A High-Density Seismic Network for Earthquake Early Warning in Taiwan Based on Low Cost Sensors

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INTRODUCTION

Because of persistent collisions between the Philippine Sea plate and the Eurasian plate, Taiwan has been constantly threatened by large and devastating earthquakes that often cause large losses of life and property. To reduce losses caused by future damaging earthquakes, it is crucial for Taiwan to seek solutions through scientific research. The Earthquake Early Warning System (EEWS) is one of the most promising tools for alleviating threats caused by large earthquakes, and has been tested and operated in many countries (Allen *et al.*, 2009; Lee and Wu, 2009; Satriano *et al.*, 2011). Taiwan has been developing an EEWS and is one of the leading countries in EEWS practices (Wu *et al.*, 1998, 1999, 2011; Wu and Teng, 2002; Hsiao *et al.*, 2009, 2011).

The present EEWS in Taiwan has been operated by the Central Weather Bureau (CWB) since 1995 and consists of 109 telemetered seismic stations that span the entire region of Taiwan. The EEWS can provide earthquake information within 20 s following an earthquake occurrence (Hsiao *et al.*, 2009, 2011; Wu and Teng, 2002). Although a 20 s reporting time is short, if the number of seismic stations operating within the network is increased, this time period can still be reduced. However, the cost of building such a high-density seismic network by traditional, force-balance seismometers is extremely high.

Since the 1990s, the Micro Electro Mechanical Systems (MEMS) accelerometers introduced in seismic applications (Holland, 2003) have been cost-saving miniature devices and ideal for recording strong ground motions. The Earthquake Early Warning (EEW) research group at National Taiwan University (NTU) worked with a technology corporation to develop a *P*-wave alert device named *P*alert (Fig. 1) that uses MEMS accelerometers for onsite earthquake early warning. The cost of the *P*alert device is less than 1/10 the cost of traditional strong-motion instruments and can record real-time, three-component acceleration signals. The *P*alert signal resolution is 16 bits with a $-2g$ to $+2g$ range and the sampling rate is 100 samples per second. Once an earthquake is detected by the trigger algorithm embedded in a *P*alert, a corresponding earthquake watch or warning alarm is sent by the system. The trigger algorithm includes procedures for the continuous monitoring of peak ground acceleration (PGA), the short-term-average (STA)/long-term-average (LTA) ratio (Allen, 1978), and the peak amplitude of the filtered (a high pass at the 0.075 Hz corner) vertical displacement of the *P* wave (*Pd*; Wu and Kanamori, 2005a, 2008a,b; Wu *et al.*, 2007). *P*alert also has networking capabilities that include the streaming of real-time acceleration signals to the data collection server, the automatic connection of up to two servers, and the synchronization of clocks by the network time protocol (NTP). Therefore, *P*alert devices can be connected in order to build a regional EEWS (Kanamori, 2005; Wu and Kanamori, 2005b). An experimental system was successfully tested in Hualien, Taiwan (Wu and Lin, 2013). Because of this successful experiment for both onsite and regional EEWS purposes, we began to install *P*alert devices over the entire island of Taiwan. In this work, we present the concept and the results from a high-density low-cost sensor network that consisted of 400 *P*alert devices deployed for both onsite and regional EEWS in Taiwan during the testing period from June 2012 to May 2013.

SYSTEM CONFIGURATION

Since 2010 and supported by the National Science Council (NSC), NTU began to build up the *P*alert real-time strong-motion network. Following three years of installation, 400 stations were deployed and configured. Figure 2 provides 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 the network was reduced. To provide four hours of backup power, a display for shaking intensity, and a mechanism for issuing a sound warning, a touch screen controller named *i*Touch (Fig. 3) was installed with a *P*alert device. The devices were installed in elementary schools for the purposes of cost reduction and earthquake hazard-mitigation education.

