Evaluation of Conversion to Quake-Resistant Buildings in Terms of Wide-Area Evacuation and Fire-Brigade Accessibility

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ABSTRACT

It is important to evaluate the effects of improving the disaster vulnerability of towns by using various indices related to human damage. In this paper, we focus on conversion of low quake-resistant old buildings. Firstly, we construct a simulation model, which describes property damage (such as building-collapse and street-blockage), wide-area evacuation behavior, and fire-brigade's activities immediately after a large earthquake occurs. Next, using the simulation model, we estimate the travel time required for evacuation, the number of evacuees trapped on streets (or in blocks), and the access time of fire-brigades to fires in case that the ratio of quake-resistant buildings in the area increases to a certain value. Based on the results, we discuss the effects by converting old buildings into quake-resistant ones on reducing the difficulty in wide-area evacuation and improving the accessibility of fire-brigades in multiple study areas with different characteristics.

Keywords

Conversion, quake-resistant building, property damage, wide-area evacuation, fire-brigade.

INTRODUCTION

In order to strengthen the resilience of densely populated residential areas to natural disasters, it is necessary to visually and quantitatively grasp the potential of property/human damage caused by disasters, to draw up a concrete plan for reducing the risk of such damages, and to encourage the reconstruction/demolition of vulnerable buildings based on disaster prevention/mitigation planning. In some cases, municipalities or residential developers provide a grant for residents to accelerate the redevelopment project, but in many cases, residents have to pay almost all the money for reconstruction by themselves. To motivate them and promote the improvement of the urban vulnerability to disasters, it is important not only to provide more grant for more residents but also to sufficiently consider the effects on enhancing local disaster prevention/mitigation performance by reconstructing/demolishing each vulnerable building on the basis of quantitative analyses from the various viewpoints (such as economic loss, number of damaged buildings, number of human casualties, etc.).

In Japan, it has been said that major earthquakes equivalent to the Great Hanshin-Awaji Earthquake in 1995 (magnitude 7.3) will occur near multiple large cities (including Tokyo Metropolitan Area) with a probability of 70% in 30 years (Cabinet Office, Government of Japan, 2015; Headquarters for Earthquake Research Promotion, 2017). In these cities, there are many densely built-up wooden residential areas, which consist of many wooden houses and narrow street networks, with high risk of devastating property damage (such as building-collapse, street-blockage by rubbles of collapsed buildings, and fire-spread) and human damage at the time of a large earthquake. Therefore, it is highly necessary to convert wooden houses with insufficient quake-/fire-resistant performance into quake-/fire-resistant buildings (such as reinforced concrete structure, steel-frame structure, etc.).

There are some previous studies that focus on conversion of building structures or materials to an incombustible state. For instance, Osaragi (2004) proposed a statistical model that can evaluate characteristics of buildings and location, which affect the life span of buildings. Also, a model for evaluating the speed of conversion to an incombustible-city state was developed, and simulations of conversion of buildings for 30 years were executed by using actual data taken from the densely built-up areas (Osaragi, 2005). On the basis of the simulation results, the author suggested that effective planning (e.g., providing subsidies) was necessary for promoting conversion of buildings structures into an incombustible state. Furthermore, the effect and efficiency on promoting the incombustibility of residential areas by applying some urban regulations (such as changing building-use regulation designated in each area, increasing floor-area ratio of buildings, etc.) were evaluated by simulating the time-series changes of building structure (Osaragi, 2013). The proposed models of conversion of buildings in urban areas are detailed, therefore, the results in these studies are meaningful for understanding the mechanism of conversion of buildings and for considering disaster prevention/mitigation planning. However, the impact of the conversion on human activities such as wide-area evacuation and travel of emergency vehicles was not analyzed in these studies. In other words, on the basis of the simulation results in these studies, it is difficult to realize whether the specific measures regarding conversion of buildings are sufficiently effective or not for the improvement of human activities in the event of a large earthquake.

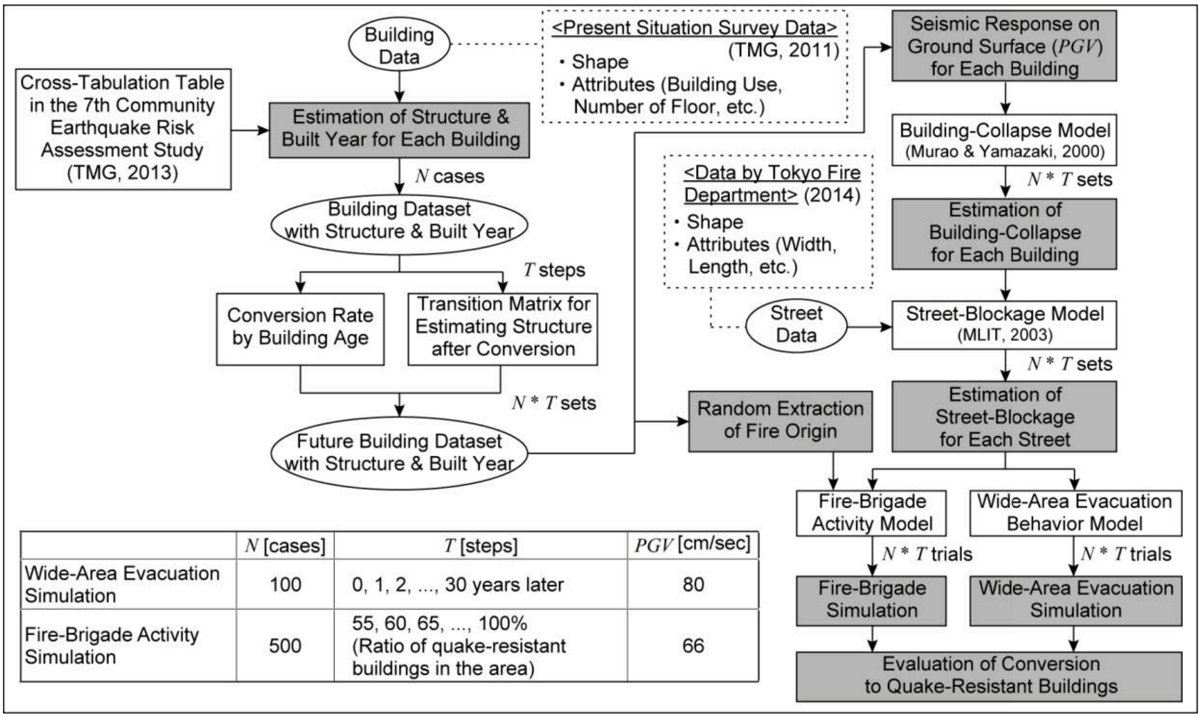
Other studies attempt to quantify the effects on reducing property or human damage due to the specific natural disaster by converting towns. For instance, Kuwasawa and Katada (2008) and Ito et al. (2015) developed the simulation models which described street-blockage by rubbles of collapsed buildings and the evacuation behavior from tsunami immediately after a large earthquake occurred. Using the models, the authors estimated the number of casualties/survivors or the time required for completing evacuation in case that the ratio of quake-resistant buildings increased. Also, Oki and Osaragi (2016) constructed the simulation model which described wide-area evacuation from fire-spread after a major earthquake occurred, and evaluated the actual project to improve buildings and streets implemented in the past based on the estimated number of people with difficulty in wide-area evacuation. Additionally, as an example of applying the simulation model to urban disaster mitigation planning, the authors demonstrated the effects of adding new evacuation routes between two intersections of streets with narrow width and long distance. These studies are suggestive for considering the relationship between the improvement of disaster vulnerability of towns and the decrease of human damage in disaster prevention/mitigation planning. However, in these studies, only few indices related to wide-area evacuation in human activities were used for evaluating the effects. Moreover, the difference of the effects among multiple areas with different urban characteristics was not sufficiently considered.

