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An empirical evolutionary magnitude estimation for early warning of earthquakes

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ABSTRACT

The earthquake early warning (EEW) system is difficult to provide consistent magnitude estimate in the early stage of an earthquake occurrence because only few stations are triggered and few seismic signals are recorded. One of the feasible methods to measure the size of earthquakes is to extract amplitude parameters using the initial portion of the recorded waveforms after P-wave arrival. However, for a large-magnitude earthquake ($M_w > 7.0$), the time to complete the whole ruptures resulted from the corresponding fault may be very long. The magnitude estimations may not be correctly predicted by the initial portion of the seismograms. To estimate the magnitude of a large earthquake in real-time, the amplitude parameters should be updated with ongoing waveforms instead of adopting amplitude contents in a predefined fixed-length time window, since it may underestimate magnitude for large-magnitude events. In this paper, we propose a fast, robust and less-saturated approach to estimate earthquake magnitudes. The EEW system will initially give a lower-bound of the magnitude in a time window with a few seconds and then update magnitude with less saturation by extending the time window. Here we compared two kinds of time windows for measuring amplitudes. One is P-wave time window (PTW) after P-wave arrival; the other is whole-wave time window after P-wave arrival (WTW), which may include both P and S wave. One to ten second time windows for both PTW and WTW are considered to measure the peak ground displacement from the vertical component of the waveforms. Linear regression analysis are run at each time step (1- to 10-s time interval) to find the empirical relationships among peak ground displacement, hypocentral distances, and magnitudes using the earthquake records from 1993 to 2012 in Taiwan with magnitude greater than 5.5 and focal depth less than 30 km. The result shows that considering WTW to estimate magnitudes has smaller standard deviation than PTW. The magnitude estimations using 1-s time widow have larger uncertainties. Progressively adopting peak displacement amplitudes (P_d) from 2- to 10-s WTW is suggested for EEW systems.

1. Introduction

Earthquake Early Warning (EEW) systems provide warnings to people or automatic reaction systems before the intense ground shakings which may cause damages to target areas. With timely earthquake information (such as location and magnitude) after large earthquakes, we can take immediate precautions against seismic hazards. Currently, earthquake locations can be well determined by P-wave arrivals measured by dense stations around the source area (Rydelek and Pujol 2004; Satriano et al., 2008). However, the most challenging work in EEW systems is to improve the reliability and accuracy of the empirical methods for earthquake magnitude estimation since only a few stations with the initial portion of the seismic signals are available. If precise magnitude and hypocenter estimations can be obtained, ground motion can be predicted more reliably. In contrast, overestimation and underestimation of earthquake magnitude may lead to false or missed alarms that would result in additional economic loss and other impacts on human society.

To precisely measure the size of an earthquake, a certain length time window of waveforms after the P-wave arrival must be recorded. The required time window length depends on the adopted EEW algorithm and is one of the components contributing to the delay in the overall alert time (Behr et al., 2015). For EEW purposes, it is necessary to detect earthquake magnitude in the

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early stage of an earthquake occurrence. Wu et al. (1998) used an empirical method to correlate local magnitude over 10 s after the first P-wave arrival is detected. However, this method is time consuming because information from the waveform is not timely extracted in every second within the 10-s time window. Recently, P-wave methods have been widely studied and implemented in EEW systems. There are two kinds of P-wave methods. One generates warnings associated with the frequency content of the initial waveforms. Allen and Kanamori (2003) has proposed a method based on the predominant period (τ_p) measured over a varying time window after the P-wave arrival. When seismic waveform are progressively available in 1-, 2-, 3-, and 4-s time windows, τ_p values are measured and the magnitude is updated. In addition, the average period parameter (τ_c) of the initial 3-s P waves can be used for estimating magnitudes (Wu and Kanamori, 2005). The other kind of P-wave methods adopt the amplitude content of the initial waveforms. Wu and Zhao (2006) took the peak amplitude in vertical displacement (P_d) over a 3-s time interval after P-wave arrival. It is shown that the upper limit of the magnitude prediction is 6.5 because the time window is too small to contain the whole rupture information from large events. Using the combinations of P- and S-wave signals, Zollo et al. (2006) demonstrated that the peak displacements measured in 2-s P-wave time window and 2-s S-wave time window can be correlated to earthquakes with magnitude in the range from 4.0 to 7.4. Lancieri and Zollo (2008) used peak displacement over 2- and 4-s P-wave time window and 1- to 2-s S-wave time window to estimate magnitude at each time step by Bayesian approach. The magnitude estimations in these EEW algorithms are using the empirical regression equations over a fixed time window or varying time windows.

In this study an approach to better use the first 10-s time window is proposed. We consider two kinds of time windows (PTW and WTW) for measuring amplitudes. The peak displacement amplitudes (noted as P_{d1} to P_{d10}) in vertical component of the waveforms are measured from 1- to 10-s PTW and WTW. For magnitude estimations, empirical regression equations for 1- to 10-s time window are also built.

