SIMULATION OF FIRE SPREAD IN THE SAKATA FIRE AND INVOLVED FIRE FIGHTING ACTIVITIES

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ABSTRACT

Fire spread behaviors of the 1976 Sakata Fire was examined by numerical simulation with a physics-based urban fire spread model. The model is capable of predicting fire spread in densely-built environment as well as evaluating suppression effect of fire fighting which was supposed to have great contribution to the reduction of damage in the Sakata Fire. Although qualitative features of the fire spread agreed well with the fire record, there were several discrepancies in the eventual burnt area. Comparison of the numerical results with and without fire fighting activity showed that fire fighting is effective especially on suppression of fire spread in the direction orthogonal to the wind.

KEYWORDS: Urban fire, Conflagration, Sakata Fire, Fire spread, Fire fighting

INTRODUCTION

A devastating fire occurred in a northern city of Japan called Sakata in a windy day of October 1976 [1]. The fire originated from a movie theater in the middle of downtown and propagated to the adjacent buildings sequentially. In spite of the considerable effort made by fire fighters, the fire enlarged its area and lasted for about 11 hours after the outbreak. As a result, as much as 1,774 buildings and site area of 22.5 ha were burnt. Outline of the fire is depicted in Table 1.

The bird’s-eye view and aerial photograph of the burnt area are shown in Figs. 1 and 2, respectively. In each figure, the overall burnt area is surrounded by dotted lines. The predominant direction of fire spread was east-south-east from the fire origin, which was roughly the same as the wind direction throughout the fire. The fire finally reached as far as the Niidagawa-river (about 50 m wide) about 800 m away from the fire origin. Although there was a fairy broad street called Hamamachi-dori (about 15 m wide) on the way, the momentum of the fire was overwhelming that it did not work as a fire-break.

The weather data recorded at the meteorological station about 1 km away from the fire origin is shown in Fig. 3. Even though the Sakata area is well known for its frequent strong winds, the day of the fire was especially windy that the average wind velocity was 11.0 m/s. During the fire, rainfall was also observed intermittently. However, as the maximum precipitation rate was 2 mm/hr and the overall precipitation amount was 12 mm throughout the fire, its contribution to fire suppression was supposed to be limited.

TABLE 1. Outline of the Sakata Fire

Date and time of the outbreak	17:40, October 29th, 1976.
Date and time of the control	05:00, October 30th, 1976.
Fire origin	Initiated from a movie theater in the downtown of Sakata.
Cause of the fire	Unknown.
Weather condition at the fire outbreak	Rain; Intermittent rain showers, Wind direction; WSW, Wind velocity; 12.2 m/s, Ambient temperature; 8.5℃, Relative humidity; 73%.
Burnt area	Burnt site area; 22.5 ha, Burnt building area; 15.2 ha.
Burnt buildings	1,744 buildings were burnt, in which 1,767 of them were fully burnt and the else were partly burnt.

