

A Fundamental Study on Multi-agent Pedestrian Model Based on Risk Avoidance Behavior during Road Blockage and Evacuation Simulation of Regional Urban Disaster

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Abstract: Regional cities in Japan are at the risk of experiencing big fire accidents or earthquakes every day. However, neither the number nor the capacity of shelters has increased because local governments might not consider them owing to budget shortfall. By contrast, wide-area evacuation simulations can easily provide an antagonizing image of regional urban disasters. After a disaster, the city collapses and the evacuation routes are closed; consequently, evacuees feel anxious and they cannot move as usual. This anxiety behavior has not been considered in previous related studies and simulations. In this study, a wide-area evacuation simulation is developed; this model can not only calculate the possibility of blocking escape routes when the city is broken but also provide safe and more realistic evacuation plans before a disaster occurs by incorporating into the simulation the risk avoidance behaviors of evacuees from road blockage, such as “the route re-seeking behavior” and “the shelter re-selecting behavior”.

Key words: Wide-area evacuation simulation, multi-agent model, risk avoidance behavior, regional disaster prevention plan.

1. Introduction

1.1 Background and Purpose of This Study

When transferring a crowd behavior model, which has been used in the verification [1] and evaluation of the evacuation safety within a building, to a wide-area evacuation simulation model, which is used in urban spaces, particularly the regional disaster prevention plan, road blockage seems to be an important environmental factor in wide-area evacuation behavior,

as evident from the research and reports on the Great Hanshin-Awaji Earthquake and the Great East Japan Earthquake. Road blockage makes evacuees anxious and they adopt a uniform action pattern, such as they anticipate the danger or perform risk avoidance behavior. The purpose of this study is to build a multi-agent pedestrian model based on risk avoidance behavior, which can express a series of disaster prevention actions, such as evacuees seeking designed shelters autonomously and completing the evacuation.

1.2 Literature Review

From the urban disaster prevention perspective,

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there are many studies on wide-area evacuation simulation. However, studies conducted using a network or mesh model type have not sufficiently expressed the actual phenomena with problems that the city block model is abstract and evacuees are treated as a crowd and not as individuals [2]. The wide-area evacuation simulation of a multi-agent model type (MA model) addresses and resolves these problems. In this simulation, the evacuees are set that they proceed on the optimum route and complete evacuation when they arrive at the first destination. Because it uses evacuation completion time and distance, there is need to understand and analyze the evacuation process [3, 4].

In recent MA models, the wide-area simulation calculates room time of evacuation for tsunami and evaluates the location of shelter for tsunami in Otsuchi town, Iwate prefecture. Although Watanabe practices the wide-area evacuation simulation considering the collapse of buildings and road blockage, it is not set to re-select another destination. In addition, studies that refer to the behavioral determinant of agents and

systematization exercise numeric calculations [6, 7] define road blockage caused by the collapse of buildings as the “visual information of long distance” and state that there is a need to build an analysis numerical model that considers the judgment of agents (Table 1).

The model’s advantage is as follows:

(1) By grasping non-stationary behavior of disaster evacuation visually and in advance, this model facilitates expert judgment or rehearsal of the evacuation plan at the time of local disaster management planning.

(2) By reflecting the anxiety of evacuees into the model as risk avoidance behavior, it is possible to grasp the impact of it during a disaster and consider whether it can be a considerable factor for a wide-area evacuation plan.

(3) By comprehending the geographical characteristics of the target area at the time of a disaster, it is possible to conduct a correlative analysis of the regional disaster prevention plan and the wide-area evacuation simulation.

Table 1 Behavioral determinants and systematization exercise numeric [6, 7].

	Item		Basic elements of the walking motion	Result of behavior	
Behavioral determinant	A	Willingness to reach destination		Destination reaching behavior Arrive at the destination	
	B	Perceptual information by touch		Antagonism of pressure and shock Maintenance of situation and posture	
	C	Visual information of medium and short distance	Short distance	Avoidance behavior	Pass each other without collision
				Follow behavior	Walk without disturbing the flow
				Tracking behavior	Keep the optimal speed
				Attendance behavior	Walk along the wall
			Medium distance	Gap seeking behavior	Interrupt and overtake reasonably
	D	Intentional turn		Drop in behavior Buy a ticket at the ticket machine Shop at the store	
	E	Visual information of long distance		Intellectual judgment Take the risk avoidance behavior from the collapse of buildings Search an alternative route	
	F	Global information acquired intentionally	Local navigation	Prediction and determination by the information acquisition	Turn by intuitive walk support Wayfinding
Global navigation			Avoid congestion by acquisition of information in car navigation		
G	Internal consciousness		Feeling and speculation Fortuitous behavior		

2. Present Condition of the Disaster Prevention Plan

2.1 Disaster Prevention Plan of Japan

There are two types of disaster prevention plans in Japan. One is the basic disaster prevention plan, which is formulated at the national level [1]. The other is the regional disaster prevention plan, which is formulated by each municipality [5]. Although the latter typically requires more detailed consideration, it only follows the basic disaster prevention plan and its specific numerical values because the evacuation plan has not been inspected.

2.2 System of Evacuation Behavior

Evacuation behavior is also of two types: emergency evacuation, for protecting human life from emergency, such as fires and tsunami caused by earthquakes, and temporary evacuation, for making a living for the time being owing to the collapse and burning down of the house. In this study, we perform simulations by assuming a staged evacuation in which evacuees perform emergency evacuation behavior immediately after a disaster and thereafter evacuation toward shelters. According to emergency evacuation, evacuees should evacuate toward small temporary shelters first and then proceed toward evacuation areas. The evacuation sphere of evacuation areas is defined at about 2 kilometer and of the temporary shelter is defined at 0.5 kilometer.

3. Initial Condition of Wide-area Evacuation Simulation

3.1 Target Area

The target area in this study is the center of Otsu-city, Shiga Prefecture (Fig. 1). It is an area with high-density wooden city and a center for administrative and economic functions. There are also residents, workers, and visitors. The analysis is

performed for each district in the area.

3.2 Present Evacuation Plan of the Target Area

In the target area of Otsu-city, Shiga prefecture, the policy of evacuation behavior and establishment of evacuation facilities is provided according to the Otsu-city regional disaster prevention plan (Table 2). However, these policies are provided by merely using numerical life-threatening. Even though it is a policy of the basic disaster prevention plan proposed by the Cabinet Secretariat and does not consider whether it is adequate according to the number of evacuees and geographical condition [3]. The problems of the evacuation plan in the target area is as follows:

(1) The relationship between the number of evacuees and the location and capacity of shelters is not considered.

(2) There are districts that are out of the sphere of evacuation shelters (i.e., 0.5 kilometer) (evacuation difficult area) 4 (Fig. 2).

(3) The location of local shelters is not prescribed definitely (Fig. 4).

3.3 Assumption of Evacuees in the Target Area

In reference to the regional disaster prevention plan, in this study, we assume the simultaneous evacuation by earthquake and used the damage estimation of Otsu-city regional disaster prevention plan [5] to set the evacuees' initial condition.

In this study, the evacuees were local residents; workers, commuters, and visitors from outside areas were excluded. All the evacuees were to evacuate on foot; the number of temporary evacuees was set as 4,154 and that of accommodated evacuees [6] was set as 1,697. The maximum walking speed of evacuees was assumed to be distributed in the ratio of 1:3:1, 1.8 [m/sec], 1.5 [m/sec], 1.2 [m/sec], referring to the walking speed findings by Watanabe [8] and the analysis of evacuation behavior by Yokoyama [9].

