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Gotoh, Hitoshi; Harada, Eiji; Maruyama, Yuta; Takahashi, Kazuhide

Discrete Crowd Model for Simulation of Tsunami-Flood Refuge

DISCRETE CROWD MODEL FOR SIMULATION OF TSUNAMI-FLOOD REFUGE

Hitoshi Gotoh[1], Eiji Harada[2], Yuta Maruyama[3] and Kazuhide Takahashi[4]

[1] Professor, Department of Urban and Environmental Engineering, Kyoto University
Kyoto-Daigaku-Katsura, Nishikyo-ku, Kyoto, 615-8540, Japan, e-mail: gotoh@mbox.kudpc.kyoto-u.ac.jp
[2] Associate Professor, Department of Civil Engineering, Toyota National College of Technology
Eisei-cho 2-1, Toyota, Aichi, 471-8525, Japan, e-mail: harada@toyota-ct.ac.jp
[3] Graduate student, School of Urban and Environmental Engineering, Kyoto University
Kyoto-Daigaku-Katsura, Nishikyo-ku, Kyoto, 615-8540, Japan,
e-mail: maruyama@wfee.mbox.media.kudpc.kyoto-u.ac.jp
[4] Graduate student, School of Urban and Environmental Engineering, Kyoto University
Kyoto-Daigaku-Katsura, Nishikyo-ku, Kyoto, 615-8540, Japan,
e-mail: kazuhide.takahashi@t03.mbox.kudpc.kyoto-u.ac.jp

ABSTRACT

Crowd refuge simulation in human scale in consideration of individual behaviour is an effective tool for investigation of optimum refuge planning from tsunami. In this study, the Boid, which is well known as a flock model of birds and fish, is introduced into crowd refuge simulator. A crowd refuge simulator, which can simulate behaviour of age-groups with different physical attributes, is developed. Numerical simulation for crowd refuge process of 852 persons from small town to a hilltop has been performed. In addition, an influence of different refuge scenarios on refuge process is shown.

Keywords: Crowd refuge simulation, Boid, Human scale, Individual behaviour

1. INTRODUCTION

Significance of disaster prevention measures against tsunami has been widely recognized since tsunami disaster due to the gigantic earthquake in Sumatra. Measures against huge tsunami exceeding the highest design wave is a matter of great urgency, also in Japan. Quick refuge is indispensable matter for survival of local inhabitants who live in the area with a significant risk of a direct attack by tsunami. Hence preparing safe refuge road is quite important. However reproduction of same imminent situation as a real disaster is impossible in usual evacuation training and there is no means how to decide the appropriate refuge route. For that reason, we have considered that a virtual training by a refuge simulator is effective tool for selecting an appropriate refuge route. Evacuation stairs and evacuation towers are usually built for the aid of a quick evacuation. And the investigation for safety of stairs and towers is required when a crowd rush to an entrance of the evacuation stairs and towers. A consideration of crowd-blockage is very important for designing appropriate entrance space. Although, this kind of planning requires much information of the characteristics of urban districts, without a refuge simulator, which can track refuge process of each person, it is difficult to predict a refuge process in detail. In the present study, to investigate a refuge process in consideration of behaviour of each individual, we have developed the Lagrangian refuge simulator by introducing the Boid proposed by Reynolds (1987), which is well known as a distributed behavioral model of flocks like birds and fish. And we have performed the simulation for refuge process of 852 persons from urban district to the evacuation place at the backside hill. In the present study, the influence on refuge efficiency owing to pre-announcement of refuge route is investigated.

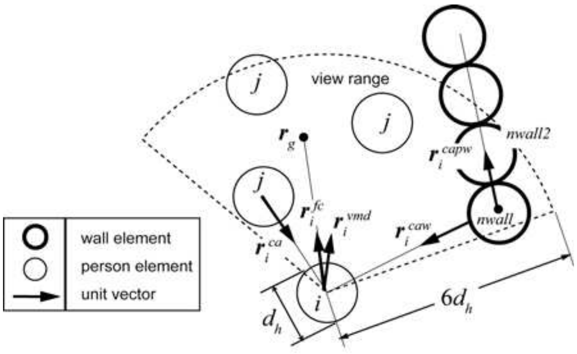

Figure 1 Person/person interacting area

2. SIMULATION MODEL

Reynolds (1987) proposed the Boid, which is the abbreviation of "birdoid", as a model of a flock of birds. The Boid is composed of three basic rules as follows: 1) separation, 2) alignment, and 3) cohesion. Behaviour of flocks is represented well by using above three rules. Separation is the avoidance rule from collision between neighbouring birds. Alignment is the adjustment rule to fit the moving direction around neighbouring birds. Cohesion is the collecting rule that each bird moves toward the center of gravity of flocks. And this rule contributed to keep flocks as well as the alignment rule. Reynolds showed the behaviour of a flock birds qualitatively by using the Boid.