In this paper, we develop a simulation model, which accounts for property damage (such as building-collapse and street-blockage), wide-area evacuation activity, and fire-brigade's activity right after a large earthquake hits. Using the integrated simulation model, we analytically evaluate the impact of converting low quake-resistant old buildings to quake-resistant ones in terms not only of wide-area evacuation but also of fire-brigade accessibility. More specifically, we estimate the travel time required for evacuation, the number of evacuees trapped on streets (or in city blocks), and the access time of fire-brigades to fire origins. Additionally, in order to understand the relationship between urban characteristics and effects of converting low quake-resistant buildings, the simulations are executed under the assumption of different ratios of quake-resistant buildings in multiple study areas with a different degree of the vulnerability to earthquake.

Hereafter, a "quake-resistant building" indicates the one built in 1981 or later based on the new building codes, which prescribe that a new building must be constructed with the quake-resistant performance so as to prevent it from the collapse even by an earthquake of rare severity. In the 1995 Great Hanshin-Awaji Earthquake, the ratio of collapsed buildings was much less in the buildings based on the new building codes than in the others (Murao and Yamazaki, 2000).

OVERVIEW OF SIMULATION MODEL

Figure 1 indicates the overview of analytical procedure in this paper. Firstly, we mention how to estimate the structure and built year for each building. Next, the models which describe the conversion to a quake-resistant building, property damage (i.e., building-collapse and street-blockage), wide-area evacuation behavior, and the activities of fire-brigade are shown. Subsequently, we implement the simulations of wide-area evacuation and fire-brigade activity separately, and attempt to quantify the effects of conversion to quake-resistant buildings in terms of these activities.



	N [cases]	T [steps]	PGV [cm/sec]
Wide-Area Evacuation Simulation	100	0, 1, 2, ..., 30 years later	80
Fire-Brigade Activity Simulation	500	55, 60, 65, ..., 100% (Ratio of quake-resistant buildings in the area)	66

Figure 1. Overview of Analytical Procedure in This Paper

Building Data

We used the building dataset based on the present situation survey on land/building use in 2011 published by Tokyo Metropolitan Government. This dataset includes the GIS data on all the buildings in Tokyo (approximately 2.8 million buildings), and we can obtain the information on shape and attributes (such as building use, number of floor, fireproof performance, *chome* [traditional Japanese address unit], etc.) of buildings. However, there are no information on the structure (wooden / reinforced concrete / steel) and built year of each building, which are necessary for building-collapse simulation. Therefore, we estimated them by using not only the present situation survey data in 2011 but also the 7th Community Earthquake Risk Assessment Study (TMG, 2013) according to the following procedure:

(1) Structure: (a) The buildings, which were categorized as “naked-wooden building” or “fireproof building” in the present situation survey data, were determined as “wooden” buildings; (b) The composition ratio of buildings was calculated by the cross-tabulation of three variables (*chome* / number of floors [1 to 3 / 4 to 7 / 8 or more] / structure) according to the 7th Community Earthquake Risk Assessment Study; (c) Each semi-fire-resistant building was probabilistically categorized as “wooden”, “reinforced concrete”, or “steel” according to the composition ratio mentioned in (b); (d) Similarly, each fire-resistant building was probabilistically categorized as “reinforced concrete” or “steel”.

(2) Built year: We calculated the composition ratio by the cross-tabulation of five variables (*chome* / fireproof performance / number of floors / structure / built year) according to the 7th Community Earthquake Risk Assessment Study, and estimated the built year range [1970 and before / 1971 to 1980 / 1981 to 1990 / 1991 to 2000 / 2001 and later] of each building as well as the structure.

Conversion to Quake-Resistant Building

Firstly, we estimated the trend of conversion to quake-resistant buildings. More concretely, we estimated the ratio of conversion by building age (elapsed year since a building was built) and the transition matrix for estimating structure after conversion based on the present situation observation data (as of 2001 and 2006) for land/building use in Setagaya Ward, Tokyo. Comparing the data for two different year (2001 and 2006) from the viewpoint of both the shape and the attribute of building, we determined whether each building had been converted in five years. Figure 2 shows the relationship between the ratio of conversion and building age. We considered that the ratio of conversion was independent of building’s structure because of estimation stability.

The graph indicates that the ratio of conversion increases by 0.05% every year since a building was built. Additionally, we constructed the transition matrix for estimating structure after conversion (Table 1). The matrix was estimated by using the cases where the structure of building before/after conversion could be known.

In the simulation, we prepared the data on conversion to quake-resistant buildings for each year/case as follows: (1) Estimating probabilistically whether each building is converted or not in the specific year based on the ratio of conversion by building age (Figure 2); (2) Estimating the structure after conversion for each building by using the transition matrix (Table 1).

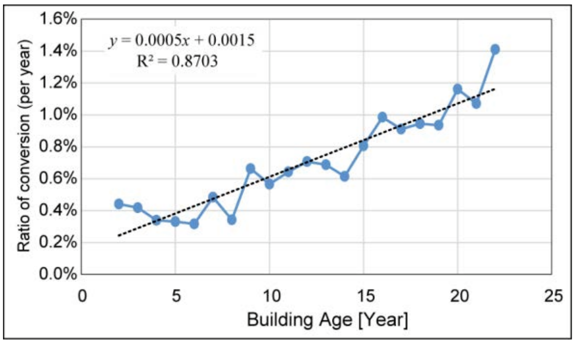


Figure 2. Ratio of Conversion by Building Age

Table 1. Transition Matrix for Estimating Structure after Conversion

Before / After [%]	W	RC	S	Total
Wooden	67.8	15.7	16.5	100
Reinforced Concrete	36.0	51.7	12.4	100
Steel	39.8	34.9	25.4	100
Total	56.4	24.7	18.9	100

Building-Collapse and Street-Blockage

The property damage models, which consist of the building-collapse model and the street-blockage model, were constructed with reference to Hirokawa and Osaragi (2016).

Peak Ground Velocity (PGV) is one of the input data to the building-collapse simulation. The velocity for buildings in each grid (50m square / 250m square) can be estimated by using the surface-ground response model considering both the decay effect by distance from the earthquake center and the amplification effect by characteristics of subsurface ground. However, in this paper, we fixed the PGV to a certain value (66 cm/sec or 80 cm/sec) in the whole study area in order to clarify the influence of composition of buildings and streets excluding the surface-ground response.

For estimating whether each building completely collapsed or not, we used the collapse probability model according to the building's structural material (wooden / RC / steel) and built year. The model was originally proposed by Murao and Yamazaki (2000) based on the survey report of building damage by the Hyogo-ken Nambu Earthquake (or the Great Hanshin-Awaji Earthquake) in 1995, and later improved by adding the data in Niigata-ken Chuetsu-oki Earthquake in 2007 (TMG, 2013).

$$P_R\left(PGV\right)=\Phi\left(\frac{\ln\left(PGV\right)-\lambda}{\xi}\right)$$

Here, λ and ξ are the average and standard deviation of $\ln(x)$, respectively; they vary according to the structural material, built year, and degree of damage. $\Phi(x)$ indicates the cumulative function of standard normal distribution, and $P_R(x)$ is the probability that a building is completely destroyed by an earthquake over a certain level (x = PGV). We estimated building-collapses based on uniform random numbers and the collapse probability.

Based on the result of building-collapse estimation, we determined whether each street was blocked or not, by using the street-blockage model proposed by MLIT (2003). In this model, the probability $f_i(W)$ that a street-blockage would occur as the result of collapse of a single building i along the street with a width of W [m] (considering the average setback distance) is expressed as follows:

$$f_i\left(W\right)=D_C\left(1.1753A-0.0514\right)\times\exp\left(\frac{-W}{2.58P_{area}^{0.379}+0.210F^{2.23}+4.90A^{12}}\right)$$

Here, D_C is the building condition (1: collapsed, 0: not collapsed); A is the building coverage ratio; P_{area} is the average ratio of completely collapsed buildings in the block where the building is located; F is the number of floors; and G is the group of buildings along the street. Therefore, the probability $P_b(W)$ that a street-blockage would occur can be formulated as follows:

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

The minimum passable width, which was calculated on the basis of $P_b(W)$, was set to: 3 m for fire engines; 1 m for evacuees; and 0 m for firefighters.

