Predicting Damage of Wooden Houses Considering the Characteristic of Earthquake Response Spectra and the Frequency Characteristic of Wooden House

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SUMMARY:

A seismic hazard maps is one of typical things of earthquake risk assessment. The seismic force is expressed on the ground peak acceleration (PGA), the ground peak velocity (PGV) or the seismic intensity at most all seismic hazard maps. But seismic force is expressed by one physical quantity, accuracy of earthquake damage evaluation is made into a sacrifice in order that some useful information may be missing, especially spectral information. Therefore, it is difficult to apply the damage function in the area where is different earthquake performances of wooden houses. In this study, the damage prediction in which the spectral characteristics of an earthquake motion and frequency characteristics of wooden houses can be taken into consideration is proposed. Prediction of earthquake motion uses a fault model and the seismic response analysis using the equivalent linearization method in consideration of a frequency characteristic estimates the degree of damage of a wooden house. Since this study uses the data which is easy to get, it can perform earthquake damage prediction easily. As the result, this study can predict the wooden house's damage in accuracy with more sufficient than the past prediction method, and accurate prediction was able to be proposed irrespective of the distance from the epicenter.

Key Words : *Damage Estimate of Wooden Houses, Earthquake Response Spectrum,*
Frequency Characteristic of Wooden Houses

1. INTRODUCTION

A seismic hazard maps is one of typical things of earthquake risk assessment$^{1)}$. The seismic force is expressed on the ground peak acceleration (PGA), the ground peak velocity (PGV) or the seismic intensity at most all seismic hazard maps. But seismic force is expressed by one physical quantity, accuracy of earthquake damage evaluation is made into a sacrifice in order that some useful information may be missing, especially spectral information. Therefore, it is difficult to apply the damage function in the area where is different earthquake performances of wooden houses.

Damage evaluation of a wooden house can be divided roughly into the experiential method and the method by seismic response analysis. In general, damage prediction which used the damage function is performed by the experiential method. If an earthquake motion can be predicted, damage will be estimated simply. Much earthquake damage data is needed to build a damage function. Since the seismic performance of a wooden house changes with areas, it needs to be careful when carrying out damage presumption using damage function built by the data of the different area. As for the seismic hazard map or the earthquake damage function, seismic intensity or PGA, PGV, etc. is used as seismic force. But these functions do not take a period into consideration. Since the damage function only shows experientially relationship between seismic force and the damage ratio, the oscillation characteristic of the wooden house is not taken into consideration generally. In order to solve this problem, Sakai et. al.$^{2)}$ propose that the average response spectrum in consideration of the longer natural period by generalized plasticity uses as the earthquake motion for damage function. The longer natural period by generalized plasticity can be explained by the equivalent linearizing method by Kasai et. al.$^{3)}$. However, there is no research which applied this idea to earthquake damage presumption.

In this study, the damage prediction in which the spectral characteristics of an earthquake motion and frequency characteristics of wooden houses can be taken into consideration is proposed. Prediction of earthquake motion uses a fault model and the seismic response analysis using the equivalent linearization method in consideration of a frequency characteristic estimates the degree of damage of a wooden house. Since this study uses the data which is easy to get, it can perform earthquake damage prediction easily.

2. ESTIMATION OF ACCELERATION RESPONSE SPECTRUM

The factor of an earthquake motion is the source characteristic, the propagation characteristic, and the amplification characteristic of the ground. So it can be assumed that the following equation 1 is adopted as an acceleration response spectrum.

$$S_a(T) = F\left\{O(T), P(T)\right\} \bullet G(T) \qquad \cdot\cdot\cdot \quad (1)$$

