SEISMIC DAMAGE EVALUATION OF HOUSEHOLD PROPERTY BY USING GEOGRAPHIC INFORMATION SYSTEM (GIS)

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SUMMARY

In this study, the method for quantitative loss estimation of household property due to an earthquake is proposed. At first, a questionnaire survey on seismic damage of household properties in the Hyogoken Nanbu Earthquake was performed. The results show that the damage ratios and patterns are different for the respective types of household property. Based on the result of the survey combined with the seismic intensity of the area, we proposed vulnerability functions that present the relation between seismic intensity and damage ratio of household property. These functions are useful for quantitative evaluation of household property damage. On the other hand, the value of household property owned by a family depends on income, family members and regions. The model of household property is established. Combining the model with the vulnerability functions of household property, the loss of household property for the hypothetical earthquake is estimated. The validation of the method is performed by comparing with the payment of earthquake insurance in the Hyogoken Nanbu Earthquake. Finally, the quantitative loss estimation of household property for the hypothetical Kanto earthquake is performed.

INTRODUCTION

Recent advances in earthquake-resistance technology have improved the ability of buildings to withstand large floor responses as caused by earthquakes. On the other hand, there are cases where household property suffers considerable damage even in buildings which escape with only slight structural damage. The estimation of such earthquake damage to household property requires a different approach to that used in estimating building damage. However, details of this type of property damage and its primary causes have yet to be clarified.

The authors developed an approach to detailed household property damage estimation on a town-by-town basis to obtain an understanding of the damage likely to be caused by an assumed earthquake [Property and Casualty Insurance Rating Organization of Japan, 1998.] The block flow diagram in Fig. 1 illustrates the approach adopted. The focus of the study is the direct damage to household property caused by earthquake ground motion, and damage resulting from earthquake-related fires is beyond its scope. The seismic intensity used in this study is based on the scale used by the Japan Meteorological Agency.

QUESTIONNAIRE-BASED SURVEY OF DAMAGE TO HOUSEHOLD PROPERTY

Outline of Questionnaire

The authors were able, between October and December 1995, to send out questionnaires to insurance company

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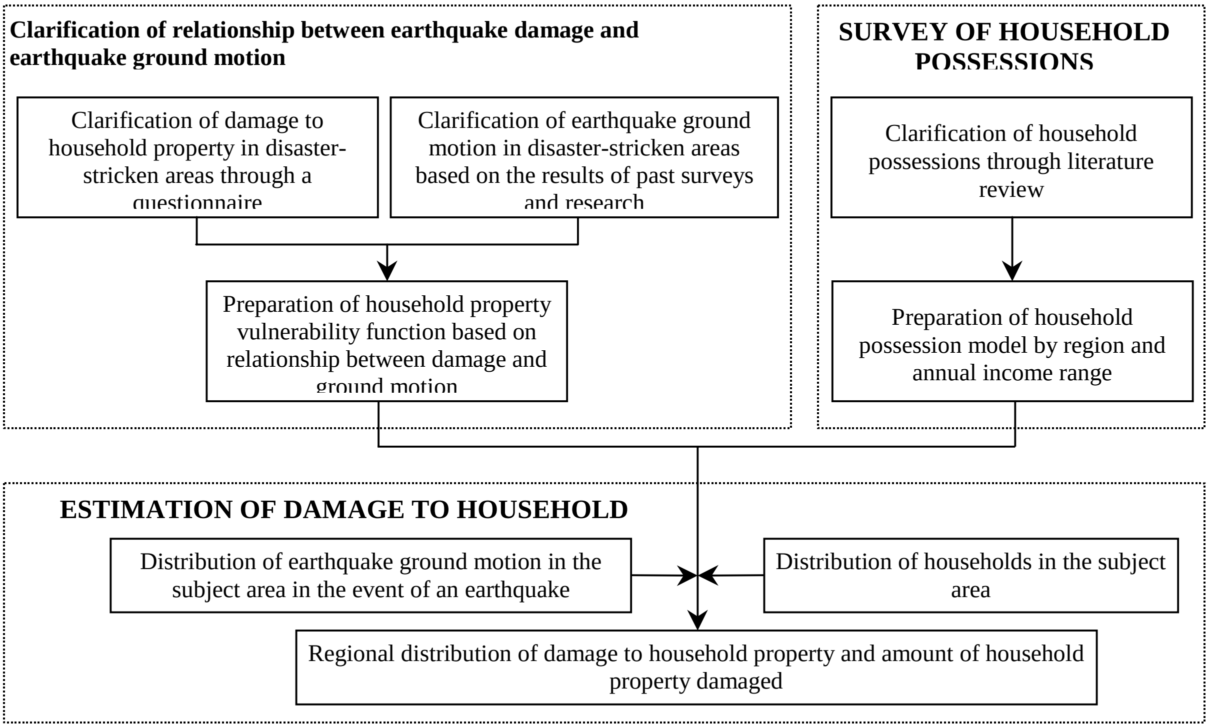


