Real-time earthquake warning by using broadband P Waveform

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Received 14 August 2002; revised 24 October 2002; accepted 15 November 2002; published 26 December 2002.

[1] We develop a system, which enables an early warning of earthquake occurrence several seconds before large ground shaking begins. We assume that the vertical displacement of the broadband P waveform can be considered as the far-field source time function of the earthquake. Based upon the seismic moment to source duration relation, we may issue an early warning that an earthquake with magnitude greater than 6 has occurred, when the initial P-wave pulse duration continues for more than 3 seconds. We have applied this algorithm to broadband seismograms recorded at Japanese broadband stations for recent large earthquakes in Japan. We found that it really is possible to assess the occurrence of earthquakes with magnitude greater than 6 within 3 seconds after the P-wave arrival. INDEX TERMS: 7215 Seismology: Earthquake parameters; 7260 Seismology: Theory and modeling; 7294 Seismology: Instruments and techniques; 7299 Seismology: General or miscellaneous. Citation: Tsuboi, S., M. Saito, and M. Kikuchi, Real-time earthquake warning by using broadband P Waveform, Geophys. Res. Lett., 29(24), 2187, doi:10.1029/2002GL016101, 2002.

1. Introduction

[2] There are several real-time earthquake warning systems, which allow users to receive earthquake information immediately after the occurrence of a large earthquake, based on modern communication technology and advances in basic seismology [e.g., Kanamori et al., 1997]. The main goal of these systems is to provide an earthquake warning several seconds before large ground shaking begins [e.g., Nakamura, 1996]. This type of early warning may be useful for disaster mitigation, if it is properly used to shutdown the systems susceptible to damage, such as ATM system. To issue an early warning for a large earthquake, we need to know the size of the earthquake before the large amplitude surface waves arrive at the station. Although we usually use the surface waves to determine the magnitude of an earthquake, apparently this procedure does not work for an early warning. We may use the duration of the initial P-wave pulse to estimate the seismic moment by using the seismic moment to duration relation. However, the smallest disastrous earthquakes in Japan are about magnitude 6, while the duration of the P-wave for magnitude greater than 7 earthquakes is longer than 10 seconds. Therefore, for the stations close to the epicenter the large ground shaking begins before we can estimate the magnitude of the earthquake.

Thus, we develop a system to issue an early warning, which indicates that a magnitude greater than 6 earthquake has occurred, based on the procedure proposed by Kikuchi [2000].

[3] Here we describe a prototype real-time earthquake warning system, which realizes this type of early warning and is currently working at Yokohama City University. We use an STS-2 broadband seismograph, from which data are transmitted to a workstation in real-time through the internet. We assume that the vertical displacement of the P-wave, which is obtained by integrating the broadband velocity seismogram in the time domain, can be considered as the far-field source time function of the earthquake. After the P-wave arrives, if the displacement seismograms exceeds a certain threshold, and does not cross zero for more than 3 seconds, we can assume that an earthquake of magnitude greater than 6 is taking place, based on the standard seismic moment to source duration relation. The system, then, sends email and continues to count the duration of the P-wave. If the duration of the P-wave becomes longer than 10 seconds, then, the system sends email, which says that an earthquake of magnitude 7 is occurring. Because we detect the occurrence of the earthquake in the time domain, it may be faster than a system which is designed to detect in the frequency domain. Because no significant earthquakes have occurred near Yokohama, since this system started to operate in 2001, we have applied this algorithm to broadband seismograms recorded at Japanese broadband stations for recent large earthquakes in Japan. We found that by choosing appropriate thresholds for each station, it is possible to detect the occurrence of earthquakes with magnitude greater than 6 within 3 second after the P-wave arrival. Thus this system will make it possible to issue an early warning successfully even before large ground shaking begins.

