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TSUNAMI EVACUATION SIMULATION CONSIDERING BUILDING COLLAPSE AND FIRE SPREAD

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Abstract. *The objective of this study is to develop a tsunami evacuation simulation system that takes into account building collapse and fire spread. Road blockage is determined by calculating the road blockage probability due to building collapse, taking into account the size of the assumed earthquake, location of buildings, and type of building. For fire spread simulation, an existing simulator based on the fire spread rate equation is used. Under average wind direction and speed conditions for the target area, arbitrary fire points are set up and fire spread is represented using fire times for each building obtained from the simulation. The applicability of this system as a scenario is extended. The present system is applied to several examples to demonstrate the validity and effectiveness of the system.*

1 INTRODUCTION

Japan has an extremely high frequency of earthquakes, and tsunami damage is a major secondary disaster. The Great East Japan Earthquake of 2011, which caused extensive damage by tsunami, has raised awareness of the limitations of hardware measures such as the construction of breakwaters. Therefore, in the event of a major disaster such as a Level 2 disaster as defined by the Cabinet Office, flexible measures in terms of both hardware and software are required. As one of the soft measures, each municipality has prepared hazard maps. However, the drawback of hazard maps is that it is not easy to understand at a glance when and how to evacuate. T Therefore, in recent years, evacuation simulation methods have been widely studied to facilitate understanding of evacuation and to examine human damage.

In our previous study [1], we have developed a tsunami evacuation simulation based on a multi-agent system. We have tried to improve the applicability of the simulation by adding factors to be taken into account for evacuees during evacuation actions. However, the blockage of evacuation routes has not been taken into account, and the applicability of the system as a scenario has been an issue.

In this study, we developed a tsunami evacuation simulation system that takes into account the collapse of buildings and the spread of fire caused by an earthquake in contrast to the authors' previous simulation method [1]. In order to verify the applicability of the system, we applied it to an area where tsunami damage from a Nankai Trough earthquake is expected.

2 SIMULATION METHOD

In this study, simulation is performed according to the flow shown in **Figure 1**.

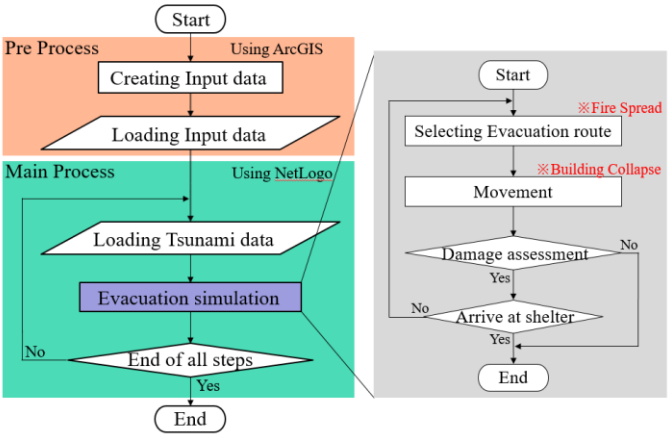


Figure 1: Evacuation simulation flow

2.1 Creation of topographic data

Based on the data provided by the Geospatial Information Authority of Japan (GSI), geographic information data is created using ArcGIS: simulation range, initial location of evacuees, shelters, evacuation routes and nodes.

2.2 Tsunami simulation

Based on the created topographic data, a tsunami simulation using the stabilized finite element method with the shallow water flow equations [2] was performed.

The initial condition for the tsunami was the amount of water level fluctuation calculated from the tsunami fault model4 provided by the Central Disaster Prevention Council; the condition that causes the maximum tsunami damage in the area.

