Evaluating the Probability of Building Damage and Human Casualty Based on Actual Damage due to 2011 Tohoku Tsunami

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Abstract

When large-scale disasters occur, it is important to understand the overall damage assessment for an effective rescue attempt and other early responses. During the 2011 Great East Japan tsunami, it was reported that the damage assessment was difficult because the communication was cut off or the government buildings were greatly affected. To focus on lifesaving activity just after the large disaster, estimating the damage situation enables to understand damage overview at earlier stage and also leads to more efficient lifesaving activity.

The tsunami fragility functions for building have been widely developed using building damage data which was collected extensive area. However, these fragility functions could not be properly used for damage prediction of every building having different structural materials or physical conditions. In this study, prediction formulas of building damage were developed by utilizing approximately 130,000 non-aggregated building damage data caused by the 2011 Great East Japan earthquake and tsunami disaster. These relational expressions include building structural materials, numbers of floors, floor area, land use type and inundation depth of every single building. The proposed relational expressions can estimate probability of each building for being washed away by the tsunami for different building conditions.

Previous analysis of human casualty has been using data that added up by city scale. However, the analysis of these scales can't capture the casualty characteristics that vary even by small administrative areas. The actual human casualty and building damage data used for our analysis were added up by districts scale. Proposing method to estimate human casualty is using building damage prediction formulas proposed in the previous section. The ratio of actual casualty and population processed by district scale is defined as a damage characteristic coefficient which can explain the characteristics of the districts using logarithmic normal distribution. Two damage characteristic coefficients based on actual damage in ria coast area and Sendai plain area were then proposed. The new method was applied to estimate the human casualty in two different coastal topography areas namely Kamaishi city and Sendai city in case of the 2011 tsunami and verified by comparing the estimated number of casualties with the actual number of casualties.

We apply this method to Ishinomaki city which suffered most intense damage during 2011 tsunami. Tsunami numerical simulation gave simulated maximum inundation depth which was used to estimate building washed away probability and human casualty. The proposed method can explain the trend of actual building damage with 85% accuracy and human casualty with 67% accuracy. The new model has benefit of broader application and estimates the damage amount with a range of uncertainty. However, it was revealed that estimation results were strongly influenced by the tsunami numerical simulation accuracy which have to be carefully considered when applying to future tsunamis.

Keywords: 2011 Tohoku Tsunami, Building damage, Human casualty, Damage estimation

1. Introduction

The 2011 Great East Japan earthquake and Tsunami caused extensive damage over the wide area. It's important to understand the overall damage assessment for an effective rescue attempt and other early responses. During the 2011 Great East Japan tsunami, it was reported that the damage assessment was difficult because the communication was cut off or the government buildings were greatly affected. Therefore, previous studies [1] promoted to use remote sensing or satellite image for searching damage information of disaster. To focus on lifesaving activity just after the large disaster, estimating the damage enables to understand damage overview at earlier stage and also leads to more efficient lifesaving activity.

However, there is still no such method that is applicable to various areas because the estimation is strongly influenced by characteristics of the original data. Previous sutdy[2-3] use added up damage data but Tani (2012) [4] showed that analyzeing the tsunami damage in fine scale is important to grasp the characteristics of damage which completely different for each small reagion. After the 2011 Tohoku Tsunami human casualty and building damage data was collected over the wide area and arranged by a fine spatial scale as small as district level. In this study, approximately 130,000 non-aggregated building damage data caused by the 2011 Great East Japan earthquake and tsunami disaster was used to develop estimation formulas of building damage. In addition, Hasegawa et al. (2016) [5] showed that human casualty and building damage have correlation under the specific condition. Therefore, building damage prediction formula is applicable to estimate human casualty. The proposed method to estimate human casualty define the ratio of actual casualty and population processed by district scale as a damage characteristic coefficient which can explain the characteristics of the districts using logarithmic normal distribution. Estimating the human casualty using this coefficient of various towns enables us to examine the amount of damage in various scenarios.

2. Building damage estimation

2.1 Data collection

The data analysis in this study were based on the data collected by "the Tohoku Earthquake Tsunami Joint Survey Group (2011)" [6] and MLIT provide it in the website. The research group surveyed the damage to buildings caused by the 2011 Tsunami in detail for each building and collected the human damage for each town.

