Progress on Development of an Earthquake Early Warning System Using Low-Cost Sensors

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Progress on Development of an Earthquake Early Warning System Using Low-Cost Sensors

Yih-Min Wu[1]

Abstract—Taiwan is one of the leading developers of earthquake early warning (EEW) systems. The Central Weather Bureau has been the primary developer of the EEW system in Taiwan since 1993. In 2010, the National Taiwan University (NTU) developed an EEW system for research purposes using low-cost accelerometers. As of 2014, a total of 506 stations have been deployed and configured. The NTU system can provide earthquake information within 15 s of an earthquake occurrence. Thus, this system may provide early warnings for cities located more than 50 km from the epicenter. Additionally, the NTU system also has an onsite alert function that triggers a warning for incoming P-waves greater than a certain magnitude threshold, thus providing a 2–3 s lead time before peak ground acceleration for regions close to an epicenter. Detailed shaking maps are produced by the NTU system within one or two minutes after an earthquake. Regions of high shaking indicated by the shalking map can indicate locations of damage and casualties and help estimate the damage incurred. The direction of earthquake ruptures are also potentially identified based on detailed shaking maps and strong motion records of the NTU system.

Key words: Earthquake, Earthquake early warning, Seismic hazard mitigation, Strong ground motion, Real-time seismology.

1. *Introduction*

The EEW system is becoming a useful tool for seismic hazard mitigation after 20 years of development (Allen *et al.* 2009; Lee and Wu 2009; Satriano *et al.* 2011). Many countries are currently involved in developing EEW systems (Allen *et al.* 2009), of which Taiwan is one. Taiwan is located in the Pacific Rim seismic zone, one of the most active earthquake regions. Since 2012, the Seismological Observation Center of the CWB has detected more than 30,000 earthquakes per year over an area of about 400 × 500 km^2. Taiwan has been repeatedly hit by damaging earthquakes. For example, on March 17, 1906, a damaging earthquake ($M = 7.1$) occurred in Chiayi in southern Taiwan. This event caused 1,258 casualties and destroyed 6,767 houses. In 1935, a disastrous earthquake ($M = 7.1$) occurred in Central Taiwan. It caused 3,276 casualties and destroyed 17,907 houses. The 1999 Chi–Chi earthquake ($M_w = 7.6$) occurred in Nantou County. It caused 2,456 casualties and about $4 billion worth of property damage (Wu and Teng 2002). Therefore, Taiwan started developing an EEW system for seismic hazard mitigation in 1993 (Teng *et al.* 1997; Wu *et al.* 1998, 1999; Wu and Teng 2002; Hsiao *et al.* 2009). Taiwan, Japan and Mexico are all located in Pacific Rim seismic zones and are the leading developers of the EEW system (Allen *et al.* 2009; Lee and Wu 2009; Satriano *et al.* 2011).

There are two types of EEW systems in operation around the world. One is an onsite EEW system that determines earthquake information form initial P-waves and predicts the more severe ground shaking associated with the following S-waves. Nakamura (1984) first proposed an onsite EEW system for the Japan railway system. The urgent earthquake detection and alarm system (UrEDAS) is a typical example of an onsite EEW system (Nakamura 1988, 1989). The other type is a regional EEW system. It is also referred to as a front-detection EEW system. The concept of the regional EEW system considers that signal communication speed is faster than the propagation of seismic waves. Thus, instruments installed in the earthquake source region give early warning to distant cities. The Taiwanese and Mexican systems are two examples of regional EEW systems.

Generally, a single station or a small array is used for onsite EEW systems. For regional warnings, a dense array should be installed in the source region in order to obtain early warning time. However, to

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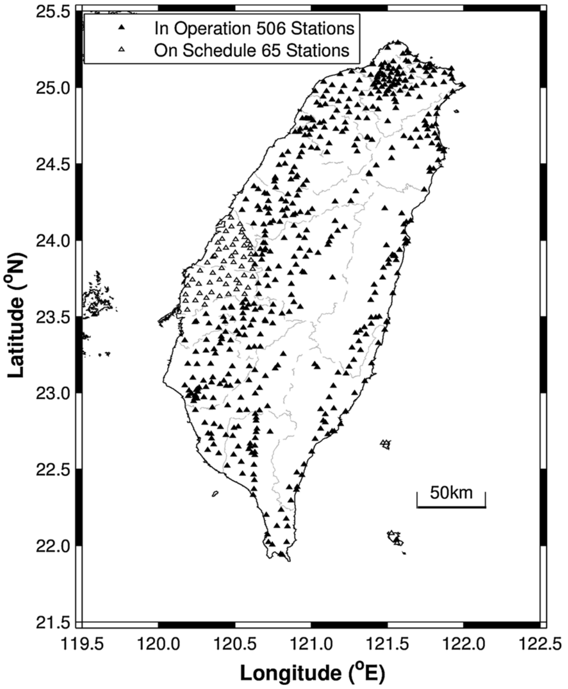

