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Rapid Estimation of Direct Economic Losses Caused by Significant Earthquakes: An Evidence-Based Model and its Applications

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This paper presents a rapid or real-time estimation method of the economic value of direct stock damages caused by significant earthquakes in Japan. The result will contribute to both the government and private sectors' early decision-making, particularly for provisional budget allocation. First, we developed a simple but evidence-based model for estimating stock losses explained by a representative earthquake hazard factor and an exposure factor, i.e., seismic intensity and existing stock of physical assets. The key characteristic of our estimation model is that the dependent variable is prefectural damage amount. Still, the explanatory variables come from municipal sources: we overcome this data availability problem through our estimation process. Second, we carefully checked the model's specification, estimation, and performance to be soundly applied to a real-time assessment of future earthquake events. We also explain the automated measuring of the prefectural direct loss value and its distribution to every 250 m mesh. Finally, we show two examples of the application of our model; one is the case of the 2018 Northern Osaka Earthquake, and the other is the anticipated Tokyo inland earthquake.

Keywords: direct economic damage, real-time estimation, seismic intensity scale, existing physical stocks, tsunami effect

1. Introduction

If the direct economic loss of physical assets could have been estimated immediately after the 2011 East Japan Earthquake and Tsunami (EJET), it would have been possible to save human resources, expense, and time. Instead, these could have been invested in securing the government organization and resources required for recovery. Promptly determining the value of damage can help affected companies and households objectively understand the situation in which they find themselves and take appropriate action. Entities unaffected by disasters can also be identified as targets for donation and other types of assistance.

The authors have developed a system that can estimate in real-time the direct economic loss resulting from a large earthquake (and tsunami) anywhere in Japan (Toyoda et al. [1] and Ikeda et al. [2]). This study reexamines the estimation methodology and expands its applications.

Below, we outline the background and significance of this research. Next, we describe the construction of the model and provide examples of its application. Specifically, we explain the model, estimate the results for multiple plausible equations, and check the applicability of the ultimately selected equations after the observed data period. In particular, we demonstrate the validity of the values estimated by the model for the 2016 Kumamoto EQ (EQ is used for "earthquake" hereafter) since this is the most recent example for which damages have been officially published. In addition, we present our estimation results for the two largest urban areas in Japan: the area affected by the 2018 Northern Osaka EQ, and area that is likely to be affected by the Tokyo metropolitan inland EQ.

2. The Background and Significance of Rapid Estimates of Direct Economic Loss

2.1. Background

When a significant earthquake occurs, various public and private organizations, such as the Japan Meteorological Agency (JMA), the Self Defense Force, and the Ministry of Land, Infrastructure, Transport and Tourism, conduct damage assessments.

In particular, the National Research Institute for Earth Science and Disaster Resilience (NIED) estimates damage in real time through various observation networks (e.g., Nakamura et al. [3] and Fujiwara et al. [4]). Furthermore, it goes to great lengths to share this information with society. For example, one earthquake damage estimation system under development (Japan Real-tIme System for earthQuake damage estimation [J-RISQ]) uses a strong-motion earthquake recording network (K-NET, KiK-NET, etc.) to transmit information about damage in real time. It covers the entirety of Japan to create a one-quarter regional mesh a 250 m mesh). The main objective of this type of rapid disaster assessment is to provide decision-making support during the initial response period immediately after the earthquake. However, a rapid economic loss assessment has not yet been included in the J-RISQ system. This study aims to develop a method to estimate damage in financial terms and economic losses as quickly as possible.

A method of understanding the value of the loss of physical assets after a disaster is to exhaustively survey the state of damage to all assets and calculate the total value. While this can be discussed in theory, physical assets include public facilities (infrastructure), buildings such as private housing, and private capital. It is difficult to estimate how much has been lost from the balance of these stocks. For example, depreciation must be considered when evaluating the current value of assets and losses, but amortization methods are not uniform. Moreover, depreciation often does not apply to public facilities in the first place.

Nonetheless, it may be possible to make estimates in a relatively short period using an exhaustive survey for small-scale disasters. In significant disasters, on the other hand, there are many assets in question, so estimating the value of losses using this method becomes extremely difficult. Moreover, the greater the level of accuracy sought, the more time required.

After the 1995 Hanshin-Awaji EQ, direct economic losses were calculated using a gradualist approach. As a result, the National Land Agency announced a figure of approximately 9.6 trillion yen about one month after the disaster, whereas Hyogo Prefecture announced an official figure of about 9.9 trillion yen three months after the disaster. This figure was obtained by aggregating the initially calculated 15 classified damage types. Nevertheless, average values, such as damage rates by area and building prices per *tsubo* (unit of land measurement), were used to calculate the value of damages to an enormous number of buildings and other physical assets.

For the 2011 EJET, the Cabinet Office (Economic Disaster Management Bureau) [5] published two cases using rough assumptions. These were approximately 16 trillion yen and 25 trillion yen, respectively. More than three months after the disaster, the Cabinet Office (Disaster Management Bureau) [6] announced an official estimate of about 16.9 trillion yen. The Cabinet Office first calculated the balance of stocks in the affected municipalities. This was then multiplied by a damage ratio obtained by taking separate past information and the extent of damage from the tsunami. Whether using the gradualist approach of the Hanshin-Awaji EQ or the damage ratio method used for the EJET, it took approximately three months for the final official estimates to be announced.

2.2. Significance

This study presents a method for understanding the economic value of losses to physical assets caused by a significant earthquake as quickly as possible. We do not intend to propose a complete alternative to the official estimates, which, as can be seen in the cases of the 1995 Hanshin-Awaji EQ and the 2011 EJET, requires approximately three months; rather, we aim to present a rapid assessment in a visual format.

