Application of Waveform Stacking to Low-Cost Local Earthquake Early Warning Arrays in Taiwan

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INTRODUCTION

Taiwan has been constantly threatened by large, damaging earthquakes as the tectonic consequence of persistent collisions between the Philippine Sea plate and Eurasian plate. Use of an earthquake early warning (EEW) system is one of the effective tools for seismic-hazard mitigation and has operated in many countries, including Japan, Taiwan, Mexico, and the United States (e.g., southern California) (Kanamori *et al.*, 1997; Allen *et al.*, 2009; Lee and Wu, 2009; Satriano *et al.*, 2011). Taiwan initiated the development of EEW after the Hualien offshore earthquake (M_w 7.8) occurred on 15 November 1986. This earthquake caused large losses of life and property due to basin amplification in the metropolitan Taipei area, with an epicentral distance of 120 km. A timely warning can be announced to the highly populated Taipei city if an EEW system in the Hualien area can provide the earthquake information within 20 s (i.e., travel time of crustal shear wave over a distance of 120 km).

There are two types of EEW system: (1) the front-type warning, which collects the seismic records close to the epicenter and dispatches the earthquake warning to a more-distant area, has higher accuracy than the onsite one because of the use of more stations and longer time window; (2) the onsite-type warning has a smaller reporting time but lower accuracy because it relies on only one or a few stations.

The backbone of the present Taiwan EEW system is the Rapid Earthquake Information Release System (Wu *et al.*, 1997, 2000) operated by a government agency, the Central Weather Bureau (CWB), since 1995. This system, consisting of 109 telemetered seismic stations, is operated in the front-type warning mode. This system can provide earthquake information mostly within 20 s following an earthquake occurrence (Wu and Teng, 2002; Hsiao *et al.*, 2009, 2010).

A high density of seismic stations is always in great demand for EEW and earthquake rapid reporting networks (Lin and Wu, 2010a,b; Lin *et al.*, 2011). Increasing the number of stations used in the front-type early warning can improve estimate accuracy of earthquake parameters and might shorten the warning reporting time.

An experimental EEW system consisting of microelectromechanical systems-type accelerometers (Holland, 2003), called "*P*alert" sensors (Fig. 1), has started operating on June 2012 in Taiwan (Wu *et al.*, 2013; Wu and Lin, 2014). Because of the successful results of the experimental Hualien *P*alert EEW network (Wu and Lin, 2014), the *P*alert devices have been installed all over Taiwan. Following three years of installation, over 500 *P*alert stations now are deployed and configured (Wu *et al.*, 2013). Another advantage of the *P*alert sensor is its low cost compared with other seismometers; it is less than one-tenth the cost of traditional strong-motion instruments.

Because the *P*alert accelerometer has a relatively low signal-to-noise ratio (SNR) compared with the traditional force-balance seismometer, we apply waveform stacking method to enhance the SNR and improve the accuracy of the onsite magnitude estimate (M_{Pd}) by treating each array as a single onsite EEW set. Two local EEW arrays, located in Tainan and Ilan (Fig. 1), are used in this study. The geological condition of these two arrays is quite similar to those in the Tainan and Lanyang plains. In addition, both arrays are close to the high-seismicity areas in Taiwan, which would record more earthquakes.

The M_{Pd} method (Wu and Zhao, 2006) is used in this study to estimate earthquake magnitude. This method is based on the attenuation of the initial vertical displacement with hypocentral distance (Pd is the peak amplitude of the filtered vertical displacement of the *P* wave; Wu and Kanamori, 2005a,b, 2008a,b; Wu *et al.*, 2007). The purpose of this study is to find the new Pd attenuation relationship for the new *P*alert array. Because the *P*alert stations are all installed on the building wall, the present Pd attenuation relationships derived by the seismic record on the free surface have to be modified to a new attenuation relationship reflecting the building effect (in this study, the "building effect" means the effect on the seismic response of a seismic sensor installed on the building wall as compared to that of the free-surface collocated one). However, because the *P*alert seismic network has operated for a mere two years, the number of earthquakes ($M_w > 4.5$) might not be adequate to perform the regression analysis for a new Pd attenuation relationship.