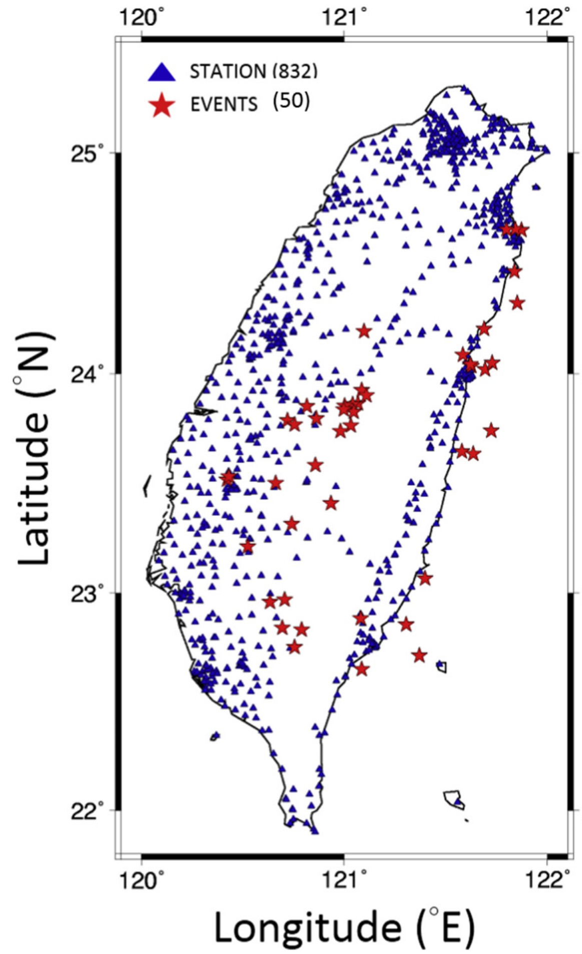

Fig. 1. The station distribution of the TSMIP seismic network and earthquakes with magnitude larger than 5.5 studied in this paper.

2. Empirical equations for magnitude estimation

To develop time dependent relationship between P_d, magnitude and hypocentral distance, we use seismic waveforms recorded by the network built by the Taiwan Strong Motion Instrumentation Program (TSMIP) (Liu et al., 1999). With more than 700 accelerometers installed on the free-field sites, triggered events are recorded by 200 samples or 250 samples per second at 16-bit or higher resolution. A total of 50 events with magnitude greater than 5.5 and depth within 30 km are recorded by the TSMIP stations from 1993 to 2012. The recorded events provide 7169 waveforms. Fig. 1 shows the distribution of the events.

Following the data analysis procedure of (Wu and Kanamori, 2005), we implemented double integration on the vertical component of the acceleration waveform to obtain displacement and then apply a 0.075 Hz high-pass Butterworth filter to those signals. Instead of using fix time interval, the peak displacement amplitudes within the time windows from 1 to 10 s were measured. Two kinds of time window, PTW and WTW, were considered. The relationship among P_{dT}, magnitude M, and hypocentral distance R is proposed:

$$\log(P_{dT}) = A + B \times \mathrm{M} + C \times \log(R) \quad (1)$$

where the unit of P_{dT} is in cm and measured within from 1- to 10-s time windows (P_{d1} to P_{d10}) and R is in km; A, B, and C are constants determined from the regression analysis. All linear regression models (Eq. (1)) have been best fitted by the R software (R Development Core Team 2011). The coefficients (given in Table 1) for the two kinds of time windows are similar. The standard deviation is decreasing as the size of the time windows is increasing from P_{d1} to P_{d10}.

Fig. 2 shows the relationship between the P_d values and the hypocentral distance at different time intervals. Initially, all points with magnitude from M_w5 to M_w7 are mixed together when the P_d values obtained in 1-s time window, as shown in Fig. 2(a). Then, the points with different magnitudes are separated gradually when the P_d values are obtained from 3-s and 7-s time window, respectively, shown in Fig. 2(b) and (c). Finally, the points with different magnitudes are distinguished and fitted to the associated regression lines well when the time window are extended to 10 s. Especially for points with magnitude from M_w 6 to M_w 7, the points are fitted to the regression line until adopting P_d values from the 10-s time window. It indicates that for larger earthquakes expanding time window is helpful to record larger amplitude because the major energy may not be released in the initial step of an earthquake nucleation.

To test the regression models, we used the same data set for acquiring the evolved P_d values from 1- to 10-s time intervals and estimated magnitudes using the corresponding regression equations from Table 1. Fig. 3 shows the relationship between the elapsed time after earthquake occurrence and the standard deviations of the estimated magnitudes. When we adopted P_d values from 1- to 10-s time interval to estimate magnitudes the standard deviations are large in the initial stage due to poor

Table 1
Coefficients from regression analysis for Eq. (1).

