Paper:

Earthquake Early Warning Technology Progress in Taiwan

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The dense real-time earthquake monitoring network established in Taiwan is a strong base for the development of the earthquake early warning (EEW) system. In remarkable progress over the last decades, real-time earthquake warning messages are sent within 20 sec after an event using the regional EEW system with a virtual subnetwork approach. An onsite EEW approach using the first 3 sec of P waves has been developed and under online experimentation. Integrating regional and onsite systems may enable EEW messages to be issued within 10 sec after an event occurred in the near future. This study mainly discusses the methodology for determining the magnitude and ground motion of an event.

Keywords: earthquake, early warning, P wave, ground motion

1. Introduction

Geologically, Taiwan is located on the western circum-Pacific seismic belt which is one of the most active seismic regions in the world. In the last century, nearly a dozen destructive earthquakes have occurred in Taiwan, including the Meishan earthquake in 1906 ($M_L = 7.1$, 1,258 death), the Hisnchu-Taichung earthquake in 1935 ($M_L = 7.1$, 3,276 death), and the Chi-Chi earthquake in 1999 ($M_L = 7.3$, 2,455 death). Since the occurrence of earthquakes can not reliably predicted by current technology, progress is being made globally in the research and development of the earthquake early warning (EEW) system [1–5]. With advances in seismic instrumentation and communication networks, EEW is becoming a practical tool for reducing casualties and damage from major earthquakes [6–9]. Two major approaches are being applied in the EEW development:

1. Regional warning, or front detection, uses real-time earthquake monitoring networks to determine the earthquake location, magnitude, and ground-motion distribution and to send EEW messages to regions far from the epicenter.
2. Onsite warning uses onsite seismometers to detect P waves and estimate the earthquake magnitude and the strong onsite motion [10].

Regional warning provides more reliable EEW messages but requires longer processing time. Onsite warning complements regional warning to speed up EEW processing and to reduce blind zones where no onsite warnings are received. Both approaches have progressed markedly in Taiwan [11], but the EEW system is still undergoing online testing and has not been applied for disaster reduction practically.

2. Real-Time Strong-Motion Network in Taiwan

In the dense earthquake monitoring network of 688 free-field strong-motion stations constructed in the Taiwan Strong-Motion Instrumentation Program (TSMIP), currently 109 are telemetered for real-time monitoring as shown in **Fig. 1**.

A three-component force-balanced accelerometer with a 16-bit resolution and a full dynamic range of $\pm 2g$ was installed for each station. The real-time data are transmitted to Taipei headquarter via dedicated telephone lines in 50 Hz. This network serves as a base for developing the earthquake Rapid-Reporting System (RRS) and the EEW system [12–15]. The RRS, developed and operated by the Central Weather Bureau (CWB) since 1995, provides such useful information as earthquake location, magnitude, and ground-motion distribution one minute after an earthquake occurs. EEW provides warnings to distant urban areas from the epicenter with a few seconds to several dozen seconds of lead time before destructive S waves arrive. With a short lead time, automatic emergency measures should be preprogrammed and implemented to reduce the potential loss due to strong shaking.

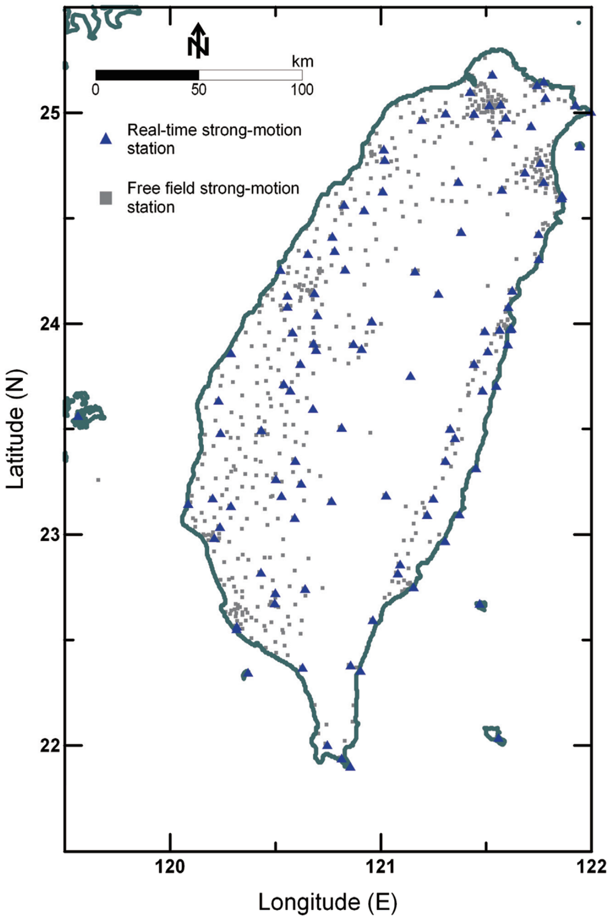

Fig. 1. Distribution of free-field strong-motion stations and real-time stations.

