Evaluation of Catastrophic Earthquake Damage throughout Japan using Estimated Micro Data

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Abstract

Japan will suffer extensive damage if another major earthquake occurs in the near future. Therefore, to reduce damage, it is necessary to develop quantitative and high-resolution methods of evaluation and comparison of damage caused by a widespread disaster that can be used with any different map-scale. In order to establish this disaster-prevention method, data that estimates earthquake damage for each building is indispensable. This paper, therefore, proposes a method for estimating each building's structural type, fire-resistance performance, and resident information derived from data on each building as well as grid-cell statistics data. The results show that our building data is highly reliable. In addition, we apply National Seismic Hazard Maps to the building data to estimate the probability of collapse and fire after an earthquake event. Finally, we estimate the ratio of the evacuees using estimated resident information throughout Japan.

1. INTRODUCTION

The government of Japan estimated that 320,000 people would die due to collapse of buildings, fire, and tsunami, if a Nankai Trough earthquake occurs. A near-field earthquake is also expected to occur in the Tokyo Metropolitan Area, and, therefore, the risk of confusion due to destruction of buildings, fire, and tsunami due to an earthquake event is increasing throughout Japan.

At present, the damage risk of earthquakes in Japan is estimated by prefecture or municipality unit, which have a 1-kilometer grid-cell unit as a minimum size (see Fig. 1). However, analysis of the number of residents, the intensity of ground motion, and the use of each building makes it possible not only to evaluate the risk with higher precision, but also to create an optimum policy for disaster prevention. Therefore, it is important to develop a solid method that can evaluate and compare the risk of widespread disaster as well as having the ability to assess the emergency response in each municipality quantitatively. In order to establish this method for evaluation and comparison, information from both macro-scale (prefecture units or land units) and micro-scale (city grid units or residents units) are fundamental.

Nevertheless, the essential data required to estimate the precise damage to each building throughout Japan by an earthquake is not fully available. For instance, to estimate the risk of building collapse and fire following an earthquake, data of the buildings' fire-resistance performance (whether a building is fire-proof, semi-fire-proof or fire-preventive), and of building structure types (whether a building is wooden or non-wooden) is required in single building units. Today, however, these data are often owned and disclosed on a limited basis by local governments. As a result, damage assessment is carried out in different ways by each local government and risk communication between municipalities is not fully promoted.

Covello (1992) defined risk communication as an exchange of information between stakeholders that depends on the quality, level, importance, and countermeasure against a risk. Risk communication between people at risk from disasters allows them to make decisions based on the shared information. If we can provide information on the risk to specific neighborhoods and regions during a disaster at a micro-scale, residents would be properly aware of the severity of their situation.

Although printed data for damage assessment is insufficient, digital maps currently allow us to observe the distribution of each building and a digital telephone directory can provide the distribution of offices and shops managed in Japan. These data can play an important role in the precise estimation of earthquake damage over broad areas. In addition, improvements in data processing due to the increased capacity of PCs enable the handling of massive quantities of micro data.

As we obtain data that can estimate the damage caused by an earthquake over a broad area with high reliability, it allows us to estimate damage on a micro scale by combining the data of the fire-resistance performance and structural type of individual buildings.

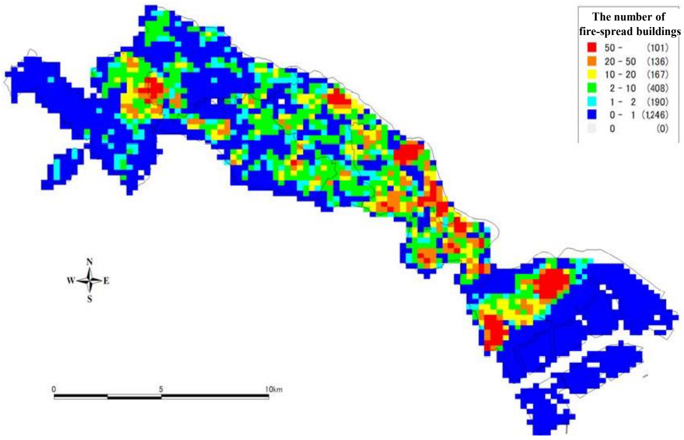


Fig. 1. Damage assessment of fire-spread in Kawasaki City in Kanagawa (caused by near-field earthquakes in the Tokyo Metropolitan Area at evening in winter).

1.1 Previous studies

Recently, many studies have been carried out in relation to the damage assessment of earthquakes in Japan. Kato et al. (2006) calculated the limits of fire spread distance by using the distance between buildings and used the cluster of fire spread to evaluate the fire risk. In addition, Nakamura and Kato (2011) compared emergency responses of municipalities all over Japan by using data such as the national census. However, their evaluation of the fire risk in 500-meter-square grid units did not consider the structural type of each building.

Furthermore, Eguchi et al. (1994) released a study establishing a real-time system of damage assessment in order to assess the damage to buildings and lifelines in California immediately following an earthquake.Most of these studies are based on statistics and evaluate the risk according to units of area.

However, these previous studies have three main problems. First, these studies could not evaluate the risk on a by-resident scale because the risk was calculated according to municipality units or 500-meter-square grid units, and therefore the spatial resolution was not high enough. Second, these studies did not consider ground motions and building usages, which are important aspects in estimating the fire risk. Third, these studies often used statistics that were taken by prefecture unit. In addition, there is also an institutional problem in Japan, where data relating to the structural types of buildings are unavailable in most municipalities. Therefore, the previous studies do not verify the reliability of estimated fire-resistance performance in each building. The subjects of most previous studies were analyzed in a limited area and the studies often referenced case studies. Therefore, the methods in previous studies are not applicable to broad areas.

1.2 Objective

In this study, we develop an automated method for estimating the structural type (wood-frame or non-wood-frame) and the fire-resistance performance (fire-proof, semi-fire-proof, or fire-preventive) of buildings using the Housing and Land Survey (Ministry of Internal Affairs and Communication), the digital telephone directory with longitude and latitude called "Telepoint Data" (Zenrin Co., Ltd.), and residential maps ("Zmap-TOWN Ⅱ" by Zenrin Co., Ltd.). These data cover the whole of Japan, excluding some remote islands. In addition, our data is cross-checked to verify the reliability of our method. Finally, using a method developed by Akiyama et al. (2013) to estimate the information on residents in each building, we estimate the risk of fatalities and create a database that can evaluate the relative risks between different regions. As a result, we can evaluate these risks in high-resolution detail for any aggregate unit, not only for municipality units but also for smaller community-based units.

