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Paper:

Assessment of Street Network Accessibility in Tokyo Metropolitan Area After a Large Earthquake

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It is difficult to evaluate the street network accessibility after a large earthquake occurs. In this paper, we construct a model to evaluate the street network accessibility for wide-area emergency behaviors under the condition of property damage in the Tokyo Metropolitan Area after a large earthquake. Additionally, we analyze the relationships between a local environment and street network accessibility by using multiple regression analysis. Finally, we discuss some important factors for evaluating risk mitigation strategies.

Keywords: large earthquake, street network accessibility, property collapse, emergency behavior, local environment

1. Introduction

In recent years, the world has experienced many natural disasters. Therefore, preparing for future disasters is an important task. Various types of hazard maps have been created by many different organizations to understand the vulnerability to disasters. **Table 1** lists examples of hazard maps that can be accessed through the Internet [1–5]. For instance, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) provides hazard maps for many disasters in Japan, which include tsunamis, volcanoes, and earthquakes, on the ‘Hazard Map Portal Site’ [1]. These are useful to roughly grasp the spatial distribution of expected damage (property collapse, human casualties, etc.) due to various disasters. However, they do not focus on the risk of damage at the micro scale, such as building collapse and street blockage. Additionally, it is difficult to evaluate the effects of future improvement projects because the ordinal hazard maps only show the present conditions.

As it is predicted that there is a 70% possibility of an earthquake directly hitting Tokyo within the next 30 years [6, 7], preparedness for a large earthquake is one of the primary concerns in Tokyo. Local governments attempt to identify areas with a high potential for 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 damage because many factors affect 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 methods of improving urban vulnerability to earthquakes. Tokyo Metropolitan Government (TMG) estimated the risk of property collapse in *chome* (a traditional Japanese address unit) by using GIS data, which include detailed characteristics of the local area (e.g., structure of buildings, density of buildings, width of streets, length of streets, etc.), and placed 5,133 *chome* in order from most to least vulnerable [8]. We can understand the relative state of towns in Tokyo and the change of state brought about by past projects for improving urban vulnerability to earthquakes. However, the risk of property collapse as estimated by TMG is not sufficient to evaluate the effects of risk mitigation projects in the future.

To evaluate effects of risk mitigation projects, Kugai and Kato evaluated the performance of the street network after a large earthquake by each *chome* based on percolation theory [9]. They attempted to clarify which local factors could explain the performance of the street network. However, the indices proposed in their paper do not consider emergency behaviors at the time of a large earthquake.

There are some studies discussing damage risk considering human characteristics associated with emergency behavior [10–14]. For instance, Osaragi and Oki estimated human casualties by using multi-agent simulation, and evaluated the effects of disaster mitigation countermeasures on actual projects in a specific local area [13, 14]. These studies are superior in terms of estimating the evacuation risk considering human activities in a large earthquake; however, it is difficult to perform a simulation over a wide area owing to calculation costs.

Although the number of human causalities is one of the primary concerns in the risk evaluation at the time of a large earthquake, we focus on the street network accessibility to identify areas with a high potential for devastating damages, and obtain fundamental knowledge on disaster mitigation strategies in the future. **Fig. 1** compares our current study with previous ones.

In this paper, we construct a simulation model, which estimates the property collapse (building collapse and

1. A portion of this paper was originally presented at the 20th AGILE Conference [20].

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Table 1. Examples of hazard maps.

Ref. No.	Site	Organization	Type of Disaster	Target Area
[1]	Hazard map portal site (MLIT)	MLIT (Ministry of Land, Infrastructure, Transport and Tourism)	Floods, tidal waves, tsunamis, landslides, volcanoes and earthquakes	Japan
[2]	PreventionWeb.net (UNISDR)	UNISDR (United Nations office for Disaster Risk Reduction)	Cyclones, earthquakes, volcanoes, etc.	Varied from a country to world
[3]	U.S. Volcanoes and Current Activity Alerts (USGS)	USGS (U.S. Geological Survey)	Volcanoes	United States
[4]	Flood hazard/risk map (European Commission)	European Commission	Floods	Europe
[5]	Seismic hazard map (SHARE)	SHARE (Seismic Hazard Harmonization in Europe)	Earthquakes	Europe

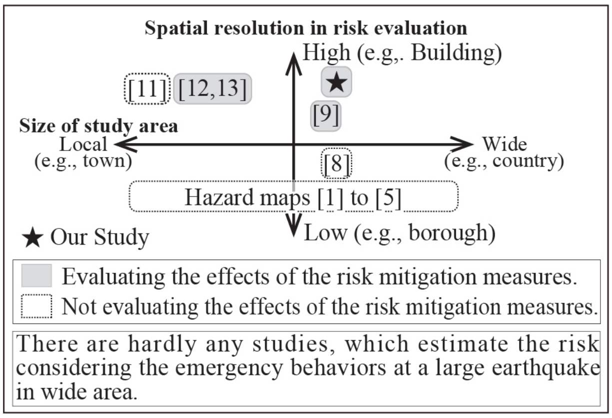


Fig. 1. Relationships between our study and previous studies.