As discussed in the following sections, the proposed approach has at least two features. First, it automatically estimates direct economic losses at the municipality level and almost in real time. Second, it is based on regression analysis using past data on economic losses and can be evaluated objectively using statistical criteria. We call the model "evidence-based" because we use past data on loss values for the regression model's target (dependent) variable.

Regarding rapid damage assessment, the implementation of various mechanisms for physical information in society (such as the number of collapsed buildings) has been well described by many researchers. However, we believe that if financial details on losses during the initial response immediately after an earthquake are added, this will prove helpful in further supporting decision-making. Furthermore, various methods for estimating losses, such as more precise, real-time estimates after several weeks and the flow of indirect losses accumulated over time, are significant aspects of the application.

The real-time information handled in this report will be helpful in the government's and local municipalities' decision-making. For example, according to the Disaster Countermeasures Basic Law in Japan, the government and administration should determine the type of disaster-response organization. They must seek and allocate necessary funds during the immediate relief and recovery phases. This fact is well recognized by policy actors. Real-time information is also an essential element for business activities. For example, insurance companies would be interested in the amount of economic loss to prepare for claims.

2.3. Prior Research

As mentioned previously, the NIED has provided real-time assessment information on earthquakes in Japan [3, 4]. However, there are very few studies on real-time estimation of the direct economic loss incurred by an earthquake in Japan. Attempts to estimate in real time by modeling historical earthquake data together with seismic motion information and socioeconomic factors have been introduced by Cui et al. [7, 8]. These were the focuses of our preliminary studies of the rapid estimation of the direct economic losses of the 2016 Kumamoto EQ and the 2018 Northern Osaka EQ. We used "*minryoku*" (a composite index of various community factors) as a proxy for the exposure variable to an earthquake hazard. However, we were not equipped to estimate economic losses from future earthquakes. Therefore, we further study the real-time estimation of direct economic loss using all types of physical stock balances at the community level as an exposure variable [1]. This report was based on our previous study [1].

In the United Status (US), there are some large research projects on the rapid estimation of hazard loss, including economic loss. Among them, the United States Geological Survey's (USGS) Prompt Assessment of Global Earthquakes for Response (PAGER) has served to provide real-time loss information of significant earthquake impacts worldwide [9]. The fundamental difference between the USGS PAGER and our approach is that the former uses a country's economic loss caused by an earthquake in some base year and allocates its value by the population of the affected municipalities to the total population of the country. In contrast, our approach uses statistical inference to estimate economic loss by an earthquake using the actual past data of various (not for one year) economic losses and hazard and exposure factors. In addition, the Federal Emergency Management Agency's (FEMA) Hazus Program provides prompt multi-hazard loss information regarding structural, social, and economic consequences [10]. It provides standardized tools and data for estimating the risk from earthquakes and other hazards, such as floods and hurricanes. It also differs from our approach because it is geographical information system-based software. However, Hazus and our approach have one similar features for estimating direct economic losses. Namely, both approaches use seismic intensity as the hazard factor and physical stock data as the exposure factor. Recently, Wald et al. [11] proposed an assessment method for rapid hybrid post-earthquake impact that takes advantage of the merits of both loss models.

Some authors have presented regression analyses for estimating direct economic losses, as we do. However, to the best of our knowledge, no researchers have used all existing physical stocks as explanatory variables for the exposure factor. Some authors have used the stock of buildings only for the exposure factor (e.g., Zhang et al. [12]). On the other hand, some authors have used GDP per capita as the exposure factor (e.g., Guettiche et al. [13]). GDP per capita may be a doubtful variable for estimating stock damage because it is a flow variable. However, it may be effective when we use international data (as in the case of Guettiche et al. [13]) because it represents income inequality among countries and works as a country dummy variable.

3. A New Model to Estimate Direct Economic Loss

3.1. The Model

Since disaster risk was proposed by, for example, Wisner et al. [14], the expression "$R = H \times V$" has been generalized as "$R = H \times (V/C)$" because of considerations concerning the accumulation of disaster hazards and vulnerabilities and the capacity to respond to hazards. Here, R denotes disaster risk, H is a hazard, V is vulnerability, and C is the hazard response capacity. Risk is a probability concept that involves exposure to visible direct damage and invisible indirect damage following a disaster. This is not easy to grasp because damage manifests in various forms, through various processes, and as various phenomena. Since this study focuses on estimating the value of damage to physical assets resulting from earthquakes, it does not address human damage or indirect damage.

Exposure and hazard factors are sources of vulnerability. We first incorporated two exposure factors in the proposed model: existing physical assets and population. However, in our preliminary study, we found that the population did not work as a significant explanatory variable. One reason is that the population is more related to human and indirect economic damage but not to direct stock damage. Another technical reason is the high correlation between population and the balance of physical assets, which causes a multicollinearity problem. Therefore, we did not incorporate population as an exposure or vulnerability factor in the present framework.

The stock of physical assets comprises (1) buildings, (2) public social facilities (infrastructure), and (3) private capital. The accumulation of physical stock increases with economic development. Industries expand; population grows, meaning an increase in workplaces; and urbanization advances. This process accumulates physical assets but is simultaneously a source of more severe damage due to "natural aggression" (Wisner et al. [14]). In addition, technological progress is gradually incorporated into the physical stock, and their response capacity improves. Even if this is incorporated, the balance of physical stock is regarded as a fundamental factor when exposed to earthquakes. Besides seismic activity, hazard factors include tsunamis, liquefaction, and landslides; however, we first consider only the effects of a tsunami.

