Initial 30 seconds of the 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0)—amplitude and τ_c for magnitude estimation for Earthquake Early Warning—

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We analyzed the waveforms of the mainshock (M_w 9.0) and three foreshocks of the 2011 off the Pacific coast of Tohoku Earthquake during the initial 30 s after P -wave onset to determine the maximum amplitudes of acceleration, velocity, and displacement, and τ_c (the period parameter of the waveform). The amplitudes for the M_w 9.0 event were quite small for the first several seconds, as small as those of the M_w 6 foreshocks, and the τ_c value was also as small as those of the foreshocks. For the first 30 s, the amplitude of the M_w 9.0 event was larger than that of the M_w 7.3 foreshock whereas τ_c was smaller. These results suggest that it is difficult to determine the eventual magnitude for very large earthquakes from the initial several seconds, that an updating procedure is important for Earthquake Early Warning using ongoing waveforms, and that τ_c might not be reliable for magnitude estimation at least for the main shock.

Key words: Earthquake Early Warning, magnitude, τ_c , the 2011 off the Pacific coast of Tohoku Earthquake.

1. Introduction

Earthquake Early Warning (EEW) systems have been researched and developed in Japan, Mexico, the United States, Taiwan, Italy, Turkey, and other countries (e.g., Hoshiba *et al.*, 2008; Alcik *et al.*, 2009; Allen *et al.*, 2009; Espinosa Aranda *et al.*, 2009; Hsiao *et al.*, 2009; Kamigaichi *et al.*, 2009; Nakamura *et al.*, 2009; Zollo *et al.*, 2009). One of the important aspects of EEW is the rapid and reliable estimation of magnitude using the early portion of ongoing waveforms. Maximum amplitudes have commonly been used for magnitude estimates, and these are adopted in some EEW systems (e.g., Yamamoto *et al.*, 2008; Kamigaichi *et al.*, 2009), in which the estimate of magnitude is updated repeatedly using ongoing waveforms.

New algorithms, such as τ_c and $\tau_p^{\max}$, have been proposed for making estimates of the eventual magnitude by using the frequency contents of the very early portion of the waveforms; these algorithms have been investigated by many researchers (e.g., Nakamura, 1988; Wu and Kanamori, 2005; Wu *et al.*, 2007; Allen and Kanamori, 2003; Yamada and Mori, 2009; Brown *et al.*, 2009; Zollo *et al.*, 2010). Most of these researches have concluded that the frequency contents are more sensitive to the magnitude than the ground-motion amplitude during the initial several seconds of the P wave. They have also claimed that the sensitivity is appropriate for EEW and that it is possible to determine the eventual size of the events from the initial several seconds. However, Rydelek and Horiuchi (2006) and Rydelek *et al.*

(2007) using the data from accelerometers networks and high-sensitivity velocity-meter networks concluded that the size of larger earthquakes are difficult to estimate from only the early part of the records. Yamada and Ide (2008) came to a similar conclusion after considering a complex-source model. The validity of the new algorithms such as τ_c and $\tau_p^{\max}$ for estimates of magnitude is not yet fully accepted.

The 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0) occurred on March 11, 2011, following foreshock activity. We have used the waveform data of the mainshock and three foreshocks to estimate the maximum acceleration, maximum velocity, maximum displacement and τ_c from the initial t_N seconds of the waveform from the onset of the P wave using t_N values from 3 to 30 s. We then consider whether the amplitudes or τ_c could discriminate the mainshock from the smaller foreshocks during the initial portion of their waveforms.

2. Data

The 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0) followed several large foreshocks. We used the waveform data of acceleration of the main shock and three foreshocks recorded at MYG002, MYG008, MYG011 and MYGH12 (surface) of the K-NET and KiK-net seismic networks of the National Research Institute for Earth Science and Disaster Prevention (NIED), which are the closest four stations to the epicenters of the events (Fig. 1). We chose to study foreshocks because of their relatively low noise level in comparison to the aftershocks of this enormous event. We used waveforms whose P -wave onsets were not contaminated by noise or by codas of preceding events, choosing three foreshocks of M_w 5.9, 6.0 and 7.3. The waveform at MYG011 from the M_w 5.9 event was noisy, so it was ex-

Fig. 1. Locations of observation sites and earthquakes used in this analysis. The times are March 9, 13:37 Japan local time (M_w 5.9), March 10, 03:16 (M_w 6.0), March 09, 11:45 (M_w 7.3) and March 11, 14:46 (M_w 9.0). The moment magnitudes are taken from the JMA catalog for the M_w 6.0, 7.3, and 9.0 events, and from the NIED for the M_w 5.9 event.

cluded. Focal depths of the events were 8 to 24 km, and the epicentral distances ranged from 121 to 164 km.