FIGURE 1. Bird's-eye view of the burnt area looking from the west to east

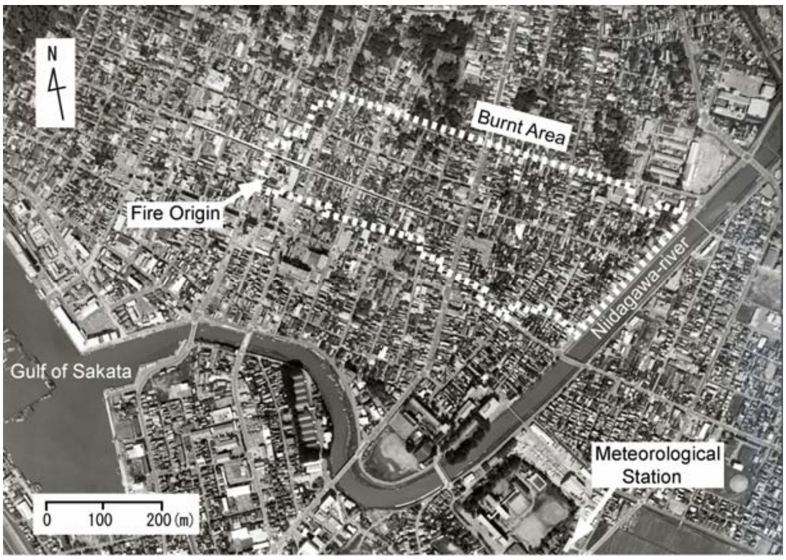

FIGURE 2. Aerial photograph of the Sakata city

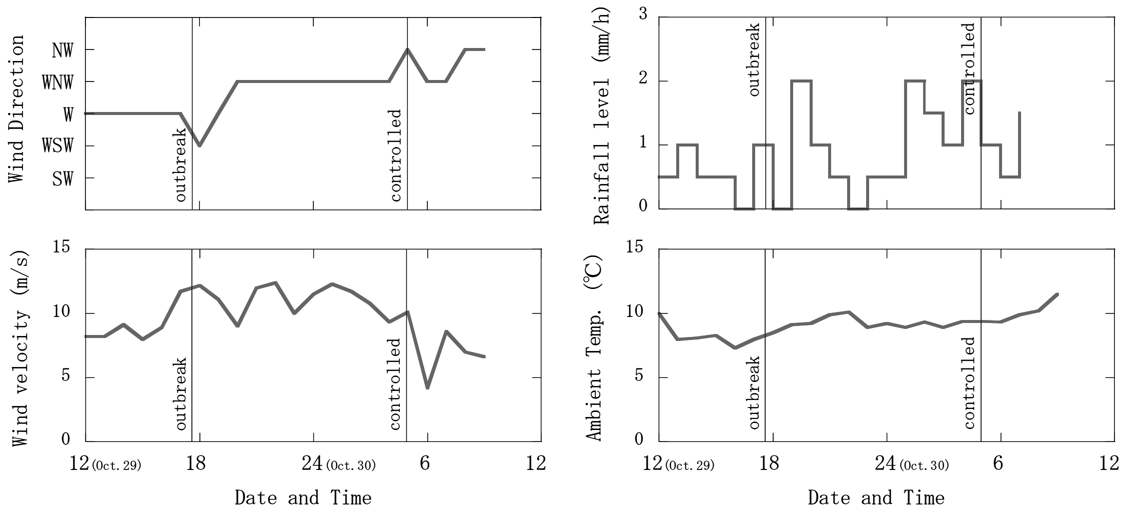

FIGURE 3. Weather data recorded at the nearest meteorological station

The number of assembled fire engines/pumps was 217, and that of available fire hydrants/tanks was about 50 excluding direct water supply from Niidagawa River. In spite of such abundant resources for fire fighting, momentum of the fire was prevailing and was unextinguishable before it reached Niidagawa River. This is because the growth of the fire was so rapid that extinguishment of the fire at the initial phase failed.

Since the Sakata Fire, which took place about 30 years ago, Japanese buildings in general became more fire-resistant along with the several revisions made on the Building Standard Law. However, as most of Japanese houses are wooden and built close together in a small area, they are intrinsically vulnerable to fire. As a result, there are still a number of cities left in Japan, in which urban fire may happen especially in a windy day or after a severe earthquake.

Although the controlling of fire failed in the case of the Sakata Fire, fire fighting activity is one of the most effective approaches in maintaining fire safety of densely-built urban areas. Thus, to evaluate quantitative effects of fire fighting activity in reducing the loss caused by urban fire is indispensable for the design of rational countermeasures. Authors have developed an integrated model of urban fire spread and fire fighting, in which reduction of fire hazard by water application is regarded as the consumption of latent heat along with the water evaporation[2,3]. In the present study, fire spread simulation is carried out in the city of Sakata by using the model and examine the effectiveness of fire fighting activity in suppressing the fire spread.

URBAN FIRE SPREAD MODEL [2]

A schematic diagram of the urban fire spread model is shown in Fig. 4. In the model, spread of fire in urban areas is described by simulating behaviors of individual building fires under the influence of nearby building fires, as urban fire is nothing but an ensemble of multiple building fires. Thus the model consists of two major sub-models: one that predicts fire behaviors inside buildings; and another that predicts building-to-building fire spread.

As to the building fire model, each room of a building is assumed as a control volume with uniform physical properties. Transient development of internal fire behaviors are calculated by solving the governing equations for the properties of these control volumes simultaneously. This uniformity assumption is appropriate as vigorous phases of fire occupies a large portion of compartment fires, and building-to-building fire spread takes place mostly within this particular phase. Such an approach is generally called zone modeling, which is widely adopted in the building fire safety engineering.

Mitigation of fire hazard due to water application is evaluated by incorporating following consequences of water evaporation into the conservation equations of the compartment gas [4]: cooling of compartment gas by consumption of latent heat; dilution of compartment gas by sudden expansion of volume; and cooling and wetting of fuel surface. Following the definition of the one layer zone model, conservation equations of mass, energy, and chemical species (oxygen denoted by O, and gasified fuel by F) for an arbitrary control volume is expressed as follows, respectively,

$$\frac{d}{dt}\left(\rho_i V_i\right) = \dot{m}_{F,i} + \phi_V \dot{m}_{V,i} - \sum_j \left(\dot{m}_{ij} - \dot{m}_{ji}\right) \qquad [1]$$

$$\frac{d}{dt}\left(c_P \rho_i T_i V_i\right) = \dot{Q}_{B,i} - \sum_j \left(c_P \dot{m}_{ij} T_i - c_P \dot{m}_{ji} T_j\right) - \sum_j \dot{Q}_{D,ij} - \sum_j \dot{Q}_{W,ij} - \phi_V \dot{m}_{V,i} L_V + c_P \left(\phi_V \dot{m}_{V,i}\right) T_V \qquad [2]$$

$$\frac{d}{dt}\left(\rho_i V_i Y_{X,i}\right) = \dot{\Gamma}_{X,i} - \sum_j \left(\dot{m}_{ij} Y_{X,i} - \dot{m}_{ji} Y_{X,j}\right) \quad (X{=}O,F) \qquad [3]$$

