

Possibility of Suppressing Fire Spread in the Event of a Large Earthquake by Greening and Demolishing Vacant Houses

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ABSTRACT

In recent years, disaster mitigation measures by greening and demolition of vacant houses to prevent large post-earthquake fire spread have been promoted. However, few studies evaluate its effects on reducing property damage and human casualties, especially in vulnerable areas for earthquakes, such as densely built-up wooden residential areas. In this paper, we develop a model to describe the delay of post-earthquake fire spread between neighboring buildings, and incorporate it into the simulation model. Using the integrated model, we evaluate the reduction of the number of burnt-down buildings and human casualties in densely built-up wooden residential areas, and demonstrate the effectiveness of greening and demolition of vacant houses.

Keywords

greening, demolition of vacant houses, fire-spread model, large earthquake, simulation.

INTRODUCTION

Research Background

Greening policies are being promoted around the world, primarily from the perspective of preserving the living environment, with the hope of reducing CO₂ emissions and alleviating the urban heat island effect. Concurrently, with natural disasters increasing in recent years, the function of trees is being evaluated from the perspective of disaster prevention and mitigation (Shin et al., 2014). The role of trees as windbreak forests and tidewater control forests, for example, goes without saying, but trees can also be expected to have an effect in delaying and blocking the spread of fire in urban areas. Based on a field survey of a large fire in the city of Itoigawa on December 22, 2016, Iwasaki (2019) reported that even inside the affected area were hedges with most of the leaves on the surface of the crown still green. He also reported that the houses that were spared from the spread of the fire were adjacent to trees or empty lots. If it can be shown that greening policies are effective in suppressing the spread of fires, this could serve as an important argument for promoting greening policies in Japan. The research question of this study is validating whether urban greening can be expected to be effective in reducing fire spread damage followed by a large earthquake. Based on this background, “greening” in this paper is defined as the act of planting plants, especially evergreen or deciduous trees which have higher resistance than coniferous trees to prevent fires, between buildings to increase the effectiveness of preventing and delaying the spread of urban fires.

Recently, the problem of empty homes has worsened (Ministry of Land, Infrastructure, Transport and Tourism, 2017). The question of how to use vacant houses as housing stock is an important issue, but leaving deteriorated houses without occupants is a major problem in terms of preventing disasters and crime. Old wooden houses are

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considered particularly problematic as elements that increase the risk of collapse and fire spread in the event of a large earthquake.

Because of these issues, efforts to enhance disaster prevention capabilities by greening and demolishing vacant houses are being made in areas such as those that are crowded with wooden housing (hereafter, densely built-up wooden housing areas). A method for quantitatively examining ways of greening and demolishing vacant houses to reduce property damage and human casualties effectively and efficiently in the event of a large earthquake is required.

Related Research

Li and Davidson (2013) extended their urban fire simulation model to include a fire ignition-spread-suppression process by taking into account firefighting activities and evaluated the effectiveness of the fire department's efforts. They also applied this model to a region in California and conducted parametric studies to investigate the key factors that influence fire spread. Khorasani and Garlock (2017) focused on the past 20 large fires following earthquakes from seven different countries, and reviewed the latest literature on post-earthquake fire mitigation techniques, as well as analytical tools for assessing fire ignition and spread. Manzello et al. (2018) suggested that research on large urban fires that occur after earthquakes and how to reduce the loss of buildings from such fires has lagged, and attempted to develop a roadmap for international research needs to reduce the risk of large outdoor fires. Manzello et al. (2020) reviewed experiments, models, and simulations related to firebrand generation, lofting, burning, transport, deposition, and material ignition in large-scale outdoor fire spread. They also pointed out that most of the knowledge in Japan that caused serious large-scale outdoor fires is still not available in English literature. Even if the technology or characteristics are unique to Japan, it is of great significance to communicate in English the experience and knowledge cultivated in Japan, which is prone to earthquake disasters. Vitorino et al. (2024) presented a review of the state-of-the-art on previous post-earthquake fire events, its risk estimation, fire ignition models, and probabilistic loss assessment. They also introduced several mitigation strategies that can help reduce or prevent post-earthquake fires.

Large-scale urban fires have occurred not only in Japan but also in various parts of the world, leading to the development of numerous sophisticated fire spread models. However, Japan's unique characteristics, including building structures (degree of fireproofing), open space sizes, road widths, distances between buildings, and the density of vegetation between structures, pose challenges in directly applying these validated models. Additionally, the rarity of large-scale fire outbreaks necessitates estimating parameters for current models based on surveys such as those conducted for the Great Hanshin-Awaji Earthquake (1995). Consequently, while we will be incorporating some well-established models rooted in earlier research, our focus will remain on post-earthquake fires occurring within Japan's distinctive environment.

The Ministry of Construction's Comprehensive Technology Development Project (Technology Research Center for National Land Development, 1983) proposed a pioneering method of determining the time required for fire spread, the fire-blocking effect of structures, etc., by calculating the amount of radiant heat when a fire spread between two buildings by using a theoretical equation (solid angle projection ratio). Based on this method and the results of surveys of disasters such as the Great Hanshin-Awaji Earthquake, a model (Tokyo Fire Dept. Model 2001) for describing the spread of fire in urban areas more simply has been proposed (Tokyo Fire Department, 2001).

Excellent research on the fire-preventive function of trees during large fires in urban areas has been performed by Saito and Iwakawa (1982) and Iwakawa (1984). Using experiments and a review of the literature, their research has clarified the relationship between tree shape and heat shielding rate, heat shielding ability, ignition/burning conditions, and fire resistance threshold. Also, Saito and Tabata (1991) incorporated Iwakawa's approach for calculating the shielding rate of trees into a method for calculating radiant heat in the Ministry of Construction's Comprehensive Technology Development Project (Technology Research Center for National Land Development, 1983), and examined theoretically the fire-blocking effect as a function of tree height, crown size, etc.

Based on these theoretical models, simulations of fire spread in urban areas that take into account the presence of trees have recently been attempted. For example, using an earthquake fire spread simulation system that incorporates the fire prevention effect of trees, Futagami et al. (Futagami et al., 2006; Futagami and Kunikata, 2015; Futagami, 2023) quantitatively evaluated the fire prevention effect of trees (differences in the presence or absence of trees) by varying wind speed, wind direction, and fire point. Also, Nishi and Futagami (2019) have developed a data input interface for the earthquake fire spread simulation system that takes into account tree species and shapes such as evergreens, deciduous trees, and hedges, and used this to evaluate the effects of existing greenery, hedge placement, setbacks, the removal of vacant houses, tree planting, and planting trees around open spaces. Nagano et al. (2008) targeted densely built-up wooden housing areas in Kanazawa City to examine the

effect of tree belts on preventing fire spread. Their simulation assumed the current state of planting and additional new planting. This was similar to the simulation attempted in the present study and served as a reference. Kumagai et al. (2009) simulated fire spread in an urban area using detailed vegetation distribution data collected by remote sensing.

In research on the effect of demolishing vacant houses on disaster mitigation, Nakai et al. (2012) calculated and compared arrival rates at temporary evacuation centers in densely built-up areas of Osaka City when the sites of vacant houses are converted into roads, used for road widening, or used as temporary evacuation centers. Nakajima et al. (2018) developed a model for predicting the occurrence of vacant houses on the basis of a field survey of an area where fireproofing was being promoted in Yokohama City and made predictions for up to 50 years in the future. They used a fire-spread cluster (Kato et al., 2006) approach to estimate the reduction in the rate of buildings destroyed by fire in the event of a large earthquake that can be expected when vacant wooden houses have been fireproofed and when all vacant houses have been demolished.

