Risk of Property Collapse and Assessment of Evacuation Risk in Tokyo Metropolitan Area at a Large Earthquake

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Abstract

Precise evaluation of property collapse and evacuation risk at a large earthquake has been difficult due to the limitation of available dataset and computer resources. In this paper, we overcome these difficulties and construct a simulation model, which describes the evacuation behaviour of residents under the situation of property collapse such as building collapse/street blockage. Using the model, evaluation of evacuation risk of residents in Tokyo Metropolitan Area at a large earthquake is performed. Moreover, we discuss some fundamental aspects to improve urban vulnerability by analysing relationships between the spatial distribution of the property collapse/evacuation risk and local characteristics.

Keywords: large earthquake; evacuation risk; property collapse; evacuation behaviour; local characteristics

1 Introduction

In recent years, the world has experienced many natural disasters, and therefore, should prepare for next coming disaster. As one of effective tools to understand the vulnerability to disaster risk, various kinds of hazard maps are created by many different organizations. Table 1 shows some examples of hazard maps, which can be used through the Internet with ease. For instance, MLIT (Ministry of Land, Infrastructure, Transport and Tourism) provides the hazard maps of multiple disasters in Japan, which include tsunamis, volcanoes, and earthquakes, on 'Hazard Map Portal Site'. These are useful to roughly grasp the spatial distribution of damage risk due to various disasters (MLIT).

However, they are not sufficient to focus on the damage risk in micro scale, such as building collapse and street blockage. Also it is difficult to evaluate the effects of improvement projects in future since the conventional hazard maps are drawn under the present situation.

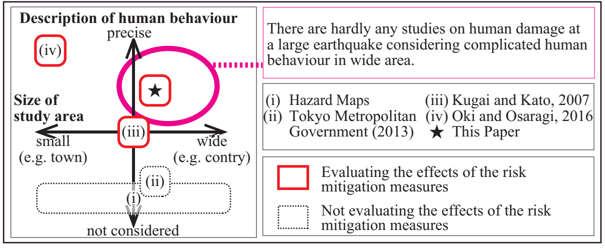
Since it is predicted that there is a 70 percent possibility of an earthquake directly hitting Tokyo within the next 30 years, the preparedness for a large earthquake is one of primary concerns in Tokyo. Local governments attempt to identify areas with a high potential of devastating damages and discuss effective countermeasures to reduce damages. Therefore, it is important to evaluate the effects of each countermeasure (e.g., replacement of old buildings with quake-resistant buildings, etc.). However, it is difficult to describe property collapse and human damage since many factors effect one another at the time of a large earthquake.

A large body of studies have been carried out to evaluate the risk at the time of a large earthquake and to discuss the methods of improving urban vulnerability to earthquake. Figure 1 shows some examples of them. TMG (Tokyo Metropolitan Government, 2013) estimated the risk of property collapse in *chome* (traditional Japanese address unit) by using GIS data, which include the detailed local characteristics (e.g., structure of building, density of buildings, width of streets, length of streets etc.), and placed 5,133 *chome* into order from the worst to the best. We can understand the relative state of towns in Tokyo, and also the change of relative state by the past projects for improving urban vulnerability to earthquake. However, these hazard maps mentioned above are not enough to evaluate effects of future risk mitigation projects. Also, human evacuation behaviour was not taken into account sufficiently. To evaluate effects of the future risk mitigation projects, Kugai and Kato evaluated the performance of road network after a large earthquake by each *chome* based on the percolation theory, and attempted to clarify which factors of local characteristics could explain the performance of street network (Kugai and Kato, 2007). However, they only evaluate performance of road network. Therefore, they could hardly evaluate evacuation behaviour of residents, which is affected by many factors including building characteristics. There are some studies discussing human causality in the evacuation behavior (e.g. Mordvintsev *et al* 2012; Mas *et al*, 2013; Oki and Osaragi, 2016). For example, Oki and Osaragi estimated human casualties by using multi-agent simulation, and evaluated the effects of disaster mitigation countermeasures of an actual project in the specific small area (Oki and Osaragi, 2016). For example, Oki and Osaragi estimated human casualties by using multi-agent simulation, and evaluated the effects of disaster mitigation countermeasures of an actual project in the specific small area.

