Directivity effect of the 2016 Kumamoto Earthquake on both the ground motion and the damage of wooden house

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ABSTRACT

In the 2016 Kumamoto Earthquake, a tremendous damage for a Japanese-style traditional framed-based wooden house occurred in Mashiki town, where the Japan Meteorological Agency seismic intensity of “7” level successively observed twice. The rupture propagation effect of a seismic fault, that is, the directivity effect may be one of some primary factors caused a great damage to wooden house. In this paper, ground motions at 50 locations around this seismic fault in the 2016 Kumamoto Earthquake were analytically evaluated by the empirical Green's function method, and the effect of the directivity effect of seismic fault on not only the ground motion but also the maximum drift angle of wooden house representing its seismic damage was investigated. Moreover, the effect of the base shear coefficient of wooden house on its maximum drift angle was evaluated in order to predict the seismic damage of wooden house against a strong earthquake ground motion.

1. INTRODUCTION

A tremendous seismic damage of collapse to wooden house was caused by the 2016 Kumamoto Earthquake occurred on both April 14 ($M_{JMA}=6.5$) and 16 ($M_{JMA}=7.3$) (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 seismic intensity of “7” level successively. In this earthquake, the rupture of a seismic fault propagated toward the northeast direction from its hypocenter, and then the rupture propagation effect of the seismic fault, that is, the directivity effect may be one of some primary factors caused a great damage to wooden structure.

In this paper, the ground motions around this seismic fault caused in the 2016 Kumamoto Earthquake are analytically evaluated by the empirical Green's function method, and the influence of the directivity effect of seismic fault on not only the ground motion but also the maximum drift angle of wooden house representing its seismic damage is investigated in detail. Moreover, the effect of the base shear coefficient of wooden house on its maximum drift angle is evaluated in order to predict the seismic damage of wooden house against a strong earthquake ground motion.
2. ESTIMATION OF SEISMIC GROUND MOTION

2.1 Estimation Method

In this paper, the seismic ground motion around a seismic fault caused in the 2016 Kumamoto earthquake is estimated by the empirical Green’s function method proposed by Nozu et al. (2009). In this estimation procedure, seismic ground motion can be evaluated based on the seismic fault model (Nozu, 2016) with 3 asperities located at the seismic fault indicated in Fig.1. These asperities are shown in Fig.2. Noze (2016) reported that the velocity wave records at observation points of K-NET and KiK-net systems in shown in Fig.1 are accurately reproduced by this estimation procedure.

Fig. 1 Location of the epicenter (star), stations, small events, and fault (square) (Nozu, 2016)  
Fig. 2 Distribution of asperities (square), peak slip velocity, and hypocenter (star sign) (Nozu, 2016)

In this paper, the seismic ground motions on both the ground surface layer and seismic bedrock at 50 locations (b1-k5) around this seismic fault in the 2016 Kumamoto Earthquake shown in Fig.3 are analytically evaluated by the empirical Green’s function method based on the seismic fault model indicated in Fig.2. The signs of A1 to A3 illustrated in Fig.3 represent the asperities 1 to 3, respectively. Asperity 1 has the same location as an estimation point e3 for seismic ground motion.

Seismic ground motion waves observed at KiK-net Mashiki location (KMMH16) for the earthquake with $M_{JMA}=4.2$ occurred at 0:50 AM on April 15, 2016 were employed as a Green’s function in the empirical Green’s function method, and also their motions are common to those of 50 locations. In addition, the site amplification characteristics required in the evaluation of seismic ground motion on ground surface layer are common to all 50 locations. This paper employed some values at KiK-net Mashiki obtained by Nagasaka and Nozu (2016) shown in Fig.4 as a site amplification effect. Also, the non-linearity of ground surface layer due to a strong earthquake motion is taken into consideration by the multi-non-linearity effect (Nozu and Morikawa, 2003) in the evaluation of a seismic motion on ground surface layer.
2.2 Estimation Results

Figs. 5 and 6 show velocity waves at c3, g1, g5 and j3 points on both the seismic bedrock and the ground surface, respectively. j3 point is located at the rupture direction of seismic fault, and c3 point is done at the opposite direction to the rupture direction of seismic fault. g1 and g5 points are located at the perpendicular to the rupture direction of seismic fault.

There is not a significant difference between the velocity amplitudes at c3, g1 and g5 points, and the periods of velocity waves at g1 and g5 locations are longer than that at c3 point. Peak ground velocity (hereafter referred as $PGV$) at j3 point is almost
Fig. 5 Bedrock velocity waveforms calculated by empirical Green’s function method

Fig. 6 Surface velocity waveforms calculated by empirical Green’s function method
three times those at c3, g1 and g3 points, and the amplitude of pulse wave at j3 point is much larger. In the same manner as the velocity waves on the earthquake bedrock shown in Fig. 5, $PGV$ at j3 point on the ground surface indicated in Fig. 6 is almost three times those at c3, g1 and g3 points. $PGV$ on the ground surface is almost 10 times those on the seismic bedrock. It is found from Figs. 5 and 6 that the seismic waves at ground surface are greatly amplified with surface layers on the seismic bedrock.