As reflected in the abovementioned prior research, many theoretical studies about the effects of trees on delaying and blocking fire spread have been carried out, as well as many simulations of the effects of greening and demolishing vacant houses on reducing fire damage. However, as far as the authors of the present paper are aware, there has been no research that examined the contribution of greening and demolishing vacant houses to reducing human casualties by linking fire damage and the evacuation behavior of residents. We were also unable to find studies that quantitatively examined effective and efficient methods for determining tree placement and vacant house demolition.

Research Objectives

Osaragi and Oki (2017) constructed a comprehensive simulation model that takes into account the interaction between property damage and human behavior (evacuation behavior, rescue activities, and initial firefighting activities) during a large earthquake (hereinafter, property damage/human behavior simulation model). A feature of this model is the incorporation of initial firefighting by local residents. In densely built-up wooden housing areas, the time it takes for a fire to spread from the building of fire origin to an adjacent building (fire-spread time) is short, and initial firefighting by local residents is less likely to succeed (Oki and Osaragi, 2018). If fire spread can be delayed by greening and demolishing vacant houses, it may be possible to improve the success rate of initial firefighting and reduce the number of fatalities and fire-damaged buildings. This was the hypothesis of the present study.

In this paper, we examine a method of incorporating the effect of delaying the time of fire spread between adjacent buildings by greening and demolishing vacant houses into the property damage/human behavior simulation model. Next, we examine the effect that delaying the time of fire spread between adjacent buildings has on reducing fire damage (number of fire-damaged buildings) and human casualties (number of fatalities) in the event of a large earthquake. Finally, we examine effective and efficient tree placement and vacant house demolition.

SIMULATION MODEL FOR EVALUATING THE EFFECT OF TREES ON DELAYING FIRE SPREAD

Method of Calculating Fire-spread Delay due to Trees

Methods proposed by the Ministry of Construction's Comprehensive Technology Development Project (Technology Research Center for National Land Development, 1983), Saito and Iwakawa (1982) and Iwakawa (1984) calculate the fire-spread time when there are trees between the building of fire origin and an adjacent building (hereafter, "Iwakawa model"). Table 1 and Fig. 1 show the variables used in the Iwakawa model. With these variables, it is possible to calculate the amount of radiant heat received between the nearest adjacent points of the building of fire origin and an adjacent building, R [kcal/(m²·h)], the amount of heat received at a heated point, q [W/cm²], and the time required for ignition, t [s] (Equations (1)–(3)). Iwakawa (1984) describes the derivation methods in detail, and because these are key equations in this paper, APPENDIX provides a summary. In Equation (1), E is the amount of radiant heat from the radiation test surface (= 44,000 kcal/(m²·h)), Φ is an urban area coefficient described by building area ratio m , F is the configuration factor for the heated point of the radiation test surface that is visible through the trees, e is the mean bright surface ratio of the radiation test surface corresponding to the configuration factor $f(a, b, r)$. Also, transmittance τ is a value determined according to tree type, tree shape, and season.

Table 1. List of variables used in the Iwakawa model

	Variables
E	Radiation from the surface of flame (constantly 44,000) [kcal/(m ² ·h)]
h_1	Height of tree [m]
B	Width of burning building [m]
c	Height of heated point [m]
U	Wind speed [m/s]
α	Wind direction [rad]
d	Distance between two buildings [m]
d_0	Distance between heated point and tree [m]
D	Simultaneous burning area [m]
c_1	Ratio of sum of fire-resistant buildings area divided by sum of all buildings area
c_2	Ratio of sum of semi-fire-resistant buildings area divided by sum of all buildings area
m	Building coverage ratio in the town
τ	Transmittance (= 1 - (shielding rate by a tree or a hedge))
R	Amount of radiant heat received between the nearest adjacent points of the building of fire origin and an adjacent building [kcal/(m ² ·h)]
q	Amount of heat received at a heated point [W/cm ²]
t	Time required for ignition [s]
Φ	Urban area coefficient described by building area ratio m
F	Configuration factor for the heated point of the radiation test surface
e	Mean bright surface ratio of radiation test surface corresponding to configuration factor
τ	Value determined according to tree type, tree shape, and season
I, J	Heating-side building, Heated-side building
i, j	Heating-side building point, Heated-side building point
N_{ν}	Set of surface combination
n_{ν}	The number of elements in the set N_{ν}
F_{ν}	Value of the configuration factor for heating-side building I and heated-side building J
F_{ij}	Value of the configuration factor for heating-side point i and heated-side point j
R_{ij}	Amount of heat received by surface j from surface i
$R_{\nu j}$	Amount of heat received by surface j from heating-side building I
R_{ν}	Maximum value of $R_{\nu j}$ over j
t_{ν}	Fire-spread time from building I to building J
D_0	Simultaneous burning area [m]
h_0	Flame height [m]
θ	Flame tilt [rad]

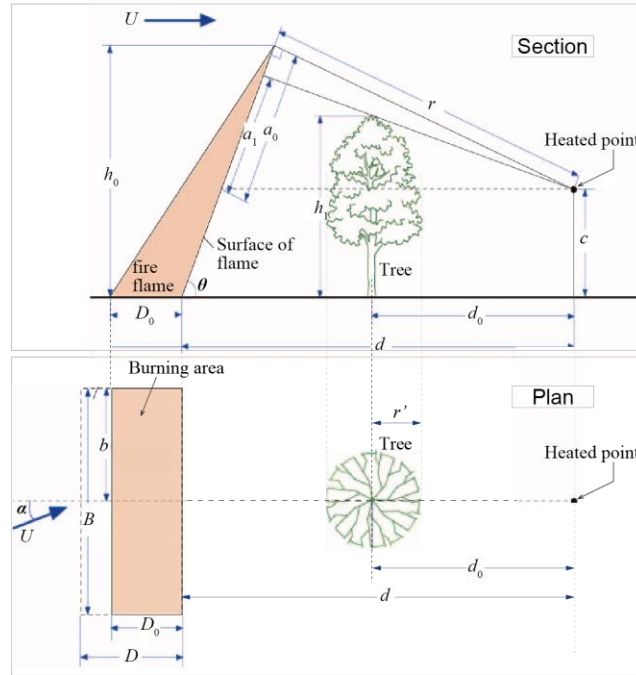


Figure 1. Illustration of variables used in the Iwakawa model

$$R = E \times \Phi^{0.5} \times F \times e \times \tau \quad [\text{kcal}/(\text{m}^2 \text{h})] \quad (1)$$

$$q = R \times 1.163 \times 10^{-4} \quad [\text{W}/\text{cm}^2] \quad (2)$$

$$t = -1.6 \times 10^3 \times \log_{10} \left(1 - \frac{0.53}{q} \right) \quad [\text{s}] \quad (3)$$

In this study, a more sophisticated model was created by incorporating consideration of the buildings on the heating-side and heated-side as face elements when calculating the amount of radiant heat received, R , rather than considering only the possibility of fire spread between the nearest adjacent points of adjacent buildings (Fig. 2).