Table 1: Examples of hazard maps

Site	Organization	Type of Disaster	Target Area
Hazard map portal site (MLIT)	MLIT (Ministry of Land, Infrastructure, Transport and Tourism)	Floods, tidal waves, tsunamis, landslides, volcanoes and earthquakes	Japan
PreventionWeb.net (UNISDR)	UNISDR (United Nations office for Disaster Risk Reduction)	Volcanic hazard map, etc.	Varied from a country to world
U.S. Volcanoes and Current Activity Alerts (USGS)	USGS (U.S. Geological Survey)	Volcanic hazard map	United States
Flood hazard/risk map (European Commission)	European Commission	Floods	Europe
Seismic hazard map (SHARE)	SHARE (Seismic Hazard Harmonization in Europe)	Earthquakes	Europe

Figure 1: Viewpoints of previous researchs

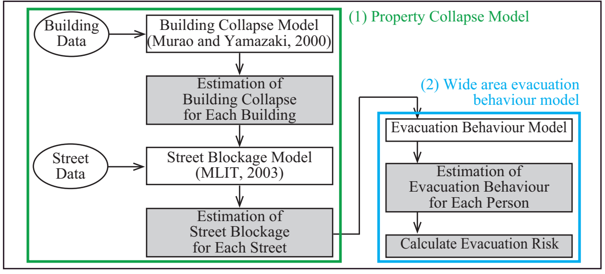


In this paper, we construct a simulation model, which estimates the property collapse (building collapse/street blockage) and the evacuation behaviour of residents at a large earthquake. To avoid the risk of fire, people evacuate to safe places such as evacuation areas at the time of a large earthquake. As the first step, it is important to reach a major street with less damage to ensure the safety of the evacuation. Therefore, we focus on the activity that he/she evacuates from a building to any of major streets. In order to reduce calculation costs, we exclude the interaction between evacuees. Using the model, evaluation of evacuation risk of residents in Tokyo Metropolitan Area at a large earthquake is performed. Next, we analyse the spatial distribution of property collapse and evacuation risk, and discuss their relations to the local characteristics. Finally, we discuss some fundamental aspects for evaluating the disaster mitigation methods.

2 Overview of Simulation Model

Figure 2 shows the overview of the simulation model that we developed in this research. This model consists of the following two sub-models; (1) property collapse model to describe building collapse and street blockage; and (2) wide area evacuation behaviour model.

Figure 2: Overview of simulation model



2.1 Property Collapse Model

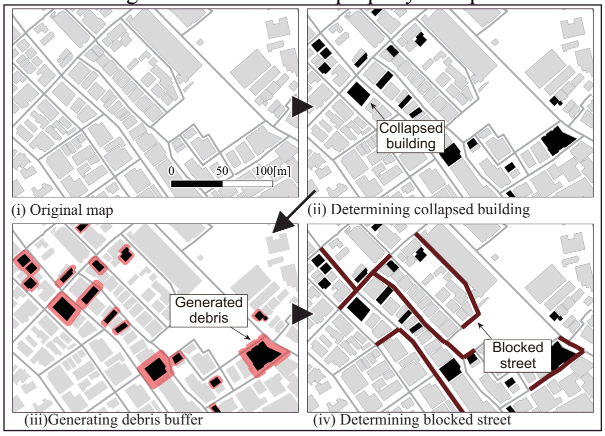
The building collapse is probabilistically determined on the basis of the fragility curves referring to the actual property collapse in the 1995 Great Hanshin-Awaji Earthquake (Murao and Yamazaki, 2000). The probability is estimated by the functions of Peak Ground Velocity (PGV), the structural material (wood, reinforced-concrete, or steel) and the built year of building.

We use the model proposed by MLIT to estimate the blockage of streets (MLIT, 2003). The probability $P_b(W)$ that a street blockage occurs on the W m width street is estimated as the probability that buildings along the street generate debris which would block a street.

$$P_b(W) = 1 - \prod_{i \in G} \left(1 - f_i(W)\right)$$

Here, $f_i(W)$ is the probability that the debris of collapsed building i would outflow to the street (Figure 3 (iii)). G is the set of roadside buildings, which generate the debris to block the street. The detail of these models is described in the previous paper (Hirokawa and Osaragi, 2016).

