A new prototype system for earthquake early warning in Taiwan

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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 $18.8 \pm 4.1 \text{s}$ after the earthquake occurrence with an average difference in epicenter locations of $6.3 \pm 5.7 \text{km}$, and an average difference in depths of $7.9 \pm 6.6 \text{km}$ 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 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].

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 [15], 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.
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 require-
ment 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 $M_{10}$, 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 determina-
tion 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] integrat-
ing 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, 12–27]. 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

![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.](image-url)
magnitude $M_L$ and the logarithmic hypocentral distance $R$:

$$\log P_d = A + B \times M_L + C \times \log R,$$

(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

$$\log P_d = -1.777 + 0.455 \times M - 1.230 \times \log R,$$

(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 $P_d$:

$$M_{pd} = 3.905 + 2.198 \times \log P_d + 2.703 \times \log R.$$

(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
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 Pd determinations 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, Pd and the characteristic period parameter \( t_c \) [21,26] will be calculated from the three-second long waveform after the P-wave arrival. Then, P-wave arrival times, Pd and \( t_c \) 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 Pd for magnitude

![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.](image-url)
earthquake and estimate the average
will declare the occurrence of an event and proceed to locate the
number of
location, and broadband instruments.

determination. For large event \( M > 6.5 \), \( \tau_c \) 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. \( M_c > 5.0 \)
2. focal depth \(< 40.0 \text{ km} \) 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 WaveRings of the Earthworm system in the simulation test. Once a station is triggered and P-wave arrival obtained, \( P_d \) and \( \tau_c \) 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 \( M_{\text{hyp}} \) 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 \( M_{\text{Pd}} \) 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 seismo-logical 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
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_s=6.2 Taitung earthquake, Shieh et al. [33] found that Pd 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.
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References