We specify the function of direct stock loss as follows:

The value of direct stock damage =
F [Amount of stock, Seismic intensity,
Related hazard factors].

This formulation aligns with the mainstream concepts of disaster science described above, but it also has been verified by relatively recent empirical studies in disaster economics. The type of function shown above is often used to estimate the amount of damage (e.g., Cavallo and Noy [15]). Although a more detailed economic logic is used to investigate the mechanisms by which indirect damage is generated, we disregard this because we concentrate on direct economic damage.

3.2. Model Specification

As a hazard, seismic intensity is reported for each municipality, that is, the location where at least one seismometer is officially installed. These data contain a large number of observations. Moreover, we created a dataset of total stocks available at the municipal level for this research project. While official damages for direct economic losses have been published for major earthquakes since the 1980s, these are issued at the prefectural (provincial) level. Damage that exists only at the prefectural level must be explained using municipal-level factors. In other words, seismic intensity data that can be used as a large sample, data on the total stock available at the municipal level, and direct economic loss data that exists only as small data are targeted. Therefore, a unique data analysis that focuses on data with different observation frequencies is required. This study concentrates intentionally on estimating damage based on evidence and does not artificially process the damage data. The model is formulated as follows, considering the differences in the frequency of observations specific to the data.

As a specific function, the priority for this linear regression model (a and b are parameters) is simplicity because this may facilitate broader application in the future:

$$Y_i = a + b_1\Sigma S5_{ij} + b_2\Sigma S6_{ij} + b_3\Sigma S7_{ij} + b_4 DT_i. \quad (1)$$

The variables are defined as follows:

Y_i: Direct economic loss by prefecture in the i-th earthquake.

ΣSI_{ij}: The total value of stock in the corresponding prefecture subject to seismic intensity I during the i-th earthquake, obtained by summing the value of the j-th municipality. ($I = 5, 6, 7$).

DT_i: Dummy variable for tsunami damage resulting from the i-th earthquake.

The magnitude of direct economic loss, the target variable, varies significantly in each case. Therefore, there is a high probability that the variance in the error term reflects this heterogeneity. However, from the perspective of ensuring the best linear unbiased estimator, heteroscedasticity of variance is undesirable. Therefore, when selecting a model in practice, we test for the homogeneity of variance and use a model that guarantees homoscedasticity of variance as much as possible.

3.3. Model Estimation

First, since there is little historical data on damage from earthquakes, to obtain as much information as possible, we went back as far as possible, examining earthquakes from the 1980s onward. Furthermore, we selected earthquakes for which official losses are available and when the Japanese seismic intensity scale (JSS) was 5 or higher. Since 1996, the JMA's previous seismic intensity classifications of 5, 6, and 7 have been subdivided into 5 low, 5 high, 6 low, 6 high, and 7. However, to maintain consistency with previous data, we chose to aggregate 5 low and 5 high as JSS 5 and to do the same with JSS 6.

Table 1 lists the target earthquakes that have occurred since the 1980s. Specifically, we collected data from the 1983 Middle Japan Sea EQ to the 2016 Kumamoto EQ.

We used the officially published loss values for each prefecture between 1983 and 2016. There are 36 target earthquakes. However, we used 31 cases in practice because we excluded five prefectures for which damage values from the 2011 EJET were unavailable. Columns 6 and 12 in **Table 1** present the numbering system used in this study.

The data for the stock values of physical assets consist of three types of stock: public capital, private enterprise capital, and building (housing and school). Stock data for each prefecture were available, but there are no officially published stock data at the municipal level. Toyoda et al. [1] and Sato et al. [16], however, did describe methods for deriving stock data for 1,901 municipalities (i.e., all cities, wards, towns, and villages in Japan). Therefore, we created a dataset for all three types of stock values at the municipal level. Furthermore, we converted the current values of stock balances and damage to 2011 prices.

Table 2 presents the estimation results. First, we found that JSS 5 is insignificant for any function type. Therefore, in **Table 2**, the estimated value for the coefficient $\Sigma S5$ is shown only for Eq. (1). After confirming that the estimated value of the coefficient of $\Sigma S5$ is insignificant in any other case, we show the estimated results excluding $\Sigma S5$ for Eq. (2) through Eq. (6).

While JSS 5 has a considerable impact, physical damage tends to be minor in practice, and the estimated results reflect that.

Next, we introduced a tsunami dummy variable to measure the effect of a tsunami ($DT = 1$) only in cases of earthquakes accompanied by a significant tsunami otherwise, 0). Finally, we introduced a constant-term dummy, a dummy for each coefficient and both dummy effects simultaneously. As a result, except for the constant term, all explanatory variables are statistically significant in Eqs. (4) and (5) (**Table 2**). In particular, the instance with coefficient dummies (Eq. (5)) had a greater significance than the constant dummy. We, therefore, adopted Eq. (5) for the analysis incorporating a tsunami. However, the effects of a tsunami with a maximum JSS of 6 cannot be determined using Eq. (5). Thus, for the time being, we used both Eqs. (4) and (5) for real-time estimation involving a significant tsunami.

An approach that uses only dummy variables may be insufficient for explicitly incorporating a tsunami's effects. A model that considers tsunami height, floodwater height, etc., is required. However, there are no official data on tsunami damage except for the 2011 EJET. Therefore, the use of dummy variables as provisional models was unavoidable. Therefore, the development of a model that considers hazard factors, such as tsunamis resulting from earthquakes, is a topic we intend to address in the future.