The configuration of the *P*alert real-time strong-motion network is shown in Figure 4. *P*alert devices in the field continuously send signals in real time to two central stations in the NTU, and the Grid Center of the Academia Sinica for data processing and storage. For earthquake monitoring and research

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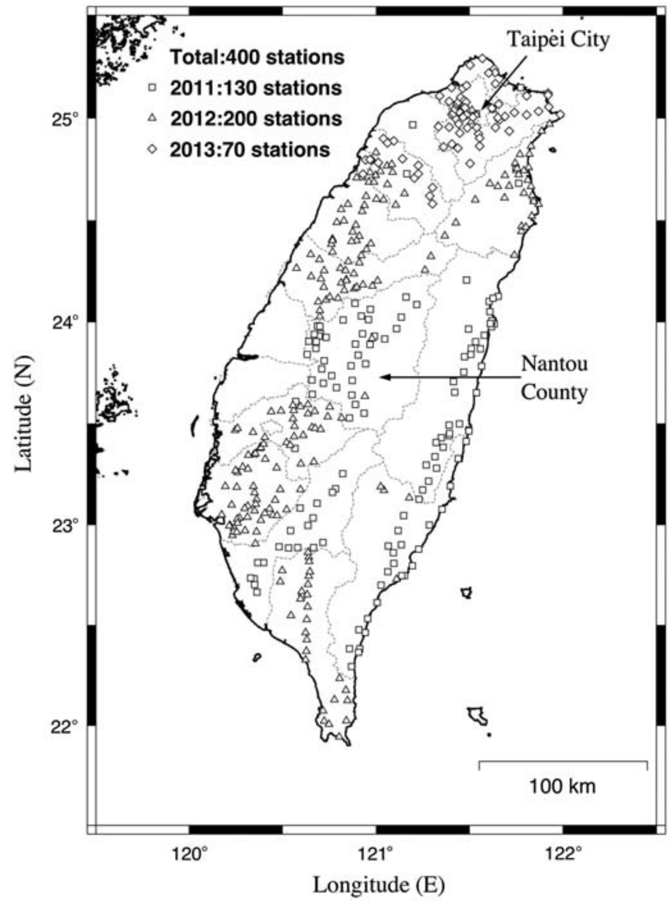
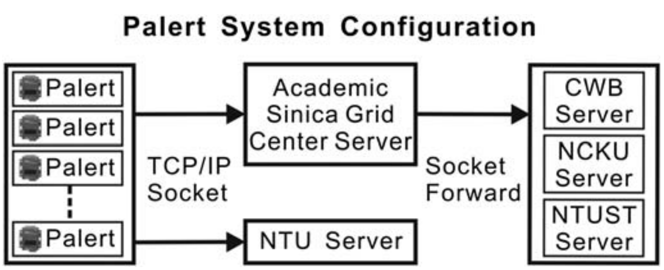
▲ **Figure 1.** The *P*alert Earthquake Early Warning (EEW) device.



▲ **Figure 2.** The station distribution of the *P*alert EEW system.