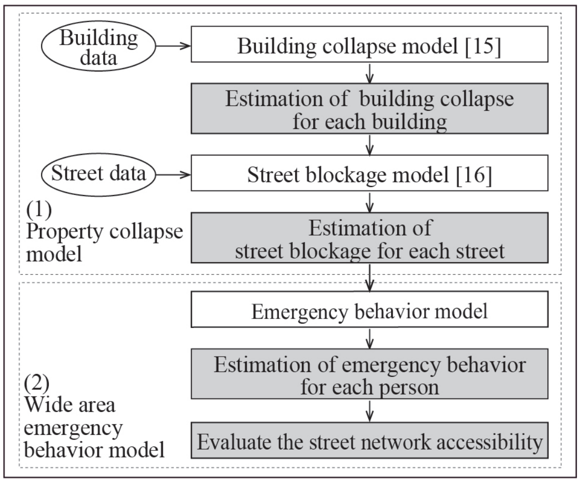


Fig. 2. Overview of simulation model.

street blockage), and evaluate the street network accessibility after a large earthquake. To avoid the risk of fire and/or falling debris, people evacuate to safe places by moving through a major street at the time of a large earthquake. At the same time, firefighters access a building on fire from a fire station by traveling through a major street. As the first step, it is important to move between each location and a major street with less damage to ensure the safety of the emergency behaviors [1]. In this paper, we evaluate the street network accessibility between a building and any major streets. Using the simulation model, the evaluation of street network accessibility in the Tokyo Metropolitan Area after a large earthquake is performed. Next, we analyze the relationships between the local environment and the street network accessibility from two viewpoints: spatial distribution characteristics and multiple regression analysis. Finally, we clarify important factors for evaluating disaster mitigation strategies.

2. Overview of Simulation Model

Figure 2 shows an overview of the simulation model that we developed. This model consists of the following two sub-models: (1) property collapse model to describe building collapse and street blockage; and (2) wide area emergency behavior model.

2.1. Property Collapse Model

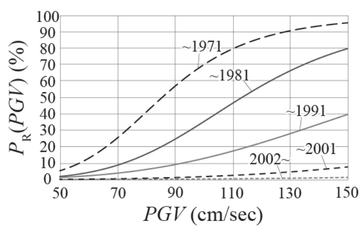
The probability of building collapse $P_R(PGV)$ is estimated from the value of Peak Ground Velocity (PGV), the structure material (wood, reinforced-concrete, or steel) and the construction year of a building (Eq. (1) and **Fig. 3**) [15].

$$P_R\left(PGV\right) = \phi\left(\frac{\ln\left(PGV\right) - \lambda}{\zeta}\right) \quad \ldots\ldots \quad (1)$$

where ϕ ( ) is a cumulative distribution function, λ and ζ are the average and the standard deviation of $\ln(PGV)$, respectively; they vary according to the structure material and the construction year of a building. Then, we determined the state of a building (collapsed or not collapsed) by comparing the probability of building collapse $P_R(PGV)$ with a generated uniform random number.

We use the model proposed by MLIT to estimate the blockage of streets [16]. The probability of street blockage $P_b(W)$ on a street of width W [m] is estimated as the probability that buildings along the street generate debris which blocks a street (Eq. (2)).

$$P_b\left(W\right) = 1 - \prod_{i \in G}\left(1 - f_i(W)\right) \quad \ldots\ldots \quad (2)$$



	All destroyed	
	λ	ζ
~1971	4.45	0.342
1972~1981	4.73	0.378
1982~1991	5.12	0.496
1992~2001	5.68	0.496
2002~	6.13	0.496

Fig. 3. Probability of building collapse [15] (example of wooden buildings).

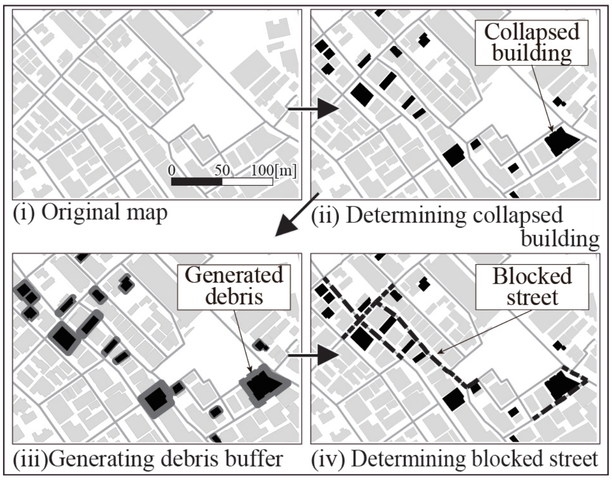


Fig. 4. Estimation of property collapse.

