EVACUATION BEHAVIORS OF RESIDENTS IN THE 1934 HAKODATE FIRE USING COMPUTER SIMULATION

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ABSTRACT

It is necessary to consider effective measures of evacuation in order to save city residents from post-earthquake fires. To accomplish this objective, we first need to know the nature of evacuation of city residents in urban conflagration. However, sufficient information on such evacuation behavior is hardly available. So we tried to figure out the evacuation behaviors of residents by comparing the observed data of a past urban fire with the results of the urban evacuation model.

In the urban evacuation model, we estimate grand-level ambient temperature rise on city ground due to wind-blown fire flow and effect by radiation to which residents are exposed in the course of evacuation. Next, we simulated the evacuation of the residents assuming that they evacuate to avoid hazard of the fire and seek for a refuge. The network of evacuation route was constructed based on the city map at the time of the Hakodate Fire. We have compared simulated results of the number of victims and their locations with those of the fire record to validate the model.

KEYWORDS: Urban fire, Evacuation, Simulation, the Hakodate Fire, Wind-blown fire flow

INTRODUCTION

Historically, urban fires have claimed tremendous number of human lives in Japan, where cities consist of mainly wooden houses. In both of the Kanto Great Earthquake in 1923 and the Great Tokyo Air Raid, approximately a hundred thousand of residents were burnt to death by the multiple fires which broke out almost simultaneously. For another example, as many as 2,054 people were killed in the Hakodate Fire, 1934, which occurred under a strong wind and yielded numerous firebrands accompanying numbers of spotting fire.

The question is unsolved: why so many people had to die while velocity of fire front is generally only a couple of hundred meters per hour at most, whereas travel speed of residents is ten times faster? It is important to understand the whole picture of evacuation of urban fire. However, it is impossible to use an experimental method to analyze urban fires and involved evacuation behaviors, neither can we figure them out from the observed data. Therefore we try to figure it out by examining the observed data with the evacuation model. Once such an evacuation model was developed, it will be valid for exploring effective measures of evacuation for assuring safety of residents from post-earthquake fires.

THE OUTLINE OF THE URBAN EVACUATION MODEL

Fig. 1 shows the outline of the urban evacuation model. The model consists of two sub-models: The model for ambient temperature rise model and the evacuation model.

First, by using the temperature-rise model, temperature rise on the ground level due to wind-blown fire flow and effect by radiation is calculated for the object area is divided into meshes, generation of heat release rate at each mesh is estimated every moment. Next, using the evacuation model, evacuation of each resident who is assumed to so escape as to avoid the hazard of fire and smoke and negotiating refugee area while being exposed to the wind-blown fire flow and heat are simulated.