Fig. 1 Approach to Estimating Earthquake Damage to Household Property

employees living in the disaster-stricken area. Since it was expected that household property damage would have occurred over a wider area than structural damage, the questionnaires were sent out over a wide area centering on Hyogo and Osaka Prefectures. The number of questionnaires sent out was 1,450, of which 965 were returned for a response rate of 66.6%.

The questions covered two main areas: the building itself and damage to household property housed in the building. Details of the address, family structure, building structural type, and degree of damage to the building were requested.

Questions related to household property damage were of two types: some related to losses that could be enumerated (mainly durable possessions such as chests and bookshelves) while others concerned property not conveniently counted (such non-durable possessions as bedclothes and clothing.) The former questions were more detailed, seeking information as to the owner, the number of items damaged, the floor where the damage occurred, whether the property was fixed, the cause of the damage, the extent of the damage, and whether the items could still be used. The latter were simply designed to elucidate whether the property was damaged, and the cause of the damage.

In the case of durables, it is possible to calculate a damage ratio, or the ratio of the number of items damaged to the number possessed. In this case, "damaged" property is defined as that which falls to the floor, is crushed, topples over, is overturned, suffers physical damage, or is contaminated by glass or other foreign matter.

Of the respondents, those living in buildings of reinforced concrete and of conventional wooden construction accounted for about 50% and 36.5%, respectively. About half of the respondents, 47.9%, were living in collective housing, including apartment buildings, while 44.4% were in detached houses.

Outline of Damage to Buildings

The questionnaire returns showed that the number (percentage) of buildings falling into the category "total loss" was 82 (8.5%), "half loss" 140 (14.5%), "partial loss" 519 (53.8%), and "undamaged" 219 (22.7%), with 5 (0.5%) giving no response. That is, 76.8% of all buildings suffered "partial loss" or greater damage. As regards the number of buildings damaged by fire, three were completely burned down, and one suffered partial fire damage. The reason for this low level of fire damage is that there were few samples in Kobe's Nagata Ward, where major fires broke out after the earthquake.

Outline of damage to household property

In the case of durable possessions, this figure is defined as the ratio of durable possessions that were damaged to the total number possessed. As can be seen from the figure, high damage ratios were suffered by large self-standing items of furniture such as cupboards and bookshelves. Wall- and floor-mounted furnishings and equipment, such as air conditioners, heaters, and cooking stoves, had relatively low damage ratios. The damage ratio in the case of non-durable possessions is defined as the ratio of the number of positive responses to the question (damage occurred) to the total number of responses. As is clear from the figure, tableware and cookware suffered badly, with damage ratios of more than 80%.

The survey specifically asked whether damaged durable possessions were fixed to the wall or floor. Respondees were asked to indicate by a check mark whether each item was "firmly fixed," "semi-fixed" or "not fixed". Excluding cooking stoves and air conditioners, the answer "not fixed" accounted for more than 90% of responses.

PREPARATION OF HOUSEHOLD PROPERTY VULNERABILITY FUNCTION

Based on the answers to the questionnaire, a household property vulnerability function, or a function representing the degree of damage to household property for each level of earthquake ground motion, was prepared as described below.

