17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Real-Time Estimation of Direct Economic Losses Caused by Major Earthquakes in Japan

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Abstract

The aim of this study is to present a real-time estimation method of economic values of direct stock damages caused by significant earthquakes in Japan. The result will contribute to both government and private sectors in their decision making, particularly for budget allocation. First, we developed a simple but evidence-based model for estimating stock losses explained by an example of an earthquake hazard factor and an exposure factor, i.e., seismic intensity, and existing stocks. Second, we carefully checked the model specification, estimation, and performance to be soundly applied to a real-time assessment of future earthquake events. Finally, we developed a methodology of showing estimated losses in a 250-meter meshed plane of an afflicted area.

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

1. Introduction

If the direct economic loss of physical assets could have been estimated immediately after the Great East Japan Earthquake, it would have been possible to save several human resources, expenses, and time. These could instead have been invested into 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 they find themselves in and take appropriate action. Entities unaffected by disasters can also be identified as a target for donations 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. Below, we first outline the background and significance of this research. Next, we present the construction of the model and give examples of its application. Specifically, we explain the model, estimate results using multiple equations, and check their applicability of the finally selected equation after the past observed data period. In particular, we demonstrate the validity of the values estimated by the model against the 2016 Kumamoto Earthquake, since this is the most recent example for which damages have been officially published. In addition, we also present the 2018 Northern Osaka Prefecture earthquake, for which damages have yet to be officially disclosed.

2. The background and significance of rapid estimates of direct economic loss

2.1 Background

When a large-scale disaster occurs, various public and private organizations, such as the Japan Meteorological Agency, the SDF, and the Ministry of Land, Infrastructure, Transport and Tourism carry out damage assessments. In particular, the National Research Institute for Earth Science and Disaster resilience (herein referred to as NIED) provides an estimation of damage in real-time through various observation networks and go to great lengths to share this information with society at large. For example, an earthquake damage estimate system under development (J-RISQ) uses a strong-motion earthquake recording network (K-NET, KiK-NET etc.) to transmit information about damage in real-time, covering the entirety of Japan to create a 1/4 regional mesh (herein termed a 250 m mesh). The main objective of this kind of rapid disaster assessment is to provide decision-making support during the initial response period immediately after the earthquake. The purpose of this paper is to develop a system to estimate damages in economic terms, that is, economic loss. While damage can be understood in physical terms using physical observation, rephrasing this in economic terms, while also termed "real-time," requires a time-difference of several hours. This is an attempt to estimate economic damages as quickly as possible under such conditions.

A method of understanding in detail the value of the loss of physical assets after a disaster, would be to exhaustively survey the state of damage to all assets and from there calculate the total value. While this can be talked about in theory, physical assets include public facilities (infrastructures), buildings such as private homes, and private capital. It is not easy to estimate how much has been lost from the balance of that stock. For example, depreciation must be considered when estimating the value of assets and losses, but methods of amortization are not uniform. Depreciation is in many cases not applied to public facilities in the first place. Nonetheless, for small-scale disasters, it might be possible to make estimates in a relatively short period of time using an exhaustive survey. In cases of large-scale disasters, on the other hand, there are many assets in question, and so estimating the value of losses using this method becomes extremely difficult. The greater the level of accuracy sought, the more time required.

Direct economic losses after the Hanshin-Awaji Earthquake (1995) were calculated using a gradualist approach. The National Land Agency announced a figure of approximately 9.6 trillion yen about one month after the disaster, while Hyogo Prefecture announced an official figure of about 9.9 trillion yen about three months after the disaster. This is the total having been classified into 15 damage types and aggregated. Nevertheless, average values, such as damage rates by area and building prices per tsubo, were used to some extent in calculating the value of damages to the enormous number of homes and offices.

In the case of the East Japan Earthquake (2011), the Cabinet Office (in charge of economic and financial analysis) initially (about 2 weeks later) published two cases under rough assumptions. These were for about 16 trillion yen and 25 trillion yen, respectively. Later, more than 3 months after the disaster, the Cabinet Office (in charge of disaster prevention) announced an official estimate of about 16.9 trillion yen. This was calculated by estimating the balance of stock existing in the affected municipalities and multiplying by a damage ratio, obtained by taking into account separate past information and the extent of damage from the tsunami. Whether using the gradualist approach of the Hanshin-Awaji Earthquake or the damage ratio method used for the East Japan Earthquake, it took about three months for the final official estimates to be announced.