purposes, real-time signals are also delivered to the CWB, National Cheng Kung University (NCKU), and the National Taiwan University of Science and Technology (NTUST). Figure 5 provides the signal-processing configuration of the *P*alert network. At the field site, real-time signals are processed by the *P*alert devices. Three-component acceleration signals are processed onsite for detecting *P* arrival and continuously double integrated to displacement signals for calculating the average period, τ_c (Kanamori, 2005; Wu and Kanamori, 2005b), and *Pd*. Following the final integration, a high-pass filter at the 0.075 Hz corner is applied to remove low-frequency drift and to obtain the filtered displacement. Finally, the filtered displacement signals are differentiated in order to obtain the velocity signals. The real-time signals are sent to the central stations every second simultaneously via the internet. The information includes three-component acceleration and filtered vertical-displacement waveforms 1 s in length. When an earthquake occurs, the *P*alert system automatically detects *P*-wave arrival, and once the *Pd* or PGA are larger than 0.35 cm or 80 gal, respectively, the *P*alert system begins its alert with a warning sound. The *P*-wave information including the *P* wave's first arrival, τ_c, the peak amplitude of the acceleration (*Pa*), the velocity (*Pv*), and the displacement (i.e., *Pd*) for the initial three seconds of *P* waves are also sent to the central stations through the TCP/IP connections. Tasks of the central stations include data clustering and processing. For real-time seismic data processing, real-time signals are processed and stored within the Earthworm system developed by the U.S. Geological Survey (USGS). In the Earthworm system, signals are again processed in order to detect the arrival of the *P* wave (Hsiao *et al.*, 2011; Chen *et al.*, 2012). *P*-wave information detected by the Earthworm platform is also sent to a shared memory. During the final stage, once eight *P*alert stations are triggered, an event is declared. The TcPd.c program fetches the event parameters stored within the shared memory and computes the EEW information. The hypocentral location is determined using a traditional earthquake location algorithm with a half-space linear increasing-velocity model (Wu and Lin, 2013). The magnitude determination is based on the relationship of *Pd* (M_{Pd}; Wu and Zhao, 2006) and *Pv* (M_{Pv}) attenuation, and hypocentral distance. Within the *P*alert system, for events with magnitudes less than 6.0, we noticed that the uncertainty of M_{Pv} was smaller than M_{Pd} due to a low signal-to-noise ratio. Therefore, for events with an M_{Pv} less than 6.0, M_{Pv} was utilized for magnitude determination. In contrast, for events with an M_{Pv} larger than 6.0, M_{Pd} was employed. For magnitude determination, the τ_c parameter is also processed by the TcPd.c program. Because *P*alert is a low-gain instrument with a relatively low signal-to-noise ratio in τ_c determinations for moderate and small events, we currently do not use magnitude information from the τ_c parameter within the *P*alert network.

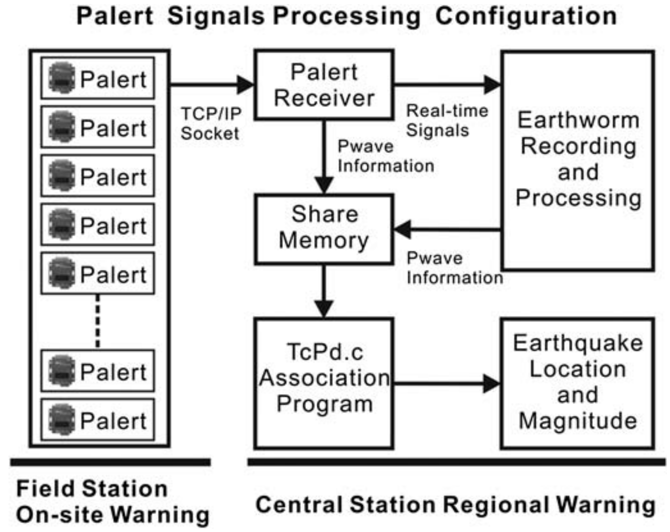
▲ **Figure 3.** The *i*Touch device is installed with a *P*alert device in order to provide backup power, a display, and a sound warning.