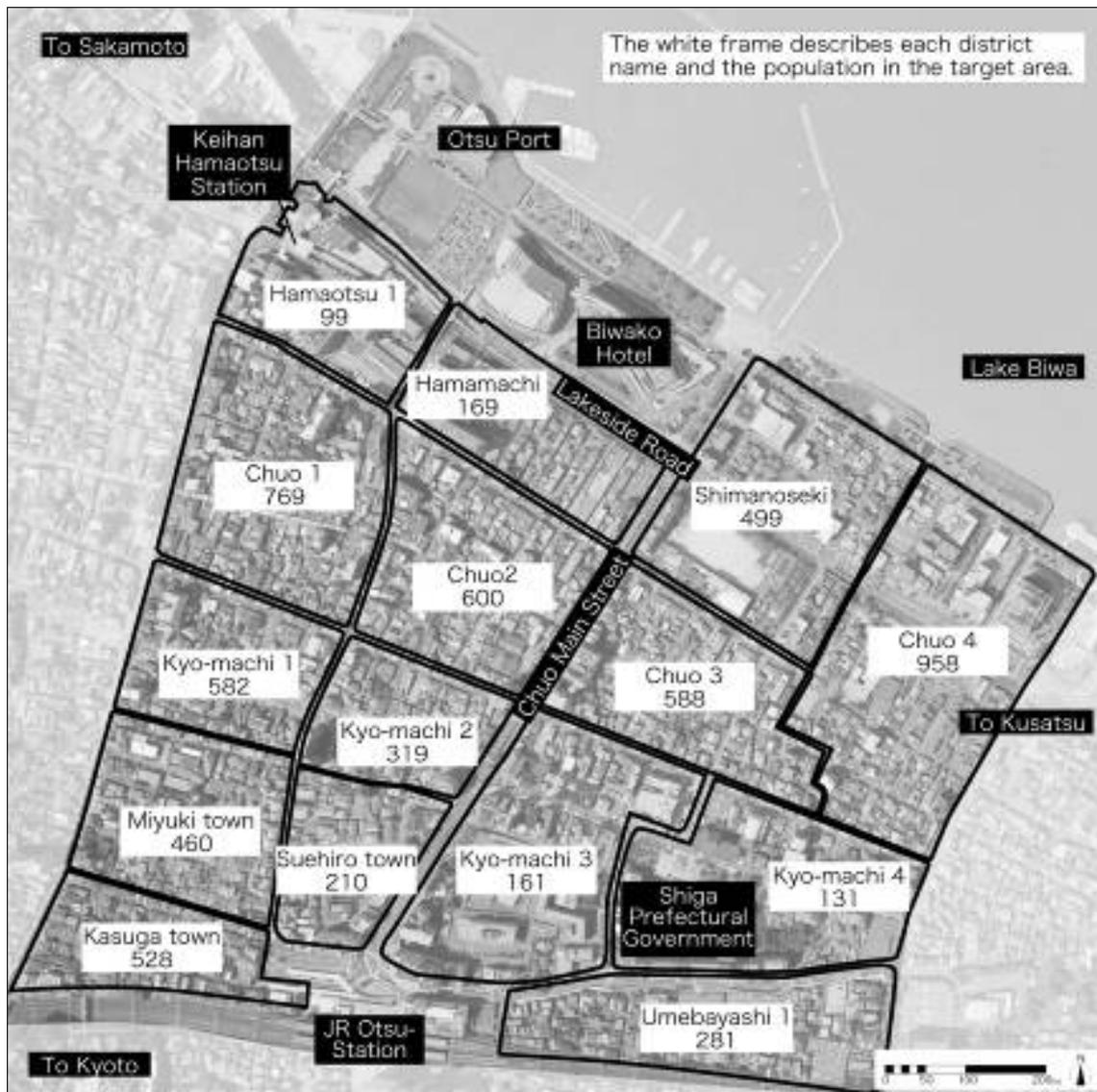


Fig. 1 Target area: district partition.

Table 2 The urban disaster prevention facilities plan in Otsu-city, Shiga Pref.

Classification of shelter	Evacuation area	(School district) shelter	Local shelter
Scale of facility	About 10 hectare or more	About 1 hectare or more	Optional
Evacuation sphere	Walk distance within 2 kilometers	Walk distance within 500 meters	Walk distance within 500 meters

