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Development of earthquake early warning system in Taiwan

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[1] With the implementation of a real-time strong-motion network by the Central Weather Bureau (CWB), an earthquake early warning (EEW) system has been developed in Taiwan. In order to shorten the earthquake response time, a virtual sub-network method based on the regional early warning approach was utilized at first stage. Since 2001, this EEW system has responded to a total of 225 events with magnitude greater than 4.5 occurred inland or off the coast of Taiwan. The system is capable of issuing an earthquake report within 20 sec of its occurrence with good magnitude estimations for events up to magnitude 6.5. Currently, a P-wave method is adopted by the CWB system. Base on the results from 596 M $\geq$ 4.0 earthquakes recorded by the real-time strong-motion network, we found that peak displacement amplitudes from initial P waves (P_d) can be used for the identification of M $\geq$ 6.0 events. Characteristic periods τ_c and τ_p^{max} of the initial P waves can be used for magnitude determination with an uncertainty less than 0.4. We expect to achieve a 10-second response time by the EEW system in Taiwan in the near future. **Citation:** Hsiao, N.-C., Y.-M. Wu, T.-C. Shin, L. Zhao, and T.-L. Teng (2009), Development of earthquake early warning system in Taiwan, *Geophys. Res. Lett.*, *36*, L00B02, doi:10.1029/2008GL036596.

1. Introduction

[2] Taiwan is located on the western portion of the Circum-Pacific seismic belt. The Philippine Sea plate subducts northward under the Eurasia plate along the Ryukyu trench. The Eurasia plate subducts eastward under the Philippine Sea plate off the southern tip of Taiwan. Most of Taiwan is under a northwest–southeast compression with a measured convergence rate of about 8 cm/year. Many disastrous earthquakes have occurred in the past. Figure 1 shows the distribution of disastrous earthquakes in Taiwan since 1900. A real-time strong-motion network has been installed by the CWB since 1995 for seismic hazard mitigation purpose. With the subsequent developments of the past decade, this network has been utilized for rapid report of felt earthquakes [*Shin et al.*, 1996; *Wu et al.*, 1997] and for developing Taiwan's EEW system [*Wu et al.*, 1998, 1999; *Wu and Teng*, 2002; *Hsiao*, 2007].

[3] Currently, EEW system is regarded as a useful tool for real-time seismic hazard mitigation. An EEW system provides a few seconds to tens of seconds of advanced warning time of impending ground motions, allowing for mitigation measures to be taken in the short term. EEW systems that estimate the severity and onset time of ground shaking are already developed and tested in a number of countries [*Nakamura*, 1988; *Espinosa-Aranda et al.*, 1995; *Allen and Kanamori*, 2003; *Erdik et al.*, 2003; *Kamigaichi*, 2004; *Horiuchi et al.*, 2005; *Zollo et al.*, 2006; *Ionescu et al.*, 2007; *Olivieri et al.*, 2008]. There are two different approaches to EEW: Regional warning and onsite warning. In regional warning systems, traditional seismological methods are used by a network of stations to determine the locations and magnitudes of earthquakes and to estimate the ground motion in the region involved. In onsite warning systems, the beginning part of the ground motion at a given site is used to predict the ensuing ground motion.

[4] Taiwan is one of the leading countries in EEW developments with operational experience of more than 10 years. It was motivated by the lesson of the 15 November, 1986, M_w 7.8 offshore Hualien earthquake. Although the epicenter was off the eastern coast of Taiwan, the most severe damage occurred in metropolitan Taipei, 120 kilometers away from the epicenter, due to the basin amplification effect. If a seismic network in Hualien area can provide an estimation of earthquake parameters within 30 seconds, there will be an advanced warning time of up to tens of seconds for Taipei before the strong ground shaking starts. Hence, a virtual sub-network (VSN) method based on regional EEW approach was adopted in Taiwan in this first attempt [*Wu and Teng*, 2002]. The VSN has been in operation for practical real-time earthquake monitoring since 2001, and the results show that the average reporting time of earthquake estimation by this system can be shortened to within 20 sec after the occurrence of earthquakes [*Hsiao*, 2007]. This means that this system can provide earthquake early warnings for metropolitan areas located more than 70 km from the epicenter.