P_d	A	B	C	SD
P_{d1}	−1.463/−1.463	0.192/0.192	−0.508/−0.508	±0.345/±0.345
P_{d2}	−1.827/−1.789	0.338/0.338	−0.712/−0.732	±0.309/±0.309
P_{d3}	−2.048/−1.822	0.388/0.394	−0.724/−0.872	±0.291/±0.296
P_{d4}	−2.284/−1.801	0.440/0.453	−0.738/−1.051	±0.276/±0.285
P_{d5}	−2.262/−1.734	0.463/0.485	−0.801/−1.166	±0.270/±0.279
P_{d6}	−2.263/−1.672	0.479/0.509	−0.833/−1.256	±0.268/±0.279
P_{d7}	−2.114/−1.673	0.519/0.541	−1.023/−1.336	±0.266/±0.273
P_{d8}	−1.797/−1.646	0.541/0.551	−1.245/−1.364	±0.262/±0.267
P_{d9}	−1.785/−1.781	0.559/0.584	−1.296/−1.372	±0.263/±0.262
P_{d10}	−1.741/−2.079	0.550/0.635	−1.285/−1.344	±0.252/±0.259

P_{dT} means Pd estimations from T-s (T is from 1 to 10) time window.
SD means standard deviation.

estimations of P_d values in the first second time window. The P_d values adopted from the fixed 3-s interval also shows large standard deviations because the time window is too short to record major energy released by earthquakes. Therefore, according to