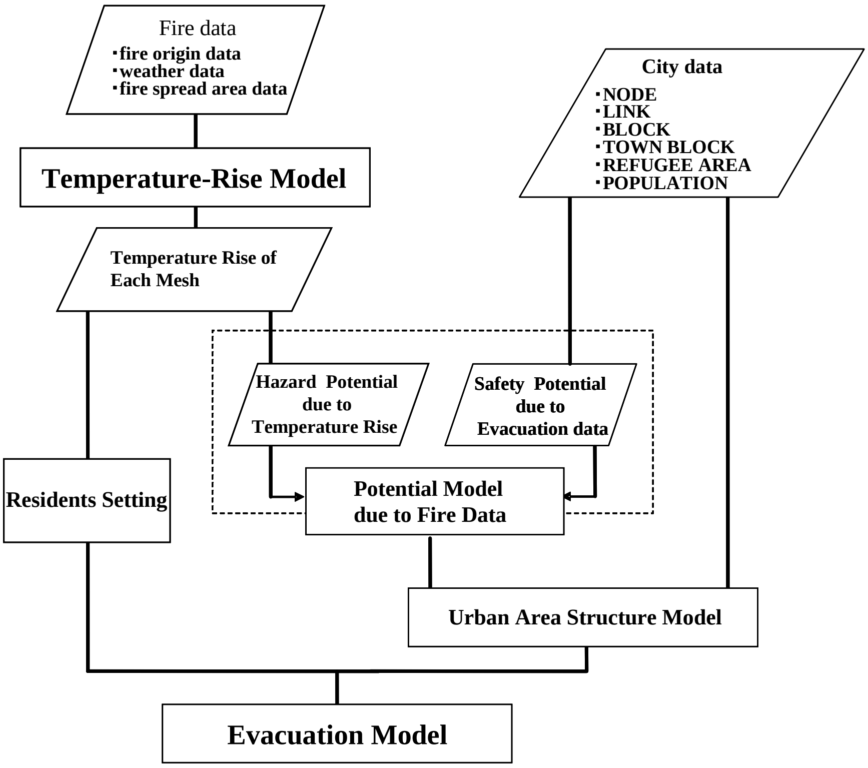


FIGURE 1. Brief of urban evacuation model

TEMPERATURE-RISE MODEL

First, this model estimates heat generation rate from the observed data of past-urban fire (fire spreading chart, wind speed and wind direction etc.) every moment. As for the effect by radiation, meshes adjoining fire spread area are regarded as radiation receiving meshes. The estimated radiation heat flux is converted to effective temperature for the purpose of estimating regard exposure level to evacuate. Letting each burning meshes be a heat source, temperature rise on the ground level at target unburned meshes in the leeward of wind due to the fire plume from all the burning meshes are calculated. Fig. 2 illustrated the relationship between location of a fire plume axis that rises from a burning mesh and a target mesh.

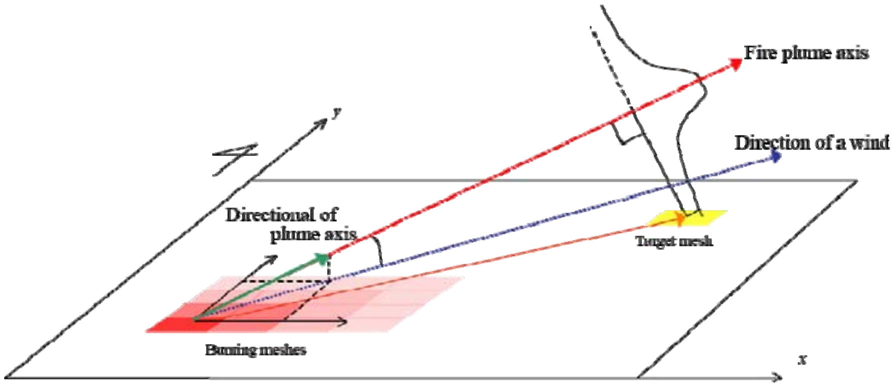


FIGURE 2. Location of a fire plume axis that rises from a burning mesh and a target mesh

EVACUATION MODEL

This model simulates aspect and location of residents every moment. Amount of fire exposure of residents are calculated based on temperature rise estimated using temperature rise model. They evacuate to avoid fire and smoke hazard and seeking for evacuation area. Residents evacuate selecting route whose gradient of potential is biggest at node. Details of this model are outlined below.

POTENTIAL MODEL DUE TO FIRE DATA

Hazard potential is based on temperature rise calculated by the temperature rise model. Safety potential at a node is determined according to distance from node of refugee area. The safety potential is scaled as the hazard potential due to temperature rise. Hazard potential of a node is calculated at every moment by adding the hazard potential and the safety potential as.

$$Po_i = HazardPotensial + SafetyPotential = TemparetureRise + \frac{S_i}{ESCleng} \times safeT \qquad [1]$$

Po_i = potential of node i, S_i = distance between node and node of evacuation area, $ESCleng$ = distance working for safety potential.

SELECT ROUTE

When residents select evacuation route at node, the potential is very important. Residents select evacuation route where value of equation [2] is biggest. That is to say, route for which potential gradient is steepest per unit time is selected by residents.

$$Po = \frac{(Po_i) - (Po_j)}{D_{i \to j} / VL(i, j)} \qquad [2]$$

Po_i = potential of node i, Po_j = potential of node j, $D_{i \to j}$ = distance between node i and node j, $VL(i, j)$ = walking velocity of link(node i, node j). Fig. 3 illustrated potential at node and potential gradient of links, which change with time according to hazard situation due to fire flow.

