JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.97, December 2021, pp.1525-1532

Earthquake Early Warning Systems in Taiwan: Current Status

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ABSTRACT

The earthquake early warning (EEW) system in Taiwan is the outcome of rigorous research work carried out at various levels after the occurrence of the 1986 Hualien earthquake that caused destruction. After more than 25 years of development, three different EEW systems exist in Taiwan. Currently, the nation wide regional EEW system is operated by the Central Weather Bureau (CWB), whereas, a hybrid (regional & onsite) system based on Micro-Electro-Mechanical System sensors is run by National Taiwan University (NTU). The third EEW (onsite system) is run by the National Center for Research on Earthquake Engineering (NCREE). Both CWB and NTU systems are capable of reporting the EEW warnings within 20 seconds of earthquake occurrence. The CWB system is incharge of providing earthquake alerts in Taiwan via text message through mobile phone, TV, and directly broadcasting system to schools and is providing earthquake alarms to the general public since 2016. During recently damaging earthquakes in Taiwan, the NTU system provided 2-8 seconds onsite warning (lead time) in the blind zone around the epicenter. The NTU system also can generate near real-time shake maps for rapid response purposes. The NCREE system consists of about 98 stations and can provide several seconds lead time in the area near the epicenter. The NCREE system also can receive CWB regional EEW messages for warning the regions away from the epicenter. Individually every system has its advantage, however, the hybrid approach will be one of the future systems for real operation.

INTRODUCTION

Taiwan is one of the leading countries to develop the earthquake early warning (EEW) system. An EEW system is to identify ground motion exceeding a certain threshold in the early stage of an earthquake and alert the users before the arrival of strong ground shaking (Satriano et al., 2011). Most of the EEW systems in the world detect an earthquake and estimate its location and magnitude using real-time seismic data and this information is adopted for calculating expected ground motion at a particular location. The regions with expected ground motions larger than a certain threshold will be alerted. This is the so-called regional EEW system. Taiwan (Wu et al., 1998, 1999; Wu and Teng, 2002) and Mexico (Espinosa-Aranda et al., 1995) systems are examples of this type. There is also another type, named onsite EEW system, which determines the earthquake parameters from initial P waves and predicts the ground shakings of the following S-waves. The urgent earthquake detection and alarm system (UrEDAS) (Nakamura, 1988) and Taiwan P-Alert system (Wu, 2015) are covered under the onsite EEW system.

Taiwan is located on the boundary of the Philippines Sea Plate and Eurasian Plate with a convergence rate of about 8 cm/yr. Taiwan has been repeatedly experiencing damaging earthquakes (Figure 1). The destruction caused by the 15 November 1986 Hualien earthquake of M_L 6.8 (or M_w 7.8) motivated Taiwan to develop the EEW system. This earthquake occurred offshore of Hualien but, the Taipei metropolitan region was the most damaged region during this earthquake, located at a distance of about 120 km away from the epicenter. In case, a monitoring system can detect earthquake size and location within 20 seconds after the large event occurs in the eastern Taiwan, the Taipei urban area can have about 10 seconds of lead time before the damaging S-waves arrival. Based on research and recommendations, two prototype EEW systems were implemented in Hualien by the Central Weather Bureau (CWB) in 1994. After about five years of testing, results showed that the EEW system could provide about 15 sec of lead time before S-waves arrival in the Taipei urban

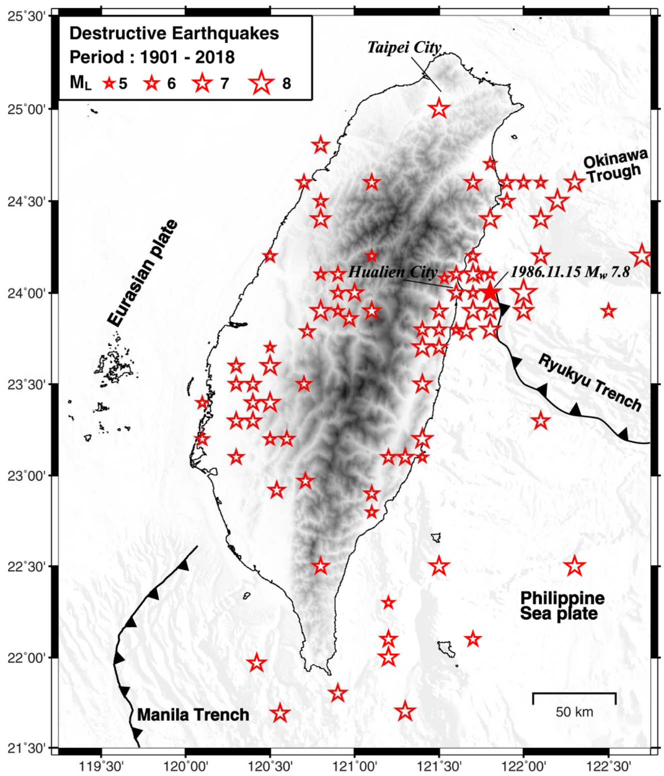

Fig.1. Epicenter distribution of the damage earthquakes occurred in Taiwan since 1900.

