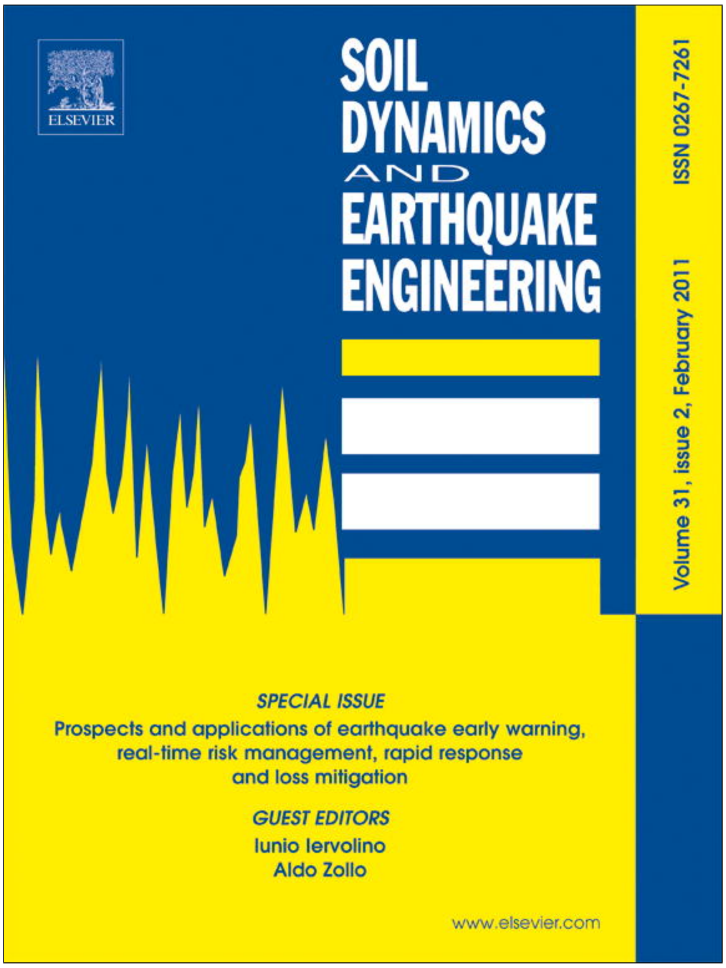
ELSEVIER
SOIL DYNAMICS AND EARTHQUAKE ENGINEERING
ISSN 0267-7261
Volume 31, issue 2, February 2011
SPECIAL ISSUE
Prospects and applications of earthquake early warning, real-time risk management, rapid response and loss mitigation
GUEST EDITORS
Iunio Iervolino
Aldo Zollo
www.elsevier.com

Soil Dynamics and Earthquake Engineering 31 (2011) 201–208

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

A new prototype system for earthquake early warning in Taiwan

Nai-Chi Hsiao [a,*], Yih-Min Wu [b], Li Zhao [c], Da-Yi Chen [a], Wei-Ting Huang [b], Kuan-Hung Kuo [a], Tzay-Chyn Shin [a], Peih-Lin Leu [a]

[a] Seismological Center, No. 64, Gongyuan Rd., Central Weather Bureau, Taipei 10048, Taiwan
[b] Department of Geosciences, National Taiwan University, Taipei, Taiwan
[c] Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan

ARTICLE INFO

Article history:
Received 29 July 2009
Received in revised form
7 January 2010
Accepted 17 January 2010

Keywords:
Earthquake early warning system
P_d magnitude
Earthworm system
Taiwan

ABSTRACT

A new prototype earthquake early warning (EEW) system is being developed and tested using a real-time seismographic network currently in operation in Taiwan. This system is based on the Earthworm environment which carries out integrated analysis of real-time broadband, strong-motion and short-period signals. The peak amplitude of displacement in the three seconds after the P arrival, dubbed P_d, is used for the magnitude determination. Incoming signals are processed in real time. When a large earthquake occurs, P-wave arrival times and P_d will be estimated for location and magnitude determinations for EEW purpose. In a test of 54 felt earthquakes, this system can report earthquake information in 18.8 ± 4.1 s after the earthquake occurrence with an average difference in epicenter locations of 6.3 ± 5.7 km, and an average difference in depths of 7.9 ± 6.6 km from catalogues. The magnitudes approach a 1:1 relationship to the reported magnitudes with a standard deviation of 0.51. Therefore, this system can provide early warning before the arrival of S-wave for metropolitan areas located 70 km away from the epicenter. This new system is still under development and being improved, with the hope of replacing the current operational EEW system in the future.

1. Introduction

Earthquake early warning (EEW) system is considered as one of the most useful tools for emergency response in reducing seismic hazards [1]. When a large earthquake occurs, an EEW system provides the warning a few to tens of seconds in advance of impending disastrous ground motions, allowing for immediate mitigation actions to be taken. For instance, high-speed trains can slow down to resist strong ground shakings, critical facilities such as gas pipelines can be turned off automatically, and surgeries in hospitals can be suspended in time, etc. To be sure, the early warning time is too short for people to evacuate buildings. However, through careful planning, training, and drills, an educated general public can take necessary measures in time to avoid loss of lives from large earthquakes.

Taiwan is located on the western portion of the Circum-Pacific seismic belt with a plate convergence rate of 8 cm per year, and earthquake is one of the most serious disasters in Taiwan. Nearly 18,000 seismic events occur around the Taiwan region every year, and numerous destructive earthquakes with severe casualties and property losses have happened in the last century (Fig. 1), such as the 1906, M_L=7.1 Meishan earthquake (1258 deaths), the 1935, M_L=7.1 Hsinchu-Taichung earthquake (3276 deaths) and the 1999, M_L=7.3 Chi-Chi earthquake (2455 deaths). Therefore, it is essential for Taiwan to seek means through scientific research to reduce earthquake hazards.

