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Integrated Earthquake Fire Risk Evaluation Based on Single Building Fire Probability Applicable to All Map Scales

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ABSTRACT

It is difficult to create a fire risk evaluation method that is applicable to different map scales from a single building to the whole region of Japan. Conventional simulation methods use city indices or mesh-data, but in the proposed method the fire destruction probability of each single building can be calculated. Thus the method reflects the actual spatial characteristics of a city and can be used for general purposes with no margin of error. It is possible to rearrange the results in different area units and to obtain the numbers of burned out houses and areas. In addition, the method provides appropriate information for conveying the fire risk to the public by showing them cluster data of the simulation. This cluster data is sometimes referred to as the Fatalistic Collaboration Community Unit.

1. INTRODUCTION

The Central Disaster Prevention Council[1] claims that is a high risk of earthquake fire disasters.

Recognizing the risk of earthquake fire disasters is important for developing national, prefectural, and citizen's countermeasures. Accurate comprehension of the risk provides essential data for formulating national strategies to reduce the earthquake fire risk in 6,000 ha of major densely-populated areas[2] in Japan. Such information is also necessary for prefectural promotion of the public awareness of disaster prevention, incorporating disaster control in urban planning, conducting disaster prevention urban development, and other activities. Information on the earthquake fire risk is also useful for making decisions at a personal level or city level to build fire-proof houses or fire-resistant houses and to simultaneously rebuild houses in a neighborhood. For measures at any level, it is important to understand the balance between risk reduction and cost in making decisions. For these reasons, information is required on not only earthquake probability but also earthquake fire damage probability or expected earthquake fire damage.

Earthquake fire risk information is often demonstrated as an estimating damage by assuming specific scenarios of fire breakout locations and fire spread. It is important information for considering detailed measures against the fire disaster, and should be acknowledged as an image of possible damage. In practice, fire breakout is a probability event, but the fire breakout probability is not included in the framework of the damage estimation. In the evaluation of earthquake fire risk, it is hence important to take into account the probability of earthquake fire breakout and assess possible damage caused by the breakout and fire spread. In addition to damage estimation, the disaster risk is sometimes presented in relative risk levels in various locations, as performed in District-based Vulnerability assessment to an earthquake in Tokyo[3], which is designated by the Tokyo Metropolitan Government , although it would be more helpful for detailed examination of measures to use, not relative, but absolute risk levels.

Risk communication is also important at the citizen level. Information on earthquake fire risks should be easy to understand and realistic as well as emphasizing the individual perspective of risk sharing.

Technology for evaluating earthquake fire risks such as the creation of digital city maps and the power of computer processing has greatly advanced, enabling improved evaluation methods reflecting the times to be developed.

In the present paper, we propose a practical earthquake-fire risk evaluation method that is highly accurate and meets various needs. The method applies to all map scale, meets national, prefectural, and citizen's needs and provides absolute fire spread risk levels by taking account of not only fire spread but also fire breakout probability. Here, the earthquake fire risk is defined as the probability of suffering fire damage or the expected cost of fire damage.

Conventional methods use functions of explanatory variables of district indices for simple evaluation of fire spread risk[4−6], or simulations to draw and analyze fire spread behavior[7−10]. The former method is versatile as it calculates the fire destruction rate based on city indices, but is limited because it models cities as a uniforme city image. The latter method is useful for showing temporal changes in the fire spread behavior based on city data, but it is limited in its high dependency on the fire breakout location because it shows fire spread damage images starting from specific fire breakout locations. Conventional methods thus have advantages and disadvantages in earthquake fire risk evaluation, depending on the development purposes. The proposed method takes account of the techniques and advantages of the conventional

KEY WORDS: fire risk evaluation, urban disaster, fire destruction probability, urban fire-spread, earthquake, GIS.

methods and minimizes their disadvantages.

The simulation method sets a fire breakout location and describes successive fire spreads starting from that location. In contrast, the proposed method but also identifies buildings in an entire city area that are expected to burn down finally instead treats fire spread between buildings dynamically. The fire destruction probability of the buildings is calculated from the probability of fire breakout in the buildings. This allows us to handle single building data, which directly reflects the spatial characteristics of the cities, as well as national-scale data, and to obtain useful data of the fire destruction probability of each building, that is not dependent on fire breakout locations. Moreover, the conventional methods treat fire breakout and fire spread in a separate manner, while the proposed method makes logical connections between each building's fire breakout probability and the fire destruction probability and enables the process from fire breakout to fire spread to be handled in an integrated manner. In the present study, a fire that would be extinguished in fire fighting at the early stages of the fire was incorporated into the fire breakout probability, and we examined only fires that would not be extinguished.

In this paper, we summarize the conventional methods, and characterize and describe our evaluation method. Then, we use the earthquake fire risk evaluation system of nationwide building data that was made in the present study to present an evaluation example with the proposed method and discuss the versatility and usability of the evaluation results produced. In this paper, we focus on the development of the evaluation method, and analysis of the evaluation results such as the characteristics of the evaluation, and regional distribution of earthquake fire risk will be given elsewhere.

2. SUMMARY OF CONVENTIONAL METHODS AND NECESSARY EVALUATION METHOD

(1) Summary of conventional methods

Conventional methods of evaluating the risk of earthquake fires spreading can be classified into ones that use the functions of explanatory variables of district indices[4−6] and ones that perform simulation[7−10]. The simulation methods are further classified according to the data used: ones that use mesh data[1] and ones that use single building data[6, 9, 10]. Below, we summarize the characteristics of each method and expected issues in the present evaluation.

a) Method of using functions with explanatory variables of city indices

Based on the relation between city indices and fire spread risk that is obtained with the simple modeling of cities and fire spread process, the method calculates the fire spread risk from the city indices. Typical methods use the "ratio of the noncombustible area"[4] and the "wooden building coverage ratio"[5]. For example, in the method that uses the ratio of the noncombustible area, a city is modeled by assuming that noncombustible areas and combustible areas are randomly distributed over 101x101 square lattice sites according to the ratio (left in **Fig. 1**) and fire spread is modeled by assuming that fire propagates to combustible buildings located in neighboring sites. Based on the modeling, numerical simulation is performed to obtain the relation between the ratio of the noncombustible area and the fire destruction rate (right in **Fig. 1**). This method was developed for simple treatment of urbanized area and the fire spread process.

In this method, the fire destruction rate can be calculated from the relation shown in the right graph in **Fig. 1** if we know the ratio of the noncombustible area of the target area. The same ratio of noncombustible area gives the same evaluation result. For example, in a comparison between a relatively uncrowded residential area with wooden buildings and a relatively crowded residential area with some large noncombustible areas including schools, the city characteristics of both areas, and hence the fire spread risk, may be different, although the ratio of the noncombustible area may be the same in both areas.