2.1 Moving direction model of person

In addition to these three rules, namely 1)separation, 2)alignment and 3)cohesion, are taken into account: 4)avoiding a collision with a wall, 5)movement along wall, 6)inertia effect, 7)following to external indicator and 8)freak behaviour. The moving direction of person is decided by using eight rules mentioned above. The Boid is the individual-interaction model, in the present study, circle is assumed as an interaction area of person. And it is assumed that these interaction rules works between the person and the persons in his/her vision. The vision is defined as the range of fan of 120 degrees, center of which corresponds to moving direction of each person. The person/person interacting area is shown schematically in Figure 1.

The vector of separation is described as follows:

$$\boldsymbol{r}_i^{ca} = \frac{\boldsymbol{r}_i - \boldsymbol{r}_{nei}}{|\boldsymbol{r}_i - \boldsymbol{r}_{nei}|} \tag{1}$$

in which $\boldsymbol{r}_i$=positional vector of i-th person; and $\boldsymbol{r}_{nei}$=positional vector of the nearest person, who is in the influence area of radius r_{ca}, from i-th person. The vector of alignment is defined as follows:

$$\boldsymbol{r}_i^{vmd} = \sum_{j \neq i} \frac{\boldsymbol{r}_j}{|\boldsymbol{r}_j|} w(\boldsymbol{r}_i - \boldsymbol{r}_j); \boldsymbol{r}_e = \boldsymbol{r}_e^{vmd} \tag{2}$$

$$w(\boldsymbol{r}) = \begin{cases} 1/N_w \left(0 < \boldsymbol{r} < \boldsymbol{r}_e; \cos\alpha_{ij} > 0.5\right) \\ 0 \quad (otherwise) \end{cases} \tag{3}$$

$$N_w = \sum_{j \neq i} w(\boldsymbol{r}_i - \boldsymbol{r}_j) \ ; \ \cos\alpha_{ij} = \frac{\boldsymbol{r}_i \cdot (\boldsymbol{r}_j - \boldsymbol{r}_i)}{|\boldsymbol{r}_i||\boldsymbol{r}_j - \boldsymbol{r}_i|} \tag{4}$$

in which $w(\boldsymbol{r})$=weight function; N_w=number of the other persons except for i-th person in the influence area; and α_{ij}=angle for alignment formed by positional vector of i-th and j-th person. The vector of cohesion is defined as the vector toward to the center of gravity of crowd as follows:

$$\boldsymbol{r}_i^{fc} = \frac{\boldsymbol{r}_g - \boldsymbol{r}_i}{|\boldsymbol{r}_g - \boldsymbol{r}_i|} w_{rand}(t) \ ; \ \boldsymbol{r}_g = \frac{1}{N}\sum_{j \neq i} \boldsymbol{r}_j \, ; \boldsymbol{r}_e = \boldsymbol{r}_e^{fc} \tag{5}$$

Next, the vector of avoiding a collision with a wall is described as same as the description of the vector of separation as follows:

$$\boldsymbol{r}_i^{caw} = \frac{\boldsymbol{r}_i - \boldsymbol{r}_{nwall}}{|\boldsymbol{r}_i - \boldsymbol{r}_{nwall}|} \tag{6}$$

in which $\boldsymbol{r}_{nwall}$=the positional vector of wall-element, which is the nearest wall-element from the range of vision of i-th person. The vector of the inertia is defined as the moving vector of each person of the previous time step as follows:

$$\boldsymbol{r}_i^{ine}(t) = \boldsymbol{r}_i^{unit}(t - \Delta t) \tag{7}$$

in which $\boldsymbol{r}_i^{unit}$=unit vector setting the moving direction of i-th person which is defined as Eq.11; and Δt=calculating time step. The vector moving along wall elements is described as follows:

$$\boldsymbol{r}_i^{capw} = \frac{\boldsymbol{r}_{nwall2} - \boldsymbol{r}_{nwall}}{|\boldsymbol{r}_{nwall2} - \boldsymbol{r}_{nwall}|} \tag{8}$$

in which $\boldsymbol{r}_{nwall2}$=the positional vector of the second nearest wall element in the range of vision of i-th person.