EEW systems have already been developed and tested in a number of countries [2–13]. Taiwan has been one of the leading countries with more than ten years of operational experiences on EEW. For the sake of rapid reporting of felt earthquakes, a real-time strong-motion network was established in Taiwan by the Central Weather Bureau (CWB) and has been in operation since 1995 [14]. Fig. 1 shows the distribution of these strong-motion stations. The network consists of 102 stations currently. When a potentially felt earthquake occurs around the Taiwan area, the location, magnitude and shake map of seismic intensities can be automatically reported within about 1 min [15]. For large earthquakes, the magnitude [16], shake map [17] and losses [18,19] can be estimated within 2 min after the earthquake occurrence. Within 3–5 min, an official earthquake report can be disseminated to various organizations and individuals.

Meanwhile, this network has been utilized for the development of Taiwan's EEW system [4,5,13,20]. As an experiment, a quick magnitude estimation using the M_{L10} approach [20], based

* Corresponding author. Tel.: +886 2 2349 1350; fax: +886 2 2349 1179.
E-mail addresses: naigi@cwb.gov.tw, naigi@scman.cwb.gov.tw (N.-C. Hsiao).

0267-7261/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.soildyn.2010.01.008

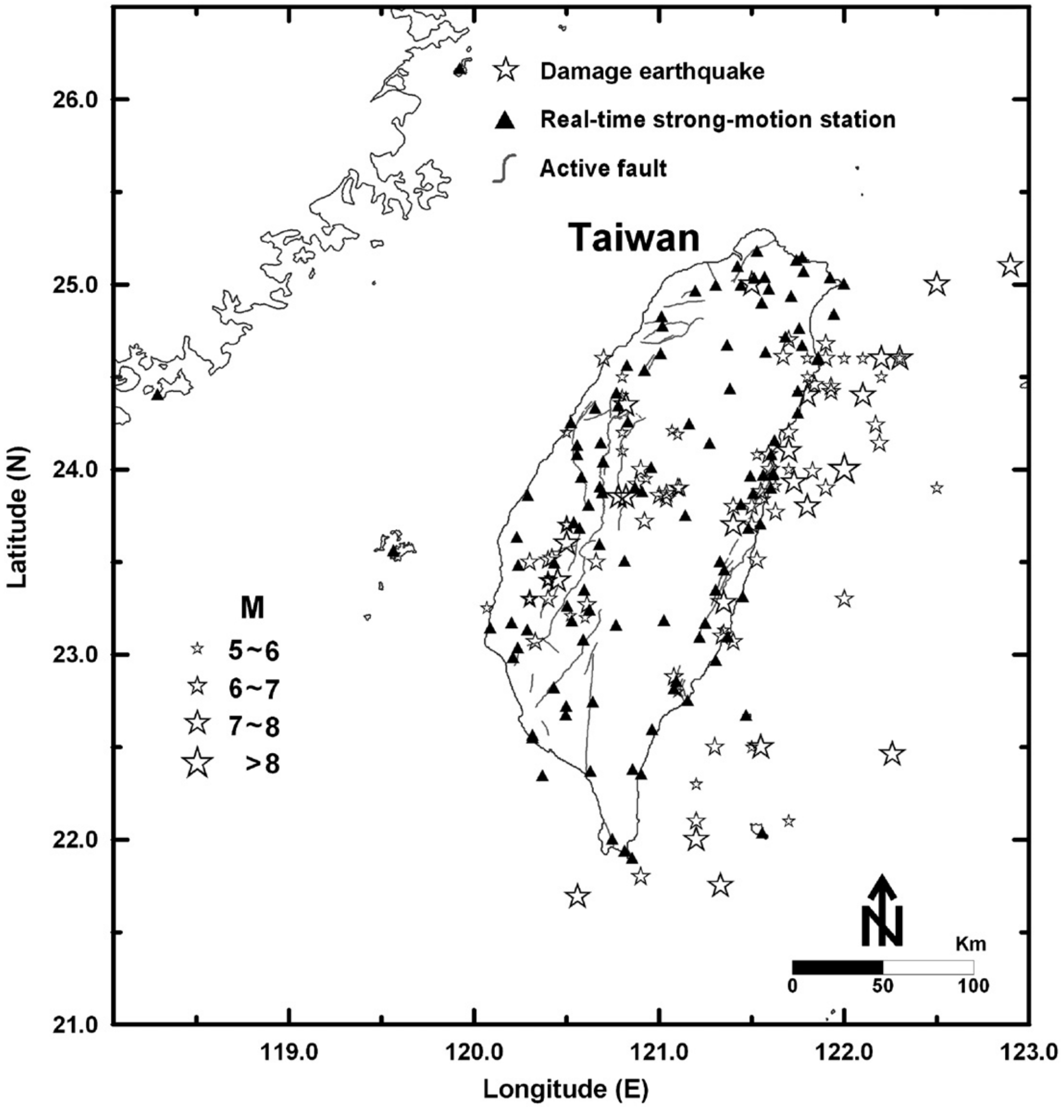

Fig. 1. Epicenters of destructive earthquakes (open stars) occurred around Taiwan since 1900. Solid triangles are locations of the real-time strong-motion stations which were used to develop earthquake early warning system in Taiwan since 2001.

on the virtual sub-network (VSN) concept, has been successfully developed, tested and in operation [5]. In this experiment, seismic waveforms in a 10-s time window starting from the first P-wave arrival time at the nearest station are used to determine the hypocenter and magnitude of an earthquake. In addition, according to the location of the earthquake, only waveforms from stations surrounding the epicenter are extracted for processing. Due to the limited length of the time window and the requirement of fewer waveforms, the processing time is effectively reduced. After its on-line operation since 2001, the EEW system was capable of issuing reports within 20 s of the occurrences of earthquakes with good magnitude estimations for events up to magnitude 6.5 [13]. This means that the system can achieve EEWs for metropolitan areas located more than 70 km away from the epicenter.