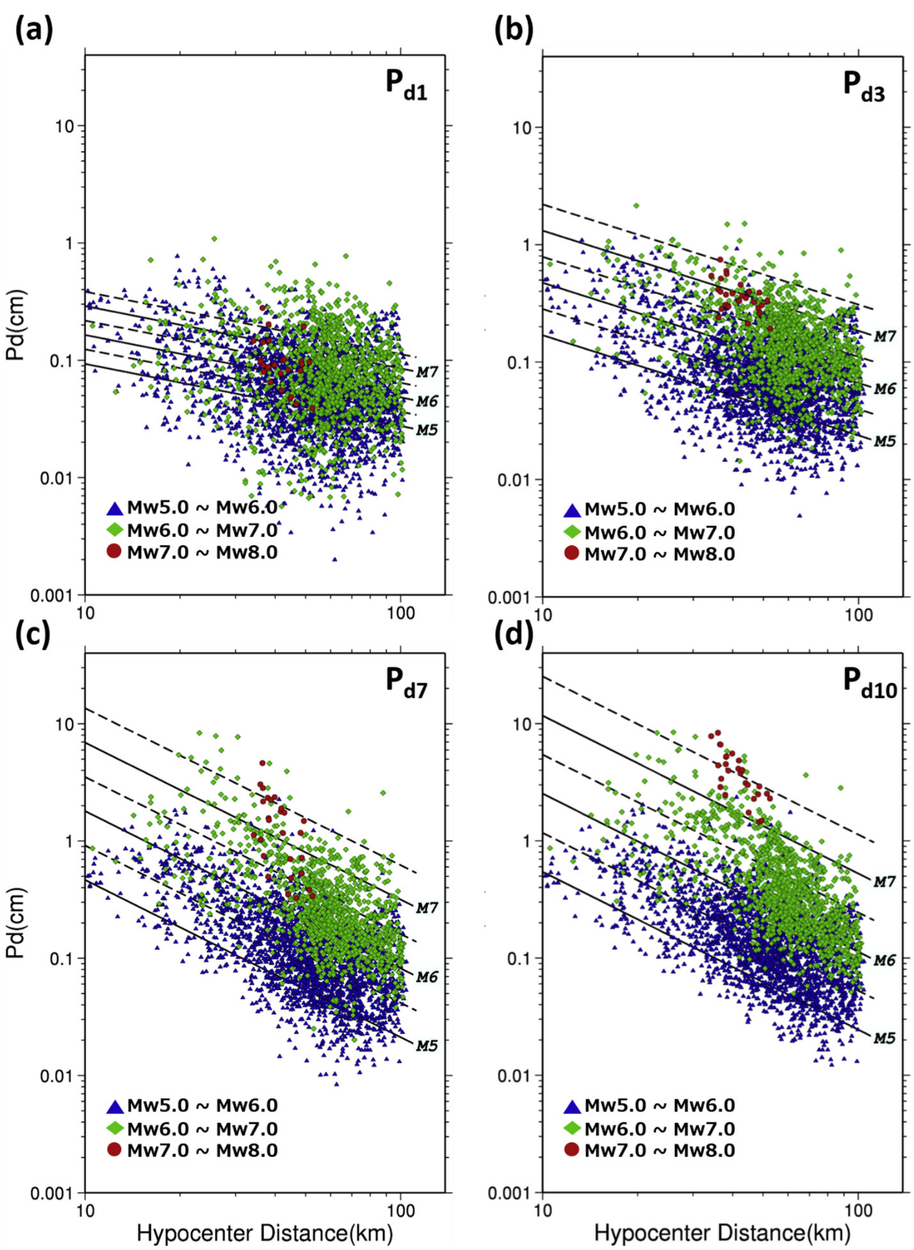

Fig. 2. Relationships between P_d values and hypocentral distance with different magnitude range. (a) P_d values obtained in 1-s time window, (b) P_d values obtained in 3-s time window, (c) P_d values obtained in 7-s time window, (d) P_d values obtained in 10-s time window.

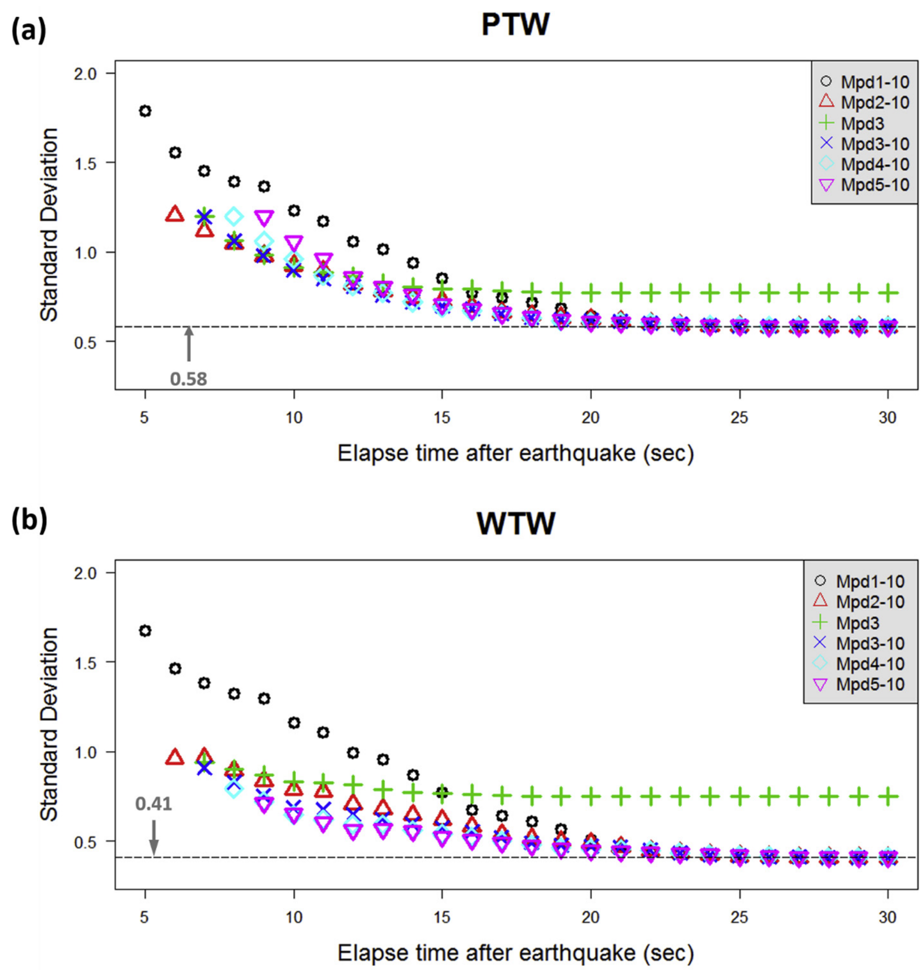

Fig. 3. Relationships between elapse time after earthquake occurrence and the standard deviations with different scenarios of time intervals.

the standard deviations the better choice is to consider 2- to 10-s, 3- to 10-s, 4- to 10-s, or 5- to 10-s time window. However, the magnitude information is given earlier than others using the 2- to 10-s time interval. Moreover, the comparison between using PTW and WTW, shown in Table 2, indicates that using WTW can have smaller standard deviations. For the sake of better using the first 10 s after the P-wave arrival, we suggest the EEW system need to progressively adopt peak displacement amplitudes from 2- to 10-s WTW.

Table 2
Magnitude estimations using different time window.