Estimated Intensity of Earthquake Ground Motion at Points Where Answers to Questionnaire Were Obtained

To determine the household property vulnerability function, it is necessary to know the intensity of earthquake ground motion at each point where a response to the questionnaire was obtained. For this purpose, a seismic intensity measure that is usable over a broad area is required, and to evaluate damage to household property on a town-by-town basis, this study makes use of two sources of such data: a questionnaire survey conducted in Hyogo Prefecture [Takada and Kajima, 1996] and an estimate obtained from the ratios of low-rise buildings that completely and half collapsed [Building Research Institute, 1996]. To improve the reliability of this seismic intensity data, only data for blocks where at least 10 responses were obtained (for the former) and where the number of low-rise buildings exceeded 100 (for the latter) were used.

Seismic intensity is calculated from the ratios of low-rise buildings that completely and half collapsed using the following steps:

(1) The relationship between building damage ratio $P(V_{max})$ and maximum velocity V_{max} can be expressed as a standard normal distribution function, as given by equation (1). [Hayashi et al., 1997]

$$P\left(V_{max}\right) = f^3\left\{\ln V_{max} - \lambda\right\} / \xi \qquad (1)$$

where λ = average of $\ln V_{max}$ (= 4.71); and ζ = standard deviation of $\ln V_{max}$ (= 0.552).

(2) Based on the estimated maximum velocity, seismic intensity, I, can be obtained from equation (2). [Tong et al., 1996]

$$I = 2.30 + 2.01 \cdot \log_{10}\left(V_{max}\right) \qquad (2)$$

These two sources of data for the town-by-town estimation of seismic intensity have different characteristics. Responses to the questionnaires reach a saturation level where the earthquake ground motions were large, and the intensity is generally lower than indicated by actual measurements. Using the latter method based on collapse of structures, it is impossible to estimate seismic intensity at points where no partial or complete collapse occurred. This indicates that the questionnaire method is most suitable for making intensity estimates in the fringes of the affected area, where damage was light, while the collapse method is useful for more central areas where buildings suffered severe damage.

In this study, the seismic intensities obtained using the two methods were plotted on a map, and whichever was greater at a particular location was taken as the intensity for that point. Seismic intensities as calculated from actual waveforms collected at a number of points in Hyogo Prefecture were compared with these estimated intensities, and good agreement was obtained at all points.

In the case of the Osaka Prefecture map, 0.7 was added to the intensity obtained using the questionnaire method at each mesh point (about 1.1 km wide in an east-west direction, and about 0.9 km in a north-south direction) to ensure correspondence with measured seismic intensities. [Tsurugi et al., 1996] The addresses given in questionnaire responses yielded seismic intensities at 815 points (679 and 136, respectively, in Hyogo and Osaka Prefectures).

Classification of Household Property

To prepare the household property vulnerability function and a household ownership model, it is necessary to classify household property into types according to an appropriate standard. The standard for the classification is as follows.

- Classify household property into durable possessions (quantified by the number possessed and the unit price) and non-durable possessions (measured by total value).
- Classify household possessions of similar form into one type.
- Classify household possessions that suffer similar damage modes (falling to the floor, toppling over, crushing, overturning, physical damage, or contamination by glass or other foreign matter) into one type.
- Classify household possessions having different damage ratios into different types.

Based on this standard, durable and non-durable possessions are classified into 6 types and 4 types, respectively, for a total of 10 classifications, as listed in Table 1. The household property vulnerability function is determined from the relation between household property damage ratio by type and seismic intensity. In the table, the primary causes of damage to each type of household property are listed in parentheses. These "damage modes" are based on the results of the questionnaire.

Preparation of Vulnerability function by Household Property Type

The relation between the seismic intensity estimated at each point where a questionnaire response was obtained and the property damage ratio is studied. Based on responses obtained for locations with equivalent intensity, the damage ratios of durable and non-durable possessions at a particular seismic intensity are defined as follows.

