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Progress on the earthquake early warning and shakemaps system using low-cost sensors in Taiwan

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Abstract

Building an earthquake early warning (EEW) network requires the installation of seismic instruments around the seismogenic zone. Using low-cost sensors to build a seismic network for EEW and to generate shakemaps is a cost-effective way in the field of seismology. The National Taiwan University (NTU) network employing 762 P-Alert low-cost sensors based on micro-electro-mechanical systems (MEMS) technology is operational for almost the last 10 years in Taiwan. This instrumentation is capable of recording the strong ground motions of up to ± 2 g and is dense enough to record the near-field ground motion. The NTU system has shown its importance during various earthquakes that caused damage in Taiwan. Although the system is capable of acting as a regional as well as an onsite warning system, it is particularly useful for onsite warning. Using real-time seismic signals, each P-Alert device provided a 2–8 s warning time for the near-source earthquake regions situated in the blind zone of the Central Weather Bureau (CWB) regional EEW system, during the 2016 M_w 6.4 Meinong and 2018 M_w 6.4 Hualien earthquakes. The shakemaps plotted by the P-Alert dense network help to assess the damage pattern and act as key features in the risk mitigation process. These shakemaps are delivered to the intended users, including the disaster mitigation authorities, for possible relief purposes. Currently, the P-Alert network can provide peak ground acceleration (PGA), peak ground velocity (PGV), spectral acceleration (S_a) at different periods, and CWB intensity shakemaps. Using shakemaps, it is found that PGV is a better indicator of damage detection than PGA. Encouraged by the performance of the P-Alert network, more instruments are installed in Asia-Pacific countries.

Keywords: Earthquake early warning, Low-cost sensors, Shakemaps, Peak ground acceleration, Peak ground velocity, Spectral acceleration

Introduction

Taiwan is located in one of the seismically most active regions of the world. The ongoing collision between the Philippine Sea Plate and the Eurasian Plate poses a serious threat of large to devastating earthquakes in Taiwan (Fig. 1). On average, Taiwan witnesses one damaging earthquake every year and a severe earthquake every 10 years. Earthquakes are inevitable and our inability to predict their location and magnitude well in advance makes them hazardous to society. Since most damaging earthquakes are unpredictable, seismically active countries, must mull out some techniques for seismic risk mitigation, to save the basic structure and human lives. In many countries, including Taiwan, the EEW system has emerged as one of the potential life-saving systems in the last two decades.

The EEW is in an advanced stage in many countries including, Taiwan, Japan, Mexico, South Korea, and the USA, whereas in other countries it is in the developing or real-time testing stage (Espinosa-Aranda et al. 1995; Wu and Teng 2002; Alcik et al. 2009; Satriano et al. 2011;

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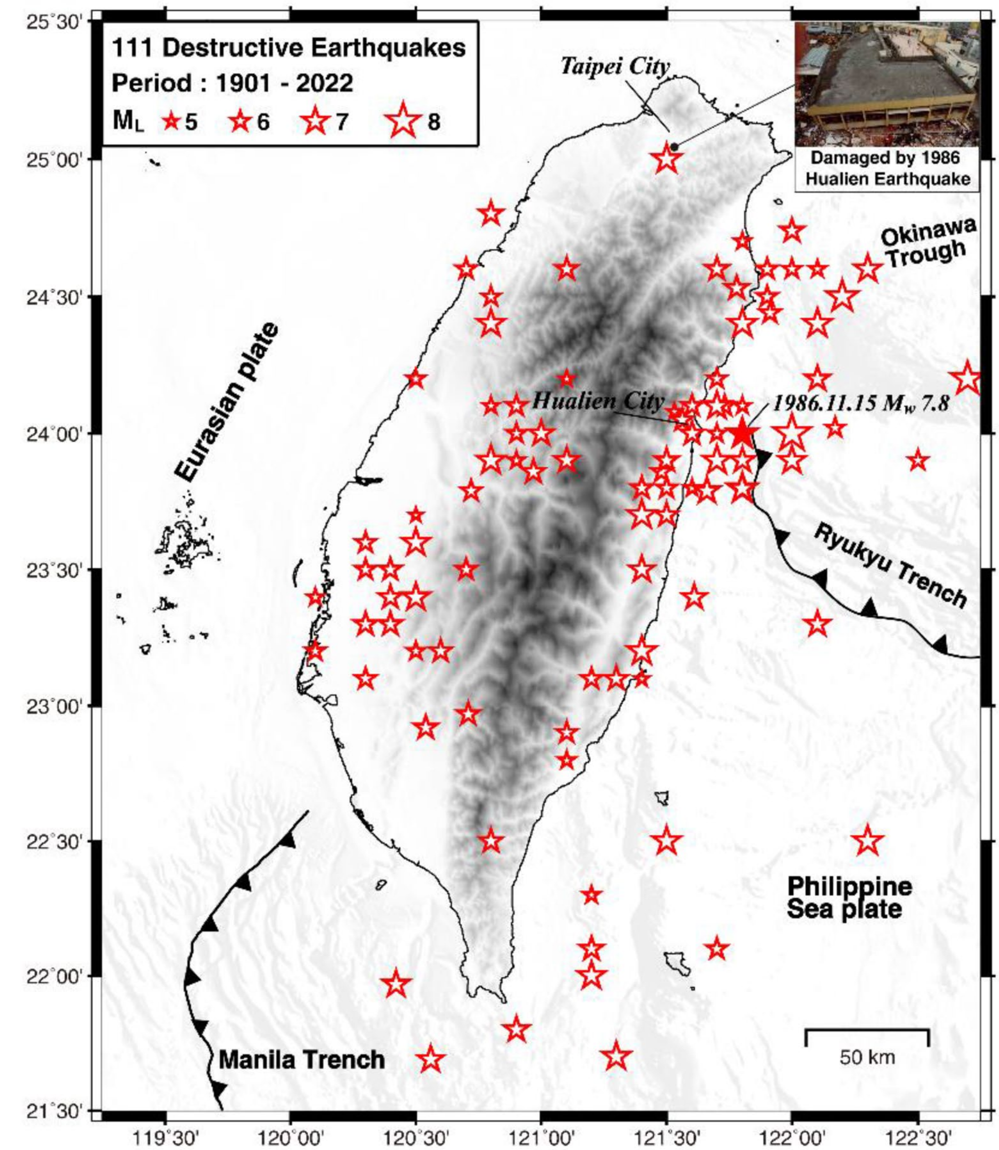

Fig. 1 Epicenter distribution of the damaging earthquakes that occurred in Taiwan since 1900. The solid red star shows the epicenter of 1986 M_w 7.8 Hualien earthquake

Kumar et al. 2014, 2020; Chen et al. 2015; Sheen et al. 2017; Hoshiba et al. 2008; Kodera et al. 2021; Chung et al. 2020; Wu et al. 2021; Peng et al. 2021). The earthquake alert for the potential areas in EEW is transmitted through electromagnetic (EM) waves and because of the difference in speed of EM and seismic waves, a time window is possible between the warning and arrival of seismic waves, hopefully, adequate for the mitigation measures involving slowing down of fast-moving trains and stopping of elevators. The working principle of EEW systems may vary from one country to another; some of them use directly measured ground motion parameters, whereas others use earthquake source parameters. Because of the instrumentation network of EEW systems and followed methodologies, the EEW systems may be categorized as onsite, regional, and hybrid systems.