The state equation of gas is given by,

$$\rho T \cong 353 \qquad [4]$$

In the above Eqns. [1] to [4], c_P is the gas heat capacity, ρ is the gas density, T is the gas temperature, T_P is the pyrolysis temperature of combustibles, V is the volume of control volume, Y is the mass fraction of chemical species, $\dot{m}_F$ is the mass production rate of gasified fuel due to pyrolysis of combustibles, $\dot{m}_V$ is the rate of water discharge, ϕ_V is the efficiency of water discharge, $\dot{m}$ is the mass flow rate through opening, $\dot{Q}_B$ is the heat release rate, $\sum \dot{Q}_L$ is the sum of heat loss rate through openings and walls, and $\dot{\Gamma}$ is the mass production rate of chemical species. Subscripts ij and ji denote the direction of mass flow between compartments i and j. Transient change of gas temperature, density, and mass fraction of chemical species are calculated by solving these equations simultaneously.

As to the building-to-building fire spread, following mechanisms are considered as contributing factors:

(I) thermal radiation heat transfer from fire involved buildings;
(II) temperature rise due to wind blown fire plumes;
(III) spotting of firebrands to the downwind.

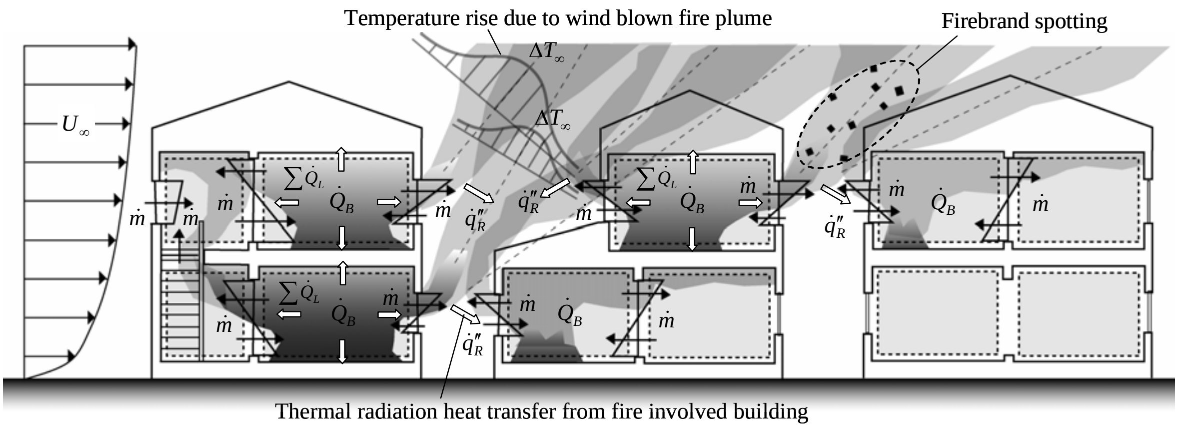

FIGURE 4. Schematic of the urban fire spread model

Under the influence of these phenomena, occurrence of fire spread is determined when one of the following conditions is met: incident heat flux through opening exceeds a critical value; surface temperature of exterior wooden wall exceeds a critical value; or a firebrand at high energy state is fallen upon combustibles.

FIRE FIGHTING ACTIVITY MODEL [3]

In an urban fire which involves plural on-burn buildings, specific buildings are identified as targets of fire fighting activity as the number of available fire hoses is limited. Although there are a number of factors which govern the selection of target buildings, we categorized them into two major groups:

(A) conditions on thermal environment induced by surrounding building fires which interferes with implementation of fire fighting activity;
(B) conditions on decision making of fire fighters influenced by surrounding fire spread behaviors.

In the present model, we take two steps before identifying target buildings of fire fighting. First, buildings in the concerning area are screened through conditions given in the category (A) and select buildings which we name ‘potential target buildings’. Then, the potential target buildings are further screened through conditions given in the category (B) and specify ‘target buildings’ as many as the number of available fire hoses.

