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Paper:

Simple Estimation Method for the 2016 Kumamoto Earthquake's Direct Damage Amount

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It takes a significantly long time to estimate a direct damage amount based on a damage investigation. However, in the response immediately after a disaster, the investigation and estimation of damage are often conducted later because of a lack of human resources. Especially in the case of a huge earthquake that affects a wide area, the disaster cannot be fully responded to by the municipalities and prefectures alone. Support from the entire country, and in some cases from other countries, is essential to the disaster response. Precise information regarding the direct damage amount must be transmitted promptly. Accordingly, in this study a simple method to promptly estimate the direct damage amount caused by an earthquake disaster is proposed and applied to the case of the 2016 Kumamoto Earthquake.

Keywords: Kumamoto Earthquake, seismic intensity scales, direct damage amount, multiple regression analysis, promptness

1. Introduction

The structures and social infrastructures accumulated with high density within urban areas have an additional value for both, the infrastructures of civic life and the support of economic activities. Earthquake disasters in urban areas cause complicated and compound consequences [1] and affect the economic activities of the local community for a long time afterwards [2]. The economic damage caused by earthquake disasters can be divided as follows: the damage of capital stock in the local community such as housing, production facilities of enterprises, and roads (referred to as "direct damage" hereafter) and that of flow such as the reduction of economic activities like production and consumption (referred to as "indirect damage" hereafter). In the Great East Japan Earthquake, the capital stock damage was estimated to be about 16–26 trillion yen and that of flow to be about 6.3–11.3 trillion yen [3].

Since around 2000, the local economic resilience [4], which is "the force which can restore the production of the economy damaged by natural disaster swiftly," has been focused on and discussed vigorously. In considering the precautions against huge, wide-area earthquakes, it is especially important to grasp the economic damage caused by such earthquakes in advance. As for earthquakes with a high possibility of occurrence in the future, the direct damage amount was estimated based on the knowledge of past earthquake disasters. For example, the direct damage amount caused by the Nankai Megathrust Earthquake (a series of interrelated earthquakes under a simulation where strong ground motion will occur on the shore side) was estimated to be about 169.5 trillion yen [5], and that caused by an earthquake with its epicenter directly below Tokyo (a magnitude 7.3 earthquake in the northern part of Tokyo Bay) to be about 66.6 trillion yen [6].

A huge, wide-area earthquake is estimated to occur with a frequency from once in several decades to once in several hundred years. For this reason, it would have to be said that forecasting the details of such an earthquake, such as timing of occurrence and scale, is extremely difficult. It is common to sum up the direct damage amount by item based on the actual damage situation after the occurrence of an earthquake disaster. In the case of a huge, wide-area earthquake, the designation of a disaster as one of extreme severity [7] is prerequisite for the local governments to receive additional financial support from the central government. After the local governments affected by the disaster report the damage to the competent authorities, they confer with the Cabinet Office, the Ministry of Finance, and other relevant ministries and agencies regarding the designation of the disaster as one of extreme severity. During these procedures, the local governments determine the damage situation and the direct damage amount.

It takes a significantly long time to estimate the direct damage amount based on damage investigation. However, in the response immediately after a disaster, the investigation and estimation of damage are often conducted later because of a lack of human resources. Huge, wide-area earthquakes especially cannot be fully responded to by the municipalities and prefectures alone. The support of the entire country, and in some cases from other countries, is essential to the disaster response. Precise information about the direct damage amount must be transmitted promptly.

Accordingly, this study aims to propose a simple estimation method for the direct damage amount caused by earthquakes by taking the 2016 Kumamoto Earthquake as a case study. This simple estimation method for the direct damage amount consists of the estimation model for the direct damage amount that has been built on past earthquake cases as well as the estimation method to which the estimation model is applied. In this study, importance is attached to the balance between promptness and precision so that the local governments in a disaster-stricken area will be able to publish the direct damage amount as soon and as accurately as possible in the case of a huge, wide-area earthquake.

2. Relevant Studies and Approach

2.1. Economic Damage by an Earthquake

The economic damage caused by an earthquake is divided into direct and indirect damage amounts. Direct damage includes that of facilities and buildings, and it is related to the total amount of stock possessed by the local community. The direct damage amount grasps the disaster-stricken area as a spatial range and is estimated mainly by using the replacement value of the damaged stock, such as the cost of reconstruction and insured value. In Japan, the financial measures for restoration and reconstruction are determined mainly based on the direct damage amount. Accordingly, it is vitally important from the viewpoint of policies to estimate the direct damage amount as promptly and as precisely as possible.

The indirect damage amount is the total amount of damage including items such as the reduction of economic activities that is followed by a direct damage amount. It is pointed out that the indirect damage amount differs depending on the range of the spatial and temporal influences of the disaster as defined by the researchers so that the estimated values also differ [2]. The direct damage amount is one of the factors leading and closely related to that of the indirect damage. Without reconstruction of the damaged stock, the restoration of the economic activities would also be significantly affected and delayed. Therefore, Taniguchi advocates a disaster prevention plan in which the direct damage amount is estimated in advance and the economic aspect is incorporated [8]. Toyoda researches the relation between the direct and indirect damage amounts by industry and estimates the direct damage amount in the total disaster-stricken area [9]. These previous studies indicate that it would be theoretically possible to estimate the indirect damage amount (influences on flow) of the local economy by using the direct damage one (influences on stock) if the direct damage amount is estimated in the area to be researched. In addition, in this context, attention has been paid to the method by which the direct damage amount is estimated.

2.2. Current Condition and Problems of the Direct Damage Amount Estimation Model

To estimate the direct damage amount there is a method by which to sum up the cost for restoration, replacement value, and payment via damage insurance. In the case that the direct damage amount is estimated based on the actual condition survey conducted by a research group after the disaster's occurrence, a large-scale survey is carried out, an enormous amount of data is collected, and the direct damage amount is estimated. Although these procedures take a long time, precise estimation results can be obtained and the direct damage amount kept on the disaster record at the level of prefecture or municipality. Some local governments that have suffered significant damage have also published detailed breakdowns of the direct damage amounts by item [10]. However, the structure of items may differ depending on the specific earthquake disaster and the affected local government.

