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SEISMIC DAMAGE PREDICTION FOR JAPANESE-STYLE WOODEN HOUSE IN THE 2016 KUMAMOTO EARTHQUAKE

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Thousands of wooden houses were destroyed by the 2016 Kumamoto Earthquake. A seismic damage prediction function for wooden houses taking into consideration the consecutive strong earthquake motions, the amplification effect of ground surface layer, and the rupture propagation effect of seismic fault was proposed in this paper. Relationship between three ground characteristics above mentioned and the seismic damage for wooden house in the 2016 Kumamoto earthquake was analytically investigated by 3-D collapsing process analysis. The maximum drift angle was evaluated in this collapsing analysis of two-story wooden house.

Keywords: Seismic performance, Collapsing process analysis, Drift angle, Empirical Green's function.

1 INTRODUCTION

A tremendous seismic damage of collapse to wooden houses was caused by the 2016 Kumamoto Earthquake occurred on both April 14 and 16 (Building Research Institute 2016). In particular, Mashiki town located at near the hypocenter of these earthquakes has twice earthquake ground motions with the Japan Meteorological Agency (hereafter referred as JMA) seismic intensity of "7" level successively. As main factors to the destruction of wooden houses in the 2016 Kumamoto Earthquake, strong earthquake motions due to fore-shock and main shock, the amplification effect of ground surface layer, and the pulse wave due to seismic fault rupture propagation have been indicated by many researchers and engineers. Also, Nozu (2017) reported that the effect of the rupture propagation of seismic fault in the main shock in the 2016 Kumamoto Earthquake affects seismic damage of bridge in the north-east area in its epicenter region (Building Research Institute 2016, Goto *et al.* 2017). The purpose of this paper is to propose a seismic damage prediction function for two-story wooden house by taking into consideration the consecutive strong earthquake motions, the amplification effect of ground surface layer, and the rupture propagation effect of seismic fault.

2 GENERATION OF INPUT EARTHQUAKE GROUND MOTION WAVE

In this paper, several earthquake motion waves are evaluated by an empirical Green's function method using seismic fault model considering a hypocenter location of the main shock and its asperity in the 2016 Kumamoto Earthquake. These earthquake motion waves have three seismic motion characteristics in this earthquake mentioned above. Difference between the rupture propagation effects on earthquake motion waves at 50 location points around a seismic fault is investigated. Earthquake ground motion waves observed at KiK-net Mashiki in the earthquake (M_{JMA}=4.2) occurred at 00:50 on April 15, 2016 are employed in the empirical Green's function method. In order to investigate the site amplification characteristics, earthquake ground motion wave at each location is calculated using the site amplification characteristics with three different frequencies. In the calculation of earthquake motion wave on the ground surface, the non-linearization of ground due to a strong seismic motion can be considered by the multi non-linearity effect.

Using earthquake motion waves calculated by the empirical Green's function method, seismic collapsing behavior of wooden house is numerically investigated by 3-D collapsing process analysis of "wallstat", which was developed by Nakagawa *et al.* (2010). To investigate the effect of consecutive earthquake motion wave on seismic performance of wooden house, earthquake motion waves in the foreshock, the main shock, and both the fore and main shocks are employed in this 3-D seismic collapsing process analysis of wooden house (Takatani and Nishikawa 2017). Based on the maximum drift angle of wooden house obtained from collapsing analytical results, seismic damage state of wooden house is classified, and also seismic damage prediction map is made.

2.1 Empirical Green's Function Method

Empirical Green's Function Method can calculate an acceleration wave at the estimation point by some small to medium size earthquake motion waves occurring on a seismic fault of the target earthquake. In this paper, the empirical Green's function proposed by Nozu (2017) was used to numerically calculate some acceleration waves. Propagation path characteristics were referred to a research paper by Kato (2001). 61 location points in the analytical area in Kumamoto prefecture and the asperity locations of A1, A2, and A3 are employed in this paper. The fore-shock (M_{JMA}=6.5) in 2016 Kumamoto Earthquake occurred on 21:26 on April 14, 2016.

2.2 Hypocenter Model

Hypocenter model employed in the empirical Green's function method is referred to a characterized hypocenter model of both the foreshock and main shock in the 2016 Kumamoto Earthquake proposed by Nozu (2017). In this paper, characterized hypocenter model is not described due to the limited space.