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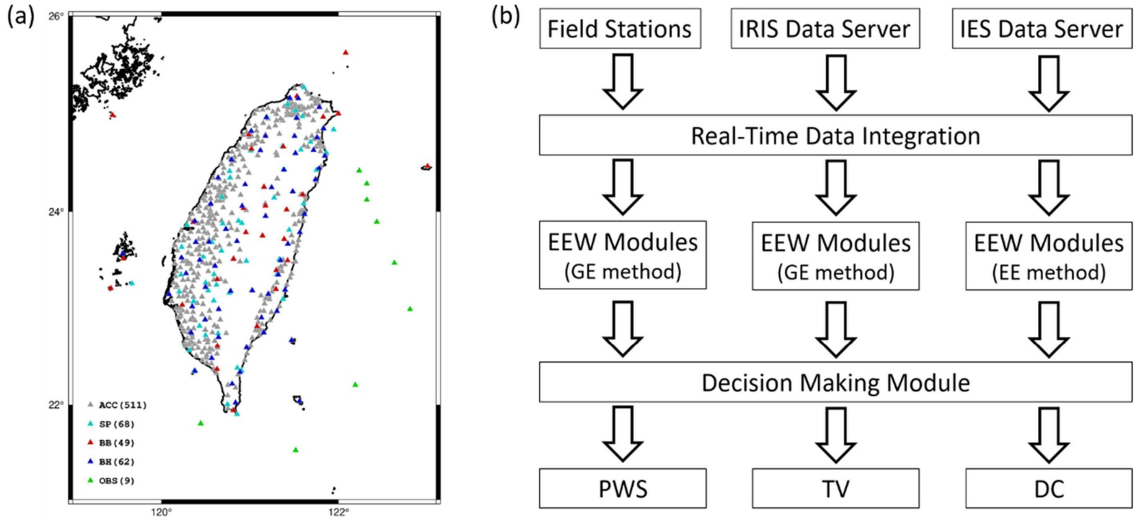

Fig.2. (a) Stations distribution of the CWB early warning system. It includes 511 acceleration (ACC), and 68 short-period (SP), 49 broadband (BB), 62 boreholes (BH), and 9 cable-based ocean bottom (OBS) seismometers. **(b)** System configuration of the CWB early warning system. The earthworm-based platform is used for the integration of seismic signals from CWB, IRIS, and the Institute of Earth Sciences (IES) of Academia Sinica, Taiwan. There are two kinds of location methods in EEW modules of the CWB system. GE represents Geiger's method. EE represents effective epicenter method. When systems are triggered. Results will be delivered to decision making module. When meets certain threshold. Warning will be issued by three ways including public warning system (PWS), TV, and dedicated connection (DC).

area (Wu et al., 1999). Based on the performance of the EEW system and the devastation caused by the damaging Chi-Chi earthquake in 1999, CWB implemented a nationwide EEW in Taiwan by installing sensors for detecting the earthquakes (Wu et al., 2015).

After more than 25 years of development, there are three major EEW systems in Taiwan. The nationwide regional EEW system is operated by the CWB and two onsite systems are run by National Taiwan University (NTU) and the National Center for Research on Earthquake Engineering (NCREE). Currently, the CWB system can regularly issue warnings within 20 seconds after earthquake occurrence via cell phone. For recently damaging 2018 M_w 6.4 Hualien earthquake, the CWB system issued the alert around 17 seconds after the occurrence of the earthquake (Chen et al., 2019). The NTU P-Alert system provided 2-8 seconds lead time in the blind zone around the epicenter and generated a detailed shake map within 2 minutes using signals from about 700 stations (Wu et al., 2019). The NCREE system consists of about 98 stations and provides several seconds lead time in the area near the epicenter (Hsu et al., 2018a). An introduction to EEW systems of the CWB, P-Alert, and NCREE are provided in this article.

REGIONAL EEW SYSTEM OF THE CWB

The EEW system of the CWB is the outcome of the study and development over the last two decades. The first generation of this EEW system was the virtual sub-network (VSN) system which could provide alarms about 22 seconds after earthquakes occurred (Wu and Teng, 2002). The magnitude estimation algorithm in the VSN system takes 10 seconds time window after the first P-wave arrival data and so it cannot provide earthquake information within 15 seconds after the occurrence (Wu et al., 1998). Because of the 10 second window in the VSN system, a blind zone of 60 km radius exists around the epicenter without early warning and is the most damaging area. Later, to reduce the blind zone, a P-wave-based method was adopted using a 3 seconds time window after P-wave arrival. The P-wave arrivals are used for estimations of event location and origin time. The vertical peak displacement amplitude is used for magnitude estimation (Wu and Zhao, 2006). Based on this algorithm, the second-generation system is developed and tested (Hsiao et al., 2009, 2011).