We consider three criteria which are included in the category (A) and buildings which satisfy all of the three criteria are regarded as the potential target buildings. They are:

(A1) the potential target buildings are in the area where water is available by extending fire hoses from fire hydrants, in other words, potential target buildings are in circles of radius corresponding to the length of joined fire hoses;
(A2) the potential target buildings are not isolated in the area surrounded by on-burn buildings where safety of fire fighters is not maintained;
(A3) the potential target buildings are in the area where ambient temperature rise due to wind blown fire plumes are below a certain value at which activity of fire fighters are not interfered.

Fig. 5 shows an example of the potential target buildings in a hypothetical urban area where buildings of identical configuration were aligned at a certain separation. Colored boxes indicate buildings involved in fire and areas of constraint are surrounded by dotted lines. Number of the potential target buildings in this specific case is two which are designated with bold lines.

When a sole potential target building is selected through the screening process of the category (A), then all of the available fire fighting resources will be thrown into this specific building. While, when there are plural potential target buildings, fire fighters or the superior commanders will make decision on selecting the target buildings. The decision may be influenced by a variety of factors such as behaviors of the fire, or character/experience of the decision maker, etc. Although the process of decision making usually becomes complicated, outcome of the decision making process may be generalized into a number of fire fighting strategy. Followings are the examples:

(B1) to minimize time required for extinguishment within the overall urban area;
(B2) to minimize time required for extinguishment of a specific building;
(B3) to avoid the fire spread to specific buildings or structures;
(B4) to choose identical/different buildings with/from those of other groups of fire fighters;
(B5) to minimize starting time of water discharge.

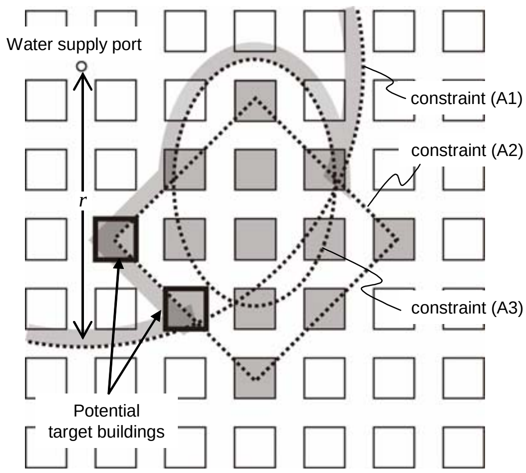

FIGURE 5. Restriction of target buildings under the constraints (A1), (A2) and (A3)

Out of these criteria, the approaches (B1) and (B3) can be taken only when rational and strategic countermeasure planning is possible from a broad viewpoint of minimizing the fire loss. Taking these approaches is possible when right information is obtained at right time and right decision is made for the purpose of loss reduction, which is ideal. While, the approaches (B2), (B4) and (B5) show conditions at which selection of target buildings is made under limited information of fire spread. It is not simple to know which approach will be taken in actual fires. Thus, we tentatively adopt the simplest approach (B5) for selecting target buildings. In other words, the nearest building from the fire hydrant out of the potential target buildings will be selected regardless of the overall fire spread behaviors.

FIRE SPREAD SIMULATION IN THE CITY OF SAKATA

Fire spread simulation in the city of Sakata was carried out. Data on building configuration, number of stories, structure needed for the numerical simulation were scanned all from the city planning map of that time drawn in the scale of 1/1000. Inequalities of the ground level are not considered in the current simulation. The number of scanned buildings was 2,158, whereas the number of recorded burnt buildings was 1,774. The control volume for the simulation of an individual building fire was set to the occupational space of a floor. Wind and ambient temperature data obtained at the meteorological station were used as the input weather data as shown in Fig. 3. However, the effect of rainfall was not considered in the current simulation as the rate of precipitation was small.

Positions of fire hydrants were scanned from the record of fire fighting activity, while Niidagawa-river was also assumed as a source of water. The maximum reachable distance by fire hoses was 200 m from fire hydrants or the river, which is the result of joining 10 pieces of 20 m fire hoses together. The rate of effective water application to fire involved buildings $\phi_v \dot{m}_v$ was 1.0 kg/s which was adjusted so that the results of the simulation agree with the fire record. This seems rather small compared to the nominal power of a fire pump which is roughly 5.0 to 10.0 kg/s. However the rate $\phi_v \dot{m}_v$ indicates what is actually evaporated in fire compartments and thus it becomes smaller than the nominal power to some extent.

Enormous amount of lofted firebrands were observed in the Sakata Fire and numbers of fire spreads were actually caused by them. The present model is capable of predicting fire spread caused by firebrands. However, as the model takes probabilistic approach for the spotting simulation, obtained results may become different for every trial of simulation even if the input data are unchanged. One way of evaluating such results is to duplicate simulation by the Monte-Carlo approach and deduce expected behaviors of fire spread. Yet, the fire behavior observed in the Sakata Fire itself is only an example of considerable number of expected fire scenarios. Thus, the observed time and place, at which secondary fires caused by firebrands, were used as the input data instead of predicting them.