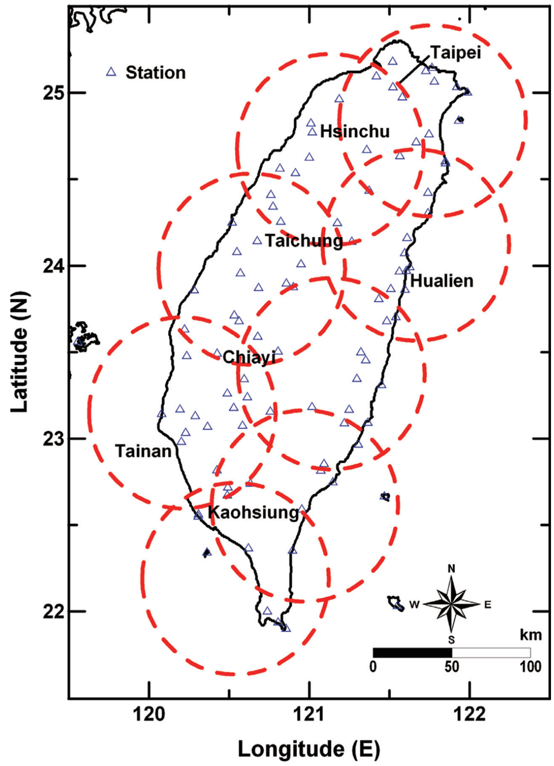

Fig. 2. Virtual subnetwork of 109 real-time stations.

3. Virtual Subnetwork Approach

3.1. Methodology

The Hualien offshore earthquake in November 15, 1986, magnitude (M_w) 7.8, with an epicenter 120 km from metropolitan Taipei, caused severe damage due to basin amplification and serves as a lesson in developing the regional EEW approach to reduce disaster effects. Obtaining the EEW information within 20 sec after an event occurred could ensure a lead time of 20 sec for Taipei before strong shaking starts. With this in mind, the Virtual Subnetwork (VSN) approach based on the regional approach has been developed and applied in the practical EEW operation since 2001 [2], as shown in **Fig. 2**.

Once the real-time monitoring network is triggered, the VSN data stream will be recorded for 10 sec after the first P-wave arrives. An average local magnitude (M_{L10}) is determined from the 10-second waveform among VSN stations. M_{L10} determination follows the conventional calculation of the local magnitude (M_L) using the peak simulated Wood-Anderson amplitude among vertical and horizontal components. However, earthquake magnitude (M_L) cannot be determined in this time frame because of the incomplete shear waveform recorded at some stations. A correlation relation was used to obtain M_L from M_{L10} [16]:

$$M_L = 1.28 \times M_{L10} - 0.85 \pm 0.13 \quad (1)$$

3.2. Online Experiments

The on-line experiments for EEW capabilities of the VSN have been proceeding since 2001. To verify its performance, we select earthquakes detected by the VSN until 2008 using the following criteria:

(1) $M_L > 4.5$

(2) Focal depth < 35 km

(3) Earthquakes occurring inland or within 50 km of the island

The 255 earthquakes detected achieved a 90% trigger rate, for which we compared automatic and manual processing results. The performances of automatic locations are shown in **Fig. 3**. Latitudinally, 60% of earthquakes were located within 2 km and 80% within 4 km; longitudinally, 50% located within 2 km and 70% within 4 km, and for depth difference, 60% were located within 4 km.

The magnitude determined automatically by the VSN and manually by CWB earthquake catalogs are compared in **Fig. 4**, showing considerable consistency for earthquakes up to $M_L = 6.5$ with a standard deviation of 0.28. For larger offshore earthquakes, however, magnitude was underestimated by the VSN due to the limited waveforms used. The March 31, 2002, Hualien offshore earthquake, shown in **Fig. 4**, is a typical case. As shown in **Fig. 5**, the average reporting time for the entire network by the RRS is within 50 sec in these two years. Using fewer stations with the VSN effectively shortens the average reporting time to within 20 sec. The VSN performance for determining hypocenter location is stable and acceptable for early warning targeting disaster reduction.