The CWB has integrated different kinds of seismic instruments using the Earthworm-based software since 2012. Using this Earthworm-based system an earthquake reporting system (eBEAR) has been created and tested (Hsiao et al., 2011; Chen et al., 2012). Figure 2 shows the station distribution and system configuration. The seismic network used in the EEW system includes 511 accelerometers, 68 short-period instruments, 49 broadband instruments, 62 borehole instruments, and 9 cable-based ocean bottom seismometers. Both Geiger's (GE) method and effective epicenter (EE) method (Chen et al., 2019) are used for estimating earthquake locations and this information will be sent to the decision making module. Currently, the eBEAR system is in charge of providing earthquake alerts in Taiwan via text message from mobile phone, TV, and directly broadcasting system to schools (Chen et al., 2015; Chen et al., 2019). This system is providing earthquake alarms to the general public since 2016. There are three ways to issue alarms. One is on the Public Warning System (PWS). Under this system, the CWB sends a warning to the National Science and Technology Center for Disaster Reduction (NCDR). The NCDR send message to mobile phone companies and finally, the message is broadcasted to the public. This kind of system can disseminate alarms to millions of people in a short period and is the most powerful tool to let people know about the possible earthquake. The PWS system started operating on April 1st, 2016 and issued the first warning on May 12, 2016. The second way is through the television (TV) system. The CWB established dedicated connections with 9 TV companies. Currently, the CWB delivers earthquake alarms to these TV companies and the warning message is directly posted on the TV screen after the warning is received. The third way is for specific users. The CWB provides 6000 connections to government agencies, schools, and 15 commercial companies for transmitting earthquake alarms.

The eBEAR system is in operation since 2014. Figure 3 shows errors in epicenter location and reporting times of the CWB EEW system in comparison with the CWB catalog. For inland earthquakes, location errors are smaller and reporting times are shorter than offshore events. The average reported error is 4.1 km and 0.27 units for epicenter and magnitude, respectively. This system is robust as no false alarms are reported. The average processing time in this system is about 17.3 seconds after earthquake occurrence and the system uses Geiger's method for earthquake location. Once the average travel-time residuals are less than a certain threshold, the system will start generating reports.

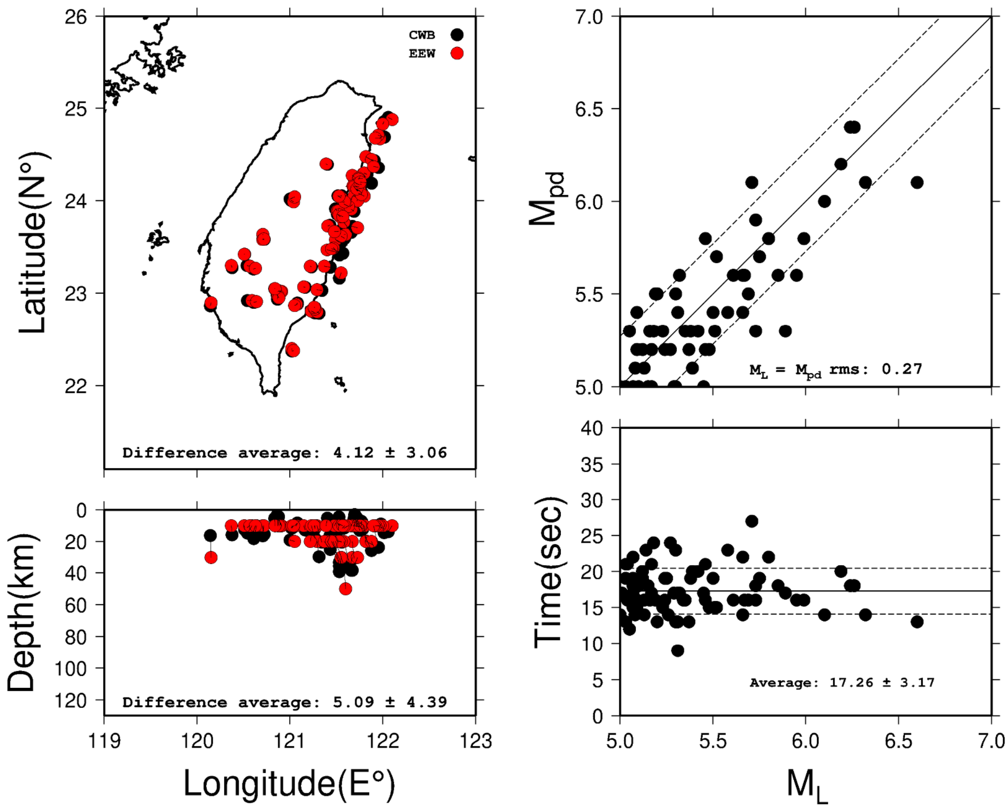

Fig.3. Difference in location estimation using CWB-EEW system and CWB catalog, the comparison of CWB-EEW magnitude with (CWB catalog), and earthquake reporting time of the CWB-EEW system from 2014 to 2020. Only events with magnitude larger than 5.0 and depth less than 40 km and 10 km near the coastline, are presented.

