# Testing a *P*-Wave Earthquake Early Warning System by Simulating the 1999 Chi-Chi, Taiwan, $M_w$ 7.6 Earthquake


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## INTRODUCTION

The earthquake early warning (EEW) system is becoming a key practical tool for mitigating loss due to seismic events. Depending on the distance to the earthquake, it provides a few seconds' to a few tens of seconds' warning for people or automated facilities. Currently, many countries have an online operating or experimental EEW system, such as Japan (Nakamura 1988; Odaka *et al.* 2003; Horiuchi *et al.* 2005), Taiwan (Wu *et al.* 1998; Wu *et al.* 1999; Wu and Teng 2002; Hsiao *et al.* 2009; Hsiao *et al.* 2011), Mexico (Espinosa-Aranda *et al.* 1995; Espinosa-Aranda *et al.* 2009), the United States (Allen and Kanamori 2003; Wu *et al.* 2007; Allen *et al.* 2009; Bose, Hauksson, *et al.* 2009), Italy (Zollo *et al.* 2006; Zollo *et al.* 2009), Turkey (Alicik *et al.* 2011), Beijing (Peng *et al.* 2011), and Romania (Bose, Sokolov, and Wenzel 2009).

Taiwan is situated at two converging plates, the Eurasian plate and the Philippine Sea plate. Located in this seismic active region, with a convergence rate of about 8 cm/year (Yu *et al.* 1997; Hsu *et al.* 2009), Taiwan has experienced many destructive earthquakes in the past century; the 1999 Chi-Chi earthquake is the largest such event. At that time, there was no real-time, online EEW system in Taiwan; however, a rapid reporting system had been operating since 1995 (Wu *et al.* 1997). Fortunately, during the 1999 Chi-Chi event the earthquake rapid reporting system had good estimates of hypocenter (23.87°N, 120.75°E, depth = 10 km) and magnitude ($M_L = 7.3$) and provided an intensity map in 102 seconds after the earthquake occurrence (Wu *et al.* 2000).

The first EEW system in Taiwan was tested in 1998 in the Hualien area (Wu *et al.* 1999). The principle of this tested system is to use sub-networks of fewer stations, closer to the earthquakes, to quickly estimate the event information instead of using the whole network of stations (Wu and Teng 2002). Since then, on the basis of this principle and adopting the magnitude estimate method of $M_{L10}$ based on the first 10 seconds of signals (Wu *et al.* 1998), this system has been implemented by Taiwan's Central Weather Bureau (CWB). This system has an average reporting time of about 22 seconds, and timely warning is available for areas up to about 70 km from the epicenter (Hsiao *et al.* 2009). At the moment, CWB has not yet issued the EEW information to the public.

In order to shorten the EEW processing time and hence reduce the blind zone without timely warning, the initial part of the *P*-wave (usually three seconds) has been adopted to estimate earthquake magnitude and the approaching ground shaking (the average period [$\tau_c$] by Kanamori 2005, Wu and Kanamori 2005a, Wu *et al.* 2007, Wu and Kanamori 2008a, 2008b; the dominant period [$\tau_p^{\max}$] by Nakamura 1988, Allen and Kanamori 2003; and the initial peak vertical displacement [P*d*] by Wu *et al.* 2007, Wu and Kanamori 2005b, 2008a). Recently, a new EEW system has been proposed and tested in Taiwan (Hsiao *et al.* 2011). Hsiao *et al.* (2009 and 2011) propose to use P*d* and $\tau_c$ of the initial three seconds of *P* wave to determine earthquake magnitude on the Earthworm platform developed by the United States Geological Survey (USGS).

As a result of the large ground shaking of the 1999 Chi-Chi earthquake, several electrical power towers collapsed, which resulted in real-time data interruption. If the 1999 Chi-Chi earthquake were to happen again with limited workable stations and signal recording length, we wonder if the proposed EEW system would provide precise and reliable event information. It is a big challenge to the current EEW methods in magnitude and intensity estimations, because the data streams might be broken within the initial 10 seconds after the first *P*-wave arrival, as happened in the 1999 Chi-Chi earthquake.