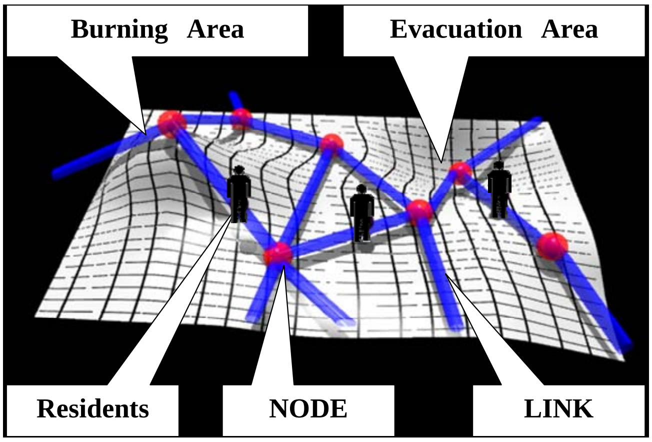


FIGURE 3. Potential model

CITY STRUCTURE MODEL

The city structure model consists of node, link, block, town-block and evacuation area. Fig. 4 shows urban area structure model.

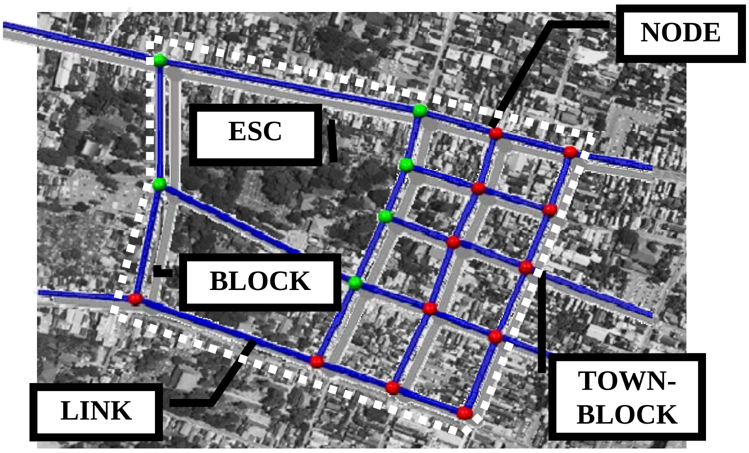


FIGURE 4. City structure model

RESIDENTS SETTING

Amount of exposure to elevated temperature of residents are estimated as (temperature of exposure)^n × (time of exposure).

$$I(t) = \int_{t_{start}}^{t} \{X(t) - X_0\}^n dt \qquad [3]$$

$I(t)$ = accumulative amount of fire exposure, $X(t)$ = temperature of exposure, X_0 = minimum of physiological influence, t_{start} = the time of $X(t) > X_0$.
Residents evacuate depending on amount of fire exposure.

Fig. 5 shows evacuation behavior depending on amount of fire exposure. When $I(t) > I_{early}$, a certain percentage of residents start to evacuate. According to the magnitude of $I(t)$ when $I(t) > I_{late}$, all residents start to evacuate. When $I(t) > I_{death}$, a resident has been exposed to lethal amount of temperature, which means death. This amount of fire exposure is determined by the observed data of the Sakata City Fire.