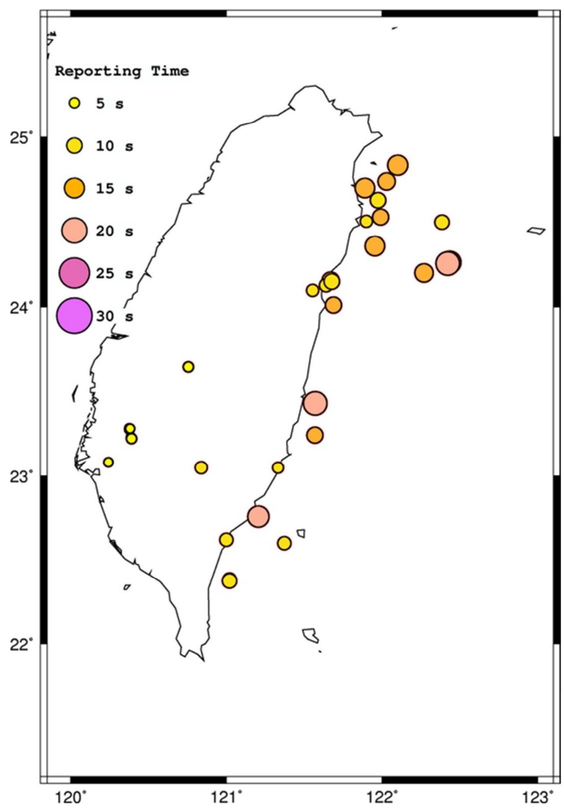

Fig.4. Reporting time of the CWB EEW system from effective epicenter method. From April to December of 2020, there are totally 12 inland and 21 offshore events issued by the effective epicenter method. The average processing time for inland and offshore events are 10.5 s and 20.9 s, respectively

For events occurring offshore or in poor stations coverage regions, travel-time residuals may not quickly decrease and the system takes more time to generate EEW report. To shorten reporting time, an "effective epicenter method" is developed and tested successfully (Chen et al., 2019). Figure 4 shows that from April to December of 2020, the average processing time for inland and offshore events are 10.5 seconds and 20.9 seconds, respectively. For inland earthquakes it is capable of providing warnings to the regions of more than 40 km away from the epicenter.

THE P-ALERT EEW SYSTEM

Given the importance of the subduction zone in the vicinity of Taiwan and seismogenic inland faults within Taiwan, the country should be densely instrumented for a precise warning. The NTU network tries to fill this gap. The NTU system consists of Micro-Electro-Mechanical System (MEMS) based P-Alert instruments that record three-component data at 100 samples per second. The feasibility to use them in EEW applications was tested for the first time in 2010 by installing 15 of these instruments in the Hualien region (Wu and Lin, 2014). The instruments worked efficiently and based on the performance of these instruments, the instrumentation was extended to the other parts of the country (Wu et al., 2013; Wu, 2015). The present NTU system consisting of 761 P-Alert instruments (Figure 5a) is installed in various elementary schools, where necessary logistics for installation of instruments is available. The instruments are mounted vertically on the walls, generally on the ground or the first floor of the building. The functioning of this system is explained in Figure 5b.

This instrumentation can meet the requirements of both regional, as well as, on-site EEW systems. The instruments installed in the field continuously look for the earthquake occurrence using the short-term-averaging (STA)/long-term-averaging (LTA) algorithm. The data is double integrated using the inbuilt algorithm to check the peak

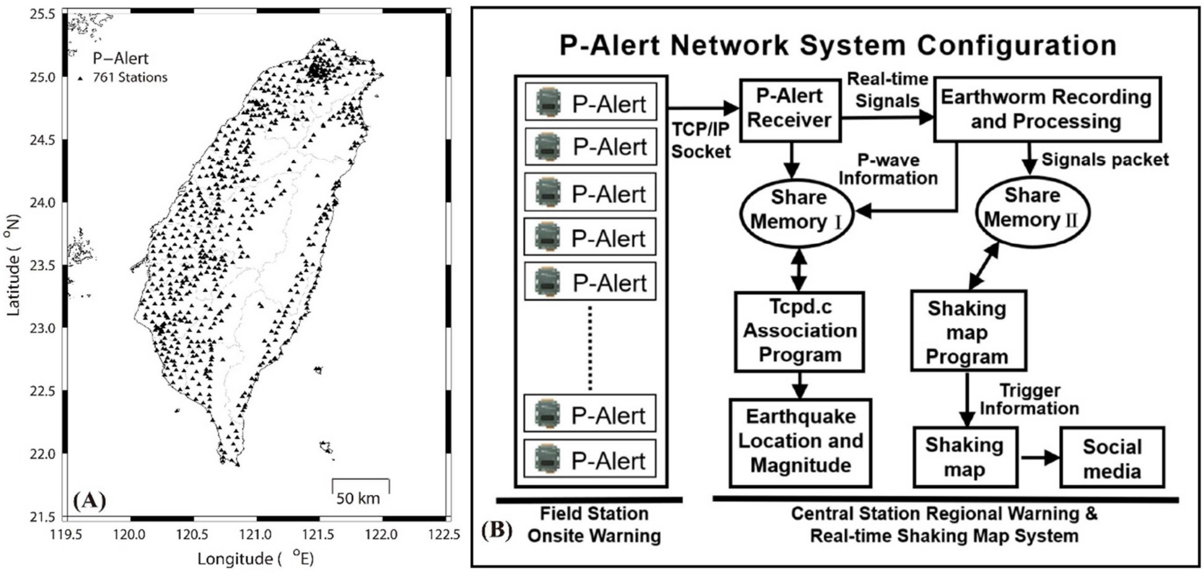

Fig.5. (a) The location of P-Alert instruments installed in different parts of the country and **(b)** the functioning of the P-Alert network.

