地震初達波強震即時警報系統之研發

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摘 要

台灣位在地震頻繁的環太平洋地震帶上，地震活動頻繁，災害性地震也經常發生。因此，地震防減災是必須持續加強的研究課題。強震即時警報系統之發展是目前最有效的減災。快速的地震資訊，除了是地震防救災反應重要的指標外，也能滿足社會大眾及新聞媒體的期待。地震預警系統所提供之訊息，更是直接提供重大工程及民生設施採取緊急地震應變的關鍵。為了增加地震預警時間，建立地震初達波監測系統一個重要的方法，因此，本研究重點希望能以 linux 系統開發地震初達波監測系統，以達地震預警之效應。目前我們已經完成寬頻地震震網中之測試，並有良好之測試結果。

As urbanization progresses worldwide, earthquakes pose serious threat to lives and properties for urban areas near major active faults on land or subduction zones offshore. Earthquake Early Warning (EEW) can be a useful tool for reducing earthquake hazards, if the spatial relation between cities and earthquake sources is favorable for such warning and their citizens are properly trained to respond to earthquake warning messages. An EEW system forewarns an urban area of forthcoming strong shaking, normally with a few sec to a few tens of sec of warning time, i.e., before the arrival of the destructive S-wave part of the strong ground motion. In this project, we would like to design a system using initial P waves for EEW purpose. In this year, we had achieved an EEW system under currently broadband network and with a nice performance.

壹、緒 言

台灣位在地震頻繁的環太平洋地震帶上，地震活動頻繁，災害性地震也經常發生。地震預測一直都是一個熱門的地震防災研究議題，儘管有許多的前兆現象被確認，但目前仍未達實用階段。由於體認到地震預測之運用成效仍低，因此，許多國家進而投入地震預警系統之發展。快速的地震資訊，除了是地震防救災反應重要的指標外，也能滿足社會大眾及新聞媒體的期待。地震預警系統所提供之訊息，更是直接提供重大工程及民生設施採取緊急地震應變的關鍵。

所謂地震預警為當地震發生之後，在破壞性的地震波尚未來襲前之數秒至數十秒提出警告稱之。這段時間可直接用於降低地震災害，運用的範圍如下：

(1) 學校學童躲入桌子底下尋求保護及心理應變。墨西哥市的預警系統研究成果顯示，接受地震預警訊息的學童，在心理上大幅降低對地震之恐懼。

(2) 工人能離開危險的工作位置。

(3) 醫院進行的手術能暫時停止或調整精細及關鍵的操作，例如：眼科手術等。

(4) 運輸系統能自動停止或減速，例如：高速鐵路列車減速以降低翻車之風險。

(5) 維生管線及通訊網路能自動調整、重組或關閉，例如：關閉瓦斯及供水管線，減少地震所引起之火災及其他災害。

(6) 工廠能及時進行緊急應變，保護振動敏感之設備，例如：晶元製造廠。

地震預警系統是目前經評估有效的地震減災方法，美國、日本、墨西哥及台灣都投入這項工作。台灣預警系統設計的動機是基於 1986 年 11 月 15 日 M_L 6.8 (M_W 7.8) 花蓮地震所帶來的警示。該地震之震央雖然在花蓮地區，然而主要的震災卻發生在 120 公里外的台北地區。根據地震波走時資料，剪力波由花蓮地區傳遞至台北地區至少須 30 秒的時間，如果地震監測系統能在 30 秒內提供震央的地理位置及其規模。則將能在破壞性振動來襲之前，爭取數秒至十餘秒的預警時間，運用於緊急減災應變。因此，中央氣象局於 1994 年開始投入地震預警工作。

從 1995 年起中央氣象局開始安裝即時強震觀測系統，從事地震速報系統。為了加強運用即時的強震訊號，地震預警系統也積極發展中，採用 M_{L10} 的地震規模估計方法(Wu et al., 1998)及區域地震子網(Wu et al., 1999)或虛擬子網(Wu and Teng, 2002)之設計，計算出地震參數的時間估計可以縮短至約 20 秒，因此，對於離震央 70 公里外的都會區，將以提供不同程度預警時間。如圖一所示為以集集地震所做之案例。