Mainly two types of EEW systems are in operation around the world. Under the regional system, the real-time data from the seismometers/accelerometers installed in the epicentral area are used to estimate the earthquake source parameters, namely, hypocenter, origin time, and magnitude. After obtaining the source parameters, the shaking intensity and S-waves arrival time are estimated using the available region-specific ground motion prediction equations involving magnitude and source-to-site distance. Once the estimated intensity exceeds the predefined thresholds in an area, an early warning is issued. The warning time is a function of source-to-site distance. It is also named the front-detection EEW system. The other is an onsite EEW system, which predicts the more severe ground shakings of the S-waves using the initial portion of the P-waves from one instrument or a cluster of instruments.

The Hualien earthquake of November 15, 1986, caused a lot of destruction in the capital city Taipei, around 120 km away from the source zone. The painful experience after the occurrence of this earthquake in Taiwan and the destruction caused by the earthquake in near-source and far-source regions encouraged the researchers to think of some risk mitigation plans. Based on the non-damaging nature of P-waves, it was conceptualized that if an earthquake-recording network can detect and estimate the source parameters including the location and magnitude of the earthquake within 20 s after the arrival of P-wave, a warning of approximately 10 s was possible for Taipei city. The theory was initially formalized for Taipei city, located around 120 km away from the earthquakes in Hualien County in eastern Taiwan, located close to the subduction zone. Based on research to reduce seismic risk, CWB Taiwan started exploring the significance of developing the EEW system in the Hualien area in 1994 (Wu et al. 1999). For experiment purposes, the CWB installed 10 force-balanced accelerometers in the Hualien area and the real-time data were transferred to the central receiving station at Hualien where the data were processed and the results were communicated to Taipei. The data were also transferred to another receiving station placed in Taipei. The experiment was successful to locate the earthquake; however, the sparse network introduced uncertainties in magnitude and location determination. It was concluded that a warning of more than 10 s was possible for Taipei city. Based on the success of this experiment, the authorities at CWB decided to extend the EEW to different parts of the country. Finally, in 2002, Taiwan established a nationwide EEW network (Wu and Teng 2002). The CWB has deployed about 500 traditional seismometers for earthquake recording and EEW in the Taiwan region and is the responsible agency to issue regional EEW warnings. Currently, the CWB system can provide earthquake alerts in Taiwan within 20 s via text message through mobile phones, TV, and directly broadcasting systems to schools (Chen et al. 2015; Wu et al. 2021). Figure 2a shows the working of the regional EEW system by the CWB in Taiwan. Being a regional system, the CWB system is not able to provide the warning in near-source regions, termed blind zone. To fill this gap, another EEW system is run by National Taiwan University (NTU) which works as a regional, as well as, an onsite system. The working of the NTU system is mainly treasured as an onsite system and is shown in Fig. 2b.

In comparing regional and onsite EEW systems, the regional EEW system cannot give a warning for

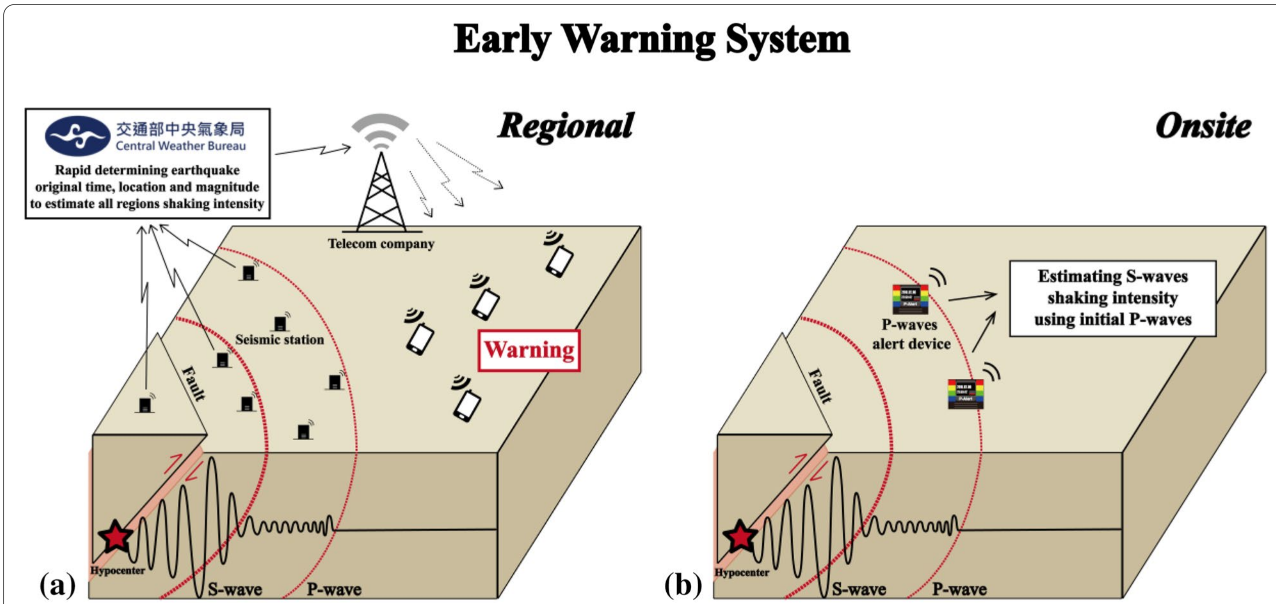

Fig. 2 **a** Concept of the regional earthquake early warning system operated by the Central Weather Bureau, Taiwan. **b** Concept of the onsite earthquake early warning system

earthquakes in near-source regions, whereas the onsite type could. However, the precision of onsite EEW for shaking intensity estimation is less compared to the regional one. The regional type can widely be applied to the general public including the places having no sensor installed. As the warning in case of onsite is a function of recorded data from a single instrument, the onsite type needs a seismic sensor included in its system which limits its application. Because of the exorbitant price of traditional sensors, low-cost sensors based on MEMS technology are widely applied in different fields. The MEMS accelerometers for seismological studies were introduced in the 1990s (Holland 2003). Installation of several MEMS sensors in the epicentral region provides a good opportunity for the onsite warning to general application. For configuring a dense EEW network in Taiwan, the NTU network uses these low-cost sensors known as the P-Alert. As a result, MEMS-based sensors have opened the doors to new opportunities. Zambrano et al. (2017) designed an EEW system using smartphones, intermediate servers, and a control center which demonstrated robust results. Minson et al. (2015) implemented an EEWS in the USA with consumer smartphones via crowdsourcing. In California, Allen et al. (2020) activated a smartphone-based EEWS called "MyShake" using artificial intelligence. Similar to MyShake, researchers from Italy implemented an EEWS "EarthQuake Network" using an android application (Finnazi 2016, 2020; Bossu et al. 2021). In 2020, Google launched the Android Earthquake Alerts system by forming a public–private partnership with the United States Geological Survey using the already constructed MyShake EEW model (Allen and Stogaitis 2022).