Evaluation error is dependent on the evaluation unit, and an error may be observed if a different evaluation unit is used[11]. For example the ratio of a noncombustible area could change depending on whether a school located in the vicinity of the evaluation unit boundary is included in the evaluation.

Thus a method that uses city indices is useful to simply, globally understand fire spread risk, but it also has a limitation in its evaluation precision as it handles large areas but does not reflect the spatial characteristics of districts.

b) Simulation method

The simulation method focuses on dynamic aspects of fire spread. It uses city data as input data for a simulation program to obtain time series changes in the fire destruction area. Mesh data is used in traditional simulation methods, while single building data is used in more recent simulation methods.

In the mesh data method, statistical values in the mesh area are used as basic data, and hence the mesh area is treated as a uniform urban area. Therefore, even if there is a wide main street or large open space, which is expected to have a fire-spread prevention effect, in the mesh area, it is sometimes not taken into account for fire spread behavior. **Fig. 2** shows a sample mesh area with wide main streets that have fire-spread prevention effects. The main street running from south to north in the center of the figure is so wide that it can interrupt fire spread from the left side of the street (**Fig. 2** (b)-1). In the method using the mesh data, however, the area inside the mesh is assumed to have uniform city characteristics and the main street is not effectively presented (**Fig. 2** (a)-2). As a result, the street has the effect of reducing the fire spread speed but does not stop the fire spread over the street (**Fig. 2** (b)-2).

The method that uses single building data has been widely used in recent years with the development of digital maps and the improvement of computer capability. High precision simulation

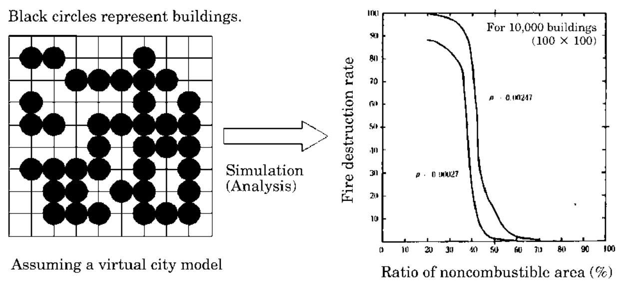
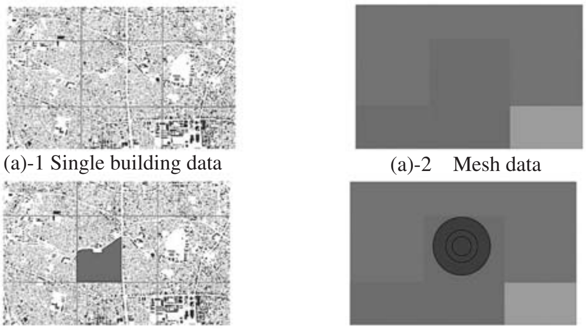


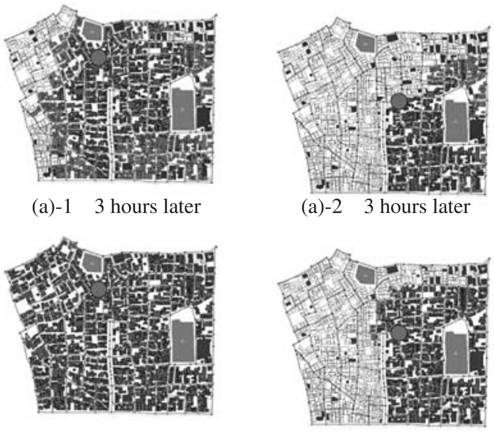
Fig. 1 Development of evaluation method, using city indices



(a)-1 Single building data (a)-2 Mesh data

(b)-1 Results (b)-2 Results (image)

Fig. 2 Limitations in the simulation method using mesh data



(a)-1 3 hours later (a)-2 3 hours later

(b)-1 6 hours later (b)-2 6 hours later

Fig. 3 Limitations of the simulation method that uses single building data (1): Different fire breakout locations have different results. The red circle in the figure shows the fire breakout location. The red color indicates burning buildings and the black color indicates burned-down buildings. All the figures use the same setting for the speed and direction of the wind.

has become possible because the smallest unit of burning, i.e. a building, is incorporated in the simulation data. Despite the improved computer capability, it is still difficult to simulate a wide city area due to the limitation of computational time(2), and the evaluation results are dependent on the location of fire breakout because fire spread is highly dependent on the situation around the fire breakout location. **Fig. 3** shows an example in which the evaluation results change with the fire breakout location. Different fire spread patterns were obtained, depending on whether the fire breakout point was set on a certain building with an open area nearby or on a building with no road around. **Figs. 3** (a) and (b) show the results of fire spread at 3 hours and 6 hours after the breakout, respectively. In the left figure, almost the entire area is burned out, while in the right figure the road on the north side of the fire breakout building stops the fire spread at an early stage. Hence the areas burned out in 6 hours in both cases are very different from each other(3).

To eliminate these negative effects, it is necessary to perform simulations for as many fire breakout patterns as possible and take the average of the outcomes and use it as the fire spread risk of the area12). However, performing simulations is time-consuming and current technology does not allow large area simulations (**Fig. 4**).

Fig. 4 Limitations of the simulation method that uses single building data (2): All fire breakout patterns were simulated based on the assumption that there is only one fire breakout in the area. The colors in the figure indicate the number of burned out buildings. This simulation was relatively time-consuming.

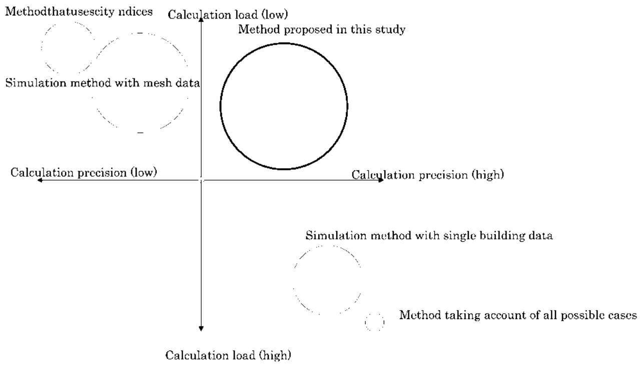


Fig. 5 Proposed method in relation to conventional methods

3. BASIC IDEA OF THE PROPOSED EVALUATION METHOD OF EARTHQUAKE FIRE RISK

Conventional methods have advantages and disadvantages as summarized above. The proposed method retains the advantages and minimizes the disadvantages (**Fig. 5**). The vertical axis in **Fig. 5** shows the computational load. Higher points on the vertical axis indicate the capability of calculating a wider city area, or indicate a higher calculation speed for a fixed city area.