Therefore, in this study we modified the existing Pd attenuation equations to define a best-fit equation specific for the *P*alert local array. We significantly improve the accuracy of magnitude estimation for onsite EEW by means of the waveform stacking method in an array.

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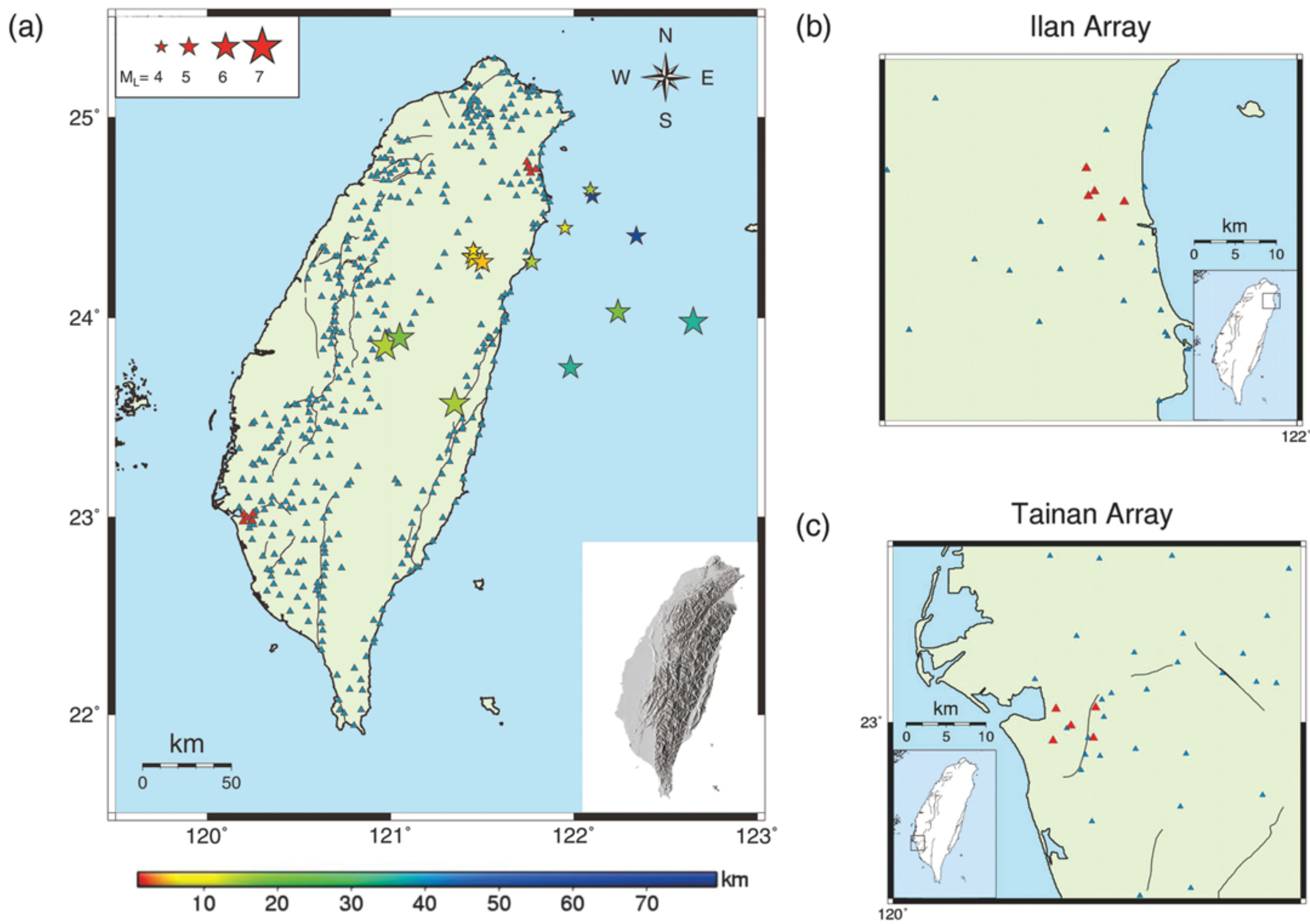
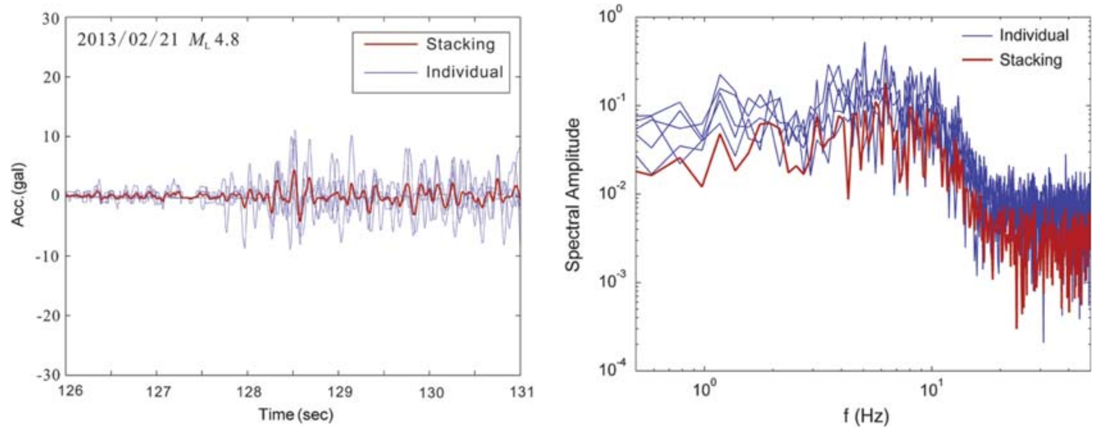