For durable household property (Types A-F)

Damage ratio (%) = (number of items damaged)/(total number of items possessed) $\times$ 100

For non-durable household property (Types G-J)

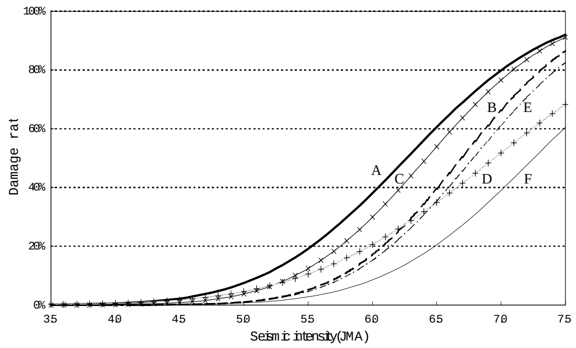
Damage ratio (%)

= (number of residences where items were damaged)/(number of residences containing items) $\times$ 100

Since the damage to household property depends on the floor response of the building, structures are classified into three types according to the number of residential floors: 1 & 2 stories; 3-5 stories, and over 6 stories. Based on the results of a survey of seismic intensity in medium- and high-rise buildings in the 1978 Miyagiken Oki Earthquake [Omote et al., 1980], 0.3 and 0.7 are added, respectively, to the seismic intensity at the ground to determine the intensity on the third to fifth floors and the sixth and higher floors.

The household property vulnerability function is obtained by carrying out a regression analysis on the damage ratios for the three floor ranges using the modified seismic intensities. From the results of a previous study [Okada and Kagami, 1991], it is assumed that the relationship between household property damage ratio $P(I)$ and seismic intensity (I) has a normal distribution, as expressed by a probability density function in equation (3).

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2/2\sigma^2} \qquad (-\infty < x < \infty) \tag{3}$$



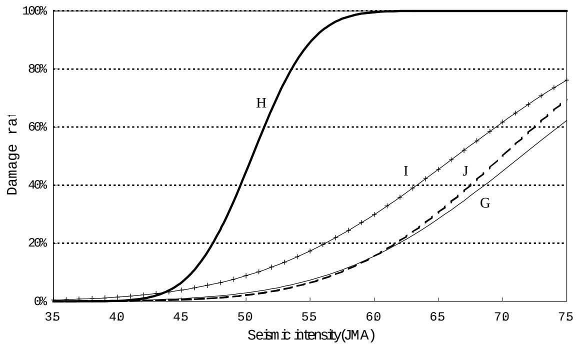


Fig. 2 Comparison of Types A-F Durable Household Property Vulnerability functions Obtained through Regression Analysis

Fig. 3 Comparison of Types G-J Non-durable Household Property Vulnerability functions Obtained through Regression Analysis

Table 1 Classification of Household Property

Type		Household property	
Durable possessions	A	Large self-standing furniture mainly used for storage (overturning)	Chests, bookshelves, and cupboards
	B	Household electrical appliances (overturning)	Electric refrigerators and washing machines
	C	Household electrical appliances (falling to the floor, toppling over)	Microwave ovens
	D	Household entertainment equipment (falling to the floor, toppling over)	Audiovisual equipment, personal computers, tele-communications equipment, and musical instruments
	E	Floor-standing furniture (crushing)	Dining tables, chairs, living room furniture, and cooking stoves
	F	Heaters and coolers (crushing, overturning)	Air conditioners and heaters
Non-durable possessions	G	Indoor accessories and miscellaneous items (crushing)	Curtains, sliding doors and screens, health and medical equipment, sporting goods, bags, shoes, *Tatami* mats, and carpets
	H	Tableware (falling to the floor, toppling over)	Tableware
	I	Home entertainment items, miscellaneous items (falling to the floor, toppling over)	Clocks, cameras, lighting fixtures, records, CDs, miscellaneous items, and toys
	J	Clothing and bedclothes (physically damaged or contaminated by glass or other foreign matter)	Clothing and bedclothes

Taking into account the distribution of damage ratios at each seismic intensity, and the fact that the greater the population parameter (number of items possessed) the higher the reliability, a regression analysis is carried out by the least squares method with weights assigned to the number of items possessed. This yields an arithmetic mean and standard deviation for each household property type, as listed in Table 2. Because there are few samples at modified seismic intensities ranging from 7.1 to 7.4, they are considered unreliable and are excluded from the analysis. For Type H household property (tableware), there are not enough examples of damage at low seismic intensities up to about 5.0. Accordingly, the results of a survey of tableware damage carried out after the Chibaken Toho-Oki Earthquake [Okada, 1989] are used in the regression analysis at seismic intensities up to 5.0, and the data obtained from this study are used at seismic intensities greater than 5.1.