These data were added up by very fine scale as small as town or district scale. As for the damage caused by the tsunami different for each district, using such data to capture disaster is important to understand characteristics of damage. Non-aggregate data is useful to grasp characteristics of damage due to tsunami which commonly different from each small district [4]. In this analysis, we focused on the Damage level, structural types, number of floors, use of the building (housing or others), building area and actual inundation depth of each building.

The data used for the analysis were 135,660 buildings with no data loss among the buildings in the 33 disaster-stricken municipalities as shown in Table 1.

Table 1 – Study areas.

Aomori	Hasikami, Hachinohe
Iwate	Hirono (Iwate), Kuji, Noda, Tanohata, Iwaizumi, Miyako, Yamada, Ohtsuchi, Kamaishi, Ofunato, Rikuzentakata
Miyagi	Kesennuma, Minami-Sanriku, Onagawa, Ishinomaki, Higashi-Matsushima, Matsushima, Rifu, Shiogama, Shichigahama, Tagajo, Sendai, Natori, Iwanuma, Watari, Yamamoto
Fukushima	Shinchi, Soma, Minami-Soma, Hirono (Fukushima), Iwaki

In the archives, the building damage level was classified in six categories [7] as shown in the Fig. 1: (1) minor damage, (2) moderate damage, (3) major damage, (4) complete damage, (5) collapsed and (6) washed away. In this analysis, we define Collapsed and Washed away as Destroyed, and the others as Survived.

Descriptive statistics of data are shown in billow Table 2 to table 5.

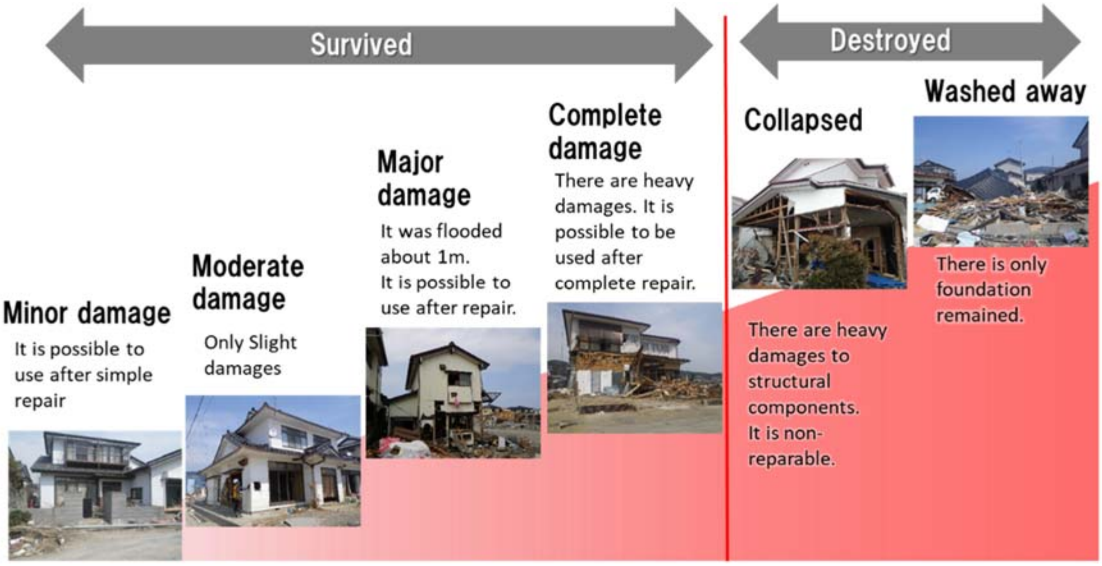

Fig. 1 – Damage levels by MLIT and definition of destroy in this study.

Table 2 – Descriptive statistics of structural material.

Structural material	*N*	Percent	Cumulative percent
Reinforced concrete	4632	3.4	3.4
Steel	9667	7.1	10.5
Wood	121366	89.5	100.0
Total	135,665	100.0	

Table 3 – Descriptive statistics of damage level.