2.2 Significance

The aim of this paper is to present a method of understanding the economic value of losses to physical assets and stock caused by the occurrence of a significant earthquake as quickly as possible. We do not propose a complete alternative to the official estimates which, as can be seen in the cases of the Hanshin-Awaji Earthquake and the East Japan Earthquake, require about three months, but rather aim to present a rapid estimate in a visible format. In regard to rapid damage assessment, the implementation of various mechanisms for physical information in society has already been described; however, we believe that if economic information about losses during the initial response immediately after an earthquake are to be added, it would prove useful in further supporting decision-making. There are various methods for estimating losses, such as real-time, more precise estimates with a short delay, and the flow of indirect losses accumulated over time, each of which possess their own significance in application.

The real-time information handled in this report is useful in the decision-making surrounding what kind of disaster-response organization should be organized by the government and administration and surrounding the policy as to how people, equipment, and particularly money (budget) should be allocated during the immediate relief and recovery phases. This fact is well-recognized by policy actors. This is also valuable information to private companies and households for them to quickly and objectively understand their situation and take appropriate action. It is also useful to those not affected by the disaster in making decisions about providing support for the affected area.

2.3 Prior Research

As has been mentioed above, NIED has been providing real-time assessment information of earthquakes in Japan [1,2]. However, to our knowleghe, there exist very few studies on real-time estimation of direct econmc loss of an earthquake in Japan. Attempts to estimate in real time by modeling historic earthquake data together with seismic motion information and socioeconomic factors was introduced by Cui et al. [3,4]. These were our preliminary researchs on rapid estimation of the direct economic losses of the 2016 Kumamoto earthquake and the 2018 Osaka earthquake, respectively. In them, we used a composite index of various community facotors as a proxy for an exposure variable to an earthquake hazard but did not prepare to estimate economic losses of future earthquakes. We made a further study on real-time estimation of direct economic loss using all kind of physical stock balances at community level as an exposure variable [5]. The present report is based on our former paper [5].

In the U.S.A., there are two big research projects on rapid estimation of hazard loss including economic loss. The United States Geological Survey's Promt Assessment of Global Earthquakes for Response (PAGER) has been serving to provide real-time loss information of significant eathquake impacts in the world [6]. Federal Emergency Management Agency's Hazus has been providing prompt multi-hazard loss information in terms of structural, social and economic consequencies [7]. Recently, Wald et al. [8] proposed an assessment method of rapid hybrid post-earthquake impact that takes advantage of the merits of both loss models.

3. A new model to estimate direct economic loss

3.1 The model

Since disaster risk was proposed by e.g. Wisner et al. [9], "R = H x V" has been generalized as "R = H x (V / C)" with consideration of the accumulation of disaster hazards and vulnerabilities, and the capability to respond to hazards. Here, R denotes disaster risk, H is hazard, V is vulnerability, and C is hazard response capacity (3). This risk as a probability concept is demonstrated as visible direct damage and invisible indirect damage following a disaster. Because damage manifests in various forms, processes, and phenomena, it is not easy to grasp. Since this paper focuses on estimating the value of damage to physical assets resulting from earthquakes, it does not address human damage or environmental degradation.

The stock of physical assets considers (1) buildings, (2) public social facilities (infrastructure), and (3) private capital. The accumulation of physical stock increases with economic development. Industries expand; the population grows, which means a growth in workplaces; and urbanization advances. This process accumulates physical assets but is simultaneously a source of greater damage due to "natural aggression" (Wisner et al.[9]). In addition, technological progress is gradually incorporated within physical stock and their response capacity improves. Even if this is incorporated, the balance of sphysical tock is regarded to be a fundamental factor that is exposed to earthquakes. Besides seismic activity, hazard factors include tsunami, liquefaction, and landslides; however, we considers only the effects of a tsunami, at moment.

As described earlier, it is not easy to immediately estimate from the assumed risk what economic damage will result from a specific earthquake occurrence. In particular, disaster risk is revealed with different hazard distributions in each disaster area, resulting in different states of damage in different areas. With this in mind, we consider a method of estimating the value of economic damage across the entire disaster area. In so doing, we emphasize two points as characteristic of the method: (1) its simplicity and (2) its emphasis on evidence from past data on damage.

We specify the function of dirct stock loss as follows:

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

This formulation is in line with the mainstream concepts of disaster science described above, but it also exhibits empirical studies in disaster economics that have emerged more recently.The type of function shown above is often used to estimate direct damage, e.g. [10]. Although some more detail economic logic is used in investigations into the mechanisms by which indirect damage is generated, but we disregard it since we are concentrating on direct economic damage.