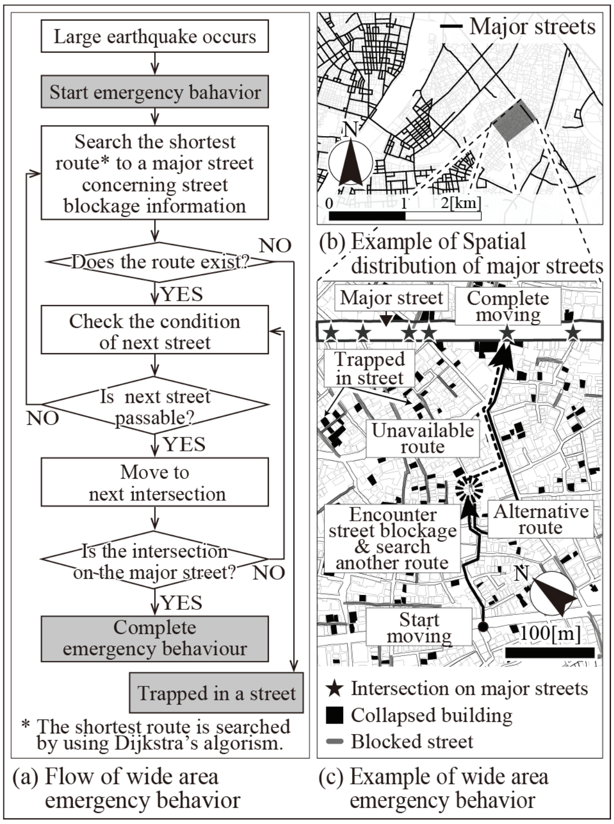


Fig. 5. Overview of wide area emergency behavior model.

where $f_i(W)$ is the probability that the debris of collapsed building i outflows to the street (**Fig. 4(iii)**) and G is the set of roadside buildings that generate the debris. The details of these models are described in previous research [17].

2.2. Wide Area Emergency Behavior Model

Figure 5 shows the overview of the wide area emergency behavior model. In this model, we consider the influence of property collapse at the time of a large earthquake. For instance, people are trapped in a building/a street, or forced to take a large detour during emergency behaviors due to blocked streets.

In this research, we consider that the safety of emergency behaviors is ensured on major streets whose width is 8 m or more [1]. We describe the behavior of each person that moves between a building and any major streets whose width is 8 m or more. First, it is assumed that people choose the shortest route from/to a major street considering the information on street blockages. It is also assumed that people know the street network and do not have any information on street blockages initially. In the model, the shortest route is estimated by using Dijkstra's algorithm. People move from/to the major street by selecting the shortest route from one intersection to the next repeatedly. If people encounter street blockages, they update their knowledge on the locations of street blockages. In addition, people search for an alternate route from/to a major street referring to the locations of street blockages already encountered.

It is assumed that emergency behaviors are completed when people arrive from/at a major street. By contrast, it is assumed that they are trapped in a street if there are no routes from/to major streets.

2.3. Study Area and Assumptions in Simulation

In this paper, we estimate the property collapse in the Tokyo Metropolitan Area (**Fig. 6(i)**), and evaluate the street network accessibility by performing a simulation of movements between major streets and each building. To evaluate street network accessibility, we assume only one movement between major streets and each building, and do not consider the population distribution in the study area. **Table 2** shows the definition of indices of property collapse and street network accessibility used for simulations. To clarify the differences of simulation results among areas, these indices are averaged in a grid cell (417.5 m × 566.5 m) (**Fig. 6(ii)**).

The building data used in simulations are based on the land use survey conducted by Tokyo Metropolitan Government in 2011, and the street data (as of 2014) are provided by the Tokyo Fire Department. Some attributes of buildings and streets are prepared beforehand [17] (**Fig. 6(iii)**).

To consider the effects of the variance of property collapse in each case, we prepare 100 cases of property collapse [3] and execute a simulation for each case to evaluate the risk. To exclude the influence of the ground characteristics and the epicenter location, Peak Ground Velocity (PGV) is fixed at 66 cm/s.