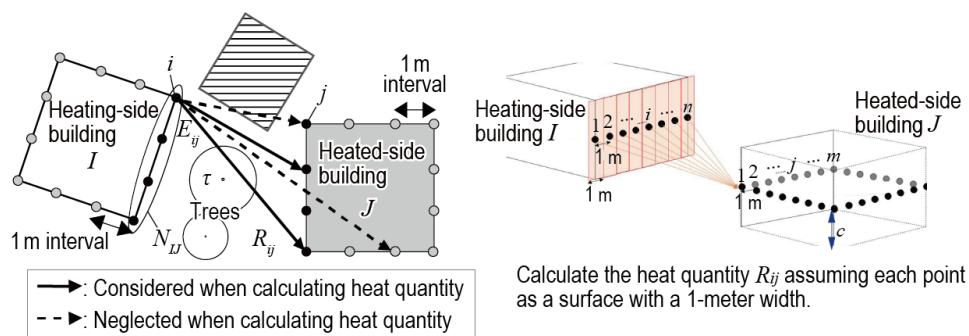


Figure 2. How to consider heating surface and heated surface for calculating the amount of radiant heat received

Specifically, we consider a heating-side building I and a heated-side building J . First, surfaces i and surfaces j are formed by dividing the outer circumference of each building into approximately 1 m intervals. Points are generated at equal intervals on the outline of the building using the “Densify” tool of ArcGIS. The interval between points is automatically adjusted to be proximate to the specified interval (here, 1 m) such that the start and end points of the point generation coincide. It is assumed that every surface i can be a radiating surface and every surface j can be a heated surface. The set of surfaces i is denoted by N_{IJ} and the number of elements in the set is denoted by n_{IJ} .

If the line segment $i-j$ established between surface i and surface j intersects with a building, etc., radiant heat along $i-j$ is considered to be blocked and so is not included in the thermal calculations. In this case, the configuration factor for heat received from the area of the radiation test surface i ($\in N_{IJ}$) (Fig. 2, right), F_{ij} , can be expressed as follows:

$$F_{ij} = \frac{F_{IJ}}{n_{IJ}} \quad (4)$$

where F_{ij} is the value of the configuration factor, F , for heating-side building I and heated-side building J . In this case, from Equations (1) and (4), the amount of heat received by surface j from surface i , R_{ij} , is

$$R_{ij} = E \times \Phi^{0.5} \times F_{ij} \times e \times \tau \quad [\text{kcal}/(\text{m}^2\text{h})] \quad (5)$$

When the distance from the center of a tree to the path of fire spread (line segment $i-j$) is shorter than the radius of the tree, the shielding effect, $\tau < 1$, of the tree is considered. Next, the sum of R_{ij} giving the amount of heat received by surface j from heating-side building I is found, denoted R_j [$\text{kcal}/(\text{m}^2\text{h})$], and the maximum value of R_j over j , denoted R_{IJ} , is taken to be the amount of heat that heated-side building J receives from heating-side building I (Equation (6)). This is used to calculate the fire-spread time from building I to building J , t_{IJ} [s] (Equations (7) and (8)).

$$R_{IJ} = \max_j R_j = \max_j \sum_{i \in N_{IJ}} R_{ij} \quad [\text{kcal}/(\text{m}^2\text{h})] \quad (6)$$

$$q_{IJ} = R_{IJ} \times 1.163 \times 10^{-4} \quad [\text{W}/\text{cm}^2] \quad (7)$$

$$t_{IJ} = -1.6 \times 10^3 \times \log_{10} \left(1 - \frac{0.53}{q_{IJ}} \right) \quad [\text{s}] \quad (8)$$

Using the above method, the fire-spread time between adjacent buildings taking into account the presence of trees is calculated, and the difference in fire-spread time, Δt , is regarded as the fire-spread delay attributable to trees.

Generally, as a fire spread, heat is received from multiple burning buildings, and therefore the fire-spread time becomes shorter. However, this paper discusses the initial stage of fire spread from the building where the fire breaks out to an adjacent building, not fire spread between multiple buildings.

Incorporation into Urban Fire-spread Model

Using the model developed by Tokyo Fire Department's Fire Prevention Council (Tokyo Fire Dept. Model 2001), this paper describes the spread of fire not only between adjacent buildings but also at the urban area level. In Tokyo Fire Dept. Model 2001, fire-spread time is calculated using parameters that include the distance between adjacent buildings, wind speed, and building structure on heating-side/heated-side. Fire-spread time for between adjacent buildings can be calculated without performing complicated thermal calculations, but it is not possible to directly consider changes in the amount of heat received due to the shielding effect of trees (delay of fire spread).

Therefore, by finding the difference in fire-spread time between with and without trees, Δt , with the method described in the preceding section and adding this value to the fire-spread time, T , calculated using Tokyo Fire Dept. Model 2001, the shielding effect of trees can be incorporated into the fire-spread model at the urban area level. Here, two parameters (height of heated point and opening ratio) were adjusted so that the fire-spread time between adjacent buildings without trees approximated the calculation results of Tokyo Fire Dept. Model 2001 (Fig. 3). For wooden buildings, the difference between the two models is minimized by taking the height of the heated point to be half the height of the building on the fire origin side (3 m above ground). For fire-resistant and quasi-fire-resistant buildings, the height of the heated point is set at 3 m above the ground and the opening ratio (percentage of wall height taken up by opening height) at 55%. At a distance between adjacent buildings of less than 1 m, the difference from Tokyo Fire Dept. Model 2001 becomes rather large, but this was not considered to be an issue within the realistic range of distances between adjacent houses (Fig. 3). The rationale behind setting specific parameters for particular building combinations stems from the fact that the likelihood of fire spreading is influenced by the combination of building structures on the heating and heated sides. Specifically, wooden buildings have a higher likelihood of catching fire from adjacent burning structures compared to fire-proof buildings. Additionally, the amount of heat generated during combustion, which contributes to the spread of fire to neighboring buildings, is greater for wooden buildings and lesser for fire-resistant buildings.

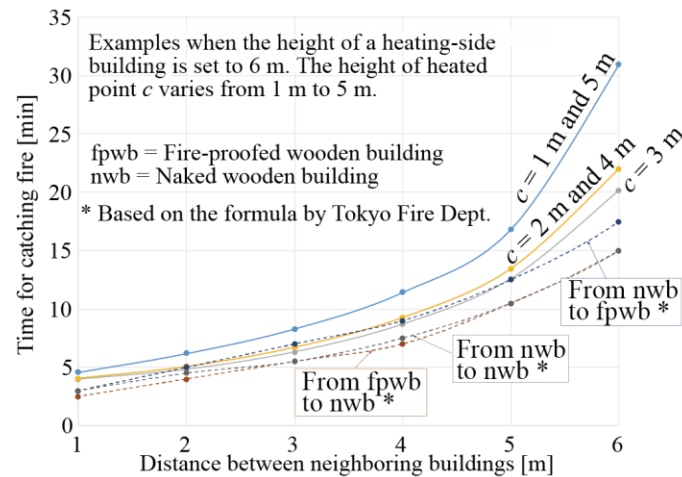


Figure 3. Distance between neighboring buildings and time for catching fire (in case of fire spread between wooden buildings)

Also, when fire spread enlarges, flame height h_0 exceeds 10 m and flame tilt θ also increases due to the effect of wind speed U and wind direction α , so a shielding effect cannot be expected from groups of trees such as those considered in this paper. Therefore, the effect of trees is not taken into account in calculations concerning the stage of fire-spread enlargement that follows the initial stage.