The purpose of this study is to offline test the new proposed EEW system (Hsiao *et al.* 2011) by feeding the raw records of the 1999 Chi-Chi earthquake into the system. Both $\tau_c$ and P*d* were used to estimate the magnitude. The results indicate that the first warning is available in about 12 seconds after the earthquake origin time and the magnitude estimated by the $\tau_c$ method ($M\tau_c = 7.4$) is better than that from using the P*d* method ($M_{\mathrm{P}d} = 6.3$). Even with limited stations and data interruptions such as occurred during the 1999 Chi-Chi earthquake, the proposed EEW system still can provide quick and satisfying event information.


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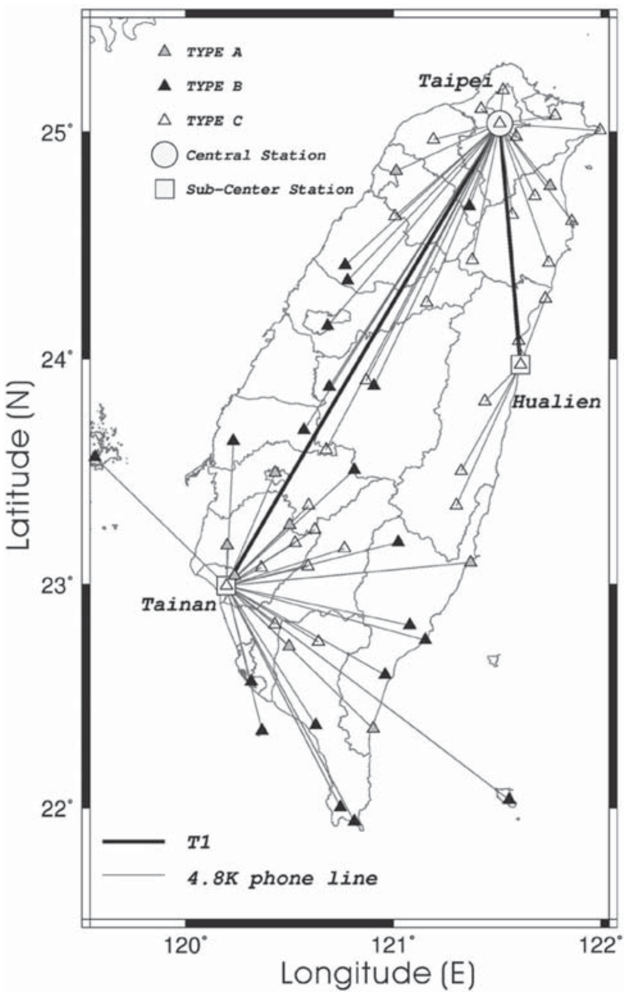
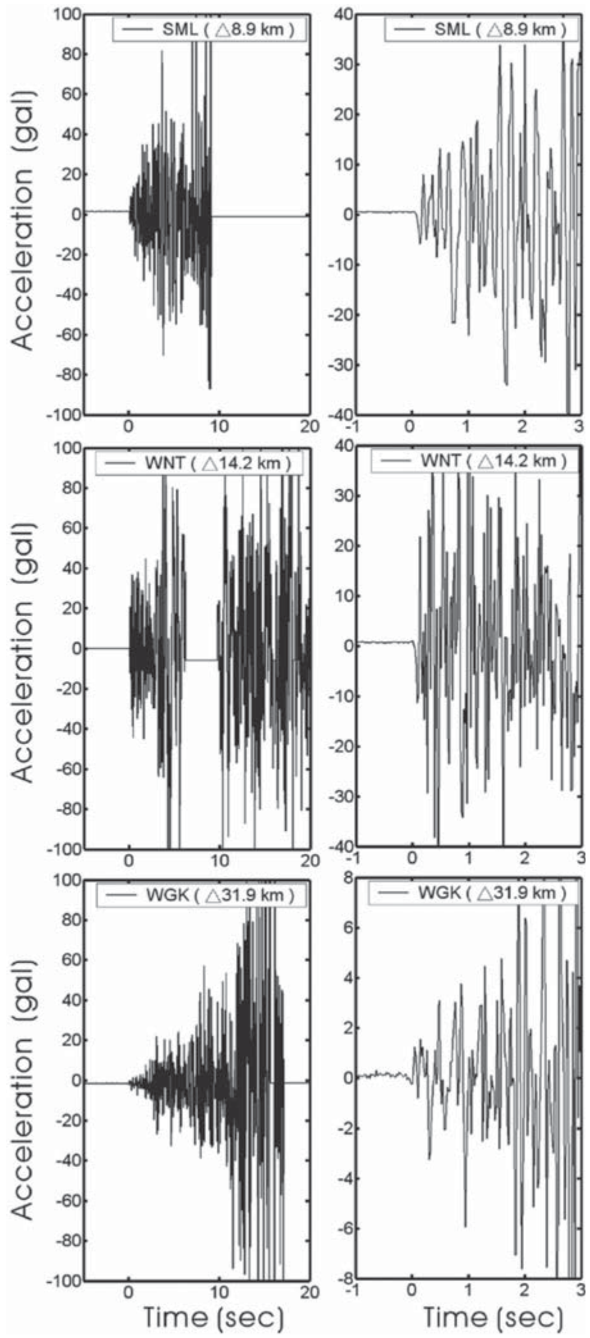