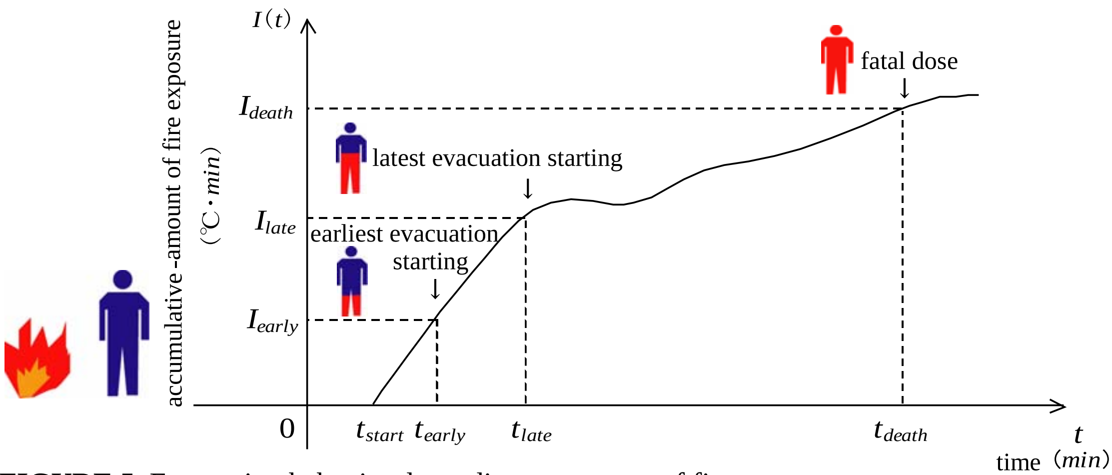


FIGURE 5. Evacuation behavior depending on amount of fire exposure

EVACUATION ASPECTS

Evacuation aspects of residents are determined by index of cumulative exposure temperature-time at time t, $I(t)$ as equation (4). A resident who arrived at refugee area is given a flag of evacuation completion (4).

$$flagP(k)=\begin{cases}1:\ \text{before evacuation} & (I(t)<I_{early})\\ 2:\ \text{evacuation on the } L\text{INK} & (I_{early}\le I(t)<I_{death})\\ 3:\ \text{evacuation on the NODE} & (I_{early}\le I(t)<I_{death})\\ 4:\ \text{evacuation completion} & (-)\\ 5:\ \text{evacuation impossibility} & (I_{death}\le I(t))\end{cases} \quad [4]$$

SETTING OF BEFORE EVACUATION

Fig. 6 illustrated initial setting of residents before evacuation. Fig. 6(a) shows that population of every town-block is distributed in sub-blocks enclosed by streets according block area. Fig. 6(b) shows that residents distributed in a block are initially located on the gravity center of block mesh. Fig. 6(c) to (f) shows that optional resident who have exposed to such amount of heat as to feel necessity of escape, i.e. $I(t)>I_{EVACUstarting}$, selects link where gradient of hazard potential from the position of the evacuee is steepest of all the links concerned. Resident start to evacuate along the link after the time lag associated with distance of the initial location of the resident to the selected link.