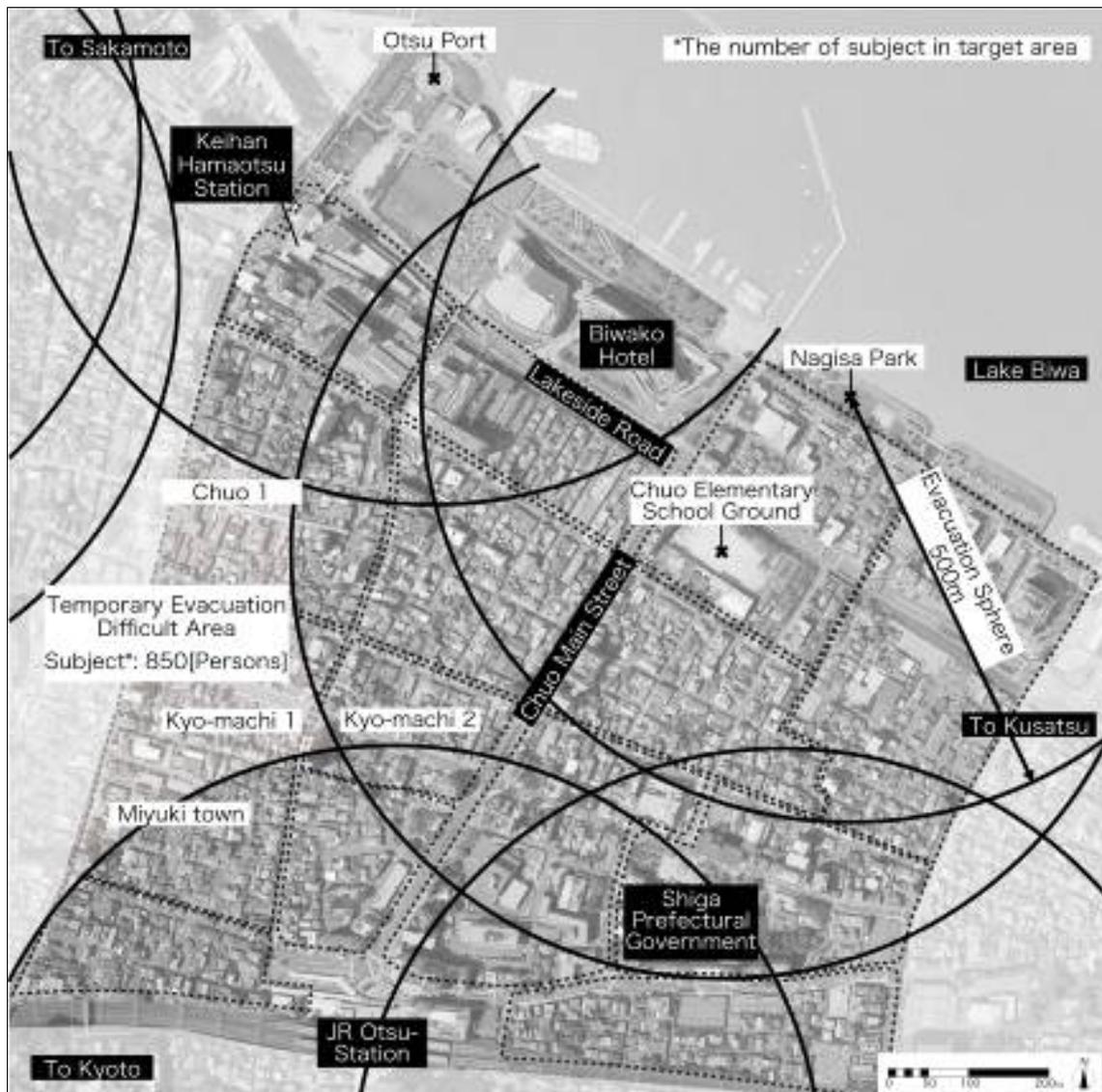


Fig. 2 Target area: evacuation sphere.

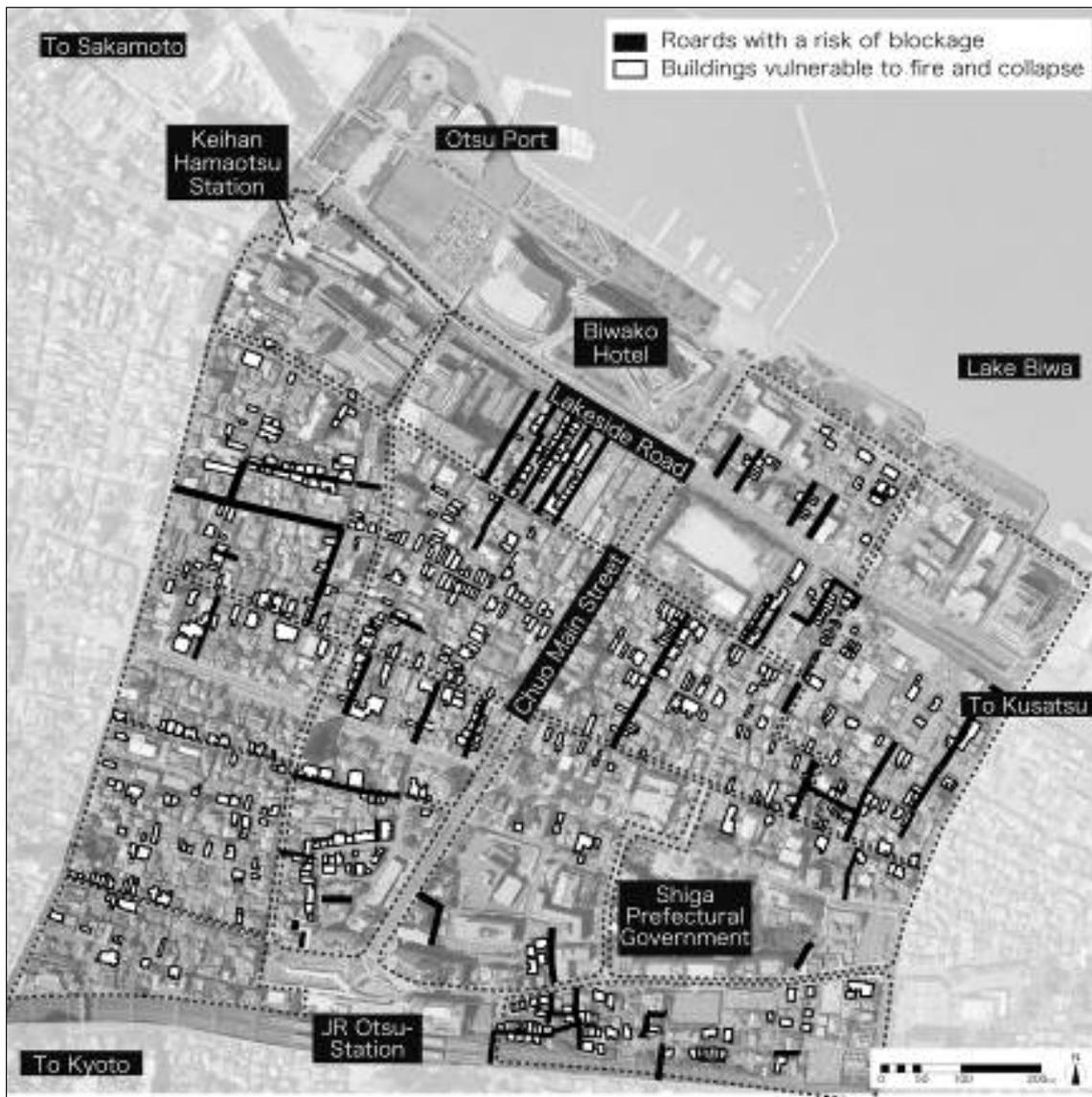


Fig. 3 Probable blockage road and buildings vulnerable to fire and collapse.