Figures 2 and 3 compare vulnerability functions of Types A-F durable household property, and Types G-J non-durable household property, respectively, as obtained through the regression analysis. Household property which falls within damage modes "falling to the floor" and "toppling over" is apt to suffer damage at relatively low seismic intensities. On the other hand, property which falls within damage modes "crushing" and "physically damaged or contaminated by glass or other foreign matter" suffers damage after property that is damaged by other modes, or after a certain seismic intensity is exceeded. Further, even for items with the same damage mode, as seen by comparing Types A and B and also Types C and D, the damage ratio differs according to the arrangement and location of the property. Also, tableware (Type H household property) is in most cases placed in locations from where it is liable to fall, such as in cupboards, and so breakage is common. This means that the damage ratio for Type H property is much higher than for other types.

Table 2 Mean and Standard Deviation of Vulnerability function by Each Household Property Type

Household property type	A	B	C	D	E	F	G	H	I	J
Arithmetic mean, μ	6.27	6.69	6.42	6.95	6.78	7.26	7.15	5.05	6.64	7.00
Standard deviation, σ	0.878	0.732	0.799	1.157	0.764	0.917	1.133	0.364	1.212	0.984
Coefficient of correlation, R	0.970	0.950	0.931	0.947	0.918	0.897	0.941	0.953	0.944	0.932

PREPARATION OF HOUSEHOLD PROPERTY OWNERSHIP MODEL

In estimating the damage caused to household property by an earthquake, it is necessary to have a quantitative grasp of property ownership by household. The required household ownership model is prepared based on the results of investigations of household possessions as described in "Annual Survey Report on Consumption Trends," Research Bureau, Economic Planning Agency, and "Monthly Survey Report on Family Income and Expenditure," Research Bureau, Management and Consultation Agency.

To prepare the model, parameters related closely to the quantity and value of household possessions are first extracted. The results of this indicate that ownership of, and expenditure on, household property have clear linear relationships to both annual income and the area in which the household resides, and that the ownership of specific items, such as air conditioners and heaters, differs by region. Since the number of households at each income level in each city, ward, town, and village can be determined from housing surveys of Japan, this study takes the annual income of a household as a primary parameter defining ownership. This is then used to establish relations between annual income and the number, unit price, and quantity of various items possessed. Other characteristics are incorporated into the model as required. The actual damage to household property is then estimated by combining the vulnerability function with this model of ownership. Therefore, as with the function described in Section 3.3, household property is classified into 10 types as listed in Table 1, the quantity and unit price of owned items are determined by annual income classification, and the total amount of household property is then obtained as the quantity times the unit price.

In the interests of simplicity, this study disregards regional differences in the ownership of heaters and air conditioners (which arise due to differences in climate), and in the ownership of clothing and bedclothes due to varying family sizes. Table 3 lists the quantity of each type of household property owned by annual income range.

Table 3 Quantity of Each Type of Household Property Owned by Annual Income Range (not adjusted for regional differences nor varying family size)

Household property type	A	B	C	D	E	F	G	H	*I*	J
Annual income below ¥4 million	18.0	18.5	18.0	50.7	16.0	23.6	24.0	10.3	31.1	90.5
Annual income ¥4-10 million	54.0	18.5	18.0	59.5	32.5	33.3	33.7	15.0	40.2	150.0
Annual income over ¥10 million	118.8	18.5	18.0	65.7	62.0	40.2	40.6	18.4	46.7	192.5

ESTIMATION OF DAMAGE TO HOUSEHOLD PROPERTY

The overall goal of this study is to estimate the household property damage ratio, or a ratio of the amount of household property damaged to the amount of household property possessed, for every city, ward, town, and village. The flow diagram of the estimation process is shown in Fig. 4.