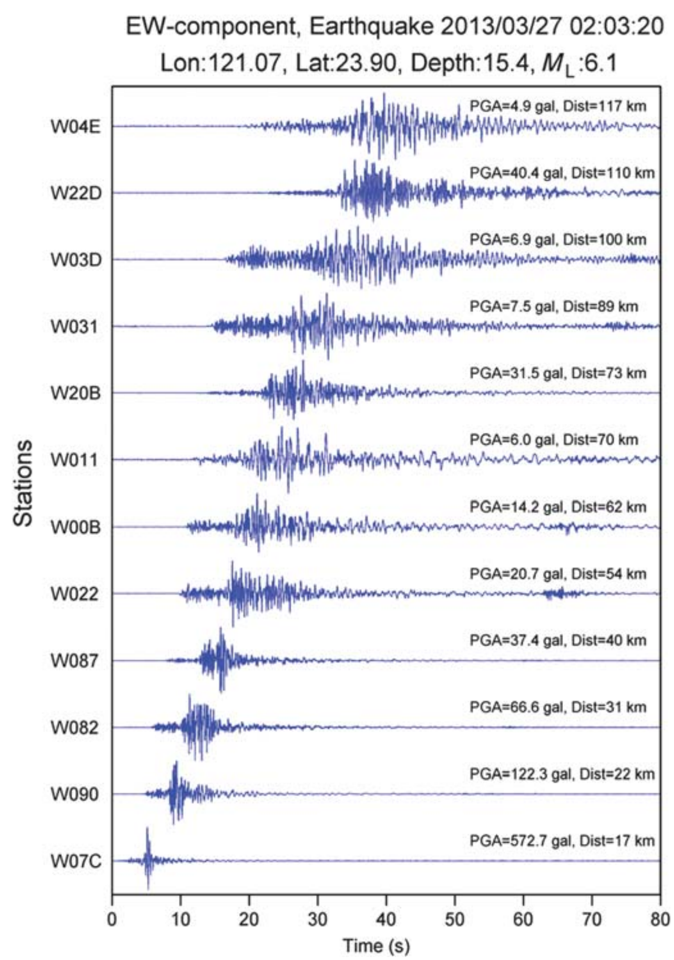
▲ **Figure 4.** The system configuration of the *P*alert network.

SYSTEM PERFORMANCE

Since June 2012, the implemented EEWS has operated using the *P*alert network. During the period from June 2012 to May 2013, 27 earthquakes with M_L magnitudes ranging from 4.6 to 6.1 have been detected. The signals were well recorded by the central stations. In general, 80% of local stations routinely and reliably send data to the central stations. Power interruptions and internet firewalls at some sites are the reason that 20% of local stations cannot send data to central stations. Figure 6 provides strong motion records for the 27 March 2013 M_L 6.1 Nantou earthquake. Thus far, this earthquake is the largest



▲ **Figure 5.** The signal-processing configuration of the *P*alert network.



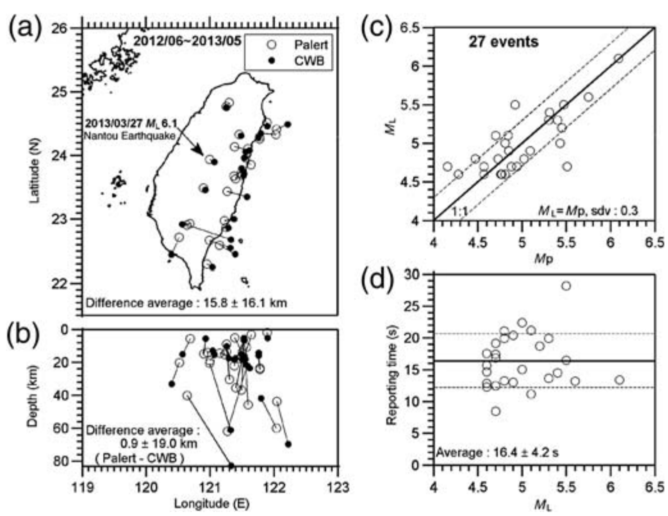
▲ **Figure 6.** Strong-motion records of the 27 March 2013 M_L 6.1, Nantou earthquake as recorded by one of the central stations of the *P*alert network.

event that has been detected by the *P*alert network. EEWS performance of the *P*alert system is summarized in Figure 7. The online real-time results of the *P*alert network were compared with those reported by the CWB, determined off-line and manually (http://www.cwb.gov.tw, last accessed May 2013). The initial warning alarm is triggered by the first eight *P*alert stations that detect the *P* wave and ignite other reactions in an early stage. However, the *P*alert system will continue to collect *P*-wave information from local stations and improve the accuracy of the estimated hypocenter and magnitude until the end of an earthquake for a shaking-map determination. The real-time results shown in Figure 7 are the initial triggering results.