In order to provide warning for regions within 70 km from the epicenter, a new prototype EEW system base on a P-wave method is developed in Taiwan. Instead of M_{L10}, we adopt the "P_d magnitude", M_{pd}, as our magnitude indicator in the new system. P_d is defined as the peak amplitude of the initial P-wave displacement, which could be used for estimating the subsequent shaking intensity [21–23]. By analyzing the P_d attenuation relationship, Wu and Zhao [24] used P_d in magnitude determination for earthquakes in Southern California, which demonstrated P_d to be a good magnitude estimator for EEW purpose. Thus, we adopt the P_d magnitude in developing our next generation EEW system in Taiwan based on the Earthworm system [25] integrating all available real-time seismic waveforms.

2. Method

The relationships between the earthquake magnitude and several characteristic parameters obtained from the first few seconds of the P-wave have been developed for EEW applications recently [6,21–27]. When the EEW system is triggered by an earthquake, these relationships can be utilized to quickly estimate the magnitude based on a regional seismic network [3,5,9,13] or a single station [2]. In this study we mainly consider the P_d as the magnitude estimator.

Following Wu and Zhao [24], we assumed a simple linear regression model among the logarithmic P_d, the reported local magnitude M_L, and the logarithmic hypocentral distance R:

$$\text{Log}P_d = A + B \times M_L + C \times \log R, \quad (1)$$

where A, B and C are constants to be determined from the regression analysis. In this study, we selected a total of 186 shallow earthquakes in Taiwan with local magnitudes M_L from 4.5 to 7.3. The seismic records used for the regression analysis include strong-motion and broadband waveforms. Among the waveforms, strong-motion records are available mostly for moderate to large earthquakes, whereas broadband waveforms are available for small to moderate earthquakes since the records may be clipped in the near-source region of large events. Meanwhile, the records were selected with a good azimuthal coverage for each event to average the effect of the P-wave radiation pattern. The distance span in the regression analysis was limited to within 120 km.

For data processing, the strong-motion and broadband records were integrated twice and once, respectively, to obtain the displacement. Following previous studies [21–23,26–28], we adopt a time-window length of 3 s starting from the P-wave arrival time in magnitude estimation, and use a high-pass recursive Butterworth filter with a cutoff frequency of 0.075 Hz to remove the low frequency drift in the displacement signal.

The attenuation relationship was obtained by a linear regression, and the resulting best-fitting relationship for $\log P_d$ is

$$\text{Log}P_d = -1.777 + 0.455 \times M - 1.230 \times \log R, \quad (2)$$

with a standard deviation of 0.362. In Fig. 2, the observed P_d values are compared with those predicted by Eq. (2) separately for magnitudes 4.0, 5.0, 6.0 and 7.0.

In the EEW system, earthquake locations can be determined from the P-waves at the same stations. With hypocentral distances available, we can invert the regression result in Eq. (2) to estimate the magnitude M_{pd} from the P_d:

$$M_{Pd} = 3.905 + 2.198 \times \text{Log}P_d + 2.703 \times \log R. \quad (3)$$

Fig. 3 shows the P_d magnitude determined by averaging the P_d measurements from six nearest stations for each earthquake. The M_{pd} estimated with Eq. (3) has approximately a 1:1 relationship with M_L with a standard deviation of 0.43. Although there are scattering for small earthquakes, the magnitudes of bigger earthquakes agree well. For instance, the estimated M_{pd} for 1999 Chi-Chi earthquake is 7.23.

3. The EEW system

The new EEW system is designed and constructed based on the Central Weather Bureau Seismographic Network (CWBSN). The CWBSN is a real-time seismographic network with more than one hundred digital telemetered seismic stations distributed over the entire Taiwan region covering an area of 36,000 square kilometers. Fig. 4 shows the distribution of stations. The records are transmitted from field stations to the CWB headquarters in Taipei continuously and in real time. Currently, there are three