The Cabinet Office and some private companies have adopted methods by which to calculate the direct damage amount caused by an earthquake by multiplying the estimated value of stock in the disaster-stricken area by the damage rate [11–13]. The data from past earthquake disasters or the factor indicating the difference between their scales are substituted for the necessary parameters, such as the damage rate, but the scale and range of the earthquake disaster as well as the amount of damage are considered uniformly. This means that the promptness of the estimation is prioritized over its precision immediately after the occurrence of an earthquake. Moreover, the actual condition survey is needed to some degree to set the parameters for the estimation.

Other estimation models are reported that focus on the relation between human and economic damages [14, 15]. Hayashi [15] especially proposes this method for estimating the economic damage in the entire disaster-stricken area promptly in order to use the data as the basis for determining reconstruction finances after the occurrence of a natural disaster. Concretely, the model is proposed to estimate the direct damage amount by using the natural disaster data by prefecture from 1995 to 2009 and setting the human casualties caused by the natural disasters during the 15-year span as the explanatory variable. A result of 44–50 trillion yen was acquired by applying this method to the direct damage amount estimation of the Great East Japan Earthquake. The estimated result is to be verified based on the actual situation in the future, but this method can be evaluated as a prompt one in an emergency because the direct damage amount can be estimated as early as 40 days after the occurrence of a disaster. On the other hand, it is obvious that human and economic damages are dependent on the sort and extent of a disaster. The estimation model using human damage as the explanatory variable does not take factors such as the sort and extent of the disaster into consideration. Therefore, the conditions of application and the method of use of the estimation model remain unclear.

Taniguchi et al. [16] proposes a model by which to estimate the direct damage amount of an earthquake by using the data on the damaging earthquakes that occurred from the 1964 Niigata Earthquake until 1994. Pak et al. [17] proposes a new model by which to estimate the direct damage amount by tsunami by analyzing the difference between the hazard of earthquake and that of tsunami. As for the direct damage amount caused by past earthquake disasters, which is used in the analysis, the economic value is adjusted using the deflator. The deflator in this context means the index indicating the influence of price increase that is calculated based on the GDP of the System of National Account of the Cabinet Office. The above-mentioned studies indicate the possibility of estimating the direct damage amount of a complex disaster by inputting the multiple hazards of earthquake, tsunami, and others based on the database of past damaging earthquakes. However, any of the above models uses the data of the damaging earthquakes before 1995 and does not verify the direct damage amount by adding the new data since 1995. The Great East Japan Earthquake on March 11, 2011 was especially far beyond the expectations of the government and the people in terms of the scale of earthquake and tsunami as well as the range of the disaster-stricken area. Therefore, the model by which to estimate the direct damage amount should be improved by taking a combination of the different characteristics of disasters, such as earthquakes and tsunamis, into consideration.

2.3. Characteristics and Changes in Earthquake Direct Damage Amounts

The cases of the earthquakes with high-ranking direct damage amounts in the past 50 years are characterized by extensive damage around urban areas and high seismic intensity scales. In urban areas, many goods and people are concentrated with a high density. If an earthquake occurs in such an area, the damage is extensive, and its amount becomes larger accordingly. In the case of a huge, wide-area earthquake, the differences in the characteristics of the disaster and the district structure in each local government must also be taken into consideration. If different disaster characteristics, like those of earthquakes and tsunamis, occur complexly, it should be considered that the local damage cannot be simply explained using the same damage rate. For example, in the case of the 1993 Southwest-off Hokkaido Earthquake, the total amount of social stock of Okushiri Town was small, but the town was devastatingly damaged by the disaster compounded by the earthquake, the fire triggered by the tsunami, and the landslide.

To analyze the characteristics and the change in the earthquake direct damage amount since 1995, the 1995 Southern Hyogo Prefecture Earthquake and the 2011 Off the Pacific Coast of Tohoku Earthquake are considered as important damaging earthquakes, among others. In the 1995 Southern Hyogo Prefecture Earthquake, Kobe City, where goods and people are concentrated, was damaged, and the direct damage amount in Hyogo Prefecture is reported to be about 10 trillion yen [10]. The total amount accounts for 13% of the national budget and about 2.5% of the GDP at that time, and it was the maximum postwar direct damage amount at the level of a single prefecture. Many companies went bankrupt, had difficulties resuming their businesses, and withdrew to other prefectures, which provided an opportunity to examine the industrial damage. On March 11, 2011, the Off the Pacific Coast of Tohoku Earthquake occurred with a magnitude of 9.0, the greatest earthquake ever observed in Japan, with its seismic center located off the Sanriku region. The huge tsunami triggered by the earthquake reached a height of 38.9 m at most, hit the coast of the Pacific Ocean in the Tohoku Region, and caused tremendous damage in and around the Iwate, Miyagi, and Fukushima Prefectures. The Japanese government decided to name the earthquake the "Great East Japan Earthquake" in a cabinet meeting, and the damage ranged throughout 21 prefectures, from Hokkaido to Kochi [18]. The scale of the earthquake and tsunami and the extent of the disaster-stricken area of the Great East Japan Earthquake were far beyond the expectations of the government and populace. In considering the resilient restoration of the disaster-stricken area from such a tremendous disaster, it becomes even more difficult to grasp the direct damage amount promptly and precisely.

With diverse changes of the social and economic structures in the future, the characteristics of earthquake damage are also expected to change. Accordingly, it is important that the estimation of the direct damage amount responds to the characteristics of the earthquake disaster. The importance is indicated by the fact that such analysis of an earthquake disaster from the viewpoint of economic damage could lead to mediation between the social scientific and natural scientific studies on disaster prevention [8, 19]. The analysis and review of earthquake disasters in urban areas, a center of politics and economics, from the viewpoint of economic damage would provide important information that will not only guide the recommendations for disaster responses but also those for concrete policies (plans) and investments (budget) for the enhancement of social disaster prevention in the future. Such information could form a basis for concrete measures.

The available database on damaging earthquakes is expected to be enhanced further in the future. In recent earthquakes, the magnitude indicating the characteristics of an earthquake and the source parameters are incorporated into the database so that detailed information is published. This can be understood as a result of the improvement of the strong earthquake observation network and the drastic progress of seismological studies. Moreover, each concerned academic society has conducted detailed disaster investigations after damaging earthquakes, and the direct damage amounts have been increasingly published.