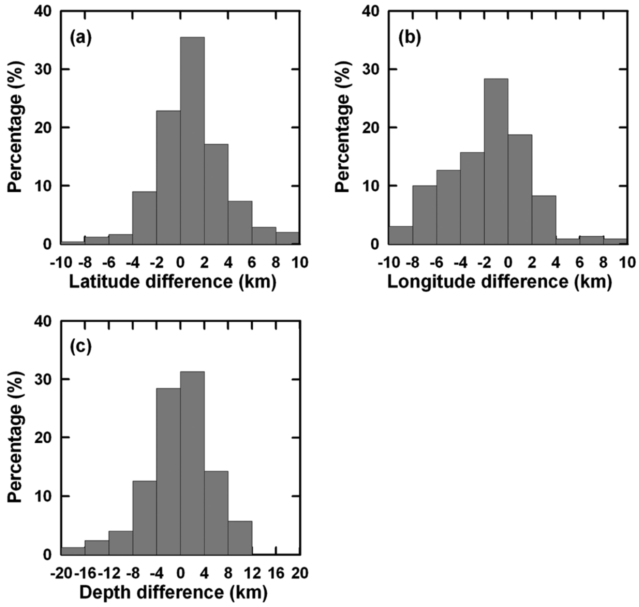

Fig. 3. Automatic versus manual processing of hypocenter location.

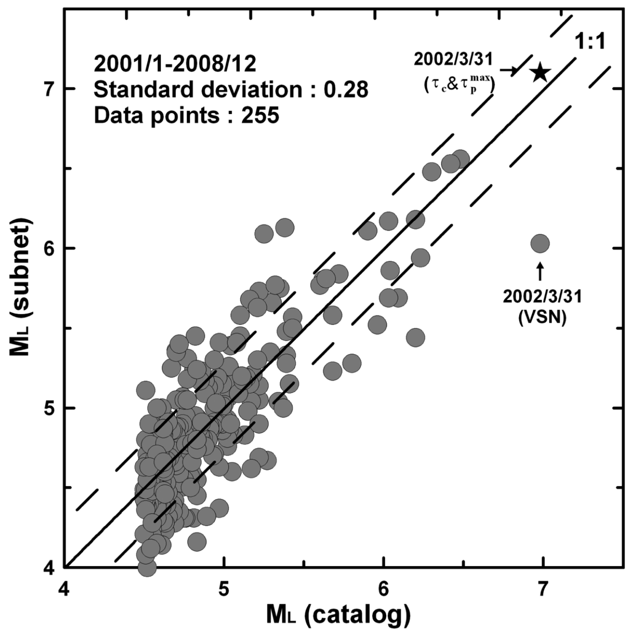

Fig. 4. Magnitude determined automatically by the VSN versus manually by earthquake catalogs, modified after [15].

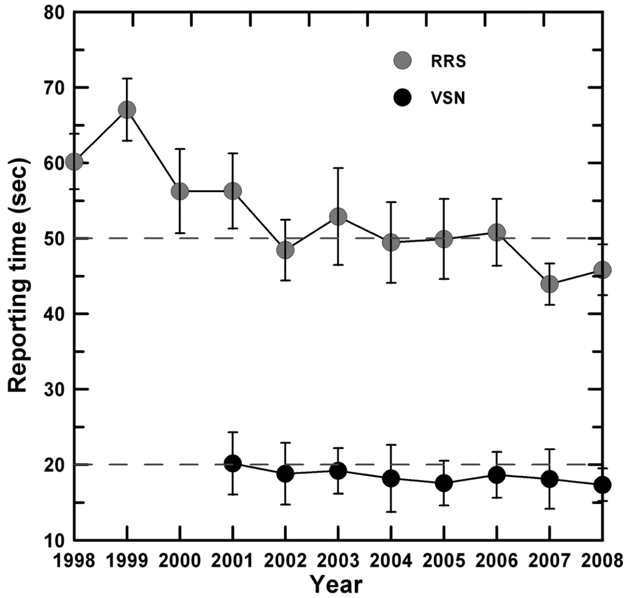

Fig. 5. Averaged reporting time by the VSN and the RRS, modified after [15].