Figure 3: Estimation of property collapse



(i) Original map
(ii) Determining collapsed building
(iii)Generating debris buffer
(iv) Determining blocked street

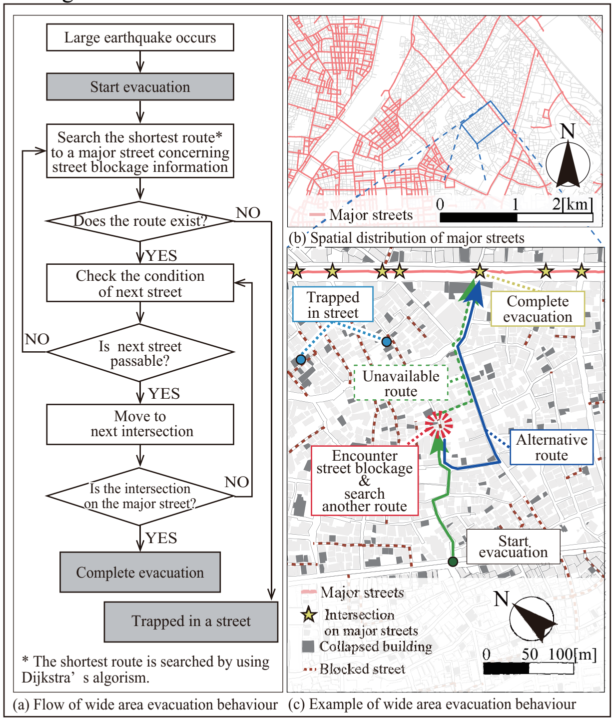
2.2 Wide Area Evacuation Behaviour Model

Figure 4 shows the overview of wide area evacuation behaviour model. In this model, we consider the influence of property collapse at the time of a large earthquake. For instance, people would be trapped in a building/a street, or forced to take a large detour during evacuation due to blocked streets.

In this research, we consider that safety of evacuation is ensured when evacuees reach major streets whose width is 8 m or more, since these streets are expected to play an important role as major emergency streets when a large earthquake occurs. We describe the behaviour of each person that evacuates from a building toward any of major streets whose width is 8 m or more. Firstly, an evacuee is assumed to choose the shortest route to a major street considering street blockage information. Here, it is assumed that an evacuee completely understand street network and does not have any information on street blockage at the beginning. In the model, the shortest route is estimated by using Dijkstra’s algorism. He/she evacuates to the major street by moving on his/her route from an intersection to next one repeatedly. If an evacuee encounters a street blockage, he/she updates the knowledge on the locations of a street blockage. In addition, an evacuee searches an alternative route to a major street referring to the locations of street blockages that he/she has already encountered.

Evacuation is assumed to be completed when an evacuee reaches to the major street. By contrast, an evacuee is assumed to be trapped in a street if he/she cannot find any routes to major streets.

Figure 4: Overview of wide area evacuation behaviour



(a) Flow of wide area evacuation behaviour (b) Spatial distribution of major streets (c) Example of wide area evacuation behaviour