Actually, person knows his/her town in general. And person would choose the refuge-route based on his/her knowledge. Furthermore, there is much information not only given by watching behavior of crowd around each person but also given by external condition such as signs along streets and preliminary study about optimum refuge-route. To consider these conditions, the vector $\boldsymbol{r}_i^{sig}$ is introduced. This vector $\boldsymbol{r}_i^{sig}$ acts on person as a dummy element, which is located on the intersection area, where selection of moving direction must be done. And the dummy element influences the moving direction when the dummy element is in the vision of person. Each person moves with referring the sign at the intersection. We can also perform the simulation in consideration of difference in good sense of locality of each person by setting the special sign acting on only the particular group of person. And also, we consider the irregular behavior of person with introducing the freak-vector as follows:

$$\boldsymbol{r}_i^{rand} = \frac{\xi_{r1}\boldsymbol{i} - \xi_{r2}\boldsymbol{j}}{|\xi_{r1}\boldsymbol{i} - \xi_{r2}\boldsymbol{j}|} \tag{9}$$

in which ξ_{r1}, ξ_{r2}=random numbers following to the standard Gauss distribution; and i, j=unit vector in x and y directions respectively.

These rules are normalized taken weight into account, the directional vector for movement of person is described as follows:

$$\Theta_{md} = C_{ca}\boldsymbol{r}_i^{ca} + C_{vmd}\boldsymbol{r}_i^{vmd} + C_{fc}\boldsymbol{r}_i^{fc} + C_{caw}\boldsymbol{r}_i^{caw} + C_{ine}\boldsymbol{r}_i^{ine} + C_{capw}\boldsymbol{r}_i^{capw} + C_{sig}\boldsymbol{r}_i^{sig} + C_{rand}\boldsymbol{r}_i^{rand} \quad (10)$$

$$\boldsymbol{r}_i^{unit} = \frac{\Theta_{md}}{|\Theta_{md}|} \quad (11)$$

in which C_{ca}, C_{vmd}, C_{fc}, C_{caw}, C_{ine}, C_{capw}, C_{sig}, C_{rand}=coefficients of weight for separation, alignment, cohesion, avoidance of collision with wall, inertia effect, movement along wall, external indicator including knowledge, and a freak effect, respectively. In this study, C_{ca}=4.0, C_{vmd}=2.5, C_{fc}=2.25, C_{caw}=3.0, C_{ine}=1.75, C_{capw}=4.0, C_{sig}=6.0, and C_{rand}=1.0 are used. The element of person is represented as a circle 0.52m in diameter, area of which is equal to person-ellipse proposed by Fruin and Nagashima(1974). The length of vision is set $r_e^{vmd}=r_e^{fc}$=6dh.

2.2 Moving velocity model of person

The moving velocity for each person is described in the same way as the refuge simulator based on the DEM proposed by Gotoh et al.(2004) as follows:

$$v_i = \mathrm{Min}\left(|v_i(t - \Delta t)| + \alpha\Delta t, v_{equi} - 0.426\rho_c\right) \quad (12)$$

in which α=acceleration of person; v_{equi}=equilibrium velocity of person; and ρ_c=number density of person(number/m^2).

$$\rho_c = \frac{3}{\pi r_e^2}\sum_{j \neq i} w_\rho\left(|(\boldsymbol{r}_i - \boldsymbol{r}_j)|\right) \quad (13)$$

$$w_\rho(\boldsymbol{r}) = \begin{cases} 1 & (0 < \boldsymbol{r} < \boldsymbol{r}_e ; \cos\alpha_{ij} > 0.5) \\ 0 & (otherwise) \end{cases} \quad (14)$$

By using above equations, we can get the moving velocity vector of person as follows:

$$\boldsymbol{v}_i(t) = (1 - \gamma_{sl}) v_i \boldsymbol{r}_i^{unit} \quad (15)$$

in which γ_{sl}=damping coefficient of equilibrium velocity of person due to slopes or stairs, for example 0.0 at a flat, 0.15-0.5 at a slope (see Figure 3).

We have performed the simulation of moving crowd at a flat street for calibration of weight coefficients. The condition of simulation are as follows:1.39m/s in equilibrium velocity, 0.861m/s^2 in acceleration. We have compared simulation result with the observation result of crowd at the intersection by Ozeki and Watanabe (1967). Figure 2 shows the relation between number density of persons and moving velocity. Validity of the parameters using in the present simulation is confirmed from the good agreement between simulation and observation.