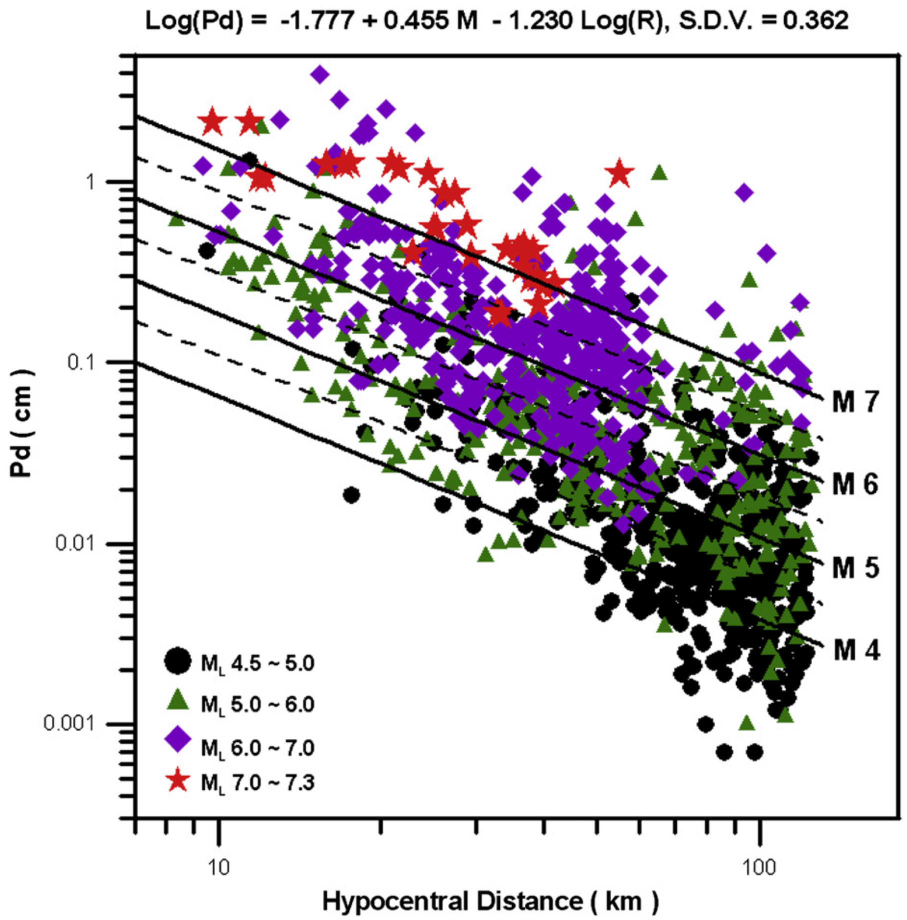

Fig. 2. Distribution of the observed P_d measurements. The diagonal lines are calculated from the linear $\log(P_d)-\log(R)$ relationship. Solid lines are for magnitudes 4, 5, 6 and 7, and dashed lines are for magnitudes 4.5, 5.5 and 6.5.

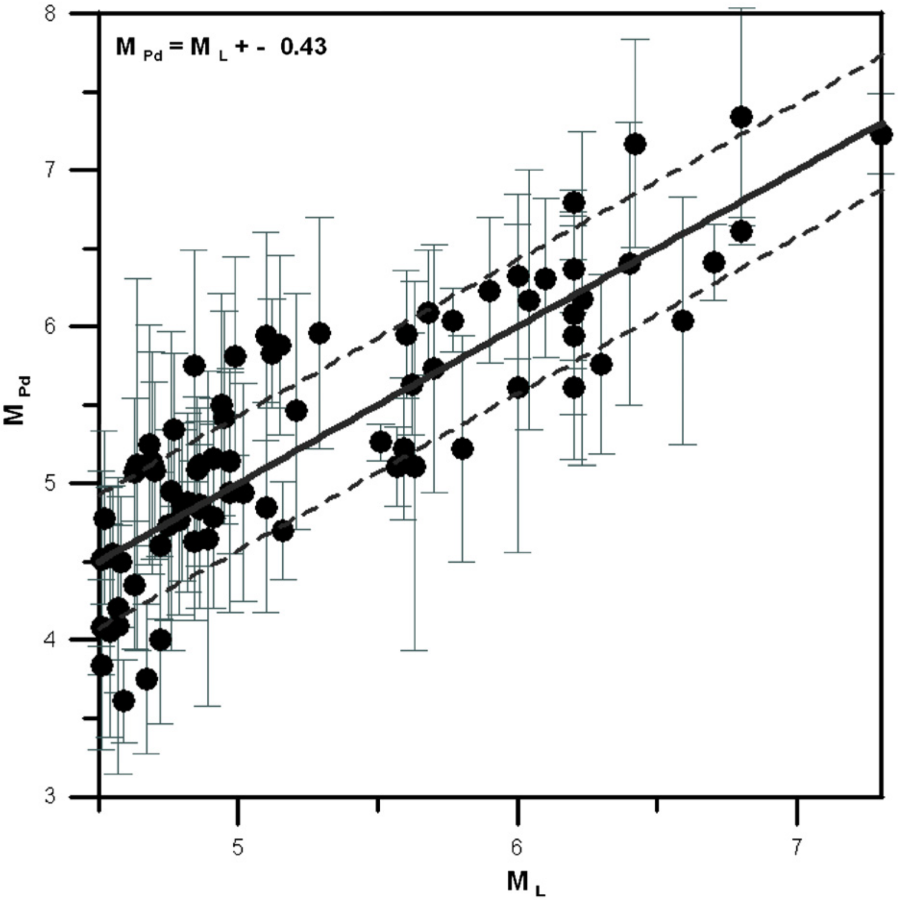

Fig. 3. Regression of catalog magnitudes M_L with the average of magnitudes M_{pd} estimated by P_d in this study. Solid line shows the least-squares fit and the two dashed lines show the range of one standard deviation. M_{pd} has a 1:1 relationship with M_L with a standard deviation of 0.43.

types of seismic instruments installed at the stations, either co-site or separately installed, including short-period seismographs, accelerometers, and broadband instruments. Strong-motion and broadband signals are used for automatic P-wave arrival time and P_d determinatiosn in the EEW system. However, short-period signals are only used for P-wave arrival time picking in the process.

Fig. 5 shows the configuration of EEW system being developed. Real-time seismic signals are packaged and transmitted to the headquarters via various IP-based networks, such as Frame-Relay, ADSL, GPRS or satellite telemetry. Different telemetered networks can be arranged as a secure environment for seismic data transmission. A cluster of computers running Earthworm system is installed at the central station in Taipei. The Earthworm system, distributed by the United States Geological Survey (USGS), is developed as a multi-functional seismic data processing system. The system mainly consists of modules and shared memories. Modules are a series of programs designed for different purposes, whereas shared memories are the physical memory spaces in computers, which are used for data access and result storage. In our EEW system we use the Earthworm as a common platform to integrate all real-time signals, coming from different types of seismographs with different formats, into shared memories for EEW operations.

The flowchart of the Earthworm-based EEW system is shown in Fig. 6. Based on the framework of the system designed, there are a total of three main parts involved, including data acquisition, clustering and processing. For the data acquisition, using the import modules provided by manufacturers of each seismic instrument, the data packets can be transmitted from field stations continuously and feed into the Earthworm system in near real time (about 3 s in our system). In the Earthworm environment, large quantities of memory blocks called "Wave Rings" are created for storing and clustering the seismic signals. Then, these clustered signals will be extracted for further data processing in EEW. The main purpose of the Earthworm system is for real-time signal integration.