Damage level	*N*	Percent	Cumulative percent
Washed away	43,929	32.4	32.4
Collapsed	17,523	12.9	45.3
Complete damage	7,646	5.6	50.9
Major damage	23,082	17.0	67.9
Moderate damage	25,436	18.7	86.7
Minor damage	13,414	9.9	96.6
No damage	4,635	3.4	100.0
Total	135,665	100.0	

Table 4 – Descriptive statistics of stories, inundation depth and building area.

	N	Min	Max	Mean	SD
Number of stories	135,665	1	14	1.662	0.595
Inundation depth (m)	135,665	0	27	3.748	3.948
Building area (m^2)	135,665	0.681	46,492	154.2	461.8

2.2 Estimation of building damage

In this study, the analysis is carried out using the generalized linear model according to the binomial distribution function. A regression equation to predict the probability of building loss was constructed using a generalized linear model. Logistic regression analysis is expressed by the following Eq. (1).

$$p = \frac{1}{1+\exp(-a_0 - a_1 x_1 - a_2 x_2 - \cdots)} \tag{1}$$

Where p is building damage probability, x_n is explanatory variable and a_n is partial regression coefficient of each explanatory variable. The partial regression coefficient is calculated by the maximum likelihood estimation. Variables were selected using stepwise forward selection method and that AIC prediction accuracy was highest when estimating with all variables: structure, number of stories, functions, inundation depth and building area. The maximum likelihood estimates calculated by the analysis are shown in the Table 5. It was found that the inundation depth and structure strongly affect the results.

Fig. 2 show the actual building damage and estimated damage probability by the proposing model for Ishinomaki City. Estimate was based on the 2011 actual damage data and estimated damage probability were classified 0.5 or more as destroyed and less than 0.5 as survived and compared with actual damage (destroyed or survived). It was found that the prediction by the model can reproduce the actual building damage with 86.4% of collect. From the fig. 2, the borderline of destroyed and survived was almost reproduced. This prediction formulas of building damage include only structural factors about every building and does not rely on geometric or human factors, it may be possible to apply other areas for example Nankai area in the west of Japan.

Table 5 – Maximum likelihood estimates.

	Estimate	Sd. Error	Z value	Pr (>|z|)	
Intercept	-3.925	0.0514	-76.43	< 2e-16	***
RC	-1.797	0.0814	-22.08	< 2e-16	***
W	1.412	0.0440	32.11	< 2e-16	***
Num. of stories	-0.4242	0.0164	-25.85	< 2e-16	***
Functions (housing)	0.2272	0.0277	8.205	2.31E-16	***
Inundation depth	1.053	0.0060	174.1	< 2e-16	***
Building area	-0.0003	0.0000	-7.1890	6.53E-13	***

Signif. Codes: 0 ’***’ 0.0001 ’**’ 0.01 ’*’ 0.05 ’.’ 0.1 ’’ 1

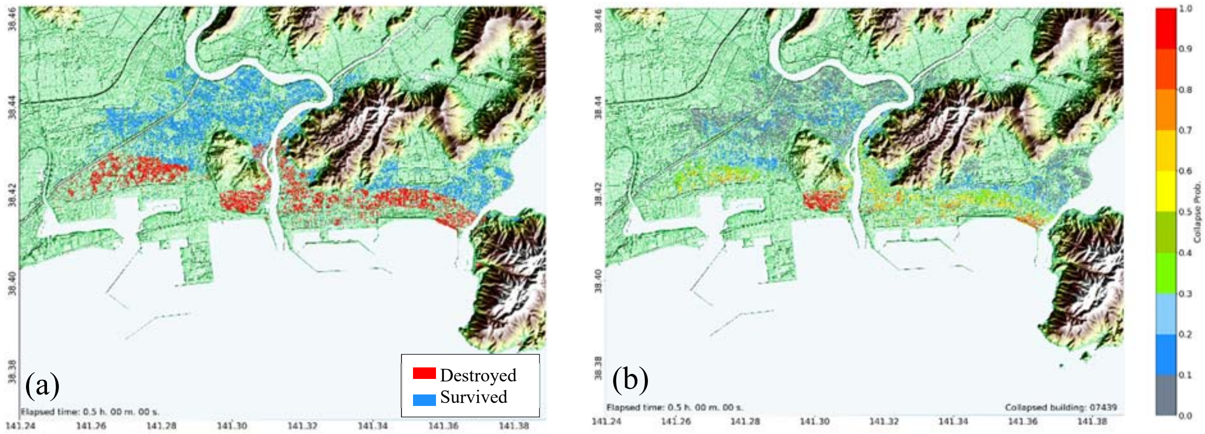

Fig. 2 – (a) Actual building damage and (b) reproduced building damage probability in Ishinomaki.