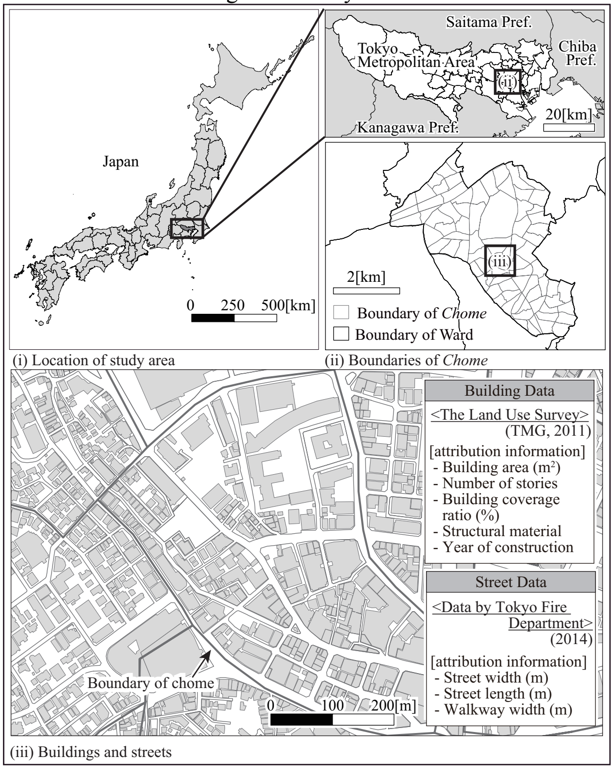
2.3 Study Area and Assumptions in Simulation

In this paper, we estimate the property collapse in Tokyo Metropolitan Area (Figure 5 (i)), and also evaluate the evacuation risk by performing a simulation for each person being in each building. To estimate the evacuation risk of each building, we assume only one evacuee in each building and do not consider the population density in the study area. Table 2 shows the definition of indices of property collapse and evacuation risk, which are used for simulation results. Making it clear the difference of simulation results among districts, these indices are averaged by *chome* (Figure 5 (iii)).

The building data are based on the land use survey conducted by Tokyo Metropolitan Government in 2011, and the street data (as of 2014) are provided by Tokyo Fire Department. Some attributes of buildings and streets used in simulations are prepared with reference (Hirokawa and Osaragi, 2016).

To consider the effects of the variance of property collapse in each case, we prepared 100 cases of property collapse and executed a simulation for each case to evaluate risks. For excluding the influence of the ground characteristics and the epicenter location, Peak Ground Velocity (PGV) is fixed to 66 cm/s. Therefore the relation to the local characteristics of each district, which vary according to the composition of buildings and streets, would be clarified.

Figure 5: Study area



(i) Location of study area (ii) Boundaries of *Chome* (iii) Buildings and streets

Table 2: Indices of property collapse and evacuation risk

Property collapse risk		
1	Building collapse risk [%]	The proportion of collapsed buildings to total building number. (Aggregated value in each *chome*)
2	Street blockage risk[%]	The proportion of length of blocked streets to total street length. (Aggregated value in each *chome*)

Evacuation risk		
1	Evacuation difficulty [%]	The proportion of evacuees trapped in streets to total building number. (Aggregated value in each *chome*)
2	Frequency of encountering street blockage [/100m]	The number of encountering blocked streets while moving 100 m. (Aggregated value in each *chome*)
3	Travel distance increment [m]	The difference of the distance between the cases with/without street blockage. (Aggregated value in each *chome*)

3 Spatial Distribution of Property Collapse and Evacuation Risk

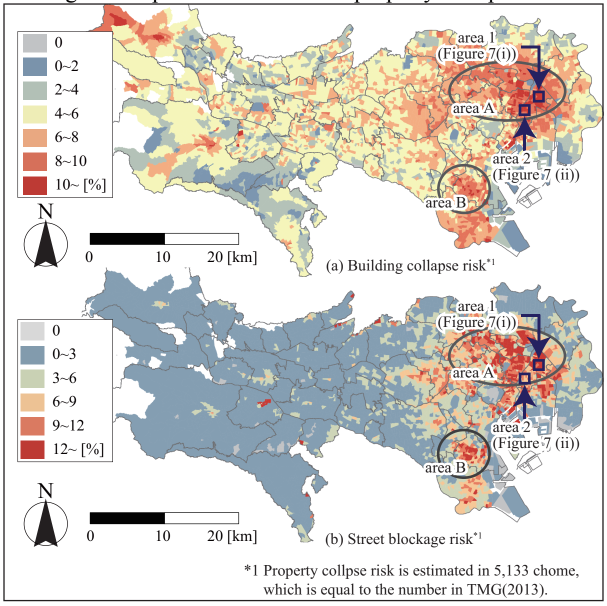
3.1 Spatial Distribution of Property Collapse

Figure 6 shows the spatial distribution of property collapse risk (building collapse risk and street blockage risk). The value of building collapse risk is more than 5% in almost all areas. More in detail, the values of some areas are more than 10% (indicated by red colour). Regarding street blockage risk, the values are high in the eastern part of Tokyo.