Figure 1
Station distribution of the *P* alert earthquake early warning network

predict where the next big earthquake will occur is very difficult. Thus, it is very important to enhance station coverage for a regional warning approach. For example, Japan started a new EEW system in October 2007. Information is primarily provided by the Hi-net seismic network (Hi-net). Average distances between Hi-net stations is about 25 km. It challenging for this network to deploy more stations in epicenter vicinities because approximately 10-times more sensors would be needed to meet this demand. This is cost prohibitive for the Japanese government. An alternative solution for enhancing station density is low-cost micro-electromechanical system (MEMS) accelerometers (Horiuchi *et al.* 2009).

The MEMS accelerometer has been used in seismology since the 1990s (Holland 2003). It is a cost-saving miniature device and ideal for recording strong ground motions. The EEW research group at NTU worked with a technology corporation to develop a P-wave alert device named "*P* alert" that uses MEMS accelerometers for onsite and regional EEW. The cost of the *P* alert device is less than one-tenth the cost of traditional strong motion instruments and can record real-time three-component acceleration signals. As a result, development of a dense network for regional EEW is becoming possible.

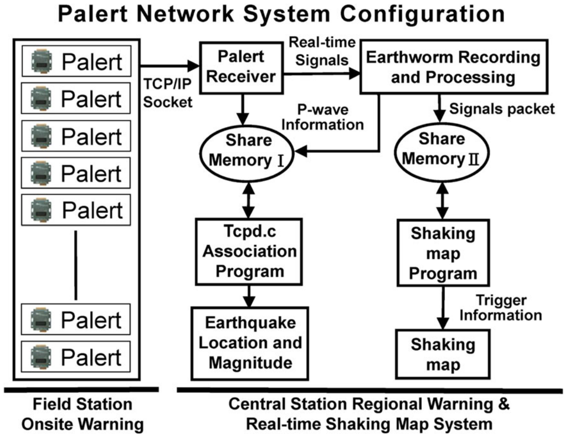

Figure 2
Configuration of the *P* alert real-time strong motion network for earthquake early warning

Supported by the Ministry of Science and Technology (MOST) of Taiwan, the NTU began building the *P* alert real-time strong motion network for onsite and regional EEW purposes. Following four years of installation, a total of 506 stations were deployed and configured. Another 65 stations are on schedule to be installed in the following year. Figure 1 shows the distribution of the *P* alert stations. Most of the stations are located in elementary schools where power and Internet connections are provided. Therefore, the cost of building this network was greatly reduced. Thus, a dense and low-cost real-time strong motion network has been installed in Taiwan for EEW purpose (Wu *et al.* 2013). The recent development and progress of this system will be reported in this paper.

2. *System Development and Configuration*

The configuration of the *P* alert real-time strong motion network is shown in Fig. 2. At the field site, real-time signals are processed by the *P* alert devices. The *P* alert signal resolution is 16 bits with a −2 to +2 g range and the sampling rate is 100 samples per second. Three-component acceleration signals are processed onsite for detecting P-wave arrival using the trigger algorithm of the Short-Term-Average

(STA)/Long-Term-Average (LTA) ratio by Allen (1978) and are continuously double integrated into displacement signals for calculating the P_d, the peak amplitude of the P-wave (Wu and Kanamori 2005a, b, 2008a, b; Wu *et al.* 2007). When an earthquake occurs, the *P* alert device automatically detects the P-waves, and once the P_d or PGA are greater than 0.35 cm or 80 gal (Wu *et al.* 2011), respectively, the *P* alert device begins its alert with a warning sound on site. The P_d and peak ground velocity (PGV) have a logarithm–linear relationship, according to previous results (Wu and Kanamori 2005a, b, 2008a, b). So, when the *P* alert detects a P_d larger than a certain threshold, it gives a warning. Generally, it can give a few second of warning before PGA, even in regions very close to the epicenter.