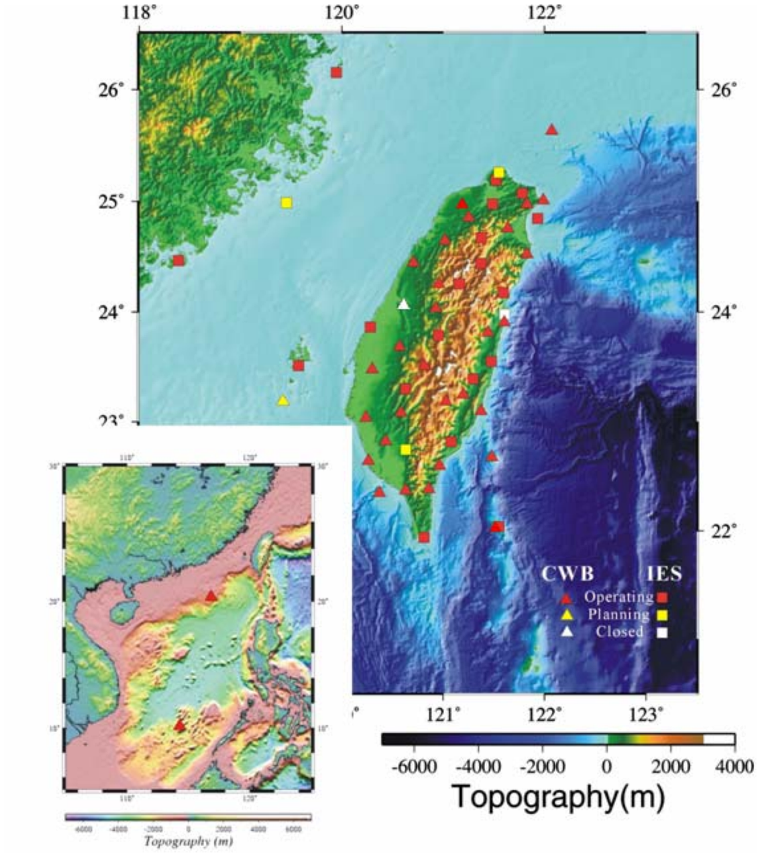
然而，目前的方法對於離震央 70 公里內的區域是無法提供預警。主要為採用 M_{L10} 的地震規模估計方法，是一個較為傳統的估計方法，需要利用地震被偵測後 10 秒的地動訊號，因此，無法將提供警告的時間縮短至地震發生後 15 秒以內。因此，本計畫希望利用地震初達波**(**P波**)**之方法從事地震預警研究(Wu and Kanamori, 2005a, 2005b, 2008a, 2008b; Wu et al., 2007, 2007; Wu and Zhao, 2006)，以期能將提供警告的時間縮短至地震發生後 10 秒。

貳、Earthworm環境預警系統之發展

中央氣象局於 2001 年開始設置寬頻地震站，與中央研究院聯網，至今總共設有有 52 站(圖一)。其中 50 站為即時觀測站，即時地動訊號由Earthworm系統所接收及處理。Earthworm系統是於 1994 年由美國地質調查所發展出來的地震資料處理系統，其利用模組與共享記憶體的概念，能夠快速地進行觀測網整合、資料交換、傳遞以及處理等工作。

我們將新研發的預警系統，建立在Earthworm系統的架構下。增加地震預警模組程式Earthworm中，由從Earthworm的共享記憶體，截取即時資料進行預警作業處理。

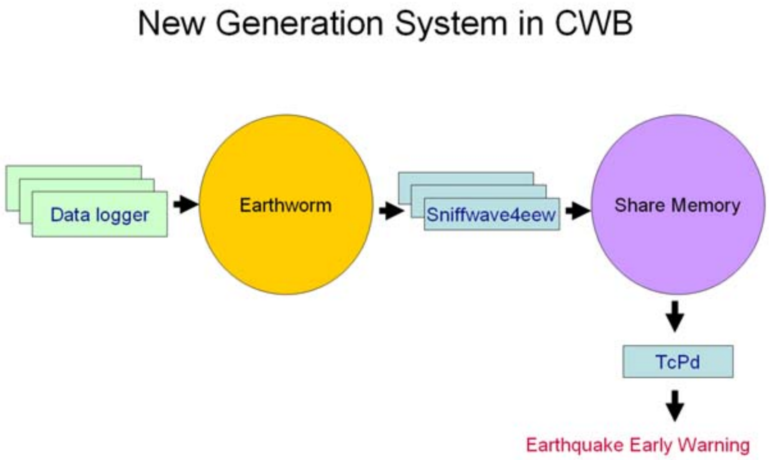
本文將詳述在Earthworm系統下進行預警作業的相關技術、資料處理方式以及系統成效。



圖一、台灣寬頻地震網 52 個測站之分佈圖

系統架構

在預警系統內，Earthworm 系統負責即時資料的接收及整合，我們撰寫 Sniffwave4eew 程式處理即時資料，並且把相關參數送入共享記憶體中，最後由另一 TcPd 程式進行地震定位及估算規模，並輸出地震資訊(圖二)。