Hypocenters provided by the *P*alert network versus those from the CWB catalogue are plotted in Figure 7. The hypocenters determined by the two systems agree, with the exception of a few offshore events that have larger differences. The average difference in epicenter location was 15.8 km with a standard deviation of 16.1 km. The average difference in focal depth was 0.9 km with a standard deviation of 19.0 km. Prior to 2013, due to a fewer number of stations installed and a lack of *S*-arrival times, the large location errors present in the *P*alert system were expected. However, after 2013, with more stations installed in Taiwan, the quality of the location estimations improved over those from 2012.

The magnitudes (M_P) determined by the *P*alert network and the corresponding M_L values from the CWB earthquake catalog are listed. Figure 7 also provides a plot of M_P values against those of the CWB earthquake catalog. In general, magnitude uncertainty was on the order of 0.3, an acceptable value for EEWS.

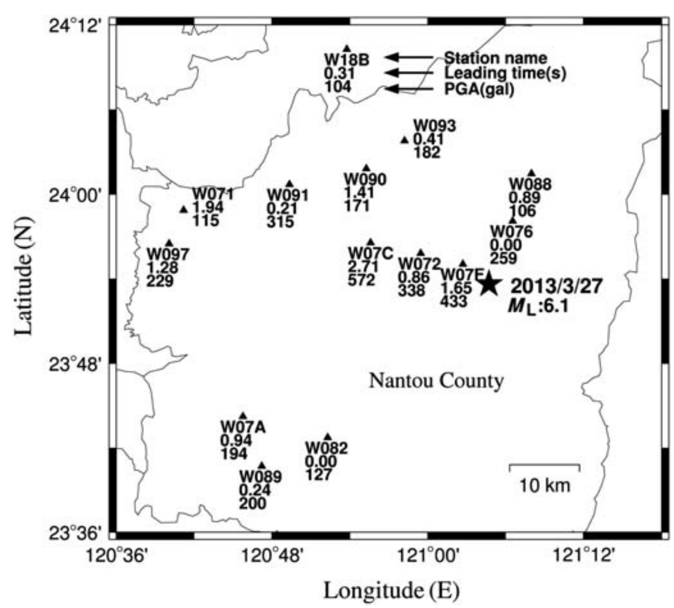
For the year of *P*alert EEWS network operation we achieved an early warning earthquake reporting time Tr the time between earthquake occurrence and the time the EEWS provides warning information, varying from 9 to 28 s, with an average of 16.4 s and a standard deviation of 4.2 s (Fig. 7). The results indicated that for the majority of events the *P*alert EEWS can issue an early warning report within approximately 20 s following an earthquake occurrence. Practical regional EEW is feasible using the *P*alert system.