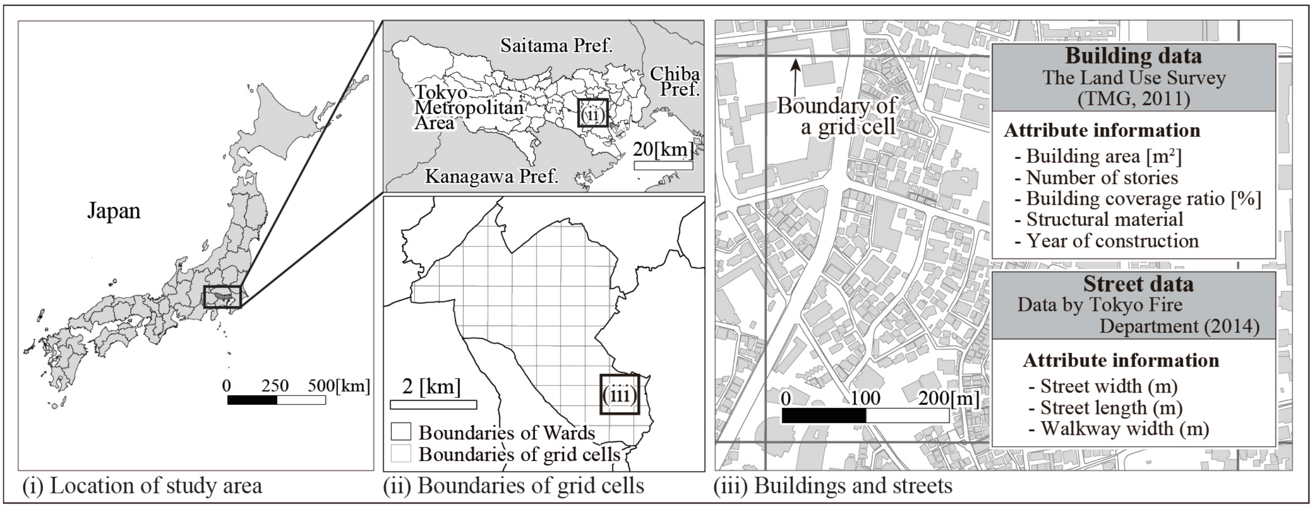


Fig. 6. Study area.

Table 2. Indices of property collapse and street network accessibility.

Property collapse indices		
1	Building collapse risk[a] [%]	The proportion of collapsed buildings to total number of buildings.
2	Street blockage risk[a] [%]	The proportion of blocked streets to total number of streets.
Street network accessibility indices		
1	Movement difficulty[a] [%]	The proportion of movements trapped in streets to total number of movements.
2	Frequency of encountering street blockage[b] [/100m]	The number of encountering blocked streets while moving 100 m.
3	Travel distance increment[b] [m]	The difference of the distance between the cases with/without street blockage.

a. Aggregated value in a grid cell.
b. Average value of all movements in a grid cell.

3. Spatial Distribution of Destruction Damage

3.1. Spatial Distribution of Property Collapse Indices

Figure 7 shows the spatial distribution of building collapse risk and street blockage risk. The values of property collapse indices are high in the eastern part of Tokyo, especially in densely built-up wooden residential areas (areas A and B). This is because these areas tend to have an unfavorable local environment from the viewpoint of vulnerability to a large earthquake. For instance, there is a dense distribution of old wooden buildings and narrow streets in area 1 (**Fig. 8(i)**). Additionally, the number of buildings along a street is comparatively high.

In comparison to these areas, there are some areas with high building collapse risk and low street blockage risk, such as area 2 (**Fig. 7**). In these areas, the street length (the distance between the nearest two intersections) is short because the density of intersections is high (**Fig. 8(ii)**). This indicates that increasing the number of intersections or decreasing the number of roadside buildings will result in the reduction of street blockage risk.

3.2. Spatial Distribution of Street Network Accessibility Indices

Figure 9 shows the spatial distribution of street network accessibility indices; in densely built-up wooden residential areas (such as areas A and B), all indices exhibit high values (**Fig. 9**). Furthermore, the spatial distribution in micro scale shows that movement difficulty is high in areas where buildings along streets have a high street blockage risk (**Figs. 8(i)** and **10**). This indicates that people will be trapped in streets or forced to take a large detour because of blocked streets.

4. Relationships Between Destruction Damage and Local Environment

4.1. Multiple Regression Analysis Using Local Environmental Variables

To identify which local environmental factors affect the indices of property collapse and street network accessibility, we perform stepwise multiple regression analysis based on datasets that include local environment variables (**Table 3**) and the indices of each grid cell in the study area [5]. However, grid cells that satisfy the following conditions are removed from the dataset:

i. Grid cells included in urban control areas.

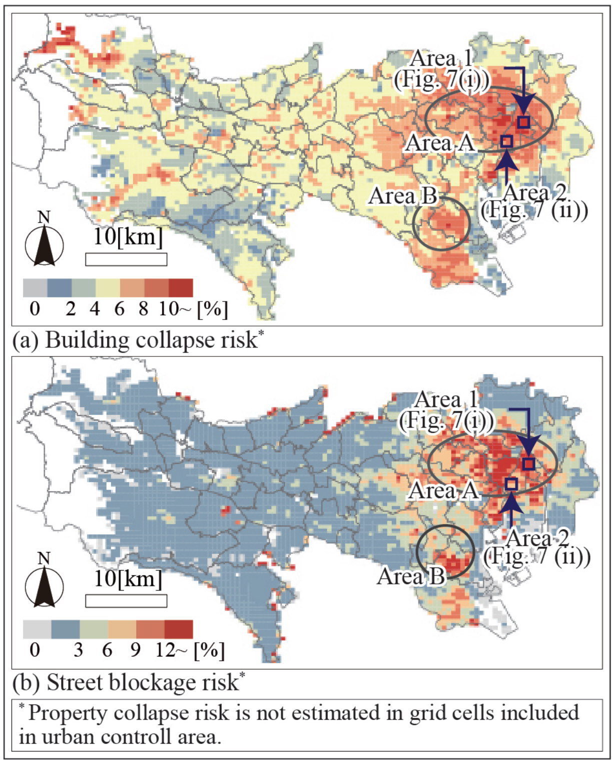


Fig. 7. Spatial distribution of property collapse indices.