Wide-Area Evacuation Behavior (Figure 3(c))

We assumed the rule of evacuation behavior as follows:

Start evacuation: People inside buildings start evacuating (travelling) as the time has elapsed after an earthquake occurs base on Poisson distribution (Figure 3(a)). By contrast, pedestrians start evacuating (travelling) immediately after an earthquake occurs.

Destination of evacuation: It is considered that evacuees can travel to an evacuation area more safely when they pass through wide streets as long as possible. Such wide streets have a low possibility of blockage by rubbles of collapsed buildings and work as firebreak belts. Therefore, in this paper, we assumed that people travel to national/prefectural roads with a width of 8 m or more, and considered that they complete evacuating when arriving at any of intersections on the roads.

Route choice: Evacuees select the route to their own destination so that the total value of L/W (length divided by width for each street-link) is minimized in order to enhance a possibility of using wide streets.

Street-blockage and evacuation behavior: Firstly, evacuees do not have any information on the number and spatial distribution of street-blockage. They memorize the situation of blockage on the street connected to the intersection they passed. When an evacuee encounter a street-blockage and cannot use the evacuation route, he/she searches another evacuation route considering the situation of street-blockage in the whole area that he/she has already grasped. At the same time, the number of street-blockage that he/she encounters is updated. If an evacuee cannot reach any intersections on all the target streets (national/prefectural roads with a width of 8 m or more) due to street-blockage, he/she is considered as "a person with difficulty in wide-area evacuation (a person trapped on a street / in a block)".

Walking speed: It is considered to be a function of evacuees' density (Figure 3(b)) on each street-link (not faster than 4 km/h).

The location of each evacuee at an earthquake occurrence time is set in a building or on a street intersection, which is, for instance, estimated based on the data of the person-trip survey referring to the method proposed by Osaragi and Hoshino (2012).

Activity of Fire-Brigade (Figure 3(c))

When a fire-brigade leaves a fire station, it firstly travels to any water source by a fire engine. After arriving at a water source, firefighters get off the fire engine and run to the fire origin (building). Namely, we estimated the time required for travelling from a fire station to a fire origin. Here, the cases where a fire-brigade could not reach a fire origin due to street-blockage were excluded in the calculation of the travel time.

All fire-hydrants were assumed to be unavailable because the water supply was cut off due to earthquake. Also, we assumed that a fire-brigade moved toward the water source (excluding fire-hydrants) so that the expected travel time, which was defined as the sum of T_1 (the time distance from the current location of the fire-engine to a water source) and T_2 (the Euclidean distance from a water source to a fire origin divided by 167 [m/minute]), could be minimized.

The influence on the activity of fire-brigades by street-blockage was considered to be basically same as the case of evacuees. The difference was that fire-brigades were assumed to spend 30 seconds for restarting the travel after encountering a street-blockage. The travel speed was assumed as shown in Table 2.

Table 2. Travel Speed

Attribute	Travel Speed
Firefighter	167 [m/minute] (= 10 km/h)
Fire-engine on urgent transportation road	Speed limit of the road
Fire-engine on street with a width of more than 6 m	0.8 times of speed limit of the road
Fire-engine on street with a width of 6 m or less	0.5 times of speed limit of the road

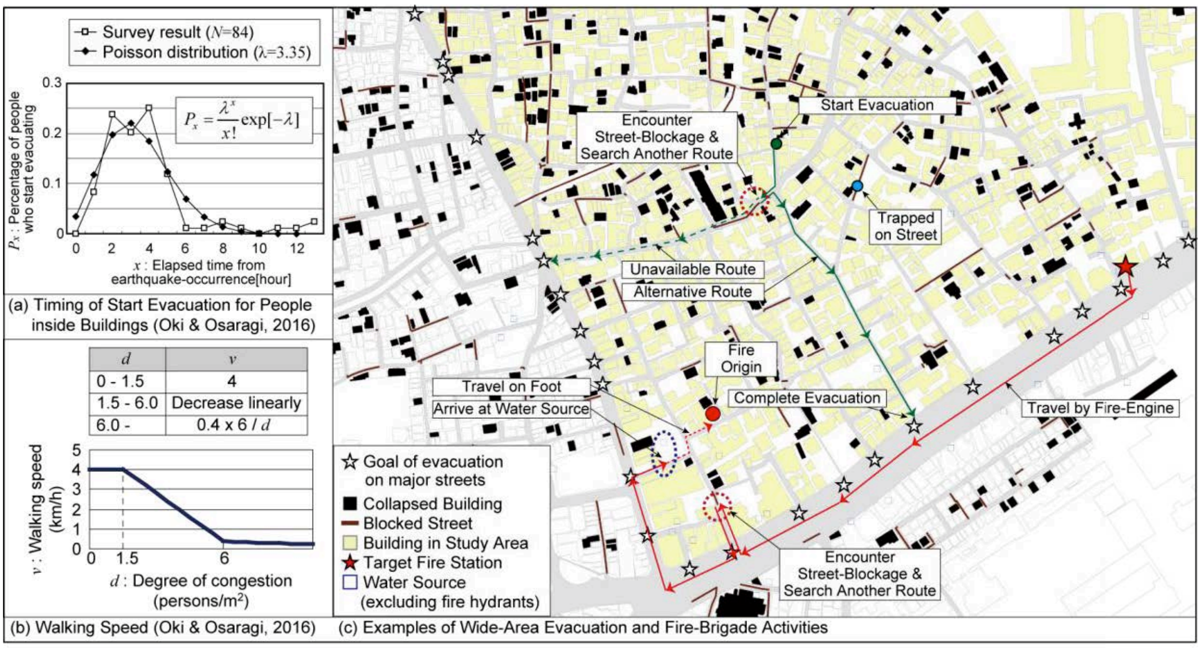


Figure 3. Wide-Area Evacuation Behavior and Fire-Brigade Activity

EVALUATION OF CONVERSION TO QUAKE-RESISTANT BUILDINGS IN TERMS OF WIDE-AREA EVACUATION

Study Area and Assumptions in Simulation

We extracted multiple study areas from densely built-up wooden residential areas in Tokyo (Table 3). Many national/prefectural roads form a mesh, and all of the study areas are surrounded by such major roads with a wide width. Sumida A, Sumida B, and Arakawa are located in the eastern part of Tokyo 23 Wards. According to the 7th Community Earthquake Risk Assessment Study (TMG, 2013), these areas have high risk of building-collapse in a large earthquake (Figure 4, upper left-hand panel). Also, most streets inside each study area are extremely narrow (Figure 4). By contrast, Suginami and Shinagawa are located in the western part and southern part of Tokyo 23 Wards, respectively. Although the width of streets inside each study area is narrow as well as the other areas, the risk of building-collapse in a large earthquake is comparatively low (Figure 4).

In the simulation, the evacuees are considered to succeed in evacuating when they arrive at any of intersections (indicated by star in Figure 4) on major roads. The numbers of buildings, street-link, and people in each study area are shown in Table 3. We prepared 100 cases of property damage (building-collapse and street-blockage) estimated by the property damage model, and carried out one trial for each case.

Table 3. Profile of Study Areas (Wide-Area Evacuation)

	Sumida A	Sumida B	Arakawa	Suginami	Shinagawa	Total
Constituent *Chome*	Sumida 1 – 5 Higashi-mukoujima 4 – 5	Yahiro 1 – 5 Higashi-mukoujima 6	Arakawa 5 – 6 Higashi-ogu 1 – 3	Koenji-minami 2 – 4 Asagaya-minami 1 – 2	Nakanobu 1 – 6 Nishi-nakanobu 1 – 3 Higashi-nakanobu 1 – 2 Hatanodai 2 – 5 Kita-magome 1 – 2 Kami-ikedai 1	
Num. of Buildings	6,713	5,851	4,931	6,300	9,799	33,594
Num. of Street-link	1,359	1,096	1,123	1,423	2,237	7,238
Num. of People (*)	16,269	14,336	11,091	22,035	26,321	90,052
Area [km^2]	1.63	1.04	0.77	1.37	1.76	6.57

*) We took into account people inside buildings and pedestrians at 6:00 pm on a weekday, which was estimated on the basis of the person-trip survey conducted in Tokyo Metropolitan Area in 2008. Other people (such as railway passengers, automobile users, etc.) were excluded because we focused on the people's evacuation behavior to major roads from small residential areas surrounded by the roads.