The proposed evaluation method: (i) Reflects city characteristics in the evaluation by using single building data, under the current situation where a digital map has been developed and GIS's versatility has been enhanced. (ii) Calculates a wider city area than the simulation methods can do, by using a simple fire spread model. (iii) Retains connection with the fire breakout probability.

The proposed method uses a deterministic model of fire spread between buildings (with fire spread limit distance d^*) and firstly determines the buildings (referred to as a "cluster") that are expected to be burned out (**Fig. 6**). If we have a probability of fire breakout in a group of buildings, we can obtain the fire destruction probability of each building in the group. In this study, the fire destruction probability thus obtained is called the earthquake fire risk.

In this study, the earthquake fire risk is calculated for each building, and hence the result is not dependent on how the area unit is selected. In other words, any area unit can be used for the calcu-

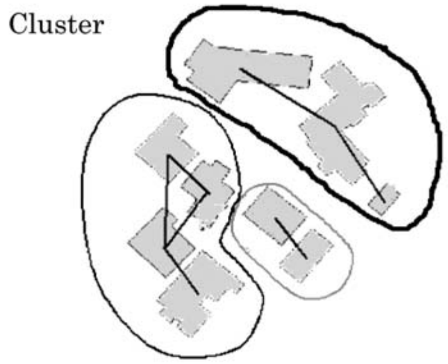


Fig. 6 Cluster generation: Neighboring buildings located within the fire spread limit distance d^* belong to the same cluster.

lation of fire risk. For example, to determine the expectation value of the number of fire destroyed buildings, we add the fire destruction probability of each building located in the area unit of interest, e.g. mesh units, city blocks, community units, fire department control areas, etc. To determine the fire destruction probability of the area unit, we divide the expectation value by the number of the buildings in the area. We can also obtain the expectation value of the burned area by multiplying the fire destruction probability of each building by the total floor area. This method thus gives an output that is highly processable and versatile for use in calculating various other values.

This study was developed, based on the concept of "CVF (Covering Volume Fraction)" [13], on which macro-evaluation methods of "Development of Assessment and Countermeasure Technologies for Disaster Prevention in Town Planning" [6], the General Technology Development Projects (hereafter referred to as General Project) of the Ministry of Land, Infrastructure and Transport are based. The differences between the proposed method and the macro-evaluation method are: (i) In the proposed method, the speed and direction of the wind are taken into account to set fire spread limit distance d, which is used in the macro-evaluation of the General Project. (ii) In the macro-evaluation, fire spread limit distance d is given for fire spread from a single building, while in the proposed method it is given for fire spread from multiple buildings. (iii) In the proposed method, the fire destruction probability is integrated with fire breakout in the cluster. (iv) Calculation on a nation-wide scale is technologically realized in the proposed method.

In addition, we developed a database of all the buildings over the country (about 62.5 million polygons) and developed a system for calculating the fire destruction probability in only a few seconds based on the fire breakout probability using a standard area mesh (third-level area division).

The overall flow of the evaluation method is shown in **Fig. 7**. We first need to prepare polygon data with structural attributes of a single building to make basic data. This kind of data has already been prepared for example in Tokyo. Based on the data, we assign parameters that affect fire spread, i.e. the speed and direction of the wind, to each building, and make polygon data with not only structural attributes but also wind-speed and -direction attributes.

Next we calculate the inter-building distance and angle for each building and compare the distance with the fire spread limit distances of various wind speeds and directions and various build-

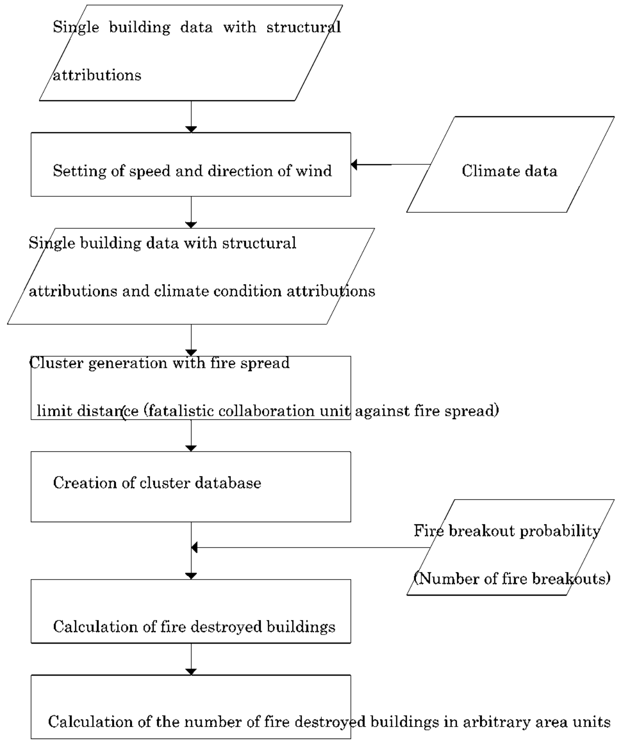


Fig. 7 Flowchart of the present evaluation

ings that are defined in the building polygon data. We then determine the cluster that is formed by the buildings located within the fire spread limit distance. The cluster is a kind of "fatalistic collaboration unit", inside which buildings would be burned out if the fire were to start from any single building in the cluster.

Finally, we calculate the occurrence probability of one or more fire breakouts inside the cluster by using the fire breakout probability of each building in the cluster. The fire destruction probability of each building is calculated by using the fact that the probability that buildings in the cluster are burned out is the same as that of fire breakout in the cluster. By adding up the fire destruction probability of each building, we can calculate the number of buildings that are expected to be burned out in the area unit.

4. DETAILS OF THE EVALUATION METHOD

(1) Model of fire spread limit distance

a) Conventional model of fire spread limit distance

Hamada's fire spread speed equation is a typical equation giving the fire spread limit distance. There are three types of Hamada model equations, which are given respectively for wooden structures, fire-proof structures, and simple fire-resistant structures. They are respectively called Hamada type[14], Horiuchi type[15], and Murosaki type[16]. When a Hamada-type fire spread limit distance is 1, that of the Horiuchi type is 1/2 and that of the Murosaki type is 1/4. The fire spread limit distance is determined according to the direction of the propagation, i.e. whether fire propagates down wind, up wind, or perpendicularly to the wind.