2. Development

2.1 Procedure for estimating the risk of fatalities

Figure 2 shows the processing flowchart for our method. To evaluate damage to each building, we use residential maps (2008–2009) and the Telepoint Data (2008) to understand the information for each building (number of floors, area, and usage). In addition, the commercial accumulation statistics (CAS) polygon data (2008) developed by Akiyama et al. (2011) are used to estimate fire-resistance performance based on whether or not each building is located in a commercial area. The distribution of structural types and fire-resistance performances for each building are deeply dependent on land-use zoning, as some zones are established as firebreaks, called “firebreak zones”. Polygons of land-use zoning do not exist throughout Japan, but most CAS are designated to control firebreak zones.

Next, the calculation of fire probability is determined from ground motion intensity, obtained from the Probabilistic Seismic Hazard Maps (PSHM) in each building area. PSHM are prepared in 250-meter-square grid polygon data. As a result, fire-resistance performance and fire probability are used to calculate fire spread probability. The probability of collapse for buildings is also estimated from the structural type and ground motion intensity.

Finally, we estimate the damage to humans, such as the number of fatalities, by combining resident information and each building’s fire spread and collapse probability. This can be aggregated to any unit to obtain the numbers of fatalities for each unit.

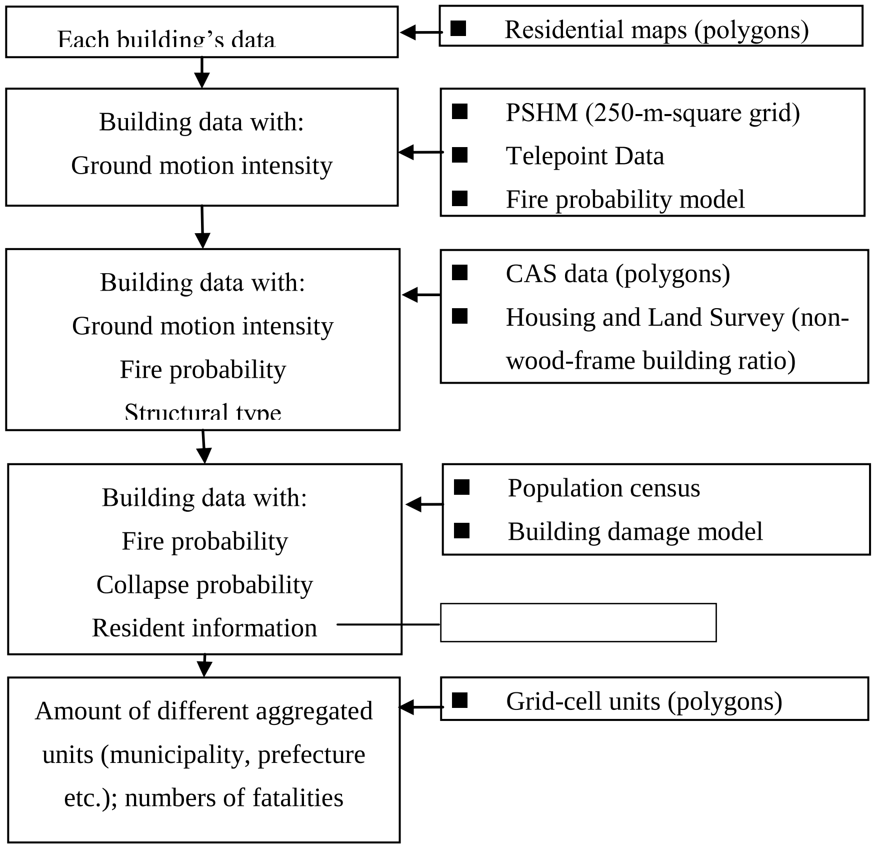


Fig. 2. Flow chart for estimating the risk of fatalities.

2.2 Estimation of a building's fire-resistance performance

2.2.1 Definition of a building's fire-resistance performance

There are three types of fire-resistance performance: fire-proof, semi-fire-proof, and fire-preventive buildings. In Japan, fire-proof buildings have the highest fire-resistance performance, followed by semi-fire-proof buildings, and fire-preventive buildings have the lowest. High-rise buildings and large-scale commercial facilities distributed in main commercial areas and business areas are required to be fire-proof or semi-fire-proof. On the other hand, most low-rise buildings and houses are only required to be fire-preventive. As the fire risk to buildings varies, risk evaluations must include these differences. Therefore, this study requires a method for estimating the fire-resistance performance for each building.

2.2.2 Method for estimating a building's fire-resistance performance

Kato et al. (2006) suggested a simple method for estimating a building's fire-resistance performance using residential maps. Residential maps provide each building's attributes, such as number of floors and usage. Figure 3 shows the estimation of fire-resistance performance using attributes and known information. Buildings with two or less stories are given the standard rating of fire-proof and semi-fire-proof, as shown in Table 1. To correct differences in the numbers of fire-proof, semi-fire-proof, and fire-preventive buildings, a region coefficient k is defined using the ratio of non-wood-frame houses, which are obtained for each municipality unit from the statistical data (Housing and Land Survey). The region coefficient k is defined as:

$$k = \frac{(\sum n_i)Q}{\sum(n_i(q_{1i}+q_{2i})}, \qquad (2.2.1)$$

where n_i is the number of buildings of area i, and q_{1i} and q_{2i} are the standard ratios of fire-proof buildings and semi-fire-proof buildings, respectively, of area i. Then the ratio of fire-proof buildings is kq_{1i} and the ratio of semi-fire-proof buildings is kq_{2i}. Finally, a computer uses a randomly generated number to distribute fire-proof buildings and semi-fire-proof buildings for each building data. However, this method was not verified.

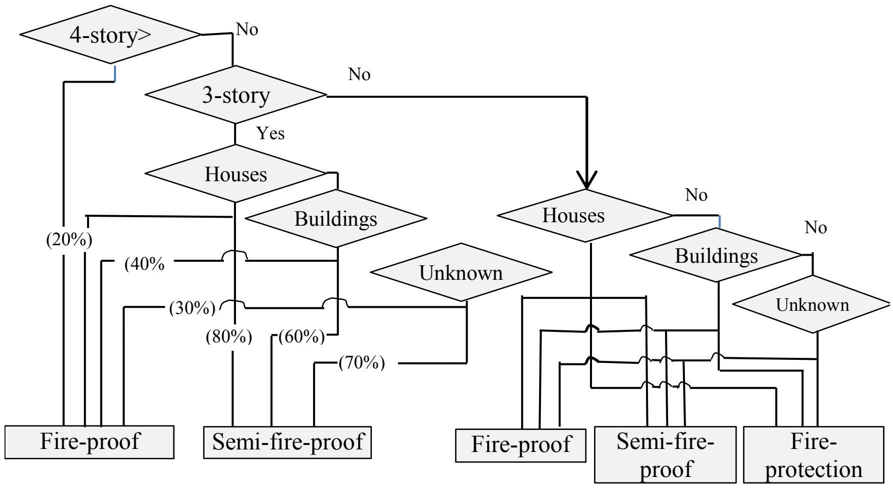


Fig. 3. Method of estimation of fire-resistance performance in previous study.