P alert devices also send one-second signals via TCP/IP connections in real-time to two central stations at the NTU and the Grid Center of the Academia Sinica Taiwan for data processing and storage. Most of the stations are located in elementary schools. All of the schools and universities are in the same internet framework. Thus, telemetry latency is generally within one second for a signal to be sent from the field site to the central station. In practice, about 80% of the station's signals can be received by the central stations. Power interruptions and internet firewalls preclude the other 20% of local stations from sending data to the central stations (Wu *et al.* 2013; Hsieh *et al.* 2014). Tasks performed at the central stations include data clustering and processing. For real-time seismic data processing, signals are processed and stored within the "Earthworm" system developed by the US Geological Survey (Johnson *et al.* 1995). In the Earthworm system, signals are again processed in order to detect the arrival of P-waves (Hsiao *et al.* 2011; Chen *et al.* 2012; Wu *et al.* 2013). P-wave information [including the P arrival, the peak amplitude of the acceleration (P_a), the velocity (P_v) and P_d for the initial 3 s of P-waves] detected by the Earthworm platform is sent to shared memory (I). P-wave information detected by field *P* alert devices are also sent to the shared memory (I) via software named *P* alert receiver (Fig. 2). As soon as 12 *P* alert stations are triggered by P-waves, an event is declared. The TcPd.c computer program analyzes the event parameters stored within the shared memory (I) and computes the earthquake origin time, hypocenter and magnitude. The hypocentral location is determined via a traditional earthquake location algorithm using a half-space linear increasing velocity model (Wu *et al.* 2013; Wu and Lin 2014). The magnitude determination is based on the relationship of P_d and hypocentral distance (Wu and Zhao 2006).

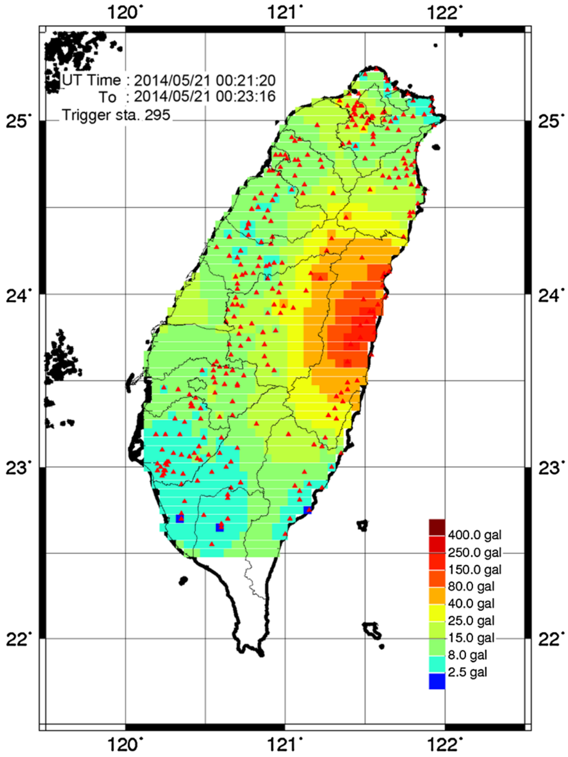

Figure 3
Shaking map of the 2014/05/21 M_L 5.9 earthquake produced and delivered by the *P* alert network

In the Earthworm system, real-time signals are also sent to shared memory (II) (Fig. 2). The shaking map program analyzes the signals stored within the shared memory (II). When 12 stations detect PGA > 1.2 gal, the system will be triggered to produce a shaking map. One to three minutes after the system is triggered, shaking maps will be delivered via e-mail to specific users every minute. Figure 3 shows an example of a shaking map delivered from this system.