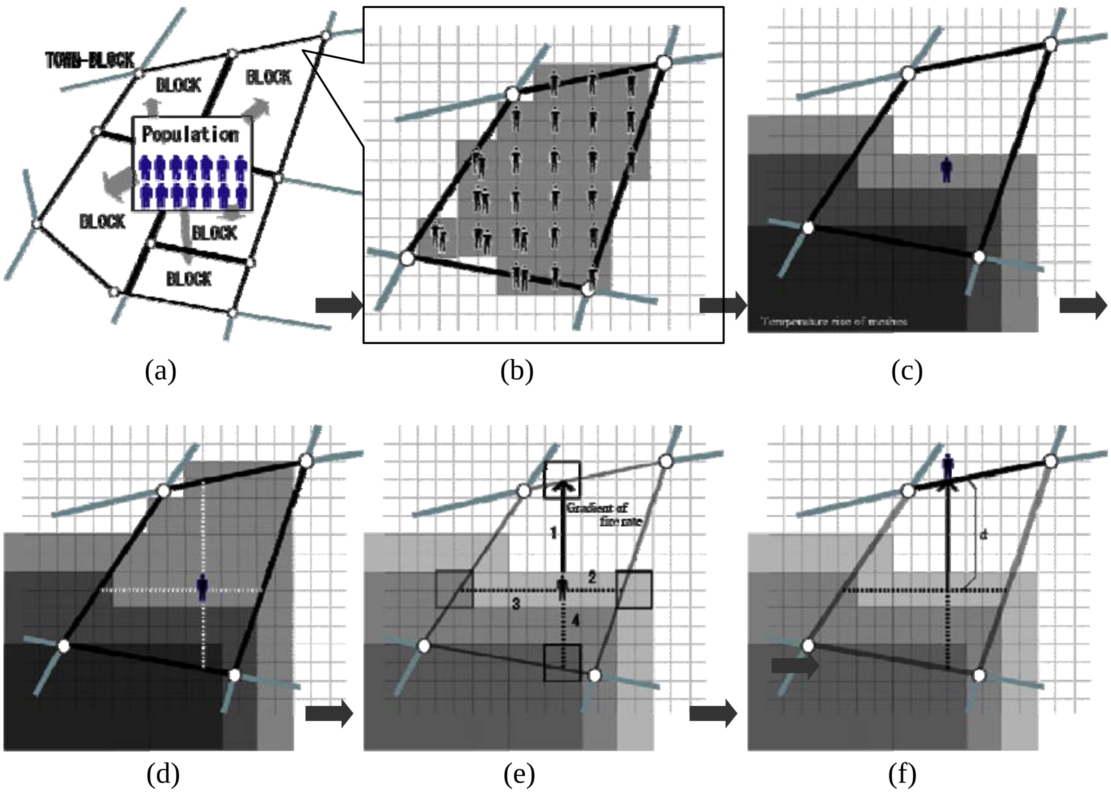


FIGURE 6. Setting of residents before evacuation

OUTLINE OF THE HAKODATE FIRE

The reason that Hakodate Fire is chosen in this study is that the fire is the latest urban fire in which many people lost their lives in Japan.

The outline of the fire is summarized in Table 1, and its fire spreading chart, from post-fire investigation is as shown in Fig. 7. The fire, which broke out at 6:53 p.m., 21st March, 1934, was fanned by the strong wind caused by the very low atmospheric pressure near the scene at the very time and, burned down the 41,639 ha of city area, ashes by 6 a.m., next morning. The fire claimed 2.054 deaths tall from Hakodate citizens.

TABLE 1. Outline of the Hakodate Fire

Date and time of fire outbreak	18:53, 21st March, 1934
Date and time fire controlled	6:00, 22nd March, 1934
The fire spread condition	Mainly firebrands lofted by firewhirl
Weather condition	Maximum instantaneous wind speed 23.5m/s
Burnt area	416.39ha(one third of Hakodate City)
Fatalities	2,054(-)
Number of residents	102,001(-)

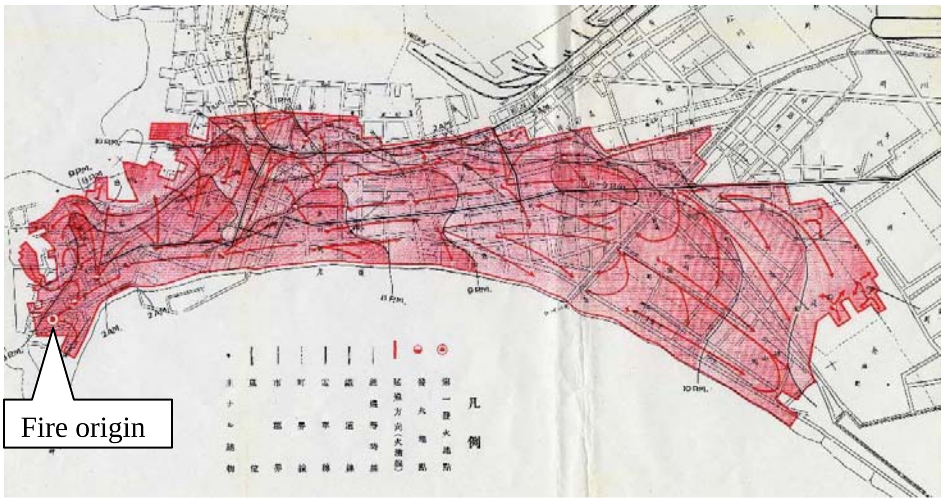


FIGURE 7. Fire spreading chart of the Hakodate Fire

SETTING CONDITION OF SIMULATION

Object urban area is divided into 20 m × 20 m meshes. The *ESCleng* , distance working for safety potential is set at 300 m. Fig. 8 shows node, link, block and refugee area.