Table 2 shows the results of the regression analysis. Eq. (1) is the case that included all stocks for JSS 5, 6, and 7; Eq. (2) excludes stocks for JSS 5. Eq. (3) is the case with the same explanatory variables as those in Eq. (2), but that excludes data for the 2011 EJET. Eq. (4) has the same specifications as Eq. (3), but it further excludes the 2017 Kumamoto EQ data to obtain the baseline prediction equation for an interpolation simulation in the next section. Finally, Eqs. (5) and (6) include the data for the 2011 EJET to account for the tsunami effects with dummy variables, that is, Eq. (5) with a constant term dummy and

Table 1. Past earthquakes (value of damage given in nominal terms).

Summary of earthquake			Earthquake damage in the prefecture		Data No. in this study
Earthquake name	Date	Mag.	Affected prefecture	Total damage [billion yen]	
(1983) Middle Japan Sea EQ	1983.5.26.	7.7	Aomori	518.11	1
(1984) West Nagano EQ	1984.9.14.	6.8	Nagano	46.87	2
(1993) Kushiro Offshore EQ	1993.1.15.	7.8	Hokkaido	53.08	3
(1993) Southwest Off Hokkaido EQ	1993.7.12.	7.8	Hokkaido	124.31	4
(1995) Great Hanshin EQ	1995.1.17.	7.3	Hyogo	9,900.00	5
Kagoshima Northwest EQ*	1997.3.26.	6.2	Kagoshima	9.26	6
Kagoshima EQ*	1997.5.13.	6.1	Kagoshima	15.06	7
(2000) Tottori West EQ	2000.10.6.	7.3	Tottori	60.08	8
			Shimane	8.85	9
(2001) Geiyo EQ	2001.3.24	6.7	Hiroshima	4.74	10
Sanriku South EQ*	2003.5.26	7.1	Iwate	11.89	11
			Miyagi	5.57	12
Miyagi Northern EQs*	2003.7.26.	6.4 (main shock)	Miyagi	64.97	13
(2003) Tokachi-oki EQ	2003.9.26.	8	Hokkaido	30.3	14
(2004) Niigata Chuetsu EQ	2004.10.23.	6.8	Niigata	3,000.00	15
(2007) Noto EQ	2007.3.25.	6.9	Ishikawa	348.22	16
(2007) Chuetsu Offshore EQ	2007.7.16.	6.8	Niigata	1,500.00	17
(2008) Iwate–Miyagi Nairiku EQ	2008.6.14.	7.2	Iwate	29.44	18
			Miyagi	119.9	19
			Akita	2.64	20

Summary of earthquake			Earthquake damage in the prefecture		Data No. in this study
Earthquake name	Date	Mag.	Affected prefecture	Total damage [billion yen]	
(2011) Great East Japan EQ	2011.3.11.	9	Aomori	133.7	21
			Iwate	4,276.00	22
			Miyagi	6,492.00	23
			Akita	No official data	–
			Yamagata	No official data	–
			Fukushima	3,129.00	24
			Ibaraki	2,476.00	25
			Tochigi	660.9	26
			Gunma	No official data	–
			Saitama	No official data	–
			Chiba	438.9	27
			Tokyo	No official data	–
(2011) Nagano Northern EQ	2011.3.12.	6.7	Niigata	28.5	28
			Nagano	16.7	29
(2016) Kumamoto EQ	2016.4.14., 2016.4.16.	7.3	Kumamoto	2,800.00	30
			Oita	650	31

Source: Created by the authors based on Cui et al. [3].
Note: * denotes an un-officially named earthquake.

Table 2. Results of estimation.

Variables & Indexes \ Equation Number	Equation (1)	Equation (2)	Equation (3)	Equation (4)	Equation (5)	Equation (6)
Constant	1.36E+11	4.97E+10	3.21E+10	−2.95E+10	−9.31E+10	1.27E+11
$\Sigma S5$	−0.0071					
$\Sigma S6$	0.1013^{***}	0.1005^{***}	0.0895^{***}	0.0818^{***}	0.0895^{***}	0.0772^{***}
$\Sigma S7$	0.334^{***}	0.3354^{***}	0.3364^{***}	0.3366^{***}	0.3406^{***}	0.3319^{***}
DT					$7.54E+11^{*}$	
$DT * \Sigma S7$						2.5975^{***}
Estimation method	OLS	White method	White method	White method	OLS	OLS
$\overline{R}^2$	0.857	0.861	0.983	0.985	0.874	0.902
F	61.16	94.07	680.89	641.31	70.52	92.6
AIC	58.11	58.05	55.92	55.96	57.98	67.74
Number of samples	31	31	24	22	31	31
Notes			Excludes the Great East Japan EQ	Excludes the Great East Japan and Kumamoto EQs		

Note: (1) *, **, and *** denote significance levels at 10, 5, and 1% levels, respectively. (2) OLS means the ordinary least squares method, and white method means the estimation method after an adjustment for homoscedasticity. (3) DT denotes a dummy variable for tsunami. AIC means Akaike Information Criterion.