P-Alert EEW System in Taiwan

In previous studies, it is found that for onsite EEW purposes, the PGV could be estimated from the vertical displacement of the first three seconds of the P-waves (P_d), using empirical relations (Wu and Kanamori 2005, 2008). For practical application of the onsite EEW, the research group of the NTU worked with a technology corporation partner in Taiwan to develop the P-Alert device that uses MEMS accelerometers and P_d technology. The cost of the P-Alert device is less than 1/10 the cost of traditional strong-motion instruments which allows the densification of the network. It can record real-time, three-component acceleration signals. The P-Alert signal resolution is 16 bits with a -2 to $+2$ g range and the sampling rate is 100 samples per second. P-Alert has the capability to perform real-time integration to obtain velocity and displacement. No storage and less dynamic range issues plagued the earlier version of P-Alert; however, these issues have been resolved in the more recent version called P-Alert Plus. Once potential damage shaking is detected by the P-Alert device, a corresponding watch or warning alarm is sent automatically. The P-Alert also has networking capabilities that include the streaming of real-time acceleration signals. Therefore, P-Alert devices can be connected to build a regional EEW system and produce near real-time shakemaps (Wu et al. 2013; Wu 2015; Yang et al. 2021).

Supported by the National Science and Technology Council of Taiwan, the NTU began building the P-Alert EEW system in 2010 by installing the P-Alert sensors in the eastern part of Taiwan. Because of the proximity of the Hualien region to numerous inland and offshore earthquakes, the P-Alert instrumentation was tested by installing instruments in the Hualien region and connecting all the instruments to the central station (Wu and Lin 2011). The successful experiment of the Hualien P-Alert EEW network during its initial phase of operation strongly encouraged the installation of P-Alerts at various places over the entire island of Taiwan. For more than ten years of installation since 2011, a total of 762 stations have been deployed in different parts of the country. Figure 3a shows the station distribution of the P-Alert EEW system. Because of the original design of P-Alert instruments as seismic switches, most of the stations are located on vertical walls in elementary schools where adequate power and Internet connections are provided. Because of the low cost of the sensors and the availability of appropriate installation sites, the cost of raising this network was greatly reduced. As a result, a dense and low-cost real-time strong motion network has been installed in Taiwan. Since its installation, the P-Alert network has recorded numerous earthquakes. However, because of the low signal-to-noise ratio, the system is more appropriate for recording strong ground motion, plotting shakemaps, and issuing a warning. The availability of elementary schools with power and dedicated internet connection has enhanced the functioning capabilities of the network.

The configuration of the P-Alert EEW system is shown in Fig. 3b. At the field sites, the incoming real-time acceleration signals are processed by the P-Alert device for detecting P-wave arrival. The signals are also continuously double-integrated into displacement signals for calculating the P_d. Once an earthquake has been declared using the embedded algorithm in the system, and the P_d or PGA is greater than 0.35 cm or 80 Gal (Wu et al. 2011), respectively, the P-Alert device issues an onsite warning with sound. Generally, it can give a few seconds of warning before PGA or PGV are detected especially in regions close to the epicenter (Wu et al. 2016, 2019).

The P-Alert devices also send 1-s signal packets via TCP/IP connections in real-time to two central stations

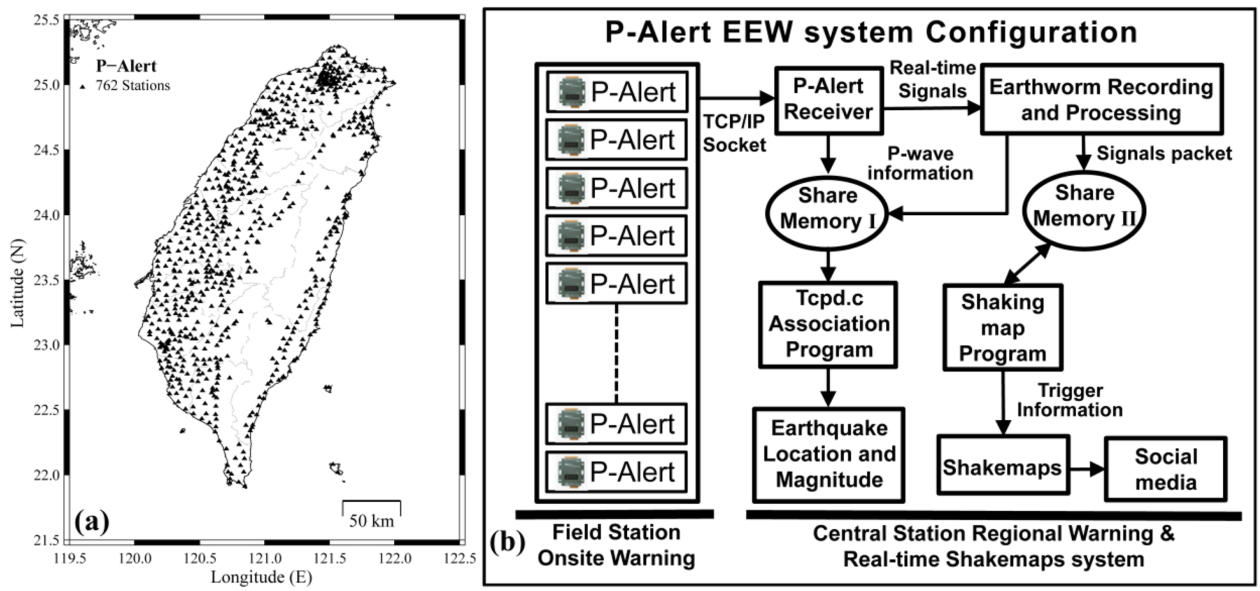

Fig. 3 **a** Station distribution and **b** configuration of the P-Alert EEW system

situated at NTU and Academia Sinica in Taipei for data processing and storage. The telemetry latency is within one second for a signal to be sent from the field site to the central station. The system is optimized on a routine basis; currently, about 90% of the station's signals can be well received by the central stations. At the central stations, signals are received and processed by the Earthworm system developed by the US Geological Survey (Johnson et al. 1995). The P-Alert Receiver module to integrate P-Alert signals into the Earthworm system is developed by our research group at NTU. In the Earthworm system, signals are processed to determine the arrival and peak amplitudes of P-waves. P arrival and peak amplitudes of the P-waves are sent to shared memory (I). The TcPd.c association program in Earthworm computes the earthquake origin time and hypocenter using P arrivals. The magnitude is estimated using the peak amplitudes of the P-waves. The P-Alert EEW system information is triggered by 12 P-Alert stations. Generally, four to six stations of information are enough for earthquake locations. However, with a dense array in operation, good station coverage is not found by triggering only four to six stations. Thus, to have good station coverage, the optimum value of the triggering threshold in the P-Alert EEW system is set to 12 stations.