RESULTS AND DISCUSSION

Simulated fire spread at 0:00 (Oct. 30th), which is 6 hours and 20 minutes after the outbreak were illustrated in Figs. 6 and 7. The former is the one that the fire fighting was not considered and the latter was. On-Burning buildings are colored with dark grey and burnt-out buildings with light grey. The buildings of secondary fire origin initiated by firebrands and their corresponding times are indicated with arrows. Buildings at which water was being discharged at the specific time were indicated with the symbol ($\triangledown$). The number of symbols does not represent that of the fire hoses thrown into the fires, but plural fire hoses were actually used.

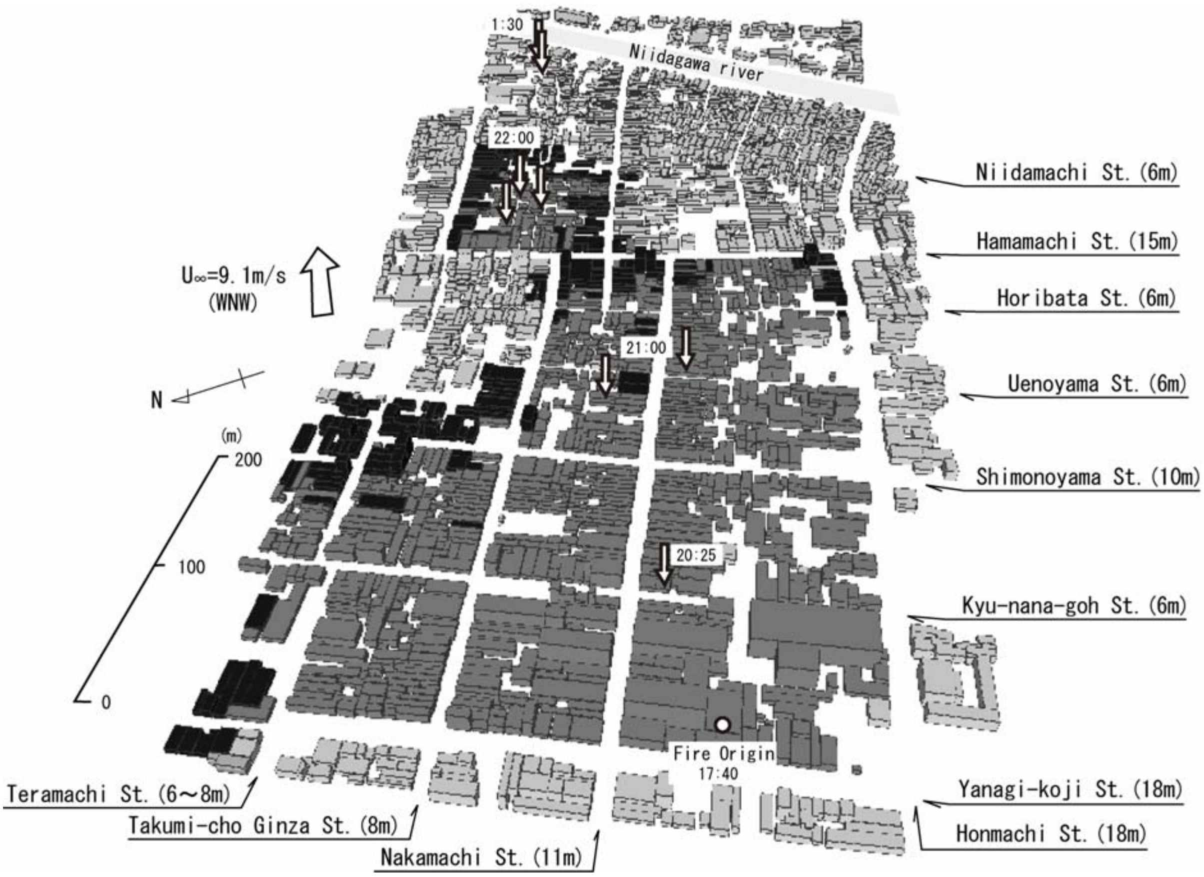

FIGURE 6. Result of fire spread simulation at 0:00 (6 hrs 20 min after the outbreak), Oct. 30th. Fire fighting was not considered. Arrows indicate buildings of secondary fire origins initiated by firebrands