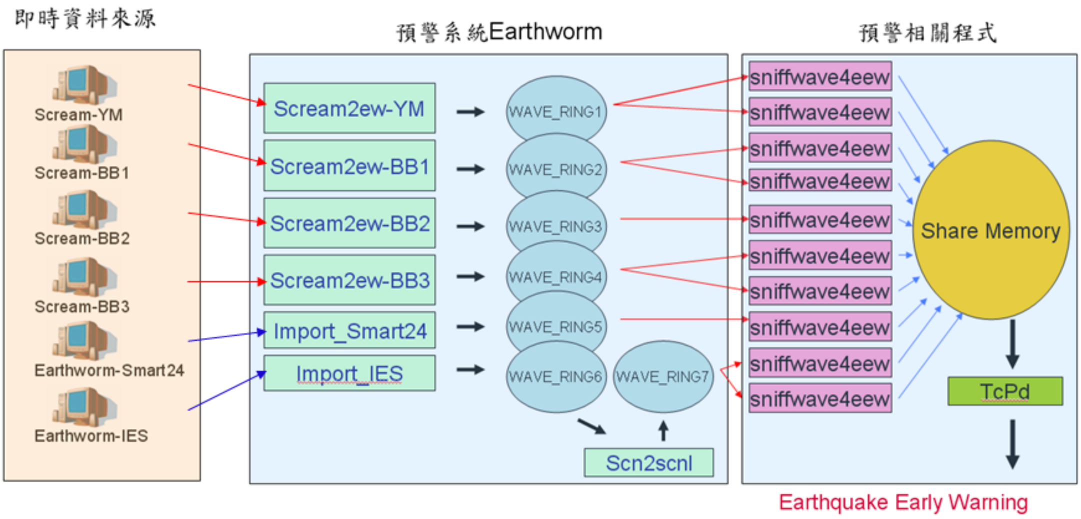


圖二. 利用 Earthworm 系統整合不同觀測網資料後，Sniffwave4eew 程式進行觸發判斷並將相關參數丟入共享記憶體中，由 TcPd 程式進行地震定位及估算規模，輸出預警資訊。

Earthworm 系統是由模組和共享記憶體所組成的。每一個模組都可以獨立的運作，模組間交換資料依賴共享記憶體 WAVE_RING。這個記憶體空間有一定的大小，會隨時更新資料。當 Earthworm 系統透過 Scream 模組接收及時資料進來時，資料會暫時存放在此記憶體中，我們再透過 Sniffwave4eew 到此處抓取即時資料進行處理。Sniffwave4eew 在處理過程中，先進行 0.075Hz 高通濾波，再進行 P 波觸發判斷，如果達到觸發標準將分別計算垂直分量 P 波後到達後三秒內之最大加速度(Pa)、最大速度(Pv)、最大位移(Pd)及平均週期(Tc)，並且將測站座標、P 波到時等資訊送入另外一個專門存放預警參數的共享記憶體中。

Earthworm 系統內部，可以使用對應的模組來接收資料。資料來源包括陽明山觀測網、台灣寬頻觀測網、SMART24 觀測網、井下地震儀觀測網、RTD 觀測網以及 S13 觀測網等。資料在 Earthworm 裡被放置在個別的共享記憶體中。Sniffwave4eew 程式再到各個共享記憶體中抓取所需的波線資料。每一個 Sniffwave4eew 程式可以針對一個測站之垂直分量進行處理，若是通過觸發判斷為地震訊號，會擷取 P 波後 3 秒內的預警資訊送至預警用的共享記憶體中。由 Tcpd

程式處理所有在此記憶體中的資訊，最後發布預警報告，如圖三所示。



圖三. 預警資料處理流程

資料處理

Sniffwave4eew 程式在執行時必須輸入測站相關資訊包含共享記憶體名稱、測站名稱、分量名稱、測站位置、取樣率、儀器修正值、儀器種類等。在程式啟動時會開啟一個預警用的共享記憶體，同時也會與 Earthworm 的共享記憶體連結將對應的波線資料讀入，然後進行儀器修正與基線修正。若儀器種類為加速度型，要先將訊號積分成速度，然後作 0.075Hz 的高通濾波。接者將速度訊號分別積分成位移、微分成加速度。以加速度訊號進行觸發判斷。若判斷為地震訊號，即可取得 P 波到時、Pa、Pv、Pd 及 Tc。再將這些參數放入預警用的共享記憶體，如圖四。

圖四. (a)執行 Sniffwave4eew 程式時前要輸入的測站參數，(b) Sniffwave4eew 程式處理資料的流程，(c) Sniffwave4eew 程式傳入預警用共享記憶體的資訊。

TcPd 程式分成兩階段處理共享記憶體。首先是篩選觸發測站，刪除共站的測站，各測站 P 波到時與系統時間比較，須在 20 秒之內，若在此範圍外，則該測站資料刪除。接者進行虛擬子網出發分析，並進行地震定位、定規模及估算震度。Tc 及 Pd 分別被利用來估算規模(Wu and Kanamori, 2005a, 2005b, 2008a, 2008b; Wu and Zhao, 2006; Wu et al., 2007)，Pd 也被用來估算震央區之震度(Wu and Kanamori, 2005b, 2008a, 2008b)。