▲ **Figure 1.** (a) The *P*alert stations (triangles) and the epicenters of 15 events (stars) used in this study. The red triangles indicate two earthquake early warning (EEW) local arrays we selected in this study (Tainan and Ilan arrays). (b) The Ilan local array. (c) The Tainan local array.

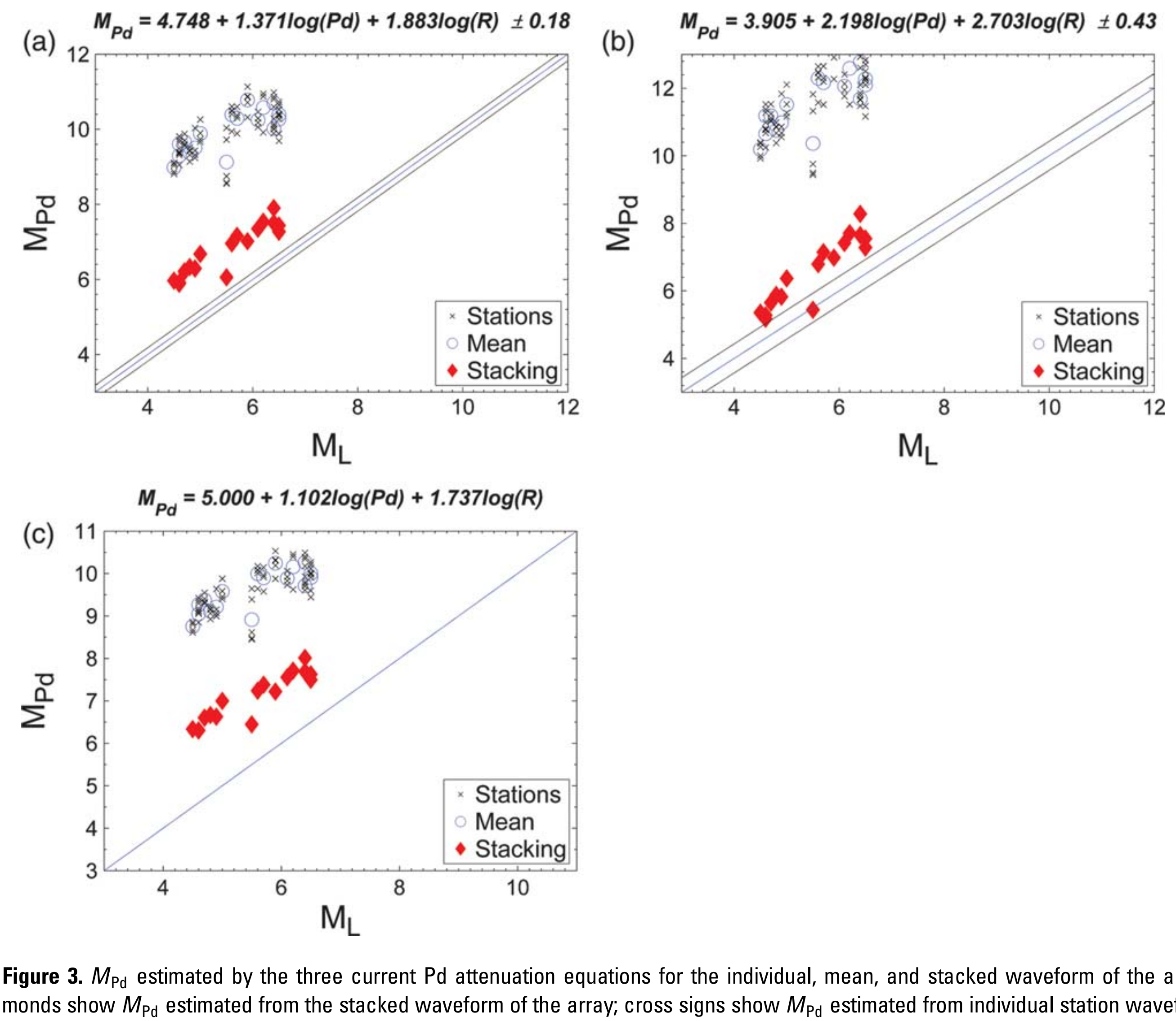
Table 1
Parameters of the 15 Events Used in This Study

Origin Time (yyyy/mm/dd hh:mm)	Latitude (° N)	Longitude (° E)	Depth (km)	Hypocentral Distance (km)*	M_w
2013/02/02 03:38	23.75	121.98	35.0	118.7	5.6
2013/02/21 18:34	24.31	121.44	6.4	59.0	4.8
2013/03/06 22:36	24.61	122.10	69.8	79.4	4.7
2013/03/07 03:35	24.30	121.46	5.6	58.8	5.9
2013/03/07 08:06	24.34	121.45	6.0	55.7	4.6
2013/03/20 07:21	24.45	121.95	12.1	40.4	4.6
2013/03/27 02:02	23.90	121.05	19.4	120.6	6.1
2013/04/21 03:06	24.41	122.34	70.6	99.1	5.0
2013/05/21 04:24	24.28	121.77	14.5	55.0	4.9
2013/06/02 05:42	23.86	120.97	14.5	128.1 (124.1)	6.5
2013/06/07 16:37	23.98	122.65	35.3	100.0	6.2
2013/06/28 23:50	24.03	122.24	19.8	61.8	5.7
2013/07/16 10:10	24.28	121.50	4.9	35.9	5.5
2013/09/18 03:32	24.64	122.09	15.1	39.7	4.5
2013/10/31 12:00	23.57	121.35	15.0	138.5 (132.4)	6.4