▲ **Figure 1.** Distribution of real-time strong-motion stations of CWB. Station signals during the Chi-Chi earthquake occurrence are classified A, B, or C for normal; capable to be used by the *P*-wave method; and unacceptable for analysis, respectively.

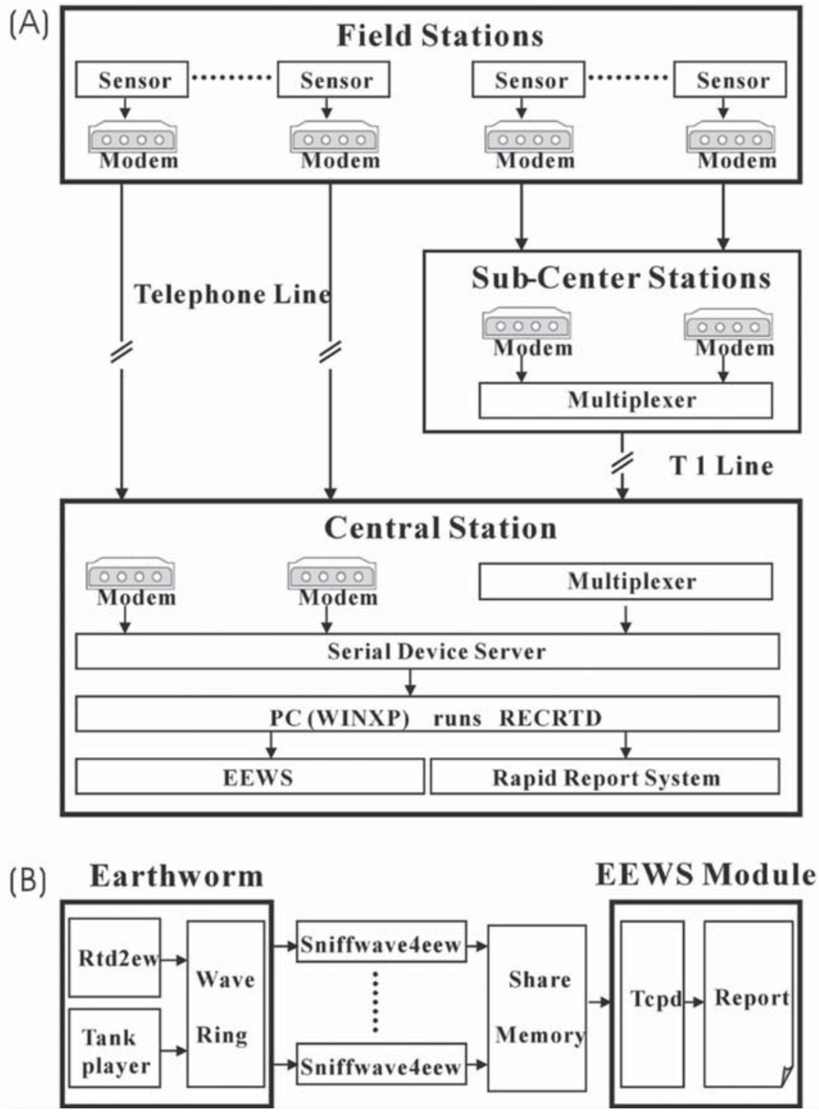
## DATA

Before the 1999 Chi-Chi earthquake, there were 61 real-time strong-motion stations operated by the CWB with a 16-bit dynamic range and a 50-Hz sampling rate. To save communication expenses, some of the stations directly transmitted data to the processing center via 4.8-K phone line, while others first transmitted data to sub-centers, which are multiplex all data streams, and then transmitted them to the data processing center via a broadband dedicated line, named the T1 line.