To investigate the spatial characteristics from $PGV$ values at 50 locations on both the earthquake bedrock and the ground surface, Figs. 7 and 8 indicates the $PGV$ distribution map of both the earthquake bedrock and the ground surface. It is found from Fig. 7 that $PGV$ values at the north-east side from the Asperity 3 trend to be larger than other locations. On the other hand, $PGV$ values at the south side of the seismic fault are larger than other locations in comparison with those on the earthquake bedrock illustrated in Fig. 7, and also even $PGV$ values at some locations around the Asperity 1 are over 100cm/s.

To investigate the relationship between the rupture propagation direction and $PGV$ value, a relationship between the cosine value of theta, $\theta$, shown in Fig. 9 and

![Fig. 7 Distribution of $PGV$ on seismic bedrock](image1)

![Fig. 8 Distribution of $PGV$ on surface](image2)
Fig. 9 Definition of \( \theta \)

Fig. 10 Relationship between \( \cos \theta \) and \( PGV_m \)

the index of \( PGV_m \) multiplied the distance \( X \) from the Asperity 1 by \( PGV \) value is shown in Fig.10. Theta, \( \theta \), can be obtained from normalizing the compass value of a measuring point with the rupture direction (52 degrees) of seismic fault. In this paper, the effect of the distance attenuation on \( PGV \) value is corrected by multiplying the distance \( X \) by \( PGV \) value. As can be obvious from Fig.9, the smaller the distance between observation point and the rupture direction of seismic fault is, the large \( PGV \) value is. It should be noted that the effect of the rupture propagation of seismic fault on \( PGV \) value significantly appears.

3. EFFECT OF RUPTURE PROPAGATION ON WOODEN STRUCTURE RESPONSE

In this section, the effect of the rupture propagation of seismic fault on the response of wooden structure is investigated. The maximum drift angle is used as an index evaluating the response of wooden structure due to seismic motion.
Maximum drift angle \( R \) of wooden house is evaluated by the performance-equivalent acceleration response spectrum, which was proposed by Saratani et al. (2006) and Hayashi et al. (2008). By a contraction method, a two-story wooden house is assumed to be a single degree of freedom with an equivalent height, \( H_e \), and equivalent mass, \( M_e \). The equivalent-performance acceleration response spectrum means an equivalent response spectrum with a seismic performance capacity of wooden house and can be given by the following equation.

\[
S_{ae} = \left( \frac{2\pi H_e R}{T_e} \right)^2 / F_h
\]  

where, \( S_{ae} \) is an equivalent-performance acceleration response spectrum (m/s\(^2\)), \( H_e \) is an equivalent height (m) in the contraction system from a two-story wooden house to a single degree of freedom, \( R \) is a maximum drift angle, \( T_e \) is an equivalent period (s), \( F_h \) is a reduction rate function of acceleration response spectrum. The hysteresis characteristics of wooden house model are assumed to be a bi-linear type, and the yielding shear force can be given by \( M_y gC_y \) for the maximum drift angle \( R_y (=1/100) \) at yielding stage as shown in Fig.11. \( T_e \) corresponding to the maximum drift angle \( R_y \) at yielding stage is given by the following equation.

\[
T_e = \begin{cases} 
2\pi \sqrt{\frac{\mu R H_e}{C_y g}} & (R > R_y) \\
\sqrt{\left(1 + 9\left(\frac{R}{R_y}\right)^{0.7}\right) / 10 \mu R_y H_e / C_y g} & (R \leq R_y)
\end{cases}
\]  

\( \mu \) is a ratio of an equivalent mass to actual mass, and \( C_y \) is a yielding shear force coefficient. The reduction rate function \( F_h \) and the damping factor \( h \) are given by the following equations.

\[
F_h = 1.5 / (1 + 10h)
\]

\[
h = 0.05 \pm (0.2 - 1) \sqrt{R / R_y}
\]

In this paper, \( \mu \) and \( H_e \) are assumed to be 0.9 and 4.5m, respectively, based on the research paper by Saratani et al.(2006). \( C_y \) are assumed to be 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 and \( S_{ae} \) can be calculated for these \( C_y \) values.

![Fig. 11 Analysis model of wooden house (Hayashi et al., 2008)](image-url)
Fig.12 shows the acceleration response spectrum, $S_a$, and the equivalent performance acceleration response spectrum, $S_{ar}$, obtained from the seismic motions on ground surface for the velocity waves at four location of c3, g1, g3 and j3. $S_{ar}$ for $R$ = 0.01, 0.02, 0.03, 0.05, 0.1 and 0.2 are indicated in Fig.12, and an intersection point between $S_a$ and $S_{ar}$ is the maximum drift angle $R$.

