Earthquake Warning System Using Low-Cost Sensors in Taiwan

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With advancements in technology and data processing speed, risk mitigation tools, such as earthquake early warnings (EEW), have emerged as life-saving guards in many earthquake-prone countries. The seconds-long warning achieved during EEW may be very helpful in saving the lives of human beings by allowing them to flee from buildings (if possible), or to take the proper shelter, or to move to a safer place within a building.

Keywords: P-Alert ; earthquake early warning ; MEMS ; shakemaps

1. Introduction

The EEW system, in its principle form, takes information related to basic phases (P-wave and other phases) from the realtime seismic signals, performs the elementary calculations, and, if needed, issues a warning. The EEW system is not limited to major earthquakes only, but also targets smaller earthquakes, which may cause high shaking in local areas, as well. EEW systems are generally categorized as regional (network-based) and on-site (single station or network-based) systems. The regional system consists of several sensors placed around the fault/source, and seismic signals from these instruments are transferred continuously to the central station for processing [1][2][3][4][5]. The regional EEW system exploits the use of P-wave and some S-wave information [6] to estimate the location and magnitude of the earthquake and to predict the ground-shaking at farther distances using ground-motion prediction equations (GMPE). Once the earthquake is triggered using short-term averaging (STA), long-term averaging (LTA), or another algorithm, the initial few seconds of data (typically 3-5 s) after the P-wave's arrival is used to perform the calculations. The regional EEW system generally takes about 10-15 s to detect an earthquake and issue a warning. By that time, the damaging S-waves reach some of the locations close to the epicenter and a warning is not possible. The areas without a warning are termed "blind zones" and may range around 40-60 km from the epicenter, depending upon how guickly an earthquake is located. The problem of the blind zone can be overcome by the on-site EEW system, under which a single station installed in the proximity of the target area will immediately sense the earthquake and issue the warning. This system will use the P-wave information and estimate the ground shaking using empirical scaling relationships. The on-site warning system is faster than the regional system and can provide early warnings to sites located in the near-source region. The accuracy of the estimation of earthquake parameters is moderate for an on-site EEW, as it is a single sensor-based or a small network-based system. Figure 1 depicts the difference in time taken for the issuance of the regional and on-site warnings.



Regional Warning v.s. On-site Warning

Figure 1. A comparison of time taken for the regional and on-site warnings. The left side shows that the CWB network took 18 s to issue a 13 s regional warning (lead-time) for Taipei City during the Hualien earthquake of 6 February 2018.

The right side of the figure shows the Pd estimation using the initial 3 s of the waveform at one of the stations of the P-Alert network, where the threshold value was achieved in 1.5 s.

2. The P-Alert Sensors and EEW

The research group at NTU worked in close association with a technology company in Taiwan for the development of a low-cost, MEMS-based, P-wave alert device named "P-Alert". These MEMS-based sensors are embedded in a small housing and can record high-frequency, near-source ground-motion. The pilot project commenced in 2010 by installing 15 P-Alert devices in the Hualien part of the country ^[Z]. The network showed its ability by detecting and recording earthquakes. Based on its performance in the Hualien region, the network was extended to other parts of the country. As of now, 761 P-Alert instruments have been installed under this network (**Figure 2**). With a threshold parameters algorithm embedded inside, the P-Alert sensors are suitable for on-site, as well as for regional warnings. Considering the proper logistics (continuous power supply and dedicated internet connection for data transfer) for the P-Alert installation, most of these instruments are installed in elementary schools on the ground or first floor. Each P-Alert device can record three-component data, having 16-bit resolution and ± 2 g of full dynamic range. The sampling rate of all the instruments is set to be 100 Hz and the real-time three-component continuous data is transferred and processed continuously at the central receiving station placed at NTU and Academia Sinica.



Figure 2. A map showing the distribution of P-Alert instruments in different parts of Taiwan. This dense array, consisting of 761 low-cost sensors, can act as an on-site, as well as a regional EEW system.

For on-site warning, as per the algorithm embedded in the P-Alert instruments, the data received by each of the field instruments is continuously monitored for STA/LTA ratios, peak ground acceleration (PGA), and P_d obtained by double-integrating the real-time data. The records are high-pass filtered after taking the integration. Once an earthquake has been declared using STA/LTA algorithm, the software will look for P_d For on-site warning, as per the algorithm embedded in the P-Alert instruments, the data received by each of the field instruments is continuously monitored for STA/LTA ratios, peak ground acceleration (PGA), and ($P_d \ge 0.35$ cm or PGA \ge 80 gals), a warning is issued ^[8].