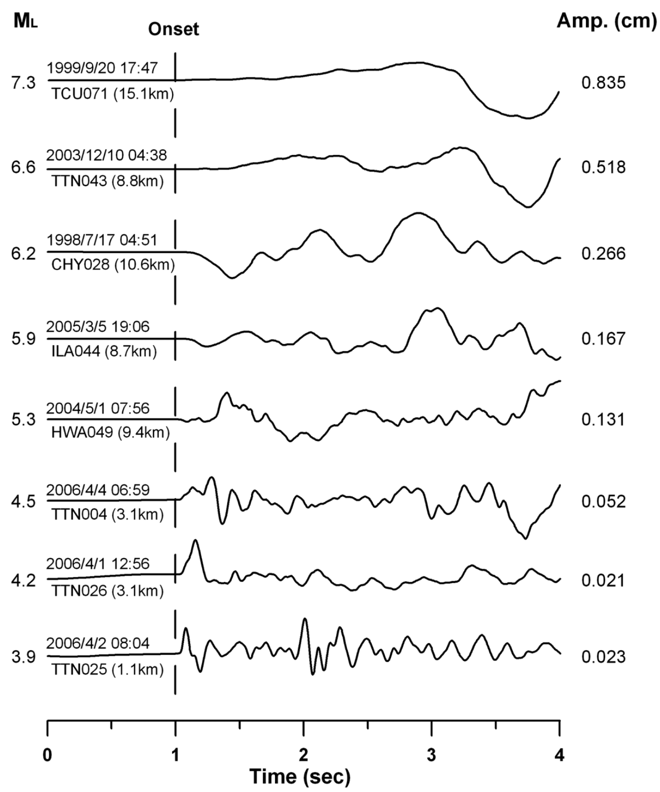

Fig. 6. Measured vertical displacement waveforms.

4. P-Wave Method

Onsite warning using P waves could shorten earthquake reporting time, since the P wave is the first arrival signal with a near source effect usable for estimating earthquake magnitude quickly [1, 3, 10, 17, 18]. As shown in **Fig. 6**, the vertical displacement amplitude is larger and the period is longer for larger earthquakes. Seismic waves with long-period energy were induced by large slip along the fault plane in larger earthquakes. Seismic waves with short-period energy and smaller amplitude were generated by smaller earthquakes, so P wave period and amplitude in vertical displacement waveforms could be used to estimate the earthquake magnitude quickly.

4.1. Methodology

Using regression of real-time strong-motion records from CWB stations, the relationship between earthquake magnitude and several parameters was obtained from the few seconds of P waves, including peak displacement amplitude (P_d), average period (τ_c), and dominant period ($\tau_p^{\max}$). Parameter τ_c is the average period within a specific time frame [18], which increased with increasing

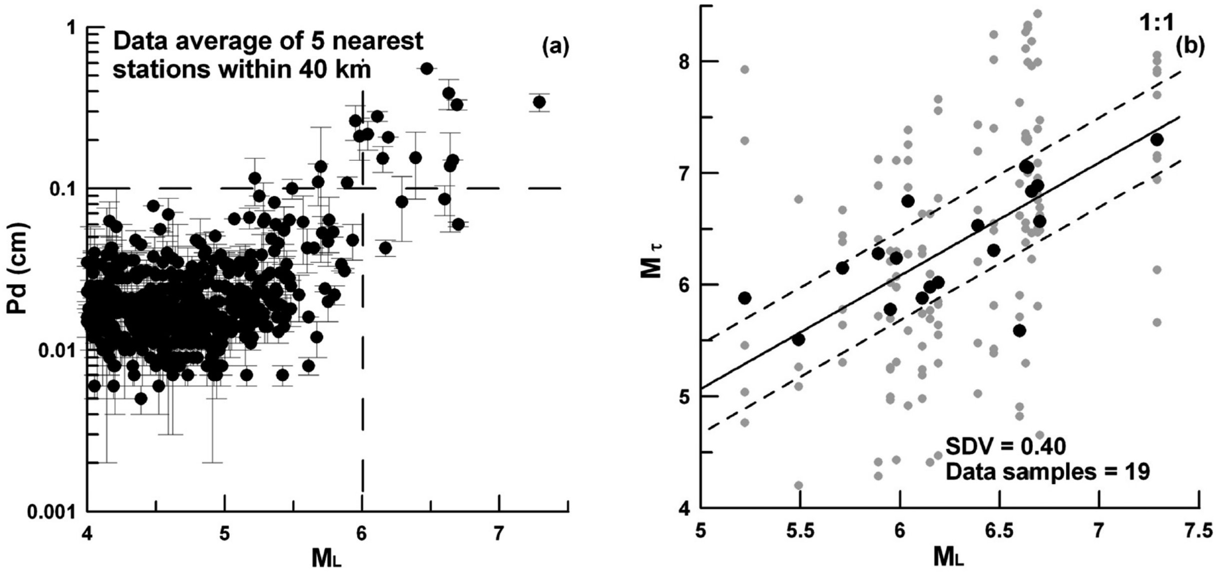

Fig. 7. Catalog magnitude M_L regression with (a) $\log P_d$; (b) M_τ estimated by averaging τ_c and $\tau_p^{\max}$ obtained at stations (indicated as gray dots), modified after [15].

earthquake magnitude, defined as follows:

$$\tau_c = \frac{2\pi}{\sqrt{r}} \quad (2)$$

with

$$r = \frac{\int_0^{\tau_0} \dot{u}^2(t)dt}{\int_0^{\tau_0} u^2(t)dt} \quad (3)$$

where $u(t)$ is the high-pass filtered displacement of vertical ground motion, $\dot{u}(t)$ is the velocity differentiated from $u(t)$, and τ_0 is the length of the specified time frame, for example, τ_0 is 3 sec in this study.