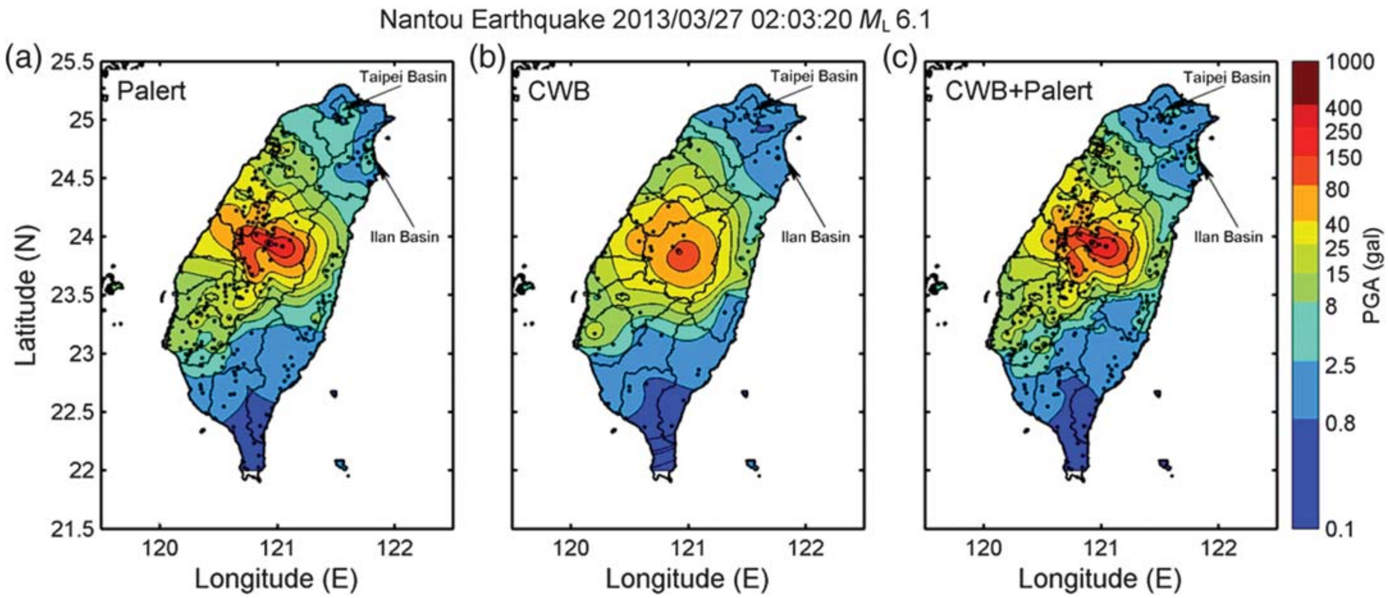
▲ **Figure 7.** A comparison of earthquake information, as follows: (a) epicenters, (b) focal depths, and (c) the magnitudes given by the real-time *P*alert network and the CWB published earthquake catalogs. (d) The reporting times of the *P*alert network.

DISCUSSION

The reporting time for the *P*alert system is similar to that of the CWB EEWS, which consists of conventional strong motion instruments (Wu *et al.*, 1999; Wu and Teng, 2002; Hsiao *et al.*, 2009). The system offers early warning to regions with an epicentral distance larger than 50 km. Additionally, *P*alert also has an onsite alert function that triggers a warning sound once the *Pd* exceeds 0.35 cm or the PGA is larger than 80 gal (Wu *et al.*, 2011). The major advantage of the onsite *Pd* approach is that it can provide a valuable early warning for epicentral regions. Figure 8 provides the resulting early warning leading times near epicentral regions for the 27 March 2013 Nantou M_L 6.1 earthquake. The early warning leading time is defined as the interval between the time when the filtered vertical displacement exceeds 0.35 cm and the time when the PGA is larger than 80 gal (Wu *et al.*, 2011). There are two stations for which the time of the filtered vertical displacement exceeding 0.35 cm is later than the time that a PGA larger than 80 gal is recorded. However, the majority of stations have a 1–2 s lead time. It is worth noting is that the station (W07C) that recorded the largest shaking (PGA 572 gal) had a lead time of 2.7 s, a sufficient time for automatic EEWS to make an emergency safety response.



▲ **Figure 8.** The early warning lead times for *P*alert stations close to the epicentral region of the 27 March 2013 Nantou M_L 6.1 earthquake. The leading time is defined as the interval between the time when the filtered vertical displacement exceeds 0.35 cm and the time for a PGA larger than 80 gal.



▲ **Figure 9.** The shaking maps determined by (a) the *P*alert, (b) the CWB, and (c) the CWB + *P*alert stations.