Thus, T is a period of earthquake motion (s), $S_a(T)$ is an acceleration response spectrum of a surface ground as h=0.05 (cm/s^2), $O(T)$ is a source characteristic, $P(T)$ is a propagation characteristic and $G(T)$ is a amplification characteristic of the ground. In this study, we predict the acceleration response spectrum in ground surface, in order to take the spectral characteristics of an earthquake motion into consideration. It requires the attenuation equation of the acceleration response spectrum and the amplification ratio of the ground. About an amplification ratio, the period 0.1 (s) to 1.5 (s) uses the formula in consideration of the influence of a subsurface layer, and the formula which took the influence of the depths foundation into consideration above the period 1.5 (s). The acceleration response spectrum in a base is calculated using the attenuation equation of Uchiyama et al.[4)] in the form which includes $O(T)$ and $P(T)$. The attenuation equation is calculated using a moment magnitude and the depth of hypocenter. The amplification ratio of the ground ($G(T)$) is used the method of NEHRP improved by Uchiyama and Midorikawa (2003)[5)] as a short period, and the formula of Steven et al.[6)] as a long period. The digital national information of J-SHIS is used for foundation information required for calculation. In this study, an acceleration response spectrum predicts for every 250(m) mesh as standard area mesh.

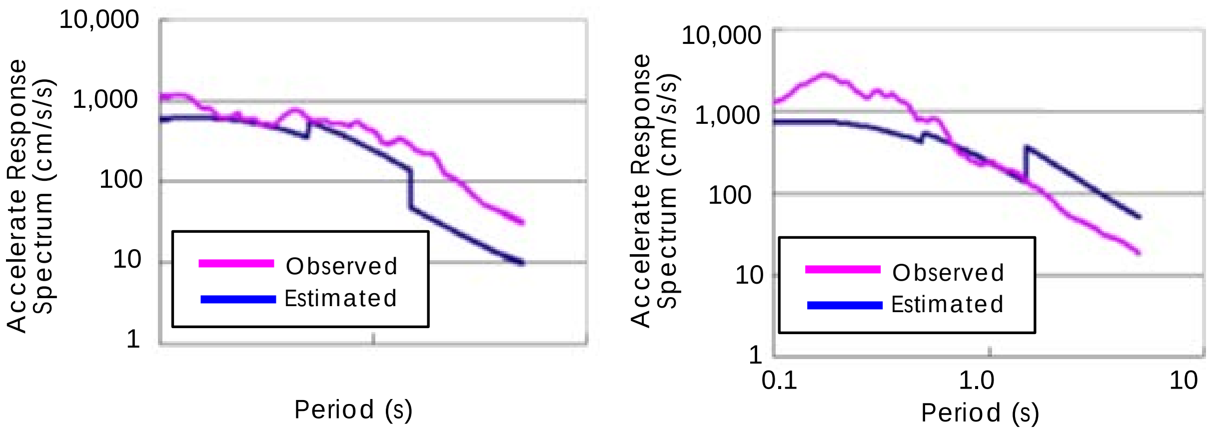
Table 1 Parameters of Earthquake

Fault Surface	Latitude	37.19	°
	Longitude	136.55	°
	Depth	1.2	km
	Length	21.2	km
	Width	13.9	km
	Strike Angle	55	°
	Dip Angle	63	°
	Slip Angle	137	°
	Slip	1.65	m
Moment Magnitude		6.7	
Depth of Hypocenter		11	km

Table 2 Parameters of Observation Sites

	ISK003	ISK006
X(km)	17.7	9.4
VS30(m/s)	243.0	401.2
Z(m)	48	702

It is estimated the acceleration response spectrum in the 2007 Noto Peninsula Earthquake in order to check the accuracy of prediction. Comparison sites use K-NET Togi (ISK006) and K-NET Wajima (ISK003) near the area for analysis. The parameter of earthquake is shown as Table 1, the parameter of analytical sites are shown as Table 2, respectively. Thus Z is depth of sedimentary layers (m) and X is the shortest distance of a fault (km). Comparison with the acceleration response spectrum and observed value which were predicted is shown in Figs. 1. As shown in these figures, it is generally in agreement that near period 1.0(s) which is periodic zones taken into consideration performing damage prediction of a wooden house. In



(a) K-NET Wajima (ISK003)

(b) K-NET Togi (ISK006)

Figures 1 Estimated Accelerate Response Spectra
((a) K-NET Wajima, (b)K-NET Togi)

this study, the spectral characteristics of the earthquake motion in object areas are presumed using this method.