Most of the P-Alert devices are installed in the building which increases the robustness of the system. About 77% of the instruments are installed on the vertical walls on the first floor of the buildings, whereas, the other 17% are located on the second floor. As the instruments are installed on the vertical walls, the measurements may be affected by the soil–building interactions. Wang et al. (2018) compared the data recorded by the P-Alert with data from the Taiwan Strong Motion Instrumentation Program (TSMIP) instruments placed in the vicinity of P-Alerts. They found that for the instruments placed on the first floor the difference in PGA was 1.07, whereas for instruments on the second floor, the difference was 1.52. So, while using P-Alert data the values should be adjusted using the above factors. The P-Alert EEW system became operational in June 2012. From June 2012 to June 2022, a total of 36 earthquakes with $M_L > 5.5$ and focal depth < 40 km have been detected by the network. To check the precision of locations determined by the P-Alert network, the epicenters estimated by the P-Alert system are plotted against the CWB catalog as shown in Fig. 4a. The average difference in epicenter location between the two networks is observed to be 12.1 km with a standard deviation of 9.2 km. The average difference in focal depth of the two networks (P-Alert—CWB) is − 3.6 km with a standard deviation of 15.9 km (Fig. 4b). The variation in magnitudes (M_P) determined by the P-Alert system and the corresponding M_L values from the CWB are shown in Fig. 4c. Magnitude uncertainty is of the order of 0.3. Figure 4d shows that the earthquake reporting time (between earthquake origin time and the time system provides information) by the P-Alert network varies from 8 to 23 s with an average of 15.5 s and a standard deviation of 4.3 s. Results indicate that for moderate to large events in Taiwan, the P-Alert EEW system can issue an early warning report at about approximately 15 s after

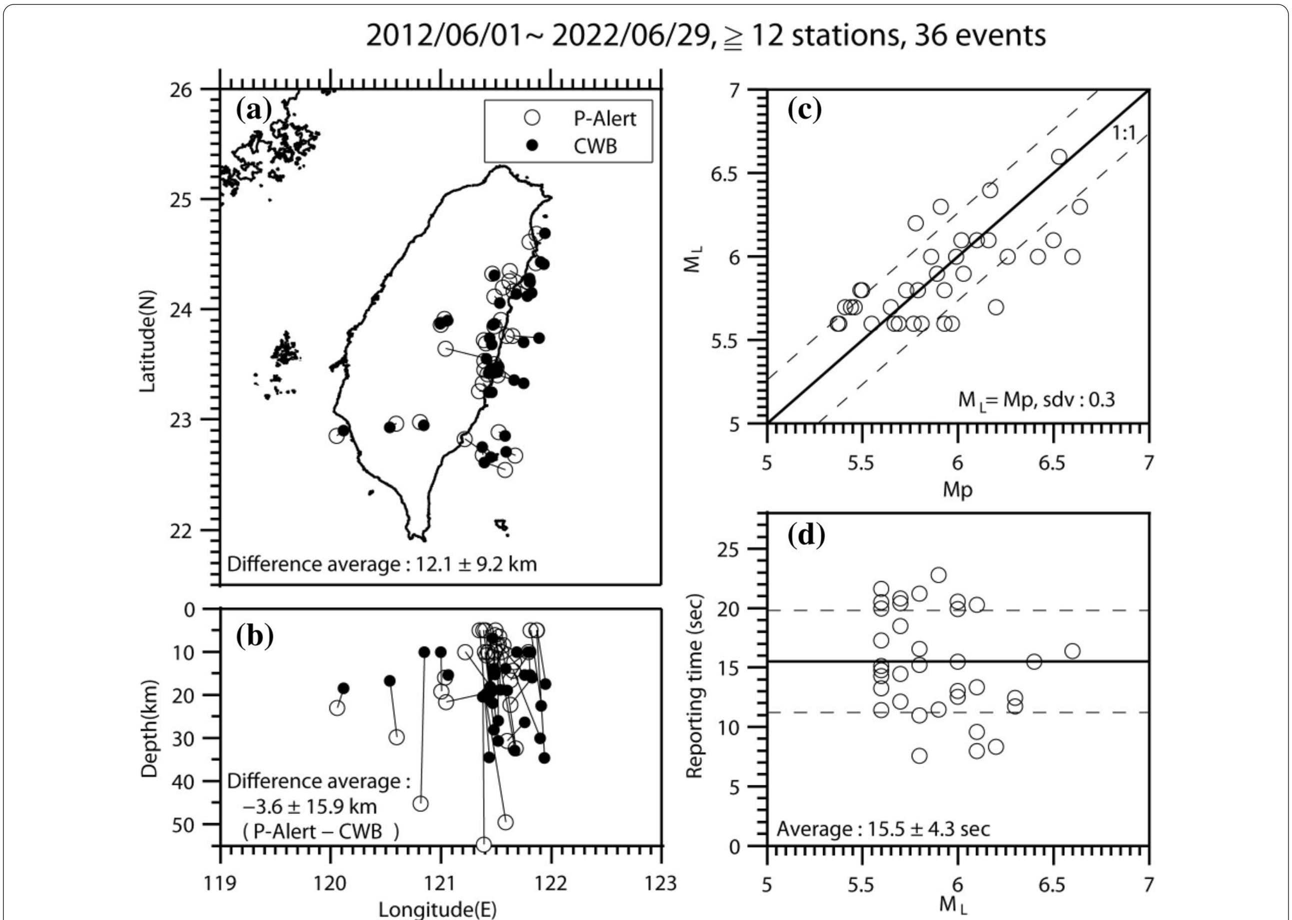

Fig. 4 Comparison of earthquake information (**a**–**c**) given by the P-Alert system and the CWB earthquake catalogs. **d** Reporting times of the P-Alert system

the origin of the earthquake. In light of the above facts, a regional EEW is feasible using the low-cost sensors network.

In the Earthworm system, real-time signals are also sent to shared memory (II) (Fig. 3b). The shaking map program analyzes the signals stored within the shared memory (II). Once 5 P-Alert instruments declare PGA ≥ 1.5 gal, the network starts plotting shakemaps (Yang et al. 2021). These plotted shakemaps include PGA, PGV, S_a at different periods, and CWB intensity maps (Wu et al. 2003). These shakemaps are updated at regular intervals after 30 s and are delivered to 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. Figure 5 shows an example of shakemaps delivered from the P-Alert EEW system for the March 22, 2022 earthquake ($M_W = 6.6$), a part of the earthquake series that occurred close to the Hualien County of Taiwan.