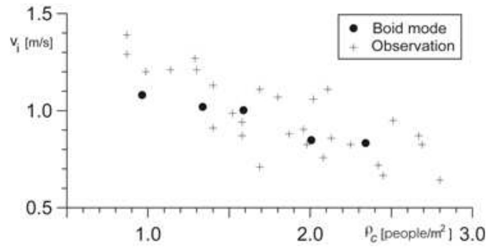

Figure 2 Comparison between observation and simulation

3. SIMULATION OF REFUGE PROCESS FROM URBAN DISTRICT

3.1 Simulation domain and condition

We have performed the simulation for refuge from tsunami flood and we have investigated the refuge process from urban districts to a backside hill through roads and stairs. Although, there is the mild slope road from urban districts to the hill: existing road(left route) shown as Figure 3, persons in the right side of the urban districts are to proceed to the existing road with much detour, hence, a way to the backside hill is too far. Therefore, we have tried to perform the simulation under the additional new three refuge paths: center route1,2 and right route, which connects urban districts to the backside hill. The values shown in Figure 3 are the damping coefficients of equilibrium velocity(=γ_{al}), we have set γ_{sl} =0.0 to all the flat roads in the urban districts. We have set a width of each road in the range of 5.0m-15.0m in consideration of the difference between causeway and alleyway. We have set the width of the refuge road as follows: left route=7.0m and center route1,2 and right route=3.0m.

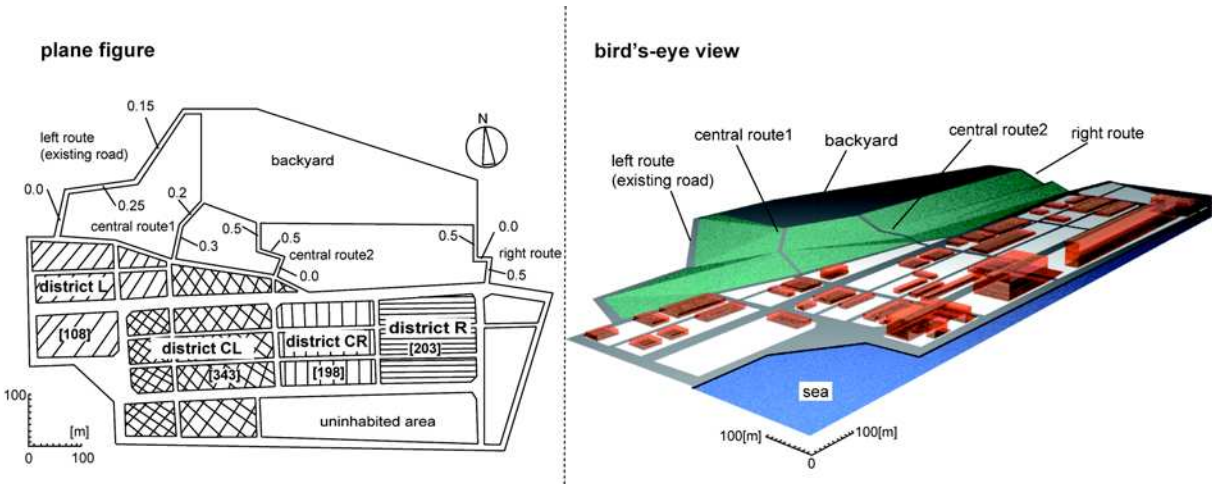

Figure 3 Simulation domain

Initial position of persons were arranged in consideration of the condition of land-use as follows: 343 persons in the district-CL as a residential area, 108 persons in the district-L, 198 persons in the district-CR and 203 persons in the district-R. Distribution of number to each district is in proportion to capacity of facilities of each district shown in Figure 3.

Crowd was composed of seven categories: male/female of the three age-ranges of 10-39, 40-69, and over 70 and child of the age range 5-9, according to the physical attributes as to equilibrium velocity. The population of each category was decided from the statistical data of the southern part of Wakayama Prefecture, the crowd refuge process of 852 persons has been tracked. The definition of each age, number and equilibrium velocity are shown in Figure 4.

In case persons leave for east-west street, persons start to walk toward west(left)- and east(right)-direction, in the urban district-CL,-L and -CR,-R respectively. In the Boid model, the moving direction each person depends on surrounding condition and the moving direction is decided automatically by information of surrounding persons. Therefore, persons can also move in the different directions against the moving direction vector which corresponds to the information or knowledge vector $\boldsymbol{r}_i^{sig}$ preliminary set in each street. Two cases of simulations have been performed. In the case A, the vector $\boldsymbol{r}_i^{sig}$ is given as follows: toward the west direction in the district-CL,-L, and toward the east direction in the district-CR,-R. In the case B, the vector $\boldsymbol{r}_i^{sig}$ is given as follows: toward the west direction in the district-L and toward the east direction in the district-CL,-CR and -R.