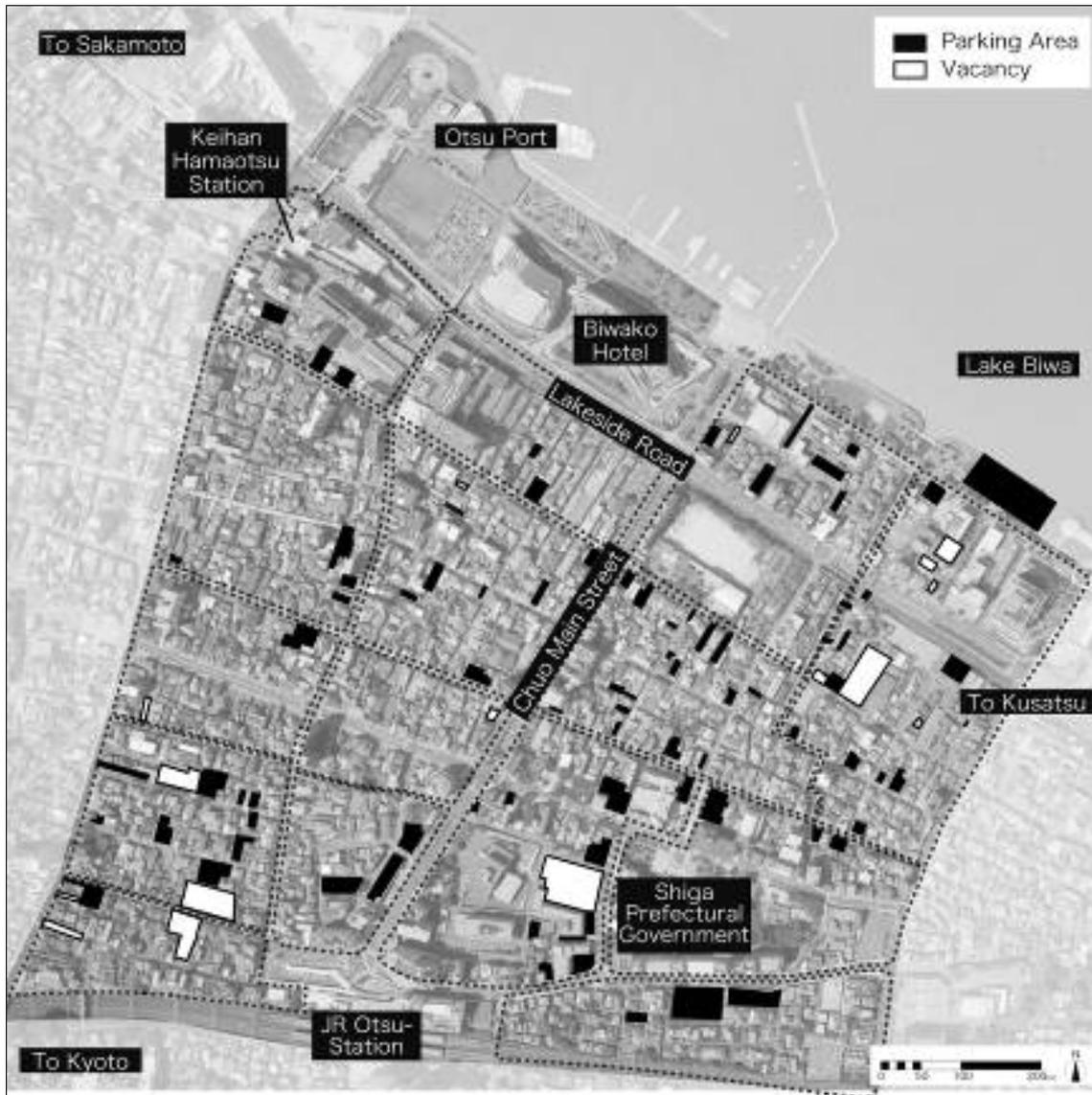


Fig. 4 Room spaces that can be shelters.

4. Construction of Risk Avoidance Behavior Model

4.1 The Definition of the Model

In wide-area evacuation simulations present in the existing research, optimum action is often regarded as evacuees evacuating all at once and taking the shortest path toward the destination. However, in reality, evacuees cannot move in the shortest path and in optimum patterns at the time of disaster because of psychological factors such that they want to avoid risk.

In this study, we incorporate the previously identified psychological factors and the behavior during disasters as risk avoidance behaviors such as the following two phenomena into the wide-area evacuation simulation to facilitate more realistic analysis and evaluation.

(A) The route re-seeking behavior: the evacuees' behavior of understanding the dangers in the place and the road blockage road during evacuation and then avoiding the route.

(B) The shelter re-selecting behavior: the evacuees' behavior of understanding the excess of shelter

capacity and then evacuating to another shelter using the knowledge of the road.

Each process of the behavior is described in Table 3.

4.2 Modeling of Risk Avoidance Behavior

The pedestrian behavior simulation in this study was performed in CAAD⁷. The construction of discrete space geodata for simulation calculation and the model of evacuation behavior considering anxiety are based on SimTread Plug-in program, which can accumulate all sequential position of agents. The multi-agent pedestrian model developed in this study consists of a simulation field and agents that are influenced by the field. The agents are set conditions of anxiety as risk avoidance behavior, such as “the route re-seeking behavior” and “the shelter re-selecting behavior.” The former is defined as walking continuously at the speed of 0.2 meters per second for 6.0 meters, while the latter is defined as walking continuously at the speed 0.5 meters per second for 15.0 meters.

4.3 Fieldwork on Road Blockage in the Target Area

During the Great Hanshin-Awaji Earthquake, which occurred on January 17, 1995, many buildings collapsed and the debris caused road blockages, which made it difficult for pedestrians and cars to pass and had a profound impact on post-earthquake rescue, firefighting, and evacuation activities. Such road blockages can cause difficulties for pedestrians and be considered life-threatening. Therefore, even though a road with such blockages might be the shortest route to a destination, most evacuees experience anxiety and select another route. Analysis of the roads blocked during the Great Hanshin-Awaji earthquake has revealed that road blockages are likely to occur on roads whose width is 4.0 m or less (Fig. 5).

There is a residual width that indicated the degree of traffic difficulty caused by road blockages resulting from collapse of walls (Fig. 6). The residual width is obtained by subtracting the height of walls that can

collapse from road width and indicates the width which pedestrians can pass after the collapse of walls. In this study, the residual width is represented as D' and calculated in the following cases (Fig. 7).

We conducted a fieldwork and identified roads that were likely to be closed. Therefore, for all the roads in the target area, we understood the present condition of road widths, existence and position of walls facing the road, and characteristics of the area. During the fieldwork, we calculated the road width and the height of the walls from a scale of 30[cm]. We also plotted the location and material of the walls on map through visual observations (Fig. 8).

From the fieldwork, we found three types of roads: (1) those with 4.0 [m] or less width; (2) those with arcades that are likely to collapse; and (3) those with stairs.

We designated 33 of these roads (total distance is 2,200 [m]) as the blockage evacuation route. In the wide-area simulation model, we expressed anxiety behavior by prohibiting the passage of evacuees through the route and building the model that they re-select another evacuation route.

The model can separate the relation between the road width and the risk avoidance behavior based on the case of the Great Hanshin-Awaji Earthquake (Table 4).

5. Trial of Wide-Area Evacuation Simulation

5.1 Construction of Geomodel

The simulation field was constructed using JPGIS data from the base map information data compiled by the Geospatial Information Authority of Japan, which is converted and transformed by computer (Fig. 11). In addition, it was also used to set the conditions of road blockage. Although the difference in height should be considered normally, we set all the geomodels on 0 altitudes. The trial of simulation considering the pedestrian loads by difference in height should be performed in further research.

Table 3 Rules of MA model's sequential behavior based on risk avoidance behavior.

	Model Diagram	Agent Behavior	Numerical Criteria		
i		① Keep walking speed U and head to the destination.	$U=1.2, 1.5$ or $1.8(m/s)$		
		② Keep walking speed U and select the shortest route towards the destination(D1).	$U=1.2, 1.5$ or $1.8(m/s)$		
		③ Complete evacuation.	—		
ii		① Keep walking speed U and head to the destination.	$U=1.2, 1.5$ or $1.8(m/s)$		
		② Slow down walking speed to U and avoid the impassable area. (Expression of the route re-seeking behavior)	$U=0.2(m/s)$		
		③ Keep walking speed U and select the shortest route towards the destination(D1).	$U=1.2, 1.5$ or $1.8(m/s)$		
		④ Complete evacuation.	—		
iii		① Keep walking speed U and head to the destination.	$U=1.2, 1.5$ or $1.8(m/s)$		
		② Slow down walking speed to U and avoid the impassable area. (Expression of the route re-seeking behavior)	$U=0.2(m/s)$		
		③ If the capacity of D1 is excess, slow down the speed to S to re-choose the route and head to next destination(D2).*	$S=0.5(m/s)$		
		④ Keep walking speed U and head to the destination.	$U=1.2, 1.5$ or $1.8(m/s)$		
		⑤ Complete evacuation.	—		
		⑥ If the capacity of D2 is excess, slow down the speed to S to re-choose the route and head to next destination(D3).*	$S=0.5(m/s)$		
		⑦ Complete evacuation.	—		
Outline of simulation field (evacuation space) *(Expression of the shelter re-selecting behavior)					
iv		Status	Legend	Rule that prescribes the Agent Behavior	Numerical Criteria
		Sta.0		Keep walking speed U .	$U=1.2, 1.5$ or $1.8(m/s)$
		Sta.1		Show the forward dangerous area (Sta.4) to the agent.	$U=1.2, 1.5$ or $1.8(m/s)$
		Sta.2		Restore the walking speed to U .	$U=1.2, 1.5$ or $1.8(m/s)$
		Sta.3		Slow down the walking speed to U .	$U=0.2(m/s)$
Sta.4		Prohibit the entry of the agent.	—		
※Divide the walking space into cells for the sake of convenience					