Table 1. Standard rates of fire-proof and semi-fire-proof buildings of less than two stories according to usage and area from previous study.

Usage	Buildings Area [m^2]	Fire-proof	Semi-fire-proof
Houses	0–75	$q_{11} = 2.0$	$q_{21} = 10.0$
	75–100	$q_{12} = 2.0$	$q_{22} = 15.0$
	100–200	$q_{13} = 3.0$	$q_{23} = 20.0$
	200+	$q_{14} = 3.0$	$q_{24} = 20.0$
Buildings	0–75	$q_{11} = 4.0$	$q_{21} = 20.0$
	75–100	$q_{12} = 4.0$	$q_{22} = 30.0$
	100–200	$q_{13} = 6.0$	$q_{23} = 40.0$
	200+	$q_{14} = 12.0$	$q_{24} = 50.0$

2.2.3 Method of estimation

We estimate each building's fire-resistance performance using the following steps. First, we obtain the distribution of buildings from residential maps. This data includes attributes such as usage (houses, condominiums, unknown) and the number of floors and houses. Second, residential maps are combined with the Telepoint data to identify the business type for each building. Third, we use CAS to identify whether or not each building is in a commercial area. In order to determine if fire-proof and semi-fire-proof buildings are non-wooden buildings, the statistical data by municipality unit (Housing and Land Survey (2008)) are used to understand the numbers of non-wooden houses for both houses and condominiums.

We estimate fire-resistance performance based on buildings. However, the Housing and Land Survey is aggregated based on house units. Therefore we convert statistical data from house units to building units (Fig. 4). First, we use residential maps to obtain the numbers of houses and buildings, and then the numbers of houses per building are calculated (called the extended coefficient, *C*). Statistical data is converted to building units using *C*. Finally, the non-wood-frame building ratio *Q* is calculated from *C* and the statistics.

Buildings with three or more stories are assigned as shown in Table 2, where parameters are determined by comparing GIS data of Setagaya-ku, Tokyo, Japan. For buildings with two or less stories, we define a region coefficient *k* to correct the difference in distribution of the fire-proof, semi-fire-proof, and fire-preventive buildings in each region or commercial area. It is defined as:

$$k = \frac{(\sum n_{ij})Q_i}{\sum(n_{ij}(r_{ij}+s_{ij}))} \quad , \tag{2.2.2}$$

where n_{ij} is the number of buildings of usage *i* of area j, r_{ij} is the standard rate of fire-proof buildings of usage i of area j, s_{ij} is the standard rate of semi-fire-proof buildings of usage i of area j, and Q_i is the ratio of non-wood-frame buildings (with two or less floors) of usage *i*. The classifications of area j are 0–75 m^2, 75–100 m^2, 100–200 m^2, 200+ m^2. Table 3 shows r_{ij} and s_{ij}. The region coefficient *k* has six values depending on whether or not it is a commercial area, and on usage (houses, condominiums, or unknown). The ratio of non-wood-frame buildings (two or less stories) Q_j is summarized by:

$$Q_j = \frac{Q*M-\sum(R^{(3)}+S^{(3)})}{\sum n_{ij}} \quad , \tag{2.2.3}$$

where M is the number of buildings in the residential map, $R^{(3)}$ is the number of fire-proof buildings (of three or more stories), and $S^{(3)}$ is the number of semi-fire-proof buildings (of three or more stories). With region coefficients k, the number of fire-proof buildings (of two or less stories) $R^{(2)}$ is given by:

$$R^{(2)} = n_{ij} * k * r_{ij}. \quad (2.2.4)$$

The number of semi-fire-proof buildings (of two or less stories) $S^{(2)}$ is given by:

$$S^{(2)} = n_{ij} * k * s_{ij}. \quad (2.2.5)$$

The number of fire-preventive buildings (of two or less stories) $T^{(2)}$ is given by:

$$P = 1 - \prod_{i=1}^{n}(1 - p_i * (1 + f_i)). \quad (2.2.6)$$

Finally, a computer uses a randomly generated number to distribute fire-proof buildings and semi-fire-proof buildings in the building data. During this process, each building is weighted according to its area, so that buildings with larger areas are more likely to be distributed as fire-proof buildings. Figure 5 shows a map of the estimated results of the fire-resistance performance of a number of buildings. Fire-proof buildings are concentrated around stations and main streets. This is because such areas are fire-break zones. The CAS and building usages are reflected in the estimated data.

House and Land Survey

	Houses	Buildings
Wooden Houses	a_{11}	a_{12}
Non-wooden Buildings	a_{21}	a_{22}

Residential Maps

	Houses	Buildings
Number of Houses	b_{11}	b_{12}
Number of buildings	b_{21}	b_{22}

	Houses	Buildings
C	$C_1 = b_{21}/b_{11}$	$C_2 = b_{12}/b_{22}$

C extended coefficient

	Houses	Buildings
Number of Wooden Buildings	$a_{11'}$	$a_{12'}$
Number of Non-wooden Buildings	$a_{21'}$	$a_{22'}$

Fig. 4. Method of converting a houses unit into a buildings unit for House and Land Survey Statistics.

Table 2. Method of estimation of fire-proof, semi-fire-proof, and fire-preventive buildings.

Floor	CAS	Usage	Fire-proof [%]	Semi-fire-proof [%]	Fire-preventive [%]
5>	-	-	100	0	0
4	Yes	-	97	3	0
	No	-	98	2	0
3	Yes	H	30	60	10
	Yes	HC	50	45	5
	Yes	CB	68	30	2
	Yes	LM	0	0	100
	Yes	O	40	20	40
	No	H	15	60	25
	No	HC	40	45	15
	No	CB	67	30	2
	No	LM	0	0	100
	No	O	60	10	30
1, 2	Yes	H	Calculate region coefficient K and distribute by each fire-resistance performance ratio.		
	Yes	CB			
	Yes	U			
	No	H			
	No	CB			
	No	U			

H: houses; *HC*: house companies; *C*: companies; *CB*: cooperation buildings; O: others; *U*: Unknown; *LM*: landmarks.