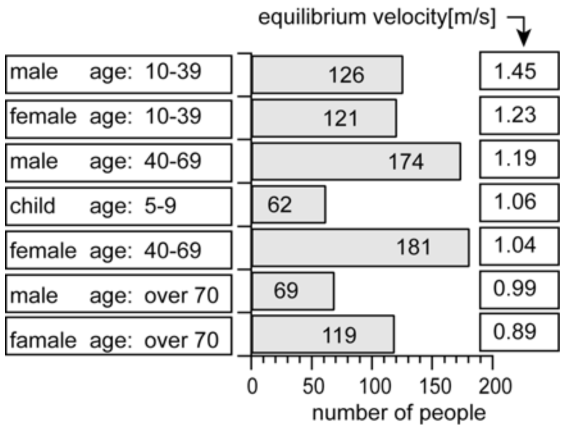

Figure 4 Categorization of crowd (age, number and equilibrium velocity)

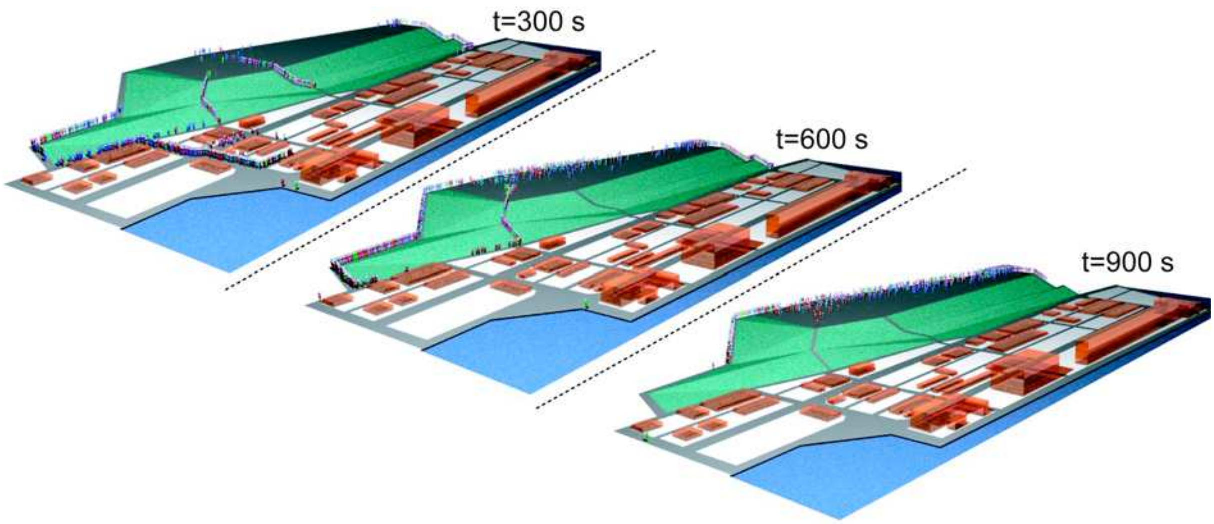

Figure 5 Snapshots of refuge process of case A

3.2 Refuge process

First, snapshots of the case A are shown in Figure 5. The process of refuge from urban districts to the backside hill can be found through 4 routes. The close-up of the road around the entrance of the stairs is shown in Figure 6. Snapshot in each route is shown at different time. Because Figure 6 shows the snapshots at the time after 60 seconds from finish of refuge of the first person at each route.

The processes of cumulative number of persons who have finished refuge of four routes in the case A are shown in Figure 7. The solid line in Figure 7 shows the time series of total number of persons who have finished refuge, the narrow dashed line shows detail of each category of age. The wide dashed line is the finishing time of refuge of each route. The difference over ten minutes is shown between the center route 2 and the left route. In other words, the capacity of the center route 2 has a margin, namely, the capacity of the refuge routes are not utilized sufficiently. To improve this situation, we specified the district from which each person comes, and this result is shown in Figure 8. Many of persons from the urban district-CL are assigned to the left route.