Table 1

Parameters of events with $M_L > 5.5$ detected by the Central Weather Bureau (CWB) and the P alert network used in this study

Time (UT)		CWB report				P alert report				
		Long. (E°)	Lat. (N°)	Depth (km)	M_L	Long. (E°)	Lat. (N°)	Depth (km)	M_p	Reporting time (s)
2013/03/07	03:36:46	121.49	24.31	15.2	5.6	121.47	24.32	11.1	5.7	14.8
2013/03/27	02:03:20	121.07	23.90	15.4	6.1	121.04	23.91	15.9	6.2	13.4
2013/06/02	05:43:04	121.00	23.87	10.0	6.3	121.00	23.86	19.2	5.9	11.8
2013/10/31	12:02:09	121.42	23.55	19.5	6.3	121.05	23.64	21.7	6.6	12.5
2014/05/21	00:21:14	121.45	23.74	18.0	5.9	121.40	23.72	10.0	6.0	11.5

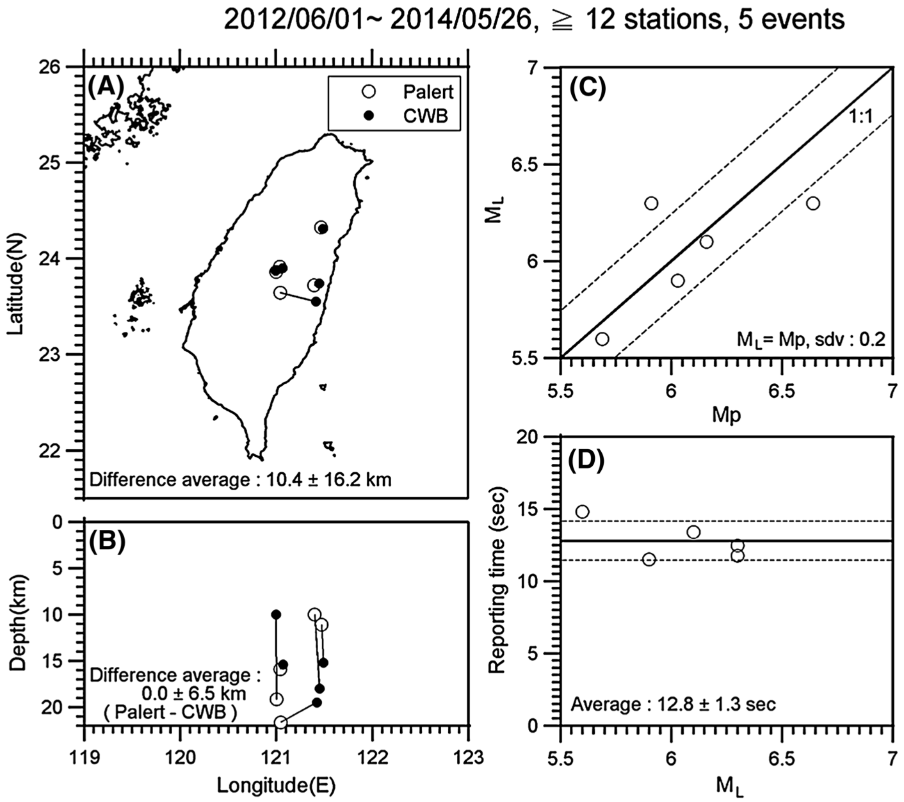

Figure 4

Comparison of earthquake information, as follows: **a** epicenters; **b** focal depths; and **c** the magnitudes given by the real-time *P* alert network and the CWB-published earthquake catalogs; **d** Reporting times of the *P* alert network

3. *Results*

Since June 2012, the EEW system has operated using the *P* alert network. During the period from June 2012 to May 2014, a total of five inland earthquakes with $M_L > 5.5$ have been detected (Table 1). The signals were well recorded by the central stations. Performance of the *P* alert network is summarized in Fig. 4. Results were compared with those reported by the CWB (http://www.cwb.gov.tw).

Generally, four to six stations detect P-waves and the information from those stations is used to determine the earthquake location and magnitude. However, the *P* alert network EEW information is triggered by 12 *P* alert stations that detect P-waves vai a dense array. Four to six stations in this network may not provide good earthquake location data. Hypocenters provided by the *P* alert network versus those from the CWB are plotted in Fig. 4. The hypocenters determined by the two systems are generally in agreement. The average difference in epicenter location is 10.4 km with a standard deviation of 16.2 km. Moreover, the average difference in focal depth was 0.0 km with a standard deviation of 6.5 km. The magnitudes (M_P) determined by the *P* alert network and the corresponding M_L values from the CWB are plotted in Fig. 4 and also listed in Table 1. In general, magnitude uncertainty is on the order of 0.2. It is an acceptable value for EEW purposes. This network achieved an earthquake reporting time—the time between earthquake occurrence and the time the EEW system provides warning information—varying from 11.5 to 14.8 s with an average of 12.8 s and a standard deviation of 1.3 s (Fig. 4). This result indicates that for large events in Taiwan, the *P* alert network can issue an early warning report within approximately 15 s. Practical regional EEW is feasible using the low-cost *P* alert network.

