Chapter 13
A Test of Earthquake Early Warning System Using Low Cost Accelerometer in Hualien, Taiwan

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Abstract The earthquake early warning (EEW) research group at the National Taiwan University (NTU) and one technology company have been developing a Micro Electro Mechanical Systems (MEMS) type of accelerometer (the "*P*alert" EEW sensor) specifically designed for EEW purpose. In addition to the physical properties of the MEMS accelerometer, the main advantage of the MEMS accelerometer comparing to the other seismometers is that it is a relatively very low-cost seismic sensor. We present the performances of the *P*alert EEW network located at the Hualien region during a two-month experiment. The results of the Hualien *P*alert network encourage the further implementations for the MEMS-type of seismometer in the EEW application.

13.1 Introduction

Taiwan has been constantly threatened by large, devastating earthquakes as the consequence of the persistent collision between the Philippine Sea Plate and Eurasian Plate. For Taiwan, the development of earthquake early warning system was first motivated by the Hualien offshore earthquake ($M_w = 7.8$) in November 15, 1986, which caused severe damage in the metropolitan Taipei of about 120 km away from the epicenter. If an EEW system in the Hualien area can provide an earthquake warning within 20 s (i.e. crustal shear-wave travelling time over a distance of 120 km) after the occurrence of the Hualien earthquake, a timely warning can be feasible for the highly populated Taipei area. Since then Taiwan has been developing EEW system and become one of leading countries on EEW practices.

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The backbone of the present Taiwan EEW system is the Rapid Earthquake Information Release System (RTD; Wu et al. 1997, 2000) operated by the Central Weather Bureau (CWB) since 1995. The RTD network at present consists of 109 telemetered seismic stations covering the entire Taiwan region. Each station is equipped with a three-component, force-balance strong-motion accelerometer with a 16-bit resolution and a ± 2 g full dynamic range recorder.

Although the station density of the RTD network is proven to be rather adequate for repaid reporting and EEW purposes (Hsiao et al. 2009), a higher density of seismic stations is always in great demand (Lin and Wu 2010a, b; Lin et al. 2011) especially for a front-detection type of EEW system, in which the seismograms recorded by closer-to-earthquake seismic sensors are used to estimate the earthquake location, magnitude, and to predict the ground motions at more distant target areas. For example, a short-distance EEW system might be possible with extensive installation of seismometers around seismogenic areas (Wu et al. 2011). However, to increase the number of seismic station equipped with traditional mechanical seismometer will significantly boost the expense of EEW seismic network. Besides, for the other seismogenic zones around the world where only a limited number of seismic stations or even no seismic network is available, a cost-effective seismic network dedicated to EEW or rapid reporting is highly favored.

The MEMS accelerometer that has been introduced in seismic applications (Holland 2003) since 1990s is miniature, cost-saving, and ideal for recording high-frequency, near-field unsaturated ground motions. Consequently, the MEMS accelerometer offers a suitable application for an economical, near-source EEW system. The MEMS accelerometer type of network has been proposed for its potential for EEW using the Quake-Catcher Network (Cochran et al. 2009).

The EEW research group at the NTU and the San Lien Technology Corp. (http://www.sanlien.com.tw) have been developing a MEMS type of accelerometer named the "*P*alert" sensor (Fig. 13.1), specifically designed for EEW purpose. *P*alert can record three-component acceleration and also can perform real-time integration to obtain velocity and displacement. Once an earthquake *P* wave is detected by the triggering algorithms embedded in the sensor, the sensor will compute the average period (τ_c; Kanamori 2005; Wu and Kanamori 2005a, 2008a, b; Wu et al. 2007) and peak amplitude of the filtered vertical displacement (P*d*; Wu and Kanamori 2005b, 2008a, b; Wu et al. 2007) from the first few seconds of the *P*-wave and accordingly send an earthquake alarm signal for on-site EEW purpose. The triggering algorithms include continuous monitoring of acceleration, displacement, and Short-Term-Average (STA)/ Long-Term-Average (LTA) ratio (Allen 1978). *P*alert features with networking capability including streaming real-time data to host, automatically connect to up to 2 servers, and Network Time Protocol (NTP) time calibration.