Figure 1 shows an outline image around a hypocenter of the fore-shock mentioned above. A mark of ★means an epicenter of the fore-shock, ★means an epicenter of the main shock, □ means an epicenter of small to medium size earthquakes in making an evaluation of phase characteristics, ▲ means analytical location points. Earthquake ground motion waves at 61 location points nearby a seismic fault, which is supposed the foreshock and the main shock in the 2016 Kumamoto Earthquake, are created by the empirical Green's function method. In order to investigate the effect of the site amplification characteristics, these earthquake ground motion waves at 61 location points are evaluated by the site amplification characteristics with three different frequency characteristics. In this paper, earthquake motion waves at KMM008, KMM011 and KMM018 in the strong motion seismograph networks (K-NET) are employed as three different frequency characteristics.

Figure 2 indicates a referred characterized hypocenter of the foreshock in the 2016 Kumamoto Earthquake. "Asperity 1" and "Asperity 2" are set in two location points of the seismic fault, where the maximum slip velocity value is estimated as a reference of earthquake motion wave inversion result. Table 1 shows some parameters regarding each asperity. Failure at each asperity is assumed to expand to the radical direction from a rupture start point of each asperity.

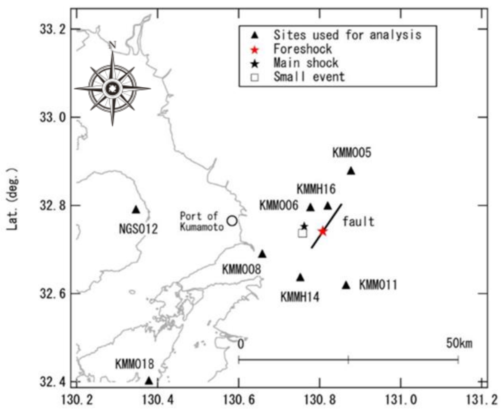


Figure 1. Information around a hypocenter of the foreshock in 2016 Kumamoto Earthquake.

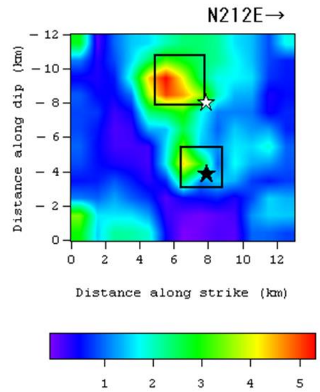


Figure 2. Characterized hypocenter of the foreshock in the 2016 Kumamoto Earthquake.

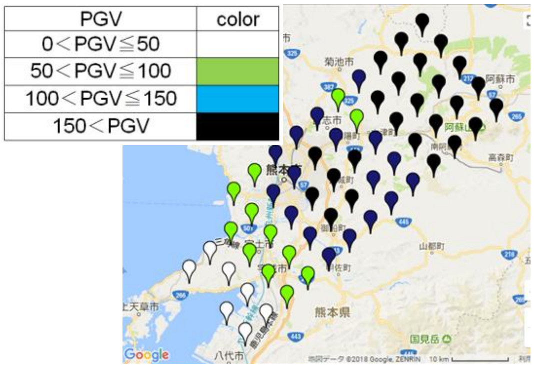
Table 1. Parameters of characterized hypocenter model of foreshock in the 2016 Kumamoto Earthquake.

	Asperity 1	Asperity 2
East Longitude at Start Point (deg.)	130.808	130.809
North Latitude at Start Point (deg.)	32.742	32.742
Depth of Start Point (km)	11	7
Length (km) * Width (km)	2.5 * 2.5	3 * 3
Seismic Moment, Mo (N・m)	1.50E+24	1.30E+24
Relative Rupture Start Time (s)	0	2.7
Rupture Propagation Velocity (km/s)	2.8	2.8
Rise Time (s)	0.33	0.4
Division Number	5 * 5 * 5	5 * 5 * 5

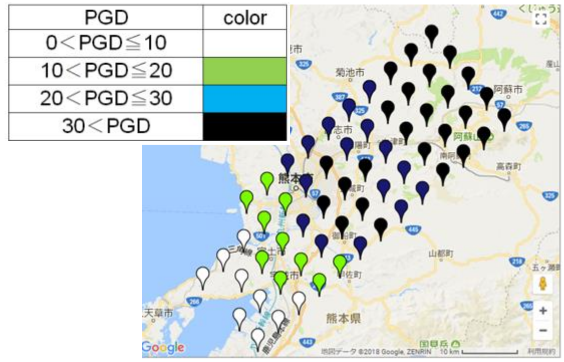
2.3 Site Amplification Characteristics

Site amplification characteristics are to display the surface soil layered ground amplification in the frequency domain, which is located on the earthquake engineering base rock (Approximately shear wave velocity 3km/s). In order to investigate the seismic intensity and the difference on seismic damage of structure, three different site amplification characteristics, KMM08, KMM011 and KMM018, are used in this paper. First natural frequencies at KMM08, KMM011 and KMM018 are 0.85Hz, 3.1Hz and 9,4Hz, respectively. Based on the ground classification of the Building Standards Act in Ja-pan, KMM011 and KMM018 correspond to the second kind of ground, and KMM008 corresponds to the third kind of ground.