Table 3. Standard ratios of fire-proof and semi-fire-proof buildings with two stories or less by usage area and commercial area.

Commercial areas	Usage	Buildings Area [m^2]	Fire-proof	Semi-fire-proof
Yes	Houses	0–75	$r_{11} = 2.0$	$s_{11} = 8.0$
		75–100	$r_{12} = 2.0$	$s_{12} = 1.0$
		100–200	$r_{13} = 3.0$	$s_{13} = 1.0$
		200+	$r_{14} = 3.0$	$s_{14} = 3.0$
	Buildings	0–75	$r_{21} = 4.0$	$s_{21} = 3.0$
		75–100	$r_{22} = 4.0$	$s_{22} = 5.0$
		100–200	$r_{23} = 6.0$	$s_{23} = 6.0$
		200+	$r_{24} = 12.0$	$s_{24} = 6.0$
	Others	0–75	$r_{31} = 3.0$	$s_{31} = 5.5$
		75–100	$r_{32} = 3.0$	$s_{32} = 3.0$
		100–200	$r_{33} = 4.5$	$s_{33} = 3.5$
		200+	$r_{34} = 7.5$	$s_{34} = 4.5$
No	Houses	0–75	$r_{11} = 2.0$	$s_{11} = 4.0$
		75–100	$r_{12} = 2.0$	$s_{12} = 10.0$
		100–200	$r_{13} = 3.0$	$s_{13} = 1.0$
		200+	$r_{14} = 3.0$	$s_{14} = 2.0$
	Buildings	0–75	$r_{21} = 4.0$	$s_{21} = 10.0$
		75–100	$r_{22} = 4.0$	$s_{22} = 10.0$
		100–200	$r_{23} = 6.0$	$s_{23} = 13.0$
		200+	$r_{24} = 12.0$	$s_{24} = 12.0$
	Others	0–75	$r_{31} = 3.0$	$s_{31} = 10.0$
		75–100	$r_{32} = 3.0$	$s_{32} = 7.0$
		100–200	$r_{33} = 4.5$	$s_{33} = 7.0$
		200+	$r_{34} = 7.5$	$s_{34} = 7.0$

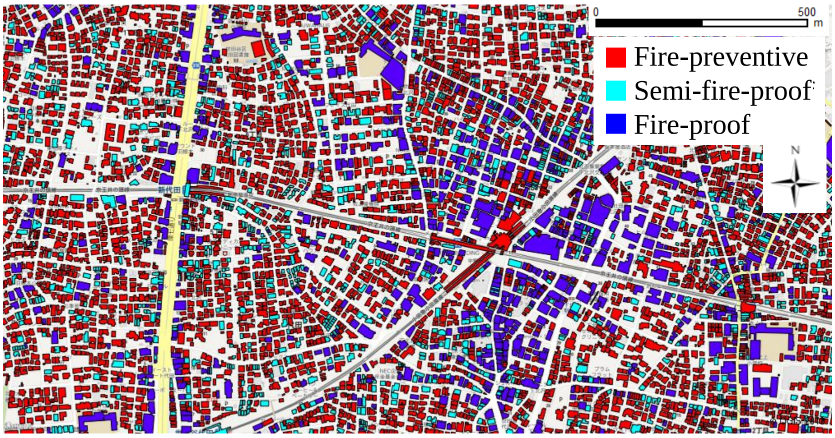


Fig. 5. Map of buildings showing fire-resistance performance using our method.

2.2.4 Verification of the fire-resistance performance

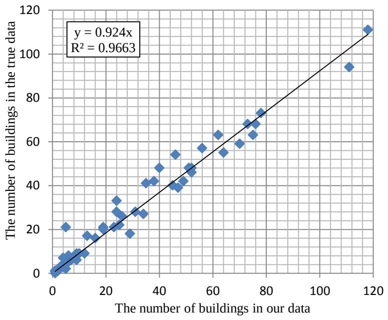
Our data is verified by checking 8341 buildings of each building type extracted from Setagaya-ku, Tokyo. The verification data uses a Building Present Situation Investigation (2008) in "SETAGAYA i-map" shown on a website published by Setagaya-ku. In this study, the verification method uses an error matrix. Table 4 shows the results of the verification by this error matrix. Overall accuracy is 77.0% and the reliability of the fire-proof and fire-preventive buildings are 83.2% and 82.3%, respectively, indicating that our method is effective in estimating fire-resistance performance. In contrast, the reliability of semi-fire-proof buildings is only 42.2% because of the similarity between the building structures of fire-proof and semi-fire-proof buildings. In addition, the building data from the residential map, which includes garrets and semi-undergrounds, are labeled with different numbers of stories.

However, our objective is to evaluate the damage for any aggregate unit. Furthermore, in Japan, the data provided by this study may not show the damage risk for each building unit because of the Personal Information Protection Law.

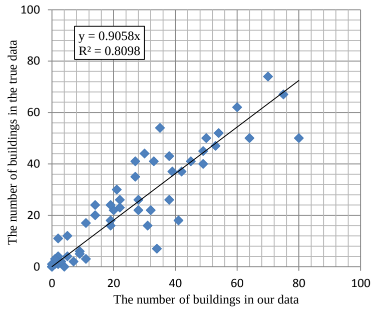
It is necessary to check the reliability not only for each building but also for each aggregate unit (grid-cell unit and district unit). We aggregate our data to 250-meter grid-cells (the local community unit in general) to compare the number of buildings in each fire-resistance performance type with verification data. Figure 6 shows the comparison results for (a) fire-proof, (b) semi-fire-proof, and (c) fire-preventive buildings. There is strong correlation between the numbers of buildings from our data with the actual numbers of buildings. The reliability of semi-fire-proof buildings is 42.2% in the error matrix, but they have a strong correlation of 0.81 in the evaluation of the 250-meter grid-cells. As a result, our estimated fire-resistance performance data is reliable for evaluating performances in each local community.

Table 4. Reliability of fire-resistance performances in an error matrix (Setagaya-ku, Tokyo).