In this study, we will present the EEW performances of the testing *P*alert EEW network located at the Hualien region (Fig. 13.2), a high seismicity region in eastern Taiwan. The results of the Hualien *P*alert EEW network during its initial phase of operation strongly encourage the further development for the MEMS accelerometer-type of EEW system.

Fig. 13.1 The *P*alert earth-
quake early warning sensor

Fig. 13.2 The location map
shows the stations (*circles*) of
the Hualien EEW network and
the epicenters of the 11 study
events (*star*). The NTU server
of the Hualien EEW network
is indicated by the *triangle*
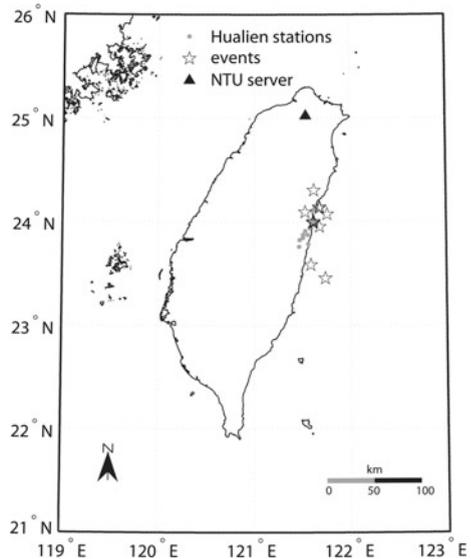
13.2 The Hualien EEW System

The Hualien *P*alert testing EEW network consists of 15 *P*alert stations, and Fig. 13.3
shows the schematic diagram for the field implementation. There are two main struc-
tures involved in the network, consisting of local field systems and a central system.
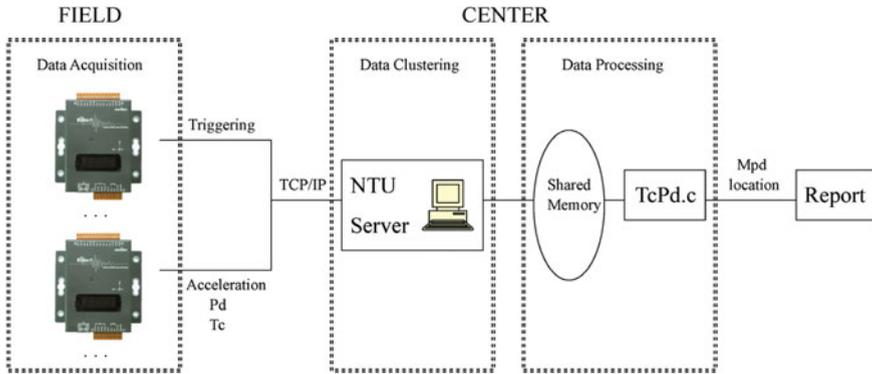
Fig. 13.3 Operation flowchart of the Hualien EEW network

The local system includes signal acquisition and processing by Palert and offers onsite early warning when Pd is larger than 0.35 cm (Wu et al. 2011). The central system includes data clustering and analysis by the network server hosted in Taipei, NTU. The information recorded by the Palert stations is transmitted to the NTU server ocer the TCP/IP protocol. In case of a power failure due to electrical power tower collapses or disconnected communication lines by strong ground shaking, each station is equipped with an internal battery to provide steady electrical power for at least 4 h. Once more than six Palert stations are triggered, an event is declared. The acquired information from the Palert stations are then stored in the system-wide shared memory and controlled by the code TcPd.c to generate the EEW/rapid reports with event location and magnitude operated by the NTU server.

The hypocentral location will be determined using the traditional earthquake locating algorithm on a half space linear increasing velocity model. The magnitude determination using the Pd attenuation relationship with hypocentral distance (R) (M_{Pd}; Wu and Zhao 2006), which can be expressed as:

$$M_{Pd} = 4.748 + 1.371 \times \log_{10}(\text{Pd}) + 1.883 \times \log_{10}(R) \tag{13.1}$$

is adopted. As more stations are triggered, the event location and magnitude are continuously updated.