2.4. Simple Estimation Method for Determining the Earthquake Direct Damage Amount Characterized by Promptness

With the progression of the technology for the measurement and observation of earthquakes as well as for

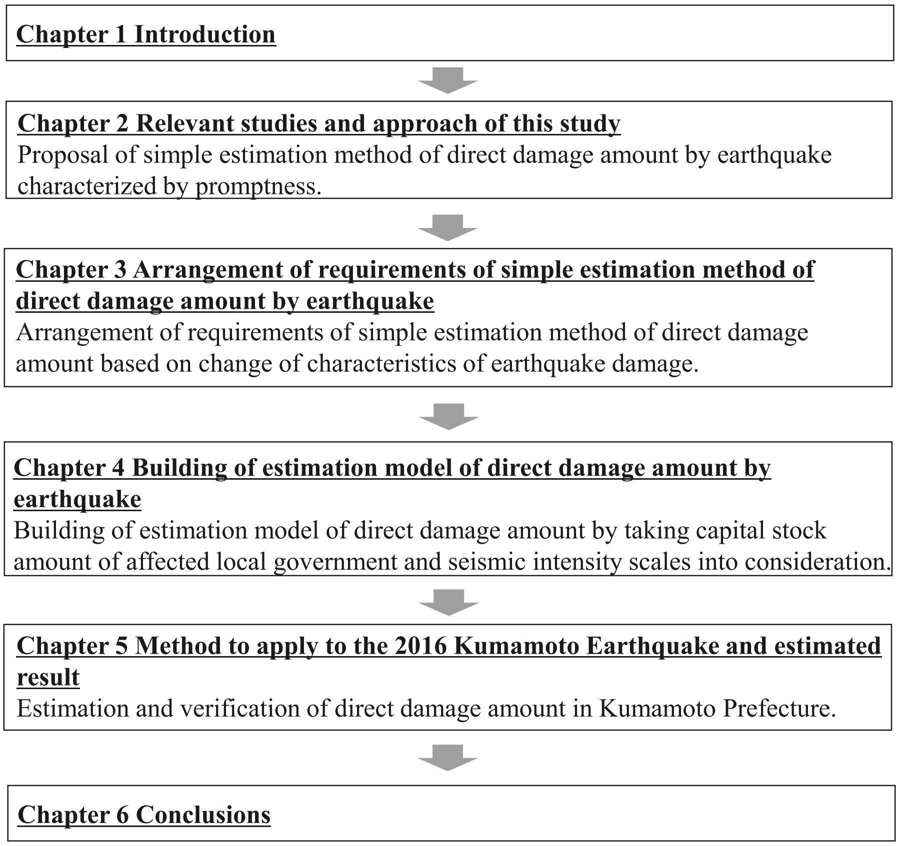

Fig. 1. Framework of this study.

telecommunications, the communication environment for disaster information, such as real-time transmission of the information on instrumental seismic intensity, has been drastically improved. For example, the National Research Institute for Earth Science and Disaster Resilience (referred to as "NIED" hereafter) of the National Research and Development Agency is now developing a Real-Time System for Earthquake Damage Estimation (J-RISQ) [20]. This system is meant to estimate and grasp the damage situation in real time to help decision making during the initial response immediately after the occurrence of a disaster, even if a huge, wide-area earthquake should occur. Moreover, in developing J-RISQ as the technique for seismic hazard evaluation covering all of Japan, the technique for immediate analysis using the seismic network data, the model of the underground structure, the model of the distribution of buildings and population, and the information on the disaster situation have been incorporated into the system. The information on instrumental seismic intensity can be reflected through the strong earthquake observation network covering all of Japan, such as K-NET and KiK-NET, which has been improved by NIED.

Accordingly, we consider that it would be possible to transmit information on the direct damage amount promptly and precisely by using the seismic intensity scales that indicate the characteristics of the disaster for the direct damage amount simple estimation method. Concretely, first, we arrange the damaging earthquakes in the past and examine the possibilities and requirements regarding a new, simple estimation method characterized by promptness. Next, we generate the database on past damaging earthquakes and build the direct damage amount estimation model, which takes the maximum seismic intensity scales recorded in the affected municipalities into consideration, by using multiple regression analysis. We then examine the indications of this estimation model. Finally, we propose the estimation method that can be applied to the characteristics of the earthquake disaster emerging in the 2016 Kumamoto Earthquake and estimate the direct damage amount for Kumamoto Prefecture. The framework of this study is shown in **Fig. 1**.

3. Arrangement of the Requirements for the Earthquake Direct Damage Amount: A Simple Estimation Method

3.1. Arrangement of the Requirements

Responding to the significant differences in the characteristics of earthquake damage, the five points described below are given as the requirements for the direct damage amount simple estimation method. First, the influences on the direct damage amount by the differences in the sort of disaster, such as earthquake or tsunami, are taken into consideration. In this study, in order to remove such differences, the cases that include tsunami influences are excluded in advance during the stage of building the database. Second, the influences on the direct damage amount by the differences in economic scale and the industrial structure of the disaster-stricken area are taken into consideration. Even if there is only a little distance, the damage scale may differ because of the different natural conditions as well as the social and economic structures. In this study, the statistics indicating the capital stock amount at the level of municipality, the minimum unit to be considered today, are used. The details of the statistics are described later. Third, the influences that the different scales of earthquake may have on the direct damage amount are taken into consideration. This study uses the values of capital stock amounts of municipalities aggregated according to the recorded maximum instrumental seismic intensity scales because the statistics cannot be aggregated according to the areas exposed by each instrumental seismic intensity scale and because the records on past damaging earthquakes do not include specific information on the disaster-stricken areas divided according to the seismic intensity scales. Fourth, the earthquake threshold that would trigger a direct damage amount is considered. According to the Table for Explanation on Seismic Intensity Scale [21] published by the Meteorological Agency, damage is generally caused by earthquakes with a seismic intensity of lower 5 or above, regardless of whether the affected building use wooden architecture or reinforced concrete construction and whether the populace uses lifelines or social infrastructures. Therefore, the range to be reviewed in this study is limited to the affected municipalities with a maximum seismic intensity exceeding lower 5 in accordance with this explanation from the Meteorological Agency. Fifth, the influences the damaging earthquake's year of occurrence has on the direct damage amount are taken into consideration. The direct damage amounts published by local governments and others are corrected by the deflator based on the GDP in 2010. The direct damage amount is estimated while taking the above five points into consideration.