The areas with high value of building collapse risk show high value of street blockage risk (such as the areas A and B). These areas are densely built-up wooden residential areas with unfavourable local characteristics from the viewpoint of vulnerability to a large earthquake. More concretely, old wooden buildings with a high possibility of collapse and narrow streets are densely existing. Additionally, the number of buildings along a street is comparatively large (Figure 7(i)), and this fact leads to the high probability of street blockage $P_b(W)$.

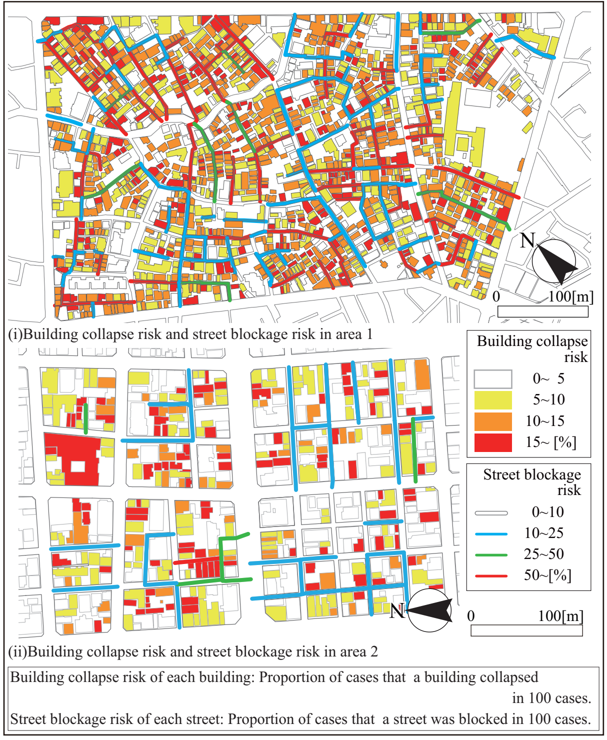
By contrast, there are some areas in which the value of building collapse risk is high, but the value of street blockage risk is low (Figure 7(ii)). In these areas, the street length (distance between the nearest two intersections) is short since the density of intersections is high. Namely, increasing the number of intersections or decreasing the number of roadside buildings results in reducing of the probability of street blockage $P_b(W)$.

Figure 6: Spatial distribution of property collapse risk



*1 Property collpse risk is estimated in 5,133 chome, which is equal to the number in TMG(2013).

Figure 7: Building collapse risk of each building and street blo ckage risk of each street



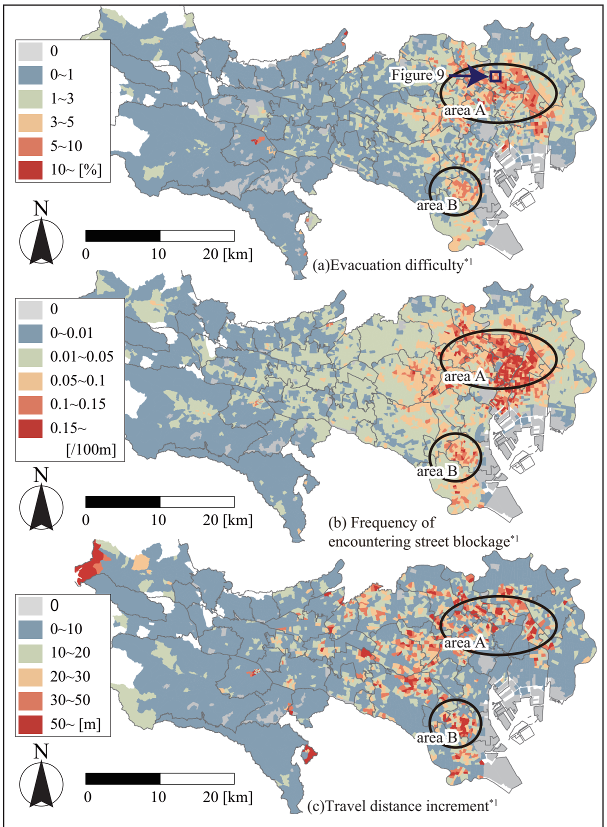
Building collapse risk of each building: Proportion of cases that a building collapsed in 100 cases.
Street blockage risk of each street: Proportion of cases that a street was blocked in 100 cases.

