_a \qquad (j = x, y) \tag{3}$$

in which f_k and f_c are the forces from the springs and dashpots of all the elements that make contact with the i-th element, f_k' and f_c' those from the virtual springs and dashpots, f_{wk}, f_{wc} those from the surrounding walls or boundaries, and f_f is the driving force and f_a the attractive force which acts when the element corners.

Table 1: Parameters used in the simulation

Parameters	Value
Physical spring constant (normal) k_n (N/m)	1.26×10^4
(tangential) k_t (N/m)	6.29×10^3
Physical damping constant (normal) c_n (Nsec/m)	1.35×10^2
(tangential) c_t (Nsec/m)	3.02×10^1
Virtual spring constant (normal) k'_n(N/m)	6.62×10^1
(tangential) k'_t (N/m)	3.31×10^0
Physical damping constant (normal) c'_n (Nsec/m)	9.79×10^1
(tangential) c'_t (Nsec/m)	2.19×10^1
Physical radius of element r (m)	0.259
Virtual radius of element r' (m)	0.717
Weight per unit volume w (N/m^3)	1.69×10^3
Time step Δt (sec)	0.01
Acceleration for driving force (m/sec^2)	0.837

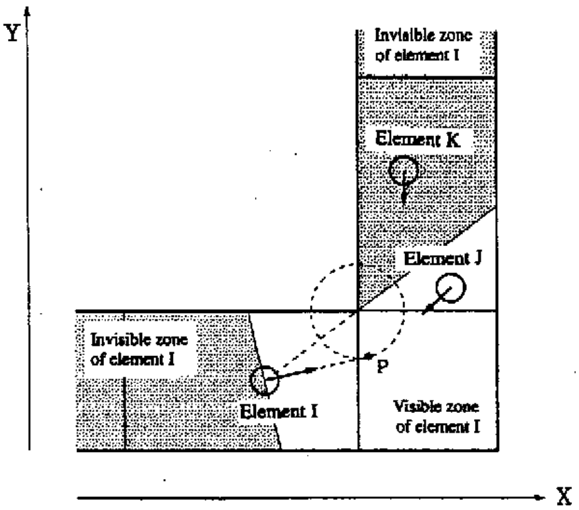


Figure 3: Visible and invisible zones for the element

Assuming that acceleration in the small time interval Δt (from time t-1 to t) is constant, the velocity and displacement of the i-th element is calculated by integrating Eqs.(1) and (2);

$$\dot{x}_i(t) = \dot{x}_i(t-1) + \ddot{x}_i(t-1)\Delta t \tag{4}$$

$$\dot{y}_i(t) = \dot{y}_i(t-1) + \ddot{y}_i(t-1)\Delta t \tag{5}$$

$$x_i(t) = x_i(t-1) + \dot{x}_i(t-1)\Delta t + \frac{1}{2}\ddot{x}_i(t-1)\Delta t^2 \tag{6}$$

$$y_i(t) = y_i(t-1) + \dot{y}_i(t-1)\Delta t + \frac{1}{2}\ddot{y}_i(t-1)\Delta t^2 \tag{7}$$