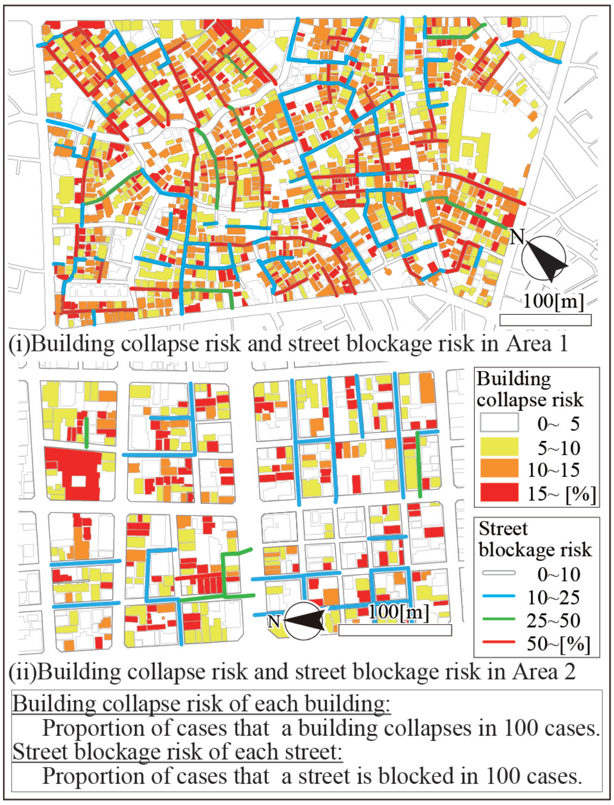


Fig. 8. Building collapse risk (each building) and street blockage risk (each street).

ii. Grid cells where no buildings, streets, or nodes (intersections) are present.

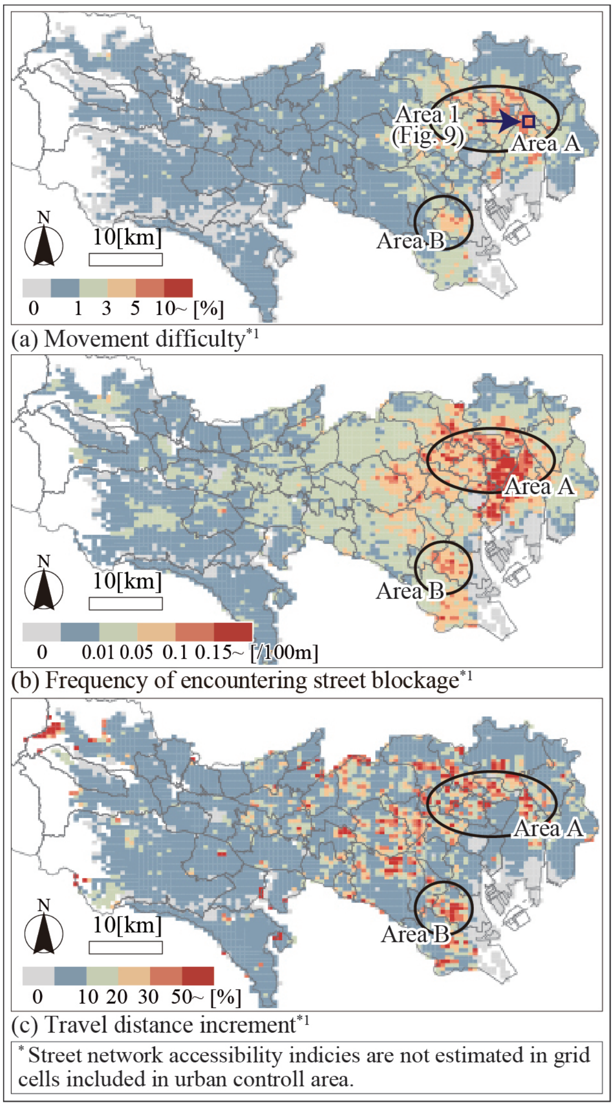


Fig. 9. Spatial distribution of street network accessibility indices.

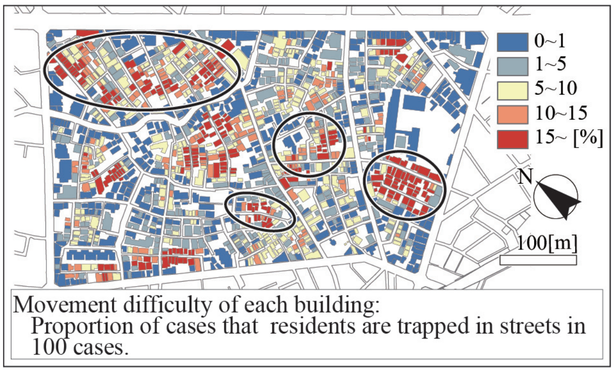


Fig. 10. Movement difficulty of each building in Area 1.

Moreover, as a dependent variable has non-linear relationships with independent variables, we take a function of dependent variables (e.g., the logarithm) to make it possible to apply a linear regression model. If the dependent variable is deformable, a grid cell is removed from the dataset.

Table 3. Local environmental variables.