Recently, the macro-evaluation model[6] of the General Project of the Ministry of Land, Infrastructure and Transport has defined "fire spread limit distance *d*". The macro-evaluation model was developed to study the fire spread risk of a city and find dangerous areas in a city block unit. The macro-evaluation model sets the fire spread limit distance for each building structure and focuses on building groups located close to each other within the limit distance. The buildings in the group are considered to have fire spread risk. The fire spread limit distance in the macro-evaluation model is defined by:

① The fire spread limit distance of bare wooden structures is set to 12 m, according to the class 4 curve of fire temperature that was used by the Building Standards Law to identify the areas that could be burn out in fire spread.
② The fire spread limit distances of fire-proof wooden and quasi-fire-resistant structures are set to 6 m and 3 m respectively, in consideration of the ratios of the Hamada-type, Horiuchi-type-, and Murosaki-type limit distances.
③ The side length of a standard house is set to be 10 m, and the elevation surface of burning buildings is assumed to be covered with fire. For houses with different building areas, the fire spread limit distance is determined to have the same fire geometric factor at the heat-receiving point under the eaves on the vertical surface of a neighboring building.

Fire spread limit distance *d* thus defined is given by the following equation.

$$d = kA^r \qquad \text{—[1]}$$

Here, *A* is the side length of the building (approximated by a square root of building area). Coefficient *k* and power *r* are given for each building structure type. The fire spread limit distance of a fire-proof structure is set to zero. Let us first consider fire spread from a single building.

b) Modeling of fire spread limit distance

In the present study we define a new fire spread limit distance d^*, based on the concept of the fire spread limit distance *d* defined in the General Project "Disaster Prevention in Town Planning".

Unlike the fire spread limit distance of the General Project, the fire spread limit distance of our model is derived with wind speed to take account of local climate characteristics and is calculated for fire spread from more than one building. In other words, our fire spread limit distance is defined by considering the condition of the burning building itself and burning of buildings nearby.

Fire spread limit distance d^* is determined in the following modeling steps in this study. First, we make an assumption of fire and set a radiant heat receiving point, taking account of wind speed. Next, we derive the limit distance of fire spread from a single building. To be more specific, we take into account the width of buildings and tilting of fire to calculate the distance. Finally, we correct the distance to obtain limit distance d^* of fire spread from multiple buildings. This distance d^* is used as the fire spread limit distance in this study.

c) Assumption of fire and setting of radiant heat receiving point

Here, we assume that the room height of each floor in a building is 3 m and that fire can reach up to 2 m higher than the upmost point of the outer wall (**Fig. 8**). In the early stages of a fire, the fire blows out from openings of the building. Then the roof starts burning and finally the fire covers the entire building. So this length is chosen in consideration of the mean fire height under these two burning conditions. The heat receiving point is set to the top of a second floor room, i.e. 6 m from the ground. The assumption that fire reaches 2 m higher than the total room height is different from that in the General Project's macro-evaluation model.

In general, wind increases the fire spread limit distance. This is because fire tilts in a downwind direction. To take account of wind speed, we need to define the relation between wind speed and fire tilting angle. The relation has been extensively studied for example in Ref. 4. For convenience, we assume constant fire length, as in Ref. 4. Reference 4 used the following equation to express the relation between wind speed ν and fire tilting angle θ (angle between fire and ground in the unit of radian):

$$\sin\theta = \begin{cases} 1 & 0 \le v < 2 \\ (2/v)^{0.2} & 2 \le v \end{cases} \qquad \text{—[2]}$$

We assume that the influence of wind on fire is taken into account only for the downwind direction. When considering fire spread in the upwind direction or fire spread in a direction perpendicular to the wind direction, we assume that fire stands perpendicularly to the ground. Elliptic approximation is used for a direction not parallel to the downwind direction.

d) Derivation of limit distance of fire spread from a single building

Next, we assume the inter-building distance to have the same geometric factor (referred to as limiting geometric factor) as the fire spread limit distance in the macro-evaluation of the General Project "Disaster Prevention Town Planning". We set this distance to be fire spread limit distance d^*. In the present study, we solved the equation for a certain fire tilting angle to calculate the distance by increasing the side length of Building *A* from 4 m to 23.5 m by 50 cm. The calculation results are presented in the form $d = kA^r$, the same functional form used in the macro-evaluation of the General Project "Disaster Prevention Town Planning". The obtained coefficient is shown in **Table 2**. The limiting geometric factor is given in **Table 1**.

e) Derivation of limit distance d^* of fire spread from multiple building

Finally, we correct the fire spread limit distance to take account of the influence of multiple-building fires. We use the city model shown in **Fig. 9** where an odd number $(2N + 1)$ of buildings are located in a line and makes a square lattice, whose center faces a heat-receiving building. We assume that the buildings in the line closest to the heat-receiving building are burning.

Here we calculate, as a function of *N*, the minimum inter-building distance to prevent fire spread to heat-receiving buildings, i.e. fire spread limit distance d^*, with the building coverage being

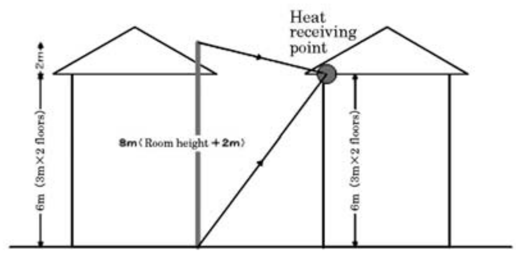


Fig. 8 Assumption of fire and setting of radiant heat receiving point

Table 1. Coefficients and powers of fire spread limit distance for various building structures

	Class 4 curve of fire temperature	Limiting geometric factor factor
Wooden	12 m	0.1428
Fire-proof wooden	6 m	0.3718
Quasi-fire-resistant	3 m	0.6579
Fire-resistant	—	∞

Table 2. Coefficient of fire spread limit distance for various building structures and various fire tilting angles

Angle θ	Wooden		Fire-proof wooden		Quasi-fire-resistant	
	k	r	k	R	k	r
90	3.79	0.49	2.03	0.46	1.28	0.35
85	4.06	0.48	2.43	0.41	1.82	0.27
80	4.30	0.46	2.84	0.36	2.38	0.21
75	4.54	0.44	3.25	0.32	2.95	0.16
70	4.77	0.42	3.67	0.32	3.52	0.12
65	4.98	0.41	4.11	0.29	4.09	0.08
60	5.14	0.39	4.60	0.24	4.63	0.05
55	5.24	0.37	5.08	0.14	5.07	0.02