In the NS component of both $S_a$ and $S_{ar}$ at c3 and j3 locations, the maximum drift angle of c3 location is over 0.1 in $C_y=0.2$ to 0.4 and also is larger in $C_y>0.05$. On the other hand, the maximum drift angle of j3 location is less than 0.03 for any $C_y$. The maximum drift angle of 0.03 means a large destruction of wooden structure. The maximum drift angle in EW component of both $S_a$ and $S_{ar}$ is larger than that in NS component. In both NS and EW components of both $S_a$ and $S_{ar}$ at g1 and g5 locations, the maximum drift angle is a large value of about 0.1 in $C_y=0.1$ and 0.2, and is 0.02 to 0.03 in $C_y>0.3$. This implies that the seismic damage of wooden structure is reduced by the improvement of seismic performance of wooden structure itself.

![Fig.12 Acceleration response spectrum and equivalent performance acceleration spectrum](image)

(1) NS component

(2) EW component
Fig. 13 indicates the maximum drift angle values for NS component at 50 locations in $C_y = 0.1$ to $0.6$. As can be seen from Fig. 11, the maximum drift angle values at almost all locations in the north side of seismic fault in $C_y = 0.1$ and $0.2$ are over 0.07 and are red markers. The locations with red marker decrease with an increase of $C_y$, and there is no red marker in $C_y = 0.5$ and $0.6$. 

![Fig. 13 Maximum drift angle $R$ for NS component](image)

(1) $C_y = 0.1$

(2) $C_y = 0.2$

(3) $C_y = 0.3$

(4) $C_y = 0.4$

(5) $C_y = 0.5$

(6) $C_y = 0.6$
Fig.14 illustrates the maximum drift angle values for EW component at 50 locations in $C_y=0.1$ to 0.6. The distribution of the maximum drift angle for EW component is almost the same tendency as that for NS component. There are many locations with large maximum drift angle value in $C_y>=0.4$ in comparison with NS component.
Fig. 15 shows the relationship between cosine of $\theta$ and the maximum drift angle, $R$. The maximum drift angle, $R$, in $C_y = 0.1$ to 0.4 trends to increase with cosine of $\theta$. The maximum drift angle, $R$, in $C_y = 0.5$ and 0.6 are almost the same for any cosine of $\theta$. The maximum drift angles at all locations are smaller in comparison with $C_y = 0.1$ to 0.4, and the seismic response of wooden structure seems to be reduced by the improvement of seismic performance of wooden structure.

The maximum drift angles at all locations for EW component trend to be larger in comparison with those for NS component, because the amplitude of velocity wave with the period of about 2 second in the acceleration response spectrum for EW component is larger than that for NS component as shown in Fig. 10.

5. CONCLUSIONS

In the 2016 Kumamoto Earthquake, a tremendous damage for a Japanese-style
traditional framed-based wooden house occurred in Mashiki town, where the Japan Meteorological Agency seismic intensity of “7” level successively observed twice. Because the rupture propagation of a seismic fault caused toward the northeast direction from the hypocenter of this earthquake, the rupture propagation effect of the seismic fault, that is, the directivity effect may be one of some primary factors caused a great damage for wooden house.

In this paper, the ground motions at 50 locations around this seismic fault in the 2016 Kumamoto Earthquake are analytically evaluated by the empirical Green’s function method, and also the influence of the directivity effect of seismic fault on not only the ground motion but also the maximum drift angle of wooden house representing its seismic damage is investigated in detail. Moreover, the effect of the base shear coefficient of wooden house on its maximum drift angle is evaluated in order to predict the seismic damage of wooden house against a strong earthquake ground motion.

The summary of this paper is as follows,
(1) There is a significant difference between the ground surface velocities in the rupture propagation direction and its opposite one of a seismic fault in the 2016 Kumamoto Earthquake. The peak ground surface velocities at several locations in the rupture propagation direction are more than 150cm/s.
(2) Based on the ground motions at 50 locations, the maximum drift angle of wooden house with the base shear coefficient of 0.1 to 0.6 was evaluated. As a result, it was found that the maximum drift angle of wooden house may have a tendency to be large in the rupture propagation direction of seismic fault.
(3) The larger the base shear coefficient is, the smaller the maximum drift angle of wooden house is. It was, consequently, verified that the improvement of seismic performance of wooden house has a significant effect in reducing the seismic response of wooden house.

In this paper, seismic motion waves observed at KiK-net Mashiki location (KMMH16) for the earthquake with $M_{\text{JMA}}=4.2$ occurred at 0:50 AM on April 15, 2016 were employed as a Green’s function in the empirical Green’s function method, and also their motions are common to those of 50 locations. Therefore, seismic motion waves were observed at Mashiki location for the foreshock earthquake with $M_{\text{JMA}}=6.5$ occurred at 21:26 PM on April 14 in the 2016 Kumamoto earthquake, and the directivity effect of seismic fault on not only the ground motion but also the maximum drift angle of wooden house against these seismic waves will be investigated in near future. In addition, some directivity analyses with changing of both the site amplification characteristics and small seismic waves used as a Green’s function may be needed to make some concrete conclusions.

REFERENCES