Regarding the seismic intensity scale that is used for the estimation of the direct damage amount, it is necessary to consider the correlation between the instrumental seismic intensity defined by the Meteorological Agency and the questionnaire seismic intensity. According to Onaka et al. [22], the relation between them is harmonious in spite of some different tendencies depending on each earthquake, and the differences between them fall within the dispersion range of previous studies. However, such verification has not been reported in the cases of seismic intensities of lower 6 or above. In this study, it is judged that any seismic intensity scale obtained by different methods can be used for the estimation of the earthquake direct damage amounts. However, to secure the promptness of the disaster information, it is desirable to use the instrumental seismic intensity. The seismic intensity scales were revised after the 1995 Southern Hyogo Prefecture Earthquake. In this study, the seismic intensity scales are unified before and after the revision, as shown in **Table 1**, so that the data on earthquake disasters before the revision could also be used.

Table 1. Setting of damage levels.

Damage Level	Seismic intensity scale	
	Until 1995	From 1996
1	Seismic intensity 7	Seismic intensity 7
2	Seismic intensity 6	Seismic intensity upper 6 Seismic intensity lower 6
3	Seismic intensity 5	Seismic intensity upper 5 Seismic intensity lower 5

3.2. Database Used in This Study

In this study, a database of 20 earthquake cases (see **Table 2**) has been built based on the cases of the damaging earthquakes that occurred during the period ranging from the 1964 Niigata Earthquake to 1994, it has been arranged by Pak et al. [17] and Taniguchi et al. [23], and the data of the damaging earthquakes since 1994 has been added [11–13, 18, 24–26]. Whenever an earthquake occurred, the reports were announced by the various research institutes and local governments, but the divisions and items of the aggregate data were not necessarily unified. Moreover, the itemization may differ by the year in which the survey was conducted. The analysis by Pak et al. [17] indicates that the individual direct damage amounts have a basic hierarchical structure (see **Table 3**). In this study, the direct damage amount is collected and arranged on the assumption that the published documents basically have three hierarchies and eight items, even if the breakdown of the hierarchical structure is not published.

To estimate the direct damage amount, this study uses the "National Strength Composite Index" [27]. The National Strength Composite Index indicates the comprehensive strength of the people in the fields of production, consumption, culture, living, etc., in the economic and social activities of each region. Concretely, all kinds of statistical indices are indexed by rate per thousand or rate per hundred thousand according to the prefectures, the areas (each prefecture has three or four areas), the urban areas, and the municipalities to analyze the local structure and grasp the relative positioning of each region. This is a regional statistical database published from 1964 until 2015. Although the National Strength Composite Index includes not only the factors of stock but also those of flow, it was decided that the amount of stock has a certain availability because of its relative rate. Moreover, these data have been prepared for a long time so that they are suitable for analysis using past disaster cases. Accordingly, this study uses the index indicating the composition rate corresponding to each municipality that assumes that the whole country is equivalent to a hundred thousand. The National Strength Composite Index has undergone some changes throughout its publication, namely, a change of administrative district due to municipal mergers since 1997, a change in part of the indices in 2002, and the

Table 2. Building of the database on past damaging earthquakes.