[5] Meanwhile, other studies for EEW applications were conducted in Taiwan. *Wu et al.* [2001] and *Hsiao* [2007] derived the empirical relationships between peak-ground acceleration (PGA), peak-ground velocity (PGV) and magnitudes, which can be used to predict strong ground shakings for urban areas and create shake maps by the EEW system. Furthermore, *Wu et al.* [2004] utilized the data gathered from the disastrous 1999 Chi-Chi earthquake to derive the empirical relationships between the peak values (PGA & PGV) of ground motion and seismic losses. As a result, after the occurrence of an unexpected earthquake, a comprehensive report can be issued within two minutes with assessment of the impending ground shaking to the area near the epicenter as well as possible seismic hazard caused by the earthquake, providing guidance for emergency response.

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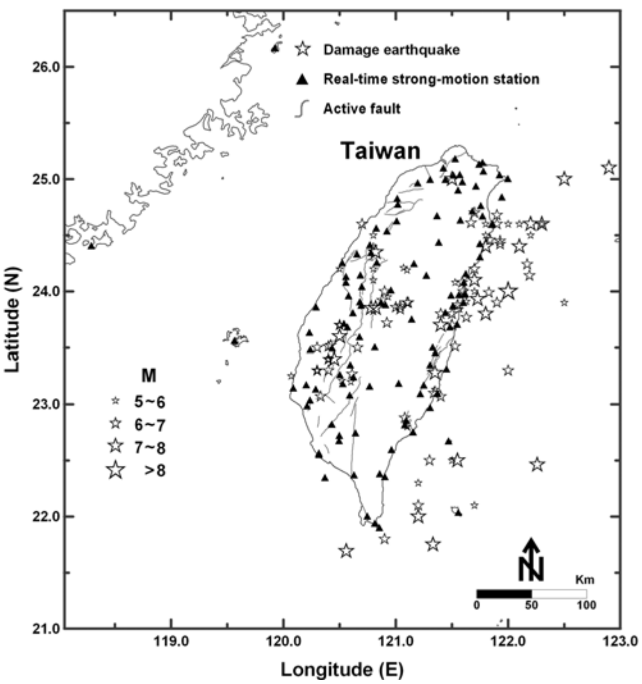

Figure 1. Real-time strong-motion stations (solid triangles) implemented by CWB for seismic hazard mitigation. Stars show the locations of destructive earthquakes occurred around Taiwan since 1900.

[6] Due to the dependence on a network of stations, the VSN approach has a "blind zone" with a radius of 70 km around the epicenter, in which warnings cannot be issued in a timely manner. For the early warning to areas closer to the source, the P-wave method is considered, in which we utilize the real-time strong-motion data to estimate earthquake magnitudes based on empirical relationships between magnitude and a few parameters determined from the initial P-wave.

2. Real-Time Strong-Motion Network

[7] The current EEW system at CWB was established based on the framework of a real-time strong-motion network. This seismographic network consists of 109 digital telemetered strong-motion stations distributed over the entire Taiwan region covering an area of 36,000 square kilometers at present. Figure 1 shows the locations of the seismic stations. Each station has a three-component force-balanced accelerometer with a 16-bit resolution, and the record has a full dynamic range of ±2g. The model of the accelerometer is A900A manufactured by *GeoTech Instruments* [1994]. Acceleration signals are continuously transmitted to the data center in Taipei at a 50 samples per second rate via 4,800-baud telephone and T1 lines. At the data center, the signals are processed continuously and automatically by a group of personal computers. At present, once a felt earthquake occurs, the system-wide rapid reporting system (RRS) can issues a detailed assessment of the earthquake information, including the location and magnitude of the earthquake and a shake map, through the Internet and mobile phones in about one minute.