	S.D. (PTW/WTW)		S.D. (PTW/WTW)
M_{Pd1}	1.795/1.795	M_{Pd1-10}	0.640/0.507
M_{Pd2}	0.923/0.915	M_{Pd2-10}	0.625/0.487
M_{Pd3}	0.772/0.748	M_{Pd3-10}	0.615/0.471
M_{Pd4}	0.674/0.626	M_{Pd4-10}	0.608/0.454
M_{Pd5}	0.647/0.575	M_{Pd5-10}	0.609/0.445
M_{Pd6}	0.638/0.548	M_{Pd6-10}	0.612/0.440
M_{Pd7}	0.625/0.503	M_{Pd7-10}	0.619/0.435
M_{Pd8}	0.630/0.483	M_{Pd8-10}	0.630/0.426
M_{Pd9}	0.657/0.457	M_{Pd9-10}	0.657/0.421
M_{Pd10}	0.694/0.422		

M_{PdT} means magnitude estimations from T-s (T is from 1 to 10) time window.
SD means standard deviation.

3. Case study for empirical equations

To verify the time-dependent empirical relationships in this study, we use the 2013 ($M_w = 6.0$ and 6.3) Nantou earthquakes in central Taiwan and 2015 ($M_w = 6.2$) Green Island earthquake occurred in Southeastern Taiwan, and the M_w 7.6 Chi-Chi earthquake occurred in central Taiwan, shown in Fig. 4. These events all caused significant shakings and were well recorded from the TSMIP.

Three scenarios for adopting P_d values from WTW and PTW (M_{pd3}, M_{pd2-10}, and M_{pd1-10}) were used to estimate earthquake magnitudes. In the scenario of $M_{pd3,}$ we adopted P_d values from the 3-s time interval of the recorded waveform collected by each triggered stations. Analogously, in the scenarios of M_{pd2-10} and M_{pd1-10}, P_d values are from the 2- to 10-s and the 1- to 10-s time intervals, respectively. At every station the P_d value is updated with time and used for estimating magnitude. The final magnitude is given by the average of the estimated magnitudes from all the stations.

Fig. 5 shows the relationships between estimated magnitudes and elapsed time after earthquakes occurrence. We found the magnitudes estimated from the scenario of M_{pd1-10} show larger uncertainties than other two scenarios. The estimated values may reach very large or small, while in comparison to the estimated values from the scenario of M_{pd2-10} are stable and reasonable. We also found the magnitudes estimated from the scenario of M_{pd3} shows magnitude underestimations. In the scenario of M_{pd2-10} the magni-

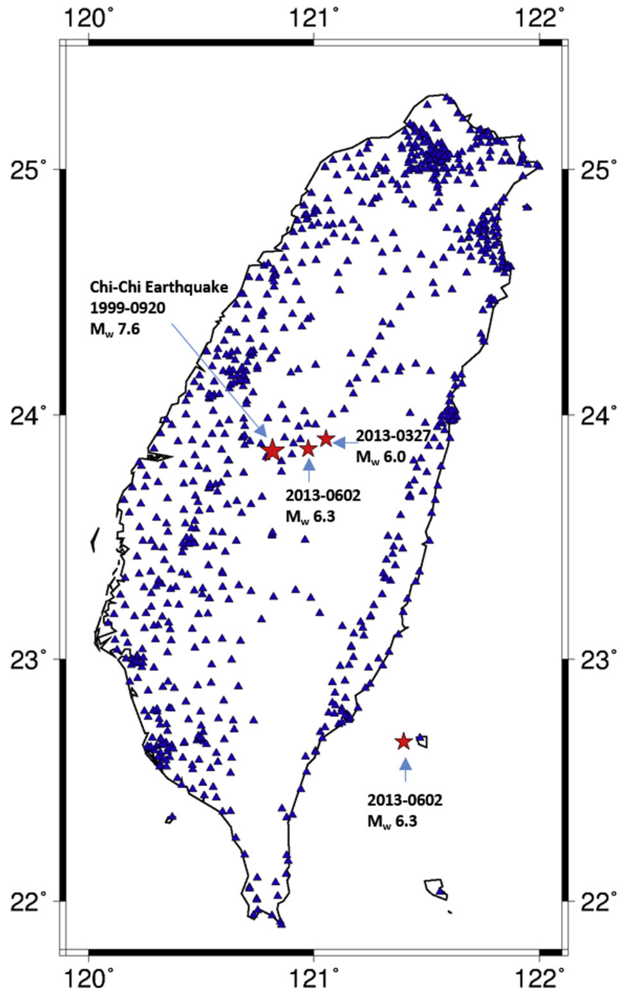

Fig. 4. The station distribution of the TSMIP seismic network and four earthquakes with magnitude larger than 6 studied in this paper.

tude estimations are more close to the magnitudes given by the global Centroid Moment Tensor (CMT) results. One exception is Fig. 5(b). The estimated magnitude from the scenario of M_{pd3} is a little bit larger than from the scenario of M_{pd2-10} because of the uncertainties within the coefficients of the empirical equations (Table 1).