P-Alert performance during 2016 Meinong M_w 6.4 and 2018 Hualien M_w 6.4 damaging earthquakes

The Meinong earthquake of February 5, 2016, and the Hualien earthquake of February 6, 2018, are two of the few high-magnitude earthquakes that occurred after the P-Alert instrumentation became operational. Both these earthquakes had the almost same magnitude M_w 6.4 and caused massive damage in close-by places including structural damage to buildings, soil liquefaction, and loss of lives (117 and 17 fatalities, respectively, during the two events). Both Meinong and Hualien earthquakes were well recorded by the P-Alert system. The individual P-Alert device installed in the field issued an onsite warning after exceedance of the predefined thresholds (e.g., PGA ≥ 80 gals or $P_d \geq 0.35$ cm). During both the 2016 Meinong and 2018 Hualien M_w 6.4 earthquakes, P-Alert devices issued 2–8 s lead time in the epicentral regions (Fig. 6) before the arrival of PGV (Wu et al. 2016, 2019).

After the Chi-Chi earthquake of 1999, the 2016 Meinong earthquake is anticipated to be the most

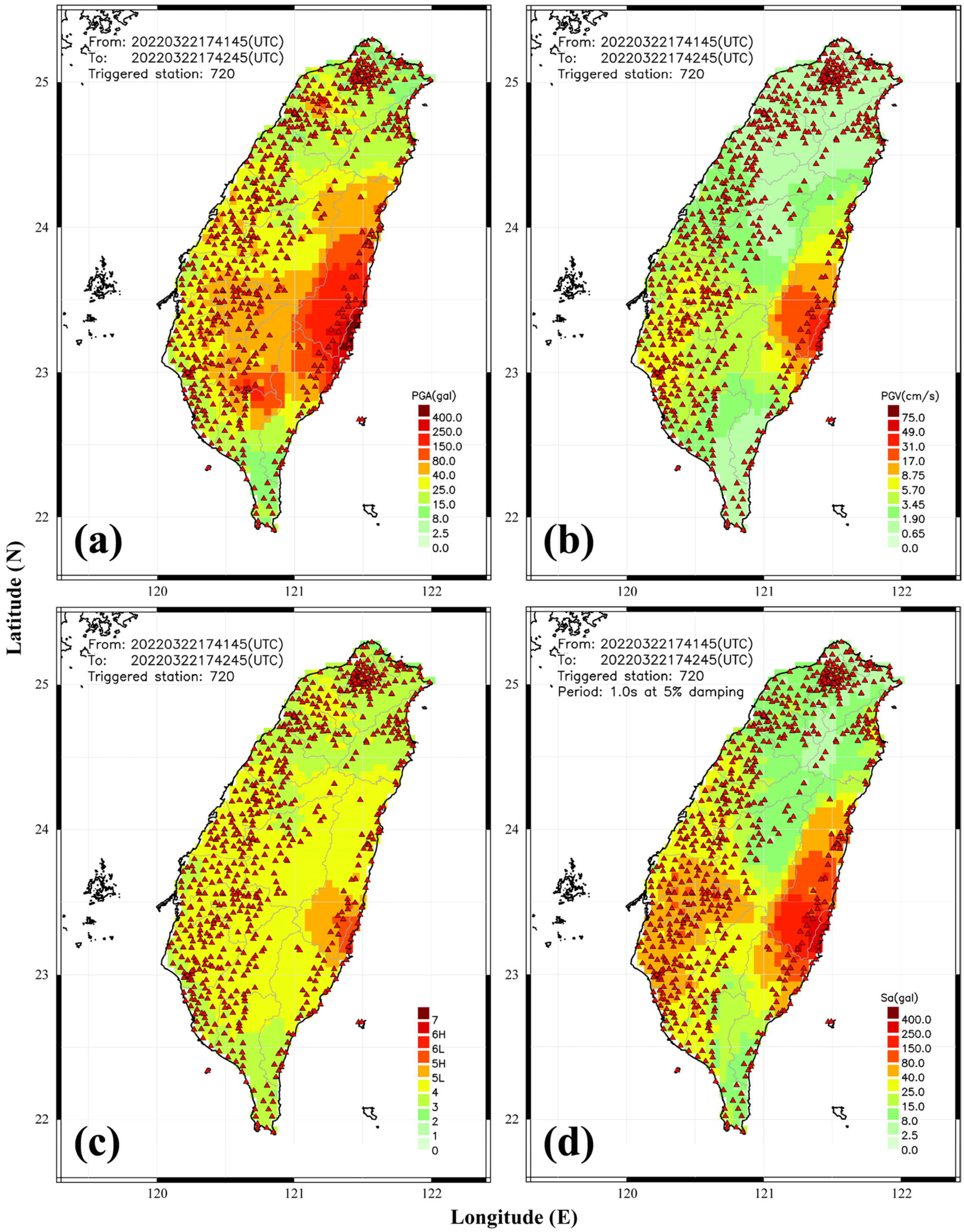

Fig. 5 **a** PGA, **b** PGV, **c** CWB intensity, and **d** 1 s S_a shakemaps delivered from the P-Alert EEW system for March 22, 2022, M_w 6.6 eastern Taiwan earthquake

destructive inland earthquake. According to the CWB intensity scale, Tainan city experienced the highest CWB intensity during this earthquake equivalent to VII (equivalent to PGA > 400 gals), which is the maximum in Taiwan (Wu et al. 2003). However, according to the first earthquake report of the CWB (Fig. 7a), Tainan city

