
A method for evaluation of wide-area evacuation difficulty in case of a major earthquake

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Abstract

In densely built-up wooden residential areas, buildings and streets must be improved so as to safeguard against high risks, which may occur during a major earthquake. In this paper, we evaluate an improvement project in terms of the difficulty of wide-area evacuation by using a multi-agent simulation model. Results show that despite an overall decrease in the average number of people who have difficulty in evacuating, some buildings along narrow and long streets still have high risk that residents cannot evacuate to any evacuation areas.

Keywords: Major earthquake; wide-area evacuation difficulty; densely built-up wooden residential area; property damage; improvement project; multi-agent simulation

1. Introduction

In densely built-up wooden residential areas, there is the possibility that big fires occur during a major earthquake. Moreover, it is highly likely that the complex network, consisting of narrow streets, prevents people from evacuating smoothly to evacuation areas. To put it another way, people’s safety depends on the elements

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constituting towns, e.g. material of buildings, width of streets, and density of buildings and streets. Therefore, the government and municipalities have developed many improvement projects for making towns more robust against disasters.

The status of each project has been mostly evaluated in terms of the ratio of incombustible buildings. This indicator enables us to make a connection between its numerical value and the average fire-safe performance of the whole town. However, the above indicator has two disadvantages: (1) it is not suitable to directly evaluate the wide-area evacuation difficulty in certain areas such as city blocks; (2) local residents and residential developers cannot easily realize the effects of the improvement projects in densely built-up wooden residential areas.

In this paper, we evaluate the projects from the perspective of the difficulty of wide-area evacuation. The difficulty is evaluated based on the potential of the difficulty of wide-area evacuation and time and distance for arriving at any temporary refuges or evacuation areas. The value of this indicator is obtained by simulation analysis and expresses the possibility that people cannot evacuate to an evacuation area after a major earthquake. More specifically, we evaluate a past project for improving densely built-up wooden residential areas on the basis of a comparative analysis of wide-area evacuation difficulty, time, and distance before/after improvement (Fig. 1.)

Furthermore, we consider critical factors of the difficulty of wide-area evacuation.

There are many studies on densely built-up wooden residential areas, but a few attempts have been made for effect validation of improvement projects in terms of disaster prevention. For instance, Igarashi and Murao evaluated the progress of improvement projects in the whole target areas based on several indicators (such as the density of wooden buildings and the risk of building-collapse.) However, it is difficult to evaluate the safety of certain areas (such as city blocks and streets.) The improvement effects of wide-area evacuation difficulty by projects have not been discussed sufficiently.

Some studies discuss the safety of evacuation routes in densely built-up wooden residential areas. Noda, et al. categorize real city blocks based on the accessibility to major streets and propose improvement methods in the blocks by category. Iijima, et al. evaluate the environment of evacuation routes on the basis of field work. It is important for us to focus on the formation of streets and discuss with local residents disaster prevention planning. Nevertheless, there are few studies about the effects of such activities. Ibrahim et al. discuss the risk of evacuation routes in case that people evacuate to evacuation areas through wide streets with comparatively low risk of fire-spreading. However, the models in their study do not address complicated situations such as building-collapse, street-blockage, and congestion caused by stranded people after a major earthquake.

![Fig. 1. Objectives of the simulation in this paper (grey color).](image-url)
Fig. 2. Overview of our simulation model that describes (a) property damage; (b) evacuation behavior.

The simulation model is integrated with two other models, which describe property damage and evacuation behaviour\(^5,6\). In this paper, first we refine the model and apply it to a particular area, and then evaluate the improvement effects.

2. Overview of wide-area evacuation simulation

2.1. Framework of our simulation model

Fig. 2 shows an overview of the wide-area evacuation simulation model, which we developed in previous studies\(^5,6\). This model consists of the following components: (1) a property damage model which describes building-collapse, fire-spreading, and street-blockage caused by a large-scale earthquake; (2) the spatiotemporal distribution of people inside buildings and pedestrians estimated using Person-trip Survey data (PT data) collected in 1998; (3) an evacuation behaviour model that describes the behaviour of people evacuating from their whereabouts just after an earthquake occurrence to the evacuation areas. The model is based on the concept of multi-agent simulation (MAS). It simulates people’s evacuation behaviour under the assumption of hourly varying fire-spreading, street-blockage, and congestion of streets.