Unexpectedly, the Hualien T1 line, consisting of six stations, was interrupted five seconds before the Chi-Chi earthquake due to a mechanical problem. In addition, during the strong ground-shaking period the electrical power tower collapsed, also causing serious signal communication problems. Many real-time data streams lacked later *S* waves or were filled with non-seismic spikes. Therefore, the current $M_{L10}$ method for estimating magnitude was difficult or impossible to implement. We divided the station operating conditions into A, B, and C types, indicating signals are normal (A), capable of being used by the *P*-wave method (B), or unacceptable for analysis (C). Figure 1 shows the distribution of stations according to the station health. Only nine out of 61 stations recorded complete waveforms. However, if we consider the initial part of *P* waves, an additional 20 stations of type B, including the nearest stations, become able to be used by the $\tau_c$ and P*d* methods. Figure 2 shows the seismograms of the three nearest stations




▲ **Figure 2.** The seismograms on the left show the type B real-time strong-motion signals of the 1999 Chi-Chi earthquake. The plots on the right show the initial three seconds of signals after the *P* arrival.




▲ **Figure 3.** (A) Hardware and (B) software configurations of the CWB *P*-wave earthquake early warning system.

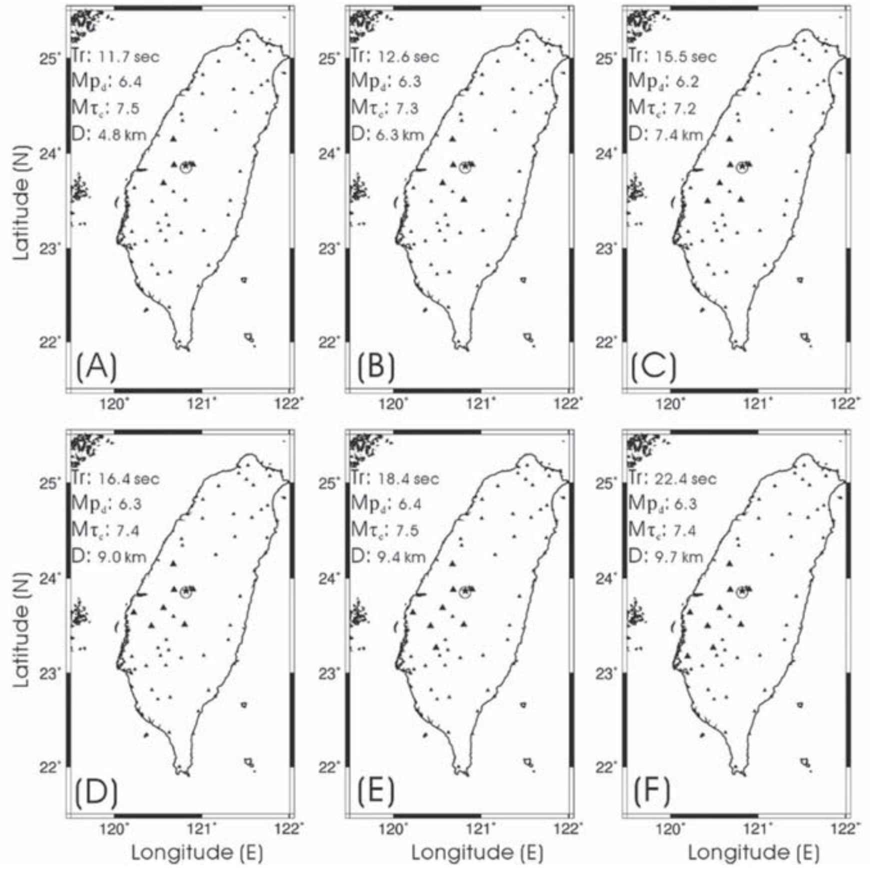
of type B. Despite the fact that the data streams of type B were spoiled by serious spikes or discontinuities, the initial portion of *P* waves are still usable, even at the nearest stations, which provides valuable records.

## EEW SYSTEM CONFIGURATION

Either a regional or onsite method is a possible way to implement an EEW system (Kanamori 2005). The regional method uses a group of seismometers near the source area to determine earthquake location and magnitude and then transmits the event information to target areas farther away from the earthquake. On the other hand, the onsite method uses only one station or a small array to predict the ground motion at the same site. It takes advantage of the initial portion of the *P* wave, which is faster than *S* waves and contains the information about earthquake source. Using the P*d* attenuation relationship with hypocentral distance, $M_{Pd}$ is more oriented to the regional method. $M\tau_c$, which can be obtained by only one station and does not need earthquake location, is computed by averaging all the available single $M\tau_c$ among the stations for the sake of minimizing the effect of abnormal values.