3.2 Model specifications

As a hazard, seismic intensity is basically reported for each municipality, i.e., the location where at least one seismometer is officially installed. This data have a large number of observations. Moreover, in this research project, we have created a data set of total stocks available at municipal level. However, while for direct economic losses official damages have been published for major earthquakes since the 1980s, these are issued at prefectural (provincial) level. Damages that exist only at prefecture level must be explained, using municipality-level factors. In other words, seismic intensity data that can be used as a large sample, data on the total stock available prorated to the municipal level and direct economic loss data that exists only as small data are to be targeted. A unique analysis of data focusing on data with differing observation frequencies is therefore required. This paper purposely focuses on estimating damage based on evidence and does not artificially process damage data. The model is formulated as follows, taking into consideration differences in the frequency of observations specific to the data.

As a specific function, priority is placed on simplicity out of consideration for broad future applications. For this reason, we consider the following linear regression model (a and b’s are parameters).

$$Y_i = a + b_1\Sigma S5_{ij} + b_2\Sigma S6_{ij} + b_3\Sigma S7_{ij} + b_4DT_i \qquad (1)$$

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 up the value of the j-th municiplality. (I = 5,6,7).

DT_i: A dummy variable for when tsunami damage occurs during the i-th earthquake..

However, the magnitude of direct economic loss, the target variable, varies largely in each case, and there is therefore a high possibility that the variance of the error term will heterogeneously reflect this. From the perspective of ensuring the best possible linear unbiased estimator, heteroscedasticity of variance is undesirable. Therefore, when selecting a model in practice, we chose to perform a homogeneity of variance test 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, in order to obtain as much information as possible, we go back as far as possible, examining earthquakes since the 1980s. Furthermore, we address earthquakes where official losses are available and where maximum seismic intensity is Shindo 5 or greater. Since 1996, the Japan Meteorological Agency's previous seismic intensity classification of 5, 6, and 7 was subdivided into 5 low, 5 high, 6 low, 6 high and 7. However, in order to maintain consistency with previous data, we have chosen to aggregate 5 low and 5 high as Shindo 5 and do the same with Shindo 6.

Table 1 shows target earthquakes since the 1980s. Specifically, data from the 1983 Middle Japan Sea Earthquake up to the 2016 Kumamoto Earthquake were collected.

Target earthquakes includes 36 cases between the 1983 Middle Japan Sea Earthquake and the 2016 Kumamoto Earthquake. However, where an earthquake covers 12 prefectures as in the East Japan Earthquake, it is treated as 12 cases. The value of damage uses the officially published values for each prefecture. In practice, we are limited to a total of 31 cases due to the exclusion of 5 prefectures for which damage values from the East Japan Earthquake were unavailable. The right side of Table 1 shows the case numbering used in this study. The appendix briefly describes the method of estimation used for stock data. Both the value of damage and the value of stock used were converted to 2011 real prices.

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	Magnitude	Affected prefecture	Total damage （Yen, billions）	
(1983) Middle Japan Sea Earthquake	1983.5.26	7.7	Aomori	518.11	1
(1984) West Nagano Earthquake	1984.9.14	6.8	Nagano	46.87	2
(1993) Kurisho Coast Earthquake	1993.1.15	7.8	Hokkaido	53.08	3
(1993) Hokkaido Southwest Coast Earthquake	1993.7.12	7.8	Hokkaido	124.31	4
(1995) Great Hanshin Earthquake	1995.1.17	7.3	Hyogo	9,900.00	5
Kagoshima Northwest Earthquake※	1997.3.26	6.2	Kagoshima	9.26	6
Kagoshima Earthquake※	1997.5.13	6.1	Kagoshima	15.06	7
(2000) Tottori West Earthquake	2000.10.6	7.3	Tottori	60.08	8
			Shimaken	8.85	9
(2001) Geiyo earthquake	2001.3.24	6.7	Hiroshima	4.74	10
Sanriku South Earthquake ※	2003.5.26	7.1	Iwate	11.89	11
			Miyagi	5.57	12
Miyagi Northern Earthquakes※	2003.7.26	6.4(main shock)	Miyagi	64.97	13
(2003) Tokachi-oki Earthquake	2003.9.26	8	Hokkaido	30.3	14
(2004) Niigata Chuetsu Earthquake	2004.10.23	6.8	Niigata	3,000.00	15
(2007) Noto Earthquake	2007.3.25	6.9	Ishikawa	348.22	16
(2007) Chuetsu Offshore Earthquake	2007.7.16	6.8	Niigata	1,500.00	17
(2008) Iwate-Miyagi Nairiku Earthquake	2008.6.14	7.2	Iwate	29.44	18
			Miyagi	119.9	19
			Akita	2.64	20
(2011) Tohoku Earthquake and Tsunami	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 Earthquake	2011. 3. 12	6.7	Niigata	28.5	28
			Nagano	16.7	29
(2016) Kumamoto Earthquake	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.