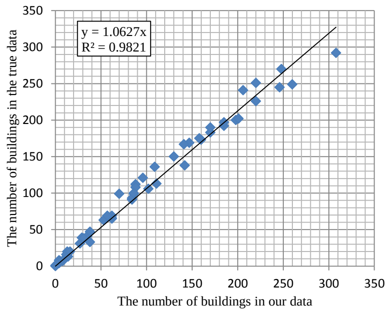
Fire-resistance performances		**Classified**				
		Fire-proof	Semi-fire-proof	Fire-preventive	**Total**	Producers
Ground Truth	Fire-proof	**1191**	158	82	**155**	83.2%
	Semi-fire-proof	284	**483**	379	**451**	42.1%
	Fire-preventive	341	694	**4807**	**5843**	82.3%
	Total	**1816**	**1445**	**5268**	**8419**	
	Users	65.6%	36.2%	91.3%		
	Overall Accuracy 77.0%					



(a) The fire-proof comparison.



(b) The semi-fire-proof comparison.



(c) The fire-preventive comparison.

Fig. 6. Correlation between the numbers of buildings in our data with the verification data.

2.3 Estimation of a building's structural type

2.3.1 Summary of the building structure estimation

Whether a building is wood-frame or non-wood-frame has a major effect on the damage assessment of the building after an earthquake. The building structure is an important consideration when evaluating building damage. Thus, our method takes particular note to estimate building structure types; we focus on only two types, wood-frame and non-wood frame because of the difficulty in identifying between steel-frame and reinforced-concrete.

2.3.2 Method of estimating building structure

Tanigawa (2012), after the Great East Japan Earthquake, estimated the quantity of buildings lost. The method for estimating building structure is as follows. For condominiums with two or less stories, we use the House and Land Survey (2008) to apply the ratio of each building structure by prefecture. Wood-frame structures are assigned to the ratio of buildings with the smallest areas; all buildings with larger areas are considered steel-frame structures. Houses with two or less stories are considered to be wood-frame. Three-story houses are assumed to be steel-frame, and buildings with more than four stories are considered to be reinforced concrete.

2.3.3 Method of estimation

We estimate building structure by combining the House and Land Survey (2008), where the number of houses for each structure is published by city unit, with the fire-resistance performance building data provided in Section 2.2. In addition, in Japan, the majority of fire-proof and semi-fire-proof buildings are known to be non-wood-frame. This study tries to estimate building structure by each building unit. The ratio of non-wood frames, Q, is calculated as shown in Section 2.2. Then the numbers of estimated buildings for each structure are calculated by the non-wood frames ratio Q and distributed to the buildings data. Because there is a possibility of both houses and condominiums with unknown usage, we use the average ratio for the non-wood frames rate *Q*.

The Building Standard Act regulates building structures that can be constructed in Japan, depending on the number of floors and the building area. Therefore, we estimate structures according to this law, using the method shown in Fig. 7. However, some buildings are not successfully captured by the low with the following reasons; some were built before the law came into effect or some are too small to be measured regardless their ages. For these buildings, therefore, we distribute building structures in the building data using a random number for the number of wood-frame structures. During this process, buildings are weighted depending on area, fire-resistance performance, and commercial areas. Figure 8 shows the results of our data; similar to fire-proof buildings, non-wood-frame buildings are concentrated around stations and main streets.

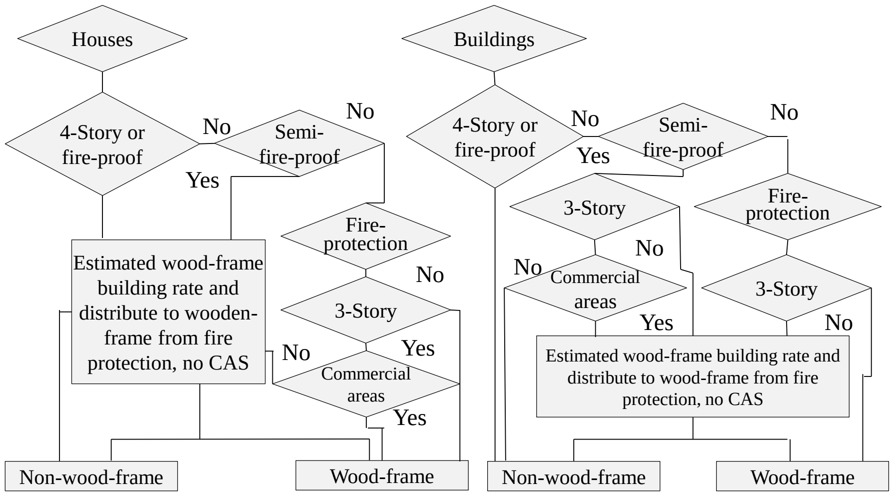


Fig. 7. Method of estimating building structure type.

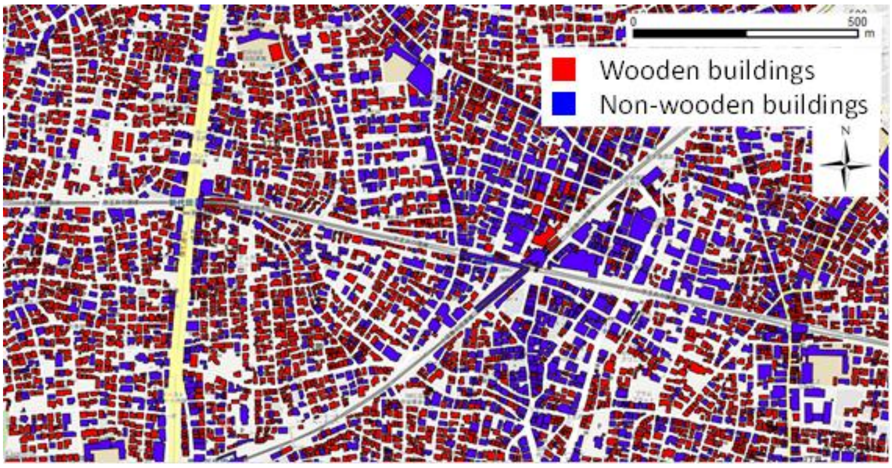


Fig. 8. Building structure data using our method.