2. Method

[4] We use a well-known proportionality between the seismic moment \( M_0 \) and \( \tau^3 \) for the basis of our early warning system, where \( \tau \) is the source duration. This proportionality is reported by many studies for various types of earthquakes [e.g., Kanamori and Anderson, 1975; Furumoto and Nakanishi, 1983; Kikuchi and Ishida, 1993; Houston et al., 1998; Tsuboi, 2000]. Here we assume

\[
M_0/\tau^3 = 1.0 \times 10^{16} \text{[N \cdot m/sec}^3\text{]} \tag{1}
\]

based on the discussion of Kikuchi and Ishida [1993] for shallow earthquakes which occurred near Yokohama. This relation gives \( M_{ew} = 4.6 \) for \( \tau = 1 \) second and \( M_{ew} = 5.6 \) for \( \tau = 3 \) seconds. \( M_{ew} = 6.7 \) corresponds to \( \tau = 10.0 \). Although this proportionality depends on the depth of the earthquake, we may assume that the difference in magnitude should be
\[ \pm 0.3 \text{ since } M_0/t^3 = 1.0 \times 10^{17} \text{ [N \cdot m/sec^3]} \] for those earthquakes with depths deeper than about 50 km.

[5] We choose a certain time interval at each point to calculate an average and a standard deviation of displacement. The threshold of the displacement is determined by multiplying some factor to the standard deviation. Since equation (1) is for shallow earthquakes, the duration of the P-wave should actually be shorter than 3 seconds for deeper magnitude 6.0 earthquakes. From the standpoint of hazard mitigation, however, we should concentrate on shallow large earthquakes. Thus, to prevent issuing false alarms for small shallow earthquakes, we should wait for 3 seconds before issuing a warning for a magnitude greater than 6.0 earthquake, even though deeper earthquakes larger than magnitude 6.0 may be missed.

3. Example

[6] We used an STS-2 broadband seismograph and a Quanterra Q4126 recording system, which are installed in Yokohama City University, to develop this early warning system. The continuous broadband seismogram with sampling frequency 20 Hz is transmitted to a workstation in real-time through the internet. We use the vertical component of this broadband seismogram to determine the P-wave arrival and integrate it in time domain to get displacement. Figure 1 shows an example of a seismogram recorded for an M4.4 local earthquake, which occurred on September 18, 2001 near Tokyo Bay. Dashed lines are at the 6\(\sigma\) level of the displacement, where the standard deviation \(\sigma\) is calculated 0.5 minute, 2 minute and 4 minute displacement before that point, respectively.

Figure 1. The P-wave portion of the vertical displacement broadband seismogram recorded at Yokohama City University for a M4.4 local earthquake, which occurred on September 18, 2001 near Tokyo Bay. Dashed lines are at the 6\(\sigma\) level of the displacement, where the standard deviation \(\sigma\) is calculated 0.5 minute, 2 minute and 4 minute displacement before that point, respectively.

[7] We found that the system successfully detected the occurrence of magnitude greater than 6 earthquakes and sent email within 3 seconds after the onset of the P-wave, using the parameters for the time-window and the multiplication factor mentioned above. Figure 3 shows the P-wave pulse for the Western Tottori earthquake recorded at station NRW. Figure 4 shows the P-wave pulse for the Geiyo earthquake recorded at station TGW. The epicentral distance for NRW is 59 km and for TGW is 26 km. Both stations are the closest to their respective epicenters among the stations used and there are about 5 seconds left until the largest amplitudes are recorded. Because of the location and size of these earthquakes, the JMA seismic intensity scale exceeded 6 at these stations causing some damage to

Figure 2. The epicenters (stars) and stations (circles) used in the present study. The closed star is for the Geiyo earthquake and the open star is for the Western Tottori earthquake. We have used broadband seismograms from the Freesia broadband seismograph network operated by the National Research Institute for Earth Science and Disaster Prevention (NIED) in Tsukuba.
The results show that we could have issued the alert email about 5 seconds before the largest shaking started at each station, if this system had been working at these sites at the time of these earthquakes.