Under the Earthworm environment, we developed two C codes for EEW purpose. The first program, Sniffwave4eew.c, was modified from the original module (Sniffwave.c) in the Earthworm system. When Sniffwave4eew.c is executed, it extracts waveform signals from the Wave Rings of the Earthworm system for the real-time P-wave arrival picking. Once a P-wave arrival is obtained, P_d and the characteristic period parameter τ_c [21,26] will be calculated from the three-second long waveform after the P-wave arrival. Then, P-wave arrival times, P_d and τ_c will be written into a share memory for earthquake location and magnitude determination. In the design, each seismographic record of a certain station will correspond to a unique execution of Sniffwave4eew.c, and only the vertical components of waveforms are analyzed.

Another code TcPd.c is an accompanying program to manage the shared memory. When the number of triggered stations reaches a specific threshold (considering both temporal and spatial clustering triggers), P-wave arrivals from triggered stations will be used for earthquake location and P_d for magnitude

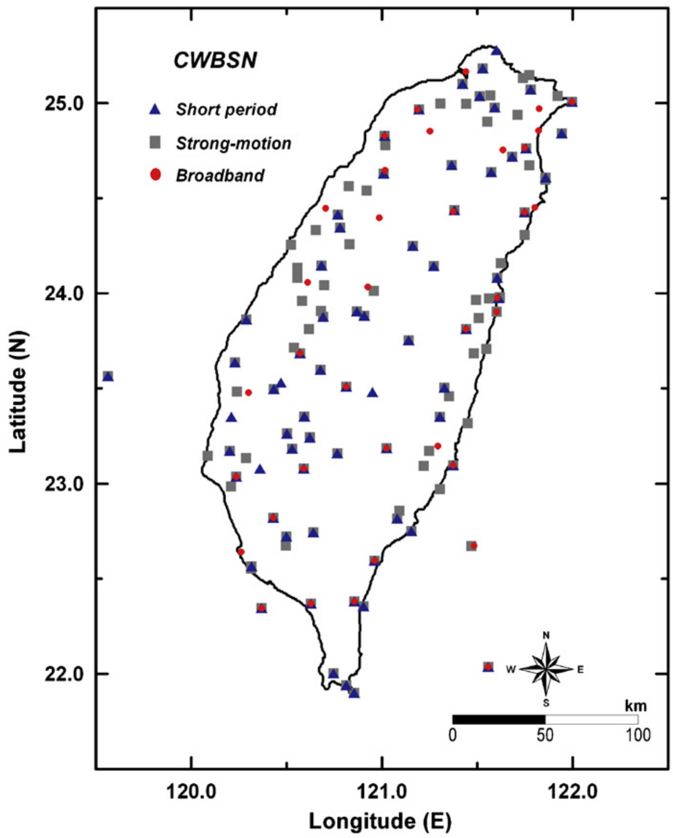

Fig. 4. Locations of seismic stations of the Central Weather Bureau Seismographic Network (CWBSN). The kinds of seismographs include short-period, strong-motion, and broadband instruments.

determination. For large event ($M > 6.5$), τ_c will be considered in magnitude determination.

4. Simulation test

In order to test the capability of the newly developed EEW system, broadband and strong-motion waveforms from 54 felt earthquakes are selected for a simulation test. The criteria for earthquake selection are as follows:

(1) $M_L > 5.0$,
(2) focal depth < 40.0 km and
(3) occurred inland or within 50 km from the shoreline of Taiwan.

Based on the flowchart shown in Fig. 6, the waveform records of each event are uploaded into the Wave Rings of the Earthworm system in the simulation test. Once a station is triggered and P-wave arrival obtained, P_d and τ_c will be estimated and written into the share memory for event association. In order to avoid false triggering, both spatial and temporal clusters are considered. The triggering of a station is accepted only when there is at least another station being triggered within 60 km in distance and 8 s in time. Based on this consideration, a lot of falsely triggered stations can be removed from the shared memory. As the number of triggered stations in the shared memory reaches five, the system will declare the occurrence of an event and proceed to locate the earthquake and estimate the average M_{pd}, as well as create an EEW report.

With additional stations being triggered, the evaluation process is repeated and the earthquake information updated. In comparison with previous information, the EEW report will be updated when the hypocenter location is changed by more than 10 km or the magnitude is changed by than 0.5 units. When the results in three consecutive reports are stable, the process will stop and the latest update will be taken as the final EEW report.

Fig. 7 shows the results of the simulation test. To inspect the accuracy of the earthquake information (locations and magnitudes) obtained automatically by the new system, they were listed together with the information in the earthquake catalog published by the CWB, in which the earthquake locations and magnitudes (M_L) are determined by manual readings of the P and S arrivals [29,30]. For most of the events the EEW locations agree with the catalogue ones, except for some offshore earthquakes with poor station coverage. The average difference in epicentral locations is 6.3 ± 5.7 km, and the average difference in focal depths is 7.9 ± 6.6 km. Fig. 7b shows the magnitude M_{pd} determined from the average of P_d versus the catalogue magnitude M_L. The magnitude approaches a 1:1 relationship with M_L with a standard deviation of 0.51.

Based on the results of the simulation test, the earthquake reporting time (Fig. 7c), which is a crucial factor of the EEW system, can be shortened to 18.8 ± 4.1 s on average. Therefore, this EEW system can provide warning in advance of the S-wave arrival for metropolitan areas located 70 km away from the epicenter.

5. Discussion and conclusion

Previous studies have pointed out that P_d magnitude may have saturation problem for large events [24,31]. However, our result indicates that the P_d magnitudes agree with the catalog ones even for large earthquakes. In our current study, by using the strong-motion records for large events, many near-source records were involved in the analysis. Effects of near-field terms pointed out by Yamada and Mori [32] may lead to large P_d as well as overestimation of the magnitude. We suggest that the near-field terms may play a role but the P_d magnitude does not saturate in this study.