Parameter $\tau_p^{\max}$ is the maximum predominant period determined continually in real time from the vertical component of velocity and defined with a recursive relation [3] within the time frame, as follows:

$$(\tau_p)_i = 2\pi\sqrt{\frac{X_i}{D_i}} \quad (4)$$

where

$$X_i = \alpha X_{i-1} + x_i^2 \quad (5)$$

$$D_i = \alpha D_{i-1} + \left(dx/dt\right)_i^2 \quad (6)$$

where $(\tau_p)_i$ is the predominant period at time i, x_i is the recorded ground velocity, X_i is the smoothed ground velocity squared, D_i is the smoothed velocity derivative squared, and α is a smoothing constant.

Calculating $\tau_p^{\max}$ and τ_c requires that a specific time frame be specified. For practical EEW operation, we used a time frame of 3 sec. A high-pass recursive Butterworth filter with a cutoff frequency of 0.075 Hz was used to remove low-frequency drift. Since most real-time stations are located in urban areas with a low signal-to-noise ratio, only records with P_d exceeding 0.08 cm were used to evaluate τ_c and $\tau_p^{\max}$.

Earthquakes occurring on Taiwan Island and in shallow offshore areas were used for regression to obtain the relationship between magnitude and the parameters. The criteria were (1) magnitude exceeding 4.0, (2) depth less than 35 km, and (3) epicenters within Taiwan Island or within 20 km offshore. A total of over 12,000 records of 596 earthquakes were used for regression, among which 28 earthquakes had magnitudes exceeding 6.0.

Currently, the average elapsed time for triggering the real-time earthquake monitoring network with a threshold of five stations is 4 to 6 sec following event occurrence [15]. Integrated by the P wave with 3 sec of the time frame in the VSN, EEW messages are expected to be disseminated within 10 sec in the near future.

4.2. Magnitude Determination

From among the 596 earthquakes selected for analysis, relationships were obtained by linear regression using measurements from the five nearest stations within 40 km from epicenters, as shown in **Fig. 7**. The solid line indicates the least squares fit and the two dashed lines show the range of one standard deviation. For P_d exceeding 0.1 cm, most earthquake magnitudes exceed 6.0, as shown in **Fig. 7 (a)**. The value of $\log P_d$ increases roughly linearly with M_L when the earthquake magnitude exceeds 5.5, meaning that P_d can be used as a threshold to judge whether an earthquake with a magnitude exceeding 6.0 is going to occur in Taiwan.

Nineteen events of $M_L \geq 5.0$ and $P_d > 0.08$ cm in all records were used in this analysis. As in previous studies [10, 18–22], $\log \tau_c$ increased roughly linearly with M_L. Linear regression for the relationship between $\log \tau_c$ and M_L is obtained as follows with a standard deviation of 0.25:

$$\log \tau_c = 0.47 \times M_L - 2.37 \quad (7)$$

The relationship between $\log \tau_p^{\max}$ and M_L is obtained as follows with a standard deviation of 0.23 using the

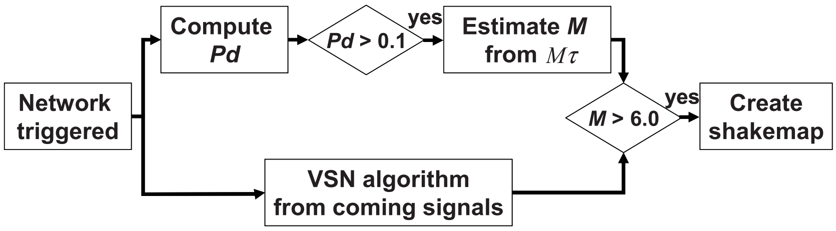

Fig. 8. EEW algorithm flowchart in Taiwan [15].

same dataset:

$$\log \tau_p^{\max} = 0.24 \times M_L - 1.51 \quad (8)$$

Based on a previous study [23], τ_c and $\tau_p^{\max}$ are combined for determining the magnitude using the mean value obtained. Estimated magnitude M_τ has a 1:1 relationship to catalog magnitude M_L with a standard deviation of 0.40, as shown in **Fig. 7 (b)**.