4. Discussion

The method we proposed in this study is different from the method, called M_{L10} method, provided by Wu et al. (1998) taking 10-s time window after the P-wave onset for faster estimating earthquake magnitude rather than using whole seismic waveform as in the traditional method. In the M_{L10} method, the seismic waveforms are first simulated to Wood-Anderson seismograms. Then, the peak amplitudes within the initial 10-s time window are picked. Finally, the peak amplitudes and the hypocentral distances of the triggered stations are used in an empirical equation for earthquake magnitude estimations. However, in our method the seismic waves are integrated to displacement seismograms and applied a 0.075 Hz high pass filter. The peak amplitudes are picked at each time step from 1- to 10-s time window. We constructed ten empirical equations in 1- to 10-s time windows for magnitude estimations. Instead of using P_d values from fixed time window, we updated P_d values at each time step and used empirical equations of each time step to calculate earthquake magnitudes. Fig. 5 indicates that using evolutionary P_d values and corresponding empirical equations at each time step provides better magnitude estimations than using P_d values from fixed time window.

In order to investigate the reliability and limitations of our proposed method for giant earthquakes, the M_w 7.6 Chi-Chi earthquake and the M_w 9.0 Tohoku earthquake were tested. For such giant earthquakes the 10-s time window length is not long enough to record the main energy from the earthquakes so that it is essential to expand the time window. When the time window is expanded larger than 10 s, we do not consider WTW for magnitude estimation because the end bound of the time-window length for WTW has not been investigated in this study. If the end bound of the WTW is not considered the magnitude will be overestimated. Here we simply extended the time-window to the entire P wave (only P wave was considered). For time-window lengths less than or equal to 10 s the empirical equations following the Eq. (1) and the corresponding coefficients given in Table 1 are used. For time-window lengths larger than 10 s, because the time dependent equations for time-window lengths larger than 10 s were not investigated in this study the 10-s empirical equation was used for magnitude estimations.

The first tested case is the M_w 7.6 Chi-Chi earthquake, the largest damage earthquake occurred in Taiwan in the past 20 years. It was well recorded by the TSMIP network in the distance range between 10 and 180 km. Fig. 6(a) shows the limitation of magnitude estimation is about 6.4 using 2- to 10-s WTW in the simulation of the M_w 7.6 Chi-Chi earthquake. The estimated magnitude is able to become 6.9 if we extended the time window to the entire P wave. The second tested case is the M_w 9.0 Tohoku earthquake, the largest damage earthquake occurred in Japan. It was well recorded by the K-NET stations of the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan (Aoi et al., 2009). We analyzed 161 vertical component acceleration data in the distance range between 120 and 500 km. The simulation of the M_w 9.0 Tohoku earthquake shows that the estimated magnitude is about 6.2 using 2- to 10-s WTW. The estimated value become 9.0 if we extended the time window to the entire P wave.

For on scale magnitude estimations appropriate time-window length and distance ranges are essential requirements (Colombelli et al., 2012). Even we used entire P-wave time window the magnitude saturation problem still exists in the simulation of the Chi-Chi earthquake because the distance range of the recorded stations is too short (less than 180 km). On the other hand for the simulation of the Tohoku earthquake we can provide on scale magnitude estimation due to enough length of time window and distance range of the recorded stations.

The time dependent equations for time-window lengths larger than 10 s were not investigated in this study. To extend the time window from 10 s length to the entire P wave, an appropriate empirical equation must be picked. From the Eq. (1) we can derive it to be:

$$M = \frac{\log(P_{dT}) - \mathrm{A} - \mathrm{C} \times \log(R)}{B} \tag{2}$$

It indicates that the coefficient B dominates the result of the magnitude estimation. According to Table 1, the coefficients B are increasing from 1- to 10-s time windows. Thus, it shows that the 10-s empirical equation provides lower value of magnitude estimation than using 1- to 9-s empirical equations. We have adopted Eq. (1) with different coefficients given in Table 1 for magnitude estimation as the time-window lengths larger than 10 s. The result shows using the 3-s empirical equation may lead to overestimate magnitude, but using the 10-s empirical equation provides on scale estimation for the Tohoku earthquake, shown in Fig. 6(b). Therefore, the 10-s empirical equation was picked for the time-window lengths larger than 10 s.