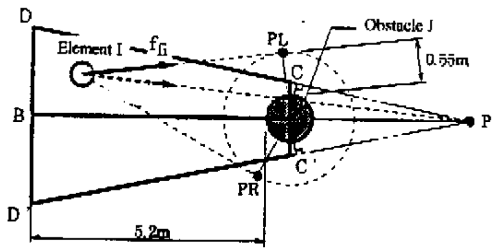


Figure 4: Avoidance zone and objective points for avoiding an obstacle

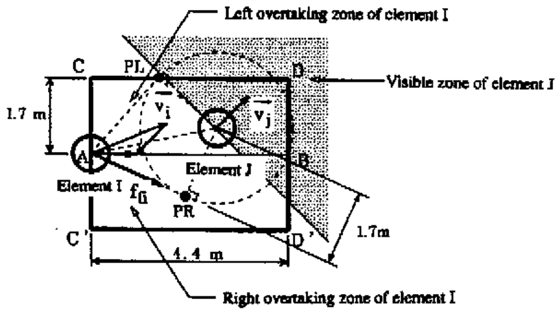


Figure 5: Avoidance zone for overtaking and the objective points

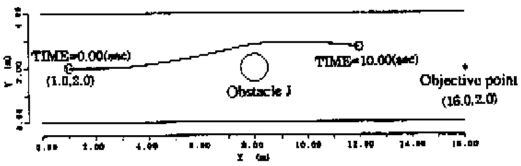


Figure 6: Simulation of obstacle avoidance

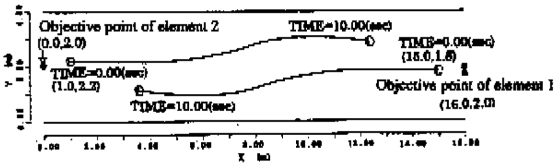


Figure 7: Simulation of passing others

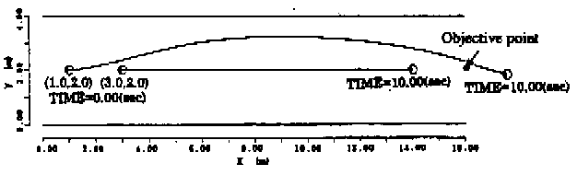


Figure 8: Simulation of overtaking

To carry out the evacuation analysis using the DEM, parameters such as the spring and damping constants, acceleration as the driving force of the element, and the walking speeds of the evacuees have to be evaluated. The spring constant of the human body, however, has never been studied. We have made a simple experiment for compression of the human body (Figure 2). The spring constant for the normal direction was determined to be $1.26\text{x}10^4$N/m as averaged for 35 university students. We also determined acceleration for a driving force acting until the velocity becomes constant under usual and an emergency conditions. Acceleration in the usual case being is 0.84m/sec^2, and in an emergency 1.84m/sec^2. We observed a large crowd of people stopping at a signal and obtained the average distance between individuals, 0.98m. As this is the distance from center to center of the individuals, the virtual radius of the element obtained was 0.72m by subtracting the physical radius of the element, 0.26m. The value of the virtual spring constant was calculated on the assumption that the virtual spring shrinks from the virtual radius, r', to the physical radius, r, when the driving force acts.

The spring constant for the tangential direction was 0.05 times that of normal direction as judged from many trial and error simulations. Critical damping was adopted for the damping coefficient value in order to rapidly attenuate the effect of element collision. The parameters used are shown in Table 1.

SET THE OBJECTIVE POINT

An objective point is set up for both straight-going and curving. The area was divided into blocks of several ten square meters, and each element moves to the objective point of two blocks ahead. It is necessary to change the course in order for the element to smoothly avoid obstacles (columns or walls) and any confronting person. Moreover, the idea of the area of sight is introduced (Figure 3). For example, element, i, in the figure has a visible area which excludes the shaded area. The element makes a detour around the element and obstacles in the visible area.

Straight-going

Avoiding obstacles

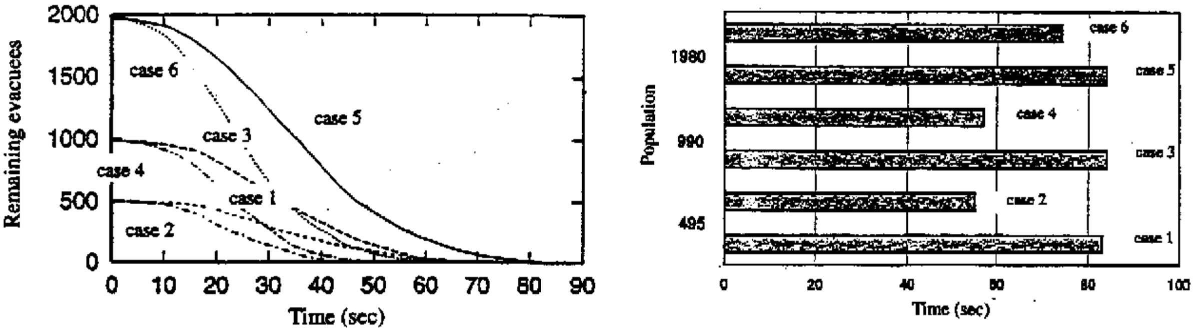
When a person wants to avoid the obstacle 0.4m in diameter and more than 5.0m in height, he begins to change course 5.2m before [Tatebe, 1989] and passes to the side 0.55m from the obstacle [Nakamura, 1977]. Based on these findings, the zone in which the element begins to avoid the obstacle is defined as in Figure 4. In this figure, an element in the left-side trapezoidal zone goes toward the point PL and that in the right-side zone toward PR.

Passing each other

When an individual wants to avoid a nearing person, he begins to change course 8.6m before [Tatebe, 1990] and passes to the side 1.7m from the person [Yoshioka, 1983]. Based on these findings, the rectangular zone in which an element begins to avoid another element also is defined as well.