Outlines of earthquake						Earthquake damage in prefecture				Data number used in this study
Number	Earthquake	Date of occurrence	Seismic center	Earthquake focal depth (km)	Magnitude	Prefecture	Maximum seismic intensity	Maximum height of tsunami (m)	Total damage amount (1,000 yen)	
E-1	Niigata Earthquake	1964.6.16	South of Awashima Island, Niigata Prefecture	40	7.5	Niigata Prefecture	5	4.0	130,076,615	-
E-2	The 1968 off Tokachi Earthquake	1968.5.16	Off Sanriku	0	7.9	Aomori Prefecture	5	3.0-5.0	47,039,564	-
E-3	The 1978 off Miyagi Prefecture Earthquake	1978.6.12	Off Miyagi Prefecture	40	7.4	Miyagi Prefecture	5	0.4	268,764,146	D-1
E-4	The 1983 Middle Japan Sea Earthquake	1983.5.26	About 80km western off Noshiro City, Akita Prefecture	14	7.7	Aomori Prefecture	5	10.0	518,114,956	-
E-5	The 1984 Western Nagano Earthquake	1984.9.14	Otaki Village, Kiso County, Nagano Prefecture	2	6.8	Nagano Prefecture	6	-	46,867,585	D-2
E-6	The 1993 off Kushiro Earthquake	1993.1.15	About 20km off Kushiro City, Hokkaido	About107	7.8	Hokkaido	6	-	53,080,964	D-3
E-7	The 1993 Southwest-off Hokkaido Earthquake	1993.7.12	Southwest off Hokkaido	34	7.8	Hokkaido	6	16.8	124,309,894	-
E-8	The 1995 Southern Hyogo Prefecture Earthquake	1995.1.17	Northern part of Awaji Island	16	7.3	Hyogo Prefecture	7	-	9,926,800,000	D-4
E-9	The Northwestern Kagoshima Prefecture Earthquake*	1997.3.26 1997.5.13	Near Akune City, Kagoshima Prefecture Satsuma Region, Kagoshima Prefecture	20 20	6.2 6.1	Kagoshima Prefecture	upper 5 lower 6	-	9,263,608 15,055,616	D-5
E-10	The 2000 Western Tottori Earthquake	2000.10.06	Mountainous region of western Tottori Prefecture	About 10	7.3	Tottori Prefecture	upper 6	-	60,076,487	D-6
						Shimane Prefecture	upper 5		8,853,742	D-7
E-11	The 2001 Geiyo Earthquake	2001.3.24	Akinada, the southern part of Hiroshima Prefecture	46	6.7	Hiroshima Prefecture	lower 6	-	4,738,012	D-8
E-12	The Sanriku South Earthquake *	2003.5.26	Off Miyagi Prefecture	71	7.1	Iwate Prefecture	lower 6	-	11,889,408	D-9
						Miyagi Prefecture	lower 6		5,573,602	D-10
E-13	The Northern Miyagi Prefecture Continuous Earthquake*	2003.7.26	Northern Miyagi Prefecture	about 12	6.4 (Main shock)	Miyagi Prefecture	upper 6	-	64,969,557	D-11
E-14	The 2003 Tokachi-oki Earthquake	2003.9.26	Off Kushiro	42	8	Hokkaido	lower 6	2.6	30,302,000	-
E-15	The 2004 Niigata Prefecture Chuetsu Earthquake	2004.10.23	Chuetsu region, Niigata Prefecture	13	6.8	Niigata Prefecture	7	-	3,000,000,000	D-12
E-16	The 2007 Noto Peninsula Earthquake	2007.3.25	Off Noto Peninsula (about 40 km west-southwest off Wajima City)	11	6.9	Ishikawa Prefecture	upper 6	0.2	348,220,000	D-13
E-17	The 2007 Niigataken Chuetsu-oki Earthquake	2007.7.16	Off Joetsu and Chuetsu regions, Niigata Prefecture	17	6.8	Niigata Prefecture	upper 6	0.2-0.3	1,500,000,000	D-14
E-18	The 2008 Iwate-Miyagi Nairiku Earthquake	2008.6.14	Southern inland Iwate Prefecture	8	7.2	Iwate Prefecture	upper 6	-	29,441,560	D-15
					7.2	Miyagi Prefecture	upper 6		119,898,750	D-16
					7.2	Akita Prefecture	upper 5		2,640,972	D-17
E-19	The 2011 off the Pacific coast Tohoku Earthquake (The Great East Japan Earthquake)	2011.3.11	Off Sanriku region	24	9	Aomori Prefecture	upper 5	4.2	133,700,000	-
						Iwate Prefecture	lower 6	8.0	4,276,000,000	-
						Miyagi Prefecture	7	8.6	6,492,000,000	-
						Akita Prefecture	upper 5	-	-	-
						Yamagata Prefecture	upper 5	-	-	-
						Fukushima Prefecture	upper 6	9.3	3,129,000,000	-
						Ibaragi Prefecture	upper 6	4.0	2,476,000,000	-
						Tochigi Prefecture	upper 6	-	660,900,000	D-18
						Gunma Prefecture	lower 6	-	-	-
						Saitama Prefecture	lower 6	-	-	-
						Chiba Prefecture	lower 6	3.0	438,900.00	-
						Tokyo Metropolis	upper 5	-	-	-
						Niigata Prefecture	lower 5	-	28,500,000	D-19
						Nagano Prefecture	lower 5	-	16,700,000	D-20

*Case that does not fall into the category of damaging earthquake

Table 3. Breakdown of the direct damage amount.

Hierarchical structure of direct damage amount			Contents
Hierarchy 1	Hierarchy 2	Hierarchy 3	
Direct damage amount	Building	Building	Housing, Non-housing, Prefectural housing and public housing
	Social infrastructures	Damage of urban facilities	Other civil engineering facilities than distribution related facilities such as erosion control, sea shore and park
		Damage of distribution related facilities	Road, bridge, railway, port, fishing port, airport and station etc.
		Damage of lifeline	Power, water and sewer services, gas and telecommunications
		Damage of medical and health facilities	Medical and health facilities
		Others	Other damage than the above
	Industries	Damage of agriculture, forestry and fisheries	Agriculture, forestry and fisheries including the related facilities
		Damage of commerce and industry	Industry, commerce and tourism including the related facilities

addition of a new item, "Living Index," in 2007. To avoid discontinuity with the data at and before the year of the rearrangement, the data after 2007 are used. To respond to the municipal mergers, the data on the National Strength Composite Index are processed based on the boundaries of the municipalities after the mergers.

4. Building the Estimation Model of the Earthquake Direct Damage Amount

4.1. Estimation Model of the Direct Damage Amount

The direct damage amount Yei,k,t in the area of i in the damage level of k at the time of t is expressed by the product of the hazard particular to the area and the vulnerability as shown in Eq. (1). Concretely, the direct damage amount is equal to the product of the strength of the impact of the hazard, such as seismic motion (maximum acceleration and seismic intensity), tsunami (maximum wave height and inundation area), and the risk of a secondary disaster, N; the vulnerability is determined by the quality and quantity of the capital stock, the degree of accumulation, industrial structure, etc., Sei,k.

$$\mathrm{Yei,k,t} = \sum(\mathrm{N} \times \mathrm{Sei,k}). \quad (1)$$

It is supposed in this study that the affected municipality of the affected prefecture can be explained by the sum of the National Strength Composite Index aggregated in three levels designated as Damage Level 1, Damage Level 2, and Damage Level 3. Then, the direct damage amount within a prefectural territory can be expressed by Eq. (2).

$$\mathrm{Ye} = a + b1 \times \Sigma\mathrm{Se1} + b2 \times \Sigma\mathrm{Se2} + b3 \times \Sigma\mathrm{Se3}. \quad (2)$$

In the above equation, Ye is the direct damage amount caused by an earthquake, a is the constant term, ΣSe1 is the aggregate value of the National Strength Composite Index in the affected municipality (Damage Level 1), $b1$ is a coefficient of ΣSe1, ΣSe2 is the aggregate value of the National Strength Composite Index in the affected municipality (Damage Level 2), $b2$ is a coefficient of ΣSe2, ΣSe3 is the aggregate value of the National Strength Composite Index in the affected municipality (Damage Level 3), and $b3$ is a coefficient of ΣSe3.

4.2. Building the Estimation Model by Using Multiple Regression Analysis

To estimate Eq. (2), multiple regression analysis is performed setting Ye as the objective variable and ΣSe1, ΣSe2, and ΣSe3 as the explanatory variables. First, only damaging earthquakes are extracted, and the damage situations of the prefectures affected by each earthquake are summarized in **Table 4**.