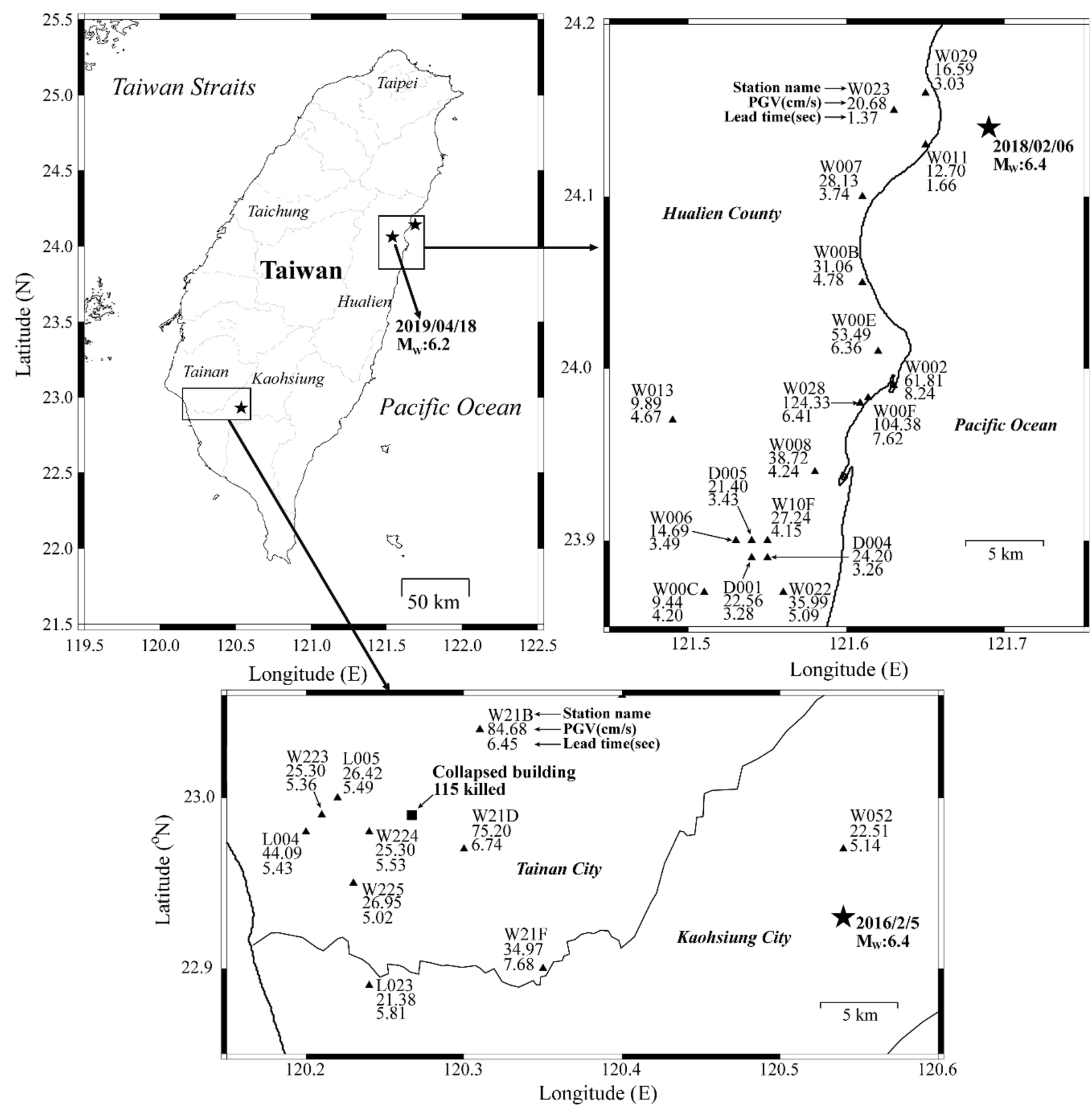

Fig. 6 Onsite warning lead time of the 2016 Meinong earthquake and the 2018 Hualien earthquake. The lead time counts from the warning time to PGV are recorded

(the most affected zone) experienced a shaking intensity of V (PGA < 250 Gal). Within 2 min of the earthquake's occurrence, the P-Alert EEW system generated a detailed PGA shakemap (Fig. 7b) and directed it to the NCDR for emergency response. The detailed shakemap by P-Alert instrumentation demonstrates that the majority of the P-Alert stations in the eastern portion of Tainan city observed a PGA higher than 250 Gal, and three stations showed a PGA larger than 400 Gal. Approximately two weeks after the occurrence of the earthquake, the CWB revised its report and reported an intensity of VII (PGA > 400 Gal) in the eastern portion of Tainan city, contrary to CWB's initial intensity report. The locations of the damage and casualties were highly correlated with the high shaking zones of the P-Alert shakemap (Fig. 7b). Figure 8 shows the comparison of intensity recorded by

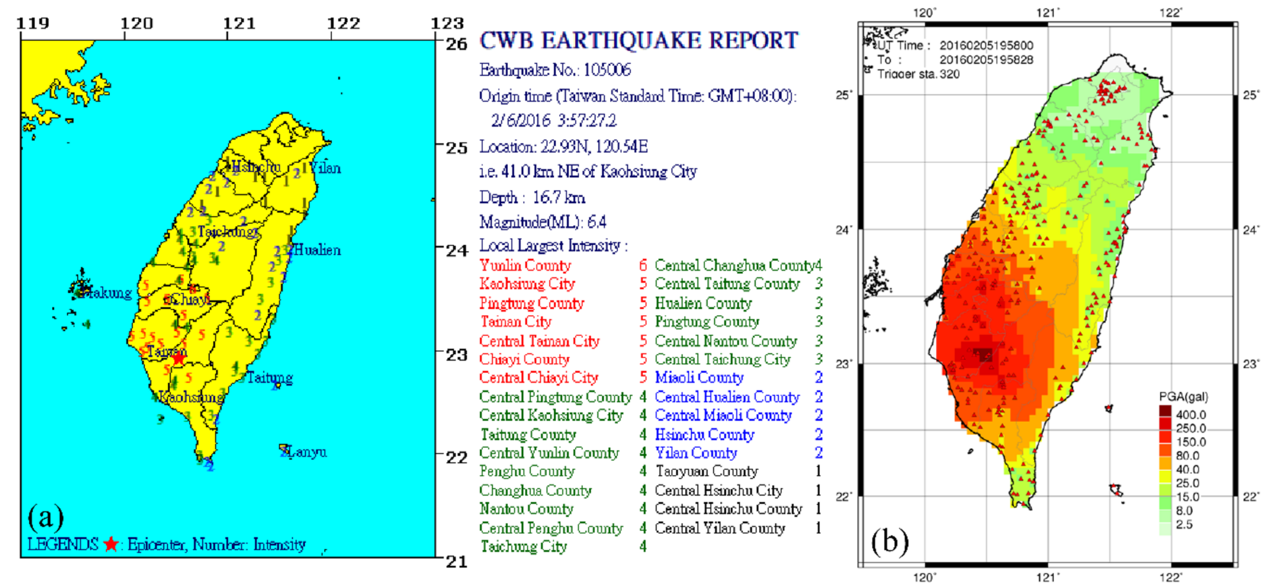

Fig. 7 **a** The first earthquake report of the 2016 Meinong earthquake from the CWB. **b** PGA shakemap delivered by the P-Alert EEW system