3. DAMAGE PREDICTION OF WOODEN HOUSES CONSIDERING FREQUENCY CHARACTERISTICS

Damage evaluation of a wooden house uses the equivalent linearizing method in consideration of the spectral characteristics of an earthquake motion, and the frequency characteristic of the wooden house. In this study, The oscillation characteristic of a wooden house is defined by the relationship between share force and displacement. This method uses equivalent stiffness k_{eq}, the equivalent period T_{eq}, and the equivalent damping ratio h_{eq} of a model which were made into the 1 degree-of-freedom model. The maximum response is calculated using the equivalent acceleration response spectrum in consideration of k_{eq}, T_{eq} and h_{eq}. The following formulas 2 show the equivalent period T_{eq} and the equivalent damping ratio h_{eq}.

$$T_{eq} = 2\pi\sqrt{\frac{m}{k_{eq}}} = \sqrt{\mu}T_0$$
$$h_{eq} = \alpha\left(1-\frac{1}{\sqrt{\mu}}\right)+\frac{h_0}{\sqrt{\mu}} \quad \cdot\cdot\cdot (2)$$

Thus, T_0 is a natural period of a wooden house(s), m is equivalent mass of a wooden house, h_0 is initial damping ratio (h_0=0.05), α is reduction coefficient (α=0.2) and μ is ductility factor. Equivalent stiffness is defined as secant stiffness over the maximum response. Therefore, equivalent stiffness carried out division of the initial stiffness by ductility factor. The hysteresis curve for equivalent stiffness assumes degrading stiffness by-linear model. As mentioned above, the maximum share force Q_{max} shown in the formula 3 is calculated.

$$Q_{\max} = mS_a(T_{eq}, h_{eq}) \quad \cdot\cdot\cdot (3)$$

It is necessary to set up yield share force Q_y in order to judge whether plasticity was carried out. The yield share force Q_y shown in the formula 4 is calculated.

$$Q_y = 4\pi^2 m \frac{\beta_y H R_y}{T_0{}^2} \qquad \cdot\cdot\cdot\ (4)$$

Thus, H is equivalent height of a wooden house, β_y is stiffness reduction factor at yield point and R_y is yield story deformation angle. R_y is defined as 1/120. β_y is should be calculated by the pull-down test of wooden houses or real-scale shaking table tests. But it is difficult to carry out. In this study, β_y is made to increase by 0 to 0.01 units, and earthquake damage prediction is performed. β_y when observation damage is able to be predicted with the most sufficient accuracy is defined as a true. So β_y is defined by 0.18. Equivalent mass is 30 (t) and equivalent height is 4.2 (m) in order to take a 2-story wooden house into consideration.

In order to take into consideration the variation in the oscillation characteristic of a wooden house, the wooden house group model distributing yield share force is evaluated. Since yield share force is related to natural period of house, the variation of natural period is expressed as a probability density function. And it is evaluated as variation in yield share force. The variation of natural period uses the relationship of a wooden house age and a natural period of house7). An expression of relations is shown in a formula 5 and Fig.2.

$$\begin{cases} \eta_T = 0.0046Y + 0.113 \\ \sigma_T = 0.0016Y + 0.0145 \end{cases} \qquad (5)$$

Thus, η_T is the average of natural period in the wooden houses for Y years (s) and σ_T is the standard deviation of natural period in the wooden houses for Y years. The variation in the year of a wooden house after construction is evaluated from the number for every construction age of a wooden house, and is approximated with the

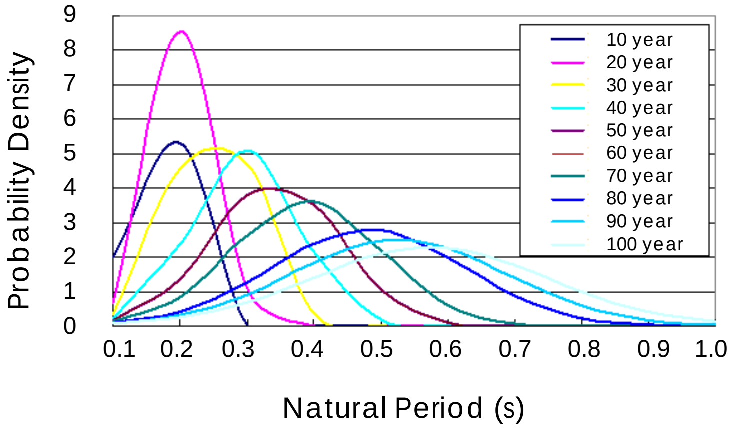


Figure 2 Relationship between wooden house age and natural period of house

Table 3 The number of wooden house in Wajima city

House Years	Number
Before 1960	2,330
1961～1970	1,010
1971～1980	1,750
1981～1985	710
1986～1990	420
1991～1995	430
1996～2000	210
After 2001	100