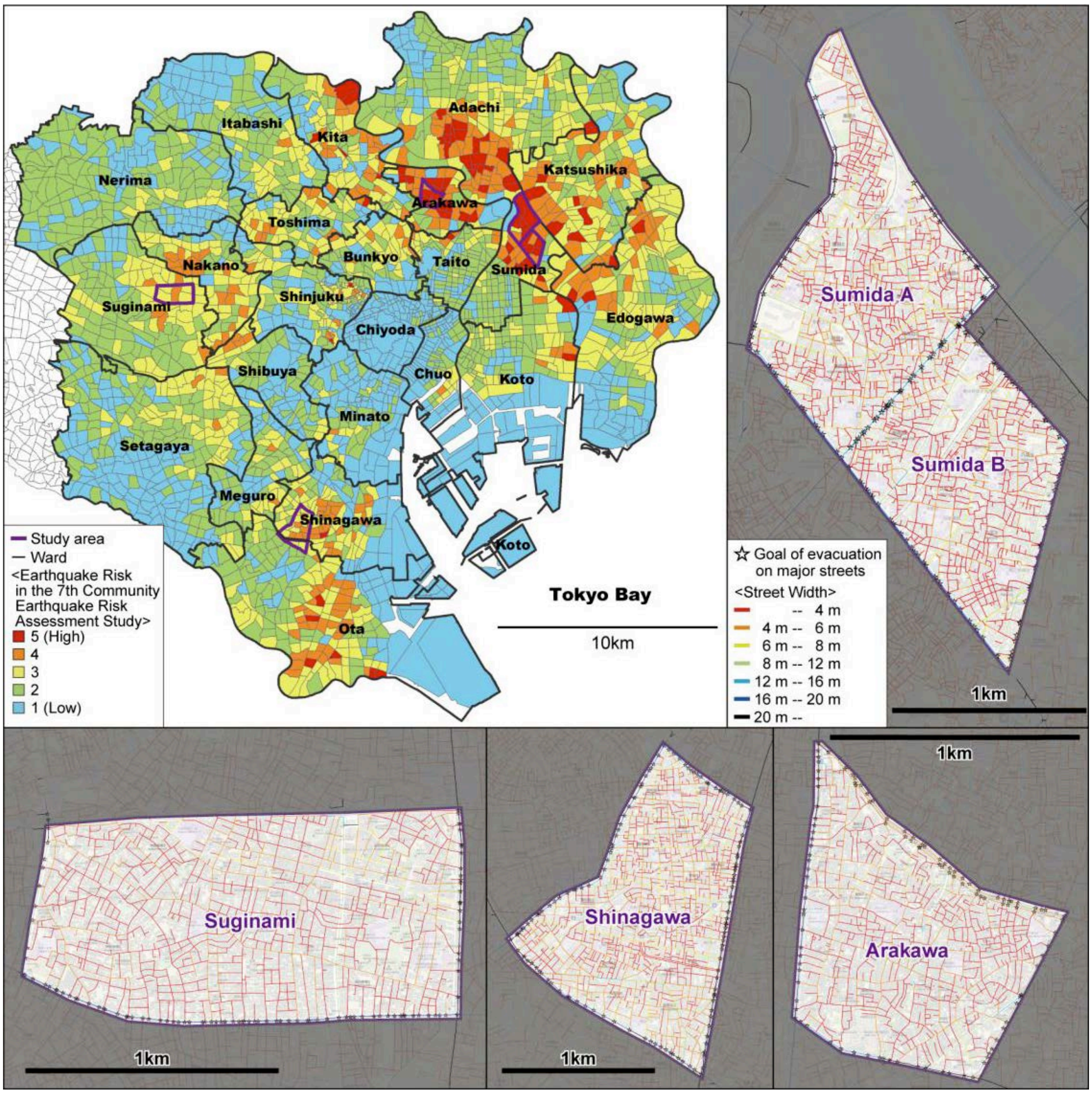


Figure 4. Study Areas for Wide-Area Evacuation Simulation

Change in Ratios of Quake-Resistant Buildings and Property Damage over the Year

Figure 5 shows the change in the ratio of quake-resistant buildings up to 30 years later (based on 2011). As time passes, the number of old buildings, which have high potential of conversion as shown in Figure 2, decreases. Therefore, the increase rate of quake-resistant buildings also gradually decreases. After 30 years, the ratio of quake-resistant buildings becomes more than 80% in most areas, and the difference of the ratio between Sumida A (the lowest ratio) and Suginami (the highest ratio) is reduced by half.

The change in the average ratio of collapsed buildings up to 30 years later is shown in Figure 6. The average ratio of collapsed buildings is much higher in Sumida A, Sumida B, and Arakawa than in the other areas because the ratio of older wooden buildings is higher in these three areas. As a result of conversion, the average ratio of collapsed buildings in these three areas can be reduced to about 10%. We can see the same trend in the average ratio of blocked streets (Figure 7). However, it is noteworthy that the ratio of blocked streets for pedestrians (passable width is 1 m or more) in Arakawa is nearly the same ratio as Suginami and Shinagawa (not Sumida A and Sumida B). This is because there are comparatively more streets with a width of more than 4 m in Arakawa.

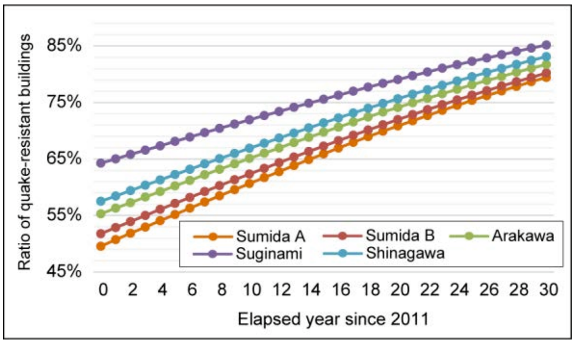


Figure 5. Ratio of Quake-Resistant Buildings

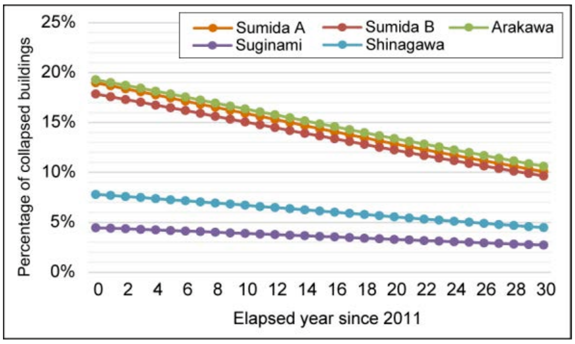
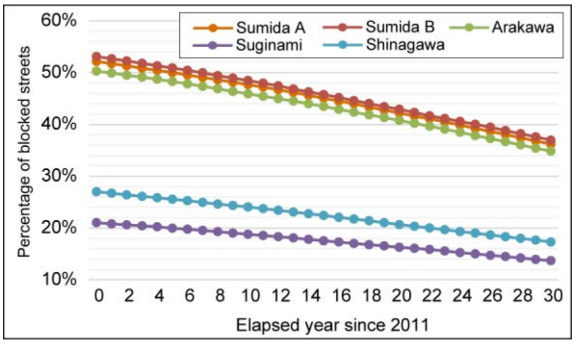