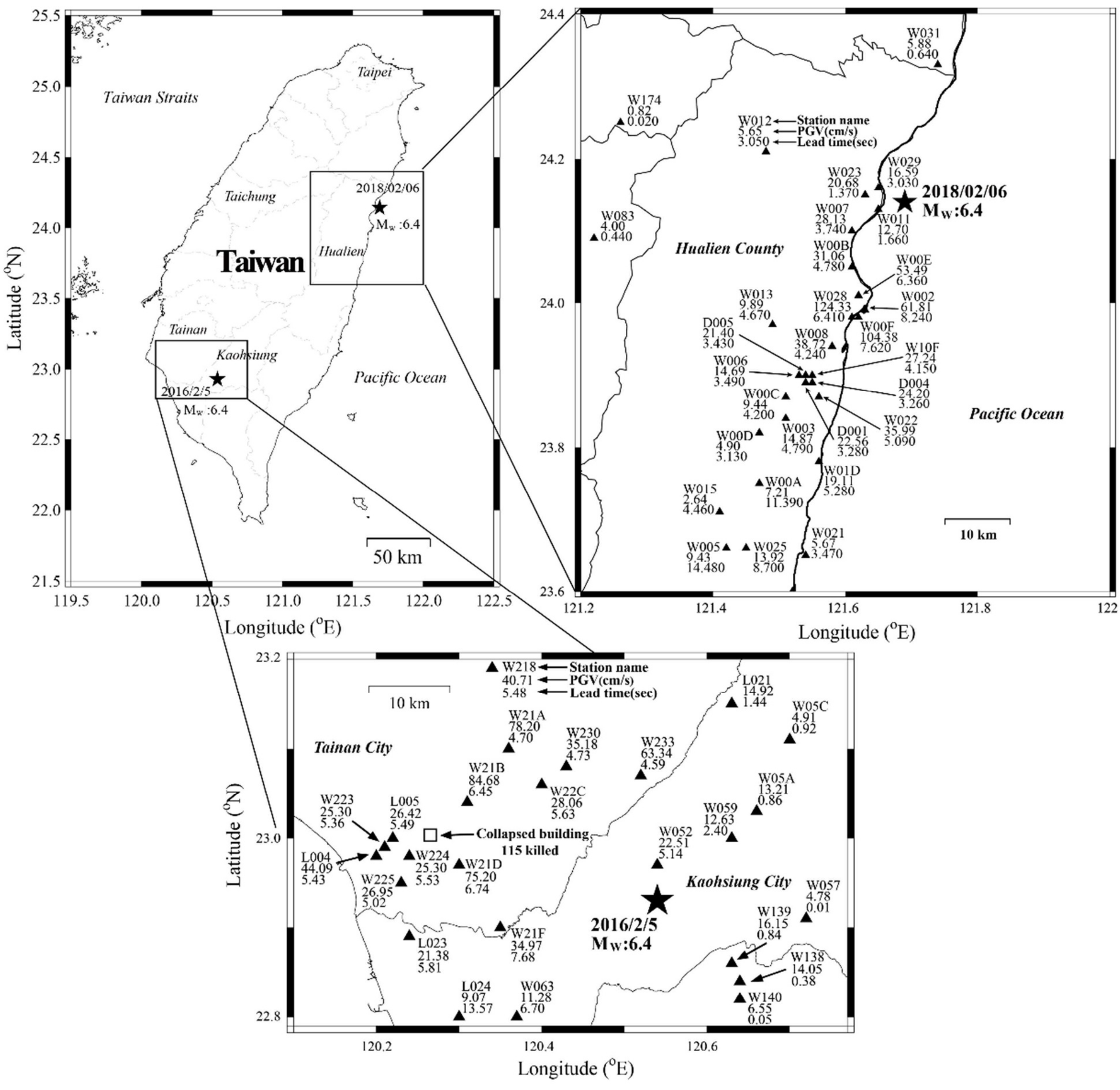

Fig.6. The obtained onsite lead time during the Meinong earthquake of February 5, 2016, and the Hualien earthquake of February 6, 2018.