Figure 1 shows the internal organization of 31 samples. The broken line shows direct economic loss. Hyogo presents the largest values for number 5, the Han-Shin Awaji Earthquake, while the value for Miyagi prefecture is the largest in number 23, the East Japan Earthquake. The bar chart shows the total stock present in the regions affected by seismic intensity. The base of the bar chart shows the stock of Shindo 5 regions, followed by the stock in Shindo 6 regions and in the top row, the stock in Shindo 7 areas in the four cases (in addition to Hyogo and Miyagi prefectures, the 15th and 30th cases in the Niigata and Kumamoto prefectures).

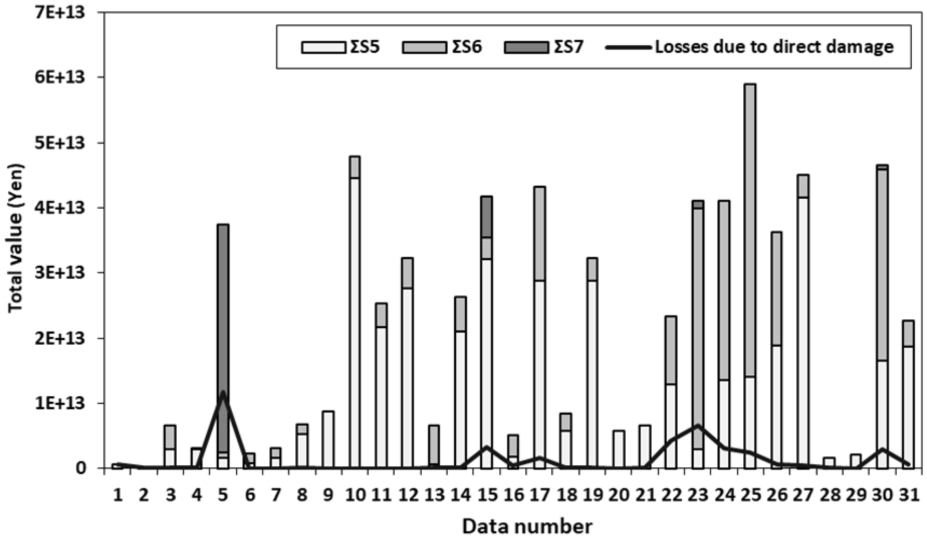

Figure1 – The data structure of stock in affected area by value of damage and seismic intensity

Table 2 – Results of estimation

Equation Number / Variables & Indexes	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
Σ S5	-0.0071					
Σ S6	0.1013***	0.1005***	0.0895***	0.0818***	0.0895***	0.0772***
Σ S7	0.334***	0.3354***	0.3364***	0.3366***	0.3406***	0.3319***
DT					7.54E+11*	
DT * Σ S7						2.5975***
Estimation method	OLS	White method	White method	White method	OLS	OLS
$\bar{R}^2$	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 Earthquake	Excludes the Great East Japan and Kumamoto Earthquakes		

(Note 1) *, **, *** indicate significance at the 10%, 5% and 1% levels respectively.

(Note 2) OLS is the ordinary least squares method, while the White method is a method of estimation following variance homoscedasticity correction.

(Note 3) DT is a dummy for tsunami. Here there are 7 prefectures from the East Japan Earthquake; Aomori, Iwate, Miyagi, Fukushima, Ibaraki, Tochigi and Chiba. Two prefectures were involved in the Kumamoto earthquake, Kumamoto and Oita.

The estimated results are shown in Table 2. First, it was found that Shindo 5 was not significant in any of the function types. In Table 2, estimated values for the coefficient of ΣS5 are only shown for Equation 1. However, after confirming that the estimated value is not significant in any other case, only estimated results, excluding that term, are shown. In fact, while Shindo 5 has a considerable visible impact, in practice, physical damage tends to be small, and the estimated results are understood to reflect that.

Next, a tsunami dummy variable was introduced to measure the effect of tsunami (DT = 1 only in cases of earthquakes accompanied by a tsunami, otherwise 0). We tried to introduce a constant-term dummy, introducing a dummy for each coefficient and introducing both dummy effects simultaneously. As a result, all explanatory variables, except for the constant term, were statistically significant in Equations 4 and 5 in Table 2. In particular, the instance with coefficient dummies (Equation 5) had greater significance than the constant dummy. We therefore adopted Equation 5 for the analysis incorporating a tsunami. However, the effects of a tsunami at maximum Shindo 6 cannot be grasped by Equation 5. Thus, for the time being, both Equations 4 and 5 will be used for real-time estimation involving a tsunami.