TcPd

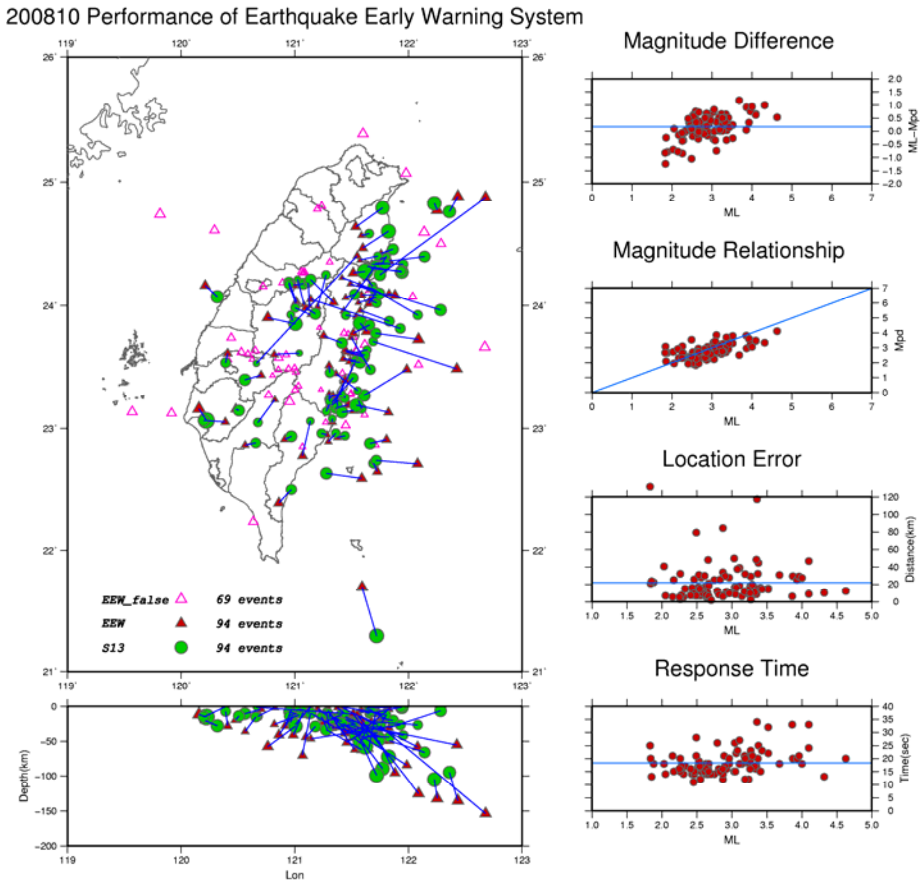
1. 開啓預警用共享記憶體
2. 刪除共站資料
3. 各測站P波到時與系統時間比較，須在20秒之內，若在此範圍外，則該測站資料刪除
4. 抓取共享記憶體中各測站的參數資料
5. 若有3個以上測站符合條件就進入觸發處理

1.各測站間的距離必須3~60公里之間，若在此範圍外，則該測站資料刪除
2.各測站間的P波到時必須小於8秒，若在此範圍外，則該測站資料刪除
3. 若有5個以上測站符合條件就進入預警報告處理
4. 發布第一報
5. 觸發的測站數必須大於前一報的測站數才會有下一報

圖五、TcPd 程式之執行流程。

系統成效

經過一個月的測試，平均處理時效為 17 秒，平均規模誤差為 0.7，平均定位誤差為 20 公里(圖六)。目前為測試階段，為了增加測試次數，我們降低觸發門檻，因此定位誤差較大。此外目前所用 Mpd 規模為加州的衰減公式，規模有系統性之偏移，下一年度將分析台灣地區 Pd 的衰減公式，進而改善規模之決定。將來陸續增加不同形態的觀測儀器進行預警工作，將能夠提升測站密度，更進一步縮短處理時間及改善地震定位準確度。



圖六、Earthworm 環境預警系統地震定位、規模估算及反應時間之測試表現。

叁、結 語

本計畫第一年已經完成Earthworm環境預警系統雛形之建立，本計畫第二年及第三年將努力讓本系統發展更加完備，例如規模及定位精確度之提升。除此之外，本計畫之努力下亦完成一篇英文文章並已投稿GRL一流SCI期刊，題目如下：

Nai-Chi Hsiao, Yih-Min Wu, Tzay-Chyn Shin, Li Zhao, and Ta-liang Teng (2008), Development of earthquake early warning system in Taiwan, submitted to *GRL* earthquake early warning special issue.

完整論文見附錄一。

肆、參考文獻

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附錄一

Development of earthquake early warning system in Taiwan

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Abstract

With the implementation of a real-time strong-motion network by the Central Weather Bureau (CWB), an earthquake early warning (EEW) system has been developed in Taiwan. In order to shorten the earthquake response time, a virtual sub-network method based on the regional early warning approach was utilized at first stage. Since 2001, this EEW system has responded to a total of 225 events with magnitude greater than 4.5 occurred inland or off the coast of Taiwan. The system is capable of issuing an earthquake report within 20 sec of its occurrence with good magnitude estimations for events up to magnitude 6.5. Currently, a P-wave method is adopted by the CWB system. Base on the results from 596 M ≥ 4.0 earthquakes recorded by the real-time strong-motion network, we found that peak displacement amplitudes from initial P waves (P_d) can be used for the identification of M ≥ 6.0 events. Characteristic periods τ_c and τ_p^{max} of the initial P waves can be used for magnitude determination with an uncertainty less than 0.4. We expect to achieve a 10-second response time by the EEW system in Taiwan in the near future.

Keywords: earthquake, earthquake early warning, seismic hazard mitigation, P wave.

1. Introduction

Taiwan is located on the western portion of the Circum-Pacific seismic belt. The Philippine Sea plate subducts northward under the Eurasia plate along the Ryukyu trench. The Eurasia plate subducts eastward under the Philippine Sea plate off the southern tip of Taiwan. Most of Taiwan is under a northwest-southeast compression with a measured convergence rate of about 8 cm/year. Many disastrous earthquakes have occurred in the past. Figure 1 shows the distribution of disastrous earthquakes in Taiwan since 1900. A real-time strong-motion network has been installed by the CWB since 1995 for seismic hazard mitigation purpose. With the subsequent developments of the past decade, this network has been utilized for rapid report of felt earthquakes (Shin et al., 1996; Wu et al., 1997) and for developing Taiwan's EEW system (Wu et al., 1999; Wu and Teng, 2002; Hsiao, 2007).