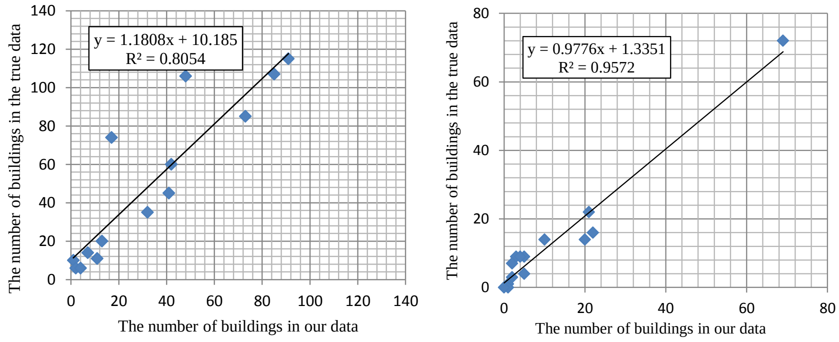
2.3.4 Verification of the building structure

Our data is verified to check 606 buildings of each building type extracted from Numazu city, Shizuoka prefecture. The verification data uses our survey data in Numazu city. Table 5 shows the results of the verification by an error matrix. Overall accuracy is 86.1%; the reliability of wood-frame and non-wood frame buildings is 77.4% and 89.1%, respectively. This demonstrates that our method is effective in estimating structure type.

We aggregate our data to 250-meter grid-cells (the local community unit in general) to compare the number of buildings in each structure type with verification data. Figure 9 shows the comparison results for (a) wood frame and (b) non-wood frame buildings. There is a strong correlation between the number of buildings from our data and the actual number of buildings. Our data have a strong correlation of more than 0.8 in the evaluation of 250-meter grid-cells. As a result, our estimated structure data is reliable for evaluating performance in each local community.

Table 5. Error matrix of reliability of building structures.

Building structures		Classified			
		Non-wooden-frames	Wooden-frames	**Total**	Producers
Ground Truth	Non-wooden-frames	**120**	35	**155**	77.4%
	Wooden-frames	49	**402**	**451**	89.1%
	Total	**169**	**437**	**606**	
	Users	71.0%	91.0%		
	Overall Accuracy 86.1%				



(a) Wooden frames comparison. (b) Non-wooden frames comparison.

Fig. 9. Correlation between the numbers of buildings structures in our data with the verification data.

2.4 Estimating resident information

The resident information in each building is obtained using the method developed by Akiyama et al. (2013); the ratio of family types in each building area is calculated from data from the national census. The resident information in each building is randomly distributed into the building data based on the number of resident ratio cited from the national census. See Akiyama et al. (2013) for more information.

3. Damage assessment due to a catastrophic earthquake disaster

3.1 Evaluation of fire risk from earthquake

First, we obtained the building information for the PSHM from the National Research Institute for Earth Science and Disaster Prevention (NRID). Second, we estimate the fire probability for each individual building. The Probabilistic Seismic Hazard is calculated as the probability of experiencing the exceeded level of ground motion intensity within a target period at a given site. For this calculation, an evaluation with variance is conducted using a probabilistic approach based on epicenter, occurrence probability, magnitude of all earthquakes that can occur in and around Japan, and the intensity of the ground motions caused by those earthquakes. We assumed the ground motion probability of six given patterns of input ground motion. The probabilistic ground motion of the six patterns is 2%, 5%, 10%, and 39% of exceedance probability within 50 years, and 3% and 6% of excess probability within 30 years.

Table 6 shows the fire probability according to input ground motion (on the Japan Meteorological Agency (JMA) seismic intensity scale) published by the Tokyo Fire Department (2007). We connect the Telepoint data to the buildings to clarify the type of industry, and assign a fire probability corresponding to each industry from Table 6. For the buildings where the Telepoint data were not distributed, we gave a fire rate based on the building use and a fire probability; 0.048% (the average fire probability of all the buildings) is applied to buildings with unidentified usage. Finally, we assign fire probabilities from predicted ground motions and the building types.

Table 6. Fire probabilities of predicted ground motions and the building types.

Type of industry	JMA seismic intensity scale (Scale in Japanese/ Meter reading)									
	5-lower / 4.5-4.9		5-upper / 5.0-5.4		6-lower / 5.5-5.9		6-upper / 6.0-6.4		7 / 6.5+	
	DS	IW	DS	IW	DS	IW	DS	IW	DS	IW
Theater	0.0043%	0.0039%	0.0116%	0.0125%	0.0300%	0.0305%	0.0832%	0.1005%	0.1865%	0.2956%
Cabaret	0.0000%	0.0041%	0.0000%	0.0100%	0.0000%	0.0242%	0.0006%	0.0860%	0.0229%	0.2902%
Bar	0.0049%	0.0058%	0.0044%	0.0086%	0.0131%	0.0231%	0.0323%	0.0771%	0.0954%	0.2292%
Restaurant	0.0069%	0.0073%	0.0096%	0.0106%	0.0291%	0.0306%	0.0808%	0,0858%	0.2058%	0.2168%
Department store	0.0271%	0.0211%	0.1000%	0.0774%	0.2531%	0.1928%	0.7232%	0.5694%	1.8200%	1.6071%
Article store	0.0017%	0.0014%	0.0041%	0.0042%	0.0107%	0.0105%	0.0384%	0.0458%	0.3243%	0.3866%
Hotel	0.0148%	0.0151%	0.0644%	0.0653%	0.1600%	0.1618%	0.4566%	0.4752%	0.9663%	1.0709%
Apartment	0.0007%	0.0012%	0.0011%	0.0027%	0.0031%	0.0070%	0.0090%	0.0249%	0.0349%	0.0757%
Hospital	0.0045%	0.0035%	0.0093%	0.0089%	0.0247%	0.0222%	0.0701%	0.0759%	0.2191%	0.4329%
Clinic	0.0013%	0.0014%	0.0013%	0.0034%	0.0040%	0.0082%	0.106%	0.0282%	0.0495%	0.1250%
Dormitory	0.0014%	0.0016%	0.0028%	0.0025%	0.0075%	0.0068%	0.0228%	0.0244%	0.1116%	0.1456%
Nursery school	0.0025%	0.0002%	0.0033%	0.0009%	0.0095%	0.0019%	00.246%	0.0094%	0.0694%	0.0393%
Kindergarten	0.0019%	0.0013%	0.0019%	0.0042%	0.0056%	0.0109%	0.0137%	0.0594%	0.0431%	0.1772%
Elementary school	0.0083%	0.0022%	0.0136%	0.0058%	0.0374%	0.0142%	0.1002%	0.0612%	0.2989%	0.2175%
University	0.0037%	0.0007%	0.0062%	0.0020%	0.0170%	0.0050%	0.0458%	0.0155%	0.1263%	0.0604%
Public bath	0.0006%	0.0009%	0.0009%	0.0027%	0.0026%	00064%	0.0073%	0.0225%	0.0282%	0.0874%
Factory	0.0016%	0.0013%	0.0046%	0.0046%	0.0118%	0.0117%	0.0330%	0.0564%	0.0796%	0.1529%
Office	0.0024%	0.0012%	0.0069%	0.0038%	0.0176%	0.0095%	0.0496%	0.0307%	0.1208%	0.0980%
House	0.0007%	0.0016%	0.0007%	0.0035%	0.0021%	0.0094%	0.0058%	0.0505%	0.0274%	0.1521%

DS: day time in summer; IW: evening in winter.