3.2 Spatial Distribution of Evacuation Risk

Figure 8 shows the spatial distribution of evacuation risk. In densely built-up wooden residential areas (such as the areas A and B), all indices of evacuation risk show high values. This is because street blockage risk in these areas is very high and evacuees are trapped in streets or forced to take a large detour to avoid blocked streets. Thus, the evacuation risk of buildings along streets with a high possibility of blockage is high.

It is, therefore, critically important to prevent streets from blockage for reducing evacuation risk. The general methods in the urban improvement projects are the conversion of old wooden buildings to quake-resistant buildings and widening narrow streets. However, it takes a lot of costs and long time to complete projects. Another method for reducing the probability of street blockage is to provide emergency evacuation routes between two intersections (Figure 10). In other words, increasing the number of intersections is effective for reducing the number of evacuees to be trapped.

Figure 8: Spatial distribution of evacuation risk



*1 Evacuation risk is estimated in 5,133 chome, which is equal to the number in TMG(2013).

Figure 9: Evacuation risk of each building

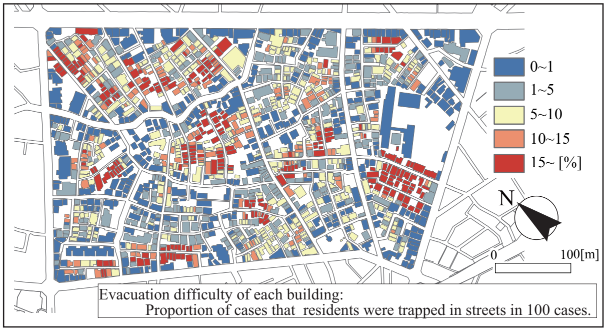
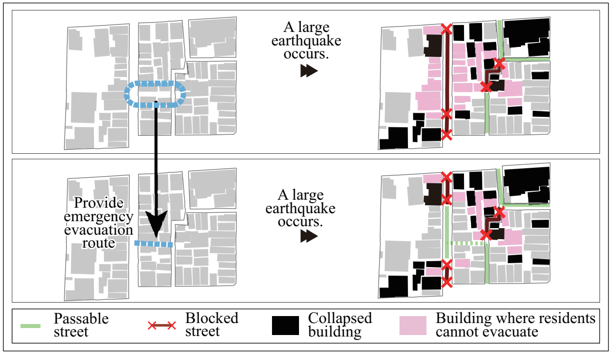


Figure 10: Concept of providing emergency evacuation route



4 Summary and Conclusions

In order to evaluate the property collapse and the evacuation risk in wide area at a large earthquake, we constructed the simulation model, which describes building collapse, street blockage, and evacuation behaviour. Analyzing the special distribution of property collapse and evacuation risk, we obtained the following new findings:

(1) The property collapse in densely built-up wooden residential areas is much larger than that in the other areas.

(2) The probability of street blockage is dependent not only on the probability of building collapse but also on the number of roadside buildings. Hence, it is comparatively large in the case that the distance between intersections is large.

(3) The evacuation risk tends to be large in the areas where the street blockage proportion is high. Namely, there is a high possibility that evacuees are trapped in streets or take a large detour.

(4) Providing emergency evacuation routes between two intersections has a high possibility to reduce the evacuation risk.

Analyzing the relationships between the evacuation risk and local characteristics quantitatively, it will be possible to evaluate the effects of improving projects for reducing the evacuation risk. Additionally, it might be possible to identify the appropriate improvement method, which differs according to local characteristics of each area. The authors have already begun to analyze the relationships between local characteristics and the evacuation risk by using statistical models. The results will be reported in near future.

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