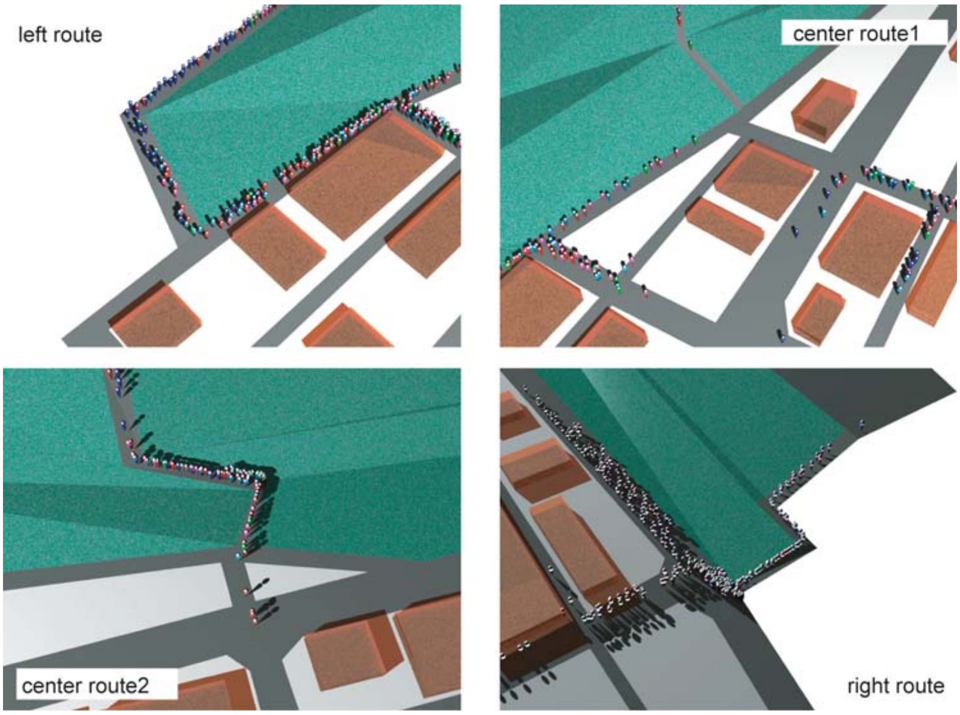

Figure 6 Close-up around entrance of four refuge routes

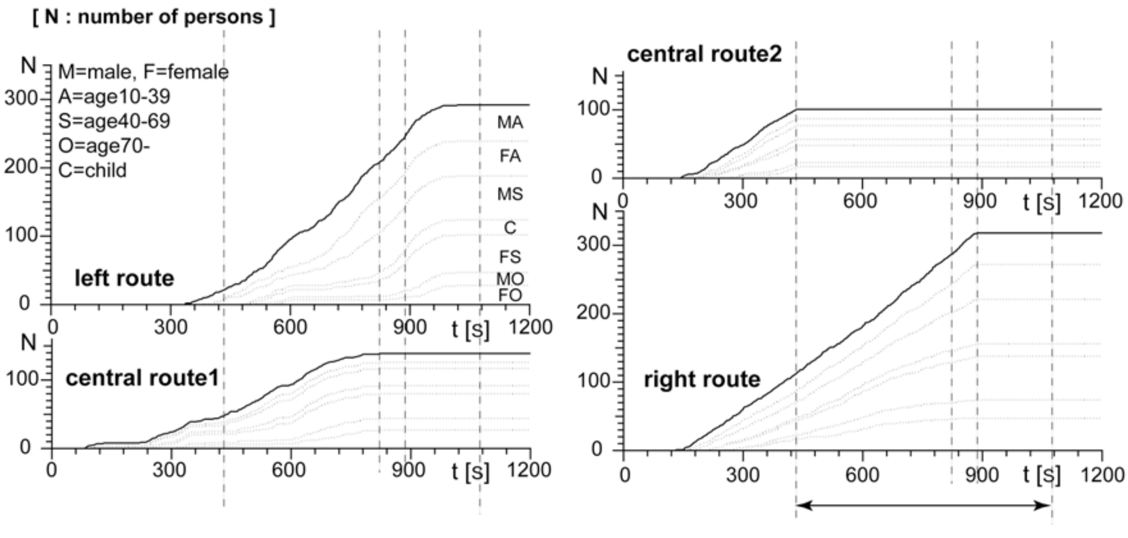

Figure 7 Time series of cumulative number of complete persons of refuge of case A

In the case B, as above mentioned, persons in the district-CL start to walk toward the east(right) at the beginning. Figures 9 and 10 show the time series of cumulative number of persons who finished refuge in four routes classified by seven age-categories and four districts, respectively. The difference of the finishing time of refuge between routes is shorten about 6 minutes at most. And the number of persons using the center route 2 is more than that of the left route. About half of the persons of the urban district-CL, where there are many persons at default setting of the simulation, make a refuge through the center route 2. The capacity of the center route 2 is used efficiently in comparison to the case A.