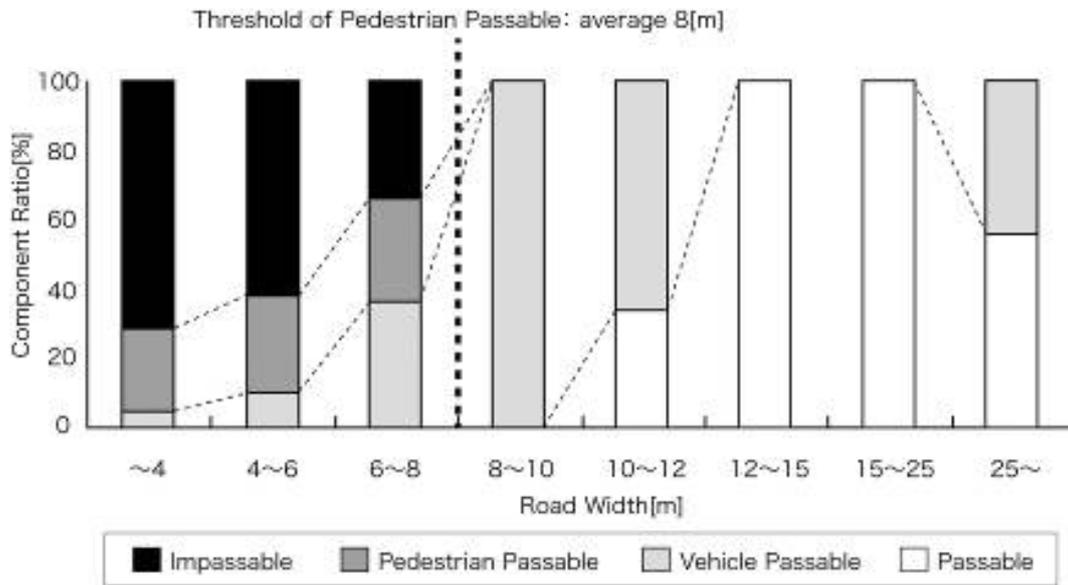


Fig. 5 Width of blockage road and traffic condition at the Great Hanshin-Awaji Earthquake.

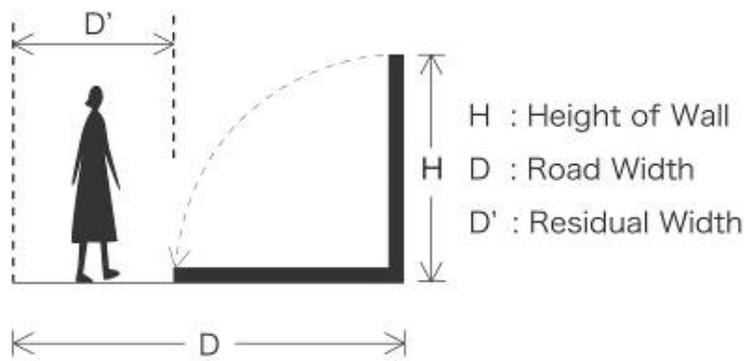


Fig. 6 The conceptual diagram of residual width.

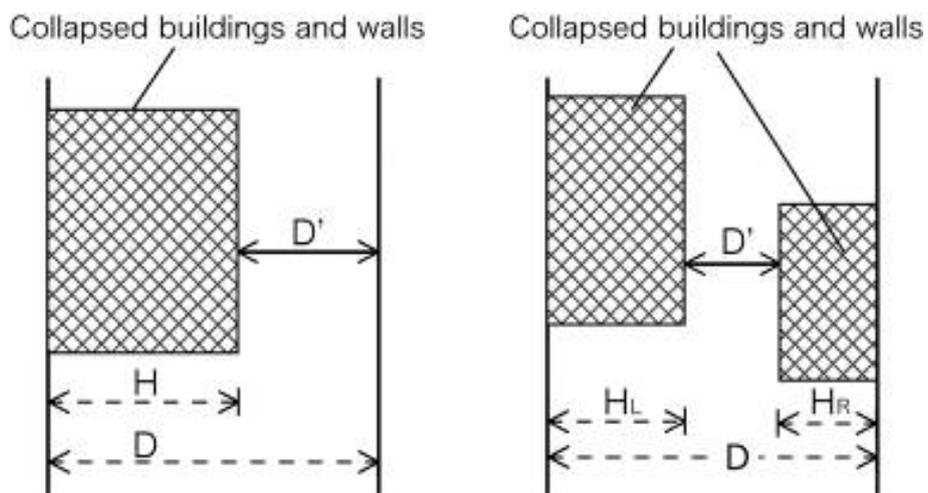


Fig. 7 Calculation method of residual width.



Fig. 8 The findings of fieldwork.

Table 4 Correlation of road width and risk avoidance behavior.

Road width D [m]	Type of road	Risk avoidance behavior
$8 \text{ m} \cong D$	A road whose width that are predicted to be capable of vehicle traffic even after the collapse of walls.	No
$6 \text{ m} \cong D < 8 \text{ m}$	A road whose width that can be a disaster prevention road.	No
$4 \text{ m} < D < 6 \text{ m}$	A road whose width that is not a narrow road, but also cannot be a disaster prevention road.	No
$D \cong 4 \text{ m}$	A narrow road that is predicted to be obstructed completely at the time of collapse of walls.	Yes

Table 5 Conditions of each simulation case.

	Case 1	Case 2	Case 3	Case 4	Case 5
	Verification of shelter capacity	Consideration of shelter re-selecting behavior	Consideration of route re-seeking behavior	Addition of shelters	Addition of shelters and consideration of re-seeking behavior
Evacuation style	Directly	Stage	Stage	Stage	Stage
Accommodate evacuees*	5,851	1,697	1,697	1,697	1,697
Temporary evacuees*	—	4,154	4,154	4,154	4,154
Shelters	6	6	6	6	6
Evacuation space	—	3	3	21	21
Road blockage set	—	—	○	—	○

(Unit: *Persons)