With the above estimated fire-resistance performance of the buildings, a predictable structure and a fire probability were given to each building. The fire risk evaluation for an earthquake event in each individual building is enabled by a combination of these. In this study, the fire-spread probability of buildings of any different totaled-unit is determined by the following method (Kato et al. 2006). The burned-down probability of any different totaled-unit is given by:

$$P = 1 - \prod_{i=1}^{n}(1 - p_i * (1 + f_i)), \quad (3.1.1)$$

where P is the burned-down probability of any different totaled-unit, p_i is the fire probability of building i, and f_i is the fire-spread probability of building i. The fire-spread probability, f_i, for a fire-proof building is 3.20%, for semi-fire-proof is 13.00%, and for fire-preventive is 21.80% according to the firefighting white paper (2007) published by the Fire and Disaster Management Agency. The fire risk is evaluated by calculating the number of burned-down buildings and can expose a high fire risk area.

3.2 Evaluation of building collapse risk by earthquake

The occurrence probability of building damage is defined using the vulnerability functions as an expression of the relationship between the peak ground velocity (PGV) and building damage. Ground motion is obtained from the PGV from a Probabilistic Seismic Hazard. We use the vulnerability functions developed by Yamazaki and Murao (2000), which are often used to assess building damage in Japan. By referring to their method, we use two kinds of structure (wood-frame and non-wood-frame) without considering the construction period. For a strong motion index x, the cumulative probability $P_r(x)$ of the occurrence of damage equal or greater than rank R is assumed to be lognormal given by:

$$P_r(PGV) = \Phi((In\ PGV - \lambda)/\xi, \qquad (3.2.1)$$

where Φ is the standard normal distribution, and λ and ξ are the mean and standard deviation of ln PGV. Figure 10 shows the interim vulnerability functions for wood-frame buildings and non-wood-frame buildings.

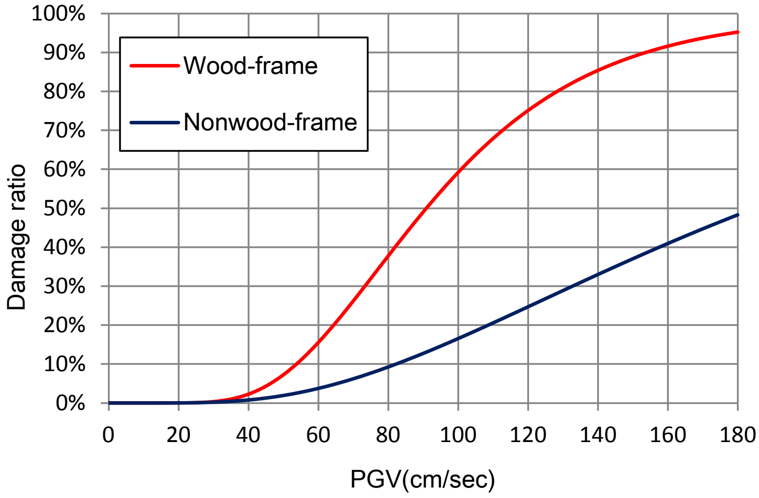


Fig. 10. Interim vulnerability functions for wood-frame buildings and non-wood-frame buildings with respect to PGV.

3.3 Evaluation of fatalities risk by earthquake

The fatalities risk evaluation supposes that death is caused by a fire or a collapse in each building unit. The calculation unit, based on each building, applies to the number of residents in a building at the time of outbreak. The method of the fatalities risk evaluation by a fire refers to the death rate with burned-out probability and the number of residents in the building. The death-by-fire ratio used is 0.046 dead/fire, which is the number of fatalities per fire (except arson) in 5 years in the whole country from 2005 to 2010. This value is also used by the Central Disaster Prevention Council 2012. The number of fatalities for each individual building is given by:

$$x_i = P_i * P_{f\,i} * R_i, \tag{3.3.1}$$

where x_i is the number of fatalities of building i, P_i is the burned-down probability of building i, P_{fi} is the death-by-fire ratio of building i, and R_i is the number of residents in building i.

The method of evaluating the fatalities risk for a collapsed building uses the death rate with building damage ratio and the number of residents in the building. The death-by-collapse ratio is 6.8% in wooden buildings and 0.8% in non-wooden buildings, which is taken from the number of fatalities per collapsed building in five different earthquakes (Tottori, Tonankai, Nankai, Fukui, and Hanshin-Awaji earthquakes) that claimed the lives of over 300 people. The number of fatalities per each individual building is given by:

$$y_i = P_{ri} * P_{ci} * R_i, \tag{3.3.2}$$

where y_i is the number of fatalities in a building i, P_{ri} is the building damage ratio of building i, P_{ci} is the death-by-collapse ratio of building i, and R_i is the number of residents in building i. Thus, an estimated value for the death-by-fire and death-by-collapse ratio is given by:

$$\mathrm{d}_i = \sum\{x_i(1-y_i) + (1-x_i)y_i\}, \tag{3.3.3}$$

where d_i is the death ratio of building i. Thus, the evaluation of the human fatalities risk in any aggregate unit (grid-cell units, district units, etc.) is given by:

$$DR = \frac{\sum d_i}{\sum R_i}, \tag{3.3.4}$$

where DR is the ratio of dead per person in any aggregate unit.

4. Results

Figures 11 and 12 show the results of evaluation of the human fatalities risk, *DR*, for buildings throughout Japan (approximately 60 million buildings), in put ground motion with a 2% exceedance probability in 50 years. This shows the methodology developed in this study is applicable throughout Japan. This data can apply not only to urban areas but also to suburban areas, such as small cities and isolated islands. In addition, this is the first dataset to input any expected seismic motion data and evaluate human fatalities by considering building structures and usage, as well as the number of residents.