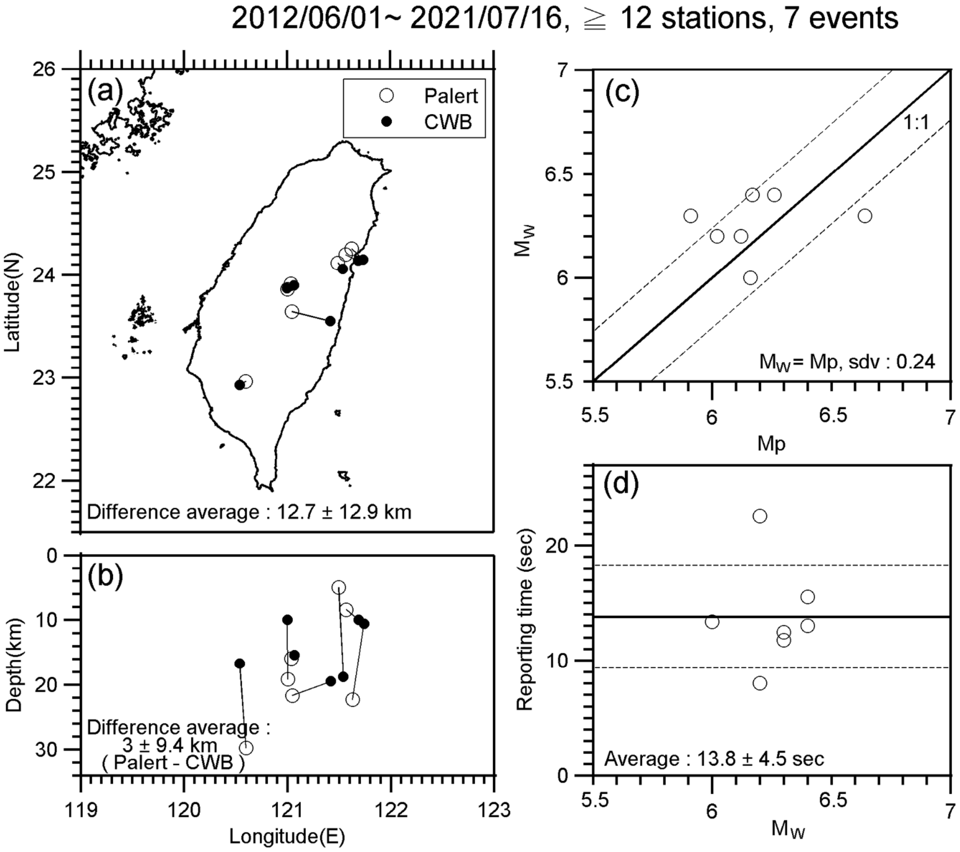

Fig.7. (a) Difference in location estimation using P-Alert and CWB network, **(b)** difference in depth using the two networks, **(c)** the comparison of P-Alert magnitude with , and **(d)** the earthquake reporting time using P-Alert real-time data.

amplitude of the vertical displacement (P_d). Once the predefined thresholds, using empirical relationships are met (e.g., PGA ≥8 0 gals or ≥ 0.35 cm; Wu et al., 2011; Hsieh et al., 2015), an on-site warning is issued. In addition, the data from the field instruments is transferred continuously to the central processing systems placed at NTU and Academia Sinica, where data is processed for earthquake magnitude and possible shaking for regional warning using earthworm software (Chen et al., 2015). As CWB is the official agency for regional warning only, the on-site warning generated using this instrumentation has proven helpful for the children in schools to take safety measures as the earthquake safety drills are conducted regularly in Taiwan.

The Meinong earthquake of February 5, 2016, that occurred in Southern Taiwan caused massive damage to nearby places including structural damage to buildings, soil liquefaction, and loss of lives. The maximum CWB intensity during this earthquake reached VII (corresponding to PGA> 400 gals), which is the maximum in Taiwan (Wu et al., 2003). The Meinong earthquake is supposed to be the most damaging inland earthquake after the Chi-Chi earthquake of 1999. Total 581 P-Alert instruments were installed throughout the country when the Meinong earthquake occurreded. The earthquake was well recorded by P-Alert instruments as individual P-Alert systems performed very well for on-site warning, and issued 2-8 seconds lead time in the epicentral region (Figure 6) before the arrival of vibrant shaking (Wu et al. 2016). During the Hualien earthquake of February 6, 2018, the PGA at some stations recorded by the P-Alert network reached around 0.6 g giving rise to a maximum CWB intensity of VII. The lead-time of the order of 1.5-8 seconds was reported using PGA and PGV by various instruments in the epicentral region (Wu et al., 2019). During both the events, the instruments placed in the damaged area provided higher lead times (5-8 seconds) as compared to other instruments.

The performance of the P-Alert system in terms of regional warning and magnitude estimation is described using seven events having a magnitude ≥ 6.0 that occurred between June 2012 and July 2021 (Figure 7). The early estimates of the location, magnitude, depth, and warning time initiate with the triggering of a minimum of 12 stations and keep on updating with the increase in the number of triggering stations. The location estimated by an automated procedure using P-Alert real-time data was compared with the location reported by the CWB network, estimated using offline data (Figure 7a). The hypocenter locations provided by both networks generally agree except for one event where the difference may be due to the lesser number of P-Alert stations recording that event. The reported average difference between two networks in location is found to be 12.7 km with a standard deviation of 12.9 km. Similarly, the average focal depth difference is reported to be 3 km with a standard deviation of 9.4 km (Figure 7b). On plotting the reported P-Alert magnitude (M_p) with the moment magnitude (M_w), two magnitudes are found to agree with each other with an uncertainty of 0.24 (Figure 7c), an acceptable value in EEW. For the past few years, with the increased number of stations, the P-Alert network has shown its capability to report the results in minimum time (increased lead time) with maximum accuracy. Before 2015, the system took 15 to 25 seconds for issuing the warning for research purposes. For these seven events under consideration, the average reporting time is found 13.8 seconds with a standard deviation of 4.5 seconds (Figure 7d). These results indicate that the P-Alert network can serve the purpose of a regional-warning EEW system with minimum errors. During the Meinong earthquake, the CWB and P-Alert EEW networks provided information in 12 and 15 seconds respectively after the earthquake occurrence with estimated magnitudes of 6.1 and 6.2. The P-Alert system took an additional 3 seconds as the minimum triggering stations are set to be 12, which are more than CWB triggering stations.