2.2. Modeling property damage

Models for property damage are getting increasingly more sophisticated due to numerical analyses using large-scale model experiments and supercomputers. However, in case of analyzing many buildings in a wide area, it is difficult to use these models, which require detailed information on the position and the size of windows. Therefore, we employ the existing models as follows:

- Collapse probabilities of each building are estimated using a function of instrumental seismic intensity based on construction types (wood and non-wood) and year of erection\(^7\). The intensity is determined on 50 meters square based on the spatial distribution of the Japanese earthquake damage scale, ranging from one to seven\(^7\) and a random number, drawn from a normal distribution (Fig. 3.). The parameters of the cumulative distribution function of the normal distribution are determined such that the number of collapsed buildings in the simulation approximates the number in the damage forecast for Tokyo\(^7\) (Fig. 4 and Table 1.) Lower and greater than 6 are respectively 5.5 to 6.0 and 6.0 to 6.5 on the instrumental seismic intensity.
Fig. 3. (a) Spatial distribution of intensity of the Japanese scale; (b) Instrumental seismic intensity determined by 50 meters square.

Fig. 4. Function describing the ratio of collapsed buildings by instrumental seismic intensity and year of erection ((a) wood; (b) non-wood).

Table 1. Parameters of the cumulative distribution function describing the ratio of collapsed buildings.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Wood</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>6.48</td>
<td>6.62</td>
<td>6.62</td>
<td>7.17</td>
</tr>
<tr>
<td>Standard deviations</td>
<td>0.28</td>
<td>0.32</td>
<td>0.32</td>
<td>0.45</td>
</tr>
<tr>
<td><strong>Non-wood</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>7.16</td>
<td>7.16</td>
<td>7.28</td>
<td>7.73</td>
</tr>
<tr>
<td>Standard deviations</td>
<td>0.50</td>
<td>0.50</td>
<td>0.55</td>
<td>0.60</td>
</tr>
</tbody>
</table>

*Each range has a relationship with the modification of the earthquake resistant standards.

- Buildings where fires break out are determined on the basis of the fire outbreak rates from the Tokyo Fire Dept.
- The fire-spreading model is based on the fire spread speed model proposed by the Tokyo Fire Dept.
- We consider that street-blockage is caused by rubble of collapsed buildings and flames and heat from burning buildings. Street-blockage caused by collapsed buildings is modeled using the height of those buildings and the...
distance between two buildings, or from a building to street boundaries. Distance from burning buildings and width of streets are used to judge street-blockage due to fire-spreading.

- Because fire-outbreak and fire-spreading affect people’s choice of routes to evacuation areas, the weight of streets is defined to be equivalent to the resistance from burning buildings as the exponential function of the distance from those buildings\(^6\).

2.3. Modeling evacuation behavior

We assume that people inside buildings start evacuating toward the nearest temporary refuge according to a Poisson distribution after an earthquake. The parameter \( \lambda \) of the function is set to 3.35 according to the results of the Great Kanto Earthquake in 1923\(^9\). On the other hand, it is assumed that pedestrians immediately start evacuating toward the nearest evacuation area. In other words, we consider a difference in behavior derived from preparation before evacuating and the need to provide for their safety. In case a refugee faces a blocked street on the way to a temporary refuge or an evacuation area, he/she tries to change the evacuation route in each case so that the influence of fire is least.

In this paper, we define people staying in temporary refuges and evacuation areas as ‘people who complete evacuating’. Also, people who cannot arrive at any evacuation areas because of street-blockage are defined as ‘people who have difficulty in wide-area evacuation’.

Fig. 5. Analytical area.
Table 2. Assumptions of wide-area evacuation simulation.

<table>
<thead>
<tr>
<th>Scenario earthquake</th>
<th>North Tokyo Bay Earthquake (M 7.3)</th>
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<tbody>
<tr>
<td>(Seismic velocity and acceleration are determined by each building based on set instrumental seismic intensity.)</td>
<td></td>
</tr>
<tr>
<td>Weather condition</td>
<td>8 m/s north wind</td>
</tr>
<tr>
<td>Number of fire outbreak buildings</td>
<td>93 buildings in whole Setagaya Ward</td>
</tr>
<tr>
<td>(This is the average number of 100 fire-outbreak simulations.)</td>
<td></td>
</tr>
<tr>
<td>Earthquake occurrence time</td>
<td>6:00pm on a weekday in winter</td>
</tr>
<tr>
<td>Number of trial times</td>
<td>100 times</td>
</tr>
<tr>
<td>(We prepare 100 patterns of property damage based on random numbers, and execute evacuation simulation one time respectively.)</td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Damage estimation published by TMG7</td>
</tr>
</tbody>
</table>

2.4. People and regions under analysis

Setagaya Ward in Tokyo Metropolis is the area where many commuters to central Tokyo live. Furthermore, it has densely built-up wooden residential areas with high risk of building-collapse and city-fire. In this paper, we focus on Wakabayashi 3-chome and 4-chome in Setagaya (Fig. 5), where the improvement projects have been executed since 1988 in order to prevent buildings from fire-spreading and secure the routes for refugees and emergency vehicles. They have been mainly executed from the following viewpoints: (1) conversion of buildings along the important streets for evacuation and around evacuation areas into incombustible ones; (2) setting lower limitations on the size of premises; (3) widening narrow streets with a width of less than four meters. The spatiotemporal distribution of people inside buildings is estimated by each building based on the PT data10. Also, we estimate the spatiotemporal distributions of pedestrians by each street11.