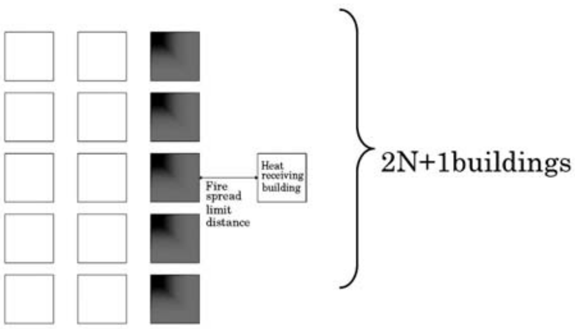
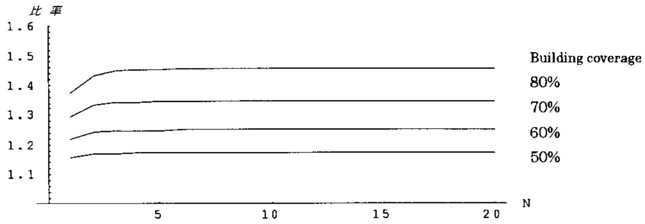
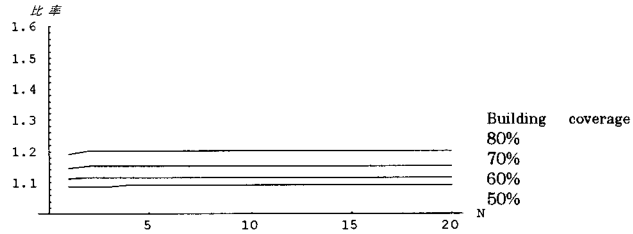


Fig. 9 Assumption on multiple-building fire in city



(a) Fire-proof wooden structure



(b) Quasi-fire-resistant eooden structure

Fig. 10 Ratio of limit distance d^* of fire spread from multiple buildings to that of fire spread from a single building: The horizontal axis presents N and the vertical axis represents the ratio of the limit distance of fire spread from multiple buildings to that of fire spread from a single building.

Table 3. Structure percentages in Tokyo Housing and Land Survey 1996

	Wooden	Fire-proof wooden	Quasi-fire-resistant
Number of buildings	197,065	957,949	210,717
Percentage	15.4%	70.1%	14.4%

m%. The side length of a building is assumed to be the square root of the mean building area 83 m^2 of residential houses, which is given in the Housing and Land Survey[18]. **Fig. 10** shows the calculated ratio of the limit distance of fire spread from multiple buildings to that of fire spread from a single building as a function of N, where $2N$+1 is the number of burning buildings on a line that face the heat-receiving building.

The figure shows that the burning buildings close to the heat-receiving building have a large influence, but the burning buildings located further from the heat-receiving building have smaller influence. This is because the geometric factor, which is used to calculate radiant heat to the heat-receiving building, rapidly decreases as the location of burning buildings becomes further from the heat-receiving building. When the burning buildings are located on the fourth line (N=4 in the horizontal axis) or further location, the ratio of the limit distance of fire spread from multiple buildings to that of fire spread from a single building does not increase and remains almost constant. The ratio changes with the building coverage or structure, and is about 1.5-2.2, 1.2-1.5, and 1.1-1.2 for wooden, fire-proof and quasi-fire-resistant structures, respectively.

We then calculated the mean value of the fire spread limit distance with the weight of the proportion of wooden, fire-proof wooden and quasi-fire-resistant structures to average all the building structures. Since we did not have the proportion data of quasi-fire-resistant structures for the whole country, we assumed the percentage of wooden, fire-proof wooden and quasi-fire-proof structures to be 15%, 70%, and 15%, respectively, based on the fire-resistant structure study of the Tokyo Housing and Land Survey (1996) as shown in **Table 3**. Using these percentages as the weight, we calculated the weighted mean of the fire spread limit distance from the ratio derived for each structure in **Fig. 10**. **Table 4.** summarizes the results for various building coverages. The mean value slightly changes with the coverage, but we assumed that the limit distance d^* of fire spread from multiple buildings was 1.5 times as long as that of fire spread from a single building.

Table 4. Weighted mean ratio of the limit distance d^* of fire spread from multiple buildings to that of fire spread from a single building

$2N+1$: the number of buildings that face heat-receiving building	Building coverage 50%	60%	70%	80%
$N=5$	1.23	1.31	1.41	1.51
$N=10$	1.23	1.32	1.41	1.52
$N=20$	1.23	1.31	1.41	1.52

(2) Determination of fire spread to neighboring buildings, calculation of inter-building distance, and generation of clusters

Before making a cluster, we need to specify neighboring buildings that can be burned out in the fire spread and calculate the inter-building distance and angle. We then build a database of the results. This is performed to shorten the calculation time for making a cluster. This calculation consumes most of the computation time. Considering the balance between calculation time and precision, we employ the following calculation algorithm:

Step 1-1: Dividing the study area into a 50 m mesh. The buildings in a 5 x 5 mesh area centering on the target building are defined as possibly neighboring buildings. However, buildings with a median point 200 m or more distant from the target building are excluded(4) from the neighboring building group.

Step 1-2: Drawing lines between the target building and the possibly neighboring buildings. We draw lines between the median points of building polygons and between the nearest points of the polygons. If a line connecting the median points of the target building polygon and a possibly neighboring building polygon does not run through other building polygons, or if a line connecting the nearest points of the target building polygon and the possibly neighboring building polygon does not run through other building polygons, we consider the possibly neighboring building to be a neighboring building. If the distance between the nearest apexes of the building polygons is shorter than 3 m, the buildings are unconditionally considered to be neighboring buildings.

Step 2-1: Measurement of the direction of the neighboring buildings. The direction is defined by a line between the median point of the target building and that of a neighboring building.

Step 2-2: Calculation of inter-building distance. The distance is measured between the target building and a neighboring building. Depending on the mutual positional relationship, the distance may be given by the shortest length between apexes or by the shortest length between the apex and the side.

To define clusters, we compare the inter-building distance and fire spread limit distance d^*, and if the former is shorter than the latter the neighboring buildings belong to the same cluster. If the neighboring buildings have different structures, fire spread limit distance d^* is given by the average of the limit distances of both structures.

(3) Assignment of fire breakout probability

In the present study, we assumed that the fire breakout probability to be an external parameter given for individual buildings.

There are different methods of estimating fire breakout probability and results are obtained in various forms (e.g. number of fire breakouts) for different area units. In this study, however, the calculations give fire breakout probabilities of individual buildings, and therefore we can rearrange the results in any format for any area unit. For example, when calculation gives the number of fire breakouts on a standard regional mesh (the third-level area division), we can obtain the fire breakout probability of individual buildings by dividing the number of fire breakouts by the total number of buildings on the mesh, assuming uniform fire breakout probability of the buildings.