In addition to EEW, the NTU network is capable of generating shakemaps during earthquakes. Once 10-12 instruments record PGA ≥1.2 gals, the network starts plotting shakemaps. These shakemaps are updated at a regular interval after 30 seconds and are delivered to specific users including National Disaster Relief agencies for possible rescue operations. The working of this network for EEW and shakemaps plotting during recent damaging earthquakes in Taiwan was explored in some previous studies (Wu et al., 2016, 2019). Yang et al. (2021) improved this network to plot Peak Ground Velocity (PGV), spectral acceleration (S_a), and CWB intensity maps along with PGA maps. By plotting PGA and PGV shakemaps using the denser network of P-Alert instruments, the PGV is supposed to be a better indicator of damage distribution as compared to PGA. The P-Alert data is also used in various seismological studies involving studying rupture direction (Hsieh et al., 2014; Wu, 2015; Jan et al., 2018) structural health monitoring (Hsu et al., 2018b), and estimating co-seismic deformation (Jan et al., 2017). To check the usefulness of P-Alert data in different applications, Wang et al. (2018) compared the data recorded by P-Alert instruments with the data by the free-field Taiwan Strong Motion Instrumentation Program (TSMIP) instruments placed close to P-Alerts. They found that PGA recorded by ground floor instrument is the same as TSMIP instruments, whereas the instruments placed at first-floor record 1.07 times of the TSMIP instruments, which is in an acceptable range. The data collected by this network is also archived for future use by seismologists and engineers.

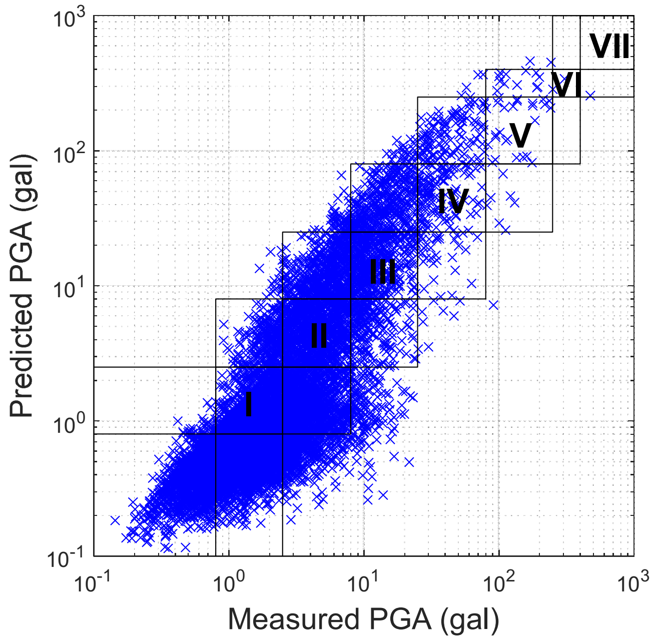

Fig.9. Comparison between the predicted and measured PGA of the NEEWS seismic stations recorded between March 2015 – July 2021.

THE NCREE EEW SYSTEM

In 2009, NCREE started to develop onsite EEW techniques, and subsequently established several pioneer stations at schools in some of the earthquake-prone zones in Taiwan. In 2013, some timely alerts were successfully issued by the NCREE's EEW system (NEEWS) before the arrival of destructing seismic waves at these pioneer stations. Based on the success of this pioneering project, the Taiwan government funded the NCREE to upgrade the NEEWS system for providing EEW services to all 3,514 public elementary and junior high schools in Taiwan. The project started in 2015 and finished at the end of 2019. Under this project, the 98 seismic stations equipped with a seismograph, a data logger, and a computer are established at different schools, distributed uniformly throughout the areas with schools for issuing onsite EEW alerts. All 3,514 schools are equipped with an alert broadcast system to receive both the onsite alert from NEEWS seismic stations and regional alert from CWB, and either of the alerts is broadcasted based on the speed of receiving the alert. The locations of the seismic stations of NEEWS and the schools are shown in Figure 8.

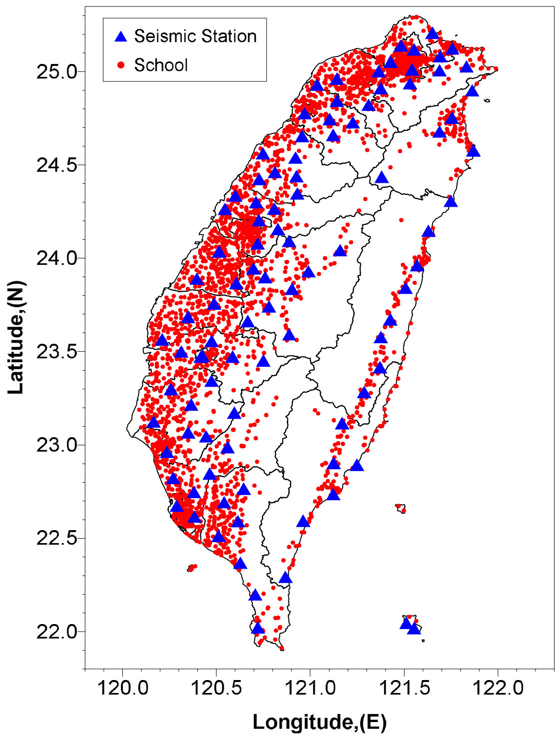

Fig.8. Locations of the 98 NEEWS seismic stations and the 3,514 schools.