Some previous studies of τ_c used waveform data from many earthquake events and many recording stations, with differences in the distance between source and recording stations: many of them were from less than 100 km, and some were from larger than 100 km for larger events. The many different source-site geometries and site amplification factors may have affected the results of those studies. Variations due to differences in path factor were small in our analysis because we used only a few events that were close together, and a few observation sites that were also close together.

3. Analysis

The offset of the vertical-component accelerogram was corrected by subtracting the mean of the early portion of the data to obtain $u_a(t)$. It was integrated, passed through a second-order one-way high-pass Butterworth filter of 0.075 Hz, and integrated and filtered again to obtain the displacement waveforms, $u_d(t)$. The displacement was then differentiated to obtain the velocity, $u_v(t)$. The peak amplitudes P_a , P_v and P_d are the maximum absolute amplitudes of $u_a(t)$, $u_v(t)$ and $u_d(t)$, respectively, for the range between t_p and $t_p + t_N$, where t_p is the P -wave onset time. For t_N , we used values of 3, 4, 5, 10, 20 and 30 s. The parameter τ_c is obtained from

$$\begin{aligned} \tau_c &= 1/\sqrt{\langle f^2 \rangle} = \sqrt{\int_0^\infty |U_d(f)|^2 df / \int_0^\infty f^2 |U_d(f)|^2 df} \\ &= 2\pi \sqrt{\int_{t_p}^{t_p+t_N} u_d^2(t) dt / \int_{t_p}^{t_p+t_N} u_v^2(t) dt}, \end{aligned} \quad (1)$$

where f and $U_d(f)$ are the frequency and the frequency spectrum of $u_d(t)$, respectively, and $\langle f^2 \rangle$ is the average

of f^2 weighted by $|U_d(f)|^2$ (Kanamori, 2005). Thus, τ_c corresponds to the average period of $u_d(t)$, and is expected to increase with increasing earthquake magnitude.

4. Results and Discussion

Figure 2 shows the waveforms $u_a(t)$ and $u_d(t)$ of the M_w 9.0 earthquake recorded at MYGH12. Both $u_a(t)$ and $u_d(t)$ are small for the initial 5 s; $u_a(t)$ is as small as 1 cm/s², and $u_d(t)$ is comparable to the noise level. This indicates that the initial phases do not suggest a large magnitude event.

Figure 3 summarizes P_a , P_v and P_d and τ_c for various values of t_N for the four events. For $t_N = 3$ –5 s, the peak amplitudes of the M_w 9.0 event are comparable to, or even smaller than, those of not only the M_w 7.3 event but also the two smaller foreshocks, and τ_c does not show a clear tendency because of the large variation among the different sites. For $t_N = 20$ s, P_a of the M_w 9.0 event is larger than that of the M_w 7.3 event beyond the variation among sites, which indicates that P_a discriminates the M_w 9.0 from the M_w 7.3 event. For $t_N = 30$ s, P_v and P_d also effectively discriminate. However, although τ_c of the M_w 9.0 event is larger than that of the two smallest events, it is a little smaller than that of the M_w 7.3 event, which suggests that it is difficult to recognize the event to be larger than the M_w 7.3 from only τ_c at $t_N = 30$ s when accelerations exceeding 100 cm/s² are recorded at all four stations.

When the analysis was performed using a different high-pass filter of 0.166 Hz, and when the second filtering pass was omitted when obtaining $u_d(t)$, the results were similar.