To propose an earthquake direct damage amount estimation model, all combinations of the explanatory variables are examined by multiple regression analysis using the above dataset. Each statistic is shown in **Table 5**. It is shown that any result of the statistics indicating the performance of the model, RMSE, AIC, and Cp, supports the model setting ΣSe1 and ΣSe2 as explanatory variables.

The leverage rate plots with the objective variable of Ye and the explanatory variables of ΣSe1, ΣSe2, and ΣSe3 are shown in **Figs. 2**, **3**, and **4**, respectively. The leverage rate is the amount of change of the estimated value in varying the value of the objective variable by 1 unit while the explanatory variable remains unchanged. The leverage rate plot graphs the testing that is applied to a general lineal hypothesis. The estimated effect when using the particular variable can be evaluated by the positional relation between the 95% confidence curve of the regression line and the horizontal line of the mean value. Concretely, the graphs confirm whether the confidence curve of the regression line and the horizontal line cross. In the case of

Table 4. Datasheet used for multiple regression analysis.

Number of data	Aggregate value of the National Strength Composite Index in the municipalities [rate per hundred thousand]			Direct damage amount [thousand yen] *The value as of 2011
	ΣSe1	ΣSe2	ΣSe3	
D-1	0.0	0.0	270.6	296,978,820
D-2	0.0	4.2	0.0	44,418,148
D-3	0.0	122.5	135.6	44,737,117
D-4	1,300.6	44.0	77.2	8,447,411,379
D-5	0.0	113.5	92.6	20,593,353
D-6	0.0	183.1	123.4	52,418,892
D-7	0.0	0.0	339.8	7,725,208
D-8	0.0	201.2	1,642.2	4,192,431
D-9	0.0	269.6	745.1	10,876,829
D-10	0.0	208.5	837.8	5,098,918
D-11	0.0	336.4	257.4	59,436,328
D-12	241.3	151.4	647.0	2,780,838,156
D-13	0.0	198.9	106.7	334,042,887
D-14	0.0	565.5	424.9	1,438,930,363
D-15	0.0	117.5	231.8	28,503,762
D-16	0.0	169.3	956.2	116,079,632
D-17	0.0	0.0	266.9	2,556,849
D-18	0.0	764.6	820.1	674,175,730
D-19	0.0	0.0	56.7	29,072,490
D-20	0.0	0.0	88.6	17,035,459

ΣSe1 and ΣSe2, the confidence curve crosses the horizontal line, which indicates that the effectiveness of the variable is significant. On the other hand, in the case of ΣSe3, the horizontal line is located within the confidence region, which indicates that the effectiveness of the variable is not significant. This means that if three explanatory variables are used, ΣSe3 does not affect the estimation of the objective variable of Ye.

Accordingly, the following result of the multiple regression analysis, which sets ΣSe1 and ΣSe2 as explanatory variables, is regarded as the estimation model of Ye in this study.

$$\text{Ye} = 4194039 + 6592169 \times \Sigma\text{Se1} + 1206871 \times \Sigma\text{Se2}. \quad (3)$$

In the above equation, Ye is the earthquake direct damage amount (1,000 yen), ΣSe1 is the aggregate value of the National Strength Composite Index in the affected municipality (Damage Level 1), and ΣSe2 is the aggregate value of the National Strength Composite Index in the affected municipality (Damage Level 2).

The plot of the estimated value of Ye found by Eq. (3) and the actual value of Ye is shown in **Fig. 5**. The plot of the estimated value of Ye and the residual is shown in **Fig. 6**. The residual is the estimated value of error and is identified by the difference between the estimated and actual values. Generally, it is used to evaluate regression equations. The relatively large earthquakes that this study analyzes do not occur frequently, so that there is not enough data for an adequate evaluation. In this study, the

Table 5. Statistics of each model of multiple regression analysis.

Model	Number of variable[s]	R-squared value	RMSE	AIC	Cp
Se1, Se2, Se3	3	0.9696	3.68E+08	855.570	4.0000
Se1, Se2	2	0.9693	3.59E+08	852.175	2.1800
Se1, Se3	2	0.9552	4.34E+08	859.693	9.5634
Se2, Se3	2	0.0166	2.03E+09	921.487	503.6921
Se1	1	0.9544	4.26E+08	856.904	8.0118
Se2	1	0.0162	1.98E+09	918.328	501.8983
Se3	1	0.0010	1.99E+09	918.634	509.8738

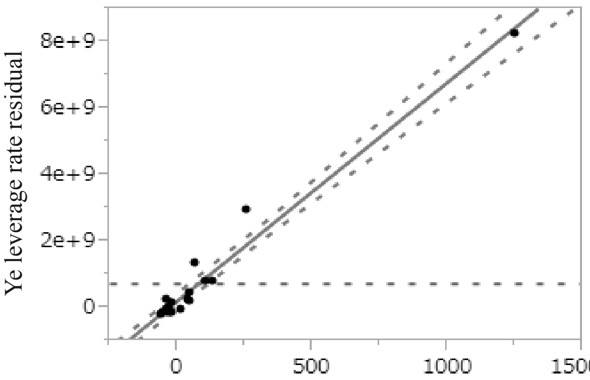

Fig. 2. Leverage rate plot with objective variable of Ye and explanatory variable of ΣSe1.

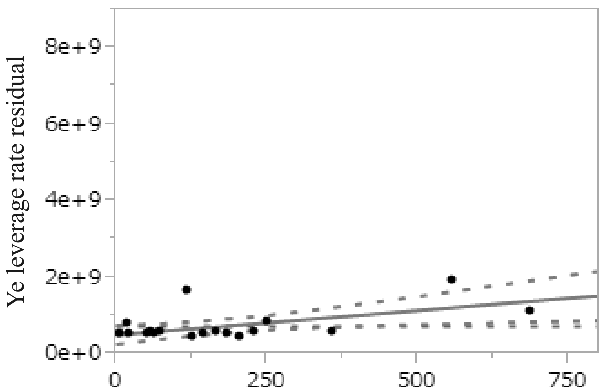

Fig. 3. Leverage rate plot with objective variable of Ye and explanatory variable of ΣSe2.