During the construction of the NEEWS in these schools, three major earthquakes with M_w larger than 6 occurred in Taiwan. The first one was the 2016 Meinong earthquake, and the alerts issued only by NEEWS' onsite stations were recorded during this earthquake. During the Meinong earthquake, the NEEWS delivered very promising onsite EEW results. The lead time before the arrival of PGA was approximately 3.8-17.0 seconds for the stations that measured PGA≥25 gals at an epicenter distance of 18.0-104.5 km. If only the data with a measured CWB intensity scale ≥ IV (or a predicted CWB intensity scale ≥ IV) are considered, the prediction performance could be estimated using the intensity prediction accuracy ratio (IPAR), defined as the ratio of the predicted intensity scale located within a one-scale difference from the real intensity scale among all the considered earthquake data. The IPAR of NEEWS during the Meinong earthquake was 10/10 = 100% (Hsu et al. 2016). During the 2018 Hualien earthquake, both the on-site and regional alerts were recorded and hence the performance of both systems could be compared. The lead-time before the arrival of PGA was approximately 5.5-14.8 seconds for the stations that measured PGA ≥ 25 gals with an epicenter distance of 6.2-68.5 km, and the IPAR of NEEWS was recorded 7/7=100% (Hsu et al. 2018). When the 2019 Hualien earthquake occurred, both the seismic stations of NEEWS and the alert broadcast system at all the 3,514 schools were almost ready, hence the performance of the "satellite-based approach" of NEEWS could be discussed. The lead time before the arrival of PGA was approximately 4.2-14.6 seconds for the stations having recorded PGA ≥ 25 gals with an epicenter distance of 11.1-119.7 km, and the IPAR of NEEWS was 31/36=86.1% (Hsu et al. 2021). The reported IPAR of NEEWS during all above three earthquakes is supposed on a higher side as the reported best annual IPAR of the EEWS of Japan Meteorological Agency is 86% (JMA, 2016).

Most of the NEEWS stations predict PGA using the algorithm developed based on the support vector machine (SVM) technique (Hsu et al. 2013). The implemented SVM model in the NEEWS predicts PGA based on six P-wave features extracted from the first 3 seconds of the vertical acceleration. Recently, the prediction algorithm at some of the NEEWS stations is upgraded to predict PGA based on the features extracted every second, hence the lead time could be improved (Hsu et al., 2021). The general performance of PGA prediction of the NEEWS using the SVM approach during March 2015 – July 2021 is shown in Figure 9. In general, the SVM model overestimates the PGA for larger earthquakes but underestimates the smaller earthquakes. Nevertheless, most of the predicted PGAs lie within a one-scale difference from the real intensity scale.

SUMMARY

Three different EEW systems are functional in Taiwan. The CWB system is the official EEW system and is responsible for issuing the warning from moderate to large earthquakes occurring in and around Taiwan. Being a regional warning system, it is not able to issue the warning to the cities or places falling in the blind zone in the vicinity of the earthquake source. The NCREE system consisting of almost 98 instruments is an onsite system and can provide warnings to the places falling in the blind zone of the CWB regional warning system. Both systems perform well and the CWB system has proven its efficiency by capturing the events and issuing the warning well ahead before the arrival of strong shaking. CWB has collaborated with the NCREE system and under this system, the broadcast systems are installed in 3,514 schools for the proper utilization of the network. The P-Alert network, on the other hand, can act as an onsite, as well as, regional warning system. For onsite warnings, the P-Alert network reported important lead times (2-8 seconds) during recent earthquakes in the epicentral region, which is crucial to take preventive measures. The P-Alert network lead time is discussed from the stations having PGA $\geq$ 80 gals, whereas for the NCREE network it is obtained from the stations that record PGA $\geq$ 25 gals. The feasibility of the P-Alert network to act as a regional warning system has been tested and established previously, and in the present work, it was tested using seven events having a magnitude $\geq$ 6.0. The location, depth, and magnitude estimated using real-time P-Alert data generally agree with the CWB estimates. The regional warning generated using the P-Alert network is used for research purposes as the CWB is the official agency for regional EEW in Taiwan. Already a dense network of 761 instruments is installed by the NTU, in the future it is planned to expand it in the eastern side of the country based on the proper logistics for instrument installation.

Acknowledgments: We would like to thank Prof. Harsh Gupta for providing the opportunity to present the development of Taiwan earthquake early warning systems. The authors gratefully acknowledge the Ministry of Science and Technology (MOST), Taiwan for sponsoring the project, under which this study was carried out. Our work was also supported by the Research Center of Future Earth of the National Taiwan University (NTU) and the National Center for Research on Earthquake Engineering, Taiwan (NCREE). This work was also financially supported by the NTU Research Center for Future Earth from the Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education (MOE) in Taiwan. The author (HM) is thankful to Dr. O.P. Mishra, Director, National Centre for Seismology, Ministry of Earth Sciences, India for providing necessary support to participate in present work.The GMT software from Wessel and Smith (1998) was used in plotting most of the figures and is gratefully acknowledged.

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(Received: 15 August 2021; Revised form accepted: 20 September 2021)