Figure 3 shows the maximum velocity, PGV (cm/s), distribution map and the maxi-mum displacement, PGD (cm), distribution map, which are obtained by the empirical Green's function method using three site amplification characteristics mentioned above. It is found that PGV and PGD values trend to increase toward the north-east direction. Three seismic motions have a tendency to become larger in order of KMM008, KMM011 and KMM018.



Maximum velocity (PGV)



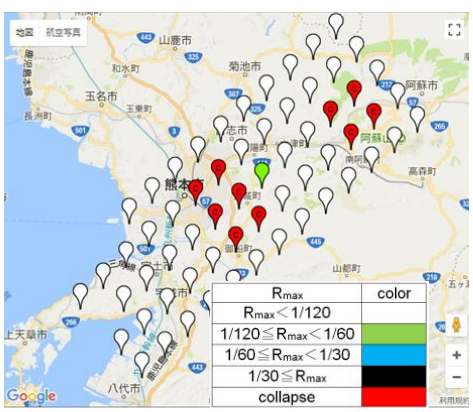
Maximum displacement (PGD)

Figure 3. Maximum velocity and displacement distribution map (KMM008).

3 SEISMIC DAMAGE PREDICTION OF WOODEN HOUSE

3.1 Evaluation of Maximum Drift Angle of Wooden House

The maximum drift angle is defined with the ratio of a horizontal displacement of each story layer to the height of each layer, and the maximum value in each direction is chosen from the maximum drift angles at four corners of wooden house. Figure 4 shows the maximum drift angle distribution maps of Rx and Ry when EW and NS components of earthquake motion wave considering the site amplification characteristics of KMM008 were employed to X direction. Rx means the maximum drift angle chosen in four drift angles in X direction, and Ry means the maximum drift angle chosen in four drift angles in Y direction.



(a) Rx

(b) Ry

Figure 4. Maximum drift angle distribution maps (KMM008, X-EW component).

3.2 Maximum Drift Angle of Wooden House

Based on the seismic collapsing process simulation results of wooden house described in the previous chapter, a prediction equation of the maximum drift angle of two-story wooden house can be written by

$$\log R_{\max} = c_1 + c_2 \log D + c_3 \left(X^2 + S \right) + c_4 X + c_5 \log f_g + c_6 f_g \qquad (1)$$

where, D is directivity coefficient, X is the minimum distance (km) of seismic fault, f_g is the first natural frequency (Hz) of the site amplification characteristics, c_1 to c_6 are recurrence coefficients, and S is the constant coefficient regarding the peak of seismic motion around a hypocenter. Eq. (1) can be obtained by the recurrence analysis changing S value. Table 2 shows each recurrence coefficients used in Eq. (1).

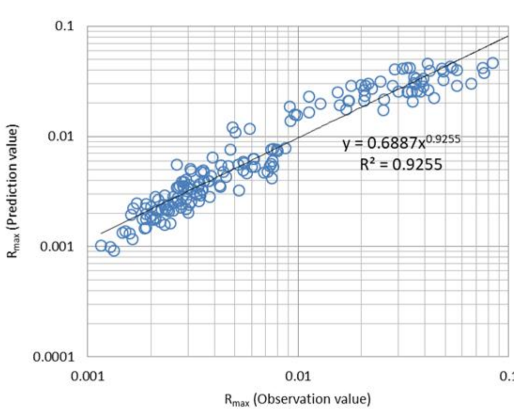
Seismic damage prediction of wooden house around Kumamoto region may be possible by Eq. (1) proposed in this paper. This seismic damage prediction of wooden house was obtained from the recurrence analysis based on some earthquake ground motion waves in the 2016 Kumamoto Earthquake, and also is used in estimating seismic damage prediction of two-story wooden house with high seismic performance and satisfying the seismic standard in the Building Stand ards Act in Japan amended in 2010. Therefore, a recurrence analysis considering the site amplification characteristics in other region may be needed in order to evaluate seismic damage prediction of wooden house in other regions. Moreover, the seismic damage prediction of old wooden house built before 2010 can be easily obtained from the recurrence analysis using seismic collapsing process results of this kind of wooden house.