[8] Since its inauguration in 2001, the VSN-enhanced EEW system has issued earthquake alerts for a total of 225 events with magnitudes greater than 4.5 occurred inland or offshore near Taiwan. The performance of the EEW system is summarized in Figure 2. Figure 2a shows the comparison between the magnitudes determined automatically by the VSN and the manually determined ones published in the CWB earthquake catalogs. Most of the magnitudes determined by VSN correlate well with the values reported in the earthquake catalogs, with a standard deviation of 0.28. However, for the 31 March 2002, offshore Hualien earthquake, the magnitude was underestimated by the VSN by about one magnitude unit. This discrepancy was caused by the limited length of the waveforms used in the VSN calculations. Even though an empirical formula was used to correct the magnitude, this earthquake occurred off the eastern coast of Taiwan and was 50 kilometers from the nearest station. As a result, at nearly all of stations in the VSN the S waves were not included in the magnitude estimation since they fell outside the 10-sec time window used in the EEW calculations.

[9] Earthquake reporting time is a crucial factor for the EEW applications. Figure 2b shows the reporting times by the VSN since 2001. Compared with the results by the system-wide RRS, with limited time window specified, the average reporting time can be effectively reduced to within 20 sec. From the viewpoint of earthquake emergency response, the performance of the VSN represents a significant step towards a realistic earthquake early warning capability. As we discuss in the next section, its performance can be further improved by the P-wave method.

3. P-Wave Method

[10] Motivated by the recent success of earthquake early warning systems, we have also conducted an investigation, using the real-time strong-motion data from CWB stations, into the relationships between the earthquake magnitude and several parameters obtained from the first few seconds of the P waveform. Here we consider the peak amplitude of the displacement P_d, the average period τ_c [*Kanamori*, 2005; *Wu and Kanamori*, 2005a, 2005b, 2008a, 2008b; *Wu and Zhao*, 2006; *Wu et al.*, 2007], and the dominant period τ_p^{max} [*Nakamura*, 1988; *Allen and Kanamori*, 2003] of the initial P-wave.

[11] τ_c is a measurement of the average period of the P wave within the first few seconds, which can be used to estimate the size of an earthquake. It is determined by selecting a specific time window and measuring the frequency content of the waveform in the window. Similarly, τ_p^{max} is also a measure of the frequency content of the P waveform. However, the procedure for obtaining τ_p^{max} is quite different, and provides a measure of the dominant period of the selected P waveform in the time window. The definitions of these two P-wave period parameters as well as the amplitude P_d and the procedures for measuring them can be found in previous studies. Here, we combine τ_c and τ_p^{max} in estimating the magnitude of earthquakes for EEW appli-

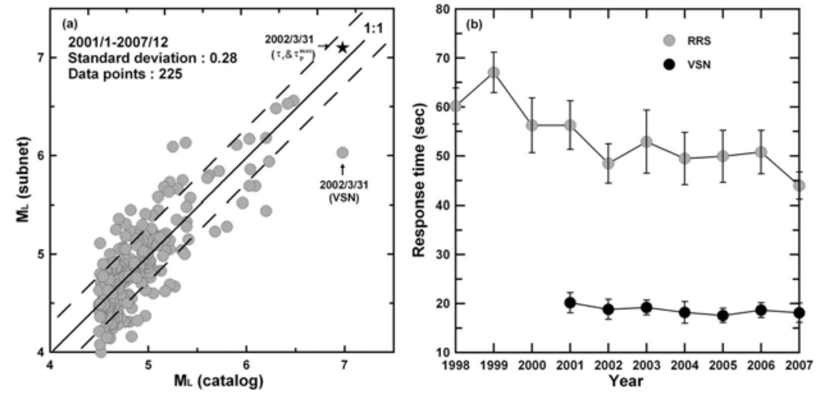

Figure 2. (a) Comparison of magnitudes determined automatically by VSN with catalog ones. Solid line shows the least squares fit and the two dashed lines show the range of one standard deviation. For the 31 March 2002, offshore Hualien earthquake, the magnitude was underestimated by about one unit by VSN, whereas the P-wave method yields more accurate result (solid star). (b) Average reporting times by VSN and the entire network (RRS) since 2001. When fewer stations are used, the average reporting times can be effectively reduced to within 20 sec.

cations in order to reduce the uncertainty [*Shieh et al.*, 2008].

[12] We adopt a time-window length of 3 seconds for the P wave in magnitude estimation and use a high-pass recursive Butterworth filter with a cutoff frequency of 0.075 Hz to remove the low frequency drift. Most of the real-time strong-motion stations are located in urban areas and records for small shakings from those stations generally have low signal to noise ratio. Thus, only records with P_d values greater than 0.08 cm were used for evaluating τ_c and $\tau_p^{\max}$.