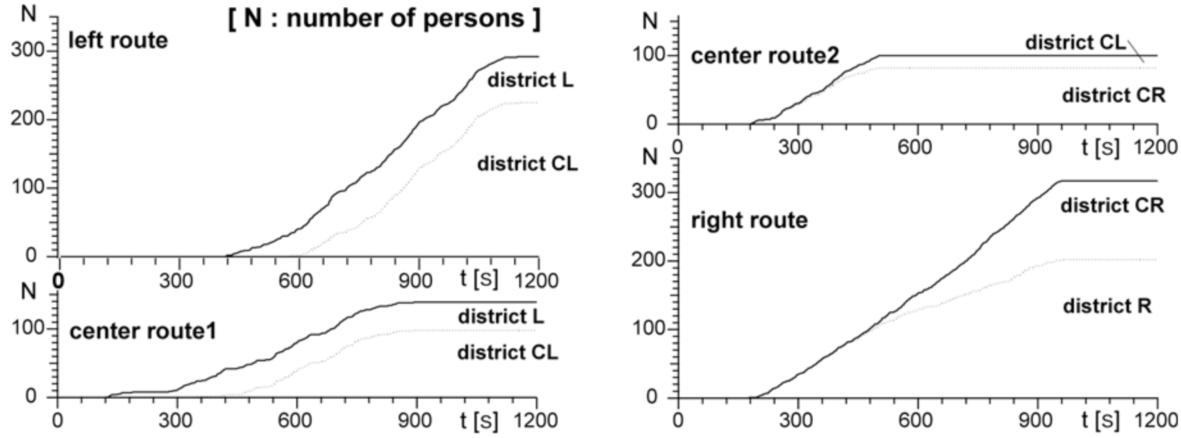

Figure 8 Time series of cumulative number of persons by districts of case A

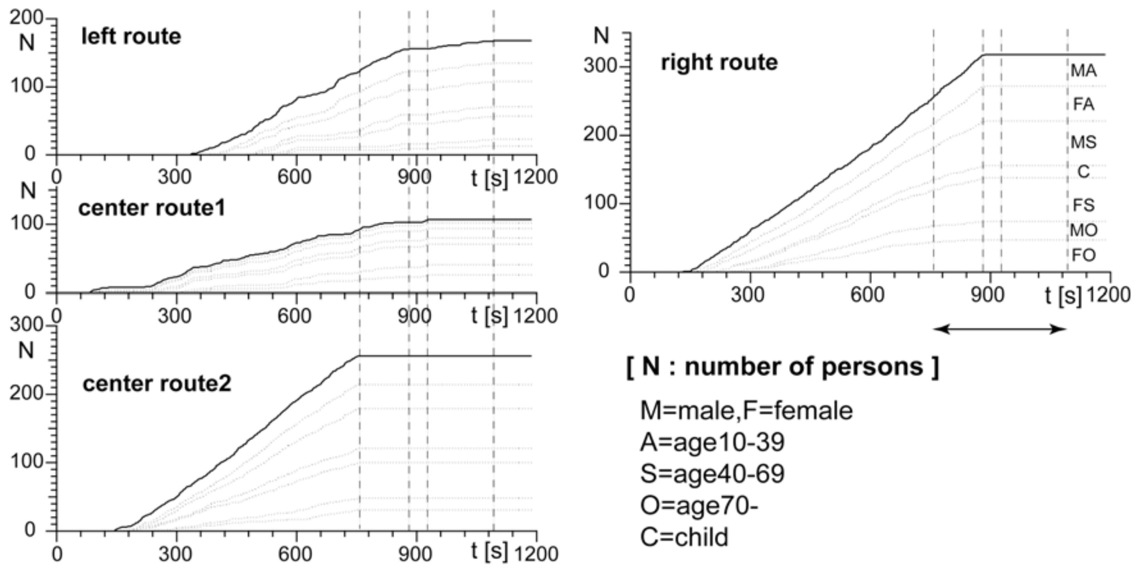

Figure 9 Time series of cumulative number of complete persons of refuge of case B