Table 2. Recurrence coefficients in Eq. (1) (Input motion wave used in X direction).

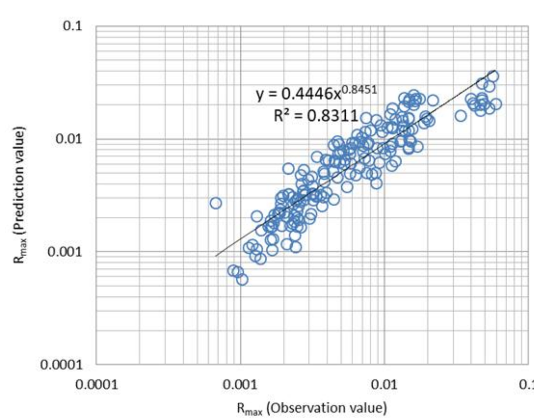
	R_{max}	c_1	c_2	c_3	c_4	c_5	c_6
NS component	X	-1.769	-3.147	-0.287	-0.17	2.147	-0.375
	Y	-1.119	-0.292	-0.221	-0.009	1.892	-0.338
EW component	X	-1.246	-0.511	-0.146	-0.018	3.273	-0.492
	Y	-1.378	-0.069	-0.025	-0.027	0.608	-0.207

3.3 Analytical Results

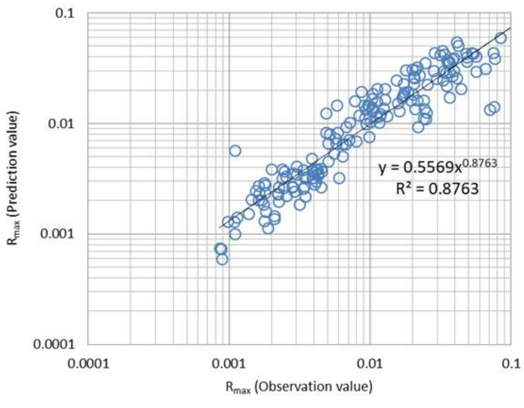
A seismic damage prediction equation of the maximum drift angle of wooden house proposed in the previous session is investigated in this session. Comparison the maximum drift angle, R_{max} (Observation value), obtained from 3-D seismic collapsing process analysis with the maximum drift angle, R_{max} (Prediction value), calculated from Eq. (1) is conducted. R_{max} in X direction is described Rx, and R_{max} in Y direction is described Ry. Coefficient of determination, R^2, of Rx is 0.93, and that of Ry is 0.88 as shown in Figure 5. Any coefficient of determination is very close to 1.0. This implies that the prediction equation of the maximum drift angle, R_{max}, written in Eq. (1) has an accurate precision to seismic damage of wooden house and can utilize seismic damage of wooden house in Kumamoto region in future.



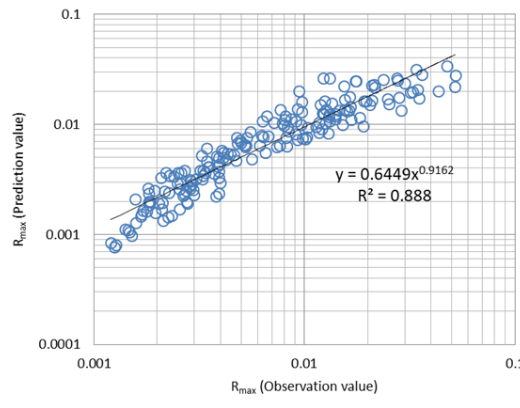
(a)Rx



(a)Rx



(b)Ry
(EW component in X direction)



(b)Ry
(NS component in X direction)

Figure 5. Comparison between R_{max} (Prediction value) and R_{max} (Observation value).

4 CONCLUSIONS

In this paper, a seismic damage prediction function for two-story wooden house by taking into consideration the consecutive strong earthquake motions, the amplification effect of ground surface layer, and the rupture propagation effect of seismic fault was proposed.

The summary of this paper is as follows,

1) The effect of consecutive strong earthquake motions with both the fore-shock and main shock in the 2016 Kumamoto earthquake on the seismic performance of wooden house was analytically revealed. There may be a possibility of a collapse of the wooden house with low seismic performance against consecutive strong earthquake motions.
2) Seismic damage prediction of wooden house around Kumamoto region may be possible by the maximum drift angle prediction equation. This seismic damage prediction of wooden house can be obtained from the recurrence analysis based on some earthquake ground motion waves in the 2016 Kumamoto Earthquake.

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