4. Results

[13] In this study, in order to find the relationships between magnitude and P_d, τ_c and $\tau_p^{\max}$ measurements, we used a total of 596 earthquakes with $M_L \geq 4.0$ recorded by the CWB real-time strong-motion network since 1998. The relationships were obtained by linear regression using the measurements from five nearest stations within 40 km from the earthquakes. The results are illustrated in Figure 3.

[14] As shown in Figure 3a, most of the earthquakes with average P_d values of 0.1 cm or above have magnitudes large than 6.0. In addition, the values of log P_d increase approximately linearly with M_L when the earthquake magnitudes are greater than 5.5. The linear regression between log P_d and M_L using the 38 events with $M_L \geq 5.5$ yields the relationship:

$$\log P_d = 1.62 \times M_L - 12.36, \qquad (1)$$

with a standard deviation of 0.80. This relationship can be used for quick magnitude estimation without knowledge on the location of the earthquake.

[15] The relationship between log τ_c and M_L is shown in Figure 3b. Nineteen events of $M_L \geq 5.0$ and with $P_d >$ 0.08 cm in every record were used for this analysis. Similar to previous studies, the values of log τ_c increase approximately linearly with M_L. The linear regression for the relationship between log τ_c and M_L is

$$\log \tau_c = 0.47 \times M_L - 2.37, \qquad (2)$$

with a standard deviation of 0.25. $\tau_p{}^{\max}$ is also analyzed using the same dataset, and the result is shown in Figure 3c. The relationship between log $\tau_p{}^{\max}$ and M_L is

$$\log \tau_p^{\max} = 0.24 \times M_L - 1.51, \qquad (3)$$

with a standard deviation of 0.23.

[16] Based on the study of *Shieh et al.* [2008], we combine τ_c and $\tau_p^{\max}$ in magnitude determination. Figure 3d shows the magnitude determined from the average values of τ_c and $\tau_p^{\max}$ versus the magnitude M_L. The magnitude determined from τ_c and $\tau_p^{\max}$, Mτ, has a 1:1 relationship with M_L with a standard deviation of 0.40.

5. Discussion and Conclusions

[17] In practice, the VSN method based on a regional EEW approach can achieve a good magnitude determination with a small standard deviation of 0.28 for earthquakes up to 6.5. However, for larger offshore earthquakes, the VSN method may underestimate the magnitudes due to the limited lengths of the waveforms used. To avoid this problem, the magnitude Mτ obtained from the average period τ_c and the dominant period $\tau_p^{\max}$ of the initial P waves may offer a satisfactory solution. For the case of 31 March 2002, offshore Hualien M_L 7.0 earthquake (Figure 2a), the VSN underestimated the magnitude by about 1 unit, whereas Mτ provides a very good estimation of 7.1.

[18] The operations of the present EEW systems in Taiwan are shown in the flow chart in Figure 4. The VSN approach and the P-wave method operate in parallel. When a felt earthquake occurs and the system is triggered, two parallel EEW procedures will be activated. The VSN