Table 2: Occupance rate and speed in each category

Category	Male or Female	Speed (m/sec)	Occupance Rate (%)
- Elementary	M	1.02	1.93
	F	1.09	6.52
Junior high - 50	M	1.45	27.45
	F	1.23	40.76
50 - 70	M	1.19	5.01
	F	1.04	5.75
70 -	M	0.99	1.41
	F	0.89	1.76
Infant with adult	-	0.88	9.22
Handicapped	-	0.75	0.18



(a) time histories of the remaining evacuees **(b) time needed for evacuation**

Figure 9: Comparison of remaining evacuees and the time needed for evacuation

Overtaking

When one person overtakes another, he begins to change course 4.4m behind [Tatebe, 1989] and passes to the side 1.7m from the other person [Yoshioka, 1983]. The zone in which the element begins to avoid the obstacle and the objective point therefore is defined as shown in Figure 5. The shaded zone in the figure is the visible area of element j, such that element j begins avoidance behavior when the other element comes into this zone.

Figure 6 and 7 show the routs of an element with avoidance behavior. Figure 8 shows the overtaking behavior. taking into account both the avoidance behavior and invisible area. The element is smoothly moving by incorporating the objective points and the idea of visible area.

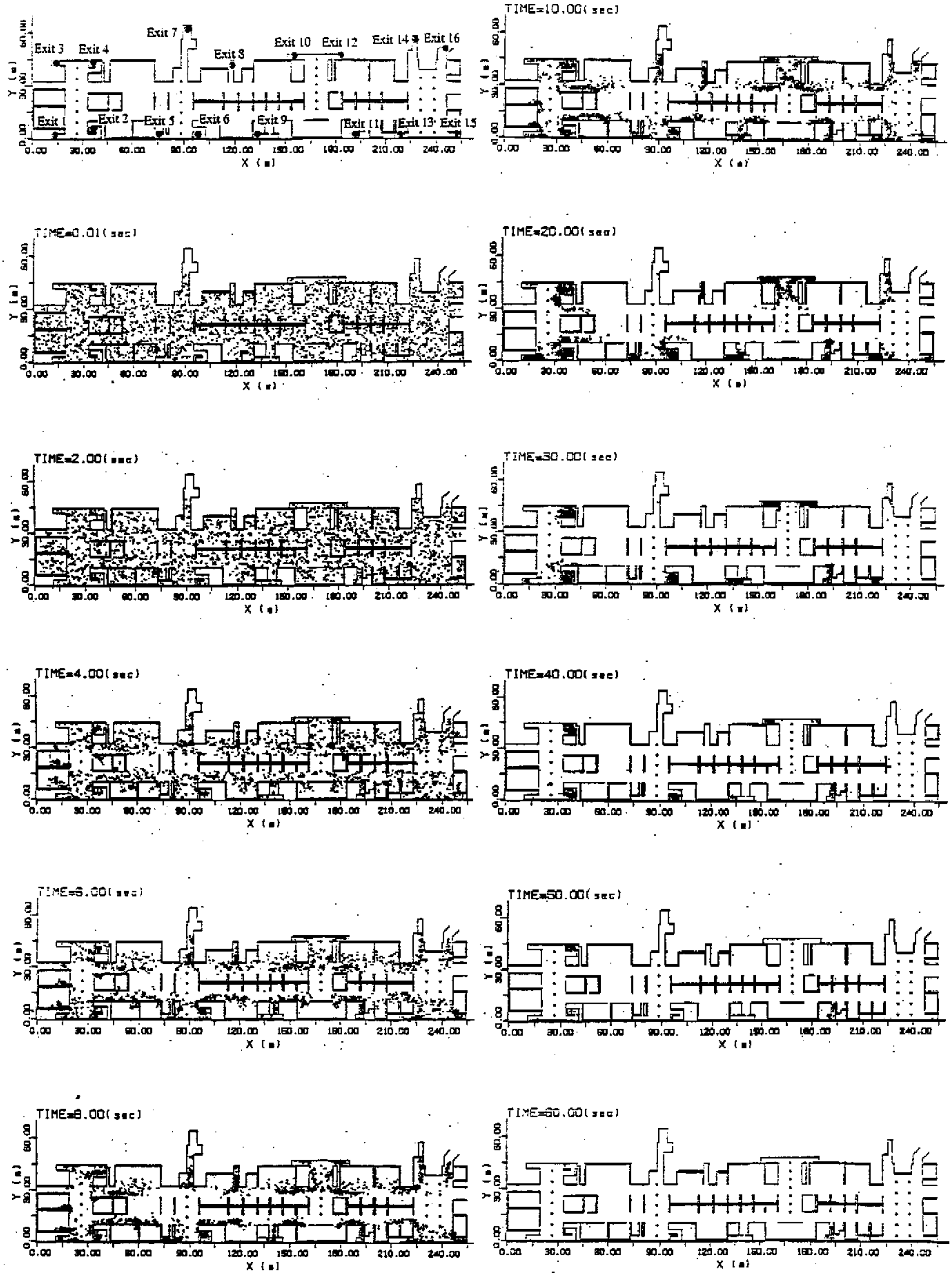


Figure 10: Snapshots of evacuation behavior

Curving

When an element curves the corner, it often runs against the wall because of centrifugal force. To avoid this phenomenon, an attraction force is operated from the inner corner, which is