13.3 The Performance of the Hualien EEWS

In this testing, 11 earthquakes in the recording period between June, 2010 and August, 2010 and located near the Hualien EEWS are used (Table 13.1, 13.2). The choices of the events near the Hualien EEW network follow the proposition as using the Hualien network to be the front-detection sensor. Comparisons of the earthquake information

Table 13.1 Source parameters of the 11 earthquakes determined by the Central Weather Bureau (CWB)

		CWB catalog			
Event no.	mm/dd/yy	Origin time	Location (lon, lat)	Depth (km)	Magnitude (M_L)
1	6/18/2010	04:24:06.1	121.68, 24.13	9.6	2.9
2	7/04/2010	02:43:05.0	121.68, 23.95	11.8	4.0
3	7/17/2010	09:04:17.2	121.74, 23.45	40.0	5.2
4	7/24/2010	23:41:10.1	121.62, 24.30	23.5	3.6
5	7/28/2010	22:18:41.2	121.68, 24.14	9.7	3.3
6	7/31/2010	08:13:17.8	121.76, 24.07	46.4	4.6
7	8/10/2010	21:57:51.4	121.53, 24.09	19.4	3.4
8	8/19/2010	07:11:21.3	121.62, 24.00	5.1	3.5
9	8/19/2010	07:45:30.1	121.61, 23.99	7.0	3.8
10	8/20/2010	06:46:23.1	121.62, 23.99	7.7	3.0
11	8/21/2010	16:38:00.0	121.59, 23.58	40.2	5.3

(locations and magnitudes) given by the Hualien EEW system and the CWB published earthquake catalogs are shown in Fig. 13.4. Since a simplified velocity model is used in the code TcPd.c to find the hypocenters and most of the events are located outside the network. So, a large variation of the earthquake locations is indicated in Fig. 13.4. However, for the events with shallow focal depths or located inside the perimeter of the stations the discrepancies of the hypocenters of those between the Hualien EEW system and the CWB catalogs are smaller. The response time as the time difference between the event original time and the first report given by the Hualien EEW system varies between 5 and 25 s with the average time of 9.5 s. Therefore, the Hualien EEW system is capable to issue a timely warning to areas located more than 35 km away from the hypocenter before the arrival of the S-wave. The large uncertainty is found in magnitude determination. M_{Pd} estimated with Eq. (13.1) has a 1:1 relationship with M_L with standard deviations of 1.25 and 1.24 for the first and final reports, respectively. However, earthquakes with magnitudes large than 4.0 have a much better correlation between Pd and the final magnitude.

13.4 Discussion and Conclusions

In addition to the physical properties of the MEMS accelerometer, the main advantage of the MEMS accelerometer comparing to the other seismometers is that it is a relatively very low-cost seismic sensor. For the commercial type of Palert the cost is generally less than 1000 US dollar. A seismic network comprising couple tens or even hundreds of the Palert sensors can be built by a much lower budget than that with the transitional seismometers.

Table 13.2 Source parameters of the 11 earthquakes determined by the Hualien EEW system

Event* no.	mm/dd/yy	Time	Location (lon, lat)	Depth (km)	Magnitude (M_{pd})
1	6/18/2010	04:24:12.8	121.63, 24.14	4.2	3.4
2	7/04/2010	02:43:10.3	121.72, 23.95	24.9	4.7
2	7/04/2010	02:43:14.3	121.64, 24.02	6.0	4.0
3	7/17/2010	09:04:41.3	121.58, 24.04	9.1	4.4
4	7/24/2010	23:41:20.1	121.61, 24.31	18.5	5.0
5	7/28/2010	22:18:48.2	121.36, 23.76	41.1	5.8
6	7/31/2010	08:13:30.7	121.57, 23.93	12.6	4.6
6	7/31/2010	08:13:31.7	121.56, 23.91	10.6	4.6
7	8/10/2010	21:58:00.3	121.15, 24.31	17.4	5.7
8	8/19/2010	07:11:27.9	121.64, 24.03	2.9	4.0
9	8/19/2010	07:45:35.8	121.57, 24.01	4.2	4.2
9	8/19/2010	07:45:37.8	121.58, 24.01	3.3	4.4
9	8/19/2010	07:45:40.8	121.57, 24.01	4.2	4.4
10	8/20/2010	06:46:29.7	121.69, 24.02	0.7	4.3
11	8/21/2010	16:38:11.1	121.55, 23.61	29.9	5.7
11	8/21/2010	16:38:12.1	121.56, 23.69	21.6	5.6
11	8/21/2010	16:38:13.1	121.56, 23.68	22.9	5.6