Method of Estimating the Number of Fire-damaged Buildings and Fatalities

The abovementioned effect of trees in delaying or blocking fire spread is incorporated into the property damage/human behavior simulation model (Tokyo Fire Department, 2001) used to examine property damage (number of fire-damaged buildings) and human casualties (number of fatalities) in the event of a large earthquake. This property damage/human behavior simulation model is a major part of the calculation process appearing in this paper. Osaragi and Oki (2017) developed a comprehensive simulation model (Fig. 4) that integrates property damages (building collapse, fire spread, and street blockage) and various activities (rescue activity, firefighting activity, and wide-area evacuation activity) by residents in a large earthquake. This model can analyze the effect and risk of rescue and firefighting activities carried out by residents under the assumption that a large earthquake directly hits the Tokyo area. Furthermore, it can analyze situations where there are many fatal casualties caused by people failing to evacuate, being trapped on streets, and so on. The details of the model is given in Osaragi and Oki (2017).

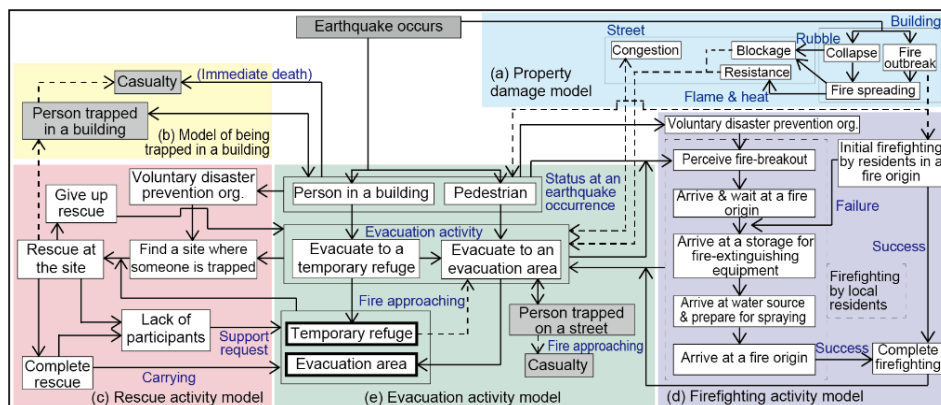


Figure 4. Overview of the property damage/human behavior simulation model (Osaragi and Oki, 2017). This is a comprehensive simulation model that integrates property damages (building collapse, fire spread, and street blockage) and various activities.

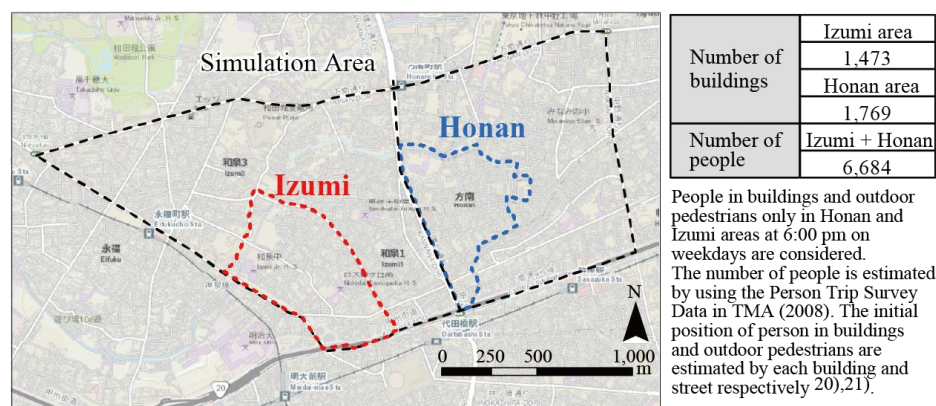
However, many pages would be required for a detailed explanation, and therefore a summary of the model is given in Osaragi and Oki (2017).

The following sections analyze the extent to which the number of fire-damaged buildings and fatalities due to a large earthquake could be reduced by reducing the fire-spread time through greening and demolishing vacant houses. Specifically, it is expected that by reducing the fire-spread time, initial firefighting by local residents using standpipes, for example, could succeed in time to limit the fire damage to the building of fire origin only. A reduction in the number of fire-damaged buildings could reduce the risk of people becoming trapped in buildings or streets being engulfed by the fire. In the Kobe Earthquake (1995), approximately 60% of the post-earthquake fires were attributed to electrical faults, occurring within 4 days following the seismic event. These fires erupted after residents had evacuated. In response to this challenge, the Japanese government has been advocating for the implementation of seismic breakers, which automatically cut off power circuits upon detecting seismic activity. This research focuses on other fires (40% of post-earthquake fires) that emerge immediately after an earthquake and are identified by nearby residents or locals before/during evacuation. When a large earthquake strikes, water pipes may be damaged, and the impact of this cannot be ignored (Osaragi et al., 2022). However, to avoid the postulated event becoming too complicated, this was not considered in the present study.

EFFECT OF EXISTING TREES ON REDUCING FIRE DAMAGE

Analysis Areas and Simulation Scope

Honan 1-chome, Suginami-ku (Honan area), which is one of the special fireproof zones in Tokyo's "Ten-Year Project to Advance Fire Resistance in Densely Built-up Wooden Housing Areas" (Tokyo Metropolitan Government, 2023a) and is also considered to be at high risk in the "8th Community Earthquake Risk Assessment Study" (Tokyo Metropolitan Government, 2023b), and nearby Izumi 2-chome, Suginami-ku (Izumi area), which has a relatively large amount of trees, were chosen as the analysis areas (Fig. 5). However, because fire could also spread from outside of these areas, an area surrounded by wide streets that could act as firebreak belts was taken as the simulation scope (Fig. 5). Evacuees were considered to have completed their evacuation when they arrived at any one of these wide streets.



* Although property damages are considered in the whole simulation area, fire-outbreaks and trees are considered only in Honan and Izumi areas.

* When a person arrives at any wide streets shown by black broken line, he/she is considered to complete evacuation.

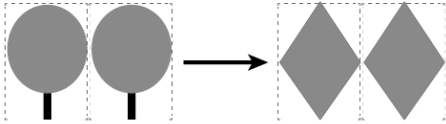
Figure 5. Study area: one of the special fireproof zones in Tokyo's "Ten-Year Project to Advance Fire Resistance in Densely Built-up Wooden Housing Areas"

Simulation Assumptions

Table 2 shows the simulation assumptions. The "current state" was taken as 2011 for buildings, while for trees, it was taken as the time of implementation of the field survey (2018). Data from 2011 building surveys (ward areas) provided by the Tokyo Metropolitan Government's Bureau of Urban Development were used here. The height of existing trees (three classes: 2 m, 4 m, and 6 m) and the type of tree (evergreen or deciduous) were judged by eye from the field survey (locations that were difficult to see were supplemented by aerial photographs). Tree width was assumed to be half of tree height. Figure 11 (discussed in detail later) shows the spatial distribution of existing trees and buildings (according to fire preventive construction).