No.	Variable	Description
1	Old buildings rate[a]	The percentage of old buildings built before 1981[4)] to total number of buildings.
2	Old wooden buildings rate[a]	The percentage of old wooden buildings built before 1981[4)] to total number of buildings.
3	Wooden buildings rate[a]	The percentage of wooden buildings to total number of buildings.
4	Gross building coverage ratio[b]	The ratio of gross ground floor area of buildings located in a block to total block area.
5	Number of buildings along a street[c]	The number of roadside buildings whose distances to a street boundary are less than 4m.
6	Narrow street rate[a]	The percentage of streets whose width are less than 4m to total number of streets.
7	Non-wide street rate[a]	The percentage of streets whose width are less than 8 m to total number of streets.
8	Street length[c]	The length of a streets.
9	Node-link ratio[d]	The number of streets connected to an intersection.

c. Aggregated value in a grid cell.
d. Average value in all buildings in a grid cell.
e. Average value in all streets in a grid cell.
f. Average value in all nodes (intersections) in a grid cell.

4.2. Property Collapse Regression Model

The regression models of building collapse risk Y_1, and street blockage risk Y_2 are described as follows:

$$Y_1 = a_0 + a_1X_1 + a_2X_2 \quad (3)$$

$$\begin{aligned} y_2 &= \ln(Y_2/(1-Y_2)) \\ &= a_0 + a_1X_1 + a_4X_4 + a_5X_5 + a_6X_6 \quad (4) \end{aligned}$$

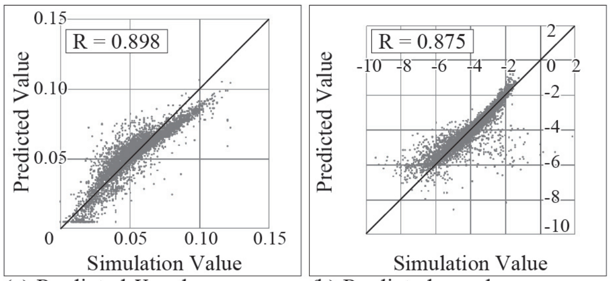
where X represents independent variables and a represents regression coefficients.

The correlation coefficient of each model is high (**Fig. 11**). Building collapse risk can be described by old buildings rate and old wooden buildings rate (**Table 4**). Street blockage risk can be described by variables on street characteristics (number of buildings along a street and narrow street rate) as well as those on buildings (old buildings rate and gross building coverage ratio) (**Table 5**).

4.3. Street Network Accessibility Regression Model

The regression models of street network accessibility indices (movement difficulty Y_3, frequency of encountering street blockage Y_4, and travel distance increment Y_5) are described as follows:

$$\begin{aligned} y_3 &= \ln(Y_3/(1-Y_3)) \\ &= a_0 + a_1X_1 + a_4X_4 + a_5X_5 + a_6X_6 + a_9X_9 \quad (5) \end{aligned}$$



(a) Predicted Y_1 values vs. simulation Y_1 values.
(b) Predicted y_2 values vs. simulation y_2 values.

Fig. 11. Simulation versus predicted plot for building collapse risk and street blockage risk.

Table 4. Summary of multiple regression analysis predicting building collapse risk ($N = 4,963$).

No.	Variable	B	β	t
0	(Constant)**	0.00400		12.3
1	Old buildings rate**	0.0960	0.645	67.3
2	Old wooden buildings rate**	0.0460	0.304	31.8

**$p < .01$.

Table 5. Summary of multiple regression analysis predicting street blockage risk ($N = 4,672$).

No.	Variable	B	β	t
0	(Constant)**	-9.34		-165
1	Old buildings rate**	3.00	0.266	29.5
4	Gross building coverage ratio**	5.56	0.422	36.3
5	Number of buildings along a street**	0.209	0.308	27.9
6	Narrow street rate**	0.972	0.131	17.0

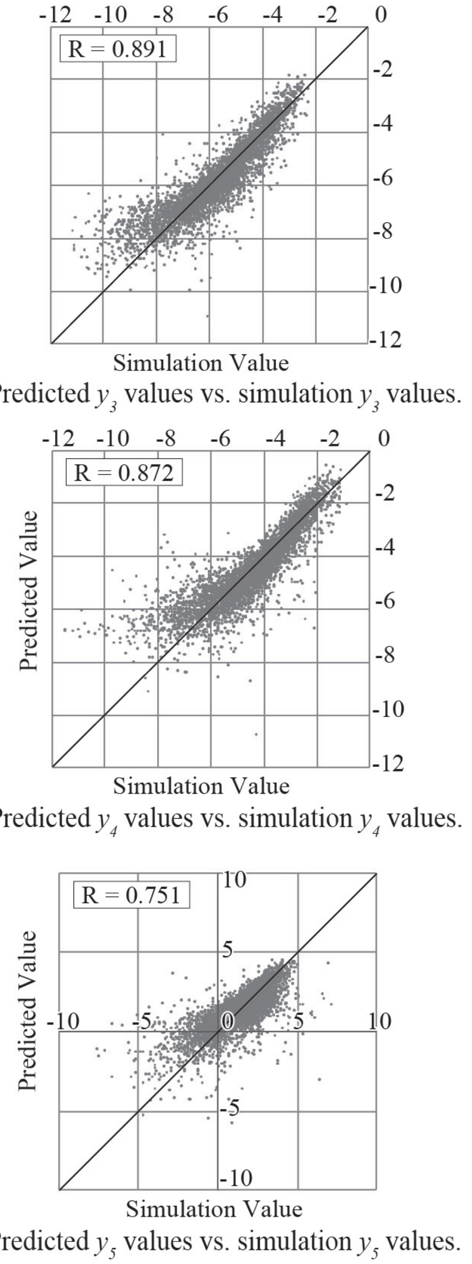
**$p < .01$.