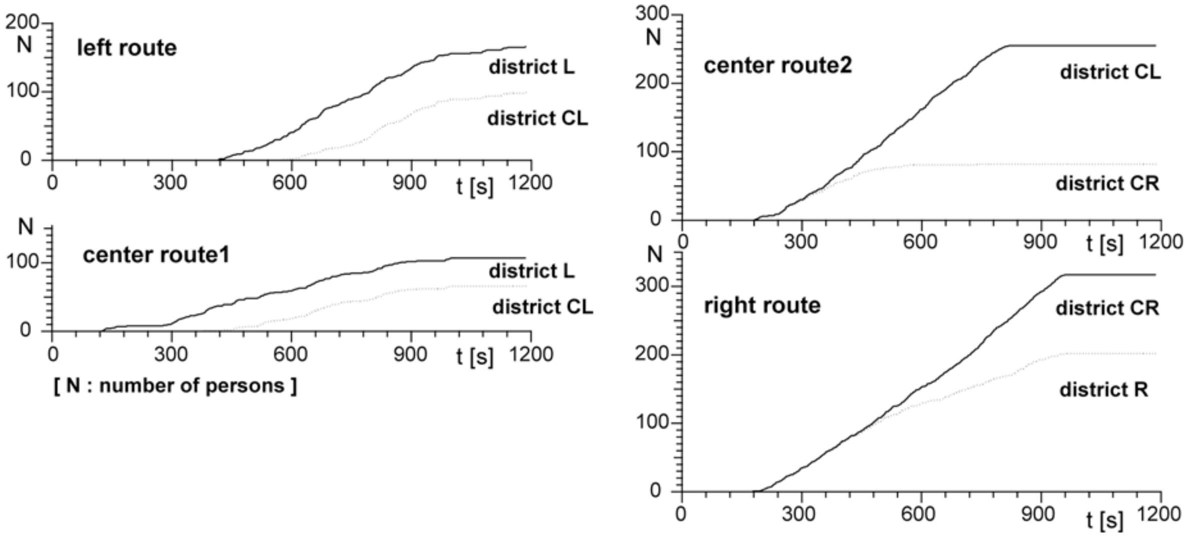

Figure 10 Time series of cumulative number of persons by districts of case B

The time series of the ratio of persons who have finished refuge of the whole routes is shown in Figure 11. The decrease of the finishing time of refuge about 50,70 seconds in the 70,90% finishing time of refuge, respectively. The scenario in the case B provides appropriate sharing of the persons in each route.

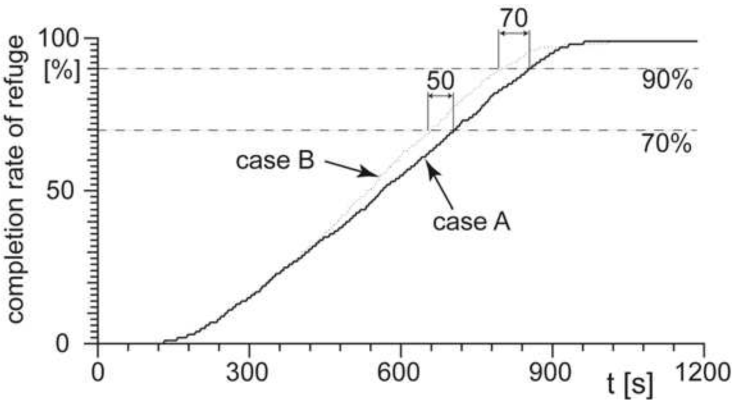

Figure 11 Time series of cumulative number of persons of the whole routes

4. CONCLUSION

In this study, we have developed the crowd refuge simulator and performed the simulation for refuge process due to tsunami from urban districts to the backside hill. This simulator is based on the Lagrangian model, and the appropriate moving direction of individual can be easily evaluated by various factors from condition of surrounding of person step by step.

The significant difference of refuge finishing time was confirmed between the simulation with or without advance information, which indicates the moving direction at the beginning of refuge. This indicates that the examination of the optimum refuge route by trial and error is important.

We can make a computer graphics of the simulation result from various points of view shown as Figure 12. And it is confirmed that a post processing technique by CG will be useful for experience of a virtual refuge with reality as an education for a disaster prevention.

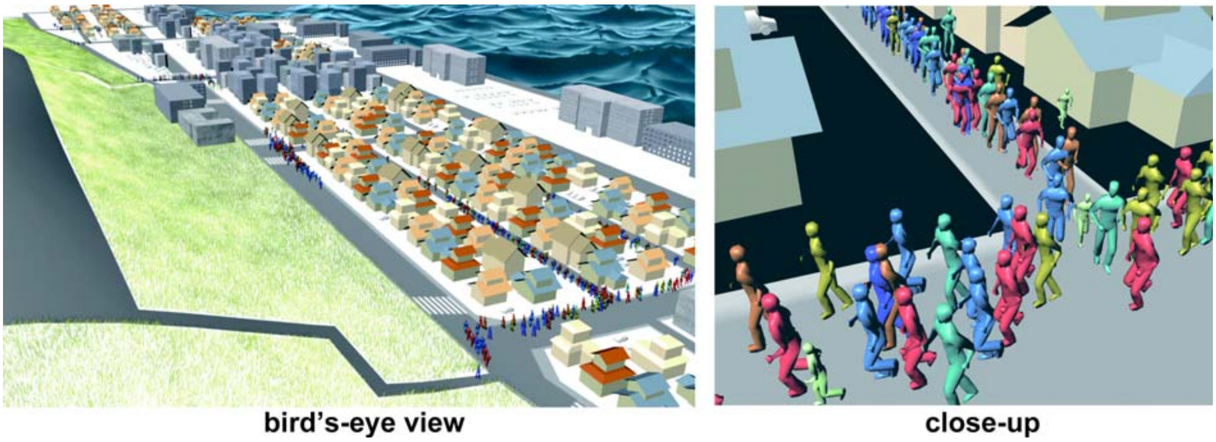

Figure 12 Snapshots of refuge process by CG technique

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