Table 2. Assumptions needed for performing simulation analysis

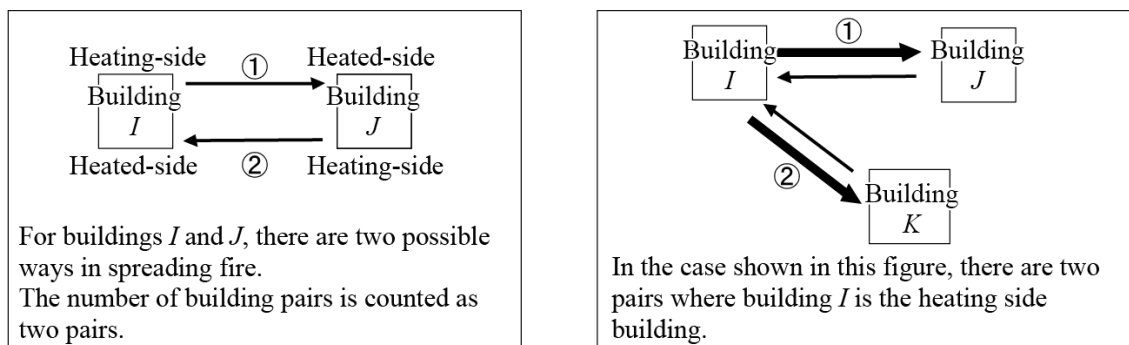
PGV (Peak Ground Velocity)	66 cm/s
Seismic intensity	5.96
Season and weather	Sunny day in winter
Earthquake occurrence time	6:00 pm on a weekday
Wind speed and wind direction	3 m/s, north wind
Shielding rate by a hedge	(Evergreen tree) 0.7837, (Deciduous tree) 0.2105
Shielding rate by a tree (except a hedge) *	(Evergreen tree) $0.7837 \times 0.5 = 0.3919$ (Deciduous tree) $0.2105 \times 0.5 = 0.1053$



* Regarding the part covered by a tree (except a hedge) as a rhombus as shown in the left figure, it can be treated as a barrier wall with half of the area obtained by multiplying the height and width of the tree. Therefore, the shielding rate of a tree trunk multiplied by 0.5 is used.

Effect of Existing Trees on Reducing Number of Fire-damaged Buildings/Fatalities

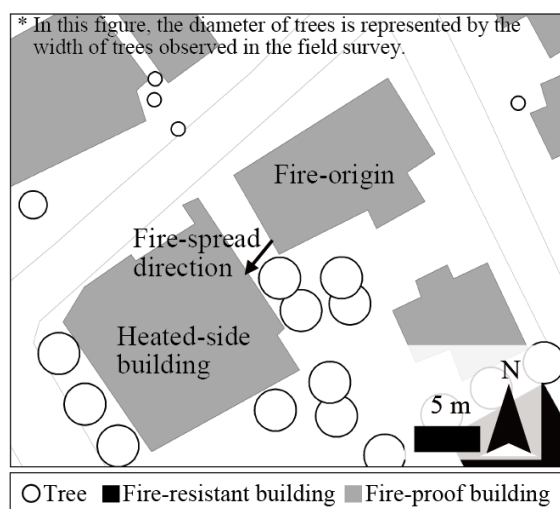
There are 41,281 building pairs with the potential for fire spread inside the analysis areas (Fig. 6). Because the property damage/human behavior simulation requires a long computation time, the following procedure was first used to narrow down the buildings to those with the potential for reduced damage, in order to efficiently verify the effect of trees on reducing damage. (1) The delay of fire spread between adjacent buildings was calculated for those with trees only. (2) The effect of delaying or blocking fire spread was confirmed in 226 pairs. (3) These 226 pairs were configured by taking 151 buildings as heating-side buildings. (4) Considering there to be a potential for damage reduction when a fire starts from these 151 buildings, fire-spread simulations were performed taking each of the buildings as the building of fire origin. An effect was found for 10 of these 151 buildings (when the fire spreads more quickly between adjacent buildings without trees, the trees do not work to delay the fire spread). (5) Assuming that a fire starts from one of these 10 buildings, the property damage/human behavior simulation was run until 24 hours after the outbreak for 100 cases with different roadblock situations (10 buildings \times 100 cases = 1,000 simulations in total).

**Figure 6. Definition of building pairs with the potential for fire spread inside the analysis areas**

Two of these 10 buildings were cases in which firefighting activities succeeded due to the trees delaying the fire spread. Large disaster mitigation effects were confirmed in cases where the roadblocks around the building of fire origin and equipment stores were minor and rapid initial firefighting was possible. Table 3 shows the specific results. For the building of fire origin 1, the fire-spread time was delayed by the trees from 19.1 minutes to 20.8 minutes (Fig. 7). This difference of 1.7 minutes is not large, but initial firefighting activities were successful in 17 of 100 cases, and as a result, the number of fire-damaged buildings was reduced from 2,003 buildings to 1 building (the building of fire origin only). Similarly, for the building of fire origin 2, initial firefighting activities were successful in 26 cases, and along with a substantial decrease in the number of fire-damaged buildings, the average number of fatalities was successfully reduced by approximately 13, and the maximum number was reduced by 58.

Table 3. The numbers of burnt-down buildings and casualties with and without the present trees

* Circled numbers ① and ② indicate the location of each fire-origin building.		Result of fire-extinguishment	①	②
Number of successful fire-extinguishment cases thanks to trees			17/100	26/100
where the fire-extinguishment are failed without trees				
Number of burnt-down buildings	Failure		2,003	1,751
	Success		1	1
Number of casualties	Ave.	Failure	20.1	28.5
		Success	16.1	15.3
	Max.	Failure	44	71
		Success	21	19
Difference of the number of casualties between successful and failed fire-extinguishment cases	Ave.		-3.9	-13.2
	Max.		-24	-58



Considering the existing trees, time from the fire-outbreak to spread of fire to the heated-side building was delayed by 1.7 minutes (from 19.1 minutes to 20.8 minutes). The delay enabled firefighting activities at the building of fire-origin successful. This resulted in decreasing the number of burnt-down buildings from 2,003 to 1 (only the building of fire-origin itself).

Figure 7. Example of the place where firefighting activities were successful by considering the present trees (corresponding with Table 3①)

The success or failure of initial firefighting activities is extremely important because it greatly influences the extent of damage in densely built-up wooden housing areas. The above simulation results are interesting because they suggest that the delay of fire spread provided by trees could allow initial firefighting activities by residents to succeed. However, it is important that the accuracy of the above calculation results be carefully examined based on the various models and parameter settings incorporated into the simulation.

EFFECT OF DEMOLISHING VACANT HOUSES AND METHOD OF DETERMINING TREE PLACEMENT

Damage Reduction Effect of Demolishing Vacant Houses

This section examines the effect of delaying the spread of fire by demolishing deteriorated vacant houses to obtain empty lots. Taking Honan area as the analysis area, a total of 12 vacant houses were identified by the field survey (Fig. 8). Here too, the buildings were narrowed down using the following procedure in order to efficiently detect the effect of demolishing the vacant houses. (1) The number of fire-damaged buildings after 24 hours was calculated assuming for each of the buildings in Honan area as the building of fire origin. (2) Cases in which the number of fire-damaged buildings was reduced by demolishing the vacant houses were detected. Figure 9 shows a case in which a fire in building A spreads to a large vacant house B and ultimately causes a huge amount of damage (number of fire-damaged buildings: 1,751); however, if vacant house B is demolished, the spread of the fire can be suppressed.