3. Estimation of human casualty

3.1 Proposing damage characteristic coefficient

Previous study [5] showed that when evacuation actions are not taken adequately, there is a correlation between human fatality and building damage. As well as this study, proposed estimation method of human fatality is based on building damage probability. Then, in order to consider the uncertainty affecting human casualty for example evacuation behaviour or experience of disaster, the result of estimation is shown with a range.

The concept of human casualty due to tsunami considered in this study is shown in the Fig. 3. When a tsunami hits an area, it is not all the population in the town but the population within the inundated area that is directly affected by the tsunami. In this study, people who were in the flooded area were defined as “inundation area population” (green area of Fig. 3). The amount of inundation area population relays on the scale of hazard and exposure. The actual number of casualty (black area of Fig.3) is usually less than the inundation area population. This reduction is mainly because of the evacuation behaviour. In addition, other variously influencing factors, for example, aging rate of the region, disaster education, distance to the refuge place, and more. These factors can be regarded as “vulnerability” of an area, and it have influence to the fatality ratio. But, it is almost impossible to evaluate the influence of each of these various damage reduction factors.

In this study, the ratio of the actual number of victims to the inundation area population is defined as the “damage characteristic coefficient” which is macroscopic variable that summarizes these human damage reduction factors. If the residents evacuate adequately, the damage characteristic coefficient of the town will be small, but if they do not evacuate adequately, the coefficient will be large. That is, the vulnerability of each town can be assessed by examining this coefficient for past disasters. And estimating the damage caused by future disasters using this coefficient of various towns enables us to examine the amount of damage in various scenarios.

Fig.3 Conceptual scheme of damage characteristic coefficient.

3.2 Calculating damage characteristic coefficient

Damage characteristic coefficient is defined as Eq. (2).

$$C = \frac{F_A}{P \times P_D} \quad (2)$$

Where, C is damage characteristic coefficient, P is town population (ppl.), and P_D is Building damage ratio (%) which defined the equation proposed by Hatori (1984) [8] shown in Eq. (3).

$$P_D\ (\%) = \frac{a+b/2}{a+b+c} \quad (3)$$

Where, a is number of washed away or complete collapsed buildings (washed away, collapsed, and complete damage in Fig. 1), b is number of partial collapsed buildings (major damage in Fig. 1), and c is number of less than partial collapsed buildings (moderate damage and minor damage in Fig. 1).

In this study, the building damage ratio is regarded as the magnitude of tsunami hazard. By using the building damage ratio instead of the inundation depth, it is possible to take into consideration the cases in which people in the inundated area survive because they are in high buildings. Correlation of building damage rate and inundation depth was shown in previous study [5].

Population P was calculated from the estimated building area, not using the statistical population. The advantage of this method is that when estimating the damage caused by future disasters, it is possible to estimate the damage even in areas where the population is not clear. The population and building area data of MLIT were added up and arranged for each district, and the regression equation was constructed by the least squares method. Using this regression equation, the population was estimated from the building area.

Human casualty data used to calculate damage characteristic coefficient was MLIT's data [6]. The target areas were 12 disaster-stricken cities (Miyako, Yamada, Kamaishi, Otsuchi, Ofunato, Kesennuma, Ishinomaki, Shichigahama, Sendai, Natori, Iwanuma and Watari). Building damage data of the archives were not aggregated. Therefore, it was added up for each district as well as human casualty data. To avoid characteristics of the specific city strongly influences the estimation results, the data was collected over the wide area and collected for each small district to identify the characteristics of damage due to tsunami.

The calculated damage characteristic coefficient is shown in the histogram of Fig. 4, red one is Ria coast and blue one is Sendai plain. Descriptive statistics of damage characteristic coefficient are shown in table 6. Estimated approximate curve of histograms are shown in Fig. 4, red line is Ria coast and blue one is Sendai plain. It was found that distribution of damage characteristic coefficient can describe by the logarithmic normal distribution.