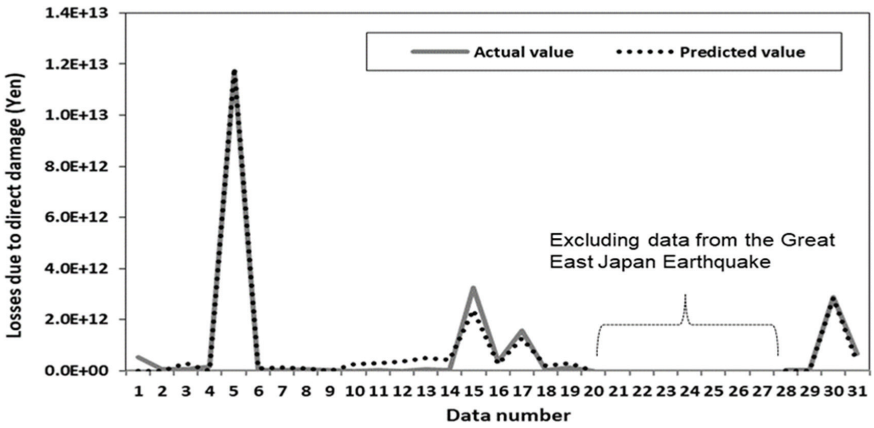

Fig. 1. Performance of Eq. (3).

Eq. (6) with a coefficient dummy.

Since we assumed possible disparities between residuals, mainly because the damage values of the 1995 Hanshin-Awaji EQ and the 2011 EJET are considerable, we conducted two types of tests for the homoscedasticity of variance for each equation. First, we applied the Breusch–Pagan test but found no significant heteroscedasticity in any equation. Second, we used the White test, which revealed variance heterogeneity in Eqs. (2)–(4). Thus, for Eqs. (2)–(4), we applied the White estimation method (i.e., heteroscedasticity-consistent covariance matrix estimation) to obtain results that maintained constant variance. **Table 2** presents the results of these re-estimations. Overall, the estimation results were more than acceptable. All multiple determination coefficient adjusted for degrees of freedom are higher than 0.85. In addition, besides Eqs. (1) and (5), all estimated coefficients were significant at the 1% level, with the exception of the constant terms. In Eq. (4), the dummy variable is significant at the 10% level.

3.4. Examining the Validity of the Model

3.4.1. Interpolation Simulation

Interpolation simulations were conducted to check the validity of the regression model. If we compare the actual and estimated values for all samples using Eq. (1), Theil's inequality coefficient, which measures the extent of inequality between two parties, is 0.164. Although the overall performance was good, estimates for the EJET were underestimated for Iwate (No. 22) and Miyagi (No. 23) prefectures and overestimated for Ibaraki Prefecture (No. 25). The reason for this may be that Eq. (2) does not incorporate the effects of a tsunami. On the other hand, Eq. (3), which excludes the EJET data (Nos. 21–27), significantly improves prediction accuracy within the sample. Theil's inequality coefficient was 0.058. **Fig. 1** shows the interpolation performance of Eq. (3).

We also checked the performance of Eqs. (5) and (6), including the tsunami impacts of the 2011 EJET. Both cases show better values for Theil's inequality coefficients than the case of Eq. (2). It would be recommended to use either Eq. (5) or Eq. (6) for a case of tsunami impact since the tsunami effect appears through either JSS 6 or JSS 7, respectively, though with different results.

From the above results, we propose selecting a model for real-time estimation in the following manner:

If there is no effect from a tsunami, or where the effect is minimal, use Eq. (3). However, where the effect of the tsunami is significant, such as with the 2011 EJET (or the anticipated Nankai Trough EQ), use Eqs. (4) and (5).

3.4.2. Extrapolation Test (Applied to the Kumamoto EQ)

Determining the accuracy of the model's predictions is accomplished using Eq. (3) by extrapolating outside the sample: To that end, we examine the predicted and actual values of the 2016 Kumamoto EQ, for which official damage values are available. First, we used 22 samples, excluding Kumamoto Prefecture (No. 30) and Oita Prefecture (No. 31), from the case of Eq. (3). The result is Eq. (4). Then, we use this estimated result to calculate the estimated values for both prefectures, yielding 2.62 trillion and 294 billion yen, respectively. Interval prediction is shown in **Fig. 2**. For Kumamoto Prefecture, the predicted interval is [0.94 trillion yen, 4.28 trillion yen]. The Kumamoto EQ was an unusual case in which JSS 7 was measured twice for the foreshock and mainshock. As a result, Tsutsumi et al. [17] calculated the direct economic loss in Kumamoto Prefecture to be 1.8–3.8 trillion yen and damages in Oita Prefecture to be 0.5–0.8 trillion yen. Thus, while there was a slight underestimation for Oita Prefecture, the predicted value was entirely in line with the actual values for Kumamoto Prefecture. We obtained this result because Kumamoto Prefecture was the largest area affected by the Kumamoto EQ. Therefore, the estimated equation was able to predict direct losses almost exactly; it can be applied to future earthquakes, especially in severe cases.

The above-estimated results are summarized based on point prediction. There are various uncertainties in the practice of prediction. We must check a model's fit-

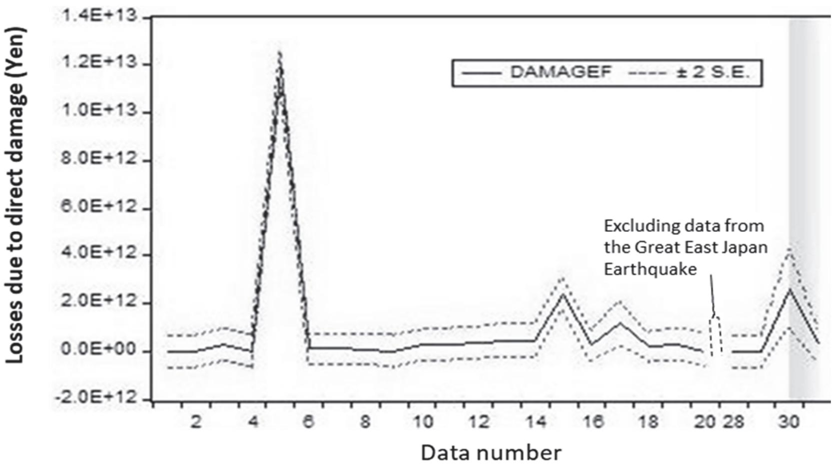

Fig. 2. Segment prediction for the 2017 Kumamoto EQ.