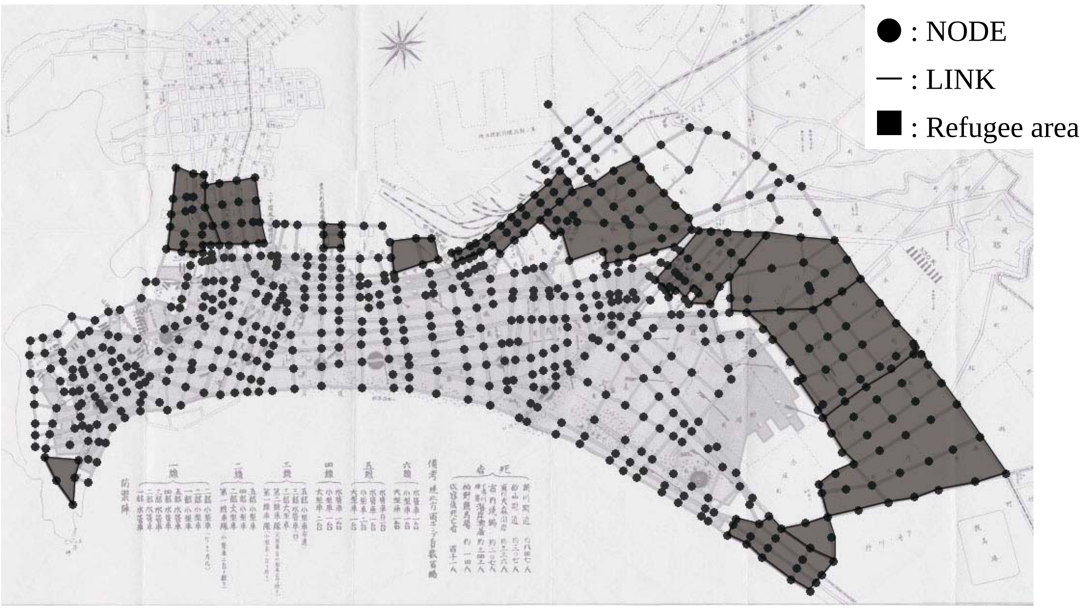
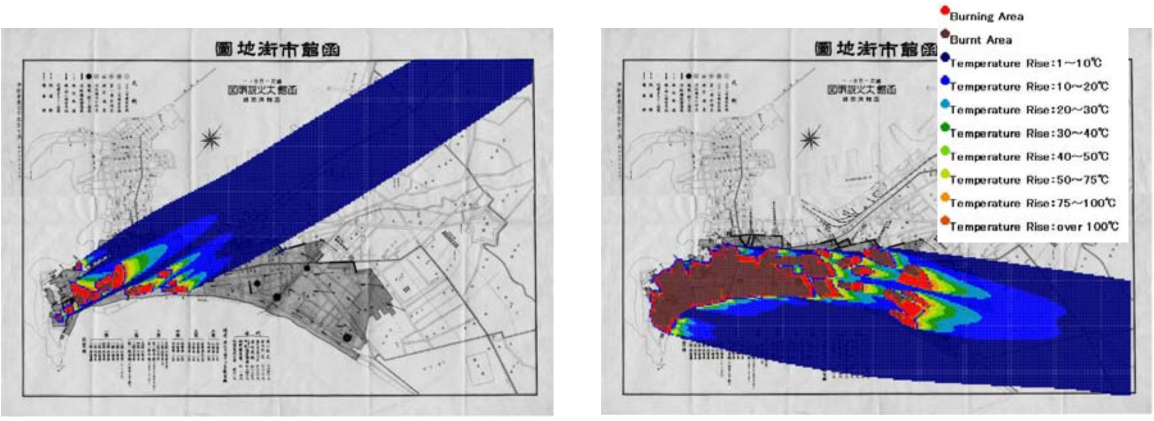


FIGURE 8. Node, link, block, refugee area

RESULTS AND DISCUSSION

Using the model, we estimate the temperature rise and evacuation behavior of residents by the Hakodate Fire. Fig. 10 shows results of temperature rise at a time and Fig. 11 shows locations of residents at the same time. Fig. 12 shows real locations of dead persons from the investigation after the fire. Fig. 13 shows locations of dead persons predicted from the model. The number of the evacuation stage at the end is shown in Table 2. Fig. 14 shows evacuation stage of residents with the elapse of time. Fig. 15 shows locations of residents at 220 minutes from the onset of fire.