Currently, EEW system is one of the most useful tools for real-time seismic hazard mitigation. An EEW system provides a few seconds to tens of seconds of advanced warning time of impending ground motions, allowing for mitigation measures to be taken in the short term. Early warning systems that estimate the severity and onset time of ground shaking are already in operation in a number of countries (Nakamura, 1988; Espinosa-Aranda et al., 1995; Wu et al., 1999; Allen and Kanamori, 2003; Erdik et al., 2003; Kamigaichi, 2004; Horiuchi et al., 2005; Zollo et al., 2006; Ionescu et al., 2007; Oliveira et al., 2008). There are two different approaches to EEW: Regional warning and onsite warning. In regional warning systems, traditional seismological methods are used by a network of stations to determine the locations and magnitudes of earthquakes and to estimate the ground motion in the region involved. In onsite warning systems, the beginning part of the ground motion at a given site is used to predict the ensuing ground motion.

Taiwan is one of the leading countries in EEW developments with operational experience of more than 10 years. It was motivated by the lesson of the 15 November, 1986, M_w 7.8 offshore Hualien earthquake. Although the epicenter was off the eastern coast of Taiwan, the most severe damage occurred in metropolitan Taipei, 120 kilometers away from the epicenter, due to the basin amplification effect. If a seismic network in Hualien area can provide an estimation of earthquake parameters within 30 seconds, there will be an advanced warning time of up to tens of seconds for Taipei before the strong ground shaking starts. Hence, a virtual sub-network (VSN) method based on regional EEW approach was adopted in Taiwan in this first attempt (Wu et al., 1998; Wu and Teng, 2002). The VSN has been in operation for practical real-time earthquake monitoring since 2001, and the results show that the average reporting time of earthquake estimation by this system can be shortened to within 20 sec after the occurrence of earthquakes (Hsiao, 2007). This means that this system can provide earthquake early warnings for metropolitan areas located more than 70 km from the epicenter.

Meanwhile, other studies for EEW applications were conducted in Taiwan. Wu et al. (2001) and Hsiao (2007) derived the empirical relationships between peak-ground acceleration (PGA), peak-ground velocity (PGV) and magnitudes, which can be used to predict strong ground shakings for urban areas and create shake maps by the EEW system. In additional, Wu et al. (2004) utilized the data gathered from the disastrous 1999 Chi-Chi earthquake to derive the empirical relationships between the peak values

(PGA & PGV) of ground motion and seismic losses. As a result, after the occurrence of an unexpected earthquake, a comprehensive report can be issued within two minutes with assessment of the impending ground shaking to the area near the epicenter as well as possible seismic hazard caused by the earthquake, providing guidance for emergency response.

Due to the dependence on a network of stations, the VSN approach has a "blind zone" in the area within 70 km of the epicenter where the EEW system provides no advanced warning time. For the early warning to areas closer to the source, the P-wave method is considered, in which we utilize the real-time strong-motion data to estimate earthquake magnitudes based on empirical relationships between magnitude and a few parameters determined from the initial P-wave.

2. Real-time strong-motion network

The current EEW system at CWB was established based on the framework of a real-time strong-motion network. This seismographic network consists of 109 digital telemetered strong-motion stations distributed over the entire Taiwan area covering an area of 36,000 square kilometers at present. Figure 1 shows the locations of the seismic stations. Each station has a three-component force-balanced accelerometer with a 16-bit resolution, and the record has a full dynamic range of ±2g. Acceleration signals are continuously transmitted to the data center in Taipei at a 50 samples per second rate via 4,800-baud telephone and T1 lines. At the data center, the signals are processed continuously and automatically by a group of personal computers. Once a felt earthquake occurs, the VSN makes a quick estimation and in about one minute the system-wide rapid reporting system (RRS) issues a detailed assessment of the earthquake information, including the location and magnitude of the earthquake and a shake map, through the Internet and mobile phones.

Since its inauguration in 2001, the VSN-enhanced EEW system has issued earthquake alerts for a total of 225 events with magnitudes greater than 4.5 occurred inland or offshore near Taiwan. The performance of the EEW system is summarized in Figure 2. Figure 2(a) shows the comparison between the magnitudes determined automatically by the VSN and the manually determined ones published in the CWB earthquake catalogs. Most of the magnitudes determined by VSN correlate well with the values reported in the earthquake catalogs, with a standard deviation of 0.28. However, for the March 31, 2002, offshore Hualien earthquake, the magnitude was underestimated by the VSN by about one magnitude unit. This discrepancy was caused by the limited length of the waveforms used in the VSN calculations. Even though an empirical formula was used to correct the magnitude, this earthquake occurred off the eastern coast of Taiwan and was 50 kilometers from the nearest station. As a result, at nearly all of stations in the VSN the S waves were not included in the magnitude estimation since they fell outside the 10-sec time window used in the EEW calculations.

Earthquake reporting time is a crucial factor for the EEW applications. Figure 2(b) shows the reporting times by the VSN since 2001. Compared with the results by the system-wide RRS, with limited time window specified, the average reporting time can be effectively reduced to within 20 sec. From the viewpoint of earthquake emergency response, the performance of the VSN has fulfilled the demand for seismic hazard mitigation. As we discuss in the next section, its performance can be further improved by the P-wave method.