When estimating future damage probability, damage characteristic coefficient is obtained as random numbers according to this parameter distribution and apply to the human casualty estimation. This way can consider human damage under various scenarios and allows for a wide range of estimates.

Table 6 – Descriptive statistics of Damage characteristic.

	N	Mean	SD
Ria coast	421	0.051	0.258
Sendai plain	158	0.199	1.181

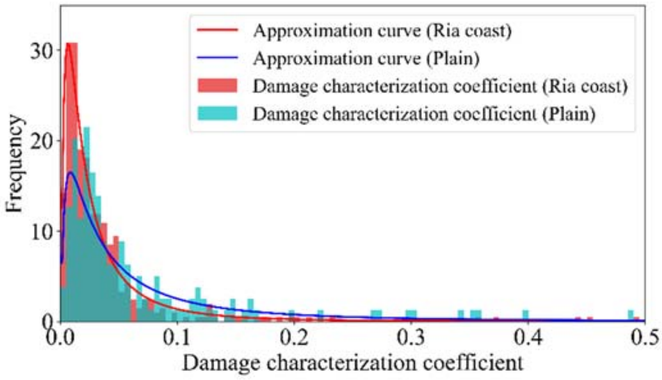

Fig.4 Damage characteristic coefficient.

3.3 Estimation of human casualty using damage characteristic coefficient

A human fatality estimation method using the coefficient is proposed in Eq. (4).

$$F_E = P \times P_D \times C \tag{4}$$

Where, F_E is estimated human fatality(ppl.), P is estimated population (ppl.), P_D is building damage ratio, and C is damage characteristic coefficient. The proposing method to estimate the human fatality was applied to Kamaishi city and Sendai city which have different coastal topography. Building damage data and population of cities was based on MLIT data [6]. and apply to the estimating model shown in Eq. (4). The damage characteristic coefficient distribution was selected according to the topographical characteristics of the two towns. In other words, the distribution of Sendai Plain was applied to Sendai City and the distribution of ria coast was applied to Kamaishi City.

The estimation results are shown in Fig. 8. The horizontal axis represents district ID, and the vertical axis represents the estimated human casualty. Grey zone in the Fig. 8 represents the range of 1st- quantile to 3rd quantile of estimated human casualty. Damage with a median level is most likely to occur, and the probability of damage at the edge of the grey zone is low. Red dots represent the actual human casualty and black dots represent the median of estimated casualty. Accuracy rate, that is probability that the actual amount of damage was included interquartile range of damage characteristic coefficient is shown in Table 7. The accuracy rate of Sendai city was as low as 37%, because many towns overestimated areas with only 1 or 2 population and no fatalities. Confirming RMSE between the median of the estimated damage and actual were to be 1.71 people in Sendai city, it seems that it is well estimated. In Kamaishi City, the accuracy rate was 66.7%, which was higher than that in Sendai city. RMSE was confirmed to be 21.9 people, so it can be said that the estimation of Kamaishi city is highly accurate. It was confirmed that the proposed method could describe the actual human fatality data.

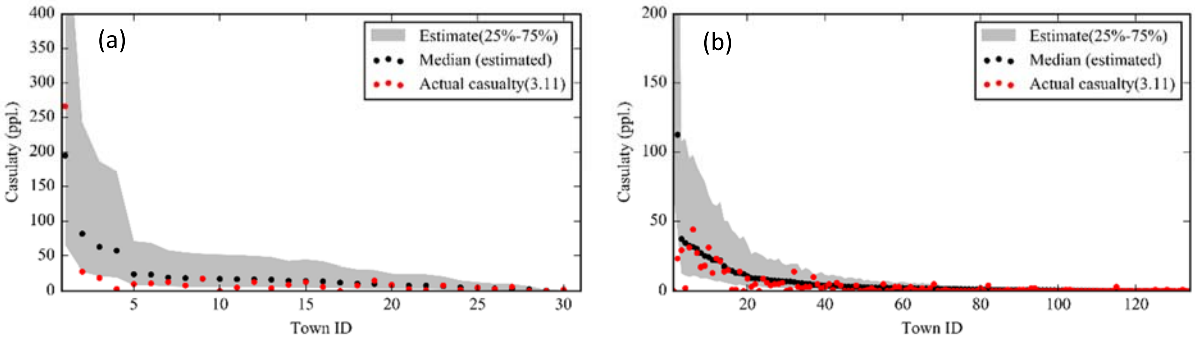

Fig.8 Result of human casualty estimation for (a) Kamaishi and (b) Sendai.