2.3 Evacuation simulation

When it is time to start evacuation, the evacuee moves to the node with the shortest distance from the initial position. After that, evacuee calculates the utility S for each adjacent node based on the gravity model shown in Equation (1), and select the node with the largest S to move to.

$$S = \frac{a}{s^{\alpha}} - \frac{b}{z^{\beta}} - \frac{c}{w^{\gamma}} - \frac{d}{f^{\delta}} \tag{1}$$

S is the utility, s is the distance to the shelter, z is the elevation, w is the distance from the waterline, and f is the distance to the fire point. a, b, c, and d are weights for the variables; the larger the value, the larger the share in the utility. α, β, γ, and δ are the influence of spatial distance on the variables; the smaller the value, the farther away the variable affects.

3 ROAD BLOCKAGE BY BUILDING COLLAPSE

There is concern about the impact on evacuation routes due to building damage caused by earthquakes. The probability of road blockage due to building collapse is calculated and considered as a factor affecting the walking speed of evacuees. The following assumptions are made in calculating the road blockage probability.

- Buildings should always face each other across the street.
- The probability density function with respect to the debris width when the building is completely destroyed is assumed to be normally distributed.
- Collapses of buildings occur independently of each other without affecting each other.
- The road blockage probability is calculated for each created node, not for each fixed section.

The width of the road was three meters, which allows pump trucks to pass through.

3.1 Calculation of road blockage probability

The road blockage probability due to building collapse is calculated based on the method presented by the Tokyo Fire Department in 2015 [3]. The road blockage probability p for each node is calculated using Equation (2) under the building placement shown in **Figure 2**.

$$p = 1 - \{(1 - x_w)^{\alpha_w} \cdot (1 - x_m)^{\alpha_m} \cdot (1 - x_p)^{\alpha_p} \cdot (1 - y_w)^{\beta_w} \cdot (1 - y_m)^{\beta_m} \cdot (1 - y_p)^{\beta_p}\} \quad (2)$$

The variable x indicates the road blockage probability between a pair of front facing buildings, and y indicates the road blockage probability between a pair of diagonally facing buildings. The subscript w indicates the combination of wooden buildings, m indicates the combination of wooden and non-wooden buildings, and p indicates the combination of non-wooden buildings. For details on these probabilities, please refer to references [4,5,6]. **Figure 3** shows the calculated road blockage probability in the target area.