Figure 6. Percentage of Collapsed Buildings



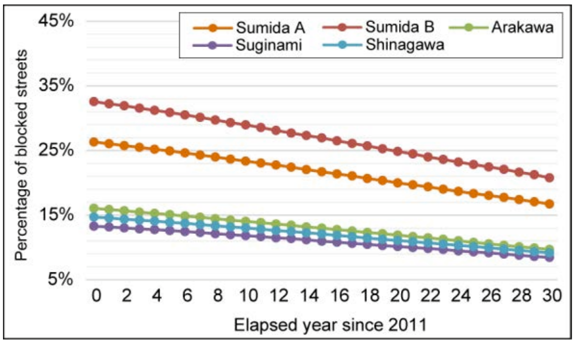


Figure 7. Percentage of Blocked Streets (Left-hand: streets where vehicles cannot pass; Right-hand: streets where both vehicles and pedestrians cannot pass)

Result of Wide-Area Evacuation Simulation

Time/Distance for Arriving at Major Streets

Figure 8 and Figure 9 show the average time and distance of evacuees required for arriving at major streets (hereafter, the results are based on the average values for 100 cases of property damage). The time and distance in the case where no street-blockage occur are indicated by broken lines. The difference of time (distance) between the cases with/without street-blockage is bigger in Sumida A and Shinagawa than in the other areas. The reason is that these two areas are comparatively larger, and therefore, the influence on making a detour in evacuation by street-blockage is also larger. On the other hand, the effects on reducing the difference by conversion of non-quake-resistant buildings are greater in these two areas.

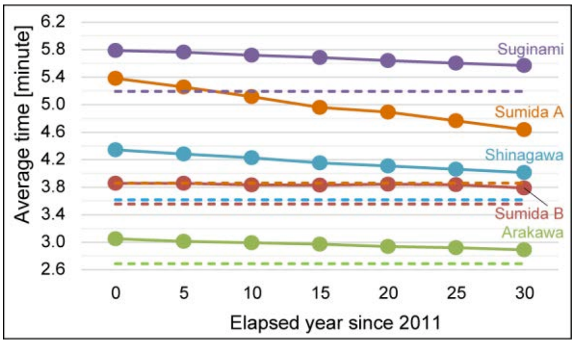


Figure 8. Time for Arriving at Major Streets

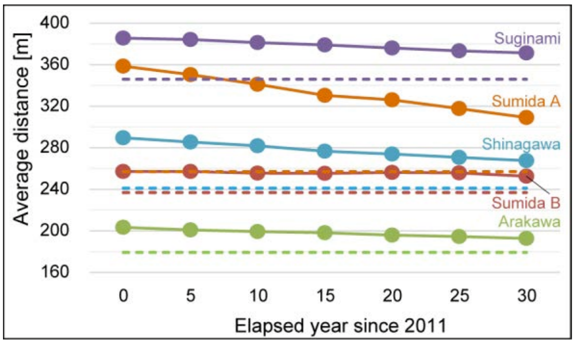


Figure 9. Distance for Arriving at Major Streets

Number of Evacuees Trapped on Streets / in Blocks

We estimated the average number of evacuees trapped on streets (or in blocks) due to street-blockage based on the simulation result (Figure 10). In 2011 (year 0), around 2,000 evacuees are trapped in Sumida A and Sumida B, respectively. Additionally, there are more than 1,000 evacuees trapped on streets (or in blocks) in Shinagawa, where the average ratio of blocked streets is comparatively low in study areas. For easily comparing the results among the study areas, we calculated the ratio of the number of evacuees trapped on streets (or in blocks), divided by total number of people in each area (Figure 11). The magnitude relation of the ratio among five areas corresponds to that of the ratio of blocked streets (Figure 7). After 30 years pass, the number of evacuees trapped on streets (or in blocks) can be reduced by less than half in these three areas.

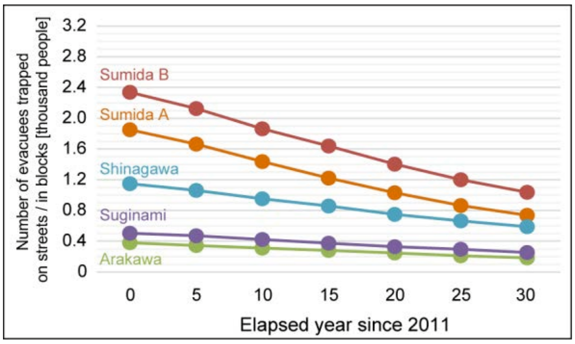


Figure 10. Number of Evacuees Trapped on Streets (or in Blocks)

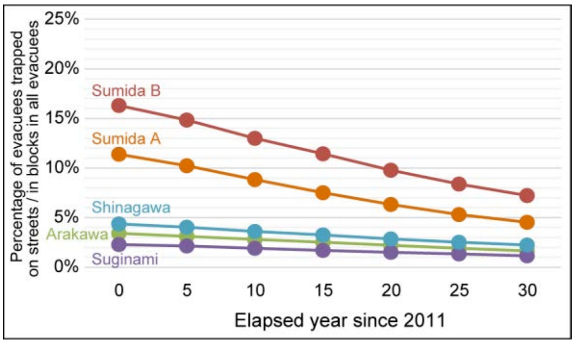


Figure 11. Ratio of Evacuees Trapped on Streets (or in Blocks) in All Evacuees

Number of Encountering Blocked Streets on Evacuation Route

Figure 12 shows the composition ratio in all evacuees by the number of encountering blocked streets on their evacuation route. The ratio of evacuees who encounter blocked streets on their evacuation route at least once decreases by about 10 points after 30 years pass.

Combining the above results, it can be said that the effects of the conversion of non-quake-resistant buildings to quake-resistant ones are not significant from the viewpoint of shortening time and distance for arriving at major streets (Figure 8 and Figure 9). By contrast, the conversion is especially effective in the areas (such as Sumida A and Sumida B) with high risk of street-blockage for reducing the ratio of evacuees trapped on streets (or in blocks) compared with the other areas (Figure 11), which contributes to the reduction of human casualties due to urban fire spread. However, it is noteworthy that the degree of change in all the indices related to wide-area evacuation (Figure 8 to Figure 12) is not yet sufficient even after 30 years pass and much smaller than that in quake-resistant buildings (Figure 5). The results suggest that the conversion of non-quake-resistant buildings is not always directly linked to the reduction of wide-area evacuation difficulty. This is because the conversion of non-quake-resistant buildings is assumed to be proceeded in random order though street-blockage depends on the collapse/non-collapse of all buildings along the street. Our future work will cover analyzing the influence of the order of conversion.

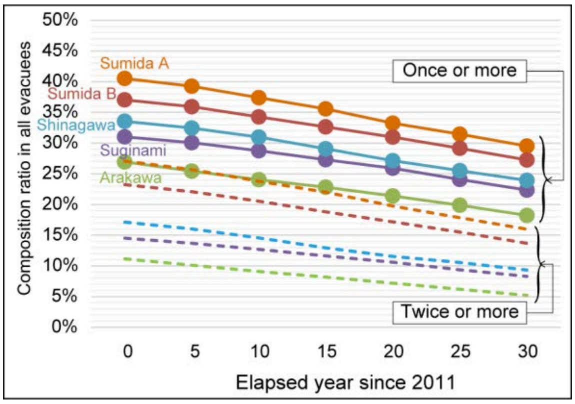


Figure 12. Number of Encountering Blocked Streets on Their Evacuation Route

EVALUATION OF CONVERSION TO QUAKE-RESISTANT BUILDINGS IN TERMS OF FIRE-BRIGADE ACCESSIBILITY

Study Area and Assumptions in Simulation

In this section, we extracted four areas with vulnerable characteristics of streets (such as narrow width, complicated street network, many dead-end streets, etc.) based on the priority development districts (TMG, 2016) and the 7th Community Earthquake Risk Assessment Study (TMG, 2013). Additionally, another three areas with comparatively good characteristics of streets were selected for comparison. The attributes and spatial distribution of these seven areas (1) to (7) are shown in Table 4, Figure 13, and Figure 14. We can also see the spatial distribution of fire stations (starting points of fire-brigades in simulation) and streets in these figures. In some cases, fire stations are located outside the study area. Therefore, fire-brigades were assumed to move to fire origins (burning buildings) by using the streets not only inside each study area but also inside the extended area (within the range of 1.0 km from the perimeter of each study area).