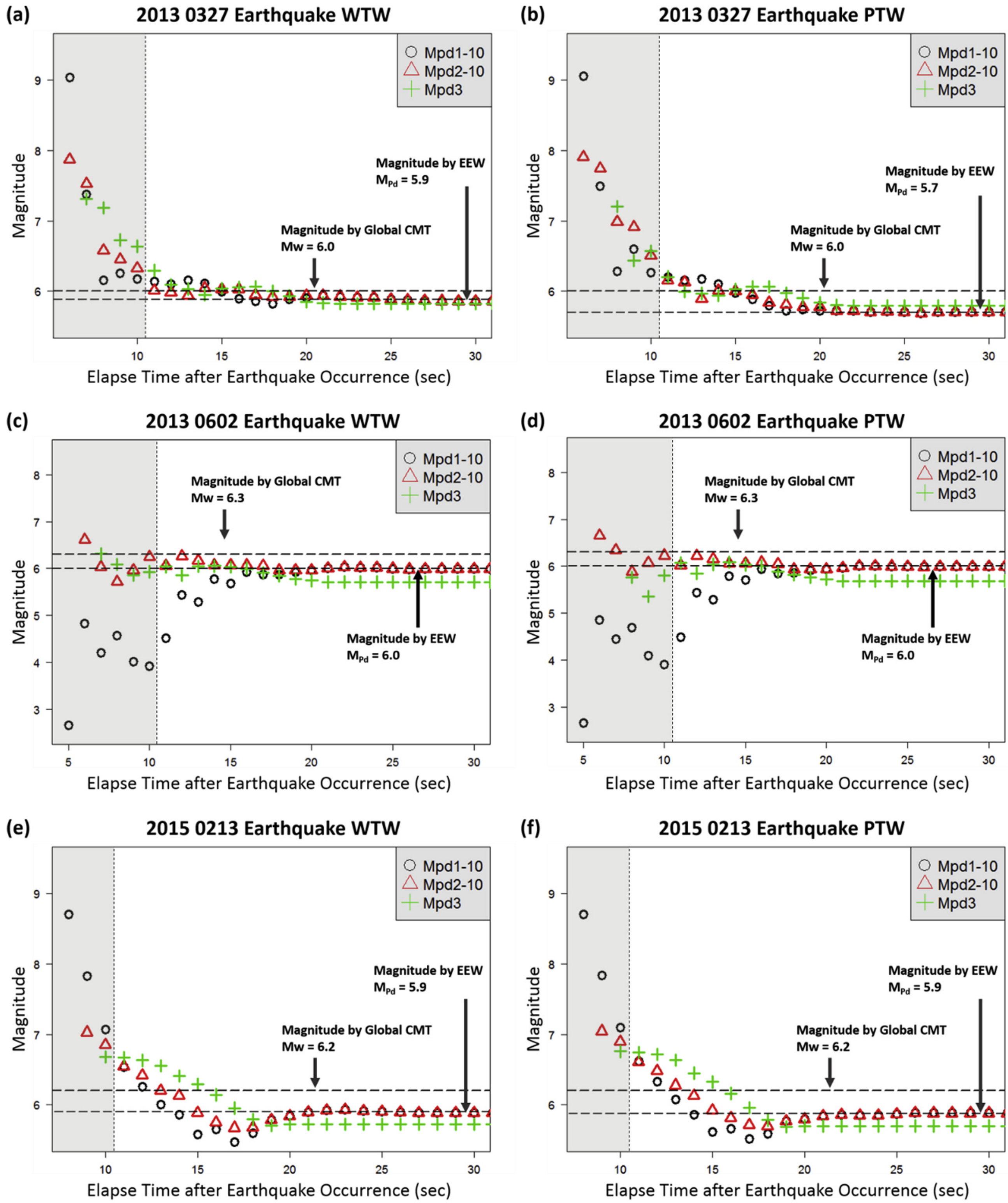

Fig. 5. Relationships between elapse time after earthquake occurrence and the estimated magnitude with three scenarios of time intervals. M_{pd1-10} means using P_{d1} to P_{d10} to estimate earthquake magnitude. M_{pd2-10} means using P_{d2} to P_{d10} to estimate earthquake magnitude. M_{pd3} means using P_{d3} to estimate earthquake magnitude. We ignored estimated magnitudes in the gray shaded regions due to radiation pattern and directivity effect. The open circle indicates magnitude estimations using 1- to 10-s time window; the open triangle indicates magnitude estimations using 2- to 10-s time window; the cross symbol indicates magnitude estimations using 3-s time window. In left column, figure (a), (c), (e), and (g) are obtained by WTW. In right column, figure (b), (d), (f), and (h) are obtained by PTW.

Through the analysis of Figs. 5 and 6, we suggest that for the initial 10-s time window after the P wave detection, the P_d values within 2-s to 10-s intervals are adopted in the scenario of the WTW progressively. Furthermore, for the time-window length larger than 10 s we progressively adopted P_d values until the S-wave arrival (only using P wave) and calculated magnitude using the 10-s empirical equation.