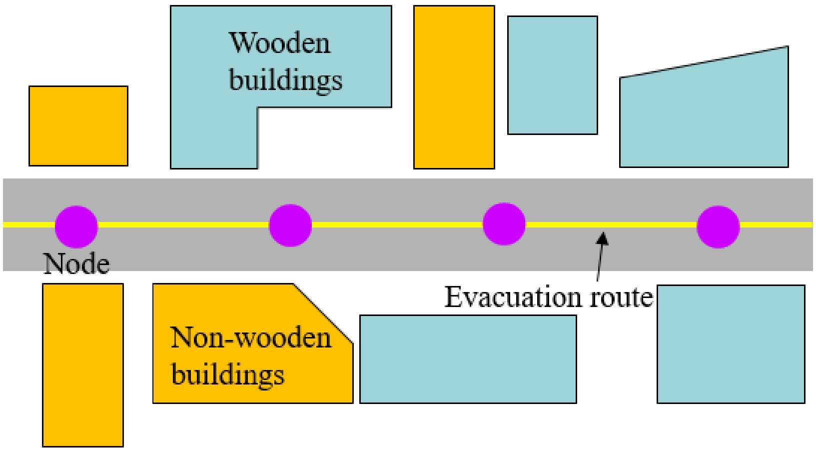


Figure 2: Example of building placement

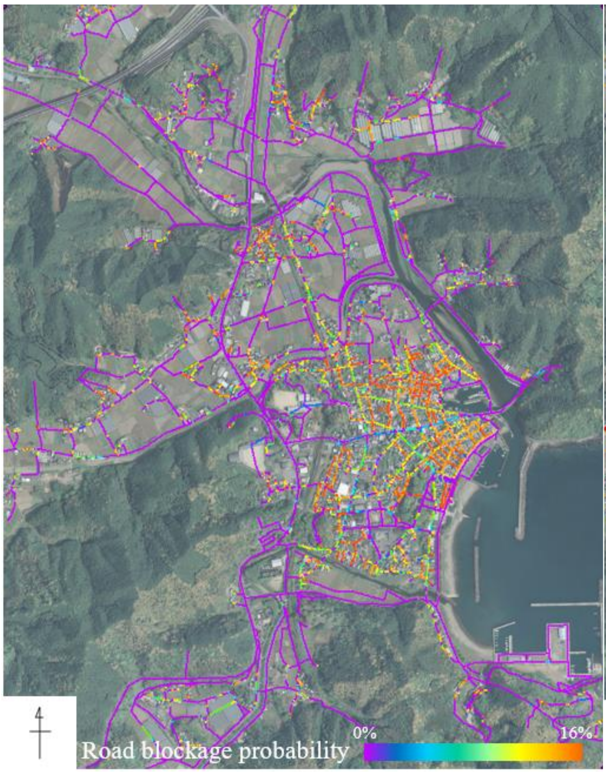


Figure 3: Road blockage probability

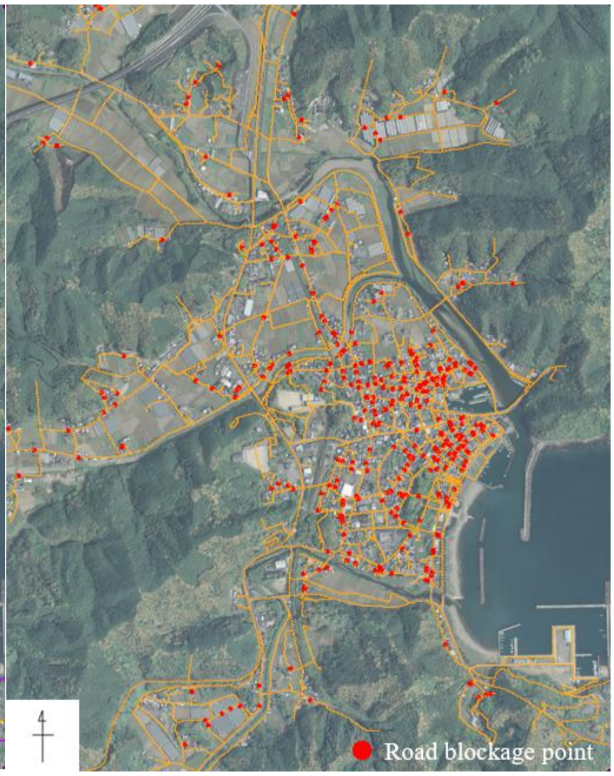


Figure 4: Road blockage points

3.2 Speed reduction due to road blockage

The nodes where road blockage due to building collapse occurs were selected from nodes with road blockage probability. The calculation results are shown in **Figure 4**. When encountering a blocked evacuation route, it is assumed that the evacuee does not take evasive action. The Evacuee passes through the blocked evacuation route, and the speed reduction due to get over the debris is taken into account [7]. In this study, the speed reduction rate obtained from the results of a tsunami evacuation drill conducted in the Kaminokae area of Nakatosa Town, Kochi Prefecture [8] is assigned to each age group to allow passage through a blocked road (**Table 1**).

Table 1: Walking speed reduction rate

Age	Walking speed [m/s]		Speed reduction rate
	Male	Female	
~14	1.33	1.29	0.75
15~34	1.47	1.44	0.63
35~54	1.39	1.36	
55~64	1.41	1.46	
65~74	1.32	1.48	0.52
75~84	1.04	1.32	
85~	0.39	0.62	

4 FIRE SPREAD SIMULATION

4.1 Examination of fire point

The fire rate and total number of fires are calculated using Equations (3) to (6), referring to the method proposed by the Cabinet Office [9]. The obtained value is the maximum number of fires in the target area.