An approach using only dummy variables is insufficient to explicitly incorporate the effects of tsunami, and a model that considers tsunami height, floodwater height, etc., as hazard factors is required. However, there are almost no cases of tsunamis where data has been published on the official value of damages, except for the Great East Japan Earthquake. Therefore the use of dummy variables as provisional models was unavoidable. However, the development of a model that considers hazard factors, such as tsunami resulting from earthquakes, is something we intend to address as a topic in the future.

Table 2 shows the results of a regression analysis in which the homosceasticity of variance was tested and homoscedasticity ensured. First, two types of homoscedasticity of variance tests were performed for each equation. When the Breusch-Pagan was applied, both equations were determined to have a homoscedasticity of variance. Secondly, applying the White test, it was determined that there was heterogeneity of variance in Equations 2, 3 and 6. Thus, for Equations 2, 3 and 6, we applied the White method (heteroskedasticity-consistent covariance matrix estimation) to obtain results that maintained uniform variance. Table 2 shows the results of these re-estimations. In addition, with the exception of Equation 4, the coefficient estimate values are significant at the level of 1%, except for the constant terms introduced in all equations. In Equation 4, only the dummy variable is significant at the 10% level.

3.4 Examining the validity of the model

3.4.1 Interpolation simulation

We conducted some interpolation simulations to check rhe validity of the regression model. If we copare the actual values and the estimated values for all samples using Equation 2, Theil's inequality coefficient, which measures the extent of inequality between two parties, is 0.164. Although the overall performance is good, estimates for the East Japan Earthquake underestimated for Iwate (No.22) and Miyagi (No.23) prefectures and overestimated for Ibaraki prefecture (No. 25). The reason for this may be that Equation 2 does not incorporate the effects of the tsunami. The performance of Equation 3, which estimates excluding the East Japan Earthquake data (No. 21 - 27), improves the accuracy of prediction within the sample significantly: Theil's inequality coefficient is 0.058. Figure 2 shows the interplation performance of Equation 3.

We also checked the performances of Equatons 5 and 6, which include the tsunami impacts at the East Japan Earthquake. Both cases show better values of Theil’s inequality coefficients than the case of Equation 2. It would be recommended to use either Equation 5 or Equation 6 for a case of tsunami impact since the tsunami effect appears either through seismic intensity Shindo 6 or 7, respectively and differently.

From the above results, the following can be proposed as a model to be used for real-time estimation. "If there is no effect from a tsunami, or where the effect is minimal, use Estimate Equation 3. Where the effects from tsunami are large, such as the East Japan Earthquake (or the anticipated Nankai Trough earthquake etc.), use Estimate Equations 4 and 5."

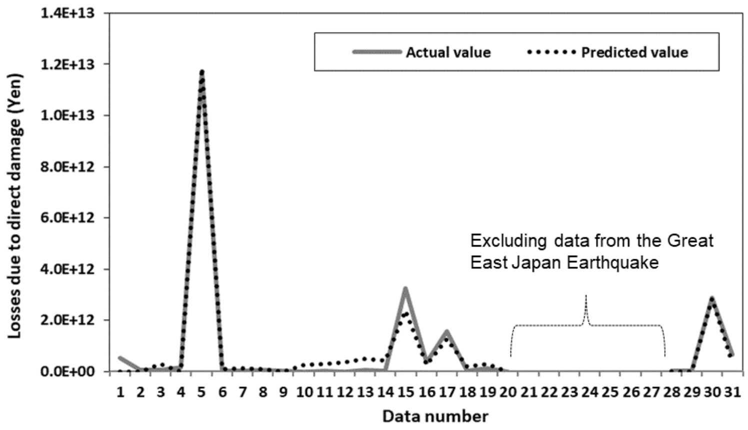

Figure 2 – Equation 3's performance

3.4.2 Extrapolation test (Applied to the Kumamoto earthquake)

The accuracy of the model's predictions uses Equation 3 by extrapolating outside of the sample. To that end, we will look at the predicted and actual values of the Kumamoto earthquake, where official earthquake damage values are available. First, we have used 22 samples excluding Kumamoto prefecture (No.30) and Oita prefecture (No. 31) from the case of Equation 3. The result is Equation 4. Using these to calculate estimated values for both prefectures yields 2.62 trillion and 294 billion yen respectively. The interval prediction is shown in Figure 3. For the case of Kumamoto prefecture, the predicted interval is [0.94 trillion yen, 4.28 trillion yen]. The Kumamoto arthquake was an unusual case where a Shindo scale 7 was measured twice, for both the foreshock and the main shock. The Cabinet Office (responsible for economic and financial analysis) calculated the direct economic loss in Kumamoto prefecture to be 1.8-3.8 trillion yen, and 0.5-0.8 trillion yen of damages in Oita prefecture [11]. Thus, while there is a slight underestimate for Oita prefecture, the predicted value is entirely in line with the actual values for the Kumamoto prefecture. The Kumamoto prefecture was the largest affected area in the Kumamoto earthquake, and its direct losses could be predicted almost exactly; it can therefore be considered applicable to future earthquakes, especially in serious cases.