Each method has advantages and disadvantages. The regional method may be more reliable but it takes much more time than the onsite method. Thus, it cannot offer early warning for regions closer to the epicenter. However, it is possible to offer more warning time than the on-site approach for regions further away from epicenter. On the other hand, an onsite system can provide timely warning to regions closer to the epicenter (Satriano *et al.* 2010). The general tendency nowadays is to integrate these two approaches (Zollo *et al.* 2010).

Figure 3A shows the configuration of the proposed EEW system (Hsiao *at al.* 2011) in the CWB. Field stations transmit real-time data streams via modem. Some of them are directly connected to the data center; others are first connected to the sub-centers and later to the data center. Then the data center




▲ **Figure 4.** Simulation results for six stages after the earthquake occurrence. Open circles and stars indicate the epicenter of the Chi-Chi earthquake from the CWB catalog and simulations, respectively. Large triangles indicate the stations (types A and B) used in simulations. Tr is the reporting time after the earthquake occurrence, and D is the focal depth from simulations. $M_{Pd}$ and $M\tau_c$ represent the P*d* magnitude and $\tau_c$ magnitude, respectively.

integrates all data in a serial port server. The program, named RTDREC, continuously generates the waveform files with a length of three seconds. These files are the data source for the EEW system.

Earthworm is one of the most popular software platforms for real-time seismic data integration processing. We developed our EEW system in the Earthworm environment (Figure 3). We modified some original modules from Earthworm to meet our requirements, including Tankplayer and SniffwaveIn order to feed the continuous data files into Earthworm, we created a new module, named Rtd2ew, modified from Tankplayer. Data streams are continuously stored in a temporal memory space, named WAVE RING, which contains a volume of 1,024 kb. Then Sniffwave4eew, modified from the Earthworm program called Sniffwave, automatically detects earthquakes and applies a 0.075-Hz recursive high-pass filter to double-integrated accelerograms. Then P*d* and $\tau_c$ are calculated within three seconds after *P* arrival. Each Sniffwave4eew can only handle one trace. Because only the vertical component is used, 61 Sniffwave4eew programs must be operated at the same time. Once the Sniffwave4eew detects a *P*-arrival triggering, parameters including station location, *P* arrival time, P*d*, and $\tau_c$ are sent to the shared memory. In the final stage, the Tcpd program fetches the event parameters stored in the shared memory and computes earthquake early warning information. Once the warning threshold (**M** > 6.0) is reached, a shaking map is generated. Once the predicted peak ground acceleration (PGA) of populated regions is larger than 80 gal, the early warning message will be delivered.

## RESULTS

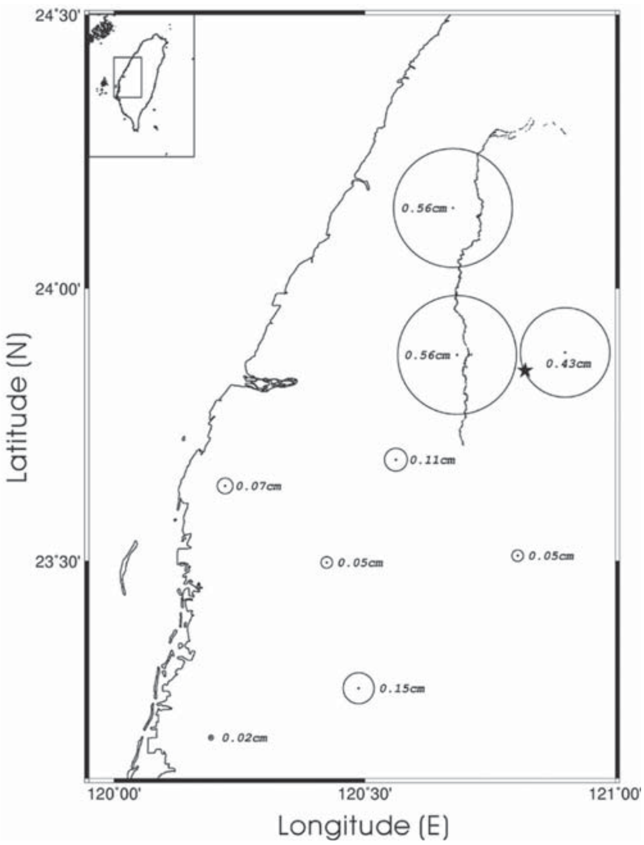
The raw records of the Chi-Chi earthquake were replayed in the proposed EEW system (Hsiao *at al.* 2011). The *P* arrival times of each station were used for locating the earthquake. The parameters P*d* and $\tau_c$ of each station were used to estimate magnitude by the empirical formulas of $M_{Pd}$ (Hsiao *et al.* 2011)