We prepared 500 cases of property damage (building-collapse and street-blockage) estimated by the property damage model in the previous section. The peak ground velocity (PGV) was fixed to 66 [cm/sec]. Herein, for each case, the structure and built year of each building in study areas (hereafter, including the extended areas) were estimated by the procedures mentioned above, and buildings to be converted were randomly extracted from non-quake-resistant buildings. The number of buildings to be converted was determined so that the ratio of quake-resistant buildings in the study area was equal to a certain percentage (from 55% to 100% in increments of 5%: totally 10 steps). Thus, we carried out 5,000 trials (= 500 cases of property damage by 10 steps of the ratio of quake-resistant buildings).

Table 4. Profile of Study Areas (Accessibility of Fire-Brigade)

	Area with Vulnerable Characteristics of Streets				**Area with Comparatively Good Characteristics of Streets**		
Area No.	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
Ward	Shinagawa	Suginami	Arakawa	Sumida	Ota	Sumida	Sumida & Koto
Fire station in study area	Ebara Togoshi Hatanodai	Suginami Mabashi Koenji	Arakawa Ogu Shimo-ogu (Tabata*)	Mukoujima Tachibana	Ichinokura Kugahara Yaguchi Shimo-maruko Nishi-kamata	Honjo Higashi-komagata (Asakusa*)	Midori* Morishita* (Hamacho*)
Area [km^2]	1.41	0.85	0.77	1.04	1.30	0.74	1.11
Daytime population [person] ([person/km^2])	25,143 (17,886)	18,776 (22,056)	13,841 (17,951)	17,786 (17,156)	22,580 (17,407)	14,979 (20,346)	24,057 (21,749)
Nighttime population [person] ([person/km^2])	35,917 (25,550)	19,017 (22,339)	19,489 (25,276)	21,996 (21,217)	29,693 (22,891)	13,830 (18,785)	25,750 (23,280)
Daytime/ Nighttime	0.70	0.99	0.71	0.81	0.76	1.08	0.93

*) In principle, firefighters take care of fires only in the ward where their fire station is located. Therefore, we assumed that: (i) Firefighters belonging to Midori Fire Station and Morishita Fire Station (Area (7)) headed for the fires which broke out in Sumida Ward and Koto Ward, respectively; (ii) Tabata Fire Station (Area (3)), Asakusa Fire Station (Area (6)), and Hamacho Fire Station (Area (7)) were excluded from the simulation because these were located in the different ward from the one where each study area was located.