- Total number of fires

$$\sum \text{Number of fires} = \text{Number of buildings} \times \text{Fire rate} \tag{3}$$

- Fire rate from general fire apparatuses

$$\text{Fire rate} = 0.0022 \times \text{Building destruction rate}^{0.73} \tag{4}$$

- Fire rate from electrical heating appliances

$$\text{Fire rate} = 0.0043 \times \text{Building destruction rate}^{0.73} \tag{5}$$

- Fire rate from electrical equipment and wiring

$$\text{Fire rate} = 0.00036 \times \text{Building destruction rate}^{0.73} \tag{6}$$

The total building destruction rate is 40% for wooden buildings constructed before 1981 and 12% for non-wooden buildings, and 10% for wooden buildings constructed after 1981 and 4% for non-wooden buildings. In this study, the total number of buildings subject to fire spread was assumed to be 3558 (3390 wooden buildings and 168 non-wooden buildings). The total number of fires calculated by Equations (3) to (6) is shown in **Table 2**. The fire points were randomly set with reference to the total number of fires calculated, and in this study, five wooden buildings were selected.

Table 2: Walking speed reduction rate

		Buildings before 1981	Buildings after 1981	Total
Wooden buildings	Number of buildings	1695	1695	3390
	Number of fires	5.9566	2.1652	8.1218
Non-wooden buildings	Number of buildings	0	168	168
	Number of fires	0	0.1099	0.1099

4.2 Fire spread simulation

Fire spread simulation is performed using an existing fire spread simulator [10,11] based on the fire spread rate equation. The fire spread rate equation considers eight directions: downwind, downwind 45 degrees, upwind, upwind 45 degrees, and lateral to the wind direction. The fire spread rate equations for the downwind, upwind, and lateral directions are shown below (Equations (7) to (9)). The V_1, V_2, and V_3 are fire spread velocities relative to wind direction, a