4. Discussion

We show that the duration of the initial broadband P-wave displacement pulse can be used to issue an early warning for a devastating earthquake. However, even in a seismically active country like Japan, large earthquakes, such as the 1923 Kanto earthquake or the 1995 Kobe earthquake, occur only once in a couple of decades. So, to make the early warning issued by the present system reliable, it is important to prevent false alarms. If the system issues early warnings for small earthquakes, which occur about once a year in the Yokohama area and do not cause any hazard, it is likely that people will not believe these warnings. Although we have demonstrated in Figure 1 that those small earthquakes with a duration of less then 1 second will be ignored by this system, we may have a problem for large earthquakes that occur near the Japanese Islands. We show the example of the September 20, 1999 (Ms 7.7) Taiwan earthquake in Figure 5 for station ISI of the Freesia broadband seismograph network and the 2001 Geiyo earthquake. Because the Taiwan earthquake occurred far from the Japanese Islands, we do not want the system to issue an early warning for this event. However, since the current system measures only the duration of the first arriving P-wave, it would have issued an e-mail alarm 3 seconds after the P-wave arrival for the Taiwan earthquake at station ISI. To prevent issuing false alarms for events like the Taiwan earthquake, we should consider the amplitude of the P-wave when the duration continues to 3 second. Figure 5 also shows the example of the P-wave at station ISI for the 2001 Geiyo earthquake. The amplitude of the P-wave at 3...
seconds after its arrival differs almost an order of magnitude between the Taiwan earthquake and the Geiyo earthquake. This result illustrates that we should take into account the amplitude of the P-wave to issue the early warnings correctly. Although we have not tested this system for earthquakes greater than magnitude 7 recorded at close distances from the epicenter, we suppose that the extremely large amplitude of the P-wave pulse will enable the system to notify the occurrence of large event successfully.

[9] We also should point out that a single-station based system, presented in the present paper, should be combined with a multiple-station system to increase the reliability of the early warning system. By comparing the source duration and the P-wave amplitude among different stations, it should be possible to distinguish teleseismic signals from those excited by local events. The combination of the single-station system and the multiple-station system should also help to issue alarms for extraordinary events. Because the earthquake stress drops of large events show an order of magnitude variation, the source duration may result a factor of three variation. Then the system may not be able to detect events with abnormally short duration. If the source duration is abnormally short for its earthquake magnitude, it is expected that the amplitude of the P-wave pulse is unusually large. Then by combining both the source duration and the amplitude of the P-wave pulse with multiple-station analysis, it may be possible to detect an occurrence of abnormal event from the first arrival P-wave pulse.

[10] We designed the system to detect large earthquakes in the time domain by measuring duration of the first arriving P-wave pulse. Another way to detect large earthquakes is by monitoring the dominant instantaneous frequency [e.g., Nakamura, 1996]. The basic idea assumes that the accelerogram divided by the velocity seismogram is proportional to the angular frequency $\omega = 2\pi f$. When the P-wave arrives, the frequency $f$ should have a minimum value corresponding to the P-wave duration. However, it is not straightforward to relate this value to the magnitude. Thus we believe that our system, which detects the occurrence of large events in the time domain from the duration of the P-wave, is a quite straightforward and robust procedure compared with a system based on the frequency domain procedure.

5. Results

[11] We found that by choosing appropriate thresholds for each station, it is possible to detect the occurrence of earthquake with magnitude greater than 6 within 3 sec after P-wave arrival using broadband P-wave duration. Thus this system will make it possible to issue early warning successfully even before large ground shaking begins.

[12] Acknowledgments. We used the broadband seismograms of Freesia broadband seismograph network obtained through the National Research Institute of Earth Science and Disaster Prevention in Tsukuba. We would like to thank two anonymous reviewers for critically reviewing the manuscript. Hisako Ozawa and Junko Fukuchi helped us with early development of the program.

References


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