ness using interval prediction if we emphasize uncertainty. Eq. (4) was estimated based on samples before the Kumamoto EQ (excluding the 2011 EJET). Using the existing values of stocks in the affected municipalities of Kumamoto and Oita prefectures, we obtain interval estimates of plus and minus 2 SE (standard error) for both prefectures, as shown by the shaded area on the right in **Fig. 2**. This indicates that the predicted mean value for Kumamoto Prefecture is 2.61 trillion yen, with an interval of $(0.94 \text{ trillion yen}, 4.28 \text{ trillion yen})$. This interval includes the interval calculated by the Cabinet Office $(1.8 \text{ trillion}, 3.8 \text{ trillion yen})$. For Oita Prefecture, the mean value is 0.20 trillion yen, with an interval of $(0 \text{ trillion}, 0.96 \text{ trillion yen})$. The predicted interval of $(0.5 \text{ trillion}, 0.8 \text{ trillion yen})$ almost exactly matches the interval calculated by the Cabinet Office. Therefore, we can apply Eq. (3) to estimate a range that accounts for uncertainty.

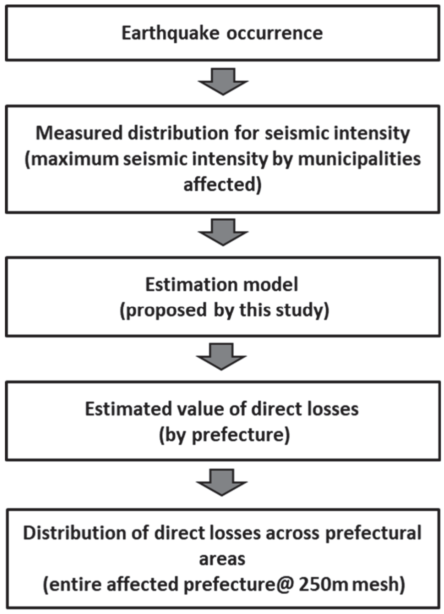

Fig. 3. Flow of loss estimation.

4. Examining the Automated Estimation System

4.1. Real-Time Estimation Procedure

We now explain how the model proposed here is used to estimate the value of damage when an earthquake occurs (Toyoda et al. [1] and Ikeda et al. [2]). **Fig. 3** shows the estimation process. First, the system obtains each region's maximum seismic intensity information from the seismic intensity distribution measured by the NIED. Then it immediately calculates the estimated values of direct losses at the municipal and prefectural levels.

Once the system obtains the value of the direct economic loss at the prefectural level, it aims to display the distribution of losses in the prefecture on a 250 m mesh. **Fig. 3** illustrates this procedure. First, the damage value is prorated across each built-up region using a 250 m mesh of these regions published in basic maps; afterward, the mesh distribution of direct economic loss within the prefecture is calculated and displayed on the map.

4.2. Automatic Acquisition of Earthquake Triggers

The Earthquake Early Warning system maintained by the JMA is a mechanism to warn of the imminent occurrence of an earthquake. Automation of the damage estimation presented in this study employed the JMA disaster prevention information XML. It can be received as a general-purpose message to detect the occurrence of an earthquake that satisfies the estimation conditions. In addition, the estimation system can also obtain seismic intensity information for each municipality. Note that when using receipt of this message as a trigger to estimate direct economic losses, it updates the Earthquake Early Warning information later. Thus, it can manage to link the record of each with an earthquake ID, including the information in the message. The estimation is reprocessed upon receipt of amended details (for details, see Ikeda et al. [2], pp. 277-279).

4.3. Distributing a 250 m Mesh According to Building Areas

Cui et al. [8] and Ikeda et al. [2] proposed a technique for further prorating the estimated value of direct economic loss over a 250 m mesh. Focusing on the highly correlated relationship between the *minryoku* index and building area allows the allocation of the estimated value of economic loss within an affected prefecture to a 250 m mesh distribution. Namely, we prorate the estimated value to a 250 m mesh, using measured seismic intensity and building distribution. A similar technique is applicable in this study. In other words, if a stable relationship exists between the total value of stock and building area in an affected prefecture, a prorating method using measured seismic intensity and distribution of buildings within a prefecture, the distribution of damage per mesh can be obtained.

The building area within each 250 m mesh can be obtained from the building perimeter data in the primary map information. In addition, the seismic intensity within each 250 m mesh can be obtained from the NIED real-time earthquake damage estimation system (J-RISQ). Note that according to J-RISQ specifications, the final report of seismic intensity data is issued approximately 10 min after the J-RISQ trigger is activated, so J-RISQ seismic intensity distribution data is obtained approximately 10 min after receipt of the earthquake occurrence trigger. In addition, meshes crossing prefectural boundaries are split at the prefectural border and treated as separate meshes.

5. Application to the Northern Osaka EQ

5.1. Direct Economic Losses from the Northern Osaka EQ

On June 18, 2018, an earthquake with a maximum seismic intensity of 6-lower occurred in the north of Osaka Prefecture. The JSS 6 low was observed in five districts: Kita-ku of Osaka City, Takatsuki City, Hirakata City, Ibaraki City, and Minoh City. JSS 5 high was observed in ten municipal areas within Osaka Prefecture and eight municipalities in Kyoto Prefecture and was felt widely throughout the Kansai region. Because this is an urban area with a high concentration of people and industries, direct damage was expected to be enormous. However, there was no significant damage to transportation or road networks and almost no damage to ports. However, damage to buildings, retaining walls, and private capital stock was common.