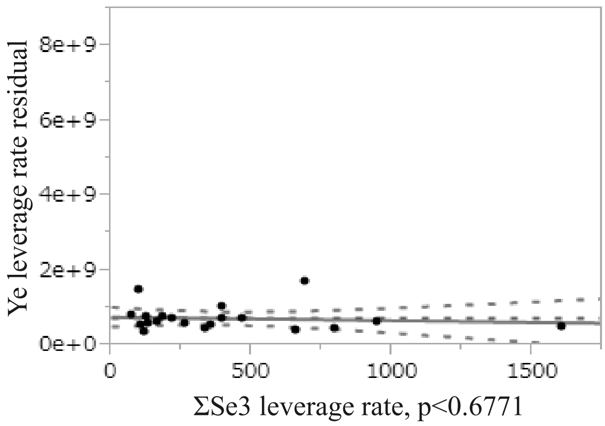

Fig. 4. Leverage rate plot with objective variable of Ye and explanatory variable of ΣSe3.

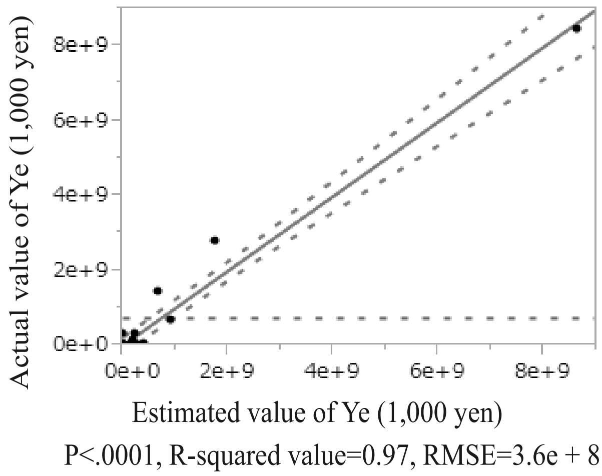

Fig. 5. Plot of the estimated and actual values of Ye.

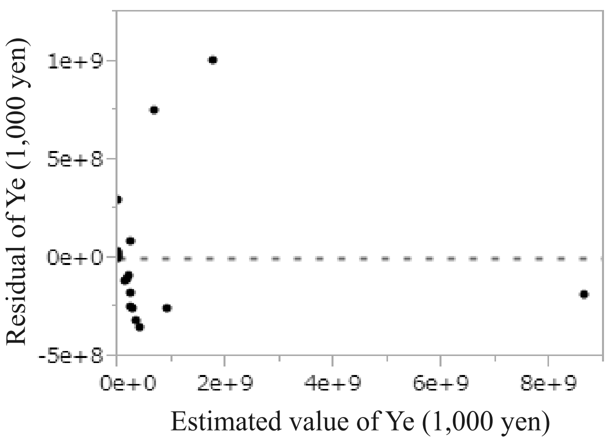

Fig. 6. Plot of the estimated value of Ye and the residual.

data show the size of the residual that exists between the estimated and actual values.

4.3. Review of the Earthquake Direct Damage Amount Estimation Model

The indications of the estimation model obtained by the multiple regression analysis are reviewed as follows. From Eq. (3), it can be seen that the damage amount per unit of ΣSe1 is equal to 6.59 billion yen and that per unit of ΣSe2 is equal to 1.21 billion yen. The variation of ΣSe3 is not considered to affect the direct damage amount. Accordingly, in the case of only Damage Level 3, without considering Damage Level 1 and Damage Level 2, the direct damage amount is equal to the constant term in Eq. (3). That is to say, if Damage Level 3 (seismic intensity of lower or upper 5) is recorded, the direct damage amount is built up from 4.19 billion yen as a base. In the case of a municipality with Damage Level 2 (seismic intensity of lower or upper 6), 1.21 billion yen is added per unit of the National Strength Composite Index. In the case of a municipality with Damage Level 1 (seismic intensity 7), 6.59 billion yen is added per unit of the National Strength Composite Index. Thus, based on the result of the multiple regression analysis and on the condition that a seismic intensity scale of 5 or above is recorded, it is thought that the model could be applied to the estimation of the direct damage amount of an earthquake. However, in applying it to earthquakes of Damage Level 3 (seismic intensity of lower or upper 5), careful examination would be required using the published data on direct damage amounts not within prefectural territories but within municipal ones.

The review of the estimation model for earthquake direct damage amounts, Ye, is summarized by the following five points. First, because the cases are limited to the earthquakes that were not influenced by tsunamis in this study, the number of records in the dataset become fewer. Second, the maximum instrumental seismic intensity in a municipality is used as a unit of measurement in the analysis in this study. Influences from the different seismic intensity scales in the divided areas of a municipality should also be analyzed hereafter. Third, the factors that influence the direct damage amount are limited to seismic intensity scales in this study. However, other disasters triggered by earthquakes, such as tsunamis, landslide disasters, and liquefaction, as well as the local disaster prevention, should be considered comprehensively hereafter. It is especially important to establish a method by which to estimate the direct damage amount assuming a complex disaster, like an earthquake and tsunami. Fourth, the capital stock amount is evaluated by using the National Strength Composite Index in this study, but the long-term data on the capital stock amount should be generated at the local government level or an even more subdivided level hereafter. Fifth, the statistic per municipality unit in the National Strength Composite Index is the smallest one, and there is no equivalence in some foreign countries. Therefore, it is difficult to set the range to be examined to be more flexible and applicable to the cases to be examined in foreign countries, which should be improved hereafter.

5. Method of Application to the 2016 Kumamoto Earthquake and Estimated Result

5.1. Method of Application to the 2016 Kumamoto Earthquake

The Meteorological Agency named the earthquake that occurred at 21:26 on April 14, 2016 the "2016 Kumamoto Earthquake." On April 16, an even larger earthquake occurred. The Meteorological Agency issued a statement on the series of earthquakes including the aftershocks that said it "considers them as the Kumamoto Earthquake and the seismic activities following it" and that it would not change the name of the earthquake. On April 21, the Meteorological Agency issued the statement that the "2016 Kumamoto Earthquake" indicates "a series of seismic activities which occurred around Kumamoto Prefecture since 21:26 on April 14" [24]. The Kumamoto Earthquake recorded a seismic intensity of 7 at both the foreshock and main shock and is characterized by a continuous occurrence of strong shocks [28].