Numerous works have been carried out for on-site warnings using the initial portion of the P-waves. Wu and Kanamori (2005b) ^[9] suggested the prediction of earthquake magnitude by using the inverse of the predominant period, τ_c , from the initial 3 s of P-wave waveforms. Considering the trade-off between cost and data quality, the dynamic range of P-Alert sensors is less than that of traditional sensors. Thus, the calculation of traditional frequency-based parameters proposed earlier for EEW, such as τ_c may not be accurate. The same authors ^[10] established a regression relationship between P_d and Peak Ground Velocity (PGV), and proposed that earthquakes may be damaging whenever $P_d \ge 0.5 \text{ cm}$. Wu and Kanamori (2008) ^[11] also worked to predict PGV with P_d using the various earthquakes recorded in Taiwan, Japan,

and California (Figure 3). Using the regression carried out from data from different parts of the world, the P_d parameter is considered one of the pioneering parameters for estimating shaking intensity.



Figure 3. The relationship of P_d with PGV by augmenting the 638 P-Alert records obtained during the 5 February 2016 Meinong earthquake and the 6 February 2018 Hualien earthquake with 780 records from Taiwan, Japan, and California via the strong motion instrument used by Wu and Kanamori (2008) ^[11].

In addition to the on-site warning data used at each station, the data from each field station, received at the central station, is processed continuously for the estimation of threshold parameters (P_d and PGA), as well as the magnitude and other parameters, using Earthworm software ^[12]. Figure 4 shows the setup of P-Alert instruments and the networking scheme of each of the field instruments to the central recording station. Each P-Alert instrument is equipped with the industrial protocol for connection and with two relays that it can switch the device on/off during emergency operations for on-site EEW purposes. The central recording station can also turn the instruments installed in the field on/off through the relay. The warning time in the regional warning is a function of data transmission and epicentral distance. Using a denser recording network, the warning time is maximized by recording the earthquakes promptly. For earthquakes occurring outside of or near the edge of the seismic network, a considerable error is reported in earthquake location and magnitude, and subsequently, the warning is delayed. As the P-Alert instruments are installed densely (5–10 km), the location and magnitude errors are minimized for in-land earthquakes. Even for the earthquakes occurring off the coast of Taiwan, the reported error is manageable. As the P-Alert instruments are installed in various elementary schools, the data flow is continuous from field stations.



Figure 4. The concept of the P-Alert networking system. Each P-Alert is equipped with the industrial protocol for connection and with two relays that can turn the device on/off for emergency operation. The central station also can turn remote devices on/off through P-Alert relays.

3. Shakemaps Using P-Alert Network

The NTU network can generate near-real-time shakemaps during earthquakes. A shakemap is a contour demonstrating the PGA, or any other ground-motion parameter distributions, recorded from different strong-motion stations. A seismic network with closely spaced instruments will deliver these shakemaps precisely, as no interpolation is required. Once five P-Alert instruments record a PGA \ge 1.5 gal, the network starts plotting shakemaps $^{[13]}$. These shakemaps are updated at regular intervals after 30 s and are delivered to the intended users, including the National Science and Technology Center for Disaster Reduction (NCDR), for damage assessment and possible rescue operations. The shakemaps are also posted on social media, including Facebook and Twitter. With P-Alert instruments distributed all over the country, the shakemaps produced using this instrumentation offer detailed shaking patterns, which are helpful for assessing the damage pattern. The ability to provide shakemaps and to determine rupture direction using this instrumentation is discussed previously in many studies $^{[14][15][16][17][18][19][20]}$.

4. P-Alert Performance during Recent Damaging Events

The NTU network has shown its ability to work as an on-site EEW system and provide near-real-time shakemaps during recent events. Hsieh et al. (2014) ^[21] discussed the performance of the P-Alert network during the two earthquakes of 27 March (M_L 6.1) and 2 June (M_L 6.3) 2013 that occurred in central Taiwan. The working of this network during the Meinong earthquake of 5 February 2016 was discussed by Wu et al. (2016) ^[4]. The Meinong earthquake was an inland earthquake that occurred in Southern Taiwan and caused more than 117 fatalities. A detailed shakemap was generated by the NTU network within two minutes of the earthquake's occurrence and the high shaking regions observed in the maps agreed with the damage locations. The individual instrument also provided 4–8 s of on-site warning time before PGA arrival (**Figure 5**), which is crucial for the locations situated in the blind zone of regional warning. The instruments recorded high PGA values (497 gals) in the epicentral region. Using PGA and PGV shakemaps, it was observed that the highly damaged areas were in high PGV (>17 cm/s) regions.