**) Daytime and nighttime population are based on the National Census in 2010.

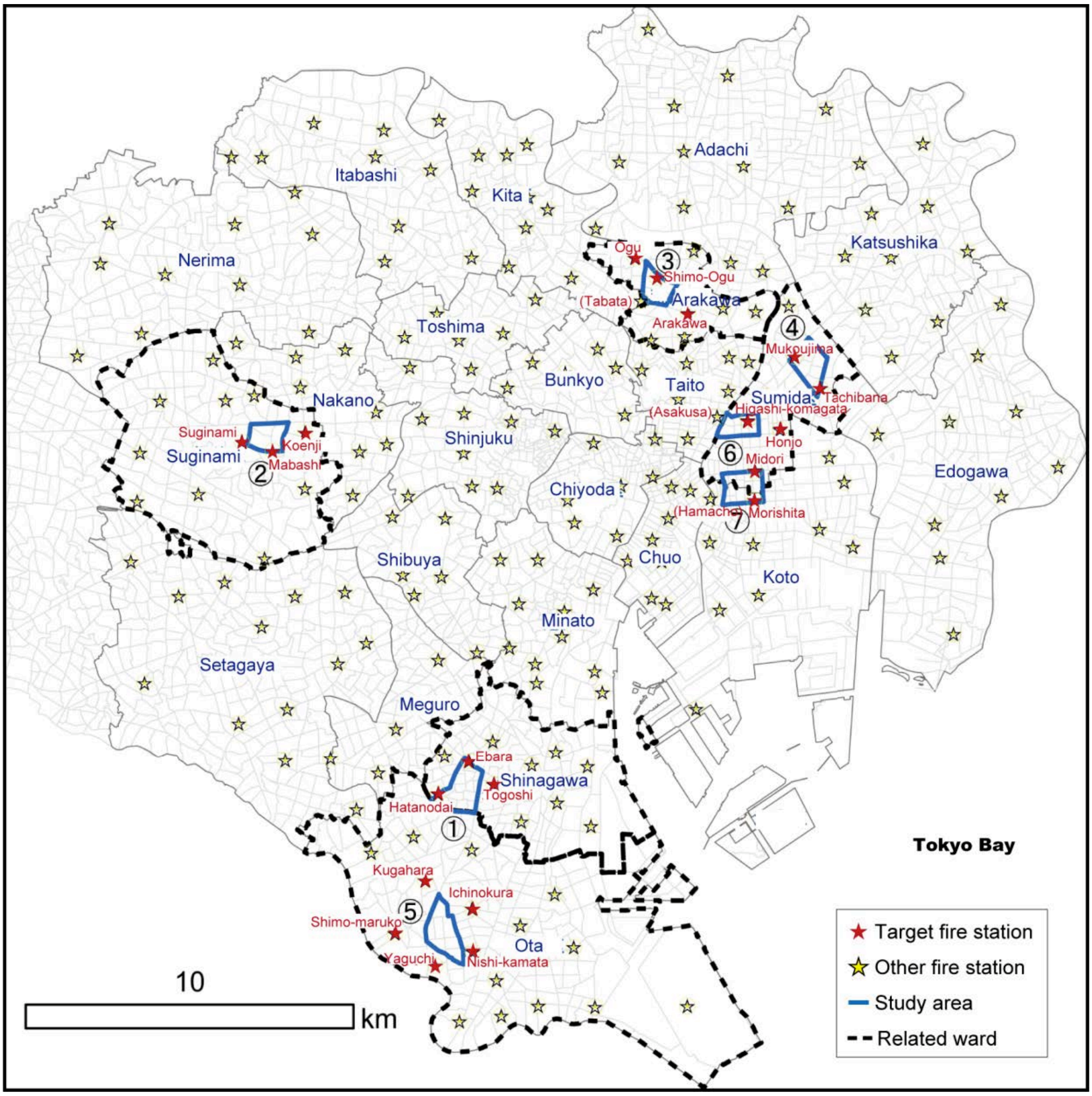


Figure 13. Spatial Distribution of Study Areas and Fire Stations

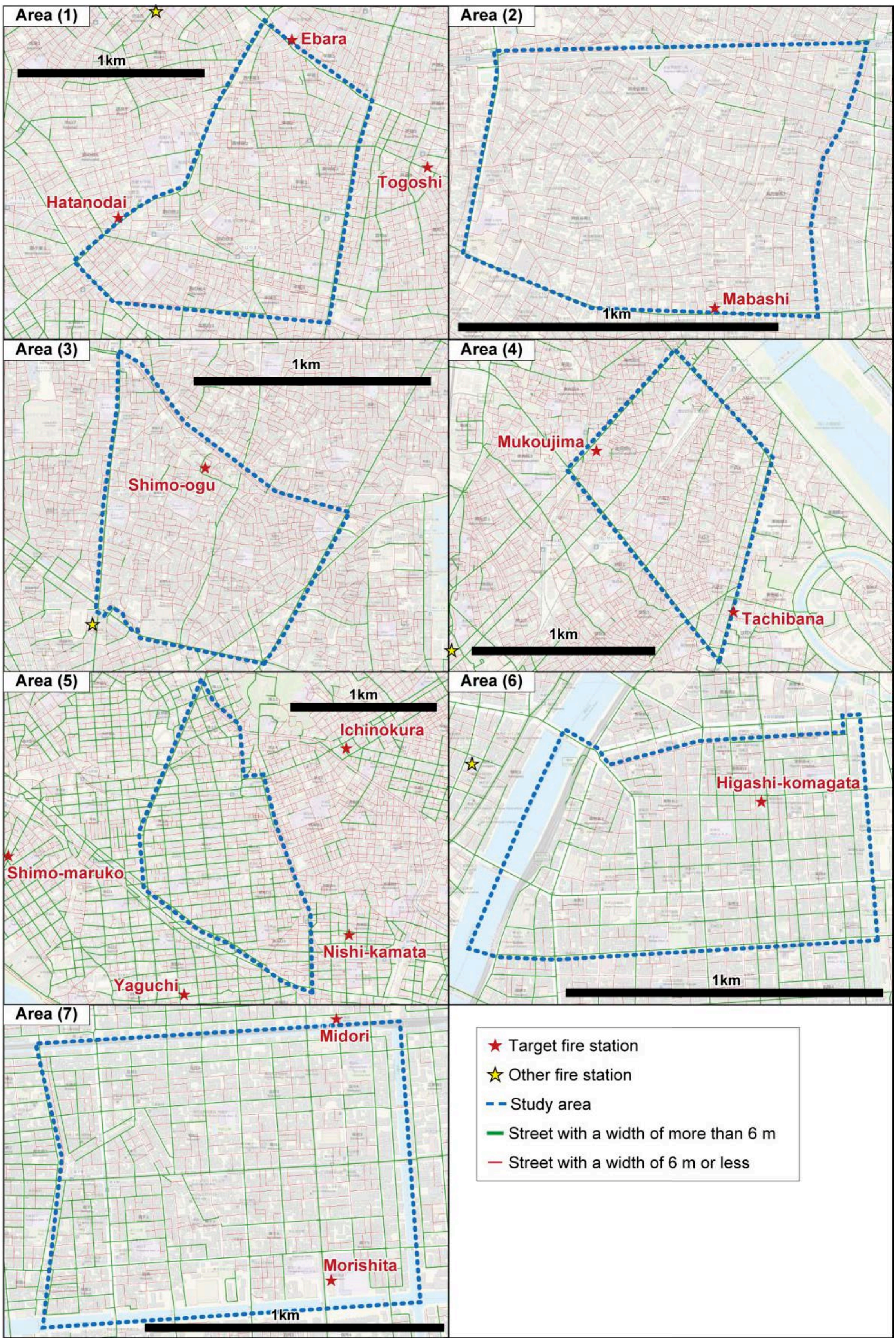


Figure 14. Detail of Study Areas

Reducing the Numbers of Collapsed Buildings / Blocked Streets by Promoting Conversion to Quake-Resistant Buildings

Table 5 shows the ratio of quake-resistant buildings in each area (as of 2011). The ratio is less than 40% in areas (4) and (6), while more than 50% in areas (2) and (5).

Table 5. Ratio of Quake-Resistant Buildings in Each Area (in 2011)

	Area with Vulnerable Characteristics of Streets				Area with Comparatively Good Characteristics of Streets		
Area No.	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
Built in 1981 or later	3,718	2,240	2,180	2,022	3,018	1,128	2,010
Built before 1980	4,412	2,012	2,716	3,748	2,640	2,004	2,812
Total	8,130	4,252	4,896	5,770	5,658	3,132	4,822
Ratio of quake-resistant buildings	45.7%	52.7%	44.5%	35.0%	53.3%	36.0%	41.7%

Figure 15 shows the reduction of the number of collapsed buildings and blocked streets by promoting conversion to quake-resistant buildings. There is little difference among study areas in the relationship between the ratio of quake-resistant buildings and the average ratio of collapsed buildings (Figure 15, left-hand panel). In other words, the ratio of collapsed buildings is nearly the same in the areas with nearly the same ratio of quake-resistant buildings. By contrast, the average ratio of blocked streets in the areas with vulnerable characteristics of streets (areas (1) to (4)) is about twice as large as the ratio in the areas with comparatively good characteristics of streets (areas (5) to (7)) in case of the same ratio of quake-resistant buildings (Figure 15, right-hand panel).

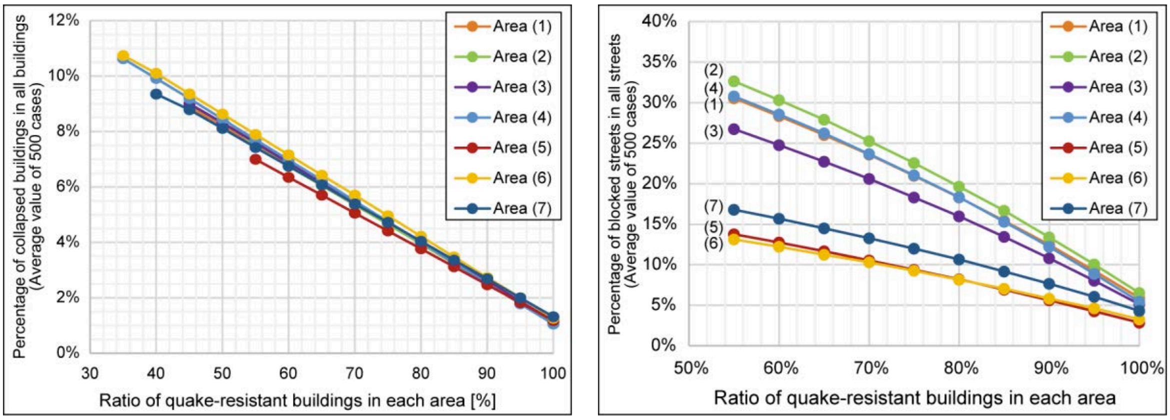


Figure 15. Relationships between Ratio of Quake-Resistant Buildings and Percentages of Collapsed Buildings and Blocked Streets

Access Time to Fires in Normal Times (without Street-Blockage)

As seen in Table 6, there is a big difference in the access time to fires under the condition without street-blockage according to the size of study area or the location of fire stations. Therefore, hereafter, in order to easily compare among multiple study areas, a fire origin was randomly extracted from the buildings where the travel time in case that no street-blockage occur (Figure 16) was 2.0 minutes to 2.5 minutes in each area for each simulation trial. Among the specific property damage case (with/without street-blockage), the location of a fire origin was the same and a fire-brigade headed from the same fire station, independent of the ratio of quake-resistant buildings.

Table 6. Time Required for Fire-Brigades to Arrive at a Building in Each Area

			Area with Vulnerable Characteristics of Streets				Area with Comparatively Good Characteristics of Streets		
		All	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Num. of buildings		36,660	8,130	4,252	4,896	5,770	5,658	3,132	4,822
Time [m:ss]	Ave.	1:29	1:18	1:38	1:15	1:28	1:45	2:04	1:11
	St. Dev.	0:35	0:29	0:37	0:28	0:38	0:26	0:24	0:32
	Max.	4:07	3:16	3:51	2:47	3:29	3:07	3:25	4:07

*) Each time in this table was calculated on the basis of simulation results for all buildings in the area.

**) In Area (6), the size of the area is small and a fire station (Higashi-komagata) is located nearly at the center of the area. Therefore, there are originally few buildings where fire-brigades take 2 minutes to 2 minutes 30 seconds in normal times. However, for comparison with the results in the other areas, we analyze the access time in Area (6) based on the time required only from another fire station (Honjo) (Table 6 and Figure 16(b)).