4.1 Application of this data

To reduce the risk of physical damage and human fatalities caused by fires or collapsing buildings during earthquakes, both hard and soft measures must be taken. In terms of physical measures, in areas of high risk it is necessary to fire-proof buildings and maintain roads, and make old buildings earthquake-resistant to prevent them from collapsing. In terms of knowledge-oriented measures, it is important for residents and local governments to be aware of disaster risks and encourage risk communication between government bodies. As residents consider the risk of damage and take more measures against earthquake events, they will become interested in participating in citizen-based urban planning. At the same time, governments will be able to plan disaster prevention on a wide scale, and this will be reflected in disaster prevention plans. To promote such risk communication, our data can be aggregated to any map scale, from a residential scale to a national scale. In particular, our data makes it easy for residents to imagine the damage situation. In addition, our data is also expected to make it easy to plan measures for damage reduction. Risk communication is usually held at workshops, briefing sessions, and lectures in each area, during which our data can be used. It is hoped that this study encourages risk communication between parties to help them shift from the understanding damage phase to the action-taking phase.

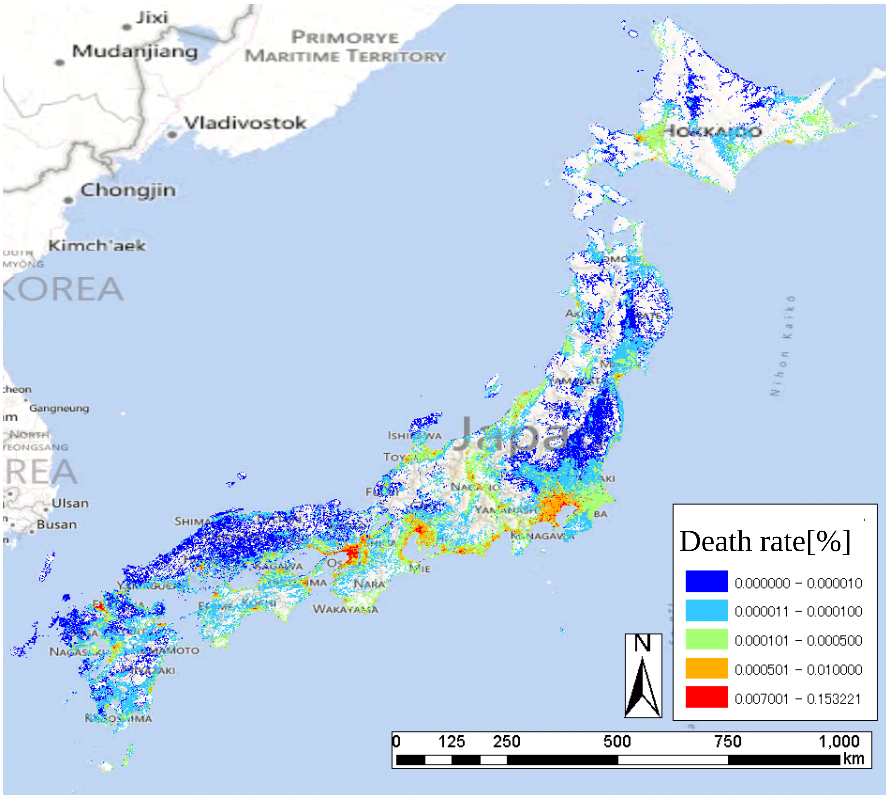


Fig. 11. Evaluation of human fatalities *DR* by earthquake across Japan.

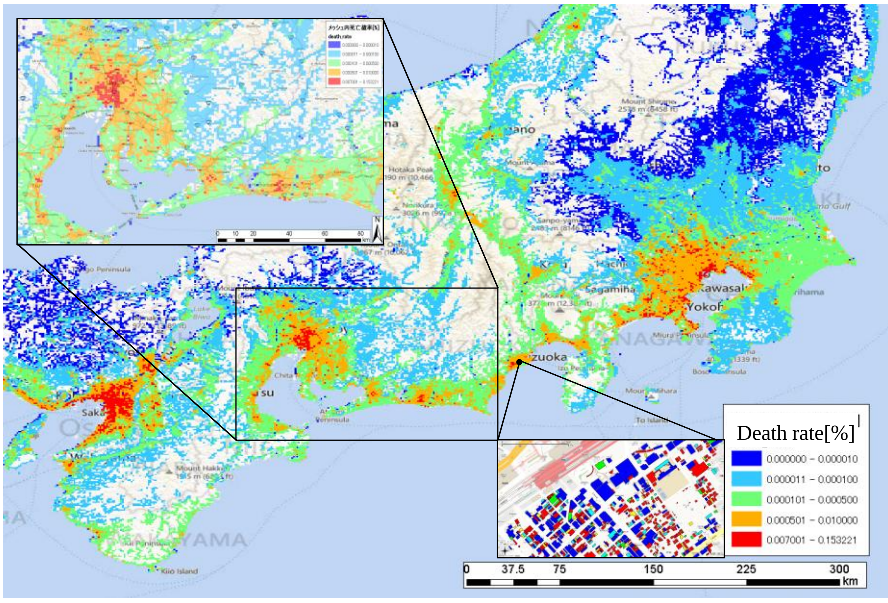


Fig. 12. Evaluation of human fatalities *DR* by earthquake.

5. Conclusion and future work

In this study, we estimated the fire-resistance performance and structural type of individual buildings by combining existing statistics and spatial data. Furthermore, we attached a probabilistic seismic hazard to each building and calculated the fire probability and the probability of building collapse in the case of an earthquake event. By combining these data with the number of residents in each building, we evaluated the risk of fatalities during an earthquake. There are three main advantages to our method. First, our method can evaluate the physical damage and fatalities risk from fires and building collapses caused by earthquakes anywhere and at any aggregate unit. Second, most of our data processing is automated, so that we can deal with a large amount of data such as national-scale data. Finally, our method makes it possible to compare the damage risk of earthquakes on a national scale by arranging national-scale data and finding relatively more vulnerable regions by using the same index. As a result, we believe that risk communication between municipalities will be promoted, and it will be easier to make optimum decisions to reduce damage than before.

Three topics are suggested for future work. First, we verified the reliability of the estimated structural types of the buildings by comparing estimated data and actual data only for Setagaya-ku, Tokyo. The data should be verified by comparing with more existing data, but currently there is no such data available in Japan. Therefore, our data should be verified regularly as more data becomes available. Second, climate conditions such as wind, which strongly influence the spread of fire, should be considered. Finally, when evaluating building collapse during an earthquake, although we considered structural types, we did not consider the age of buildings. The probability of building collapse differs greatly depending on whether the building age is more or less than 32 years, as the Building Standard Act was legislated in 1981. Therefore, we are now developing a method to estimate the age of buildings and this will be integrated into our method.

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