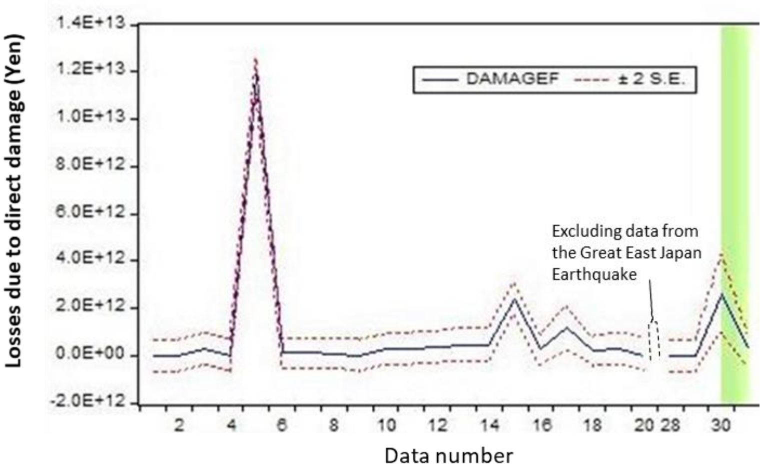

Figure 3 – Segment prediction for the Kumamoto earthquake

The above estimated results are summarized, premised on point prediction. There are various uncertainties in the practice of prediction. If we emphasize uncertainty, it is necessary to check the fitness of the model using interval prediction. Equation 3 was estimated based on samples prior to the Kumamoto earthquake (excluding the Great East Japan Earthquake), and for the Kumamoto and Oita prefectures which were affected by the Matsumoto earthquake, an interval estimate of plus minus 2se (standard error) was determined, as shown by the shaded area on the right in Figure 7. According to this, the predicted value for Kumamoto Prefecture is estimated to be 2.61 trillion yen as the central value with interval (0.94 trillion yen, 4.28 trillion yen). Intervals calculated by the Cabinet Office (1.8 trillion, 3.8 trillion yen) are fully included. For Oita Prefecture, a central value of 0.20 trillion yen was predicted, with an interval of (0 trillion, 0.96 trillion yen). This generally includes the interval calculated by the Cabinet Office (0.5 trillion, 0.8 trillion yen) (a slight underestimate). It was shown that Equation 3 can be applied with the purpose of estimating a range with consideration for uncertainty.

4. Examining real-time estimation

4.1 Real-time estimate procedure

We now explain how the model proposed here is used to estimate the value of damage when an earthquake occurs. Figure 4 shows the estimation process. Inputting the maximum seismic intensity information of each region from the seismic intensity distribution measured by NIED, the estimated values at the municipality-level can immediately be calculated

We now explain how the model proposed here is used to estimate the value of damage when an earthquake occurs. Figure 4 shows the estimation process. Inputting the maximum seismic intensity information of each region from the seismic intensity distribution measured by NIED, the estimated values at the municipality-level can immediately be calculated

Once the value of direct economic loss at the prefectural level is obtained, we aim to display the distribution of losses in the prefecture on a 250 m mesh. Figure 9 shows the procedure for this. The value of damage is prorated across each built-up area using 250 m mesh of built-up areas published in basic map information, whereupon the mesh distribution of direct economic loss within the prefecture is calculated and displayed on the map.