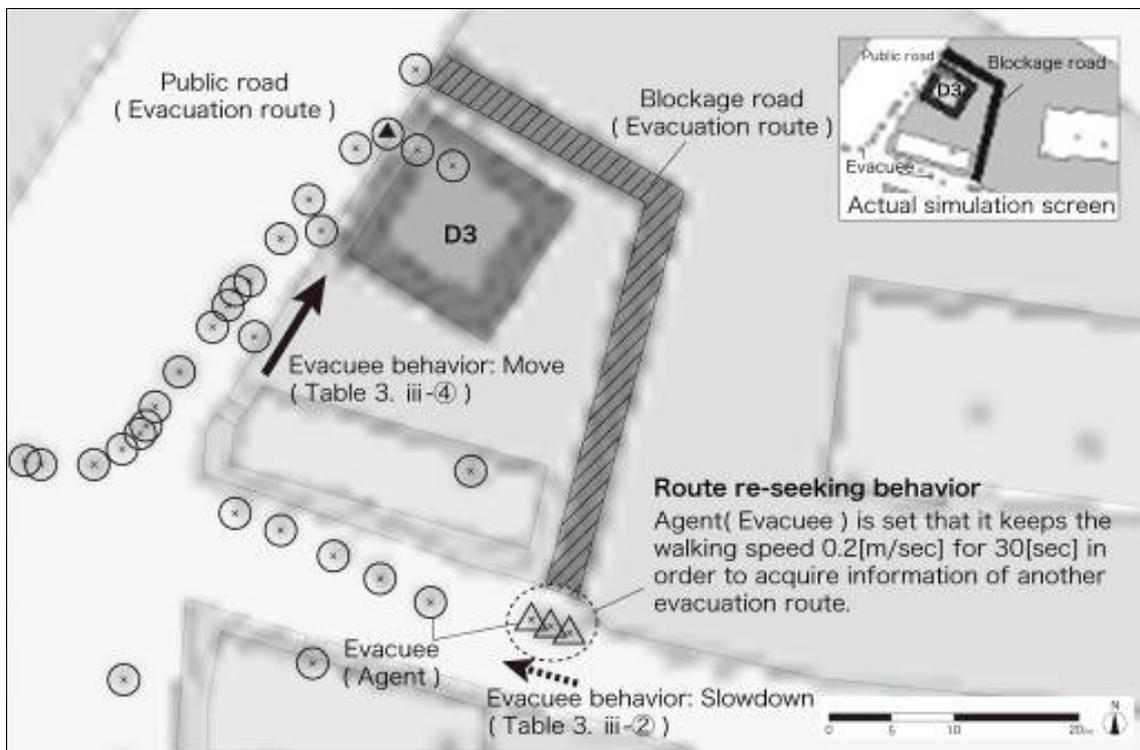


Fig. 9 Route re-seeking behavior of MA model.

5.2 Results for Each Simulation Case

By changing the following five conditions, the simulation was practiced in 5 cases, shown in Table 5.

- (1) Whether evacuees undertake the staged evacuation or not;
- (2) Whether evacuees evacuate temporary or long-term;
- (3) The number of designated shelters prescribed by the regional disaster prevention plan;
- (4) The number of undesignated shelters provided through private spaces;

- (5) The existence of a set of road blockage.

5.2.1 Verification of the Shelter Capacity

Regarding the rate of incomplete evacuation [10], the rate in districts located in the south of the target area was high (Fig. 11). However, since the median distance of evacuation in these districts did not exceed 500 [m], this suggested that the shelters were insufficient relative to the surrounding population (Fig. 12). On the other hand, since the rate of incomplete evacuation in Shimanoseki-district was extremely low, we found that the capacity of nearby shelters was

considerably relative to the surroundings. From such verifications of case 1, it can be concluded that the consideration of the relation between the shelter capacity and the surrounding population is insufficient in the present regional disaster prevention plan.

5.2.2 Comparative Examination of Distance and Time of Evacuation

In cases 2 and 3, there were many districts whose median distance of evacuation exceeded the recommended evacuation sphere 500 [m], and the maximum excess of 445 [m]. Regarding the difference between the evacuation sphere, the maximum

difference was 429.52 [m] between cases 3 and 4. The maximum of that of each district was 784.65 [m] in Miyuki-district (in cases 3 and 5). This corresponds to 585 seconds. Thus, the present regional disaster prevention plan is inadequate and there is a need for increasing the number of shelters.

5.2.3 Comparison of the Frequency of the Shelter Re-Selecting Behavior

Regarding the average of the frequency of shelter re-selecting behavior, shown in Fig. 13, we found that the frequency in nearby areas with sufficient capacity of shelters was lower than those in other areas.

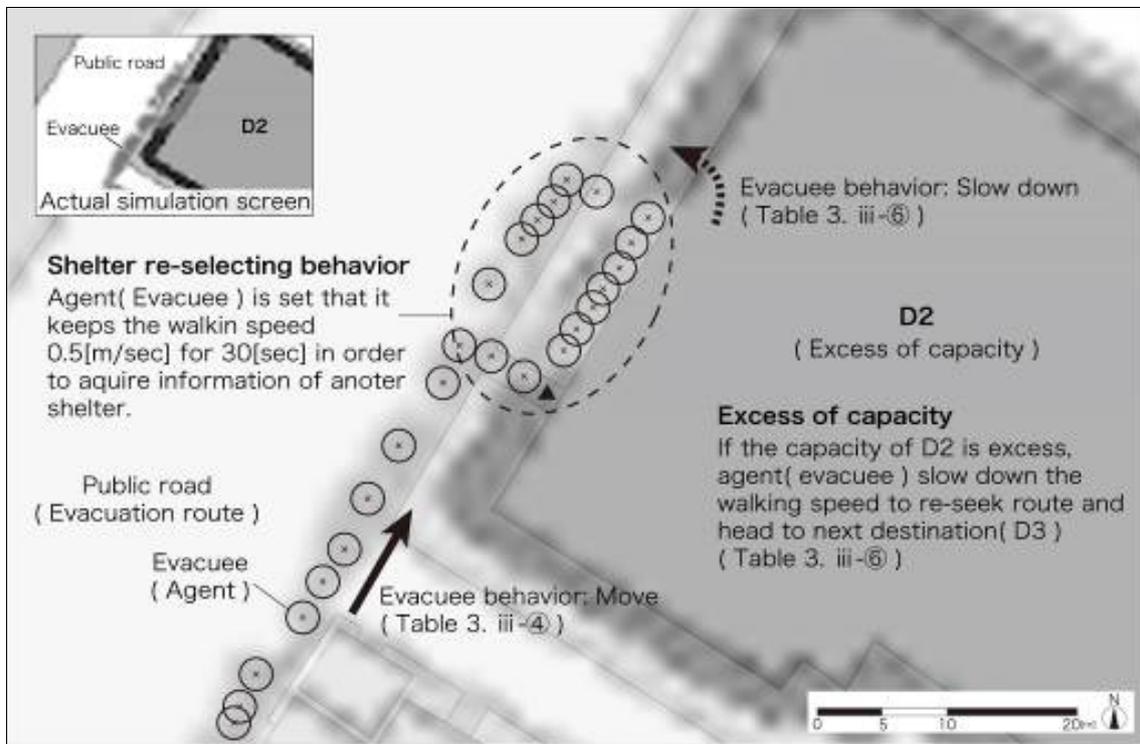


Fig. 10 Shelter re-selecting behavior of MA model.