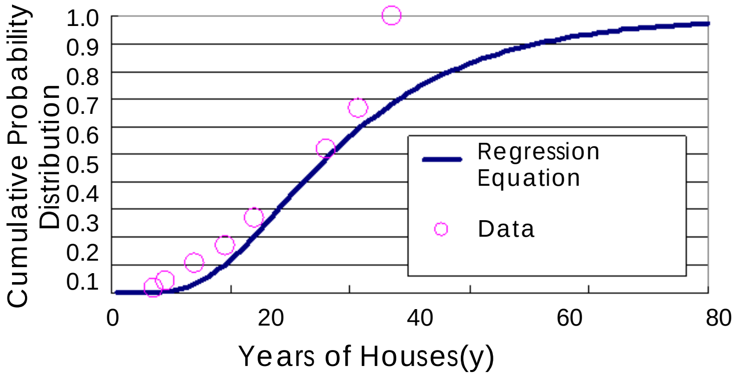


Figure 3 Regression of logarithmic normal distribution in Wajima City

probability density function of logarithmic normal distribution. The number of wooden house in Wajima city is shown in Table 3[8], the variation estimated by the regression of logarithmic normal distribution is shown in Fig. 3 and the result presumed probability density function is shown in Fig. 4, respectively. As shown in Fig. 4, natural period shows the distribution form with a peak of 0.24 (s). As mentioned above, it calculates repeatedly until it becomes $Q_{max}=Q_y$, and the ductility factor is estimated. When the damage ratio is calculated, the destructive standard corresponding to the ductility factor is needed. In this study, the ductility factor in case of wooden house is damaged seriously is used as a destructive standard (μ_{cr}) and is shown in a formula 6.

$$\mu_{cr} = \mu_0 \sqrt{\frac{0.5}{T}} \qquad \cdot\cdot\cdot\ (6)$$

Thus, μ_0 is the ductility factor in case of wooden house is damaged seriously (μ_0=8). μ is compared with μ_{cr}, μ calculates the sum of probability density in the range of the natural period which exceeds μ_{cr}. And it is defined as the damage ratio. In this study, the damage ratio in every 250(m) mesh is calculated.

4. EARTHQUAKE DAMAGE PREDICTION IN NOTO PENINSULA

In this study, wooden houses damage presumption in the 2007 Noto Peninsula Earthquake is performed. An estimated damage is compared with observation damage. And this method is compared with other general wooden house presumption method. Observed damage uses the damage distribution map in the damage area (Kuroshima: Wajima City, Tohge: Wajima City and Anamizu: Anamizu Town (Ishikawa Pref., Japan) of the 2007 Noto Peninsula Earthquake by the houses complete enumeration of the Architectural Institute of Japan.