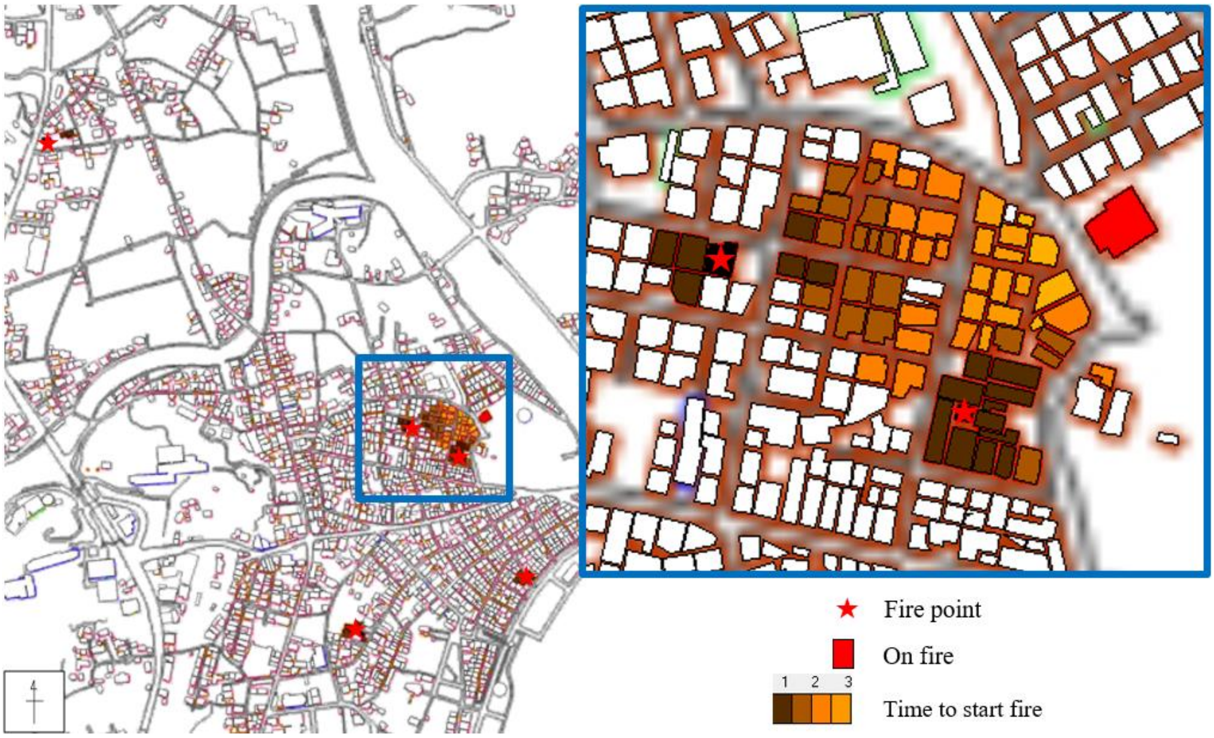


Figure 5: Fire spread simulation results

is building length, d is the distance between adjacent buildings, D_1, D_2, and D_3 are critical fire spread distances, W is wind speed, c_1, c_2, and c_3 are coefficients, and N is the fire spread velocity ratio. For details of each value, please refer to the references [10,11].

The number of fires and fire points are taken from the previous section to be five wooden buildings. Based on 2020 weather data around the target area, the wind direction was set to west. To confirm the applicability of the system by considering fire spread, a wind speed of 2 m/s, which is the average wind speed in the target area, is used. The fire spread simulation is shown in **Figures 5**.

- Upwind direction

$$V_1 = N\frac{1 + 0.1W + 0.007W^2}{c_1 + c_2 a + c_3 d/D_1}(a + d) \tag{7}$$

- Downwind direction

$$V_2 = N\frac{1 + 0.1W + 0.002W^2}{c_1 + c_2 a + c_3 d/D_2}(a + d) \tag{8}$$

- Lateral direction

$$V_3 = N\frac{1 + 0.1W + 0.005W^2}{c_1 + c_2 a + c_3 d/D_3}(a + d) \tag{9}$$

5 APPLICATION EXAMPLES

Using the above methods, a tsunami evacuation simulation was performed considering building collapse and fire spread due to an earthquake. The target area is Kure District, Nakatosa Town, Kochi Prefecture, Japan, and the Nankai Trough Earthquake Fault Model Case 4 is assumed. In order to compare the simulation results with those of previous studies, three simulation cases are conducted: one with two factors of road blockage and tsunami, one with two factors of fire spread and tsunami, and one with three factors of road blockage, fire spread, and tsunami. Note that this study does not consider damage caused by fire. All factors that contribute to victims are damage caused by tsunami.

5.1 Simulation conditions

The simulation area was set to 2652 m north-south and 2076 m east-west. Evacuees were assumed to be 2650 walking evacuees (considering walking speed by age and sex, crowd speed, slope speed, weight by age and sex, evacuee fatigue, avoidance of flooded evacuation routes, classification of shelters, and speed reduction at road blockage points). Shelters were 25 locations that were indicated in the hazard maps of the target area. From the previous chapter, the number of road blockages were set to 349, the number of fires and fire points were set to five wooden buildings, and the time of fire was set to 0 minutes after the earthquake. In consideration of fire spread, evacuees were advised to stay out of 10 m radius around the building where the fire started. The simulation was run with the start time of the evacuation set to 0 minutes after the earthquake.

5.2 Simulation results

First of all, **Figure 6** shows a comparison of the number of victims from the simulation runs considering each of the previous studies, building collapse and tsunami, fire and tsunami, and building collapse, fire, and tsunami.