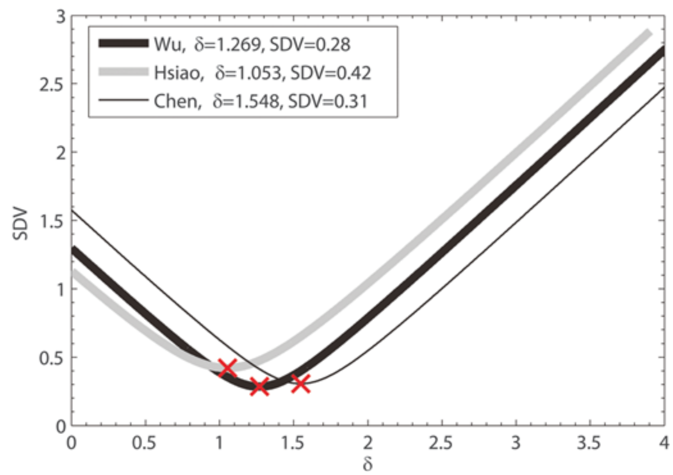
*The hypocentral distances in the parentheses are those for the Tainan array.



▲ **Figure 2.** (a) The stacking waveform (red line) superimposed on the five individual waveforms (blue lines) of one event (event number 2 in Table 1). (b) The spectral analysis of the waveforms in Figure 2a. The meaning of the line styles is the same as those in (a).



▲ **Figure 3.** M_{Pd} estimated by the three current Pd attenuation equations for the individual, mean, and stacked waveform of the array. Diamonds show M_{Pd} estimated from the stacked waveform of the array; cross signs show M_{Pd} estimated from individual station waveform without the stacking process; and circles show estimated M_{Pd} from the average Pd of the five single stations without stacking process. (a) Pd attenuation equation of Wu *et al.* (2007), (b) Pd attenuation equation of Hsiao *et al.* (2010), and (c) Pd attenuation equation of Chen (2015). In each plot, the blue line shows the least-squares fit and two gray lines show the range of one standard deviation (SDV).



▲ **Figure 4.** The SDV between estimated M_{Pd} and Central Weather Bureau catalog M_L is expressed as a function of the subtraction value (δ) for the three Pd attenuation equations. The cross signs mark the best-fit subtraction value (δ) with the minimum SDV for each line.

ARRAY AND DATA ANALYSIS

Two arrays are used for offline testing of the waveform stacking method to improve the accuracy for the onsite EEW. Each array consists of five *P*alert stations, with an average station interval of about 4 km. According to Wu and Kanamori (2005a, their equation 4), the average period of the initial motion for earthquakes with magnitudes 5.5 and 6.5 is 1.3 and 2.1 s, respectively. By assuming that a crustal *P* wave travels at a velocity of 5.0 km/s, the average wavelengths are of about 6.3 and 10.5 km, respectively. Therefore, the waveforms crossing the stations in the array should have some degree of consistency.

We selected the events occurring after the end of 2012, because the *P*alert EEW system has operated stably since then. The event selection criteria from the CWB earthquake catalog are that M_L must be greater than 4.5, focal depth less than 80 km, and hypocentral distance shorter than 150 km (Fig. 1 and Table 1). In addition, we carefully removed the waveform with the low SNR to maintain the waveform quality. Finally, the 15 events listed in Table 1 were selected for this study.

To find the time lag between stations, we apply the cross-correlation method and shift the waveforms accordingly. Then, the lagged waveforms are stacked to enhance the coherency of waveforms among the array. Finally, a single Pd value is computed for the array. Figure 2a is an example of the array-stacking waveform on top of the five individual waveforms of one study event. The SNR is clearly improved by the stacking process. The spectral amplitude (Fig. 2b) of the stacking waveform is slightly smaller than those of the five individual waveforms. This indicates that the background noise is reduced by the stacking process in the whole spectral range of signals.