(a) After 60 minutes from the onset of fire (19:53 3/21)

(b) After 180 minutes from the onset of fire

FIGURE 10. The temperature rise

(a) After 60 minutes from the onset of fire (19:53 3/21)

(b) After 180 minutes from the onset of fire

FIGURE 11. The locations of residents

FIGURE 12: The locations of dead persons from real results

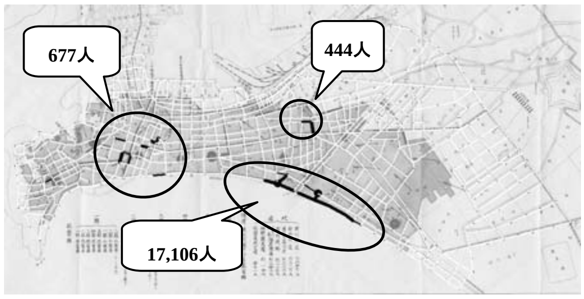


FIGURE 13. The locations of dead persons from the model

TABLE 2. The number of the evacuation stage at the end time

	before evacuation	evacuating	evacuation completion	evacuation impossibility
number	0	4,009	78,762	18,227

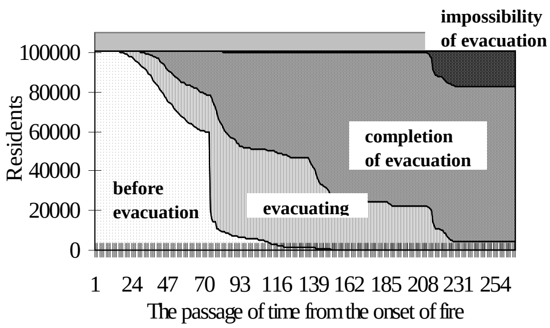


FIGURE 14. Evacuation aspects of residents among the passage of time

FIGURE 15. The locations of residents in 220 minutes from the onset of fire

Although the agreement of this prediction and the real results are not good enough, the following things are thought from the above results.

As we know from Fig. 10 (a) and (b), the wind direction changed shifting greatly, Fig. 11 (a) shows that the residents were starting to evacuate along the beech avoiding the fire. Fig. 11 (b) shows that many evacuating residents were escaping and gathered toward the beech. When we compare Fig. 13 with Fig. 12, both show that a large number of the victims ware found along the beech. It is considered that the 207 victims who were found in burned-out sites in Fig.12 correspond to the victims in Fig. 13, in number 677 and 444, who were unable to escape in downtown. Though the number of dead victims between the simulation results and in the real results are different, the locations of dead victims in the simulation seem to be similar to those in the reappearance. The number of dead victims in the simulation results is 18,277 as shown in Table 2. In Fig. 14 after 220 minutes from the onset of fire, a lot of evacuating residents seem to have found it impossible to escape from the fire. Fig. 15 shows the locations of residents after 220 minutes from the onset of fire According to it, we can see that the residents evacuating along the beech couldn’t escape anywhere at all because they were surrounded by flame.

CONCLUSIONS

In this paper, we tried to simulate the Hakodate Fire using the urban evacuation model in order to analyze the problems about evacuation of residents in case of urban fires in the past and contemporary cities. Though the number of the dead victims in the simulation results has become larger than that in the real results, it can be said that the locations of the dead victims in the simulation are close to those of the reappearance of the Hakodate Fire.

We will try to go on studying on this urban evacuation model in combination with Urban Fire Spread Model and make it measures in case of an earthquake fire in the future. We will show the following problems in the model for this.

a) It is evident that setting refugee area affects the effects greatly. So it is necessary to set $ESCleng$ as effective distance of refugee area and consider the requirements for refugee area, including the location for it.
b) Amount of fire exposure is one of the most important values in this urban evacuation model. It is also necessary to reconsider to set the value of it.
c) Speaking of the temperature-rise model, mesh including wide-roadways, blank space and ponds is treated equally with mesh including buildings. We should improve the model to calculate temperature-rise with distinction of these meshes.

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