Two consecutive shallow earthquakes occurred in the same year in Nantou County in central Taiwan, on 2013/03/27 (M_L 6.1) and 2013/06/02 (M_L 6.3). The epicenters are located in the center of the *P* alert network (Table 1; Fig. 4). It provides a nice opportunity to examine the onsite EEW for regions close to the epicenter. The *P* alert device has an onsite alert function that triggers a warning sound once the P_d exceeds 0.35 cm or the PGA is larger than 80 gal (Wu *et al.* 2011). Figure 5 provides the resulting early warning lead times for the regions close to the epicenters of the two Nantou earthquakes. The early warning lead time is defined as the interval between the time when the *P* alert network triggers a warning sound and the time PGA is recorded. A total of 28 stations were in operation in Nantou County for the first event (Fig. 5a). Four stations that recorded $P_d > 0.35$ cm triggered warning alerts, but the PGA < 80 gal. As such, they are considered to be false alarms since 80 gal is the standard threshold for giving warning. Thus, the warning success rate is 86 % with a 14 % false alarm rate. The lead times range from 0.60 to 3.57 s with an average of 2.06 s. In contrast to the first event, a total of 29 stations were in operation for the second event in Nantou County (Fig. 5b). Two stations gave false alarms. The success rate reached 93 % with only 7 % false alarms. The lead times range from 0.01 to 9.00 s with an average 3.82 s. Worth noting is that the nearest two stations (W07F and W072) both recorded a PGA > 0.3 g for both events and provided lead times of more than 3 s. Three seconds is sufficient time for an automated EEW system to make emergency safety responses.

4. Discussion and conclusions

As of the thrid quarter of 2014 there are 506 *P* alert stations installed in Taiwan (Fig. 1). Whenever an earthquake occurs around Taiwan, a detailed shaking map can be produced within one or two minutes based on data collected by the dense *P* alert network. Regions of high shaking per the intensity map produced by the *P* alert network suggest the locations of damage and casualties (Hsieh *et al.* 2014). The detailed shaking map can also identify rupture direction. Currently, there are alternative methodologies for estimating the rupture direction, but they all require more analysis time. Figure 6 shows the shaking map of the 2013/10/31 eastern Taiwan M_L 6.3 earthquake, as well as the distribution of its aftershocks. It shows that the high shaking region is consistent with the distribution of the aftershocks. The stations recording high shaking and the aftershocks are distributed in a NNE direction from the mainshock. Therefore, the rupture likely proceeded from the hypocenter in the NNE direction and resulted in high shaking being distributed towards the north. Figure 7 shows the strong motion seismograms recorded by the *P* alert network in the NNE and SSW directions from the epicenter. Strong motion records in the NNE direction show large amplitudes and radiated energies are concentrated following the S-wave arrivals. On the other hand, records in the SSE direction show small shaking amplitudes and radiated energies are divergent after the S-wave arrivals. Unilateral rupture of this event, as mentioned above, caused a strong directivity effort. The *P* alert network is able to provide a real-time shaking map via its dense array. Thus, the earthquake rupture direction is potentially identifiable using a detailed shaking map. This represents