$$M_{Pd} = 3.905 + 2.198 \times \log Pd + 2.703 \times \log R \qquad (1)$$

and $M\tau_c$ (Wu *et al.* 2007).

$$M\tau_c = 4.218 \times \log\tau_c + 6.166 \pm 0.385. \qquad (2)$$

Figure 4 shows six progressive EEW reports. The first event report is available 11.7 seconds after the earthquake origin




▲ **Figure 5.** P$d$ values of the Chi-Chi earthquake estimated from real-time strong-motion signals.

time. The reporting time is significantly reduced compared to the present average EEW reporting time of 20 seconds. Therefore, the radius of the warning blind zone is shortened from 70 km to about 40 km. The estimated earthquake location is quite satisfactory even in the first report. In each report, $M_{Pd}$ are all smaller than 7.0, implying that P$d$ may saturate for large earthquakes. On the other hand, the estimated $M\tau_c$ between 7.2 and 7.5 is rather close to the reported $M_w$ of 7.6.

## DISCUSSION AND CONCLUSIONS

After learning the lesson of the 1999 Chi-Chi earthquake, Taiwan has improved the hardware of its seismic networks. The station density and the recording devices have been gradually improved. Each station now is equipped with an uninterruptible power supply to provide steady electrical power in case of a power failure due to an electrical power tower collapse or a disconnected communication line. The real-time EEW system is easy to implement based on the Earthworm environment. Thanks to its open-source software, users can construct a user-designed real-time seismic network and also can easily modify the Earthworm modules for their own data processing tasks.

*P*-wave methods are an effective tool for EEW because only a few seconds of the initial portion of *P*-wave are needed. In the case of the Chi-Chi earthquake, the first report was generated in only about 12 seconds by the proposed EEW system. The use of the initial *P*-wave turns out to be a robust system even in those cases in which large ground-shaking may provoke data interruption. Wu and Kanamori (2005b) found the empirical relationship between the peak ground velocity (PGV) and P$d$. By taking advantage of the PGV versus P$d$ relationship, the EEW system can also immediately produce a shaking map in PGV, which is useful in emergent resource dispatch management and for quick damage assessment.

The size of a large earthquake is more difficult to estimate than that of a small one due to the source dimension and the rupture complexity. In the Chi-Chi earthquake, the fault plane ruptured from south to north and there were two seismic asperities. One is near the hypocenter; the other is about 30 to 65 km north of the hypocentral area. The average slips of these two asperities are about 3 m and 9 m, respectively (Ma *et al.* 2001). Figure 5 plots the spatial distribution of P$d$ with the surface trace of the rupturing fault for the Chi-Chi earthquake. P$d$ values are larger in the northern part of the fault plane, which is consistent with the rupture directivity of the earthquake.

The results in Figure 4 suggest that P$d$ is not as sensitive as $\tau_c$ for the large-magnitude earthquakes because of the saturation problem. The suggested upper limit of the P$d$ methods is about 6.5 $M_W$ (Wu *et al.* 2006; Wu and Zhao 2006). Estimated by the relationship of P$d$ and PGV (Wu and Kanamori 2005b, 2008a), the PGV of the Chi-Chi earthquake are underestimated again, suggesting the P$d$ saturation. The study of Lancieri and Zollo (2008) shows that extending the *P*-wave window to four seconds or more drastically reduces the saturation effect. We also tested the *P*-wave window at four seconds. We obtained an $M_{Pd}$ of 6.9, suggesting that the saturation problem really is reduced. Nevertheless, $M_{Pd}$ can build more magnitude redundancy into the EEW system for earthquakes with magnitudes less than 6.5 or 7.0 (it depends on the *P*-wave window). In real-time operation, when $M_{Pd}$ is determined to be larger than 6.5, $M\tau_c$ will be used for early warning purposes.

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