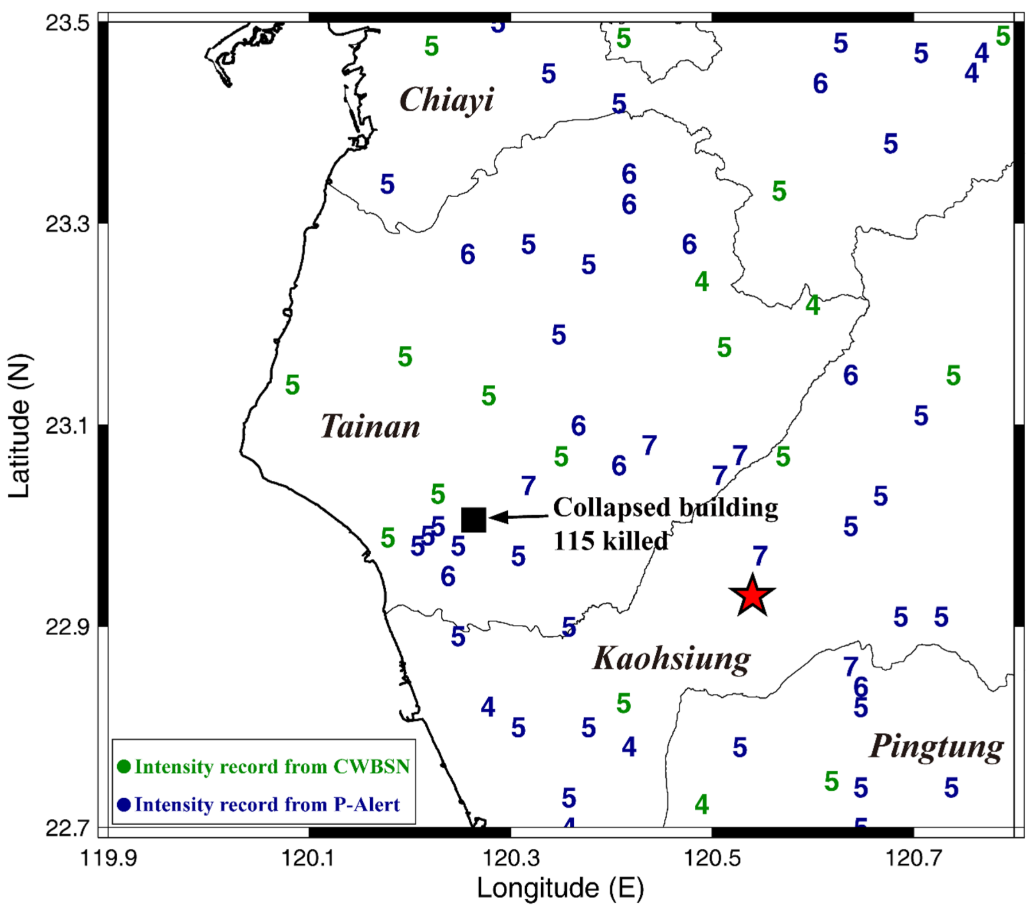

Fig. 8 The difference in intensity scale by CWB and P-Alert stations

CWB and P-Alert stations. It is obvious that a real-time dense array of low-cost sensors is helpful for rapid damage assessment.

During the Meinong earthquake of 2016, only the PGA shakemap was delivered by the P-Alert EEW system. For the 2018 Hualien earthquake, both PGA and PGV shakemaps were delivered as the system was upgraded to plot the additional PGV shakemap. By 2020, the system was upgraded to produce shakemaps of PGA, PGV, S_a at different periods, and the CWB intensity scale (Yang et al. 2021).

Mittal et al. (2021) compared the performance of plotted PGA and PGV shakemaps for the two earthquakes having the almost same magnitude (M_L 6.2 and M_L 6.3 reported by the CWB) that occurred in the Hualien region in 2018 and 2019. Figure 9 shows the PGA and PGV shakemaps of these two earthquakes recorded by the TSMIP of the CWB. Instruments installed in the epicentral regions recorded higher PGA > 400 Gal during both events. The 2018 Hualien earthquake caused a few buildings structural damage with 17 fatalities. However, the 2019 earthquake did not cause any severe damage although the magnitude of the 2019 event was more than the 2018 earthquake. According to the earthquake report of the CWB during these two events, the epicenter of the 2019 event is much close to the metropolitan area of Hualien. However, the PGV shakemaps show a different pattern as compared to PGA. During the 2018 earthquake, higher PGV values (> 50 cm/s corresponding to PGA > 250 Gal, Wu et al. 2003) were observed in the damaged areas (buildings suffering collapse and fatalities) of Hualien. However, PGV values were found less than 17 cm/s (corresponding to PGA > 80 Gal) in the epicentral region of the 2019 earthquake. From here it is inferred that in some cases, the PGV may be a better indicator of damage distribution and so necessitates the requirement of plotting of PGV, S_a, and intensity shakemaps in addition to the PGA shakemaps.

Summary and future recommendations

The invention of low-cost MEMS-based P-Alert sensors has provided a golden platform for developing countries to establish a dense EEW network at a low cost. The P-Alert device that uses MEMS accelerometers is developed to reduce the cost of instrumentation for practical application of the onsite EEW. The P-Alert devices have already made the NTU network a robust and dense network, and the introduction of new version (P-Alert Plus) instruments has increased the capabilities of the network in terms of earthquake detection and data quality as the dynamic range of new instruments is high compared to the P-Alert. With embedded P_d technology, P-Alert can issue the onsite warning. P-Alert has the function of real-time data streaming to the central receiving station. A dense array of P-Alert devices in operation can serve regional warning purposes and produce near real-time shakemaps. Based on the experience in Taiwan, the P-Alert device can provide a few seconds of warning time before the arrival of strong ground motion in the epicentral region. The NTU network can provide a regional warning, after 15 s of the occurrence of an earthquake. However, the NTU regional warning is only for research purposes and technical results are shared with the CWB. The official regional warning is delivered by the CWB in Taiwan. The NTU system can also act as a backup resource of the CWB for redundancy. For distances lesser than 60 km, the onsite EEW provided by the network may be useful. As CWB is the official agency for issuing a regional warning in Taiwan, the NTU network is specially dedicated to onsite warning and plotting shakemaps. The successful working of the NTU network during various earthquakes is discussed previously by many researchers (Hsieh et al. 2014; Wu et al. 2016, 2019). The network issued an onsite warning of 2–8 s during the 2016 Meinong earthquake and the 2018 Hualien earthquake. The shakemap methodology adopted in the P-Alert system gets updated regularly which is evident from only plotted PGA shakemaps during the 2016 Meinong earthquake and PGA and PGV shakemaps during the Hualien earthquake of 2018. The shakemaps are posted automatically on social media including Facebook and Twitter. For any earthquake around 5–6 shakemaps are posted on social media. Generally, a complete shakemap is available after 3–4 min of earthquake occurrence. The shakemap methodology adopted in the P-Alert network is applied widely in many studies (Legendre et al. 2017; Mittal et al. 2018, 2019a, 2019; Wu et al. 2016; Yang et al. 2021). During moderate to large earthquakes, at 10–15% of stations, the initial portion of data is transferred continuously to the central receiving stations but the latter portion gets disconnected due to network problems at the remote sites. However, this data can be used efficiently for warning purposes. Other than EEW and plotting shakemaps, the P-Alert data can be used in many works. The P-Alert network proved helpful in accessing the rupture direction during the 2016 Meinong earthquake and the 2018 Hualien earthquake (Wu et al. 2016, 2018). Jan et al. (2018) tested the feasibility of using rupture direction from the near-source P-Alert instruments for delivering a warning to far areas. Hsu et al. (2018) 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. Jan et al. (2017)