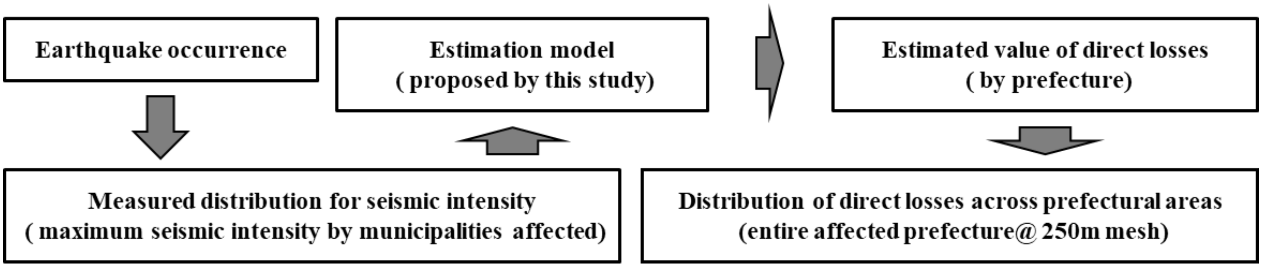

Figure 4 – Flow of damage estimation

4.2 Automatic acquisition of earthquake triggers

The Earthquake Early Warning system maintained by the Japan Meteorological Agency is a mechanism to provide warning of an earthquake's imminent occurrence. Automation of the damage estimate proposed in this paper uses the JMA Disaster Prevention Information XML. It can be receive as a general-purpose message, in order to detect the occurrence of an earthquake satisfying the conditions for estimation. It can also obtain seismic intensity information for each municipality. Note, when using the receipt of this message as a trigger to estimating direct economic losses, that the Earthquake Early Warning information may be updated later. For this reason, the records of each event are managed by linking to an earthquake ID including the information of the message, and the estimate will be reprocessed upon receipt of amended information.

4.3 Distributing a 250 m mesh according to building areas

Cui et al. [13] proposed a technique for further prorating the estimate value of direct economic loss over a 250 m mesh. Paying attention to the relationship between private resources and developed areas, from the correlation, it became possible to allocate by using measuring seismic intensity and the distribution of built-up areas. A similar technique is applicable here. In other words, if a stable relationship can be obtained by checking the relationship between the total value of stock and built-up area, a prorating method using measured seismic intensity and the distribution of buildings within Osaka Prefecture can be applied to obtain the distribution of damages per mesh.

The built-up area within each 250 m mesh can be obtained from the building perimeter data in the basic map information, and the seismic intensity in each 250 m mesh can be obtained from the NIED real-time earthquake damage estimation system (J-RISQ),4) respectively. Note that from the J-RISQ specifications, the final report of seismic intensity data is issued approximately 10 minutes after the J-RISQ trigger is activated, and so J-RISQ seismic intensity distribution data is obtained approximately 10 minutes after receipt of the earthquake occurrence trigger. In addition, meshes that cross over the prefectural boundary are split at the prefectural boundary and treated as a separate mesh.

5. Application to the Northern Osaka Prefecture Earthquake

5.1 Direct economic losses in the Northern Osaka Prefecture Earthquake

On June 18, 2018, an earthquake with a maximum seismic intensity of 6-lower occurred in the north of Osaka Prefecture. Shindo 6-lower was observed in five districts, Osaka-shi Kita-ku, Takatsuki-shi, Hirakata-shi, Ibaraki-shi and Minoh-shi. Shindo 5-upper was observed at 10 municipal areas within Osaka Prefecture and 8 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 major damage to transportation or road networks, and there was almost no damage to the ports. Stock damage to buildings and retaining walls was commonly seen.

Below, we conduct an analysis restricted to the Osaka prefecture, where the main damage was concentrated. According to the final report compiled by Osaka prefecture [12], 18 houses were completely destroyed, 512 houses were half destroyed, 55,081 houses were partially damaged and 817 buildings other than houses were damaged. Other information about significant damage to physical stock besides human injuries was not disclosed. Wihin the total stock data for the municipalities in Osaka prefecture prepared by the authors, the total stock for the five districts above was 27,197.2 billion yen (in 2011 prices). Substituting this value into ΣS6 in Equation 3 and calculating the value of stock damage Y results in a value of 276 billion yen. The affected area is also one of Japan's regions with a high concentration of physical stock. Nonetheless, most of the damage to homes was partial, and the estimated value is considered to fit within this range.

5.2 Pro-rating damage across a regional mesh

If a significant linear relationship between the total stock in each municipality within the Osaka Prefecture and the built-up area is recognized, the direct economic loss of the prefecture can be prorated across a 250 m mesh based on the seismic intensity scale (Shindo 7, Shindo 6) and the built-up area. We checked the relationship between the total stock in each of the 72 municipalities within Osaka Prefecture and the built-up area through a linear regression . The coefficient of determination is 0.83, and so a sufficient relationship can be confirmed.

On that basis, if we pro-rate using the distribution of built-up areas and seismic intensity data owned by NIED, the mesh display shown in Figure 5 is obtained. It can be seen that areas with more than 200 million yen per mesh units are situated within Osaka-shi Kita-ku in addition to Takatsuki, Ibaraki, Toyonaka, Minoh and Neyagawa cities.