Below, we conduct an analysis restricted to Osaka Prefecture, where the damage was more concentrated than in neighboring prefectures. According to the final report compiled by Osaka Prefecture [18], 18 houses were completely destroyed, 512 houses were half destroyed, 55,081 were partially damaged, and 817 buildings other than housing were damaged. Osaka Prefecture did not disclose other information about significant damage to physical stock besides human injuries. Within the total stock data for the municipalities in Osaka Prefecture, preliminarily compiled by the authors for 2018, the entire stock for the five districts above was 27,197.2 billion yen (in 2011 prices). Our automated system to estimate the direct loss for the five districts results in a value of 2.4 trillion yen. The affected area is one of the regions of Japan with a high concentration of physical stock. Nonetheless, most of the damage to housing was partial, and the estimated value was considered to fit within this range. However, we cannot confirm the accuracy of our estimated value because Osaka Prefecture has not disclosed the officially estimated damage value of the earthquake.

5.2. Prorating Damage Across a Regional Mesh

If a significant linear relationship between the total stock and building area in each municipality within Osaka Prefecture is recognized, the direct economic loss of the prefecture can be prorated across a 250 m mesh based on the seismic intensity scale (JSS 5 and JSS 6) and the building area. We checked the relationship between the total stock and building areas in each of the 72 municipalities within Osaka Prefecture using linear regression. The coefficient of determination was 0.83, confirming a good relationship.

On this basis, if we prorate using the distribution of building areas and seismic intensity data owned by the NIED, the mesh display shown in **Fig. 4** is obtained. The areas with more than 200 million yen per mesh unit are situated within Kita-ku of Osaka City in addition to the other five cities.

5.3. Estimated Losses After 2018

Table 3 shows the estimated economic losses caused by recent significant earthquakes, which were calculated similarly to the 2018 Northern Osaka EQ. However, the government has not disclosed the losses for these cases.

6. Application to an Anticipated Tokyo Inland EQ

The Earthquake Research Committee of the Headquarters for Earthquake Research Promotion of the Ministry of Education, Culture, Sports, Science and Technology has predicted a 70% probability of an M7-class earthquake occurring in the South Kanto region in the next 30 years. The Central Disaster Management Council of the Cabinet Office [19] presented 19 cases of various epicenters with almost the same M7 levels. We selected the most catastrophic case, the epicenter of which was the southern part of the capital (i.e., the northern part of Tokyo Bay). The scenario assumes that a significant earthquake of M7.3 occurs in the evening in winter. It predicts that approximately 610,000 houses will be crushed or burned. It also estimates the direct loss at 47.4 trillion yen.

Figure 5 exhibits our estimation results derived from the evidence-based model. In applying our model, we

■Earthquake Overview

Epicenter	Northern Osaka 34.8° N, 135.6° E, 10.0km depth
Magnitude	M5.9 (JMA)
Occurrence	Jun. 18, 2018 07:58 +0900 (JST)

⇒See J-RISQ for more details on the earthquake.

■Direct Damage Amount

Municipality	Direct Damage Amount (billion yen)
Takatsuki	1,073
Ibaraki	904
Hirakata	307
Minoh	97
Osaka-shi kita-ku	34
Osaka Pref. Total	*2,415*

■Distribution Map

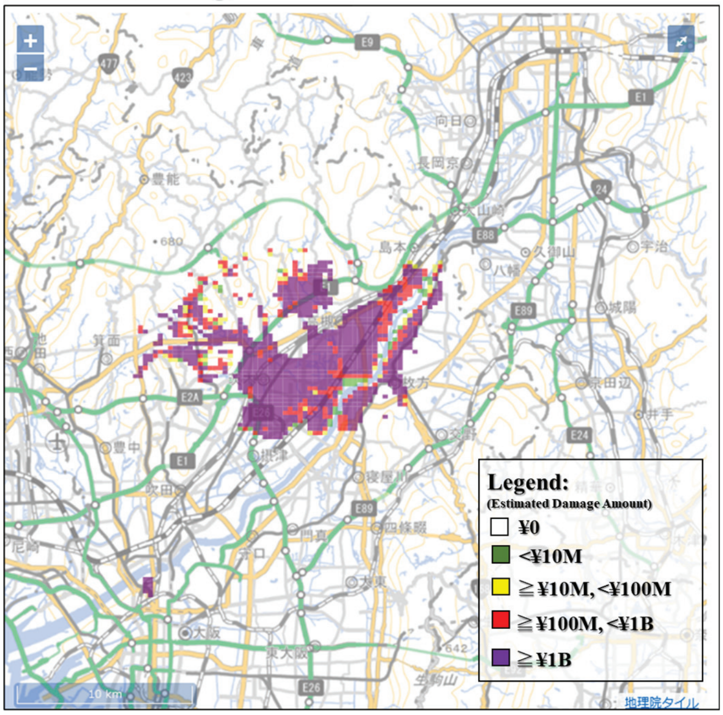

Fig. 4. Direct economic loss of the 2018 Northern Osaka EQ.

Table 3. Estimated losses from significant earthquakes since 2018.