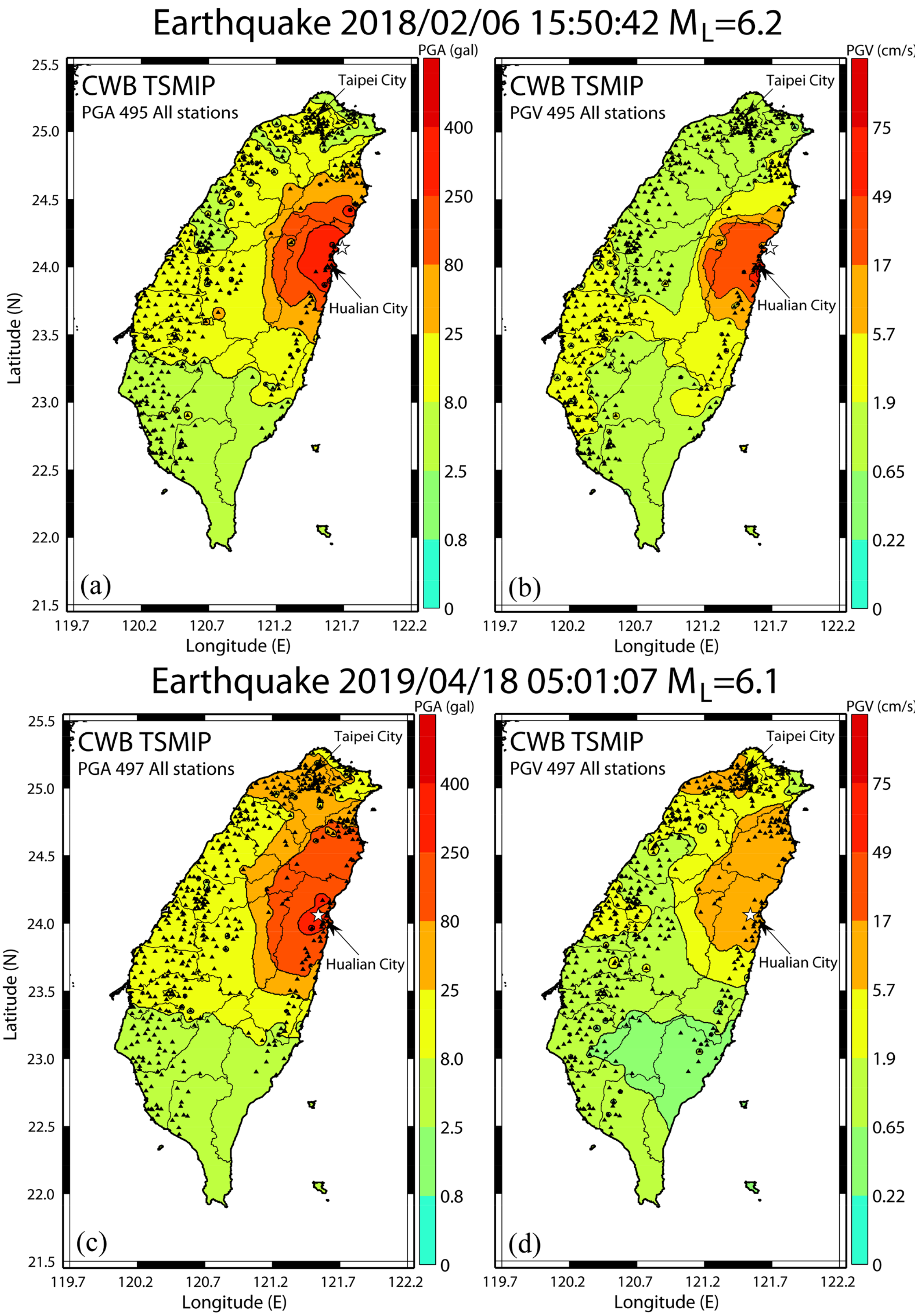

Fig. 9 The plotted **a** PGA and **b** PGV shakemaps for the 2018 Hualien earthquake ($M_L = 6.2$) and **c** PGA and **d** PGV shakemaps for the 2019 Hualien earthquake ($M_L = 6.3$)

used real-time P-Alert data to determine the coseismic deformation (C_d) in the epicentral region of earthquakes. Mittal et al. (2019b) tested the functioning of EEW in India by using the P-Alert data recorded in Taiwan.

Currently, the P-Alert system in Taiwan has 762 stations in operation. The operation rate can reach 90% with less manpower. Overall, the P-Alert network is a robust network having capabilities of both onsite and regional EEW systems with rapid reporting shakemaps. It is a low-cost and easy maintaining system and is vital to achieving a dense array in operation in Taiwan. Based on the success of EEW using low-cost sensors in Taiwan, several P-Alert instruments are installed in India, China, Indonesia, Korea, Vietnam, Mexico, New Zeeland, the Philippines, Nepal, Bhutan, and the Solomon Islands.

The traditional approach for EEW generally uses amplitude and frequency parameters from initial seismic signals as the key elements. However, it may meet the limitations in terms of source rupture area. Recently, the machine learning (ML) approach is evolved and is widely used for the EEW (Allen and Melgar 2019; Wang et al. 2022). The ML approach has the potential to overcome the limitation of the current EEW approaches. Nowadays, most smartphones are equipped with MEMS accelerometers and efficient operating systems. They are capable of receiving the regional warning message. All the networks employing smartphones are used for regional warnings. The use of smartphones in onsite warning systems for detecting a large earthquake and issuing a warning (Kong et al. 2016) will be an excellent achievement. For onsite EEW, the device needs a seismic sensor included and most of the buildings in Taiwan have these devices installed. A combination of onsite EEW and structural health monitoring systems (Hsu et al. 2018) will be an important development in the future.

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Author contributions
Conceptualization, YMW and HM; methodology, YMW and BMY; software, BMY; validation, BMY, HM, and YMW; formal analysis, BMY; investigation, BMY, HM, and YMW; resources, YMW; data curation, BMY; writing—original draft preparation, YMW and HM; writing—review and editing, HM and YMW; visualization, B.M.Y.; supervision, YMW; project administration, YMW; funding acquisition, YMW. All authors read and approved the final manuscript.

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Data availability
The strong motion waveform records from the P-Alert network used in this study can be downloaded at http://palert.earth.sinica.edu.tw/db/. The CWB strong motion data can be obtained from the website at https://gdms.cwb.gov.tw/.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no conflict of interest.

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