This process first calculates the amount of each type (A to J) of household property possessed, taking into account the type of residential building (1 to 3) that reflects the varying floor response with story and the annual income range (a to c) that gives a difference in the amount of household property possessed, and then the amount of household property damaged by the resulting amount of household property possessed times the household property vulnerability function formulated in Section 3.3. The unit area adopted for calculations is the surface area of the three-dimensional mesh (1 km long by 1 km wide) used in the digital form of the national land data.

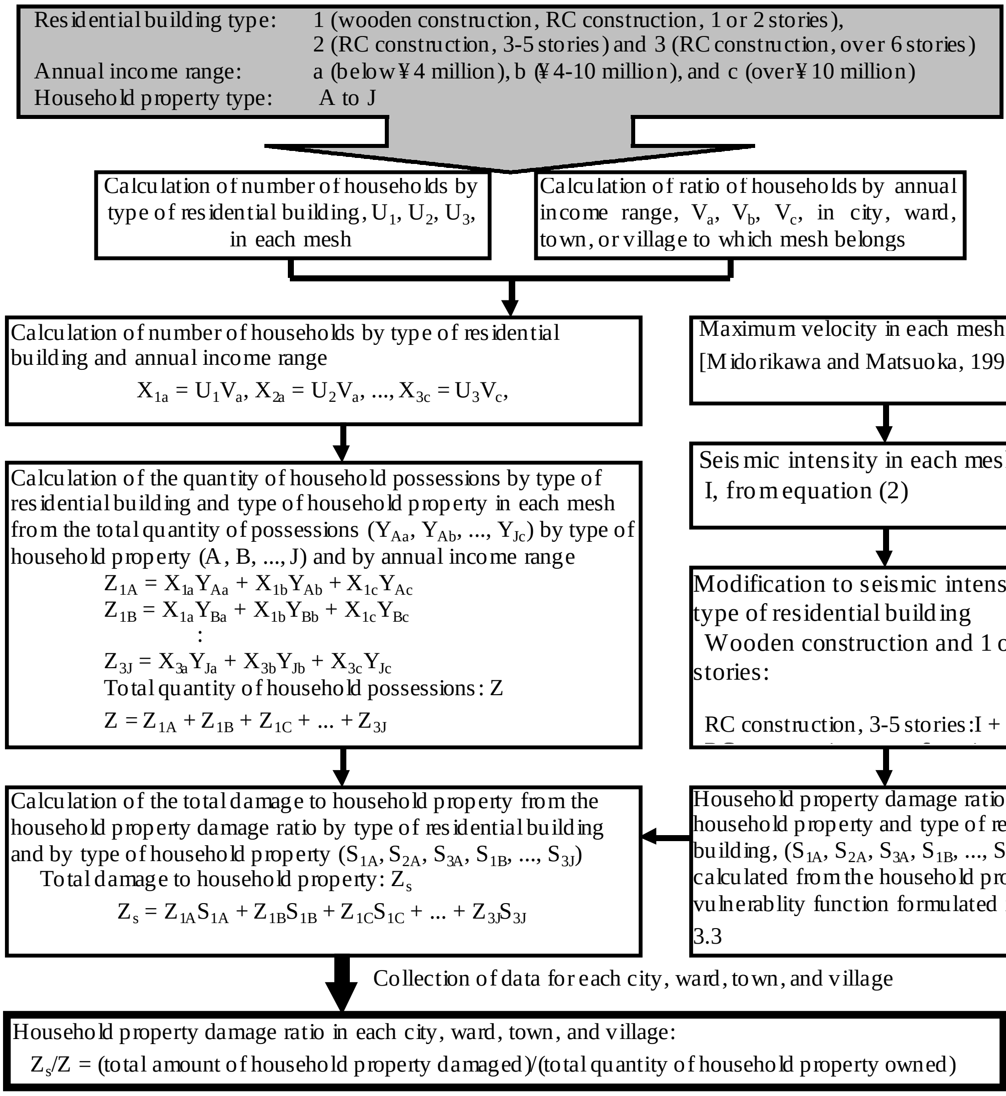


Fig. 4 Flow Diagram of Damage Estimation Process

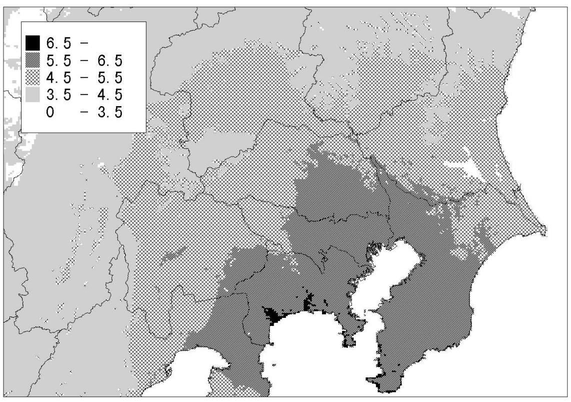


Fig. 5 Distribution of Seismic Intensity (JMA) in Each Mesh in the Event of the hypothetical Kanto Earthquake

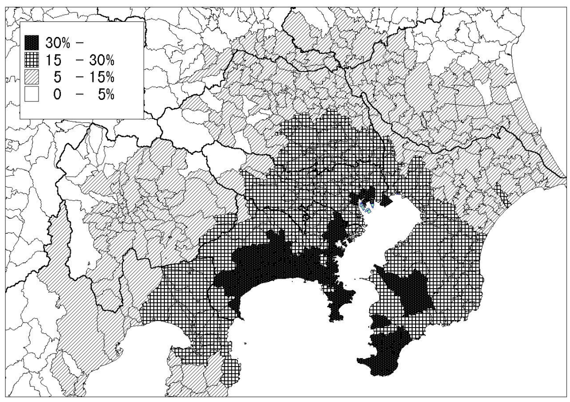


Fig. 6 Ratio of the Quantity of Household Property Damaged to the Total Amount Possessed in the Event of the hypothetical Kanto Earthquake

To verify the adequacy of this approach to estimating household property damage, the results were compared with the total amount of earthquake insurance paid out after the Hyogoken Nanbu Earthquake. The results of this comparison show that the approach is accurate for the hardest-hit areas, meaning those where the Disaster Relief Act was invoked. In areas where seismic intensities were low, however, the damage is overestimated by the proposed method. The cause of this is that, in defining damage to household property based on the questionnaire, the categorizations are made broad because of the difficulty in quantifying damage to durable possessions, with the only choices being "toppled over" and "physically damaged or contaminated by glass or other foreign matter." This leads to wider interpretations than a simple measure of unusability.