3. P-wave method

Motivated by the recent success of earthquake early warning systems, we have also conducted an investigation, using the real-time strong-motion data from CWB stations, into the relationships between the earthquake magnitude and several parameters obtained from the first few seconds of the P waveform. Here we consider the peak amplitude of the displacement P_d, the average period τ_c (Kanamori, 2005; Wu and Kanamori, 2005a, 2005b, 2008a, 2008b; Wu and Zhao, 2006), and the dominant period τ_p^{max} (Nakamura, 1988; Allen and Kanamori, 2003) of the initial P-wave.

τ_c is a measurement of the average period of the P wave within the first few seconds, which can be used to estimate the size of an earthquake (Kanamori, 2005). It is determined by selecting a specific time window and measuring the frequency content of the waveform in the window. Similarly, τ_p^{max} is also a measure of the frequency content of the P waveform (Allen and Kanamori, 2003). However, the procedure for obtaining τ_p^{max} is quite different, and provides a measure of the dominant period of the selected P waveform in the time window. The definitions of these two P-wave period parameters as well as the amplitude P_d and the procedures for measuring them can be found in previous studies (Allen and Kanamori, 2003; Kanamori, 2005; Wu and Kanamori, 2005a, 2005b, 2008a, 2008b). Here, we combine τ_c and τ_p^{max} in estimating the magnitude of earthquakes for EEW applications in order to reduce the uncertainty (Shieh et al., 2008).

Following previous studies (Kanamori, 2005; Wu and Kanamori, 2005a, 2005b, 2008a, 2008b; Wu et al, 2007; Shieh et al., 2008), we adopt a time-window length of 3 seconds for the P wave 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. Most of the real-time strong-motion stations are located in urban areas and records for small shakings from those stations generally have low signal to noise ratio. Thus, only records with P_d values greater than 0.08 cm were used for evaluating τ_c and τ_p^{max}.

4. Results

In this study, in order to find the relationships between magnitude and P_d, τ_c and τ_p^{max} measurements, we used a total of 596 earthquakes with $M_L \geq 4.0$ recorded by the CWB real-time strong-motion network since 1998. The relationships were obtained by linear regression using the measurements from five nearest stations within 40 km from the earthquakes. The results are illustrated in Figure 3.

As shown in Figure 3(a), most of the earthquakes with average P_d values of 0.1 cm or above have magnitudes large than 6.0. In addition, the values of $\log P_d$ increase approximately linearly with M_L when the earthquake magnitudes are greater than 5.5. The linear regression between $\log P_d$ and M_L using the 38 events with $M_L \geq 5.5$ yields the relationship:

$$\log P_d = 1.62 \times M_L - 12.36, \quad (1)$$

with a standard deviation of 0.80. This relationship can be used for quick magnitude estimation without knowledge on the location of the earthquake.

The relationship between $\log \tau_c$ and M_L is shown in figure 3(b). Nineteen events of $M_L \geq 5.0$ and with P_d > 0.08 cm in every record were used for this analysis. Similar to previous studies (Kanamori, 2005; Wu and Kanamori, 2005a, 2005b, 2008a, 2008b; Wu et al., 2007), the values of $\log \tau_c$ increase approximately linearly with M_L. The linear regression for the relationship between $\log \tau_c$ and M_L is

$$\log \tau_c = 0.47 \times M_L - 2.37, \quad (2)$$

with a standard deviation of 0.25. τ_p^{max} is also analyzed using the same dataset, and the result is shown in Figure 3(c). The relationship between $\log \tau_p^{max}$ and M_L is

$$\log \tau_p^{max} = 0.24 \times M_L - 1.51, \quad (3)$$

with a standard deviation of 0.23.

Base on the study of Shieh et al. (2008), we combine τ_c and τ_p^{max} in magnitude determination. Figure 4(d) shows the magnitude determined from the average values of τ_c and τ_p^{max} versus the magnitude M_L. The magnitude determined from τ_c and τ_p^{max}, Mτ, has a 1:1 relationship with M_L with a standard deviation of 0.40.

5. Discussion and conclusions

In practice, the VSN method based on a regional EEW approach can achieve a good magnitude determination with a small standard deviation of 0.28 for earthquakes up to 6.5. However, for larger offshore earthquakes, the VSN method may underestimate the magnitudes due to the limited lengths of the waveforms used. To avoid this problem, the magnitude Mτ obtained from the average period τ_c and the dominant period τ_p^{max} of the initial P waves may offer a satisfactory solution. For the case of March 31, 2002, offshore Hualien M_L 7.0 earthquake (Figure 2a), the VSN underestimated the magnitude by about 1 unit, whereas Mτ provides a very good estimation of 7.1.

The operations of the present EEW systems in Taiwan are shown in the flow chart in Figure 4. The VSN approach and the P-wave method operate in parallel. When a felt earthquake occurs and the system is triggered, two parallel EEW procedures will be activated. The VSN process works as discussed before (Wu et al., 1998; Wu and Teng, 2002). In the newly implemented process using the P-wave method, P_d values are calculated from five nearest stations. When the average value of P_d is greater than 0.1 cm, τ_c and τ_p^{max} are calculated for Mτ determination. For events with both M_L from VSN and Mτ from the P-wave method larger than 6.0, the shake map will be calculated for the earthquake early warning report.