The new EEW system is still under development. In comparison with the current VSN system, the performance of the new system is still not as stable as the VSN system. Currently, VSN system is the operational system of CWB. When the new system performs as well as the VSN system, it will become one of the operational systems together with the VSN. Currently, the new system is capable of offering earthquake warning information in less than 10 s after the occurrence of events inland. Therefore, we believe that the new system will become the major EEW system in the future.

The CWBSN is a real-time seismographic network. It has been in operation for more than ten years and has been under constant improvement. To further enhance the capability of earthquake monitoring, the CWB has decided to carry out a major expansion of the seismographic network. The new stations include borehole seismic stations and cable-based ocean bottom seismographic instruments off northeastern Taiwan. With the installation of new stations, high-quality seismic data will be integrated for seismological observation and research through the Earthworm system. We will further upgrade the EEW system in response to these new instruments, as well as to any new research results.

In order to translate the results from the EEW system into real action for seismic hazards mitigation, a promotional plan has been undertaken in Taiwan with the collaboration of government agencies, research institutions and private sectors. Under the plan, the EEW messages will be issued to transportation agencies, emergency management departments and elementary schools on

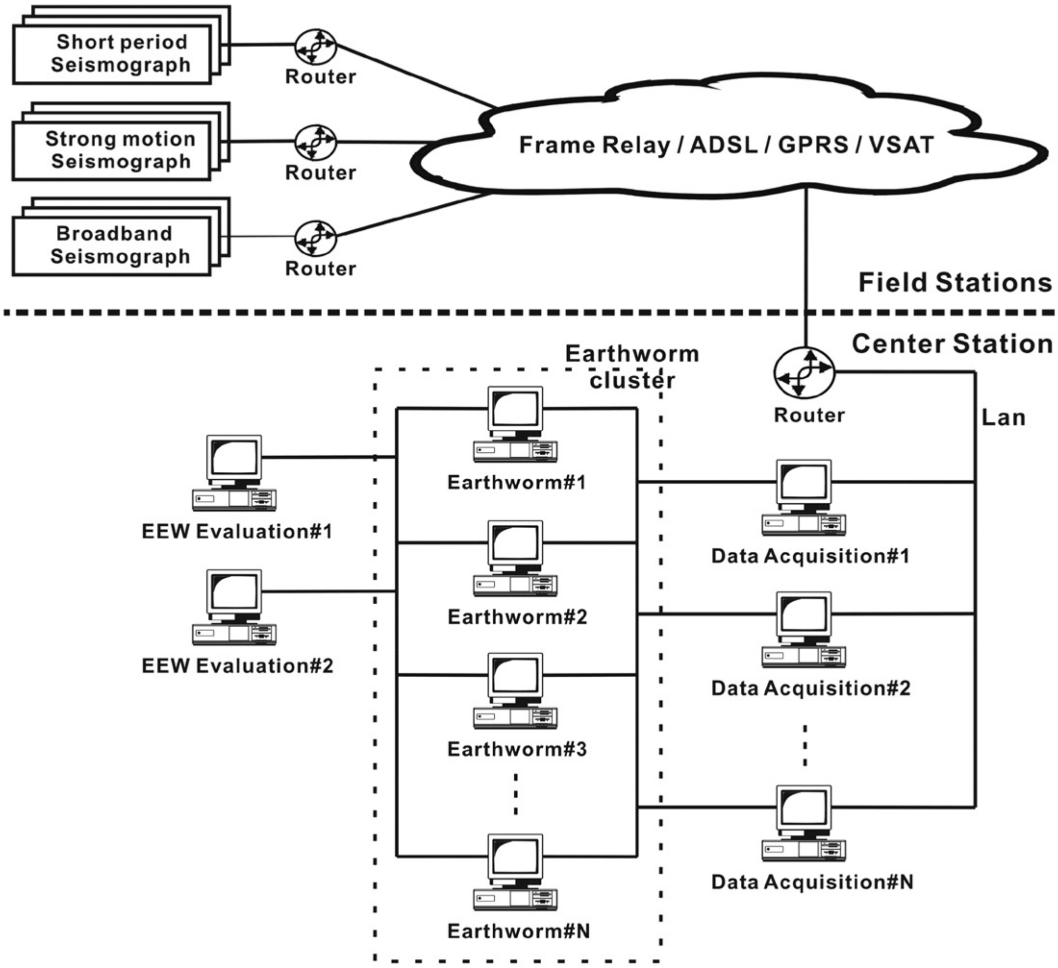

Fig. 5. Schematic diagram of the new prototype system for earthquake early warning in Taiwan.

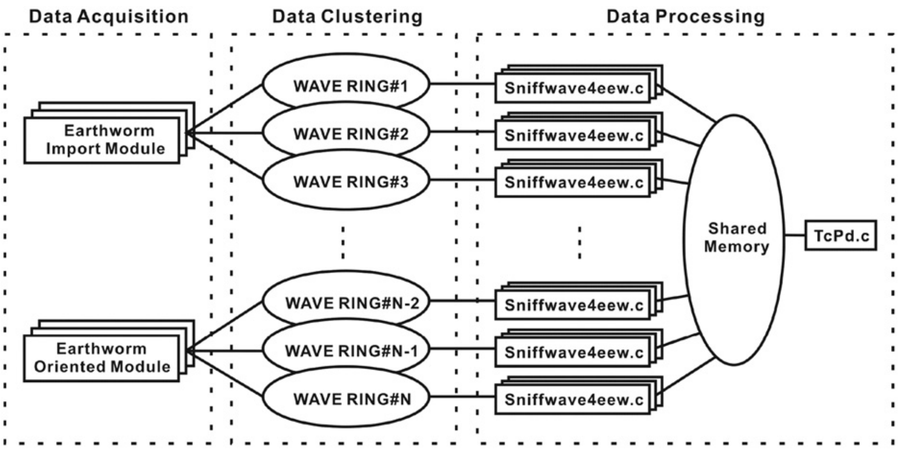

Fig. 6. Flowchart of the algorithm designed for EEW system in this study. Three major data operations include data acquisition, clustering and processing.

an experimental basis at the first stage. Once the prototype performance is verified through real earthquakes, the system will be expanded to private organizations and the general public.