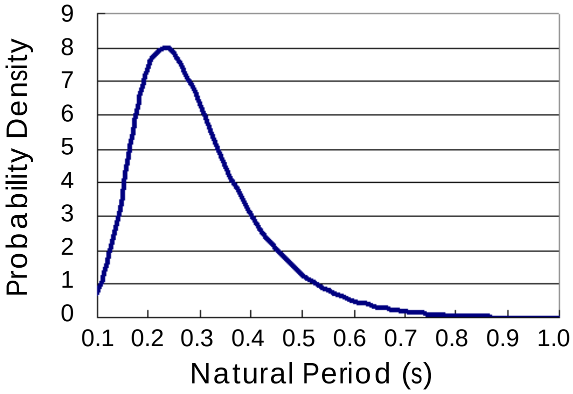


Figure 4 Presumed probability density function in Wajima City

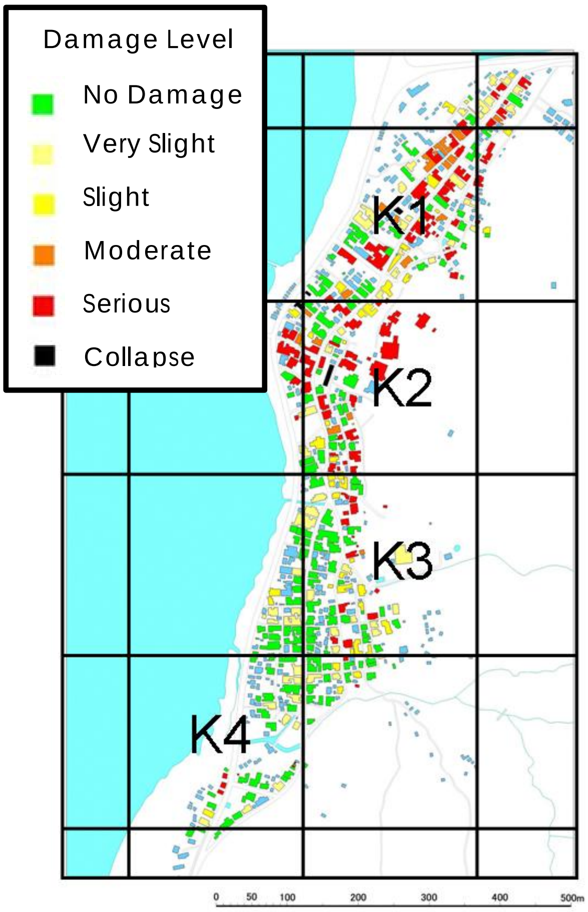


Figure 5 Damage Distribution Map of Wooden Houses at Kuroshima (Monzen)

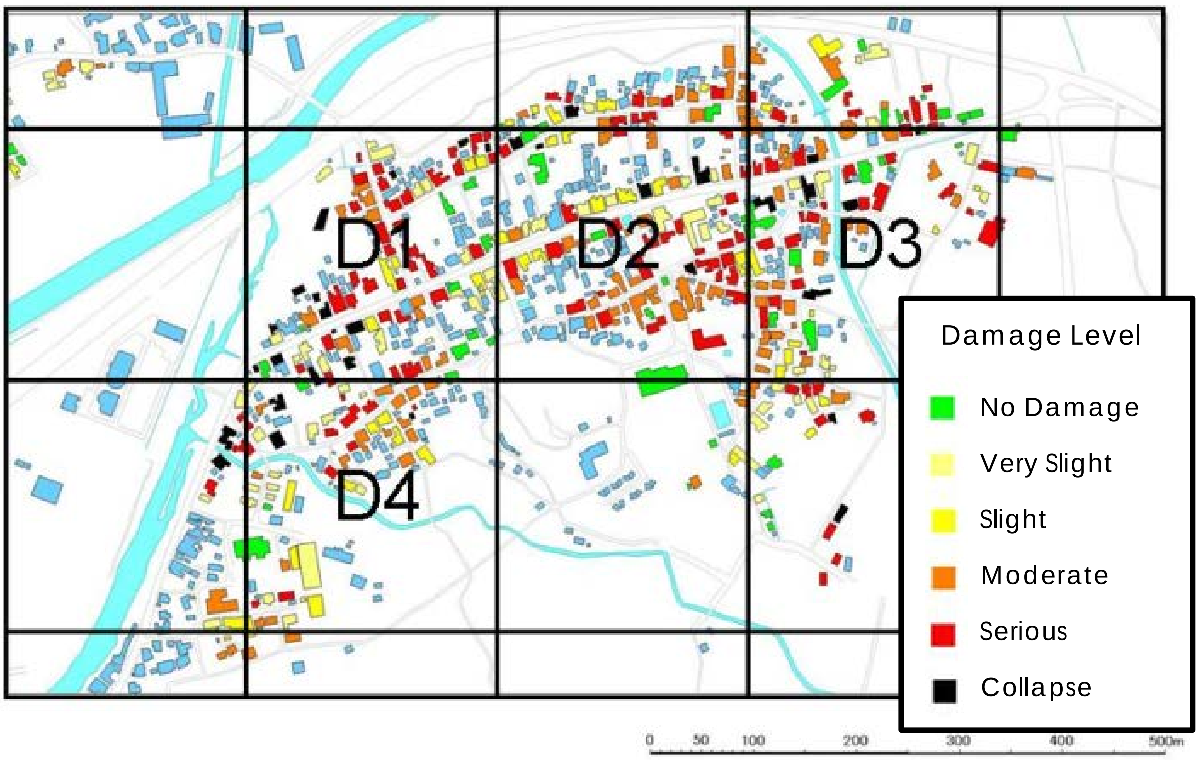


Figure 6 Damage Distribution Map of Wooden Houses at Tohge (Monzen)