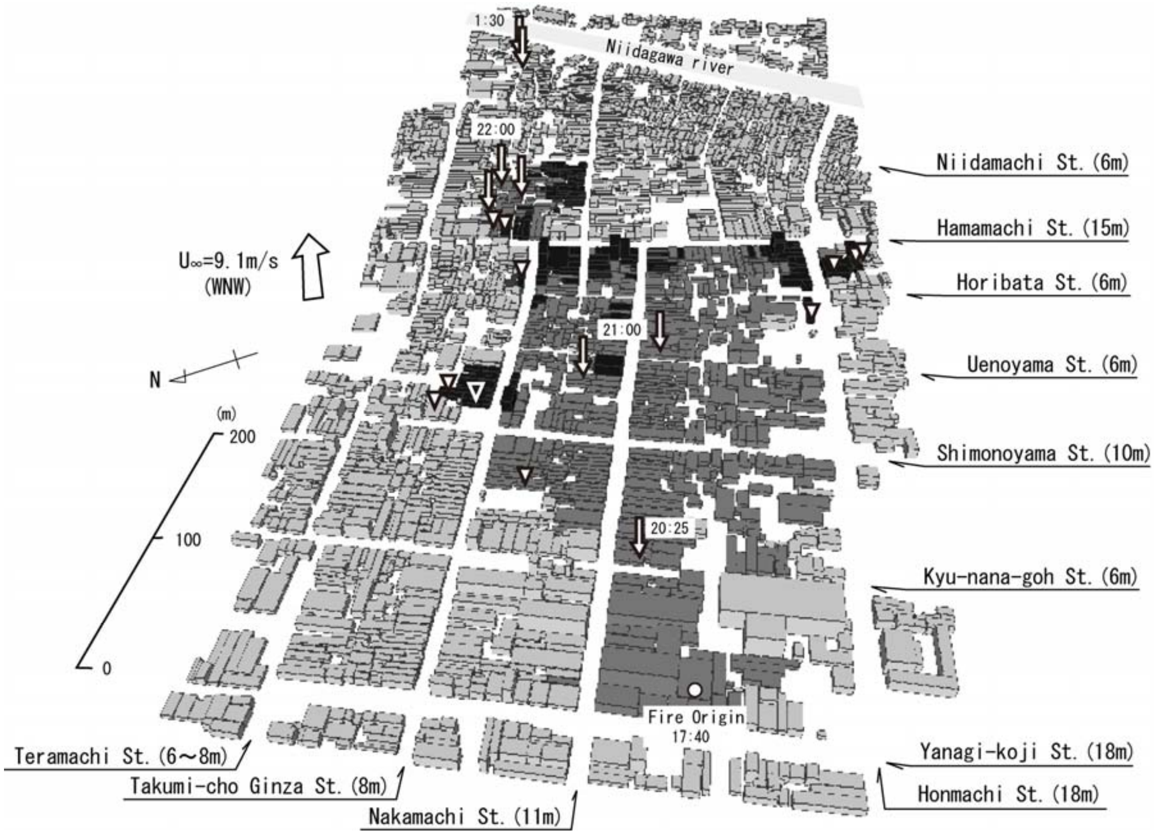

FIGURE 7. Result of fire spread simulation at 0:00 (6hrs 20min after the outbreak), Oct. 30th. Fire fighting was considered. Arrows and triangles indicate buildings of secondary fire origins initiated by firebrands and target buildings of water discharge, respectively