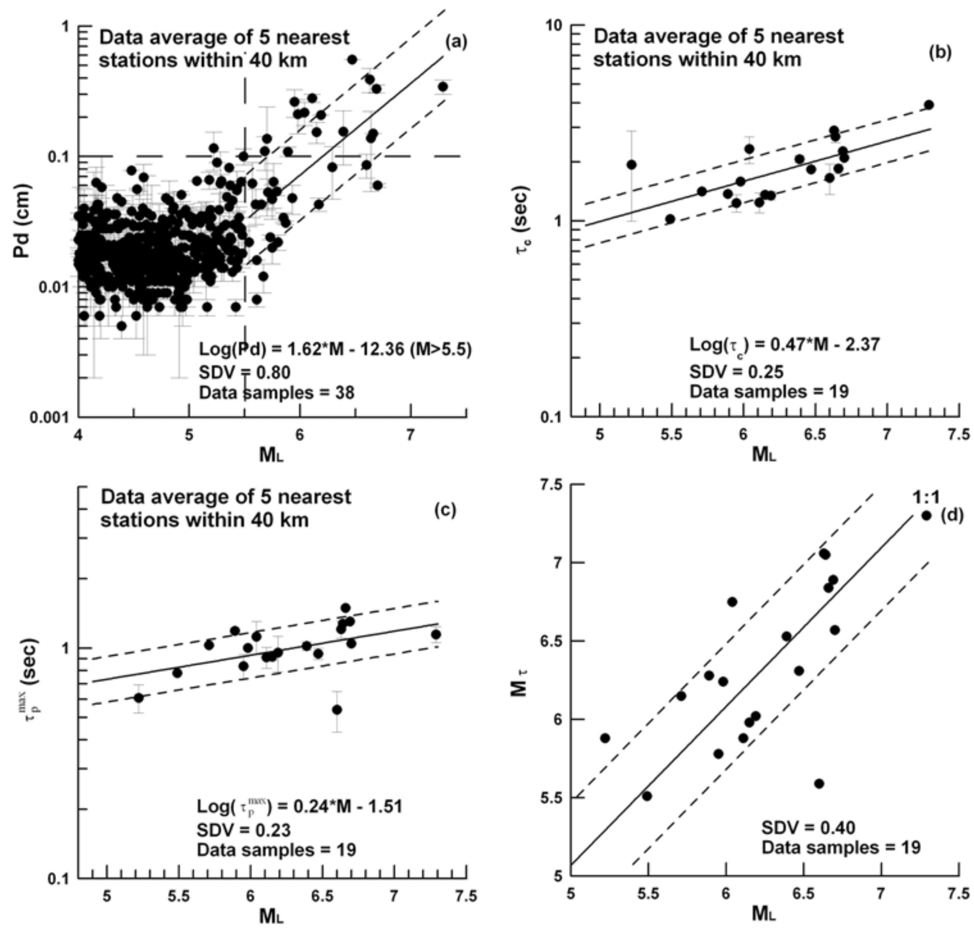

Figure 3. Regressions of catalog magnitudes M_L with different parameters derived from the P-wave method in this study. Solid line shows the least squares fit and the two dashed lines show the range of one standard deviation. (a) Regression of log P_d with M_L, (b) log τ_c with M_L, (c) log $\tau_p{}^{max}$ with M_L, and (d) regression of magnitudes estimated by the average of τ_c and $\tau_p{}^{max}$ with M_L.

process works as discussed before. In the newly implemented process using the P-wave method, P_d values are calculated from five nearest stations. When the average value of P_d is greater than 0.1 cm, τ_c and τ_p^{max} are calculated for Mτ determination. For events with both M_L from VSN and Mτ from the P-wave method larger than 6.0, the shake map will be calculated for the earthquake early warning report. Previous study [*Hsiao*, 2007] showed that when a felt earthquake occurs on the Taiwan Island, the real-time strong-motion network can be triggered within 6 seconds. Therefore, we can expect to achieve a 10-second response time by the EEW system in Taiwan in the near future.

[19] Currently in Taiwan the rapid earthquake reports issued by the EEW system are not available to the general public, except for experimental purposes by some relevant organizations such as railway administration, rapid transit companies, and disaster prevention agencies, etc. Public release of earthquake early warnings does not produce social benefits in the absence of a comprehensive approach to educating the public on how to respond to the warning messages. However, encouraged by the recent successful examples in the research and application of EEW system in Japan, a joint program to promote the EEW system with the participation of various organizations will proceed in the near future in Taiwan.

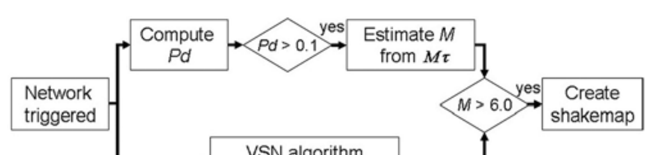

Figure 4. Flow chart of the algorithm designed for EEW system in this study. In the design, when a felt earthquake occurs and the system is triggered, the VSN and P-wave methods are activated simultaneously. When the average value of P_d is greater than 0.1 cm, τ_c and $\tau_p{}^{max}$ are calculated for Mτ determination. For events with both M_L and Mτ larger than 6.0, a shake map is calculated for the earthquake early warning report.

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