(4) Calculation of fire destruction probability and expectation value of the number of fire destroyed buildings in a defined area unit

The fire destruction probability of a building is equivalent to the probability that one or more fire breakouts occur in the cluster to which the building belongs. Fire destruction probability P of a building is given by the following equation where n is the number of buildings in the cluster and p_i is the fire breakout probability of building i in the cluster:

$$P = 1 - \prod_{i=1}^{n}(1 - p_i) \qquad \text{—[3]}$$

Expectation value χ of the number of fire destroyed buildings in the area unit should be equal to the summation of the fire destruction probability of the buildings in the area unit and hence given by the following equation.

$$\chi = \sum P_k \qquad \text{—[4]}$$

We can calculate the probability and the expectation value for any area unit, if we can identify the buildings in the area unit, i.e. administrative area unit, community unit, mesh, etc.,

To save computation time, we use an approximation form of P. The fire destruction probability can be calculated for all buildings if we perform the same calculation for every cluster. The approximation form is given by

$$P = 1 - \exp(-n\bar{p}) \qquad \text{—[5]}$$

where $\bar{p}$ is the fire breakout probability in the area unit.

The fire destruction probability of buildings is calculated by Eq. [3] or [5] under the following conditions, and the precision of the approximation can be examined by comparing the results.

- Assuming that each cluster can have four different fire breakout probabilities.
- Assuming that fire breakout probability p_i is given by a random number between 0.00001 and 0.0001 and the number of buildings by a random number between 1 and 1000.

Fig. 11 shows the results of 10,000 calculations. We see from the figure that the exact value and the approximate value almost coincide with each other, which indicates the validity of the approximation.

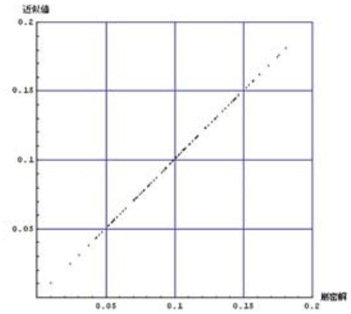


Fig. 11 Analysis of approximation precision of fire destruction probability

5. DEVELOPMENT OF A CALCULATION SYSTEM FOR EARTHQUAKE FIRE RISK OVER THE COUNTRY

(1) Data used

In the calculations, we used DAIKEI's Telemap, a commercial digital map, because of its comprehensive features, i.e. a variety of building attribute data, data conversion functions, and distinguished operability. The map data covers almost the entire country. Namely, it covers 3,052 out of all the 3,204 cities, towns and villages in Japan as of July 2003 and the coverage rate is 95.7%.

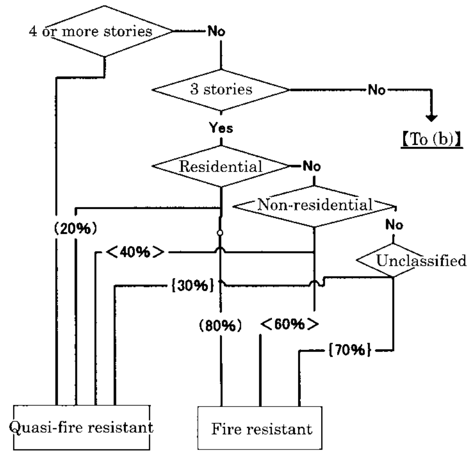
We also referred to climate information database AMEDAS of the Japan Meteorological Business Support Center for wind speed and direction data. The database contains climate data from the past 29 years (1976-2004). At total of 976 observation sites provided both wind speed and wind direction data, including sites that had already been eliminated. As wind data we obtained daily mean wind speed, daily mean wind direction and daily maximum wind speed.

(2) Assignment of structure

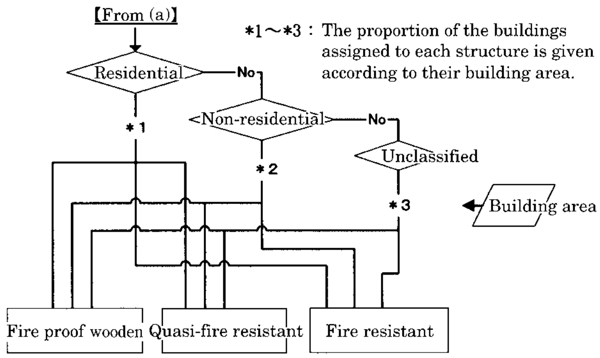
DAIKEI's Telemap provides building attributes such as building type (building/apartment, residential house, office house, unknown) and the number of floors (for buildings of three or more stories), but not structural attributes. For simplicity we estimated the type of building structure (**Fig. 12**) by using two building attributes provided by the Telemap and comparing the structures with known data(5). Herein, we refer to buildings, apartments, and office houses as non-residential buildings.

In the calculations, due to the restriction on data, we assumed that all wooden buildings had a fire-proof structure.

① Buildings of four or more stories are assigned as fire-resistant buildings.
② 0%, 80%, and 20% of residential houses of three stories are assigned as fire-proof wooden, quasi-fire-resistant, and fire-resistant buildings, respectively.
③ 0%, 60%, and 40% of non-residential houses of three stories are assigned as fire-proof wooden, quasi-fire-resistant, and fire-resistant buildings, respectively.
④ 0%, 70%, and 30% of other unclassified buildings of three stories are assigned as fire-proof wooden, quasi-fire-resistant, and fire-resistant buildings, respectively.
⑤ The percentages q_{1i} and q_{2i} of buildings of one or two stories assigned to fire-resistant and quasi-fire-resistant buildings



(a) Structure assignment of buildings of three or more stories



(b) Structure assignment of one- or two-story buildings

Fig. 12 Flowchart of building structure assignment

Table 5. Assumption on the percentages of structures for the assignment of one- or two-story residential houses(5)

Building area	Fire-resistant	Quasi-fire-resistant
-75 ㎡	q_{11} = 2.0	q_{21} = 10.0
75-100 ㎡	q_{12} = 2.0	q_{22} = 15.0
100-200 ㎡	q_{13} = 3.0	q_{23} = 20.0
200 ㎡-	q_{14} = 3.0	q_{24} = 20.0

respectively are given for various building areas in **Table 5**. The number of buildings for various building areas, n_i, is extracted from the Daikei Telemap data. Regional coefficient k is calculated by the following equation using the proportion of non-wooden buildings Q among residential houses (including those of three or more stories) given in the prefectural data[18] of the Housing and Land Survey:

Regional coefficient $$k = \frac{(\Sigma n_i)Q}{\Sigma n_i(q_{1i} + q_{2i})} \quad \text{—[6]}$$

The regional coefficient k, which is determined by the proportion of non-wooden buildings Q of all the prefectures, is used to correct the percentages of fire-resistant or quasi-fire-resistant buildings in various districts. The corrected percentages of fire-resistant and quasi-fire-resistant buildings of various building areas are given respectively by k_{q1i} and k_{q2i} where k is the regional coefficient. We assign the structure of buildings by using computer-generated random numbers according to the structure percentages thus obtained.