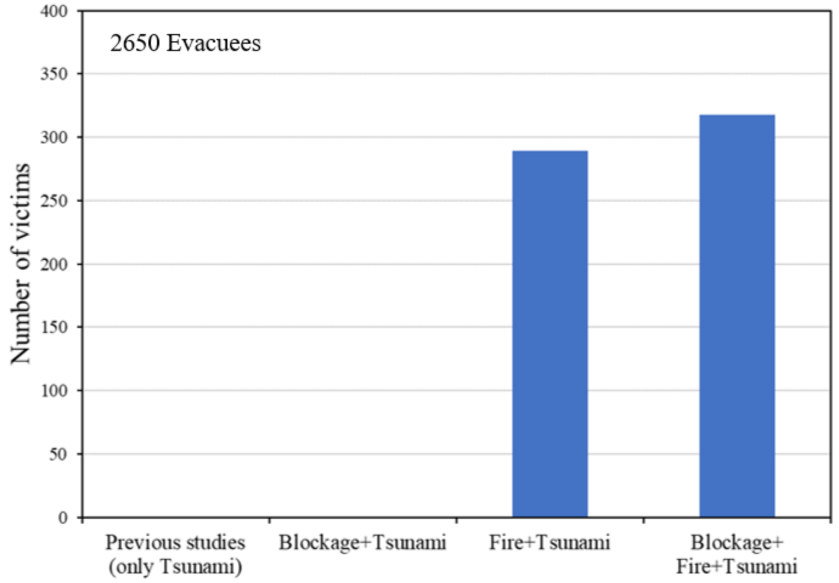
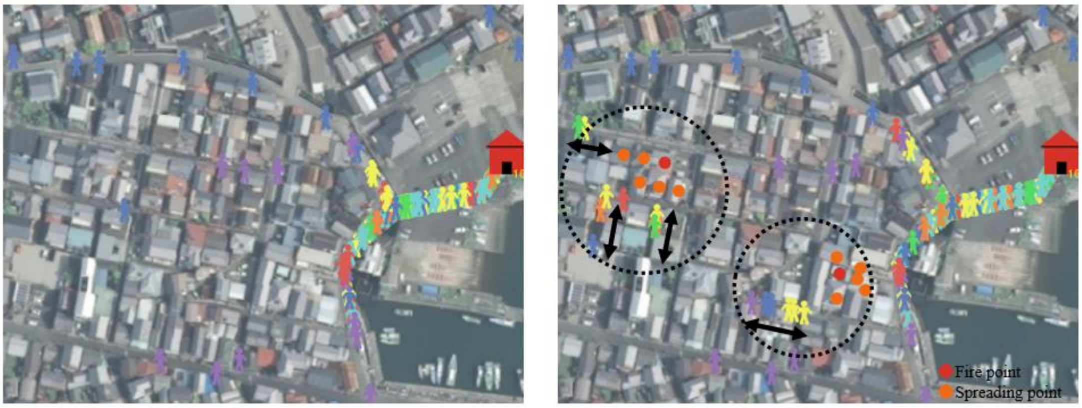


Figure 6: Factors considered

Without road blockage consideration With road blockage consideration

Figure 7: Consideration of road blockage



Without fire spread consideration With fire spread consideration

Figure 8: Consideration of fire spread

As mentioned before, these results are based on evacuation starting zero minutes after the earthquake. Similar to the simulation results of previous studies, no victims occurred in the cases considering building collapses and tsunami. In contrast, in the cases considering fire and tsunami, building collapse, fire, and tsunami, victims occurred. The results confirm that the newly considered factors have an impact on the simulation results. The results also confirmed the importance of early evacuation, as victims still occurred even after the evacuation began zero minutes after the earthquake. These results are discussed in detail in the following sections.