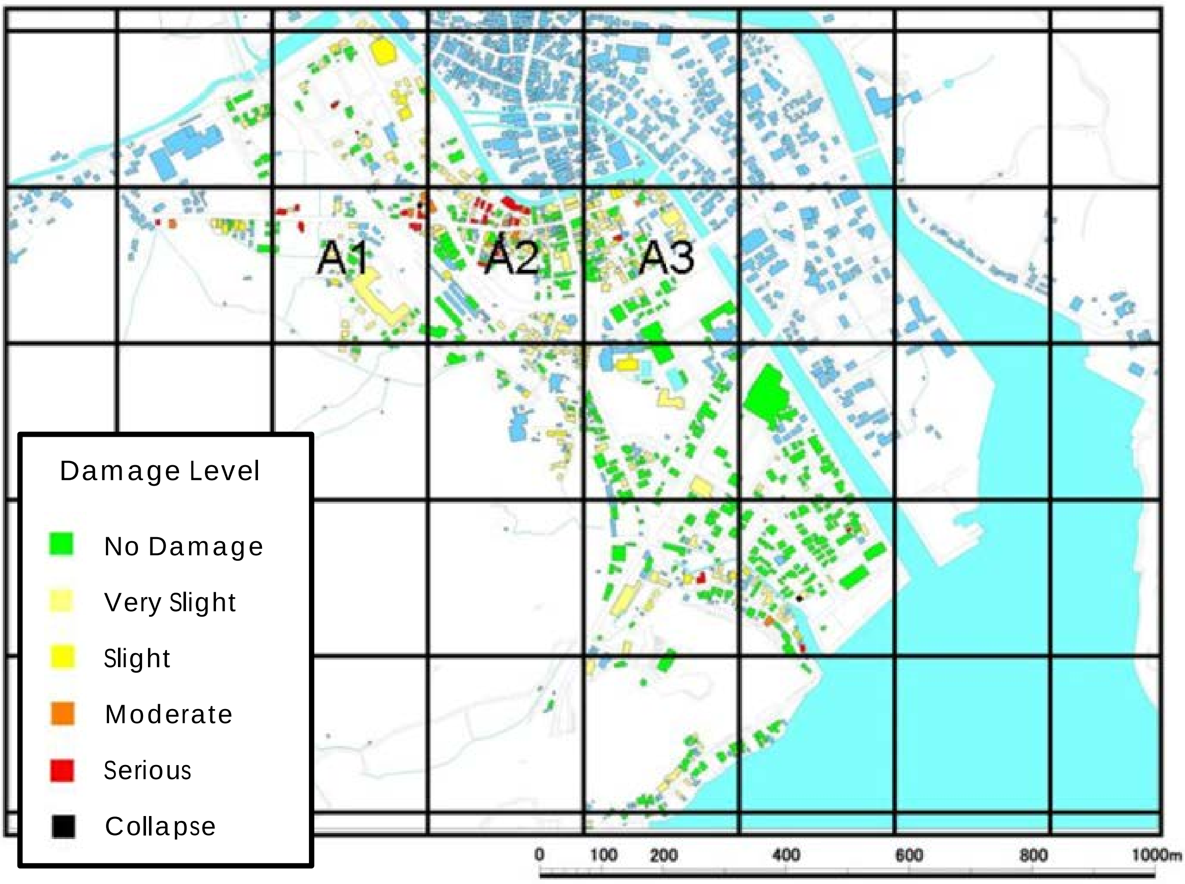
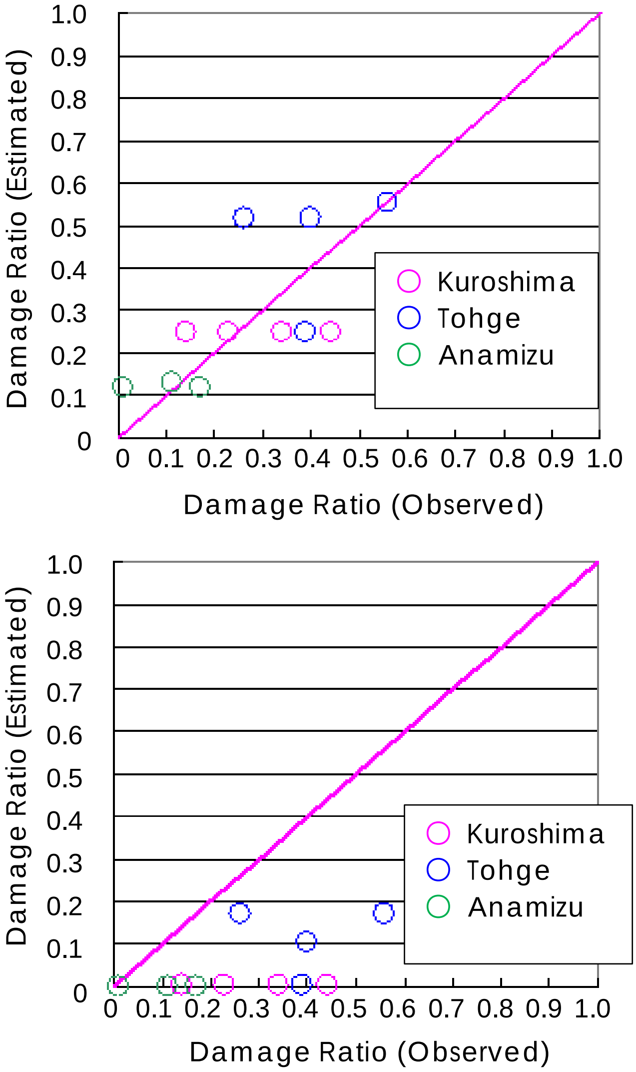