$$f_{ai} = m_i v_t^2 / r_i \tag{8}$$

in which m_i is the mass per unit height, r_i the distance from the center of the element to the corner, and v_t is the tangential component of the velocity vector.

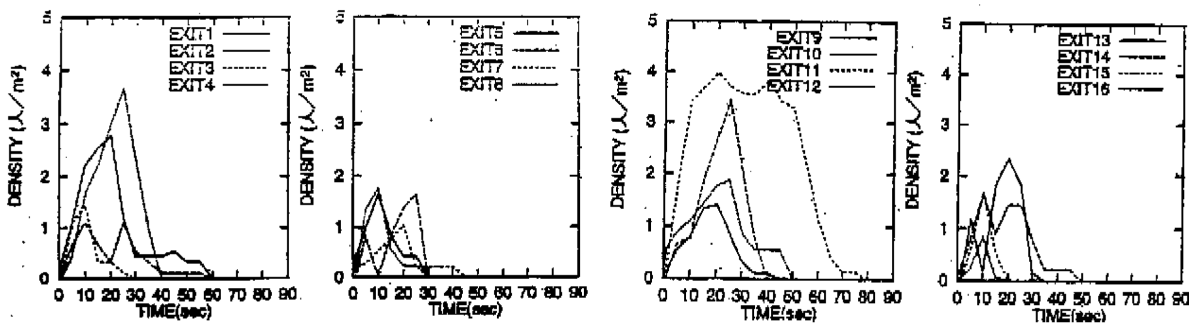


Figure 11: Variation in crowd density with time at each exit

SIMULATION OF EVACUATION BEHAVIOR

The proposed method was investigated by using it to simulate the evacuation of an underground mall. An existing underground mall in Kyoto was modeled. Before the simulation, we investigated the rate of population in the mall to classify the walking speed [Kiyono and Toki, 1998]. Individual speeds are given for each category. The rate of population and speed for each category are shown in Table 2. The effect of a difference in the total population of the mall and the escape speed of evacuees are compared. Two types of escape speeds are evaluated, the usual speed and a two times faster speed. As the peak mall population on a holiday was 990 [Kiyono and Toki, 1998], three populations, 495, 990, and 1980 were considered. Cases 1 and 2 were for the usual and emergency speeds for a population of 495. Case 3 and 4, and cases 5 and 6 are for the two types of speeds respectively for populations of 990 and 1980.

Figure 9 (a), (b) compares the time histories of the remaining evacuees and the time needed for evacuation in each case. Evacuation speed becomes greater and the time needed to evacuate becomes less in inverse proportion to the speed, but it depends on the population. As the population increases, the element encounters many factors of such as overtaking, collision with another, and a crowded exit. The tendency is particularly marked for cases 5 and 6. The effect of the crowds at the exit is most serious problem to deal with in terms of evacuation issues. Diagrams of case 2 are shown in Figure 10, in which half circle-like crowds are clustered around the steps of the Nos.4 and 11 exits. It therefore takes much time to pass out through these exits. Variation in crowd density with time is shown for each exit in Figure 11. Every exit has a high density of four to five persons per square meter. This high density state continues at exit No.11 causing a delay in evacuation. This phenomenon does not appear at neighboring exits Nos.3, and 13 and evacuation has been smoothly completed. It is important to prevent the concentration of a crowd at a specific exit and to ensure distribution of evacuees to other exits.

CONCLUSONS

What we did and the results obtained are
(1) The Distinct Element Method was used to simulate evacuation behavior during a disaster. Important parameters for the human body and driving force were determined from experiments.
(2) Objective points were introduced so that the element can smoothly avoid the obstacles and confronting individuals.
(3) As the population increases, the element encounters many effects such as overtaking, collision with another, and crowding at the exit. This effect of crowding at an exit is the most serious problem to deal with in terms of evacuation issues. It is important to prevent a concentrating crowd at a specific exit and to ensure people are distributed to other exits

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