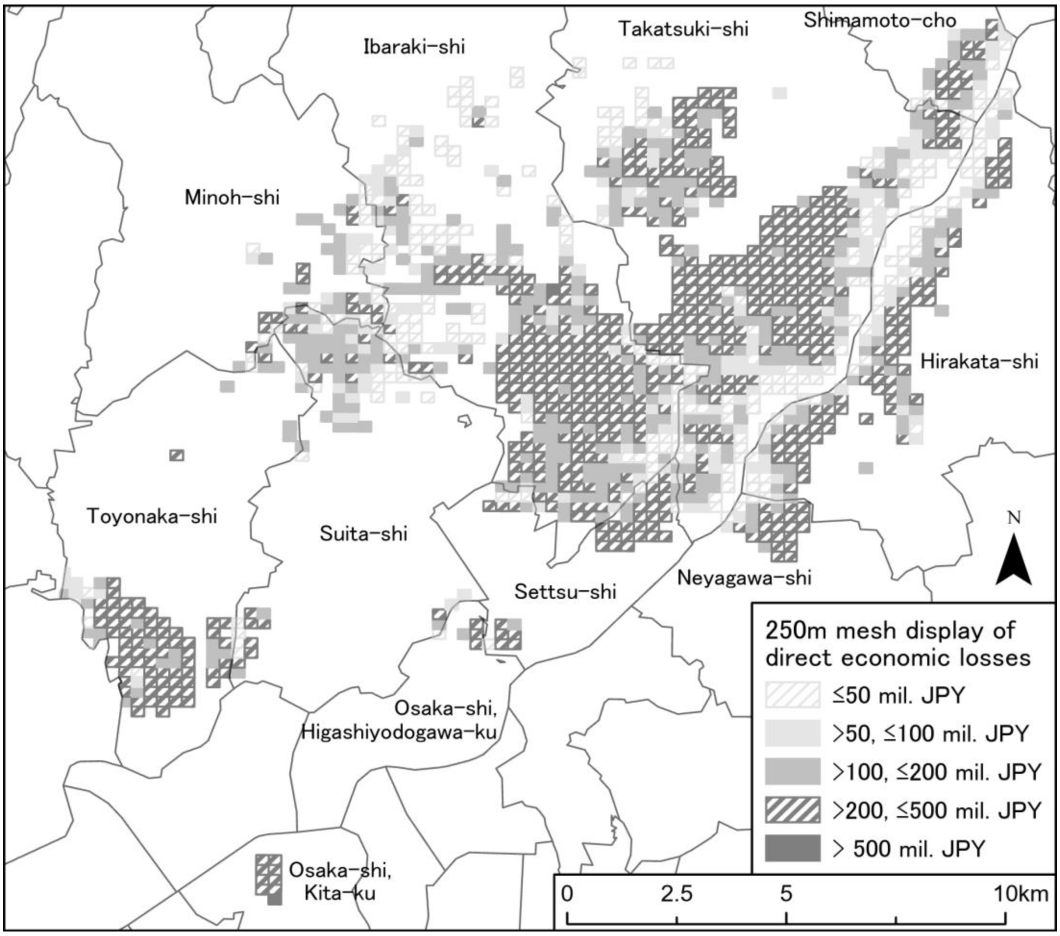

Figure 5 – A 250m mesh display of direct economic losses

6. Conclusion

We have 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 municipal level and seismic motion. In calculating the direct economic loss to society as a whole, the accumulated physical assets (buildings/ public infrastructure, private capital) are the primary elements exposed to risk from earthquake. This model is characterized by its adoption of stock balances at the level of affected local governments as an explanatory variable. An estimate formula used to make predictions was obtained, using data on all damage published, resulting from earthquakes (Shindo 5 or greater) between the 1983 Nihonkai Chubu earthquake and the 2016 Kumamoto earthquake. Its statistical robustness was checked using several criteria. In particular, it was shown that the value of damage in Kumamoto prefecture during the Kumamoto earthquake could be predicted with a high degree of accuracy. Furthermore, although official values have not been published and so cannot be compared, it was shown that the value of damage from the 2018 Osaka Earthquake was about 276 billion yen. This is a system that can immediately report on damage to stock and its distribution over a mesh immediately after the occurrence of an earthquakes with a magnitude in the range of 6-lower to 7.

The following points are considered as tasks for the future. First, for cases involving significant tsunami damage, besides the provisional model developed in this paper (Equations 5 and 6), a model should be developed incorporating tsunami hazard factors (wave height, inundation depth, etc.). Second is the development of an estimation formula that incorporates information from large samples on the distribution of seismic motion for each mesh, which NIED has been compiling for earthquakes since 1996.

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