Name of earthquake	Year	Mag.	Amounts of damage [billion yen]
Northern Osaka EQ	2018	5.9	2415.0
Hokkaido Iburi Eastern EQ	2018	6.7	213.4
Yamagata Prefecture Offshore EQ	2019	6.7	360.0
Fukushima Prefecture Offshore EQ	2021	7.3	2619.7
Fukushima Prefecture Offshore EQ	2022	7.4	2401.2

used the statistics of seismic-scale data for each affected municipality, which were produced based on simulations and provided by the Central Council. It shows a direct economic loss of 76.0 trillion yen, which exceeds the official prediction by almost 30 trillion yen. We need a thorough study of why the Central Council's estimate is relatively low. This may be why, although we consider all existing physical assets, including infrastructure and private capital stocks, as well as buildings, the council may concentrate mainly on buildings. Again, though we need a thorough investigation of the difference, we stress that our approach is an evidence-based model estimation rather than a scenario-based data-generating approach.

Both approaches, the Central Council and ours, only attempt to estimate the direct economic losses caused by a possible catastrophic earthquake in the Tokyo area. Although both use the same seismic-scale data for each affected municipality, the estimation results diverge significantly. Therefore, we can compare the results but cannot determine which is more accurate. In this sense, both approaches have limitations in their estimations.

7. Conclusions

We presented the development of a model to estimate the direct economic losses resulting from earthquakes in real time, using data on physical stock balances at the municipal level and seismic motion. In calculating the direct economic loss to society, accumulated physical assets (buildings, public infrastructure, and private capital) are the primary elements exposed to risk from earthquakes. This model is characterized by the adoption of stock balances at the level of affected municipalities as an explanatory variable. An estimate formula was used to make predictions, which incorporated data on all officially published damage values resulting from earthquakes (JSS 5 or greater), from the 1983 Middle Japan Sea EQ to the 2016 Kumamoto EQ. Therefore, the model is based on historical evidence rather than hypothetical scenarios. In addition, this system can report damage to stock for each affected municipality and its distribution over a mesh immediately after earthquakes with a seismic intensity range of 6 low to 7. Early damage information will be helpful to local governments for decision-making concerning forming response organizations and preparing budgets at the level of municipalities and severely damaged communities.

Statistical robustness was checked using several criteria. In particular, we have shown that the model can pre-

■Estimated Seismic Intensity

Epicenter	Directly below the southern part of Central Tokyo: (Earthquake in the Philippine Sea Plate)
Magnitude	M7.3

■Direct Damage Amount

Municipality	Direct Damage Amount (billion yen)
Ibaraki Pref.	1,836
Saitama Pref.	11,519
Chiba Pref.	9,459
Tokyo Metro.	39,916
Kanagawa Pref.	13,226
Total	*75,959*

■Distribution Map

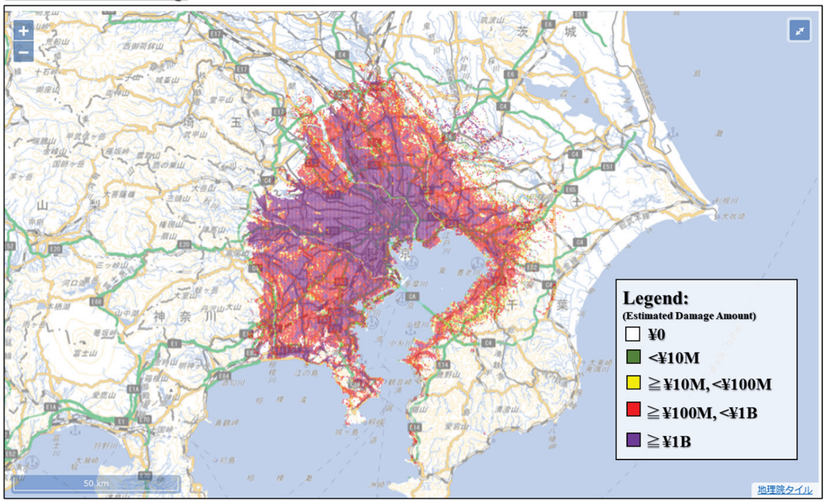

Fig. 5. Direct economic loss of an anticipated Tokyo Inland EQ.

dict with high accuracy the damage value in Kumamoto Prefecture resulting from the Kumamoto EQ. Furthermore, although the loss values have not been officially published and so cannot be compared, we showed that the value of the damage from the 2018 Northern Osaka EQ was about 2.4 trillion yen. Finally, we also demonstrated the estimated losses caused by the four significant earthquakes after the 2018 Northern Osaka EQ.

Furthermore, we used the model to predict the direct economic damage caused by a hypothetical Tokyo inland earthquake of M7.3. We found that the loss value would be approximately 59 trillion yen, which is larger than the predicted value of the Government Council by approximately 30 trillion yen.

Our remaining tasks are as follows. First, for cases involving significant tsunami damage, in addition to the provisional model developed in this study (Eqs. (5) and (6)), this model should be further refined by incorporating tsunami hazard factors such as wave height and inundation depth. Second is the development of an estimation formula that integrates information from large samples on the distribution of seismic motion for each mesh, which the NIED has been compiling for earthquakes since 1996. This will enable us to estimate direct economic losses using more detailed mesh data rather than municipality-based statistical data.

Under the Disaster Countermeasures Basic Act, the Japanese government's target is recovery or reconstruction of direct economic damage. In addition, the Disaster Relief Act and the Act on Support for Reconstruction of Disaster Victims' Lives also use direct damage (primarily residential damage) as an indicator of the conditions for application. In this regard, we focused on evaluating direct economic damage. Therefore, we acknowledge that assessing indirect economic damage is important but is outside the scope of the present paper.

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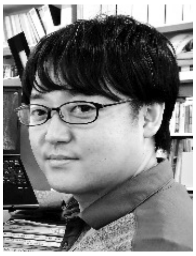

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