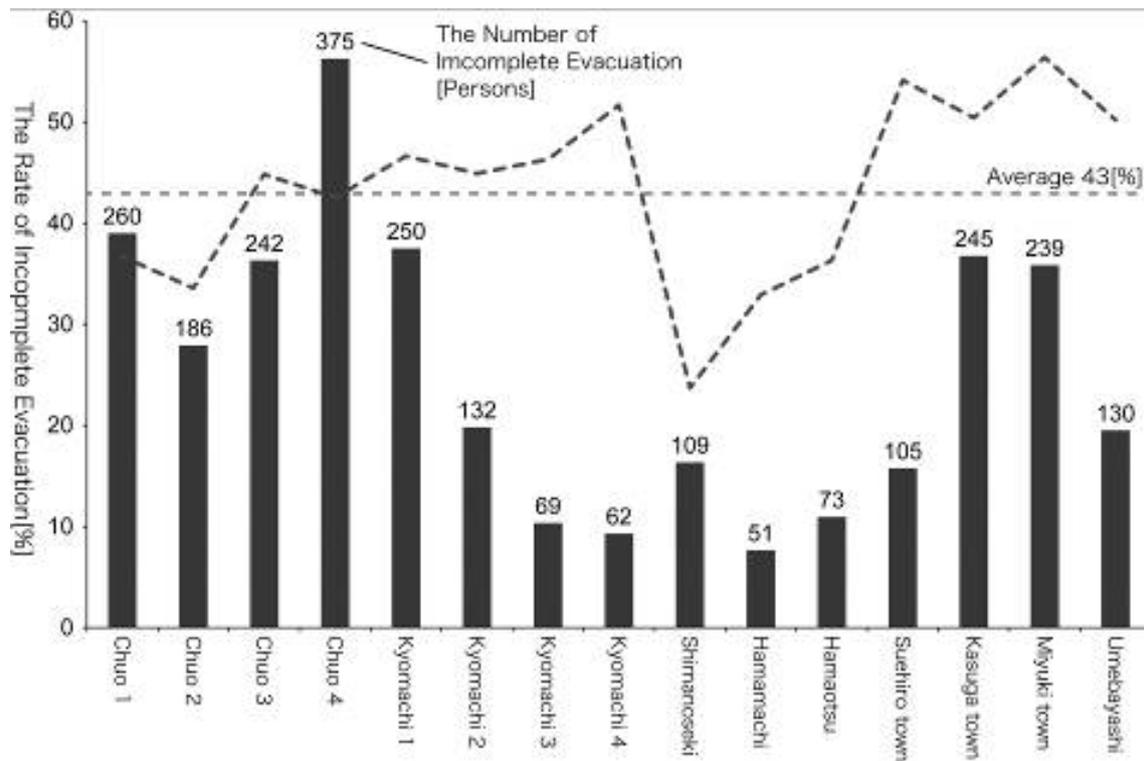


Fig. 11 The number and rate of incomplete evacuation.

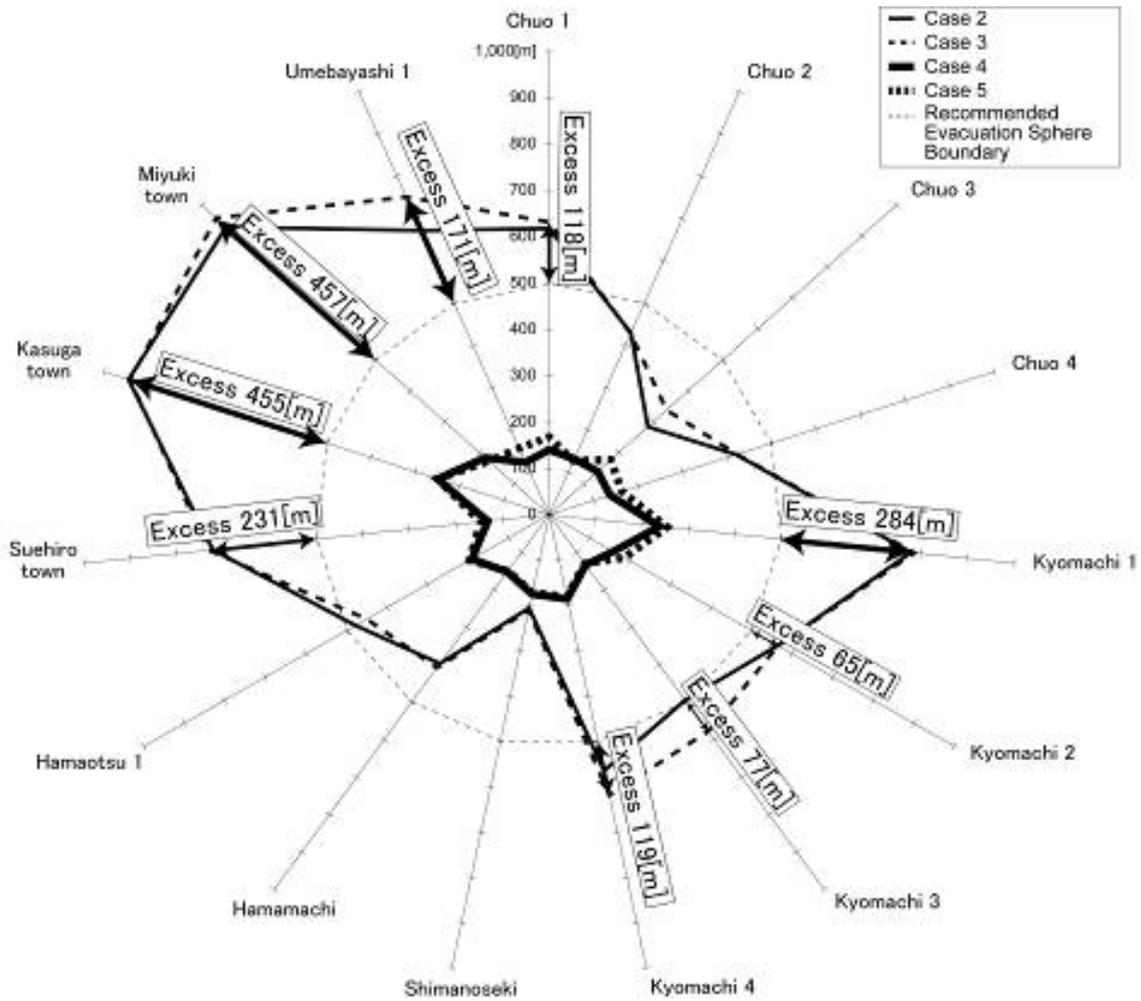


Fig. 12 The median distance of evacuation in each district and case.