The parameter $\tau_p^{\max}$ also has been investigated for rapid estimates of earthquake magnitude (e.g., Allen *et al.*, 2009), based on the expectation that $\tau_p^{\max}$ increases with increasing magnitude. $\tau_p^{\max}$ is the maximum value of the initial several seconds (4 s is used in many previous studies) of $\tau_p(t)$ which is defined as $2\pi(X_i/D_i)^{1/2}$ (Allen and Kanamori, 2003). Here $X_i = \alpha X_{i-1} + x_i^2$ and $D_i = \alpha D_{i-1} + (dx/dt)_i^2$, where x_i is the time series of the ground velocity, and α is a smoothing constant (for example, $\alpha = 0.99$ is used for 100 samples/s data). Though both τ_c and τ_p are based on the frequency contents, the main difference is that τ_c is estimated from displacement and its differential using a time window from the P -wave onset, while τ_p is computed recursively from velocity and its differential. Thus τ_c represents the average period of displacement over the time window as shown in Eq. (1), while τ_p is the average period of velocity weighted by the lapse time, in which the weight is controlled by α (the contribution of a given waveform segment decreases with time). Because τ_p is estimated recursively, τ_p is expected to be more sensitive to the lapse time than τ_c . We estimated $\tau_p(t)$ using waveforms of the M_w 9.0 events and the three foreshocks recorded at MYGH12 (Fig. 4). Here, we use $u_v(t)$ directly as x_i , or after passing through a second-order one-way low-pass Butterworth filter of 3 Hz in this analysis. The 3-Hz low-pass filter has been commonly used in many previous studies. In Fig. 4 (top: with a 3 Hz filter), $\tau_p(t)$ does not show a clear magnitude dependence at the early part of the waveforms, and while $\tau_p(t)$ of M_w 7.3 is larger than those of M 6 class earthquakes, that of M_w 9.0 is relatively small at the later part. This sug-

Fig. 2. Acceleration $u_a(t)$ (left) and displacement $u_d(t)$ (right) of the vertical component of the M_w 9.0 event at MYGH12. Magnified traces are shown below. Arrival times of the P and S phases are shown by dotted lines.

Fig. 3. Peak amplitudes P_a , P_v and P_d and the parameter τ_c versus M_w for the four events studied for various values of t_N . Locations of the four stations are shown in Fig. 1.

gests that it is difficult to recognize the M_w 9.0 event to be larger than the M_w 7.3 event from $\tau_p^{\max}$. When the analysis was performed using a different low-pass filter of 1 Hz or a different order (6th order), the results are similar. In Fig. 4 (bottom: without a 3 Hz filter), $\tau_p(t)$ of M_w 9.0 is especially small for the 4 events after 15 s in comparison to the case with a 3 Hz filter, which suggests that a higher frequency greater than 3 Hz became relatively rich in the waveform of the M 9.0 event after 15 s.

Figure 5 shows the frequency spectra of waveforms of the M_w 9.0 and M_w 7.3 events at MYGH12. The spectrum of the M_w 9.0 is flat to the frequency of the anti-alias filter around 30 Hz for the time window of t_p to $t_p + 30$ s. The spectral ratio shows that high frequencies are richer for the M_w 9.0 event than for the M_w 7.3 event as compared with low frequencies. This high-frequency content is not apparent for the time window of t_p to $t_p + 10$ s, so it is thought that the high-frequency waves arrived after $t_p + 10$ s, as is

Fig. 4. The parameter $\tau_p(t)$ versus lapse time from P -wave onset for the four events at MYGH12. (Top) with a low-pass filter of 3 Hz. (Bottom) without a low-pass filter.

Fig. 5. Frequency spectra of the vertical acceleration recorded at MYGH12 for the M_w 9.0 event (left), and M_w 7.3 event (center), and the ratio of the two spectra (right) derived from time windows corresponding to $t_N = 10$ s (light gray), 20 s (dark gray) and 30 s (black). Waveforms are shown at the top.

suggested in Fig. 4 (bottom). The high-frequency content is the reason that a smaller τ_c and $\tau_p(t)$ were obtained for the M_w 9.0 event even for a large value of t_N . The waveforms of rich high frequency from the M_w 9.0 event are contrary to the expectation that τ_c increases with increasing magnitude.

5. Conclusion

Our results suggest that it would be difficult to estimate the eventual magnitude of the M_w 9.0 earthquake from the initial several seconds, even if the parameters based on frequency contents, such as τ_c and $\tau_p^{\max}$, were used, and indicates that an updating procedure is necessary, using ongoing

waveforms, for EEW purposes. It would also be difficult to recognize that the M_w 9.0 event would be larger than the M_w 7.3 event using only τ_c based on the initial 30 s of the record, a time during which the ground-motion amplitude is clearly larger than that of the M_w 7.3 event. This is contrary to the claim that the frequency contents are more sensitive to earthquake magnitude than ground-motion amplitude.

As shown in Fig. 5, the frequency contents of the M_w 9.0 earthquake may be quite different from that expected for earthquakes of this size. The source process of the M_w 9.0 earthquake might be extraordinary for an M_w 9 class earthquake, and this analysis is only one case of an M_w 9 class

earthquake. It is impossible to conclude from this case that τ_c and $\tau_p^{\max}$ are ineffective for magnitude estimation for all larger events. But even so, our analysis shows that the extraordinary is not necessarily improbable. We believe that the EEW system should be robust even for extraordinary cases, especially for larger events.

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