Currently in Taiwan the rapid earthquake reports issued by the EEW system are not available to the general public, except for experimental purposes by some relevant organizations such as railway administration, rapid transit companies, and disaster prevention agencies etc. Public release of earthquake early warnings does not produce social benefits in the absence of a comprehensive approach to educating the public on how to respond to the warning messages. However, encouraged by the recent successful examples in the research and application of EEW system in Japan, a joint program to promote the EEW system with the participation of various organizations will proceed in the near future in Taiwan.

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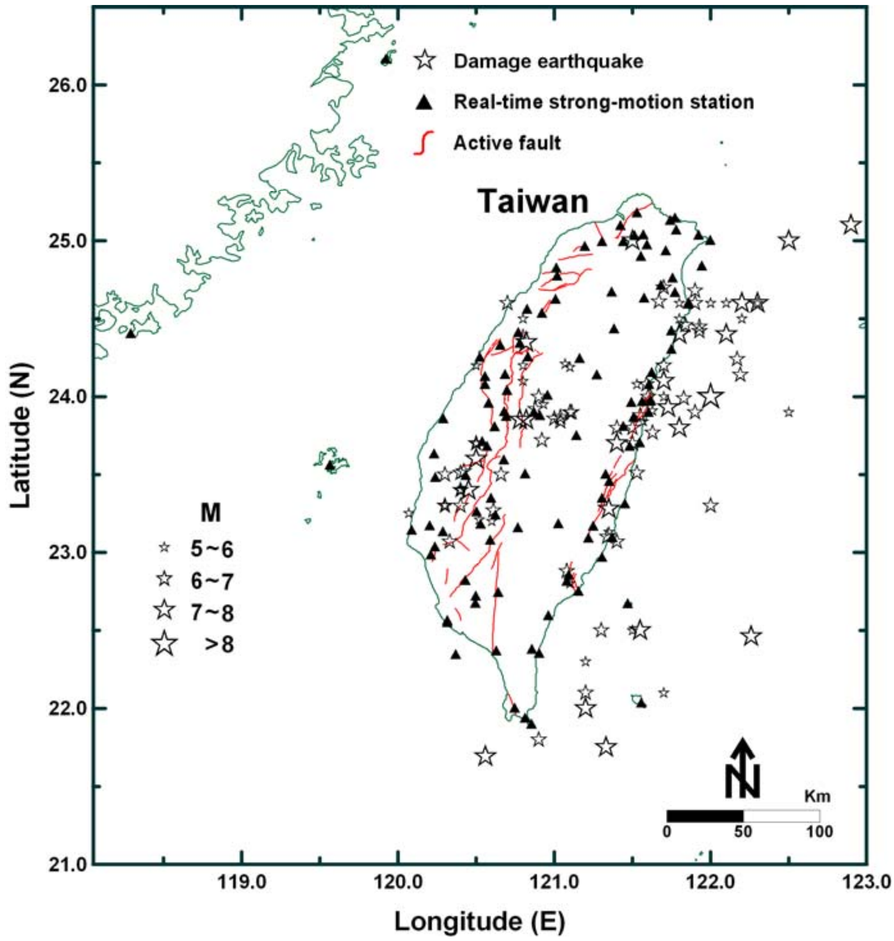

Figure 1. Real-time strong-motion stations (solid triangles) implemented by CWB for seismic hazard mitigation. Stars show the locations of destructive earthquakes occurred around Taiwan since 1900.