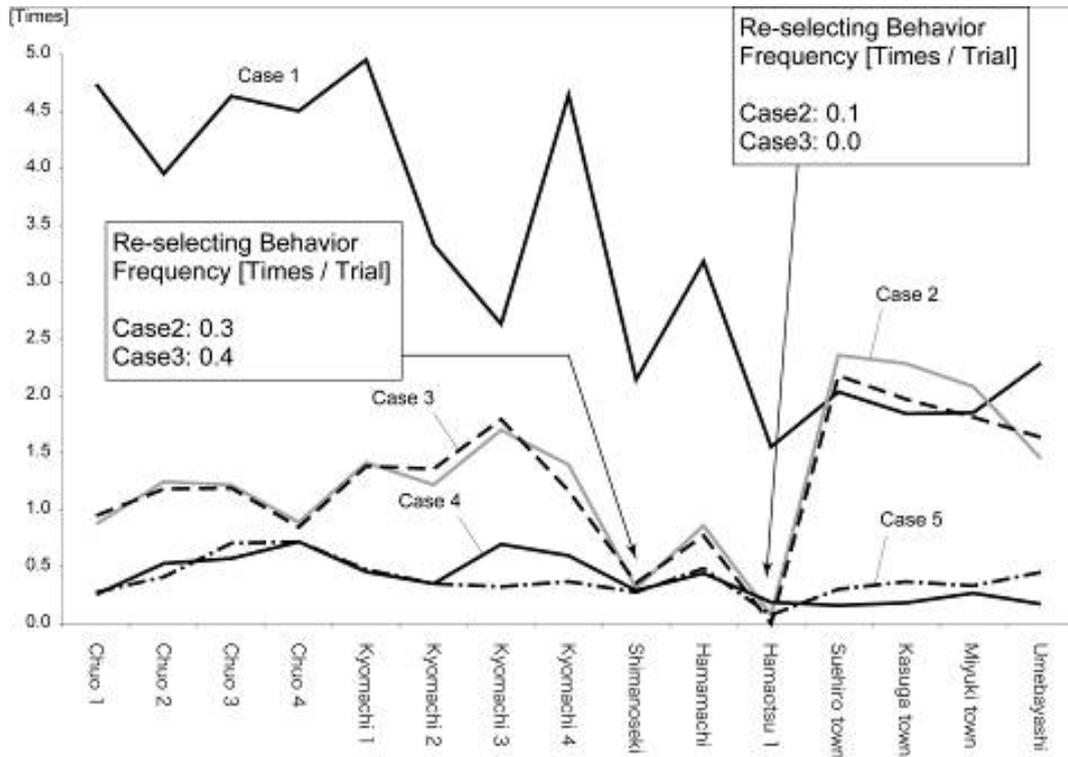
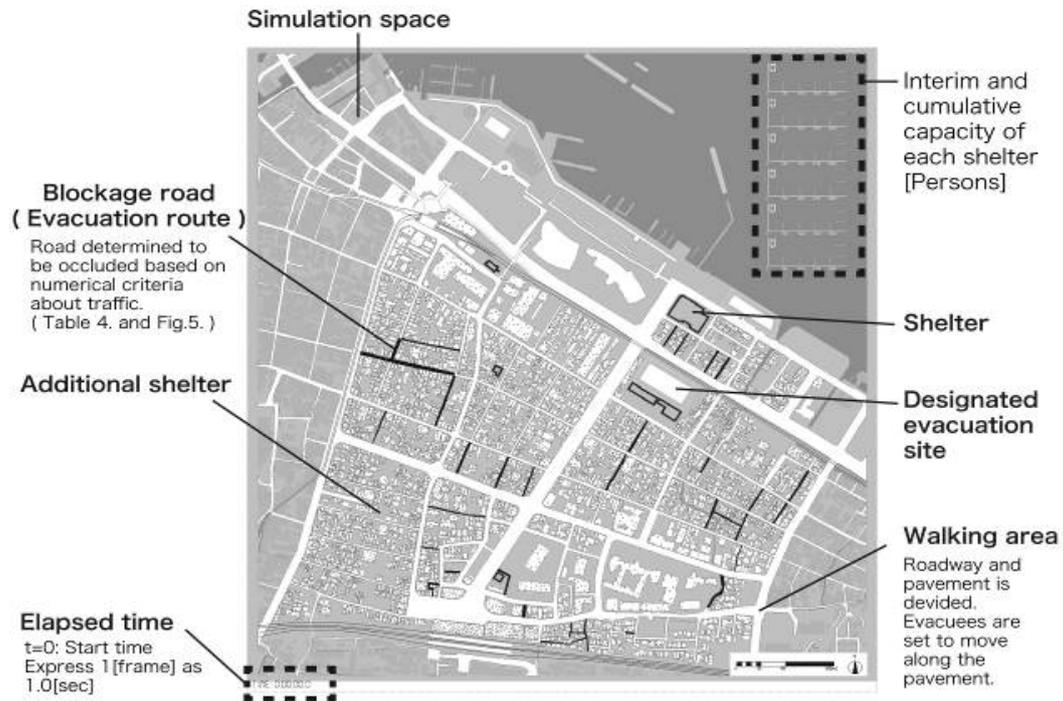


Fig. 13 Comparison of frequency of shelter re-selecting behavior in each district and case.



The above shows the analysis output screen on the simulation platform. Evacuees start the evacuation towards the designated shelter from each dwelling unit at $t = 0$. After that the simulation expresses in turn the result of selecting evacuation route, taking risk avoidance behavior and shelter re-selecting behavior.

Fig. 14 Positional relation of shelter and elements.



Fig. 15 Capture of evacuation sequential video (case 1).

6. Conclusion

6.1 Accomplishment

This study developed a model that incorporates anxiety as a risk avoidance behavior, making wide-area evacuation simulation more realistic and useful. The specific contents of an evacuation plan were comprehended with the visible model, revealing that the present evacuation plan is inadequate. The implementation of a simulation that incorporates the staged evacuation, evaluation, and analysis of the present evacuation plan are also accomplishments of this study.

6.2 Further Research

The wide-area simulation in this study facilitates the change of conditions and the understanding of each evacuation behavior visually. The model developed in this study can help understand evacuation routes using digital devices by gathering optimum evacuation plans as animations and opening them via the Web, making it a useful tool for evacuation support. On the other hand, the numerical criteria of anxiety behavior should be profoundly considered by actual detailed questionnaire on evacuation behavior at the time of disaster. The authors will certainly direct their further research toward this.

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Notes

1. In 2000, the building standard was revised as low for the performance provisions of fire prevention standards. If a building is verified that it is enough for evacuation safety performance, a part of the evacuation provisions are excluded

from it. For computer simulations and testing safety by considering evacuation behaviors, refer to “Route C,” which is a technique for evaluating the evacuation safety performance of buildings without a prescribed calculating formula.

2. In this study, we use SimTread2 provided by A&A Co., Ltd. as the pedestrian simulation platform.

3. Through talking with the disaster crisis management office of Shiga, we found out the present problems in wide-area disaster prevention. In addition, we performed a team “examination on evacuation plan study group”, whose members belonged to the crisis disaster prevention division and building guidance division of Otsu-city as well as Hideaki Takayanagi laboratory at the University of Shiga Prefecture; they shared information that must be considered while implementing measures. It was held on May 29, June 20, July 11 and December 4, 2013.

4. The rate of temporary evacuation difficult area is obtained by dividing the square measure of it by the square measure of the target area. The rate of the target area is 10 %.

5. In this study, for damage estimation, we used the earthquake caused by the fault zone of Lake Biwa at the west coast, which was assumed by the regional disaster prevention plan in Otsu-city, Shiga prefecture.

6. The number of temporary evacuees is calculated using the following formula.

$$\sum E_T = \sum P \times R_p$$

E_T : the number of evacuees in each district

P : the population of each district

R_p : the ratio of the population between day and night

The number of accommodated evacuees is obtained using the following formula, where R_S is the ratio of evacuees who evacuate long-term because of lost houses; in this study, $R_S = 29\%$, which is equal to the value obtained for the South Hyogo Earthquake.

$$\sum E_S = \sum E_T \times R_S$$

E_S : the number of accommodated evacuees in each district;

E_T : the number of temporary evacuees in each district;

R_S : the rate of the shelter habitants.

7. In this study, we used Vectorworks2013 provided by Nemetschek Vectorworks, Inc. as the simulation platform. We also prepared the environment of the agent simulation using

Vector Script and built the model.

8. The rate of incomplete evacuation is obtained by dividing the number of incomplete evacuation by the number of evacuees.

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