Because the *P*alert devices are installed on the wall inside the building instead of a free surface, we have to modify the existing Pd attenuation equations (Wu *et al.*, 2007; Hsiao *et al.*, 2010; Chen, 2015). The form of the regression equation (equation 1) assumed a simple linear regression model as follows:

$$M_{Pd} = a + b \times \log(Pd) + c \times \log(R), \quad (1)$$

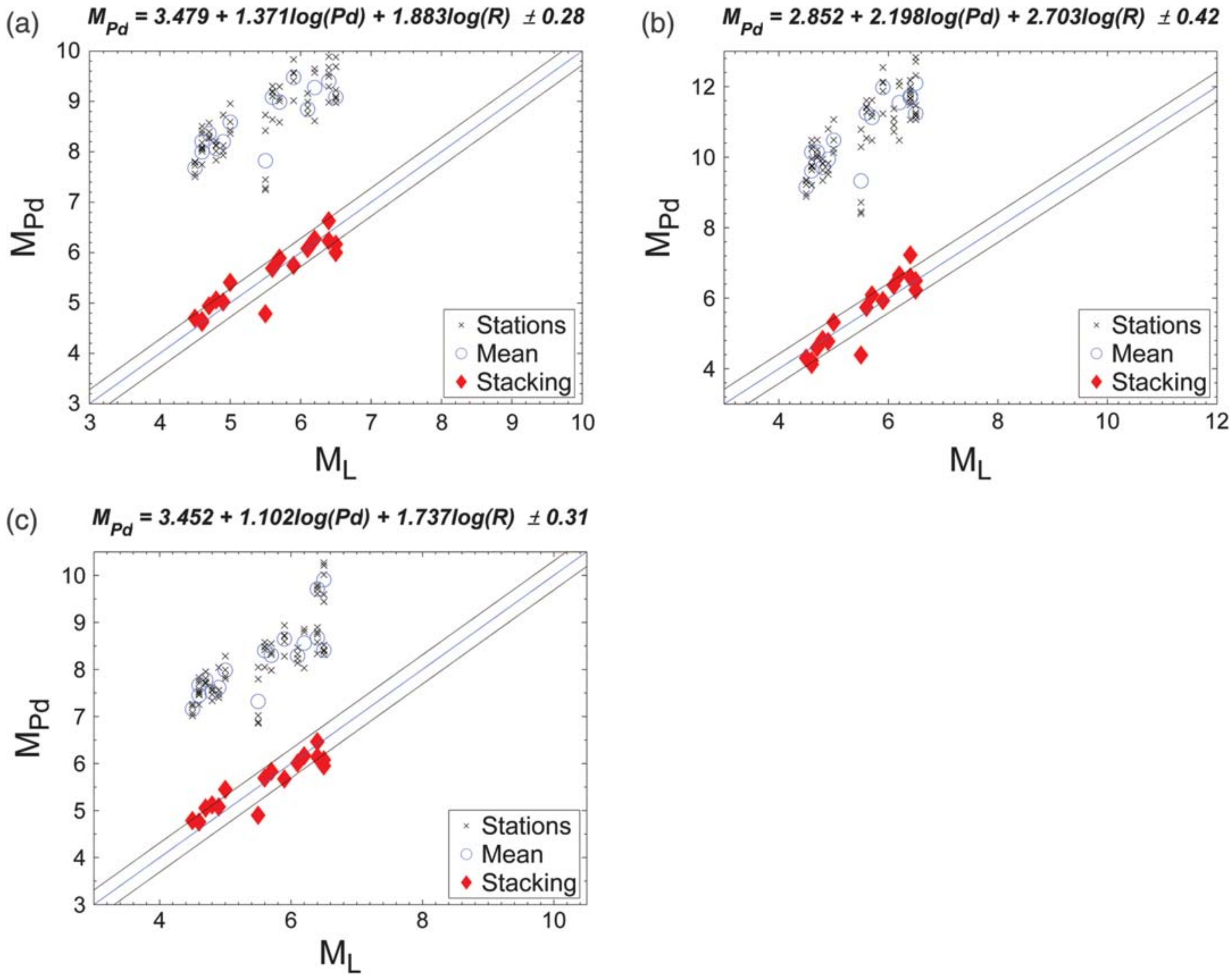
in which R is the hypocentral distance, b is the coefficient related to the magnitude, and c is the coefficient related to the geometric spreading. The wave propagation to collocated instruments installed on the free surface and on the wall of the building, respectively, does not reflect on the coefficients b and c, so we only have to revise coefficient a.