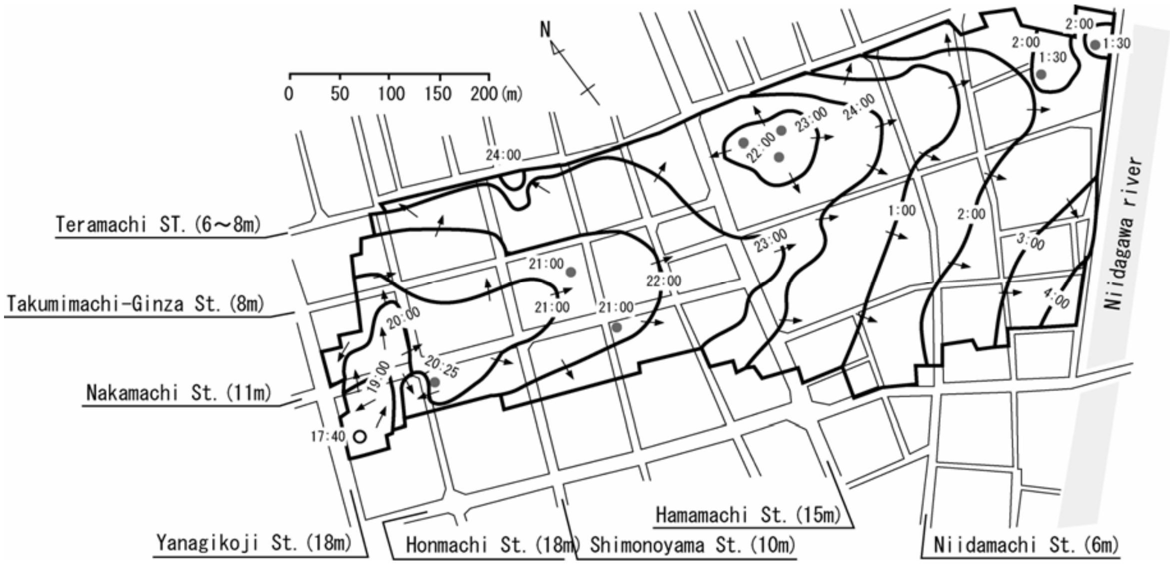

FIGURE 8. Fire spread recorded in the Sakata Fire: closed circle (○) and dots (●) designate the fire origin and secondary fire origins caused by firebrands, respectively

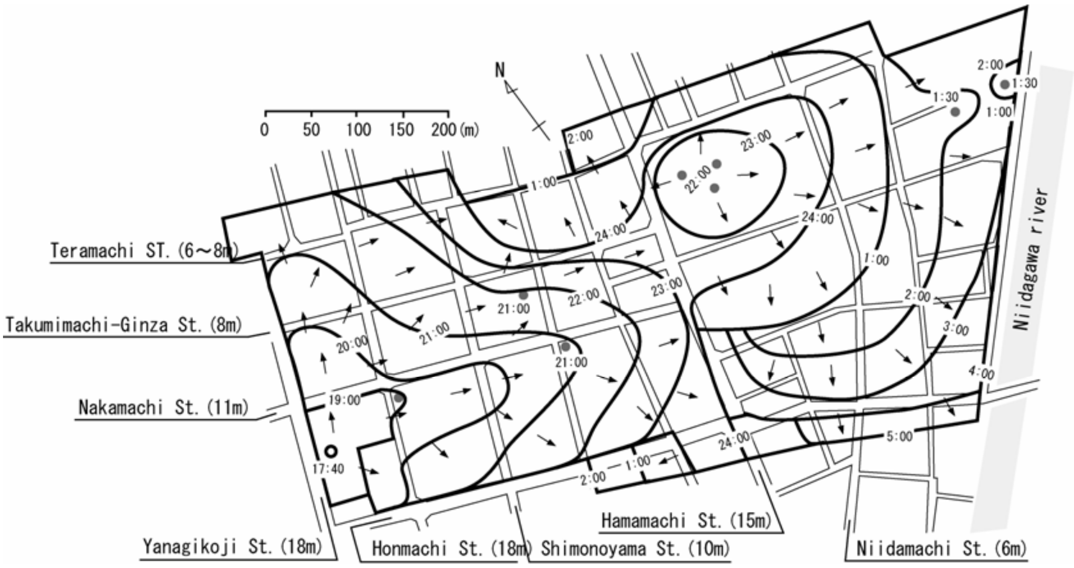

FIGURE 9. Result of Fire spread simulation disregarding the fire fighting activity: closed circle (○) and dots (●) designate the fire origin and secondary fire origins caused by firebrands, respectively

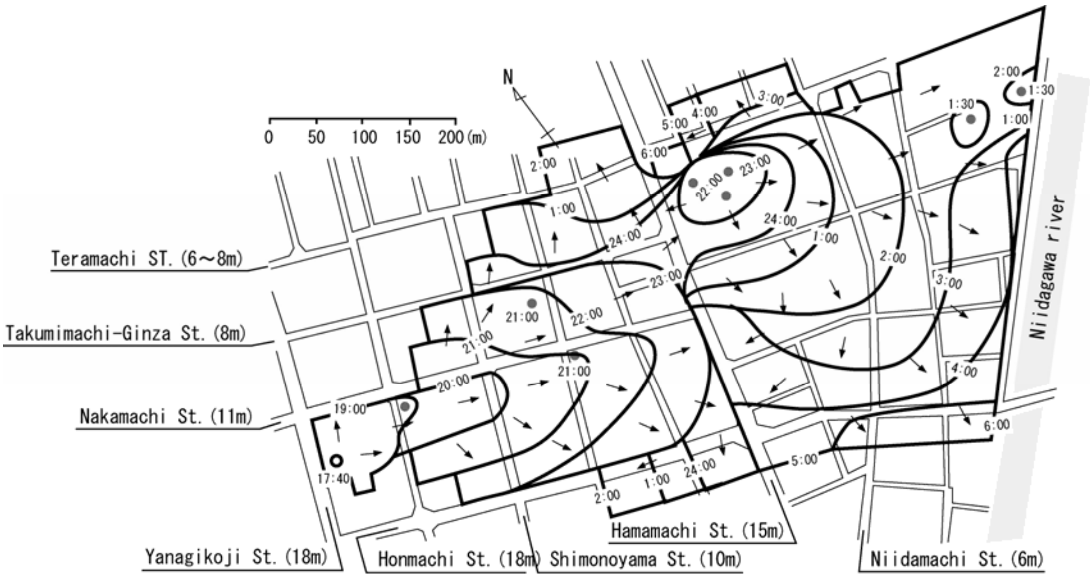

FIGURE 10. Result of Fire spread simulation regarding the fire fighting activity: closed circle (○) and dots (●) designate the fire origin and secondary fire origins caused by firebrands, respectively