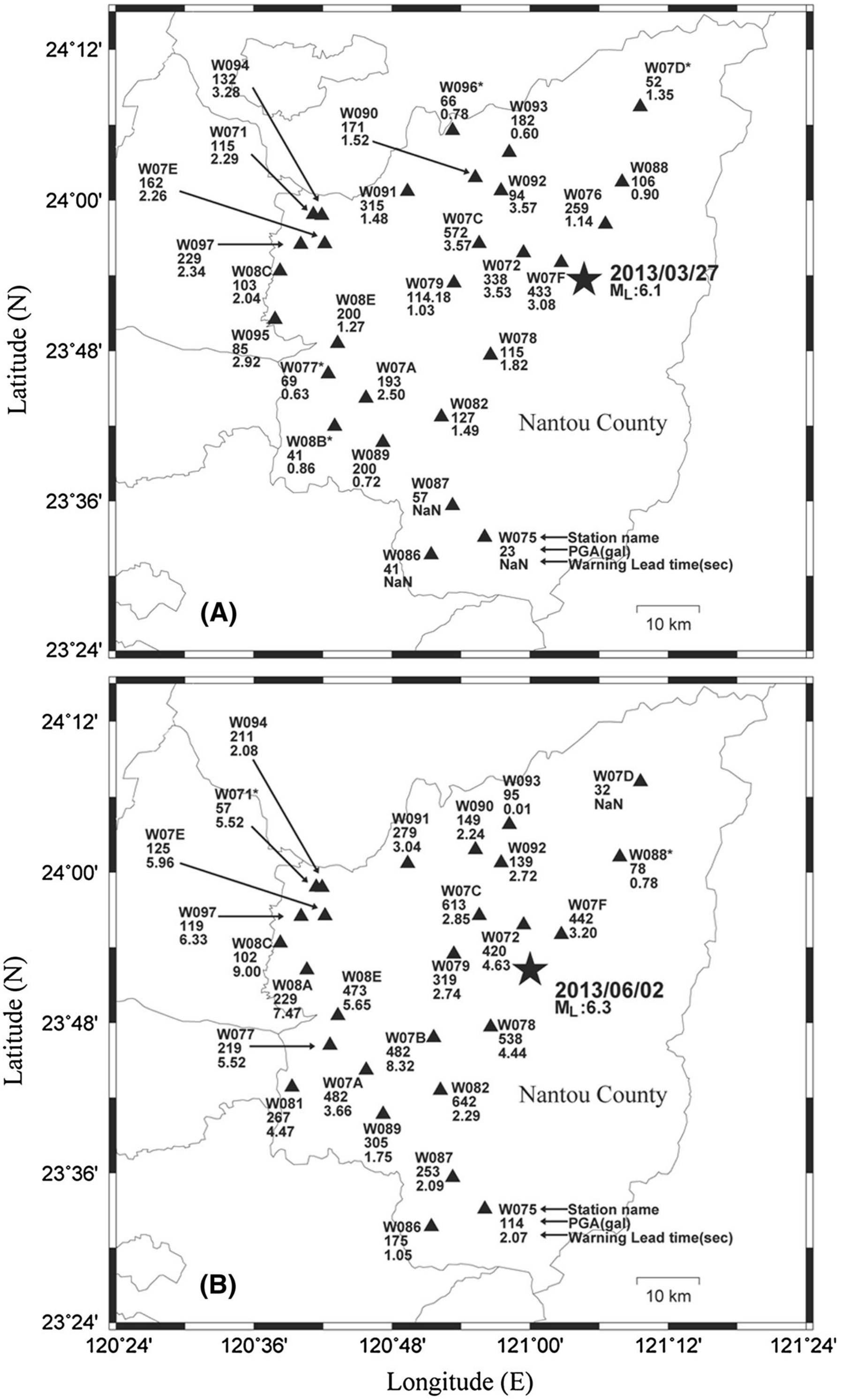

Figure 5

Early warning lead times for *P* alert stations in regions close to the epicenters of the 2013/03/27 M_L 6.1 (**a**) and 2013/06/02 M_L 6.3 (**b**) Nantou, Taiwan earthquakes. Lead time is defined as the interval between the time when the filtered vertical displacement exceeds 0.35 cm or ground acceleration >80 gal and the time of PGA