⑥ Non-residential houses of one or two stories are assigned according to the percentages of fire-resistant and quasi-fire-resistant buildings to various building areas as shown in **Table 6**.

⑦ Data analysis indicated that other unclassified buildings of one or two stories had various intermediate features between one- or two-story residential houses and one- or two-story non-residential houses. We thus assume that the structure percentages of other unclassified buildings of one or two stories are given by the average of those for the residential houses and those for the non-residential houses.

The structure assignment needs to be refined. No structural estimation is necessary if we have structural attribute data such as GIS, the city planning of Tokyo.

(3) Assignment of the speed and direction of the wind

To each building, we assigned wind data of speed and direction at the nearest observation point. With the present system, we can calculate earthquake fire risk at arbitrary wind speeds and directions. It is also possible to calculate earthquake fire risk by taking account of the occurrence probability of wind speed and direction, unless computational time is limited. In our calculation, we used data obtained at 826 observation sites that had a total of 15 months or longer observation history, and converted it to wind speed at 10 m height from the ground[6].

(4) Calculation time

We reduced the calculation time on PC by improving the algorithm, etc. The calculation of fire spread from a single neighboring building required about one week to cover approximately 62.5 million buildings. The calculation of cluster buildings took about 12 hours in total. In the calculation of earthquake fire risk on the standard regional mesh (the third-level area division) over the country, the time required to calculate the fire destruction probability with a certain data set of wind speed and direction could be reduced from ten minutes to several tens of seconds[7]. These results show that the proposed method is practical.

6. EXAMPLE OF CALCULATION

Here we show the calculation results in every scale and describe the results.

In our test calculations of earthquake fire risk, we used mean wind speed and the most frequently observed wind direction in the year as the basic data on the speed and direction of the wind.

Fig. 13 shows the results of test calculations with an assumption that the fire breakout probability in each building is constant over the country. In the calculation, we set the fire breakout probability of a residential house on a winter evening to be 0.00048 at 1,000 gal, following Ref. 19). The standard regional mesh of the third-level area division was used for the area unit. From the calculation, we see regional characteristics in each city. **Fig. 14** is the test calculation result on the fire destruction probability with the fire breakout probability being set to the estimated value[8] for Tokai-HigashiNankai-Nankai Earthquake. The fire destruction probability distribution receives relatively little influence from the seismic center, in comparison with the fire breakout probability distribution. This kind of analysis can be performed within a few minutes.

Fig. 15 shows the calculation results for Tokyo with mesh, buildings, and close-up views. As shown in the figure, the results can be arranged for arbitrary area units such as city blocks, community units, or fire department control areas, if polygon data of the area unit is provided.

7. ENABLING RISK INFORMATION TO BE CONVEYED TO CITIZENS AND CITIZENS TO SHARE THE RISK

To reduce earthquake fire risk, it is necessary to make more buildings fire-proof or fire-resistant and improve methods of preventing fire spread for example by developing roads. This cannot be done by individual people, so cooperation in local communities and towns is essential. However, cooperation is not necessarily required for reducing the risk of building collapse.

Here we describe the response when we showed our evaluation results to some citizens to convey risk information to them and to let them share the risk[9]. There are two important factors in conveying risk information and encouraging people to share the risk.

Table 6. Assumption on the percentages of structures for the assignment of one- or two-story non-residential houses[5]

Building area	Fire-resistant	Quasi-fire-resistant
-75 m²	q_{11} = 4.0	q_{21} = 20.0
75-100 m²	q_{12} = 4.0	q_{22} = 30.0
100-200 m²	q_{13} = 6.0	q_{23} = 40.0
200 m²-	q_{14} = 12.0	q_{24} = 50.0

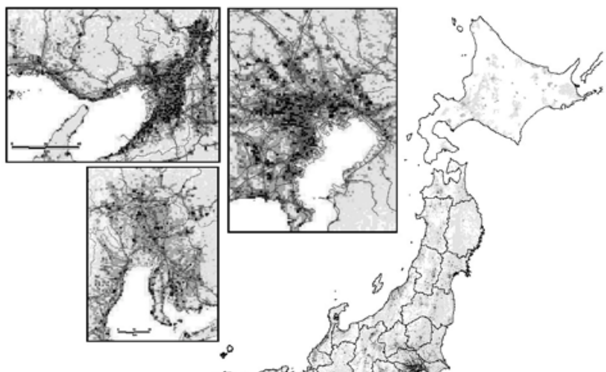
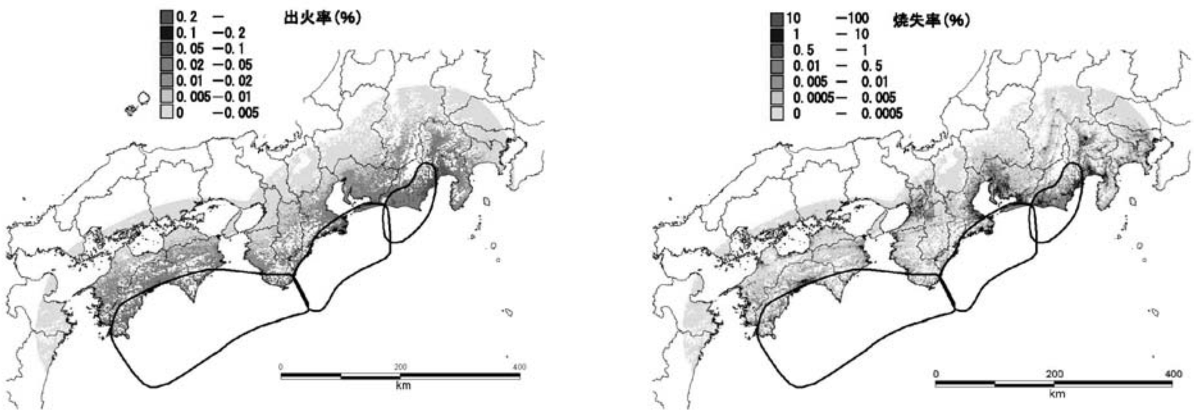
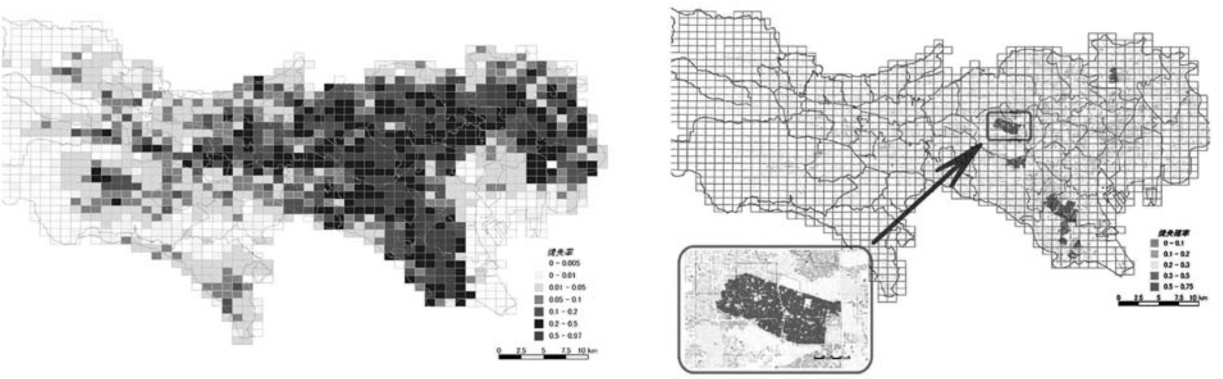