In addition, EEW for engineering applications has also been under development in Taiwan. To effectively incorporate EEW messages into the structural control of buildings, a longer response time is necessary to activate the seismic response mechanism against strong shaking. By analyzing the strong-motion data recorded in a damaged building during the April 1st, 2006, M_L=6.2 Taitung earthquake, Shieh et al. [33] found that P_d can be considered as a good indicator for the building damage. However, more seismological information such as focal mechanism, dominant frequency, and ground motion time series are also relevant to the structural control response of buildings [26]. Hence further efforts are needed to achieve effective engineering applications of the EEW system.

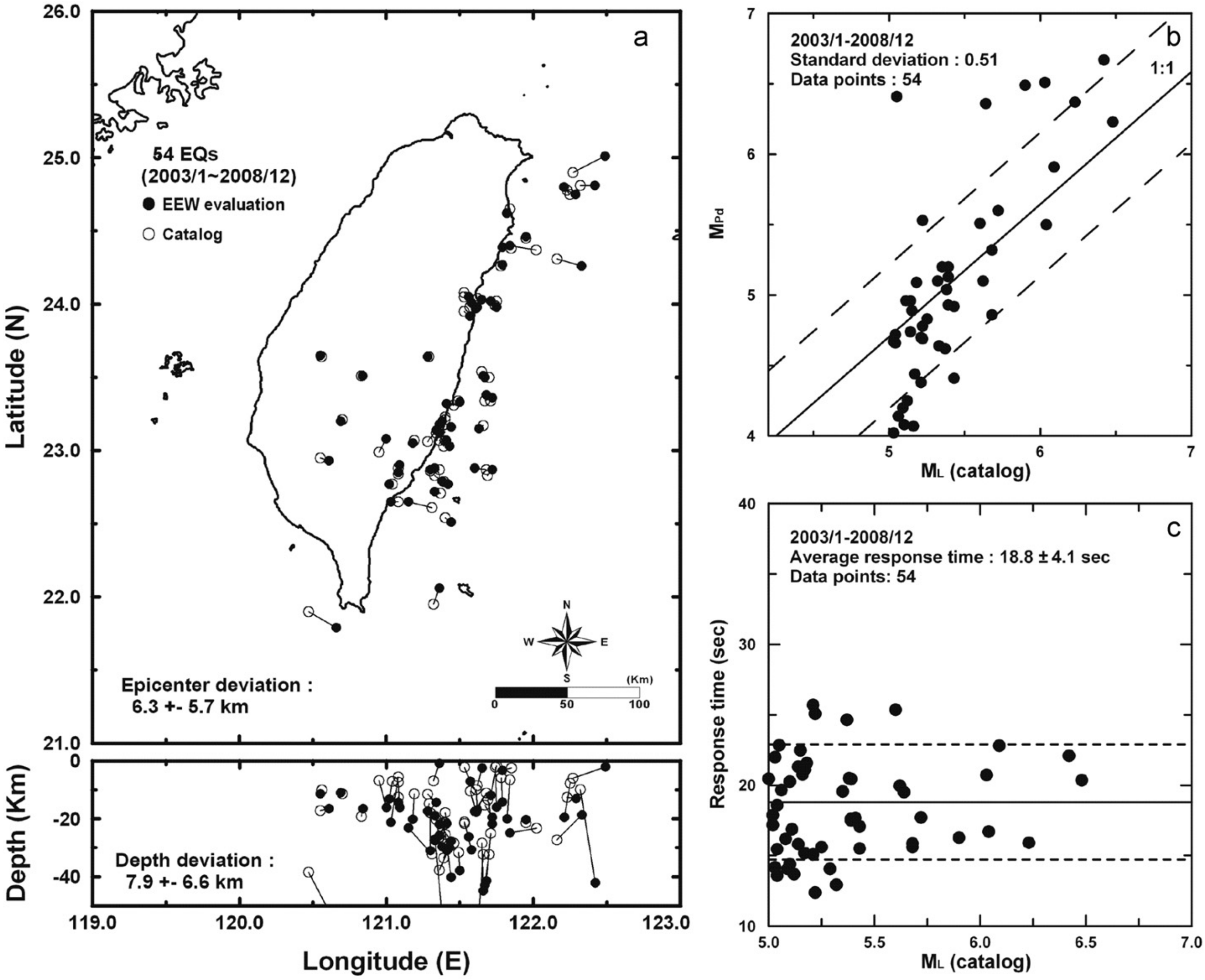

Fig. 7. Results of the EEW simulation test. (a) Map showing the comparison of earthquake locations determined by EEW system with catalogue locations. (b) Statistical plot showing the comparison of M_{pd} with catalogue M_L. (c) Statistical plot showing the earthquake response times.

Acknowledgements

This research was supported by the National Science Council and the Central Weather Bureau of the Republic of China.

References

[1] Kanamori H, Hauksson E, Heaton T. Real-time seismology and earthquake hazard mitigation. Nature 1997;390:461–4.

[2] Nakamura Y. On the urgent earthquake detection and alarm system (UrEDAS). Proceedings of the ninth world conference on earthquake engineering 1988;7:673–8.