Once initiated, the fire quickly propagated to adjacent buildings one after another and extended the burn area. The predominant fire spread directions were identical to the wind direction in the both cases. This implies that behaviors of wind-blown fire plume and firebrand spotting are influential on the dynamics of fire spread in urban fires. The difference between the two cases was notable in the fire spread rate in the direction orthogonal to the wind, in which the burn area was reduced when the fire fighting was considered. This is because there was substantial temperature rise in the downstream of the on-burn area due to the wind blown fire plumes. Thus, the fire fighting activity in the downstream area was restricted and the water discharge was implemented mainly from the orthogonal direction.

Dynamics of fire spread in the fire record, simulated results without/with the fire fighting calculation were illustrated in Figs. 8, 9 and 10, respectively. The fire origin and secondary fire origins are designated with the symbols (○) and (●), respectively. Curved lines show positions of fire front at the indicated times. Qualitative features of fire spread are similar between the fire record and the numerical results: the coincidence of the predominant fire spread direction and the wind direction; or the rate of fire spread estimated from the intervals of the fire fronts. However, there are several discrepancies especially in the resulted burn areas.

There are two areas where fire front intervals are notably short in Fig. 9 when fire fighting was not considered: one is around the cross-point of Takumimachi-Ginza St. and Shimonoyama St.; another is around the cross-point of Nakamachi St. and Hamamachi St. As obvious from the three dimensional view of the city in Fig. 6, there are fairly large open spaces around the concerning area including that of the streets, which yielded the underestimation of fire spread rate across. In the present simulation, buildings scanned from the city planning map were regarded as the only combustibles in the urban area. Whereas in actual fires, there is usually a variety of intervening combustibles, such as vegetations, warehouses or even vehicles, which probably enhance momentum of fire spread. The case of the Sakata Fire was not an exception. Additionally, it is natural to assume that the recorded secondary fire origins caused by firebrands are only a part of those actually caused as it is hard to distinguish contributing factors of fire spread in the disorder of such an extraordinary fire. Another possible reason is the lack of accuracy in the prediction of building-to-building fire spread. Although the occurrence of fire spread is judged by comparing either of the incident heat flux through opening or the surface temperature of exterior wooden wall with their critical values, hysteresis effect is not considered in the present model. This becomes influential on the ignition of material when intensity of heat is small, i.e., when separation of buildings is large.

Whereas the short fire front intervals obtained around the cross-point of Teramachi St. and Hamamachi St. in Fig. 10 is due to the effort of fire fighting. Actually, the fire was once stopped at this area which was spreading from the secondary fire origins in the south. However, the concerning area was attacked from the upstream fire after a while and eventually burnt out. The result in Fig. 10 suggests that the fire fighting activity was more effective in the earlier time period of the fire than in the later time period, as the burnt out area was underestimated in the former, whereas it was overestimated in the latter. In the present model, we assume that fire fighters are unable to implement their operations in the areas where ambient temperature are high. As a result, the number of fire hoses thrown into the fire was decreased in the later time period, when larger area in the downstream was covered with the wind blown fire plumes.

CONCLUSIONS

In this paper, behaviors of the 1976 Sakata Fire was examined by using the physics-based urban fire spread model with special emphasis on fire suppression effect of fire fighting activity. For comparison, simulations for two different conditions were carried out, i.e., the one considering fire fighting and the other not. The obtained results show that the fire fighting activity was effective in suppressing the momentum of fire spread especially in the direction orthogonal to the wind. This is because the implementation of fire fighting became difficult in the area downstream of the on-burn area where ambient temperature was high due to the exposure to wind-blown fire plumes. Similar consequences were also reported in the case of the Sakata Fire[1].

The qualitative features of fire spread obtained in the simulations, such as the predominant fire spread direction or the overall rate of fire spread, showed reasonable agreements with the fire record. However, the agreement of the eventual burnt out area was not that satisfactory, e.g., the suppression effect of fire fighting activity was overestimated in the earlier time period of the fire, whereas it was underestimated in the later time period. This is due mainly to the lack of accuracy in estimating the number of fire hoses thrown into the fire, which is originated either from inadequacy of the fire fighting model or inappropriateness of the information on water resources used as the input data.

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