Figure 7 Damage Distribution Map of Wooden Houses at Anamizu

The damage grade (Non-damage ~ Collapse) shown in Fig. 5 ~ Fig. 7 is defined by Okada et al[9]. The observed damage ratio in every 250(m) mesh is calculated from these distribution maps. Since a destructive standard is defined as more than serious damage in that case, the observed damage ratio uses serious or more levels. In addition, since many houses are needed in meshs to compare with the estimated damage, the mesh in which many houses exist is used. The index which verifies presumed accuracy uses the average error of the estimated damage and the observation damage. About the reference wooden house presumption method, it is based on the earthquake disaster prevention map creation technical data which Cabinet Office (Japan) supervised[10]. And that method uses the attenuation of maximum velocity and amplification ratio of the ground. So the attenuation of maximum velocity uses Si and Midorikawa(1999)[11], relationship between seismically intensity and maximum velocity uses Tong and Yamazaki(1996)[12], the empirical equation of ground amplification uses Midorikawa et al.(1994)[13] and the wooden house damage function uses Yamaguchi and Yamazaki(2000)[14]. Comparison with the estimated damage of this method and the reference method and observed damage is shown in Fig. 8. The average error of this method is 0.10 and the average error of reference method is 0.23. As shown in Fig. 8, estimated damage of the reference method is presumed to be 0.0 in Anamizu and this method is presumed to be 0.12. The estimated damage of the reference method is evaluated too little in Kuroshima. So it is thought that estimation of this method can be performed by the safety side.



Figures 8 Relationship of Damage Ratio between Observed Damage and Estimated Damage
(Upper: This Method, Lower: Reference Method)

5. CONCLUSION

In this study, the damage prediction in which the spectral characteristics of an earthquake motion and frequency characteristics of wooden houses can be taken into consideration is proposed. Prediction of earthquake motion uses a fault model and the seismic response analysis using the equivalent linearization method in consideration of a frequency characteristic estimates the degree of damage of a wooden house. As the result, this study can predict the wooden house's damage in accuracy with more sufficient and estimation of this method can be performed by the safety side than the reference method.

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