When the two factors of road blockage and tsunami were taken into account, the number of victims did not differ from the results of previous studies. Therefore, we checked the changes in the behavior of evacuees when road blockages were not considered and when they were considered. As shown in **Figure 7**, we observed a delay in evacuation behavior when road blockage was taken into account, compared to when it was not taken into account. In addition, the simulation was performed assuming that a road blockage occurs at all nodes with the road blockage probability, in addition to the road blockage conditions shown in the previous section. The time for all evacuees to complete evacuation in the previous studies was 59 minutes after

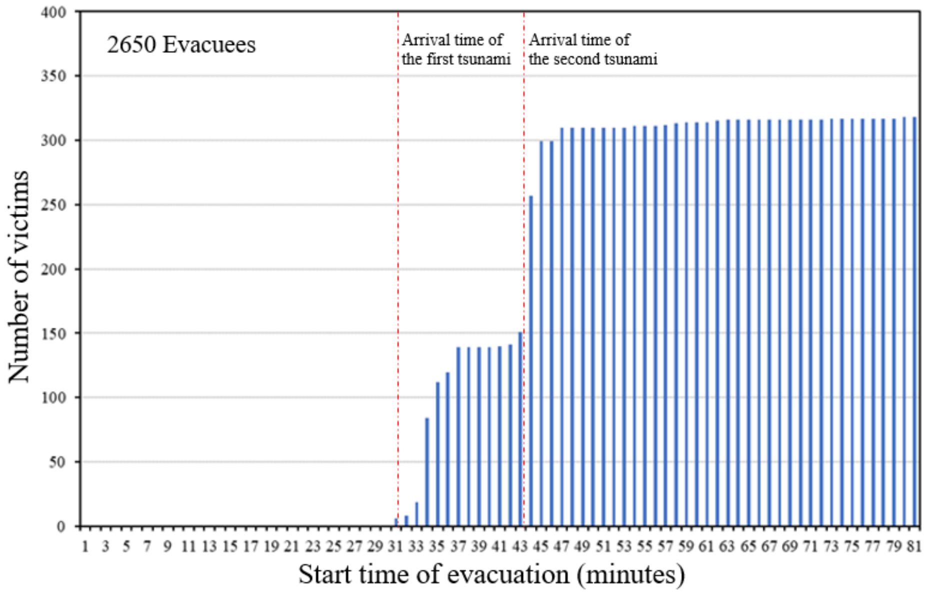


Figure 9: Number of victims

the earthquake, whereas in the present study it was 67.2 minutes. The time required to complete the evacuation was confirmed to have increased. Thus, it can be said that the speed reduction due to road blockage is taken into account.

Next, when the two factors of fire spread and tsunami were taken into account, the number of victims increased and the arrival rate at the shelters decreased even if the evacuation started immediately after the earthquake, compared to the results of previous studies. As shown in **Figure 8**, evacuees can be seen moving to the right and left because the evacuation route was blocked by the fire spreading. These evacuees were unable to reach shelters and later became victims of the tsunami. This indicates that fire spread was taken into account.

In addition, when the three factors of road blockage, fire spread, and tsunami are taken into account, the number of victims increases rapidly after the arrival time of the first and second tsunami waves, as shown in **Figure 9**. This is because, as before, there were many evacuees in the tsunami-affected areas who were unable to reach shelters due to blocked evacuation routes or avoidance behavior in consideration of the spread of fire.

The above confirmed the possibility of conducting tsunami evacuation simulations that take into account road blockage and fire spread. It was also confirmed that the occurrence of road blockage, weather conditions in the target area, and the resulting fires affect the evacuation behavior of evacuees and their survival rate. These results also enabled us to predict the hazardous areas in the target area.

6 CONCLUSION

In this paper, we extended the applicability of the tsunami evacuation simulation system by adding the consideration of the building collapse and fire spread to our conventional simulation method, and obtained the following conclusions.

- The road blockage caused by collapsed buildings and the spread of fire can be taken into account.

- This system enables the prediction of hazardous areas in the studied area in the event of a disaster.

In the future, we plan to apply the present method to various scenario and also to compare with the results of evacuation drills.

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