The present EEWS in Taiwan consists of 109 seismic stations. The *P*alert network has almost four times this number of stations. For earthquake rapid reporting purposes (Wu *et al.*, 1997, 2000), the *P*alert network can provide a detailed shaking map for damage assessments. Figure 9 provides the shaking maps for the 27 March 2013 Nantou M_L 6.1 earthquake obtained from the CWB and *P*alert networks. Obviously, the *P*alert network provides a more detailed shaking condition. For example, the Ilan and Taipei basins could easily be identified, suggesting basin effects. *P*alert signals were also sent to the CWB. Therefore, for a detailed shaking map (Fig. 9c) for emergency response purposes, the CWB can combine signals from the two networks. Here, the reader should note that number of *P*alert stations shown in Figure 9a is fewer than that in Figure 2. The major reasons include the following: (1) most of the stations close to Taipei City were built after the 2013 Nantou M_L 6.1 earthquake, (2) 20% of the local stations cannot send data to the central stations mentioned above, and (3) large shakings during this earthquake may cause the loss of 10% of signals. Ten percent of local stations cannot send data to the central stations, as generally occurred after *S* waves. We suggest that this phenomenon may be caused by the short instability of both power and internet during large shakings.

In the near future, at least 100 new stations will be deployed, and the *P*alert network will become even denser. With such a high station density, obtaining an accurate and near real-time observed-shaking map is feasible. Therefore, ground-shaking propagation can be described in detail, which is helpful either when dispatching emergency response personnel and services or tracing earthquake rupturing. For example, the center of the initially triggered stations can be regarded as an initial rupture center, similar to the effective epicenter (Teng *et al.*, 1997). The high-shaking cover area could be converted to an effective magnitude (Teng *et al.*, 1997; Lin and Wu, 2010; Lin *et al.*, 2011). Therefore, without a traditional earthquake-location process, we can still obtain earthquake information, which is crucial for an emergency response. Traditional magnitude determinations require a distance correction. Occasionally, error in earthquake location may lead to an over- or underestimation of earthquake magnitude. The concept of an effective epicenter and magnitude could be important for practical earthquake monitoring, especially for large earthquakes.

Currently, the *P*alert network uses the peak amplitude of *P* waves for magnitude determinations. When a large earthquake occurs, a magnitude saturation problem may exist especially for M_{Pd} (Wu *et al.*, 2006). However, with such a high station density, magnitude determinations using the coverage area for a certain threshold of the PGA (Lin and Wu, 2010) and the *Pd* (Lin *et al.*, 2011) could be used in the EEWS for solving the magnitude saturation problem. For a rapid reporting system, the empirical method of Wu and Teng (2004) for quick M_w determinations using time integration over the strong-shaking duration for absolute values of acceleration records could be used within the *P*alert system. Lin and Wu (2012) tested the system for the 2011 M_w 9.0 Great Tohoku Earthquake. The results indicated that this empirical approach is appropriate for extremely large events without a saturation problem and is important in damage assessments and tsunami early warnings.

CONCLUSIONS

In this paper, we describe the installation of a real-time, strong-motion network with a high station density that incorporates low-cost MEMS sensors for EEW and rapid reporting purposes, and present the performance of the *P*alert network in Taiwan. Currently, in Taiwan, when an earthquake occurs, earthquake information can be determined within 20 s with a reasonable uncertainty. Our results indicate that a practical regional EEWS is feasible. To detect the occurrence of an earthquake, each individual *P*alert device uses an onsite *Pd* approach. Based on the 27 March 2013 Nantou M_L 6.1 earthquake, most stations displayed a 1–2 s lead time as compared with the traditional method using PGA as a threshold in regions close to the epicenter. Using a dense array of stations, the *P*alert network can provide a real-time shaking map for both EEW and rapid reporting applications.

Because of its low cost, the *P*alert device may have commercial potential. The EEWS can be established for relatively little expense, or *P*alert sensors can be readily added to an existing seismic network in order to increase the density of the network. Thus far, *P*alert devices have been installed in China, Indonesia, Mexico, and Taiwan. To test the feasibility of providing EEW to New Delhi, India, a pilot *P*alert network is scheduled to be installed near the Himalayan region. Results from the *P*alert network in Taiwan are encouraging for the further utilization of EEWS in other countries.

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