Figure 5. The on-site method can give warnings in the epicentral region where no regional warning is possible. P-Alert records from two earthquakes in 2016 and 2018 show the same trend as Wu and Kanamori (2008) ^[11] in **Figure 2**.

The Hualien earthquake of 6 February 2018 caused widespread damage in the eastern part of the country. The earthquake caused strong shaking and severe damage to many buildings in Hualien. Lead-times of 1.5–8 s before the arrival of PGA (**Figure 5**) were obtained in the blind zone at different locations ^[5]. The PGA during this earthquake,

recorded by the P-Alert network, reached around 600 gals, equivalent to a maximum intensity of VII. The PGV recorded by the P-Alert network reached around 125 cm/s without any interruptions ^[22], showing the robustness of the P-Alert network. By analyzing the P-Alert data of the 2018 Hualien earthquake, it was observed that the data recorded by this instrumentation could be used for surface-wave inversion ^[5]. **Figure 5** shows the on-site warning time generated by different instruments during the 2016 Meinong earthquake and the 2018 Hualien earthquake. During both earthquakes, a useful lead-time is obtained in the blind zone of the CWB regional warning.

5. Applications of P-Alert Networks

Rupture direction is the key parameter and can cause severe destruction, as the ground motion is amplified because of a piling-up of ground motion from near- and far-end instruments. The dense shakemaps generated using P-Alert instrumentation can be used to assess the rupture direction, which is one of the key factors in studying the damage pattern after an earthquake. Wu et al. (2016) ^[4] found that the rupture direction evaluated using shakemaps during the Meinong earthquake of 2016 agreed with aftershock distribution, which is a usual way of assessing rupture direction. The timely information of rupture direction can help save a lot of lives. The rupture direction using shakemaps from this network during the 2018 Hualien earthquake correlated well with aftershock distribution and surface ruptures ^[5], which again emphasizes the ability of this instrumentation in estimating rupture direction. Using real-time shakemap interpolation and attenuation regression, Jan et al. (2018) ^[23] tested the feasibility of using rupture direction from the near-source P-Alert instruments for delivering a warning to the far areas. They used 16 moderate-to-large earthquakes to infer that directivity can be obtained precisely within 17 s of the occurrence of an earthquake, which in turn is very helpful for EEW. **Figure 6** shows the rupture direction evaluated using the recorded PGA at selected stations during the Hualien M_w 6.3 earthquake of 2013. From the figure, the rupture direction is northeast–southwest and agrees well with aftershock distribution ^[14].



Figure 6. Evaluated fault rupture direction using the recorded waveforms during the 2013 Hualien earthquake. The rupture direction agrees with the aftershock distribution.

The near-real-time detailed shakemaps can identify the direction of the source rupture. Yang et al. (2018) ^[20] proposed a nontraditional regional EEW system based on time-dependent anisotropic PGA attenuation relationships that are based on real-time P-Alert signals, named "ShakingAlarm". This is a ground-motion-driven approach using observed data from the source region to establish time-dependent anisotropic PGA attenuation and accurately predict the PGA for the far region before the arrival of the observed PGA.

Many multi-story buildings in different parts of the world need damage assessments post-earthquakes. The P-Alert instruments have proven efficient in structural health monitoring. Putting a minimum of only three of these instruments can accurately predict the structural health of any building after any earthquake. Hsu et al. (2018) ^[24] used P-Alert instruments and conducted several shake-table tests with incremental damage to check the performance of P-Alert for evaluating post-earthquake building safety. They found that acceptable damage detection for an entire building is possible using these instruments. It was found that around 50% of P-Alert

instruments were correct in identifying the damage level of each story of a building. However, when they aimed to detect the damage to the whole building, these devices displayed 100% correct results. It was concluded that, although P-Alert systems may be a poor indicator of damage location, they correctly depict the damage to an entire building.

6. Summary

The MEMS-based P-Alert sensors have proven helpful in placing the sensors closely together and monitoring the seismic activities minutely. These sensors are cost-effective, low-power consuming, and easy to install. The recent version of P-Alert is promising in terms of dynamic range and storage, the two features that were missing in the earlier version of P-Alert. The main development in the P-Alert network is the continuous increase in the number of stations installed throughout the country. The density and coverage of the instruments are enough, except in the eastern part of the country. A continuous endeavor is being considered to find the proper logistics for the installation of these instruments there. Smartphone-based technology may be another option in Taiwan. In addition to EEW, the P-Alert sensors are used to study the directivity effect, structural health monitoring, and various seismological studies. The low cost of these P-Alert devices has attracted various countries to build their EEW network using these low-cost sensors, or by adding them to their existing network to increase density and network coverage. The results obtained using recorded or real-time data are encouraging and have shown their potential in various applications.

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