[3] Espinosa-Aranda JM, Jiménez A, Ibarrola G, Alcantar F, Aguilar A, Inostroza M, et al. Mexico City seismic alert system. Seism Res Lett 1995;66:42–53.

[4] Wu YM, Chung JK, Shin TC, Hsiao NC, Tsai YB, Lee WHK, et al. Development of an integrated seismic early warning system in Taiwan. Terr Atmos Ocean Sci 1999;10:719–36.

[5] Wu YM, Teng TL. A VSN approach to earthquake early warning. Bull Seism Soc Am 2002;92:2008–18.

[6] Allen RM, Kanamori H. The potential for earthquake early warning in southern California. Science 2003;300:786–9.

[7] Erdik M, Fahjan Y, Ozel O, Alcik H, Mert A, Gul M. Istanbul earthquake rapid response and the early warning system. Bull Earthquake Eng 2003;1: 157–163.

[8] Kamigaichi O. JMA earthquake early warning. J Jpn Assoc Earthquake Eng (special issue) 2004;4:134–7.

[9] Horiuchi S, Negishi H, Abe K, Kamimura A, Fujinawa Y. An automatic processing system for broadcasting earthquake alarms. Bull Seism Soc Am 2005;95:708–18.

[10] Zollo A, Lancieri M, Nielsen S. Earthquake magnitude estimation from peak amplitudes of very early seismic signals on strong motion records. Geophys Res Lett 2006;33:L23312, doi:10.1029/2006GL027795.

[11] Ionescu C, Bose M, Wenzel F, Marmureanu A, Grigore A, Marmureanu G. Early warning system for deep Vrancea (Romania) earthquakes. In: Gasparini P, Manfredi G, Zschau J, editors. Earthquake Early Warning Systems. Berlin: Springer-Verlag; 2007. p. 343–9.

[12] Olivieri M, Allen RM, Wurman G. The potential for earthquake early warning in Italy using ElarmS. Bull Seism Soc Am 2008;98:495–503, doi:10.1785/0120070054.

[13] Hsiao NC, Wu YM, Shin TC, Zhao L, Teng TL. Development of earthquake early warning system in Taiwan. Geophys Res Lett 2009;36:L00B02, doi:10.1029/2008GL036596.

[14] Wu YM, Chen CC, Shin TC, Tsai YB, Lee WHK, Teng TL. Taiwan rapid earthquake information release system. Seism Res Lett 1997;68:931–43.

[15] Teng TL, Wu YM, Shin TC, Tsai YB, Lee WHK. One minute after: strong-motion map, effective epicenter, and effective magnitude. Bull Seism Soc Am 1997;87:1209–19.

[16] Wu YM, Teng TL. Near real-time magnitude determination for large crustal earthquakes. Tectonophysics 2004;390:205–16.

[17] Wu YM, Shin TC, Chang CH. Near realtime mapping of peak ground acceleration and peak ground velocity following a strong earthquake. Bull Seism Soc Am 2001;91:1218–28.

[18] Wu YM, Hsiao NC, Teng TL, Shin TC. Near real-time seismic damage assessment of the rapid reporting system. Terr Atmos Ocean Sci 2002;13: 313–324.
[19] Wu YM, Hsiao NC, Teng TL. Relationships between strong ground motion peak values and seismic loss during the 1999 Chi-Chi, Taiwan earthquake. Nat Hazards 2004;32:357–73.
[20] Wu YM, Shin TC, Tsai YB. Quick and reliable determination of magnitude for seismic early warning. Bull Seism Soc Am 1998;88:1254–9.
[21] Wu YM, Kanamori H. Experiment on an onsite early warning method for the Taiwan early warning system. Bull Seism Soc Am 2005;95:347–53.
[22] Wu YM, Kanamori H. Development of an earthquake early warning system using real-time strong motion signals. Sensors 2008;8:1–9.
[23] Wu YM, Kanamori H. Exploring the feasibility of on-site earthquake early warning using close-in records of the 2007 Noto Hanto earthquake. Earth Planets Space 2008;60:155–60.
[24] Wu YM, Zhao L. Magnitude estimation using the first three seconds P-wave amplitude in earthquake early warning. Geophys Res Lett 2006;33:L16312, doi:10.1029/2006GL026871.
[25] Johnson CE, Bittenbinder A, Bogaert B, Dietz L, Kohler W. EW: a flexible approach to seismic network processing. IRIS Newslett 1995;14(2): 1–4.
[26] Kanamori H. Real-time seismology and earthquake damage mitigation. Annu Rev Earth Planet Sci 2005;33:5.1–20.
[27] Wu YM, Kanamori H. Rapid assessment of damaging potential of earthquakes in Taiwan from the beginning of P waves. Bull Seism Soc Am 2005;95: 1181–5.
[28] Wu YM, Kanamori H, Allen R, Hauksson E. Determination of earthquake early warning parameters, τ_c and P_d, for southern California. Geophys J Int 2007;170:711–7.
[29] Shin TC. The calculation of local magnitude from the simulated Wood-Anderson seismograms of the short-period seismograms. Terr Atmos Ocean Sci 1993;4:155–70.
[30] Wu YM, Allen RM, Wu CF. Revised M_L determination for crustal earthquakes in Taiwan. Bull Seism Soc Am 2005;95:2517–24.
[31] Wu YM, Yen HY, Zhao L, Huang BS, Liang WT. Magnitude determination using initial P waves: a single-station approach. Geophys Res Lett 2006;33: L05306.
[32] Yamada M, Mori J. Using Tau_c to estimate magnitude for earthquake early warning and effects of near-field terms. J Geophysical Res 2009;114:B05301.
[33] Shieh JT, Wu YM, Zhao L, Chao WA, Wu CF. An examination of τ_c-Pd earthquake early warning method using a strong-motion building array, Soil Dyn Earthquake Eng, online published, 2010, doi:10.1016/j.soildyn.2009.12.015.