4.3. Ground Motion Estimation

Ground motion measured at sites was classified into main categories such as excitation, attenuation, and site terms [24]. Based on the strong motion recorded, attenuation formulas have been proposed to estimate ground motion [14, 25–27]. Hsiao [14] used an empirical formula to estimate peak ground acceleration (PGA) expressed as follows:

$$PGA = 1.657 \times e^{1.533 \times M_L} \times r^{-1.607} \quad (9)$$

where PGA is measured in gal (cm/s^2) and r is the hypocenter distance measured in kilometers. Jean [27] used TSMIP records from 59 earthquake events to obtain the following attenuation formula:

$$Y_{att} = 0.00369\, e^{1.75377m} [R + 0.1222\, e^{0.78315m}]^{-2.05644} \quad (10)$$

where Y_{att} is predicted PGA measured in G, m is local magnitude M_L, and R is the closest distance to the source measured in kilometers. Wen et al. [28] used 4,790 seismic records from 307 earthquake events recorded and based on the empirical estimation value from Eq. (10) as reference for site correction. Site correction for individual TSMIP and the Central Mountain Array stations is simplified as follows:

$$\ln(PGA_{obs})_S = C_0 + C_1 \times \ln(Y_{att})_S \quad (11)$$

where $(PGA_{obs})_S$ is observed PGA, $(Y_{att})_S$ is predicted PGA obtained from the attenuation formula in Eq. (10), and C_0 and C_1 are the site-dependent parameters for correcting site effects. Selection criteria for earthquakes are M_L exceeding 4.0 and focal depth less than 50 km.

Once the earthquake location and magnitude were obtained, a shake map could be generated by using Eq. (9). The intensity scale used in Taiwan is classified according to peak ground accelerations which is the same as that used for the Japanese intensity scale. We plan to take into consideration more attenuation formulas proposed by other researchers to produce shake maps in the future.

5. EEW Algorithm Used in Taiwan

5.1. EEW Algorithm

The operation of current EEW systems in Taiwan is shown in the flowchart shown in **Fig. 8**. The VSN and the P-wave method are operated in parallel. When an earthquake occurs and the system is triggered, two parallel EEW procedures are both activated. The VSN operates as discussed earlier [2, 16]. In the newly implemented P-wave method, P_d is calculated from the five nearest stations. When average P_d exceeds 0.1 cm, τ_c and $\tau_p^{\max}$ are calculated to determine M_τ. For events with both M_L from the VSN and M_τ from the P-wave method exceeding 6.0, a shake map is generated for the EEW report. The method and algorithm used for creating a shake map in this study are those of Hsiao [14].

5.2. Case Studies

To determine the performance of the regional EEW approach, we used an earthquake with a magnitude of 7.0 occurring offshore in Hualien and an earthquake with a magnitude of 6.5 occurred in Taitung as scenarios for our case studies.

1. The Hualien offshore earthquake on March 31, 2002 (**Fig. 9**)

The Hualien offshore earthquake claimed casualties in the Taipei metropolitan area, from which the epicenter distance exceeded 100 km. It would be meaningful to disaster reduction if the EEW operated practically. The real-time earthquake monitoring network was activated in the first stage at 12 sec of elapsed time because the epicenter distance to the closet station exceeded 40 km. At 3 sec after the network was triggered, the estimated earthquake magnitude (7.1) using the calculation of τ_c and $\tau_p^{\max}$ was very close to the final result (7.0), indicating a dramatic improvement in magnitude determination over the VSN's results for this event (**Fig. 4**). At this moment, the S wave had just arrived on the eastern coast of Taiwan and over 10 sec of lead time could be provided for most western cities.

In the second stage, the earthquake location was determined by the VSN and the shake map was created at 19 sec of elapsed time considering site effects with local magnitude M_L. Compared to manual processing, the difference in earthquake location was less than 5 km but the estimated focal depth of 5 km was less than the final result of 22.7 km. The estimated ground-motion distri-