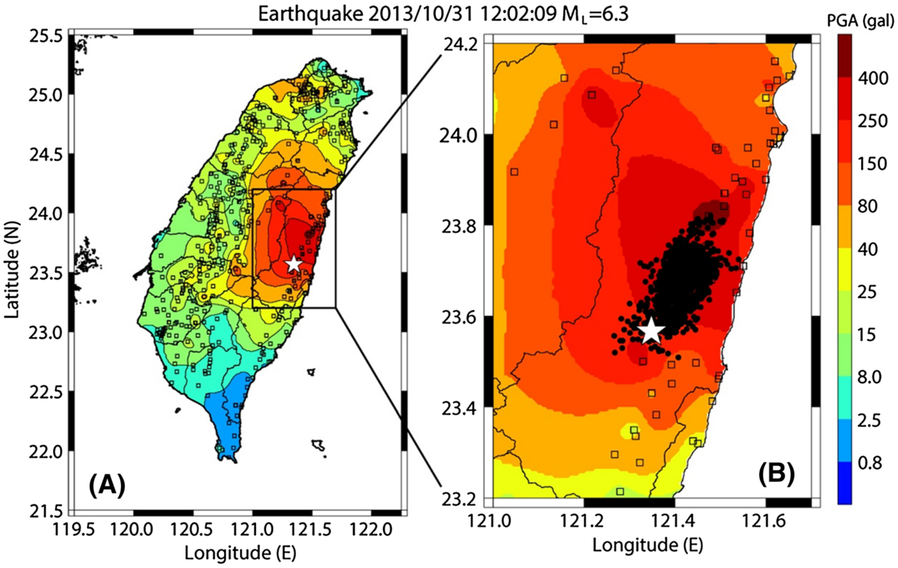

Figure 6

a Shaking map of the 2013/10/31 eastern Taiwan earthquake produced using strong motion records from the *P* alert network. The *star* shows the epicenter and *open squares* indicate the station distribution for plotting the shaking map; **b** shaking map for regions close to epicenter. *Dots* show the distribution of the aftershocks

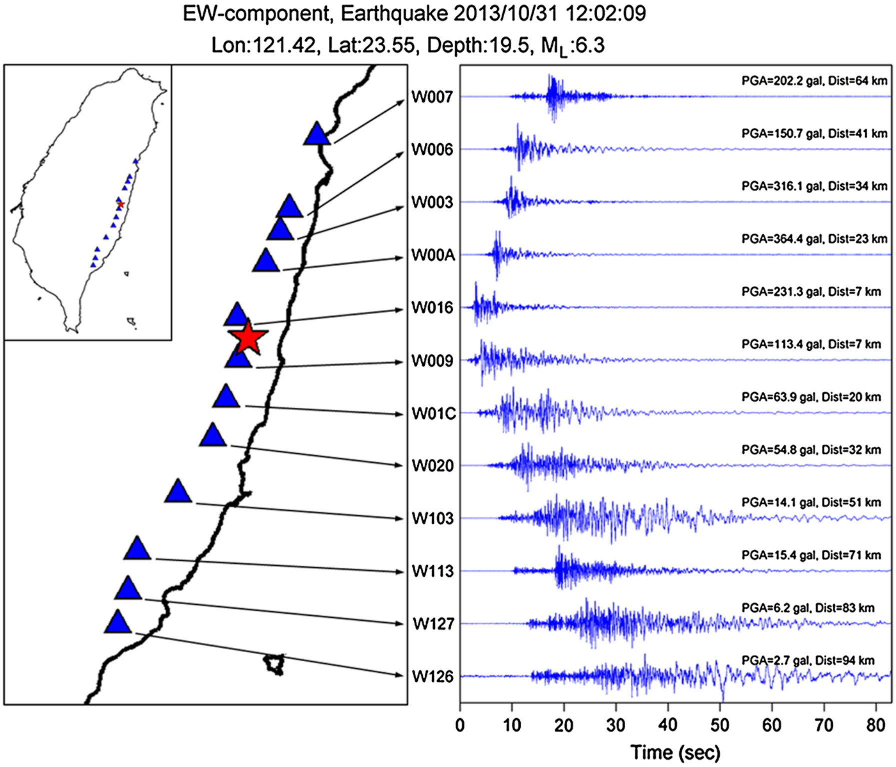

Figure 7

Strong motion records of the *P* alert network in the NNE and SSW directions from the epicenter (*star*) of the 2013/10/31 eastern Taiwan earthquake. *Triangles* show the station distribution significant progress in earthquake observations for Taiwan.

The P alert network is a hybrid EEW system. The regional EEW system can report earthquake information within 15 s. It provides warning to areas greater than $\sim$50 km from the epicenter. On other hand, the region within 50 km of an epicenter is considered the blind zone of the regional warning approach. However, the onsite P alert device can provide early warnings for the blind zone. The major advantage of the onsite P_d approach is that it provides 2–3 s early warning time before PGA for regions close to an epicenter. The hybrid EEW approach will become a major part of developing the future EEW system. As a result of the low cost of the P alert device, the EEW system could be established for relatively little expense. Outside of Taiwan, P alert devices have been installed in China, Indonesia, Mexico, the Philippines and India. It is encouraging for other countries to be developing EEW systems using low-cost sensors based on successful experiences in Taiwan.

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