Table 7 – Accuracy rate and RMSE of proposed method.

	accuracy rate (%)	RMSE (pop.)
Sendai city	37.0	1.71
Kamaishi city	66.7	21.9

4. Combining the proposed method with tsunami numerical simulation

To focus on lifesaving activity just after the large disaster, estimating the damage situation enables to understand damage overview at earlier stage and leads to more efficient lifesaving activity. By Estimating the building damage probability using the result of real-time tsunami inundation forecasting [9], it is possible to obtain the estimated amount of damage immediately after the earthquake. By using these estimation, it will be possible to make plans such as preferentially dispatching rescue teams to areas where there is a high possibility that buildings are remaining, where may be survivors. In this section, assuming the case of predicting the damage caused by future disasters, applying numerical tsunami simulation to the proposed method.

4.1 Study sites

The study area is central part of Ishinomaki City, Miyagi Prefecture, where is around the mouth of the Kitakami River. At the time of the 2011 tsunami, the maximum wave of more than 7.6 m was observed in Ayukawa, about 40 minutes after the earthquake [10]. Inundation area in the city was 73km^2 and coastal area was seriously damaged. There was 3,178 deaths and 422 missing persons [11]. A total of 53,742 houses were damaged: 22,357 were completely destroyed, 11,021 were partially destroyed, and 20,364 were minor destroyed [12]. As described above, the damage to Ishinomaki City was the largest in the disaster.

4.2 Numerical simulation of the 2011 tsunami

Numerical simulation of tsunami was reproduced the 2011 tsunami damage of Ishinomaki City. The numerical model used nonlinear shallow water equations. The fault parameters proposed by the Tohoku University model [13]. Simulation time was set to 3hours. The grid size was varied ranges as nesting slid from 1,215m to 5m. Detailed of the simulation is explain in Suppasri et al. (2019) [14]. The accuracy of model was checked by using Aida's K and κ [15]. Values of K and κ showed good value, 1.04 and 1.32.

4.3 Estimation of building damage probability

Using the maximum inundation depth distribution obtained from numerical simulation and the structural data of each building, building damage probability was calculated by the proposed method. The result of estimation is shown in Fig. 9. Fig. 9 (a) shows actual damage, with red dots represent destroyed buildings and blue dots represent survive. Fig.9 (b) shows estimated building damage probability with dots of corresponding color. The estimated probability describes the boundary between actual destroy and survive. However, there are some underestimation in the northern part of the town which caused by underestimation of tsunami inundation depth due to the inadequate roughness setting of tsunami numerical calculations. This shows that high accurate estimating of building damage probability requires accurate tsunami numerical simulation. In order to check accuracy rate of this method, estimated damage probability was classified as "destroyed" above 0.5 and "survived" below 0.5 and compared with actual damage (destroyed or survived). The proposed method can explain the trend of actual building damage in about 86.7% of precision.