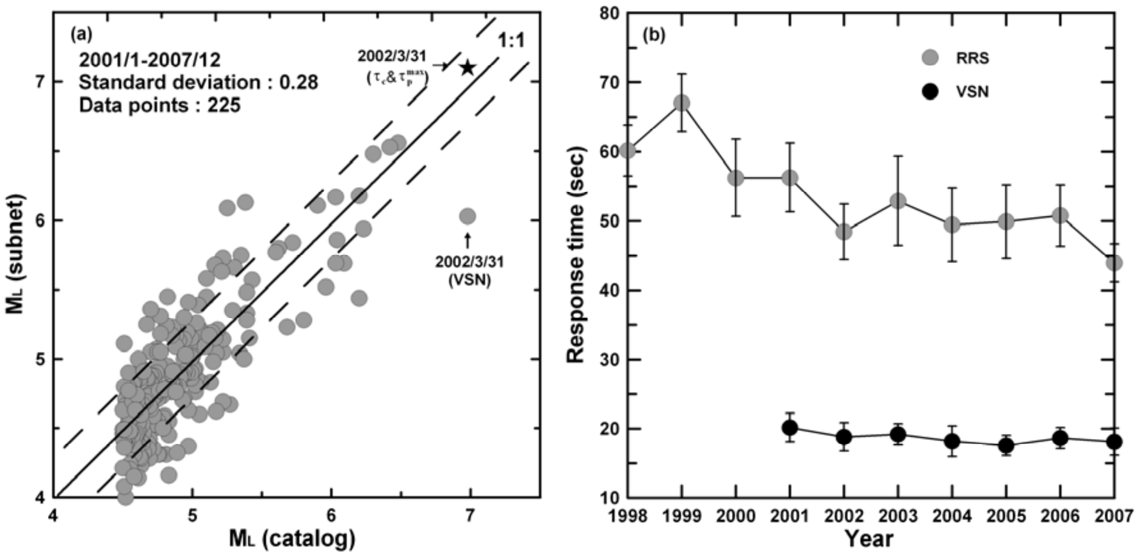

Figure 2. (a) Comparison of magnitudes determined automatically by VSN with catalog ones. Solid line shows the least squares fit and the two dashed lines show the range of one standard deviation. For the March 31, 2002, offshore Hualien earthquake, the magnitude was underestimated by about one unit by VSN, whereas the P-wave method yields more accurate result (solid star). (b) Average reporting times by VSN and the entire network (RRS) since 2001. When fewer stations are used, the average reporting times can be effectively reduced to within 20 sec.

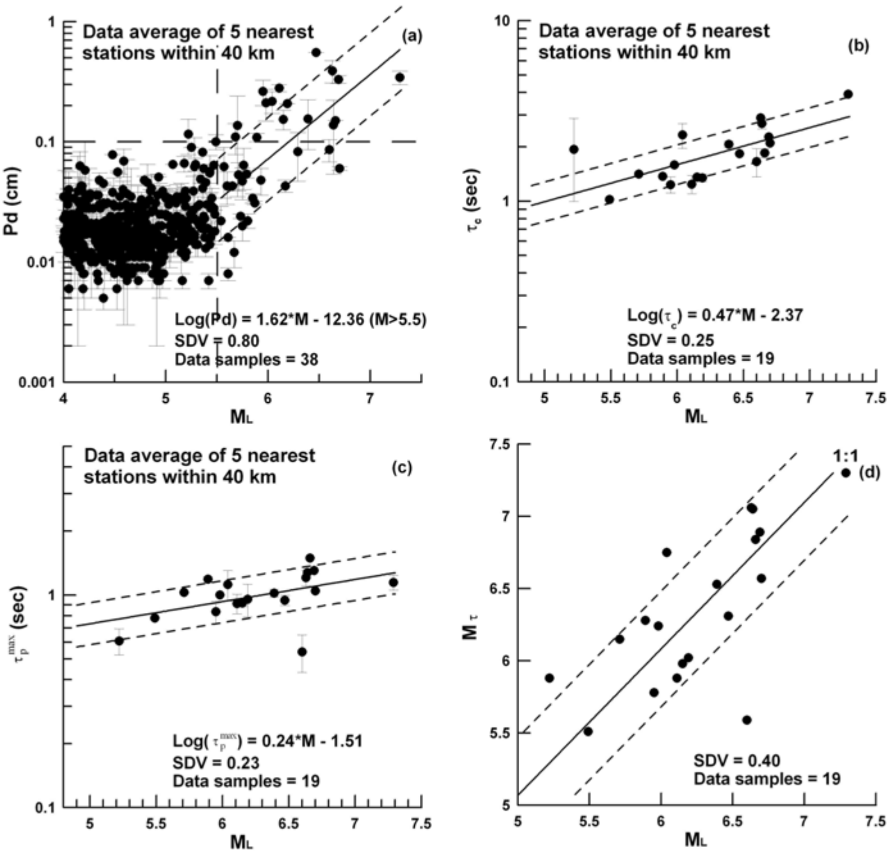

Figure 3. Regressions of catalog magnitudes M_L with different parameters derived from the P-wave method in this study. Solid line shows the least squares fit and the two dashed lines show the range of one standard deviation. (a) Regression of $\log P_d$ with M_L. (b) $\log \tau_c$ with M_L. (c) $\log \tau_p^{\max}$ with M_L. (d) Regression of magnitudes estimated by the average of τ_c and $\tau_p^{\max}$ with M_L.

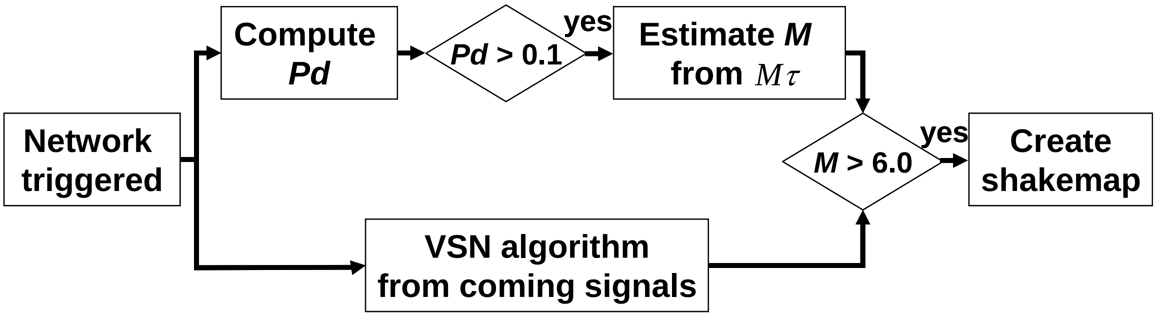

Figure 4. Flow chart of the algorithm designed for EEW system in this study. In this design, the VSN and P-wave method operate in parallel.