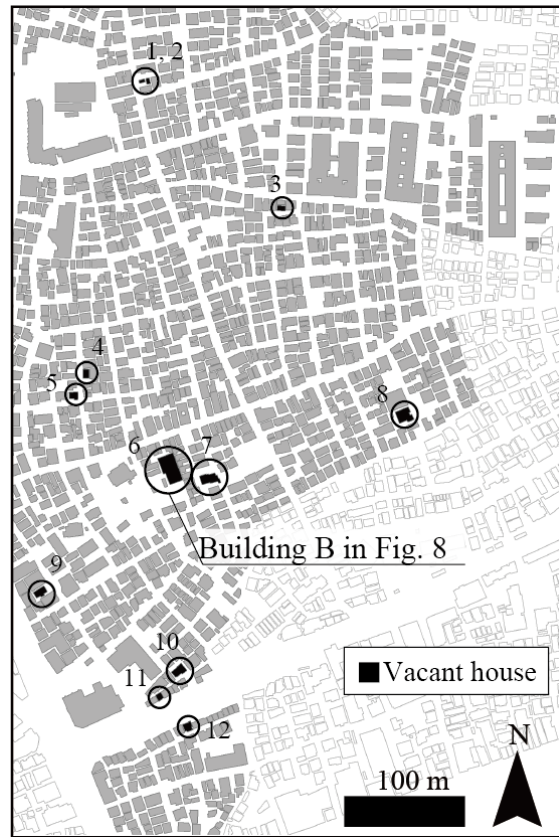


Figure 8. Spatial distribution of vacant houses in Honan area (in the present situation)

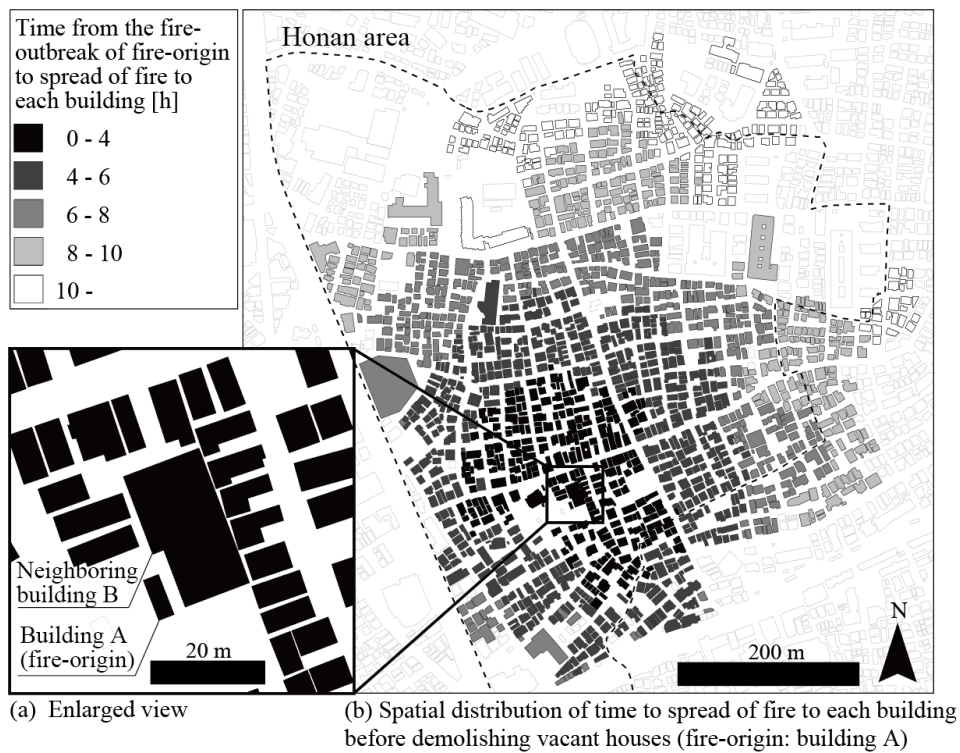


Figure 9. Example of a case where the number of burnt-down buildings is decreased due to the demolition of vacant houses

Taking the outbreak of fire in Building A as an example, the property damage/human behavior simulation was run assuming 100 cases with different spatial distributions of building collapses and roadblocks (1 building \times 100 cases = 100 simulations in total). As a result, demolishing vacant house B was found to have the effect of reducing the number of fire-damaged buildings in 13 out of 100 cases (success or failure of initial firefighting was divided). Table 4 summarizes the damage situation in these 13 cases. It shows that as a result of vacant house B being demolished, human casualties in Honan area was halved due to initial firefighting by residents succeeding and preventing the spread of the fire. Simulations were conducted to assess property damage and human behavior under various scenarios involving different spatial distributions of collapsed buildings and street blockages. However, the ignition building was fixed to Building B. In the adopted fire spread model, the range of fire spread remains consistent when the ignition building remains unchanged. Consequently, in the simulated cases, only two outcomes were feasible: either the fire was confined to building A alone, or it extended widely to encompass building B. This is just a single case amid countless combinations of conditions, but it is important as an example demonstrating the importance of initial firefighting in densely built-up wooden housing areas where evacuation routes may get cut off. Building B, an aging wooden structure showing signs of deterioration, not only lacks aesthetic appeal but also poses a potential hazard as it could collapse during a major earthquake, potentially obstructing evacuation routes. Hence, its demolition has been recommended in the community. While demolishing the building incurs financial costs, the benefits of replacing it with a fireproof structure, such as a public facility or housing complex, are expected to be substantial. Moreover, given the scarcity of parks in this area, there is considerable value in transforming the space into a pocket park, providing a safe and recreational environment for the residents.

Table 4. Difference in the number of burnt-down buildings and casualties before and after the demolition of vacant houses

	Number of burnt-down buildings [building]		Number of casualties [person]	
	Ave.	Max.	Ave.	Max.
Remain	1,751	1,751	36.1	54
Demolish	1	1	16.5	22
Difference	1,750	1,750	19.5	39

Effect of New Tree Placement on Suppressing Fire Spread

This section examines the extent to which fire damage can be reduced by newly placing trees. Figure 10 shows the method of determining the locations of new trees.

In densely built-up wooden housing areas, it is not always possible to place trees between all adjacent buildings. For the present study, we assumed that trees can be placed if the interval between adjacent buildings is at least 2.5 m (Table 5). Considering placement within residential premises, with reference to Article 128 of the Order for Enforcement of the Building Standards Act (pathways within premises), it was considered necessary to leave a distance of at least 1.5 m from one of a pair of adjacent buildings. Also, based on “greening using medium-sized trees in front of walls” in the Guidebook for Planting Greenery (Setagaya Ward, 2021), the distance from the other building was taken to be 0.5 m. Further, considering the minimum tree width to be 0.5 m (hedge), the interval between adjacent buildings in which it is possible to place trees was taken as 2.5 m or greater (Table 5). However, it is not practical or efficient to place trees wherever placement is possible. Therefore, the following method was used to narrow down the placement locations. Calculate the fire-spread delay between all adjacent buildings where tree placement is possible and a damage reduction effect can be expected (Fig. 10, Step A). Establish an order of priority based on the length of fire-spread delay (Fig. 10, Step B). In order starting from the place with the highest priority, place a certain number of trees using the method shown in Fig. 10, Step C. Basically, trees are placed according to the following rules. Rule 1: Do not place trees where they would overlap with streets or pathways. Rule 2: Plant trees that are as large as possible (Table 5). Rule 3: Plant the minimum number of trees required to block the path of fire spread. Rule 4: When it is possible to place trees on either the heated-side or the heating-side, place them on the side that is most effective.