*Multiple event numbers indicate that more than one report is made for that event

The differences of the hypocentral locations between the reports by the Hualien EEWS and the CWB catalogs are partly attributed to the simplified velocity model used in the Hualien EEW location algorithm and to the linear station distribution in the N-S direction of the Hualien EEW network. Another source of deviation might be caused by the inaccurate automated first-arrive picking especially for the smaller earthquakes. In the future development of the Hualien EEW system, a 1-D velocity model with more layers might be adopted. Eventually, for the final phase of EEW network development, a low-cost and densely distributed *P*alert-type network over the whole Taiwan region is feasible. Such extensively and densely distributed network is especially useful for a large inland earthquake or with a long rupture length, which is often more capable of causing severe damage than outland ones in Taiwan.

The discrepancies between the predicted M_{Pd} and the catalog M_L might arise from poor earthquake location and consequently incorrect distance term in implementing Pd attenuation relationship (Fig. 13.4c). Figure 13.5a shows that the standard deviation (1.24) shown in Fig. 13.4c is reduced to 1.06 by replacing the EEW-determined location with the catalog location. The region-depend Pd attenuation relationship (Wu and Zhao 2006) used in this study (Eq. 13.1) is derived for earthquakes in Southern California and there was no such relationship available during the construction phase of the Hualien EEW network. Figure 13.5b compares M_{Pd} calculated by the newly derived Taiwan Pd attenuation relationship (Hsiao et al. 2011) with the catalog M_L. The standard deviation (1.24) shown in Fig. 13.4c is significantly reduced to 0.64 without an overestimated bias as shown in Figs. 13.4c and 13.5a. A local Pd attenuation relationship specifically for the Hualien EEW network might further improve
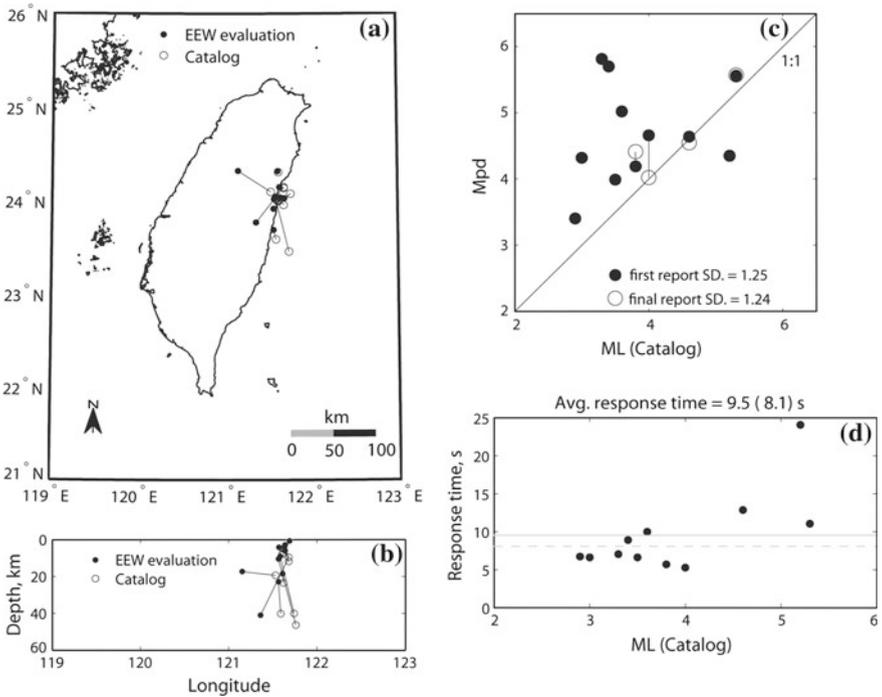
Fig. 13.4 Comparisons of the earthquake information (**a** epicenters, **b** focal depths, **c** magnitudes, **d** response times) given by the real-time, on-line Hualien EEW system and the CWB published earthquake catalogs. In **c**, the *solid* and *open circles* represent the first report with more than six triggered stations and the final report with all available stations, respectively. The response times in (**d**) are those given by the first report. The average response time of 8.1 s indicated by the *dashed line* in (**d**) is the one excluding the maximum response time of 24.1 s