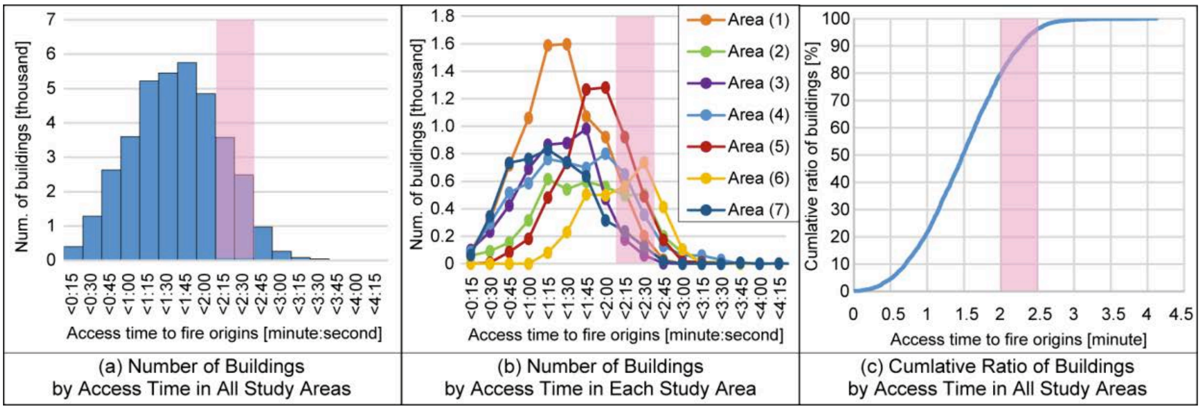


Figure 16. Access Time to Fire Origins (in the Case without Street-Blockage)

Shortening Access Time to Fires by Promoting Conversion to Quake-Resistant Buildings

Firstly, we assumed that streets with a width of more than 6 m were never blocked by rubbles of collapsed buildings in order to evaluate the effects of shortening access time by converting buildings along narrow streets to quake-resistant ones.

The relationships between the ratio of quake-resistant buildings and access time to fires are shown in Figure 17 (left-hand panel: average value; right-hand panel: maximum value). In the areas with comparatively good characteristics of streets (areas (5) to (7)), there is a slight improvement in access time because the ratio of blocked streets is comparatively low (Figure 15, right-hand panel). By contrast, in the other areas (areas (1) to (4)), the accessibility of fire-brigades is improved as the ratio of quake-resistant buildings increases, and therefore the average/maximum time required for travelling to fire origins can be greatly shortened. Specifically, the difference of access time with/without street-blockage is much bigger in Area (2) than in the other areas because there are few streets with a width of more than 6 m [1)]. However, the difference becomes significantly smaller and access time becomes closer to the time in the case with no street-blockages.

These results suggest that the effects of shortening access time to fires are larger in the areas with more vulnerable characteristics of streets. Considering the possibility that streets with a width of more than 6 m are blocked, the effects are further remarkable (Figure 18).

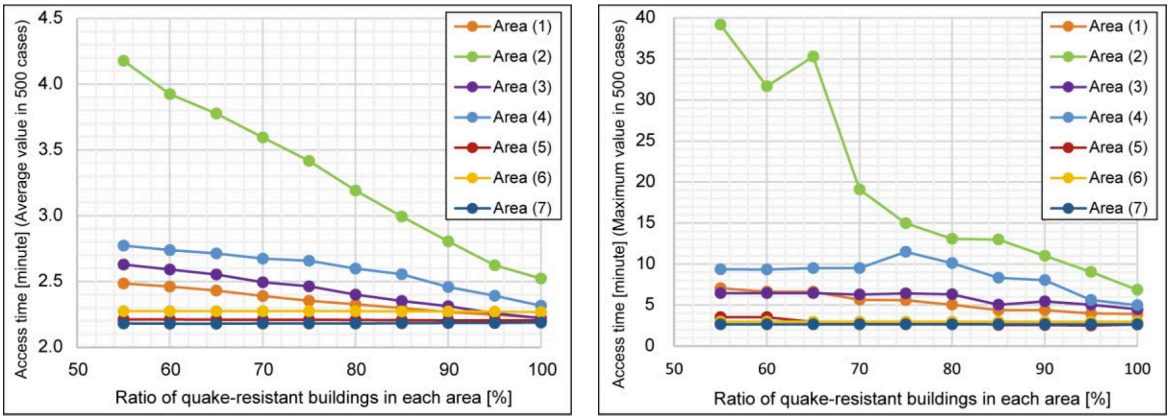


Figure 17. Relationship between Ratio of Quake-Resistant Buildings and Access Time of Fire-Brigade (Not Considering Blockage of Streets with a Width of More than 6 m)

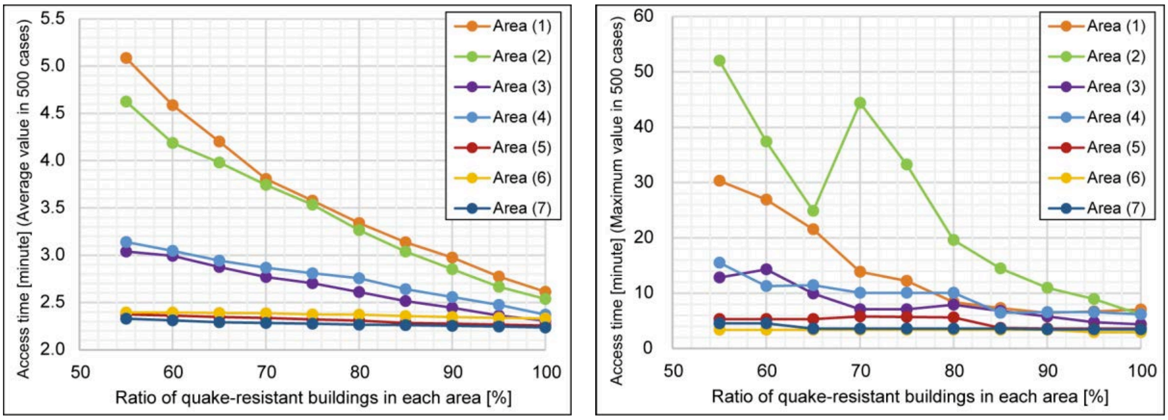


Figure 18. Relationship between Ratio of Quake-Resistant Buildings and Access Time of Fire-Brigade (Considering Blockage of Streets with a Width of More than 6 m)

SUMMARY AND CONCLUSIONS

Conversion of low quake-resistant buildings to quake-resistant ones has been important issue for the reduction of property and human damage in densely built-up wooden residential areas at the time of a large earthquake. Aiming at evaluating conversion of such buildings from multiple aspects related to human activities, we implemented the simulations in multiple study areas by using the models which described conversion to quake-resistant building, building-collapse, street-blockage, wide-area evacuation behavior, and activities of fire-brigade. The main results of the simulations can be summarized as follows:

- The ratios of collapsed buildings and blocked streets can decrease in all the study areas as the ratio of quake-resistant buildings increases.
- The influence on making a detour in evacuation by street-blockage tends to be larger in wider areas. Therefore, the effects on reducing the difference of time (or distance) between the cases with/without street-blockage by conversion of low quake-resistant buildings are greater in such areas.
- The magnitude relation of the ratio of evacuees trapped on streets (or in blocks) among the study areas corresponds to that of the ratio of blocked streets. In other words, the areas where more buildings with low resistance to earthquake have a higher potential of reducing the ratio of evacuees with the difficulty in wide-area evacuation.
- The effects of shortening access time of fire-brigades to fire origins are larger in the areas with more vulnerable characteristics of streets (i.e., the areas where almost all streets are narrow).

Using the analytical method proposed in this paper, we can evaluate conversion to quake-resistant buildings in terms of both wide-area evacuation and fire-brigade accessibility in any area. Additionally, it is possible to provide information for making a decision of more effective and efficient methods of converting buildings. For instance, the priority of providing subsidies for reconstruction among multiple areas or in the specific area can be considered based on the quantitative evidence by comparing simulation results under the condition of different conversion scenarios.

NOTES

1) The graphs of Area (2) in the right-hand panels of Figure 17 and 18 are discontinuous. As described in Section "Activity of Fire-Brigade", the cases where a fire-brigade cannot reach a fire origin due to street-blockage are excluded in the calculation of the access time. Namely, the results in Area (2) suggest that: if the ratio of quake-resistant buildings increases from 60% to 65%, the possibility that fire-brigades reach the fire origin increases but they have to make a long detour in critical cases as well.

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