$$\begin{aligned} y_4 &= \ln Y_4 \\ &= a_0 + a_1X_1 + a_4X_4 + a_5X_5 + a_6X_6 \quad (6) \end{aligned}$$

$$\begin{aligned} y_5 &= \ln Y_5 \\ &= a_0 + a_1X_1 + a_4X_4 + a_5X_5 + a_6X_6 \\ &\quad + a_7X_7 + a_9X_9 \quad (7) \end{aligned}$$

where X represents independent variables and a represents regression coefficients.

The correlation coefficient of each model is high (**Fig. 12**). The independent variables which describe street blockage risk are also selected in the regression models of street network accessibility indices (**Tables 5** to **8**). Therefore, this indicates that the street network accessibility indices are strongly correlated to street blockage risk. Moreover, other variables are also selected for a regression model on movement difficulty and travel distance



(a) Predicted y_3 values vs. simulation y_3 values.
(b) Predicted y_4 values vs. simulation y_4 values.
(c) Predicted y_5 values vs. simulation y_5 values.

Fig. 12. Simulation versus predicted plot for street network accessibility indices.

increment. The selected variables show that movement difficulty tends to be high in areas with small node-link ratios, and travel distance increment tends to be long in areas with a high non-wide street rate.

Table 6. Summary of multiple regression analysis predicting movement difficulty ($N = 4,175$).

No.	Variable	B	β	t
0	(Constant)**	-11.8		-96.5
1	Old buildings rate**	4.64	0.304	33.7
4	Gross building coverage ratio**	7.56	0.452	35.3
5	Number of buildings along a street**	0.252	0.278	25.6
6	Narrow street rate**	1.85	0.192	23.4
9	Node-link ratio**	-0.583	-0.104	-11.0

**$p < .01$.

Table 7. Summary of multiple regression analysis predicting frequency of encountering street blockage ($N = 4,599$).

No.	Variable	B	β	t
0	(Constant)**	-10.7		-160
1	Old buildings rate**	3.53	0.260	28.6
4	Gross building coverage ratio**	6.43	0.428	35.0
5	Number of buildings along a street**	0.243	0.307	26.7
6	Narrow street rate**	1.49	0.178	22.7

**$p < .01$.

Table 8. Summary of multiple regression analysis predicting travel distance increment ($N = 4,604$).

No.	Variable	B	β	t
0	(Constant)**	-6.58		-22.4
1	Old buildings rate**	3.74	0.261	20.9
4	Gross building coverage ratio**	3.93	0.247	13.0
5	Number of buildings along a street**	0.173	0.207	11.8
6	Narrow street rate**	2.22	0.251	21.1
7	Non-wide street rate**	5.52	0.348	27.6
9	Node-link ratio**	-0.788	-0.154	-11.6

**$p < .01$.

5. Summary and Conclusions

To evaluate the property collapse and the street network accessibility in a wide area after a large earthquake, we constructed a simulation model that describes building collapse, street blockage, and the movement of people in emergency behaviors. In this model, we described the movement of each person between a building and any major streets. People were assumed to choose the shortest route from/to a major street with no initial information on street blockages. Using this model, it was possible to describe the movement of people including those trapped in a street or forced to take a large detour during movement due to blocked streets.

Performing the simulation in the Tokyo Metropolitan Area, we evaluated the damage of each building/street and calculated the indices of property collapse and street network accessibility for each grid cell. Furthermore, we analyzed the relationships between local environments and their indices by multiple regression analysis (**Fig. 13**). The indices showed high vulnerability in densely built-up wooden residential areas where the local environment is unfavorable. The regression models clarified that the indices depend on the variables representing street characteristics (the number of buildings along a street, narrow street rate, etc.) as well as variables on building characteristics (old buildings rate, gross building coverage ratio, etc.). These findings indicate the effectiveness of providing emergency evacuation routes [6] between two intersections (decrease the number of roadside buildings) as well as the general disaster mitigation strategies (e.g., the conversion of old wooden buildings to quake-resistant buildings, widening narrow streets, etc.) (**Fig. 14**).

In future work, we will attempt to quantify the effects of risk mitigation strategies. Thereby, it will be possible to identify appropriate strategies, which differ according to the local environment of each area.

Acknowledgements

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Notes

1) The improvement of major streets whose width is 8 m or more has been promoted. These streets play an important role as a main network for various activities at the time of a large earthquake [18].