In determining how to apply the model to the 2016 Kumamoto Earthquake, it is necessary to take the characteristics of the earthquake into consideration. Because the design standards of the structures do not essentially consider multiple strong motions, it is thought that direct damage would be caused whenever a strong aftershock occurs. However, in the case that the individual events are not independent, it is not clear how multiple strong motions could affect the structures. In addition, as the number of strong motions increases, a structure that endured the first shock of the earthquake could shift into a hazardous condition. In this study, whenever the foreshock, main shock, and aftershock exceeding a seismic intensity of lower 5 (see **Table 6**), the direct damage amount is estimated based on the seismic intensity scales without taking the mutual interference of the damages caused by the foreshock, main shock, and aftershock into consideration. The accumulated value that is found by adding up the direct damage amounts estimated separately is regarded as the estimated value of the direct damage amount in the prefecture.

5.2. Estimated Result of the 2016 Kumamoto Earthquake

Based on the above review, the proposed estimation model for the direct damage amount is applied to Kumamoto Prefecture, the area stricken by the 2016 Kumamoto Earthquake. However, in this trial calculation the application is limited to the foreshock on April 14 and the main shock on April 16 with a seismic intensity of 7, in which the seismic intensity scales could be recorded according to the affected municipalities. The results of the estimation model based on the Disaster Levels in Kumamoto Prefecture are summarized in **Table 7**. The coefficients in the table are adjusted to the unit of estimated value, that is, 100 million. Assuming that the whole country is equivalent to a hundred thousand, the National Strength Composite Index of Kumamoto Prefecture is 1,569. The direct damage amount in Kumamoto Prefecture caused by the foreshock on April 14 is estimated to be about 0.9 trillion yen. That caused by the main shock on April 16 is estimated to be about 1.6 trillion yen. The sum is estimated to be about 2.5 trillion yen. However, the final estimated value is expected to be higher because the aftershocks and other shocks with seismic intensities of upper 6 or below are not yet included in the estimation, as shown in **Table 6**. For reference, the estimation by the Cabinet Office amounts to about 2.4–4.6 trillion yen [29]. In addition, Kumamoto Prefecture announced publicly that the direct damage amount caused by the 2016 Kumamoto Earthquake is 3.785 trillion yen as of September 28, 2016 [30]. The data reported on the 2016 Kumamoto Earthquake are provisional values and need to be verified again later.

Table 6. Foreshock, main shock, and aftershock exceeding a seismic intensity of lower 5 (The 2016 Kumamoto Earthquake).

Period of time	Number according to the maximum seismic intensities					Total
	Damage Level 1	Damage Level 2		Damage Level 3		
	7	Upper 6	Lower 6	Upper 5	Lower 5	
14.April 21–24	1		1		2	4
15.April 00–24		1		1	1	3
16.April 00–24	1	1	2	1	6	11
18.April 00–24				1		1
19.April 00–24				1	1	2
29.April 00–24				1		1

6. Conclusions

This study proposes a simple estimation method for promptly determining the direct damage amount of an earthquake. For this purpose, the database of past damaging earthquakes is built, an estimation model for the direct damage amount is built by using multiple regression analysis taking the seismic intensity scales of the affected municipalities into consideration, and the indications of this model are reviewed. The estimation method is proposed to adjust to the characteristics of an earthquake disaster, which emerged in the 2016 Kumamoto Earthquake, and the direct damage amount is estimated for Kumamoto Prefecture. The following knowledge is obtained.

1) An estimation model taking the local economic situ-

Table 7. Results of the estimation of the direct damage amount.

Earthquake	Municipalities of Kumamoto Prefecture according to the maximum seismic intensities (the National Strength Composite Index)			Ye (100 million Yen)
	ΣSe1	ΣSe2		
	7	Upper 6	Lower 6	
Foreshock on 14. April	Mashiki Town (21.6)		Tamana City (58.7) Nishihara Village (4.5) Uki City (56.6) Kumamoto City (503.8)	9,004.9
	Total: 21.6	Total: 623.1		
Main shock on 16. April	Nishihara Village (4.5) Mashiki Town (21.6)	Minami-aso Village (8.1) Kikuchi City (43.7) Udo City (29.2) Otsu Town (34.7) Kashima Town (9.9) Uki City (56.6) Koushi City (43.4) Kumamoto City (503.8)	Aso City (30.6) Yatsushiro City (113.8) Tamana City (58.7) Kikuyo Town (29.3) Mifune Town (16.2) Misato Town (10) Yamato Town (18.1) Hikawa Town (10.9) Nagomi Town (21.1) Kami-amakusa City (35.7) Amakusa City (123.1)	16,238.3
	Total: 26.1	Total: 1,196.4		

ation and the seismic intensity into consideration is proposed. The proposed estimation model can be applied to seismic intensities of lower 5 or above. Operating with the earthquake information in real time, it is possible to transmit the estimated results immediately after the occurrence of a disaster.

2) Reviewing the results of the estimation of the direct damage amount obtained from multiple regression analysis, it is found that if Damage Level 3 (seismic intensity of lower 5 or upper 5) is recorded, the direct damage amount is built up from 4.19 billion yen as a base. In the case of municipalities with Damage Level 2 (seismic intensity lower 6 or upper 6), 1.21 billion yen is added per unit of the National Strength Composite Index. In the case of the municipality with Damage Level 1 (seismic intensity 7), 6.59 billion yen is added per unit of the National Strength Composite Index.

3) As a result of the application of the model to the 2016 Kumamoto Earthquake, the value of the direct estimation amount of Kumamoto Prefecture is estimated to be about 2.5 trillion yen, taking only the foreshock and the main shock with a seismic intensity of 7 into consideration.

Hereafter, we will continue to verify the proposed simple evaluation method using the data on the instrumental seismic intensity of the 2016 Kumamoto Earthquake, which is expected to be published individually. We will research the influences of other hazards, improve the economic stock value that indicates the local characteristics, and review the indirect damage account and the ripple effect on each industry, which cannot be treated by this study.

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