3. Evaluation of wide-area evacuation difficulty and comparative analysis before/after improvement

3.1. Simulation method

Based on the GIS data as of 1991 and 2006, we evaluate wide-area evacuation difficulty before/after improvement. The assumptions of wide-area evacuation simulation are shown in Table 2. In order to easily compare the results between two points in time, we unify the analysis conditions as follows: (1) the instrumental seismic intensity determined by 50 meters square; (2) the number and the spatial distribution of fire-outbreak buildings and people just after an earthquake occurrence; (3) the timing of starting evacuation for the same persons and under the same patterns of property damages.

3.2. Progress status of the improvement project

Fig. 6 shows the spatial distribution of buildings categorized by the degree of fire-proofing. In 1991, only the areas along the wide streets are dotted with the fire-resistant or semi-fire-resistant buildings. However, the conversion into incombustible and quake-resistant buildings has been realized along the comparably wide streets by 2006. As a result, the number of fire-resistant or semi-fire-resistant buildings increases in the center part of the target area as well. Concretely speaking, although the ratio of the fire-resistant or semi-fire-resistant buildings in both Wakabayashi 3-chome and 4-chome was about 19% in 1991, it increases to about 35% in 2006 (Fig. 7(a)). The rate of fireproof area also increases (Fig. 7(b)), and it suggests that the conversion into incombustible buildings has steadily proceeded although it is still not enough in terms of the average value of the whole area. Therefore, we can consider the project of improving the densely built-up wooden residential area to have achieved a certain level of results.
3.3. Improvement effects of wide-area evacuation difficulty and time and distance for evacuation

Compared to the average ratio of people with difficulty in wide-area evacuation between 1991 and 2006, the ratio in the whole area decreases by about 8.7% in Wakabayashi 4-chome and about 2.6% in 3-chome (Fig. 8.) Additionally, time and distance for arriving at any temporary refuges or evacuation areas are shortened (Fig. 9.) These results suggest that the improvement of streets effectively functioning as evacuation routes has been positive effects.
On the other hand, observing the results in detail, areas with high risk in terms of wide-area evacuation difficulty remain largely unimproved along specific streets. These streets tend to be narrow and at a long distance between two intersections (such as from street A to street D shown with black bold lines in the right panel of Fig. 10.) Therefore, these streets may induce multiple blockages and prevent people from evacuation. Moreover, in case the streets have poor forward visibility, refugees have a risk to enter such streets without recognizing the presence of street-blockage.

Furthermore, as an extreme case, we demonstrate the simulation under the assumption that six railroad crossings between Wakabayashi 3-chome and 4-chome are blocked. In this case, not only time and distance for evacuation (Fig. 9) but also the ratio of people who cannot reach any temporary refuges and evacuation areas may get worse (Fig. 8 and Fig. 11.) In order to keep the ratio low in the whole area, it is effective to identify locally dangerous
places by using the above simulation and improve them one by one.

From what has been discussed above, buildings with a high possibility to prevent people from evacuating to temporary refuges or evacuation areas still remain locally. These buildings tend to (1) face a narrow street; (2) be distant from two intersections of the facing street. There is a possibility to decrease the wide-area evacuation difficulty of each building by shortening the distance between two intersections of such streets.

Fig. 10. Spatial distribution of probabilities that people have difficulty in wide-area evacuation by each building (in 1991 and 2006).

Fig. 11. Spatial distribution of probabilities that people have difficulty in wide-area evacuation by each building in case railroad crossings are blocked.
4. Summary and conclusions

We demonstrated a wide-area evacuation simulation and evaluated an improvement project in a densely built-up wooden residential area from the viewpoint of the wide-area evacuation difficulty. Based on the results of the simulation using the urban data as of 1991 and 2006, we quantitatively confirmed that the project has contributed to make the residential area incombustible and quake-resistant, but only to a certain degree. Results show that the areas, which have a high risk of difficulty in wide-area evacuation, remain to have a high degree of local difficulty of evacuation. Narrow streets, which have long distance between two intersections, tend to remain dangerous for neighbors. The previous improvements of densely built-up wooden residential areas have been often relied on developers’ and planners’ intuition. Instead, our proposed model can assist us to discuss the issue concretely and quantitatively.

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