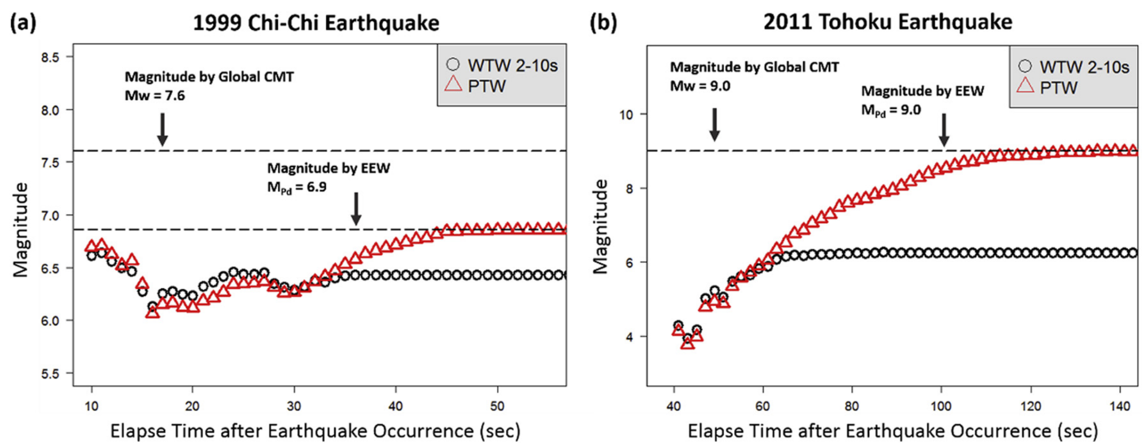

Fig. 6. Relationships between elapse time after earthquake occurrence and the estimated magnitude. Simulation test for (a) the M_w 7.6 Chi-Chi earthquake and (b) the M_w 9.0 Tohoku earthquake. "WTW 2–10 s" means extracting P_d values from 2- to 10-s WTW time window to estimate earthquake magnitude. "PTW" means extracting P_d values from entire P-wave time window (without the first second time window) to estimate earthquake magnitude.

5. Conclusions

Recent studies show that evolutionary approaches for real-time magnitude estimation usually update magnitude estimations progressively with time using the empirical regression equations over fixed time window or varying time window. However, the regression equation may not well fit the data in every time window. We estimated magnitudes by extending the peak displacement method from Wu and Zhao (2006). Instead of using fixed time interval after P-wave arrival, we updated P_d values and estimated magnitudes every second with ten regression equations (1- to 10-s time interval). Small-magnitude earthquakes are caused by small patches of fault and may radiate main energy within several seconds. However, large-magnitude earthquakes are caused by large patches of fault and may take longer time to radiate main energy. This concept is similar to Allen and Kanamori (2003) in which they used 1 s and 2 s of data to estimate smaller events (magnitudes 3.0–5.0). For larger events (M > 4.5), they adopted 4 s of data to estimate magnitude. In this paper, we used time-dependent regression equations from 1 s to 10 s of data. Moreover, we found that adopting P_d values from 2- to 10-s time window for magnitude determinations is more robust. Comparing to the fixed time interval methods which use 3-s interval, our method can reduce waiting time for smaller-magnitude events and provide more reliable results for larger-magnitude events. Another advantage of our method is effectively using the signals for near source region where only few seconds of P-wave signals are available. Empirically our method, using the initial 2- to 10-s signals, can be used to assess magnitude quickly and reliably. Due to containing S-wave information, this method can enlarge the upper bound of the magnitude estimations. Zollo et al. (2006) separately used 2 s of data for P-wave time window and 1 s and 2 s of data for S-wave time window for magnitude determination. Combining estimated magnitudes from P- and S-wave signals, they can estimate magnitudes range from M_w 4.0–7.4 without saturation. In this study, we used similar concept, including P- and S-wave signals, to estimate magnitudes. This new approach can be programmed in the Earthworm based earthquake alarm system (Chen et al., 2015) and tested with real-time data.

Small earthquakes rupture small patches of faults, therefore usually release energy quickly. If we take more than 3 s for small earthquakes (magnitude < 6.5), the processing time will be increased. In contrast, for large earthquakes, the fault plane extends long areas and the duration of slip is long. The time-window of the initial portion of the P wave should be extended to record a larger slip. For a giant earthquake like the Tohoku event, the 10-s time-dependent equations can be used to fast determine the lower-bound earthquake magnitude; then the expanded time window (> 10 s) can be used to estimate earthquake magnitude with less saturation in the EEW stage (Hoshiba and Iwakiri, 2011; Colombelli et al., 2012). In the post event stage, we can make accurate estimations within few minutes by using W-phase method (Kanamori and Rivera, 2008) or M_{ew} method (Lin and Wu, 2012).

6. Data and resources

Records used in this study were collected from Central Weather Bureau Seismic Network (CWBSN) of the Taiwan. The waveform records can be obtained from the Owners on request (http://www.cwb.gov.tw/eng/index.htm).

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The software program GMT (Wessel and Smith, 1998) and R software platforms (R Development Core Team 2011) were used in this study and are gratefully acknowledged. Our work was supported by the Ministry of Science and Technology, R.O.C.

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