ESTIMATION OF DAMAGE TO HOUSEHOLD PROPERTY IN HYPOTHETICAL KANTO EARTHQUAKE

The damage to household property that will result in the event of the hypothetical Kanto Earthquake is estimated using the same approach. As before, this estimation excludes damage caused by earthquake-related fires.

Distribution of seismic intensity

A fault plane is assumed on the basis of the static fault parameter of the 1923 Kanto Earthquake [Matsu'ura and Iwasaki, 1983], and the maximum velocity is estimated for each mesh (about 1 km square) of the national land data [Midorikawa and Matsuoka, 1995]. Further, the seismic intensity on the ground surface is estimated from equation (2). The result of this estimation is shown in Fig. 5.

Estimated Damage to Household Property

Figure 6 shows the ratio of the quantity of household property damaged to the total amount possessed. This distribution of damage ratio is similar to the distribution of seismic intensity. However, damage ratios in central Tokyo are higher than those in areas of the outskirts where the seismic intensity is almost the same as in the center. This is because residential space tends to be on higher floors in central Tokyo, so the floor responses are typically greater in central Tokyo.

In financial terms, the amount of damage estimated on a prefecture-by-prefecture basis is about ¥5 trillion in the Tokyo Metropolis, followed by about ¥4 trillion in Kanagawa Prefecture and about ¥13.4 trillion in total. As noted earlier, this does not include damage caused by earthquake-related fires. If fire damage were considerable, as in the damage estimates produced by the Tokyo Metropolitan Government, total damage would inevitably far exceed this estimate. Further, as already described in Section 5, high damage ratios spread to a considerable distance from the center, with serious damage also in Chiba, Saitama, and Shizuoka Prefectures.

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