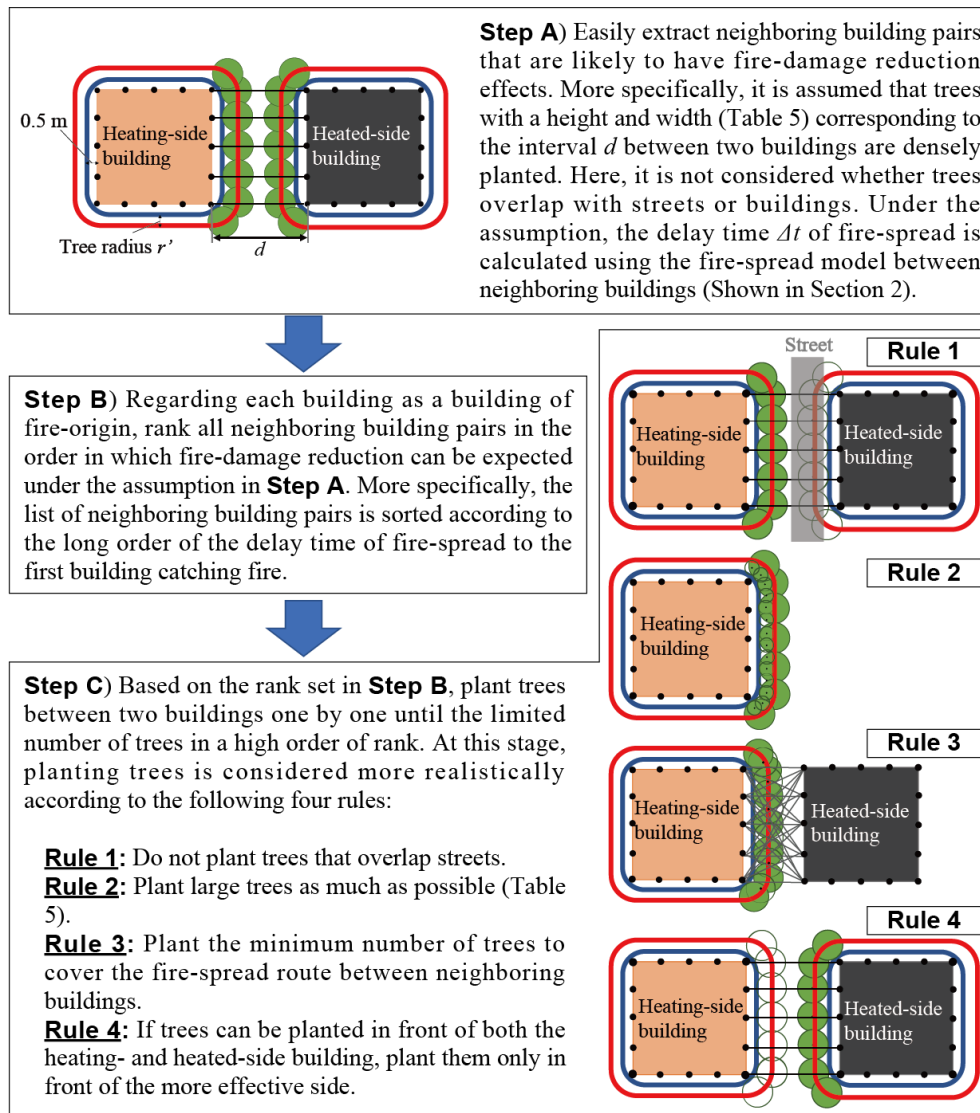


Figure 10. How to plant new trees: methods of determining the locations of new trees

Table 5. Assumption for the interval between two buildings, tree height, and tree width

	Interval d between two buildings	Tree height h_t	Tree width ($2r'$)
Level 0	Less than 2.5 m	Impossible to plant trees	
Level 1	2.5 m or more but less than 4 m	2 m	0.5 m (hedge)
Level 2	4 m or more but less than 5 m	4 m	2 m
Level 3	5 m or more	6 m	3 m

Based on the above assumptions, trees equivalent to approximately 10% of the existing trees (total 894) were placed, and (i) a method in which the trees are placed at random between adjacent buildings and (ii) the method described above in which trees are placed according to order of priority were compared. Specifically, 100 cases with different distributions of building collapses and roadblocks were analyzed (Fig. 11). In assumption (i-1), a total of 96 trees/hedges were placed between 12 pairs of adjacent buildings; in assumption (i-2), a total of 92 trees/hedges were placed between 10 pairs of adjacent buildings; and in assumption (ii), a total of 93 trees/hedges were placed between 8 pairs of adjacent buildings.

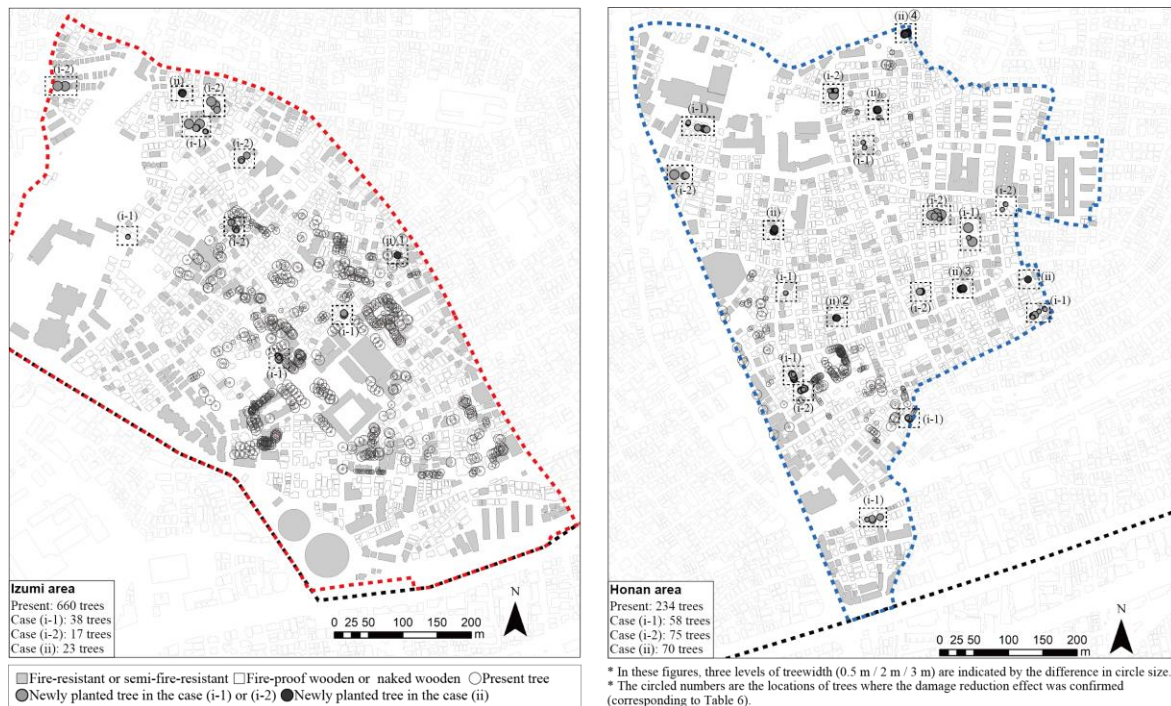


Figure 11. Spatial distribution of present/newly placing trees and the spatial distribution of existing buildings (according to fire preventive construction)

In placement method (i), fire-spread time to an adjacent building was delayed only slightly, and cases in which initial firefighting succeeded due to the addition of trees could not be confirmed. However, in placement method (ii), the effect of the trees was confirmed when the building of fire origin was one of a certain four buildings. Table 6 shows the numbers of fire-damaged buildings and fatalities in these cases (total of 19 cases). The numbers vary depending on the building collapse and roadblock situation, but a case in which the number of fatalities decreased by 89 due to the placement of trees was confirmed (Table 6, Location 3).