the EEW performance in magnitude determination. Another noticeable feature of the Hualien EEW network is the response time. For the current operating EEW system by CWB the average response time is of about 20 s (Hsiao et al. 2011).

For magnitude determination problem in EEW system, a large event with large rupture dimensions, such as the $M_w = 9.0$, 2011 Tohoku earthquake, likely consists of several strong asperities over the entire rupture volume. Using the first few seconds of the waveform from an initial nucleation rupture for estimating the eventual magnitude, which is the concept behind the EEW system, may be difficult for extremely large earthquakes. However, recently result (Lin and Wu 2012) indicates that the effective shaking method of Wu and Teng (2004) provides excellent magnitude estimation for the 2011 Tohoku earthquake, without a saturation problem. Such approach could be used in *P*alert network for updating magnitude determination. Thus, within few to ten seconds and few minutes P*d* and effective shaking methods could be used for EEW and rapid reporting purposes, respectively.
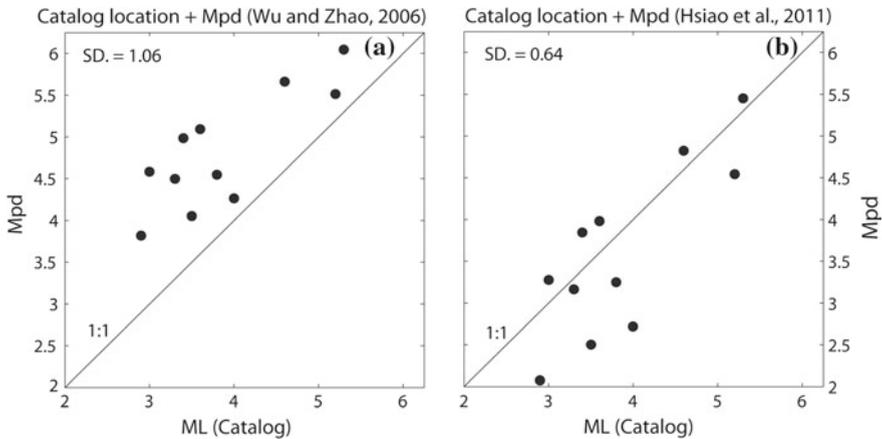
Fig. 13.5 Magnitude (M_{Pd}) determined by the Hualien EEW network by using **a** the Southern California (Wu and Zhao 2006) and **b** the Taiwan P*d* attenuation relationships (Hsiao et al. 2011), respectively, versus M_L in the CWB earthquake catalogs. Both in **a** and **b** the earthquake locations are given by the CWB earthquake catalogs

Our new EEW sensor, *P*alert, using the MEMS sensor has a high commercial potential owing to its low cost. The EEW system could be established in a relatively low budget or *P*alert sensor could be readily added to the existing seismic network to increase the density of the network. The Hualien EEW system belongs to the front-detection type. Nevertheless, our *P*alert sensor also can be used in the on-site type of EEWS, which the initial *P*-wave motion at a target site is used to predict the ground motions of the later *S* and surface waves at the same site.

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