Fig. 13 Earthquake fire risk over the country on standard regional mesh (the third-level area division) with the fire breakout probability being assumed to be constant



(a) Fire breakout probability (%) (b) Fire destruction probability (%)

Fig. 14 Trial calculation of earthquake fire risk in Tokai-HigashiNankai-Nankai Earthquake: Standard area mesh (The third-level area division)



(a) Fire destruction probability (%): Standard area mesh (The third-level area division)

(b) Fire destrucion probability: For individual buildings[10]

Fig. 15 Evaluation results for Tokyo (In-land earthquake in Tokyo)

(a) Fatalistic collaboration unit against fire spread (Cluster)

(b) Fire destruction probability

Fig. 16 Typical city area downtown Tokyo[10]

The first factor is whether they can intuitively acknowledge the risk as their own problem. The other factor is whether they can recognize the need to cooperate within cities or local communities.

The proposed method enables people to find their houses on the map and recognize how earthquake fire risks affect them personally. They can recognize the likelihood of having fire damage from the fire destruction probability of their houses and they only need to estimate the occurrence probability of an earthquake.

In addition, showing clusters on the map will promote cooperative activities in cities and local communities. **Figs. 16** (a) and **17** (a) show the clusters with colors. When explaining to the public, we use the expression "fatalistic collaboration unit against fire spread" to refer to the cluster. From the cluster map, people would not think "I just need to make my house fire-resistant" or "I'm safe in my house because it is fire-proof (or quasi-fire-resistant)", they would instantly recognize the importance of disaster prevention of the entire city or entire local community. They would also understand the directionality of the measures that are required such as fire breakout prevention in a cluster or further division of clusters. When we showed our results to some people, they found that the cluster extended over several local communities. They said, "We need to collaborate not only within our community but also with

(a) Fatalistic collaboration unit against fire spread (Cluster)

(b) Fire destruction probability

Fig. 17 Residential area uptown Tokyo[10]

neighboring communities!". This clearly indicates the effectiveness of the proposed method.

8. SUMMARY AND PROBLEMS

The proposed method has the following main characteristics:

- This is an integrated method that can handle from a single building to nation-wide scale.
- Unlike conventional methods using city indices or simulation methods using mesh data, this method uses single building digital map data and can reflect the spatial characteristics of a city.
- This method is appropriate for fire risk evaluation as it gives an absolute value of fire destruction probability based on the fire breakout probability.
- Fire destruction probability is calculated for each building. Hence the data is highly versatile and the results can be arranged for arbitrary area units such as administrative block areas, meshes, city blocks, fire department control areas, etc. No errors are expected in the data arrangement. Also, the data can be easily converted to the number of fire destroyed buildings, burned areas, and others.
- This method is effective for conveying risk information to citizens or of sharing risk among citizens if in clusters, the intermediate data created in the calculation process, are presented to them as "fatalistic collaboration units against fire spread".

The proposed method has the same advantages of conventional methods but minimizes the disadvantages and is feasible under the current technological environment.

Due to the limited capacity of PCs, we used the same fire spread limit distance of multiple-building fire to make clusters. However, as computational power and memory increase, calculation accuracy will improve and enable us to define two-level clusters, i.e. the cluster defined for the process by which a single-building fire grows to a multiple-building fire and the cluster for the process after the multiple-building fire begins.

In the proposed method, caution may be required when making an interannual comparison of the earthquake fire risk. As the fire spread process is described with the fire spread limit distance model and evaluation results are affected by position errors of building polygons in digital maps, it is necessary to pay attention to the continuity of the polygon data between new and old digital maps to be used for interannual comparison. In the map that we used in our system, buildings that are actually changed are added to the map when it is revised. However, some maps, such as city planning base maps prepared by the administration, are completely revised once every few years. In these maps, building shapes are sometimes modified in the revision even if the buildings are not actually changed. This may cause a change in the evaluation results. When studying the risk over several years, it is hence necessary to make quantitative examination of the affect that errors contained in maps have on the evaluation results.

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NOTE

(1) There are many references, such as Refs. 7) and 8). (2) For example, even the simple algorithm that we developed requires about 10 minutes for a single fire spread simulation of 100,000 buildings. (3) This is the case of the system described in Ref. 23). (4) When this distance is too short, neighboring buildings may not be included in the calculation, and when it is too long calculation is too time-consuming. We looked for the most efficient setting by changing the distance. (5) This is based on the data of Arakawa-ku, Tokyo in 1996. (6) The actual wind speed at the observation point is converted by the following equation to the speed at 10 m height from the ground:

$$\frac{V_h}{V_{h_0}} = \left(\frac{h}{h_0}\right)^p$$

Here, V_h and V_{h0} represent the wind speed at the height h and h_0 (m) respectively. We set h_0 to 0 and the constant p to 1/7.

(7) This is based on calculation using a machine equipped with 3GHz Pentium4 and 1Gb Memory. (8) This is based on a trial calculation by the Non-Life Insurance Rating Organization of Japan. (9) This was presented to a local community by Professor K. Takano at Tohoku University of Art and Design, H. Kamiya at MANU Institute for Urban Design and Architecture, and others.

The data used here is local government data. (10) Permission number Z06A-2601 of Zenrin Co., Ltd. (11) This study was part of the research (2002-2003, 2005) conducted by the Non-Life Insurance Rating Organization of Japan. (Earthquake insurance research 6, http://www.nliro.or.jp/disclosure/q_kenkyu/index.html)

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