Table 6. The number of burnt-down buildings and casualties before and after planting new trees

* Circled numbers ① to ④ indicate the location of each fire-origin building (Fig. 12).		Planting new trees			
		①	②	③	④
Number of successful fire-extinguishment cases thanks to new trees where the fire-extinguishment are failed before planting new trees		3/100	12/100	2/100	2/100
Number of burnt-down buildings	Before	2,241	1,751	1,751	1,751
	After	1	1		1
Number of casualties	Ave. Before	19.0	30.1	63.5	29.5
	Ave. After	16.7	18.7	15.5	22.0
	Max. Before	25	52	102	36
	Max. After	19	30	18	22
Difference of the number of casualties between before and after planting new trees	Ave.	2.3	11.4	48.0	7.5
	Max.	6	35	89	14

SUMMARY AND CONCLUSIONS

In this paper, we examined the possibility of reducing damage by delaying the spread of fire between adjacent buildings through greening and demolishing vacant houses, thereby improving the success rate of initial firefighting by local residents. We also examined methods of determining tree placement to reduce damage efficiently. The main results are given below.

CoRe Paper – Analytical Modeling and Simulation

Proceedings of the 21st ISCRAM Conference – Münster, Germany May 2024

Berthold Penkert, Bernd Hellgrath, Monika Rode, Adam Widera, Michael Middelhoff, Kees Boersma, Matthias Kalthöner, eds.

First, after summarizing a previous model of fire spread between adjacent buildings and a procedure for calculating the amount of heat received taking into account trees, we developed a more sophisticated model of fire spread between adjacent buildings that assumes not only fire spread between the nearest adjacent points of the heating-side building and the heated-side building, but also fire spread between the heating surface and heated surface. Also, by examining a method of incorporating this model into Tokyo Fire Dept. Model 2001, which is a proven simulation model for fire spread in urban areas, we made it possible to quantitatively evaluate the effect of trees on delaying fire spread. Furthermore, through integration with a simulation model for property damage/human behavior in the event of a large earthquake, we made it possible to evaluate the effect of trees on reducing the number of fire-damaged buildings and fatalities due to a large earthquake.

Using the property damage/human behavior simulation model, we analyzed densely built-up wooden housing areas in Tokyo and evaluated the effect of the existing trees on reducing damage. The results confirmed that, in some cases, trees delay the spread of fire between adjacent buildings and allow initial firefighting by local residents to succeed, leading to a reduction in the number of fire-damaged buildings and fatalities. We also examined the disaster mitigation effect of demolishing vacant houses and confirmed that, in some cases, the number of fatalities could be halved by demolishing vacant houses that create a path of fire spread from the building where the fire breaks out.

Another characteristic of densely built-up wooden housing areas is that, although it is unlikely, if initial firefighting does succeed, an extremely large disaster mitigation effect is obtained. Using the simulation system developed in this paper, it is possible to discover where in an analysis area it would be efficient to newly place trees. We consider this to be a valid method for making effective use of limited space and budgets to improve the safety of an area and simultaneously enrich the green environment of people's everyday lives.

However, these disaster mitigation effects were observed under limited conditions, and effects on the order of our original expectations were unfortunately not obtained. This is considered to be due to the particular spatial characteristics of densely built-up wooden housing areas. Specifically, in densely built-up wooden housing areas, because the distances between adjacent houses are extremely small, the speed of fire spread (fire-spread time) is determined not by adjacent houses with trees but by adjacent buildings with small gaps between them. Trees do not originally exist in these small gaps, and it is difficult to newly place trees in them. Also, in densely built-up wooden residential areas, there are many structurally weak houses with low earthquake resistance located along narrow streets; consequently, many roads become blocked in the event of a large earthquake. This is a factor that impedes the initial firefighting activities of local residents and is why a delay in fire-spread time due to trees cannot be exploited effectively. Comparisons with simulation analyses targeting areas other than densely built-up wooden residential areas need to be performed to examine the possibilities of the disaster mitigation effects of trees and vacant house demolition. Hence, the experimental results obtained in this research are limited by a narrow set of conditions. The authors acknowledge these limitations and would like to incorporate sensitivity analyses to assess the robustness of our findings under various scenarios to enhance the study's validity and strengthen the overall validity of this paper. We intend to address these in the future work.

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APPENDIX

The length of the perpendicular line from the heated point to the radiation test surface r [m], urban area coefficient Φ , simultaneous burning area D_0 [m], flame height h_0 [m], and flame tilt θ [rad] are expressed by Equations (a-1)–(a-5).

$$r = \left[\left(d - \frac{c}{\tan \theta} \right)^2 - \left\{ (d + c \tan \theta) \cos \theta - \frac{c}{\sin \theta} \right\}^2 \right]^{0.5} \quad (\text{a-1})$$

$$\Phi = 1 - 0.6(c_1 + 0.8c_2)m \quad (\text{a-2})$$

$$D_0 = \min(D, 50, 1.179\Phi^3 + 10) \quad (\text{a-3})$$

$$h_0 = 4.7 \times 0.0133 \times (D_0 - 10) \times (\Phi - 0.1) + \frac{3.98}{D_0^{0.6}} \times \left(\frac{D_0^3}{U} \right)^{0.2} \quad (\text{a-4})$$

$$\theta = \arcsin \left(\frac{2}{U} \right)^{0.2} \quad (\text{a-5})$$

Next, the configuration factor F for the heated point of the area of the radiation test surface is calculated. The length of the radiation test surface when there are no trees a_0 [m] and the length of the radiation test surface blocked by trees a_1 [m] are expressed by Equations (a-6) and (a-7).

$$a_0 = \frac{h_0}{\sin \theta} - c \quad (\text{a-6})$$

$$a_1 = \left\{ 1 - \frac{d_0^2}{d_0^2 - (h_1 - c)^2} \right\}^{0.5} \times \frac{(a_0^2 + r^2)^{0.5}}{\left(\frac{d_0^2}{d_0^2 - (h_1 - c)^2} \right)^{0.5} \times \sin \theta + \left(1 - \frac{d_0^2}{d_0^2 - (h_1 - c)^2} \right)^{0.5} \times \cos \theta} \quad (\text{a-7})$$

Also, the configuration factor for the surface of length a [m] and width b [m], $f(a, b, r)$, and the mean bright surface ratio e of the portion of the radiation test surface corresponding to $f(a, b, r)$ are found using Equations (a-8) and (a-9).

$$f(a, b, r) = \frac{1}{2\pi} \left[\sin \theta \left\{ \frac{a}{(a^2 + r^2)^{0.5}} \tan^{-1} \frac{b}{(a^2 + r^2)^{0.5}} + \frac{b}{(b^2 + r^2)^{0.5}} \tan^{-1} \frac{a}{(b^2 + r^2)^{0.5}} \right\} \right. \quad (\text{a-8})$$

$$\left. - \cos \theta \left\{ \frac{r}{(a^2 + r^2)^{0.5}} \tan^{-1} \frac{b}{(a^2 + r^2)^{0.5}} - \tan^{-1} \frac{b}{r} \right\} \right]$$

$$e = 1 - \frac{h_0 + h_1}{2h_0} \quad (\text{a-9})$$

From Equation (a-8), the configuration factor F for the heated point of the area of the radiation test surface that is visible through the trees is found using Equation (a-10).

$$F = 2 \{ f(a_0, b, r) - f(a_1, b, r) \} \quad (\text{a-10})$$

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