2) In this paper, we evaluate the street network accessibility from/to any of major streets whose width is 8 m or more. We assume the spatial range of emergency behavior is within a certain size of grid cell (417.5 m × 566.5 m), as the street design guideline recommends providing streets at intervals of 500 m [18].

3) Due to calculation costs, we use only 100 cases of property collapse.

4) Buildings constructed after 1981 satisfy the new earthquake resistant building standard. Those buildings are assumed not to collapse for a large earthquake of magnitude 7 or higher.

5) For the validation of the models, we estimated the regression models using 70% of data. Selected dependent variables by the Stepwise Method and the estimated values of standard regression coefficients of each model are almost the same as using 100% of data (**Tables 9** to **13**). The correlation coefficients between the values of dependent variables estimated by the simulation models and the values predicted by regression models using 30% of data are also the same as using 100% of data.

6) An emergency evacuation route, which is assumed to be used only in case of a disaster, is a passage between buildings. Construction of emergency evacuation routes has been promoted as a type of disaster mitigation measure [19].

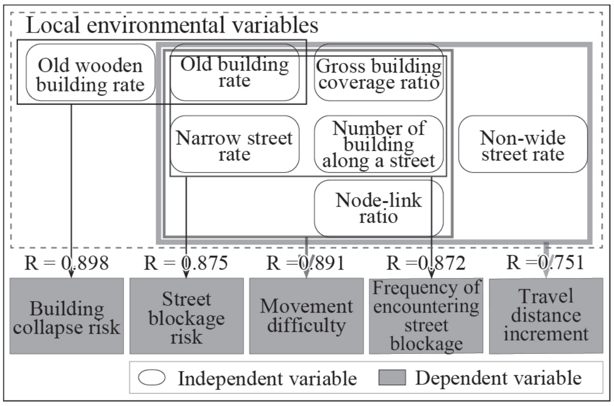

Fig. 13. Relationships between local environment and indices.

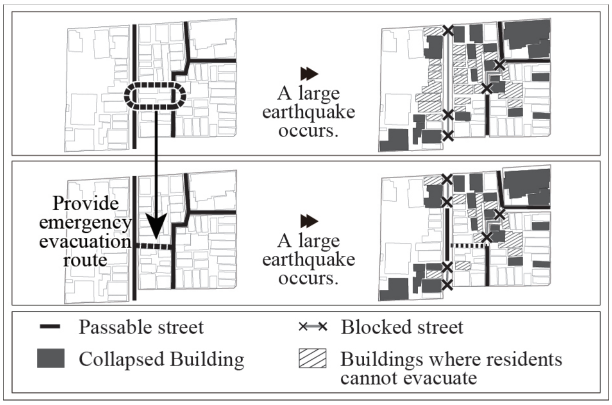

Fig. 14. Concept of providing emergency evacuation route.

Table 9. Summary of multiple regression analysis predicting building collapse risk (70% of data: $R = 0.900$).

No.	Variable	B	β	t
0	(Constant)**	0.00400		9.66
1	Old buildings rate**	0.0950	0.637	56.1
2	Old wooden buildings rate**	0.0480	0.315	27.7

**p < .01.

Table 10. Summary of multiple regression analysis predicting street blockage risk (70% of data: $R = 0.875$).

No.	Variable	B	β	t
0	(Constant)**	-9.38		-140
1	Old buildings rate**	3.11	0.273	25.5
4	Gross building coverage ratio**	5.63	0.429	31.1
5	Number of buildings along a street**	0.198	0.293	22.3
6	Narrow street rate**	1.03	0.140	15.1

**p < .01.

Table 11. Summary of multiple regression analysis predicting movement difficulty (70% of data: $R = 0.895$).

No.	Variable	B	β	t
0	(Constant)**	-11.9		-82.3
1	Old buildings rate**	4.67	0.306	29.0
4	Gross building coverage ratio**	7.80	0.465	31.1
5	Number of buildings along a street**	0.243	0.266	20.9
6	Narrow street rate**	1.95	0.202	21.0
9	Node-link ratio**	-0.588	-0.105	-9.43

**p < .01.

Table 12. Summary of multiple regression analysis predicting frequency of encountering street blockage (70% of data: $R = 0.875$).

No.	Variable	B	β	t
0	(Constant)**	-10.8		-137
1	Old buildings rate**	3.51	0.260	24.3
4	Gross building coverage ratio **	6.65	0.452	31.0
5	Number of buildings along a street**	0.227	0.288	21.0
6	Narrow street rate**	1.62	0.197	21.0

**$p < .01$.

Table 13. Summary of multiple regression analysis predicting travel distant increment (70% of data: $R = 0.757$).

No.	Variable	B	β	t
0	(Constant)**	-7.31		-20.5
1	Old buildings rate**	4.00	0.275	18.7
4	Gross building coverage ratio **	4.18	0.260	11.7
5	Number of buildings along a street**	0.163	0.192	9.32
6	Narrow street rate**	2.28	0.255	18.1
7	Non-wide street rate**	5.86	0.359	24.0
9	Node-link ratio**	-0.702	-0.136	-8.57

**$p < .01$.

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