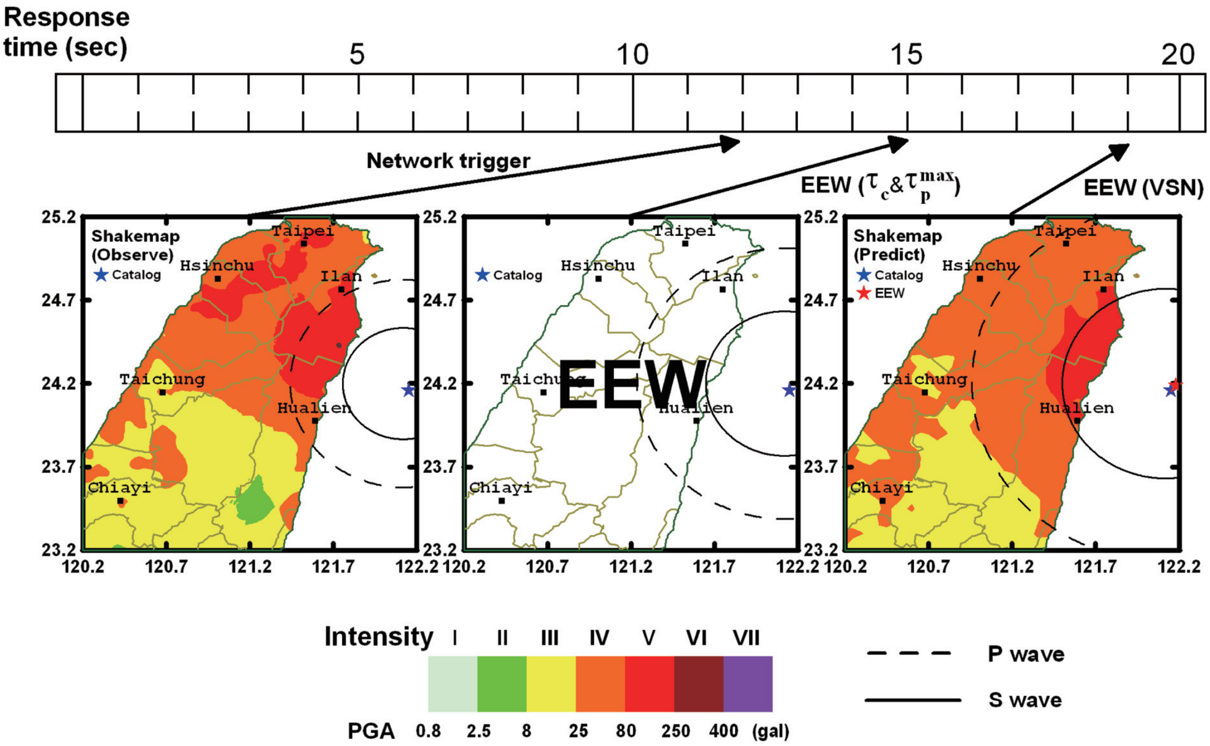

Fig. 9. EEW simulation of the Hualien offshore earthquake on March 31, 2002.

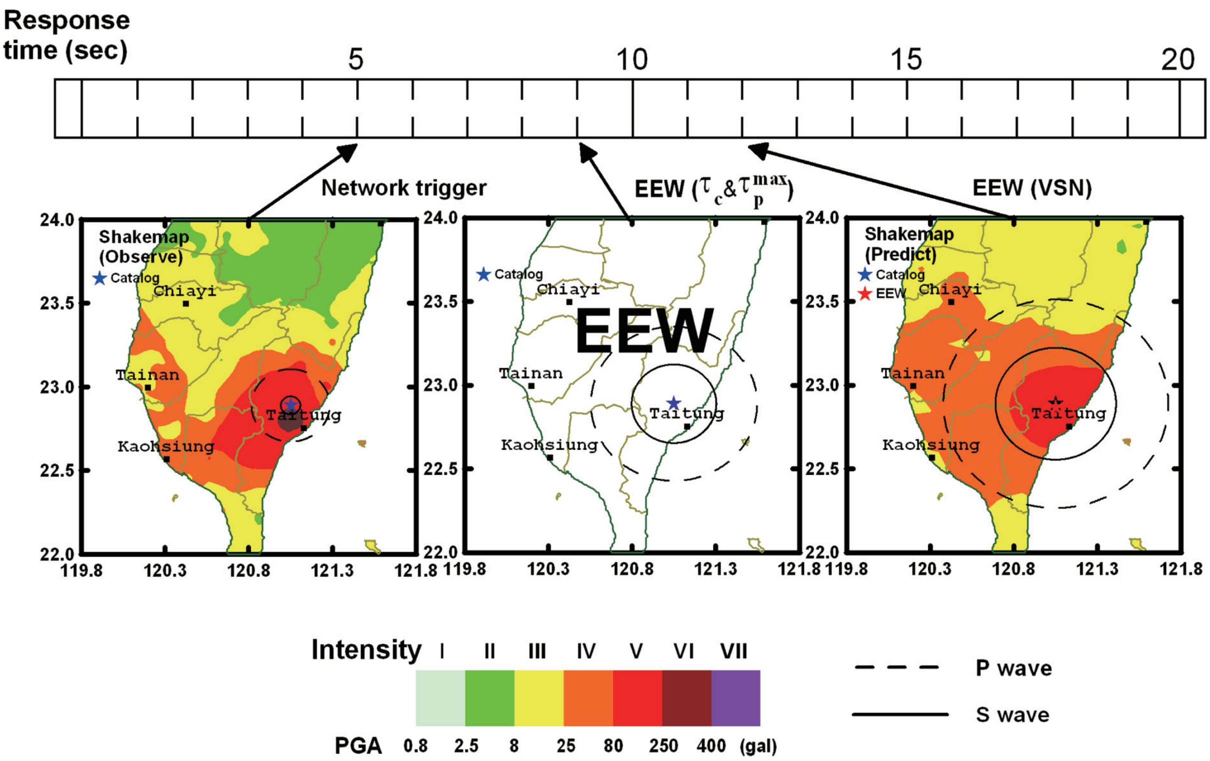

Fig. 10. EEW simulation of the Taitung earthquake on April 1, 2006.

bution with an intensity exceeding IV on the Taiwanese scale was generally consistent with the observed intensity, except for Taipei and Hsinchu, where the intensity was V, with PGA exceeding 80 gal. This may be because of the Moho reflection of S waves in areas with an epicenter distance of 100 km to 120 km, which was not taken into consideration in the attenuation formula.