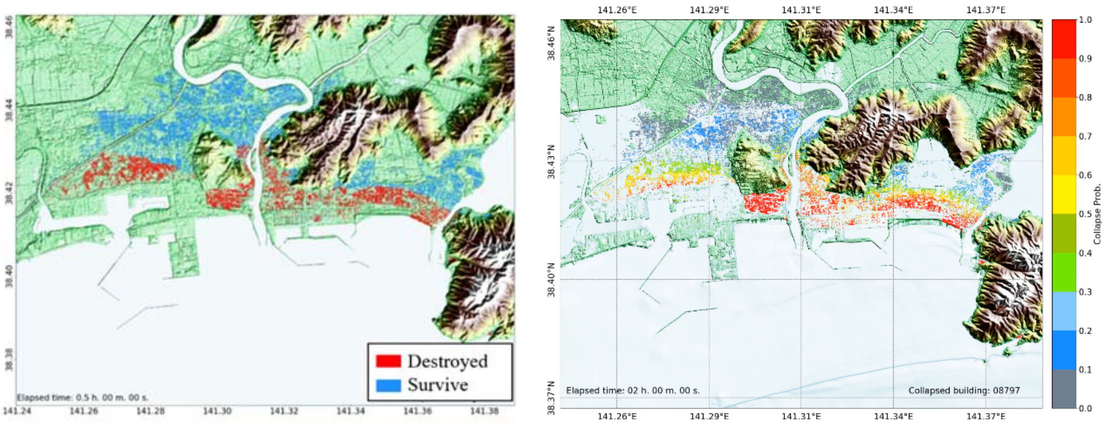

Fig.9 (a) Actual damage of buildings during the 2011 tsunami,
(b) Estimated bilding damage probabirity by prorpsed method.

4.4 Estimation of human casualty

Using the estimated building damage probability, human casualty of Ishinomaki estimates using proposing method. The result of estimation of building damage probability is non-arranged, so added it up for each district. The result of estimation is shown in Fig. 10. Accuracy rate of human casualty estimation which shown by the probability of actual amount of damage was included interquartile range of estimated was 65.17%. There were 31 towns incorrectly estimated: 12 were underestimated and 19 were overestimated. Most of overestimated towns were industrial areas such as Hibarino town or Nanko town. On the other hand, underestimated towns located relatively inland and many of them was residential area, such as Haguro town. Goto (2015) [16] reported that industrial areas were lower fatality ratio than residential area, because the people at home did not evacuate as much as those who worked for company. This trend is consistent with our results. The underestimation in some cities is caused by the underestimation of numerical simulation. It is found that proposed method to estimate human casualty strongly depend on the accuracy of tsunami simulation.

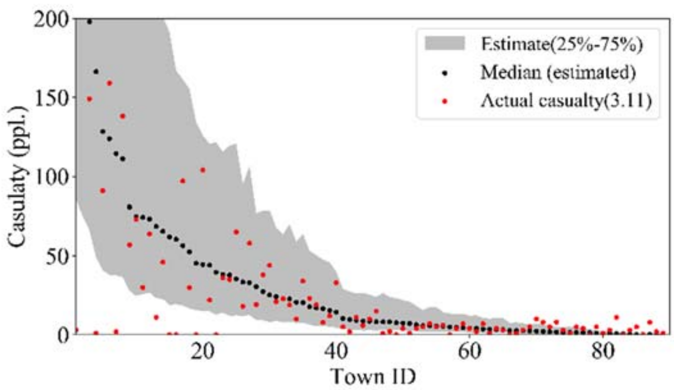

Fig.10 Result of human casualty estimation for Ishinomaki.

5. Conclusions

This study presented relational expression about building damage due to tsunami disaster by analysing approximately non-aggregated 130,000 building damage data. This relational expression relies on only structural factors and inundation depth and being able to estimate damage every building. Therefore, it is not influenced by geometric or community factor and it can apply other areas for example Nankai area.

Using estimate building damage method, a new method to estimate human damage was proposed. The ratio of actual fatality and population in inundation area is defined as a damage characteristic coefficient which can explain the vulnerability of the districts. It was found that distribution of damage characteristic coefficient can describe logarithmic normal distribution. Two damage characteristic coefficients based on actual damage in ria coast area and Sendai plain area were proposed. Human damage assessment method proposed in paper can consider the uncertainty of human damage and represent the amount of damage with a width. Applying the proposing method to the damage situation of the 2011 tsunami, it was found that the method can describe damages of two devastated city which has have quite different characteristics.

We apply both of proposed method to Ishinomaki city which suffered most intense damage during 2011 tsunami. Tsunami numerical simulation gave maximum inundation depth which was used to estimate building damage probability. And human casualty was estimated using the results of estimation of building damage probability. The proposed method can explain the trend of actual building damage with 85% accuracy and human fatality with 67% accuracy. The new model has benefit of broader application and estimates the damage amount with a range of uncertainty. Such expressions are useful for estimating disaster scenarios because they can indicate that the amount of damage varies depending on the situation at the time of disaster. However, estimation results were strongly influenced by the tsunami numerical simulation accuracy which have to be carefully considered when applying to future tsunamis.

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