RESULTS AND DISCUSSION

Because M_{Pd} is determined by the waveform amplitude, we compare M_{Pd} with M_L of the CWB catalog. Figure 3 shows that M_{Pd} estimated by the three current Pd attenuation equations using the stacking waveform and the five individual waveforms of the array. The mean M_{Pd} in Figure 3 is simply the average of the five individual M_{Pd} values. The resulting M_{Pd} values in Figure 3 are systematically overestimated compared with the cataloged M_L. The five individual M_{Pd} values and their mean value are rather dispersed and farther from M_L (Fig. 3). This indicates that Pd recorded by the *P*alert sensor cannot be used directly to estimate earthquake magnitude by the current Pd attenuation equations. In addition, the systematical shifting of M_{Pd} by the stacked waveform suggests that the coefficient a in equation (1) should be modified to reflect the building amplification effect on Pd. Because the school buildings (e.g., structure, materials, floor height, etc.) in Taiwan are built following a certain construction code and most stations were installed on the first floor, the building effect on Pd should be similar among the *P*alert stations. As a result, we have to subtract some value (δ in Fig. 4) from the coefficient $a(a - \delta)$ for the each current Pd attenuation equation to compensate for the consistent overestimation of magnitude. Finally, a best-fit modified Pd attenuation equation specific for the *P*alert array can be determined once the subtraction value is found.

Figure 4 shows that the standard deviations (SDVs) between M_{Pd} and the cataloged M_L with a 1:1 relationship are expressed as a function of subtraction value (δ) for the three Pd attenuation equations. Each of the three regression lines has a well-defined global minimum without any local minimum (Fig. 4). The SDVs in Figure 4 are between 0.28 and 0.42 magnitude unit, which is acceptable accuracy for EEW purposes. Figure 5 compares M_{Pd} of the stacked waveforms, the individual Pd, and the mean Pd of the array with M_L. The M_{Pd} values in Figure 5a–c are estimated by the three best-fit modified Pd attenuation equations, respectively.

Finally, we adopt the modified Pd attenuation equation by Wu *et al.* (2007) as the best-fit equation (equation 2) for the *P*alert array among the three existing attenuation equations because it has the smallest SDV:



▲ **Figure 5.** M_{Pd} estimated by the each revised Pd attenuation equation for the individual, mean, and stacked waveform of the array. Diamonds show M_{Pd} estimated from the stacked waveform of the array; cross signs show M_{Pd} estimated from individual station waveform without the stacking process; and circles show estimated M_{Pd} from the average Pd of the five single stations without stacking process. The revised equations with their respective SDV are shown in the title of each plot. (a) Revised Pd attenuation equation of Wu *et al.* (2007), (b) revised Pd attenuation equation of Hsiao *et al.* (2010), and (c) revised Pd attenuation equation of Chen (2015). In each plot, the blue line shows the least-squares fit and two gray lines show the range of one SDV.

$$M_{Pd} = 3.479 + 1.371 \times \log(Pd) + 1.883 \times \log(R) \pm 0.28. \quad (2)$$

We defined a new Pd attenuation equation, particularly for the *P*alert EEW array to take account of the building. Using the array-stacking method, we found that the accuracy of onsite magnitude estimation (M_{Pd}) significantly increased by enhancing the coherent long-period (> 1 s) early arrivals between stations in an array. We also calculated the τ_c (Nakamura, 1988; Allen and Kanamori, 2003; Wu and Kanamori, 2005a), which is related to the average period of the initial *P*-wave waveform. We find that the performance of the magnitude estimation by τ_c is not significantly changed.

Because the station density of the *P*alert network is rather high, more arrays can be formed, especially for the metropolitan areas. The new Pd attenuation equation for magnitude estimate suggested in this study can be readily applied to a *P*alert array.

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