2. The Taitung earthquake on April 1, 2006 (**Fig. 10**)

This earthquake occurred within beneath Taiwan Island, so the real-time earthquake network was triggered at 5 sec from the event originated. At 9 sec of elapsed time, the magnitude of 6.6 estimated by calculating τ_c and τ_p^{max} was obtained, which was also very close to the final result of 6.5. At that time, the area affected by S waves was

26 km and the EEW message may provide over 20 sec of lead time for Chiayi, Tainan, and Kaohsiung.

In the second stage, the location and depth of the hypocenter was determined by the VSN at 12 sec of elapsed time. The estimated location and focal depth are both very close to final results, with a difference of less than 5 km. The ground motion in areas near the epicenter is underestimated but that in areas far away was overestimated. This may be improved by further study of the site effect. Results from the two case studies indicate that the P wave method based on the calculation of τ_c and $\tau_p^{\max}$ demonstrates an acceptable result for estimating magnitude.

6. Discussion and Conclusions

In practice, the VSN based on the regional EEW approach achieved good magnitude determination with a small standard deviation of 0.28 for earthquakes with magnitudes of up to 6.5. For larger offshore earthquakes, however, the VSN approach may underestimate the magnitude due to the limited length of the waveforms used. To avoid this problem, magnitude M_τ obtained from average period τ_c and dominant period $\tau_p^{\max}$ of initial P waves may provide a satisfactory solution.

The real-time earthquake monitoring network at the CWB has been operating for over 10 years. With advancement of instrumentation and communication, the CWB plans to improve the capabilities of this network. For seismograph, 16-bit digital accelerographs will be replaced by 24-bit instruments that will enhance the dynamic range to 144 dB. Short-period and broadband seismographs will be linked for integrated data processing, so both strong shaking can be accurately recorded upon the occurrence of an event and P wave signals with high resolution also can be provided for EEW applications. For telemetries, 64K frame-relay networks are being prepared, and the sampling rate is going to enhance to 100 Hz. Plans have also been under way since 2007 to implement high-quality borehole seismic stations and a cable-based ocean bottom seismographic (OBS) system on and off of northeastern Taiwan. We plan to further develop the EEW system taking into account the advances on these new instruments and progress in new researches.

For experimental purposes, EEW messages are issued to some organizations such as the railway administration, rapid transit companies, and disaster prevention agencies, while a felt earthquake is detected in Taiwan. Messages includes the earthquake location, magnitude, and estimated intensity and S-wave lead time for target sites. A notification system based on the IP network has been developed to help meet emergency and broadcasting needs. EEW messages have not gone into practical operation for emergencies at tested organizations yet. Encouraged by the recent successful examples in the application of the EEW system in Japan, a pilot project for promoting the EEW system with the collaboration of government ministries, research institutions, and private sectors may be established in the near future in Taiwan.

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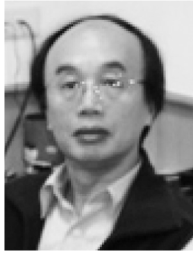
• "Identification of nonlinear site response using the H/V spectral ratio method," Ter. Atm. Oce., Vol.17, No.3, pp. 533-546, 2006.
• "Seismic hazard assessment for the Taiwan region on the basis of recent strong-motion data and prognostic zonation of future earthquakes," Natureal Hazards, Vol.33, No.3, pp. 319-363, 2004.

Academic Societies & Scientific Organizations:
• The Seismological Society of America (SSA)
• The American Geophysical Union (AGU)
• The Chinese Geophysical Society (CGS)
• The Geological Society located in Taipei (GST)
• Chinese Taiwan Society for Earthquake Engineering (CTSEE)



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• "Strong-Motion Instrumentation Programs in Taiwan," Int. Handbook of Earthquake and Engineering Seismology, Part B, pp. 1057-1062, Academic Press, 2003.

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• "Experiment on an onsite early warning method for the Taiwan early warning system," Bull. Seism. Soc. Am., Vol.95, pp. 347-353, 2005.

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Selected Publications:
• "Hazards mitigation planning for large-scale earthquakes in Taiwan," Proc., 100th Anniversary Earthquake Conf., Commemorating the 1906 San Francisco Earthquake, San Francisco, USA, 2006.
• "The planning of promoting the application of the earthquake early warning system in Taiwan," Proc., Earthquake and Tsunami Conf., Istanbul, Turkey, 2009.