Progress on Earthquake Rapid Reporting and Early Warning Systems in Taiwan

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Abstract

We report here the recent progress on real-time seismic monitoring in Taiwan. Particularly on the earthquake rapid reporting (RRS) and earthquake early warning (EWS) systems developed at the Central Weather Bureau (CWB), using the telemetered signals from strong-motion instruments in the free-field. For the RRS, CWB has provided intensity map, hypocenter, and magnitude within one minute of the occurrence of large (M>4) earthquakes since 1995. The reliability, as documented by electronic messages to government agencies and scientists, has a nearly perfect record, especially for large damaging earthquakes. Using a set of empirical relationships from a large data set collected during the 1999 Chi-Chi earthquake, CWB has been able to release through RRS the estimated distributions of PGA, PGV and potential damage within a few minutes after a big earthquake. This near real-time damage assessment is shown to be critically useful for rapid post-disaster emergency response and rescue missions.

The concept of a quick magnitude determination base on the first 10 seconds of signals from a virtual and sub-network configured automatically be the monitoring software, we are able to reduce the earthquake rapid reporting time to about 30 seconds or less. This represents a significant step towards a more realistic earthquake early warning capability. This early warning system has been in operation at CWB since 2002. Comprehensive earthquake reports have been issued mostly in less than 30 seconds, with an average of about 22 seconds from the origin time since 2002. At 3 km/sec for a typical crustal shear wave velocity, the present operation is not useful if an earthquake occurs less than 66 km from a city, but the lead time will increase to more than 10 seconds for cities at distances greater than 100 km from the source. In the latter case, a lead time of several seconds will allows pre-programmed emergency response to take place prior to the arrival of the damaging strong shaking.

Keywords: Earthquake early warning, earthquake rapid reporting, damage assessment, hazard mitigation.

1. Introduction

The idea of an earthquake early warning system was proposed more than one hundred years ago by Cooper (1868) for San Francisco, California. A modern approach for a seismic computerized alert network was published by Heaton (1985). For more than twenty-five years, Japan has benefited from an earthquake warning system on their "bullet" trains (Nakamura, 1988; Saita and Nakamura, 2003). A seismic alert system has been implemented in Mexico City (Espinosa-Aranda et al., 1995; 2003). Several sessions on earthquake early warning systems had been taken place in international meetings, including the XXI General Assembly of the International Union of Geodesy and Geophysics in Boulder, Colorado, USA (Lee and Shin, 1995), the Eleventh World Conference on Earthquake Engineering in Acapulco, Mexico (Lee and Espinosa-Aranda, 1996), and the International IDNDR-Conference on the Early Warning Systems for the Reduction of Natural Disasters in Potsdam, Germany in 1998 (Zschau and Kuppers, 2003). In the last mentioned conference proceedings, Lee and Espinosa-Aranda presented the current status and perspectives on earthquake early warning systems, and twelve other technical papers on this topic were also published.

Located on the western circum-Pacific seismic belt with a plate convergence rate of 8 cm/year (Yu et al., 1999), Taiwan had experienced numerous destructive earthquakes with severe casualties and property losses. For examples, on March 17, 1906 a damaging earthquake (M=7.1) occurred in Chiayi (Hsu, 2003), in 1935, a disastrous earthquake (M=7.1) occurred in the Hsinchu-Taichung area (Hsu, 2003), and the 1999 Chi-Chi earthquake (Mw = 7.6) occurred in Nantou County (Teng et al., 2001; Shin and Teng, 2001; Tsai et al., 2001; Wu et al., 2000, 2002, 2003b). The potential earthquake hazard will continue to increase along with the population growth. Therefore, it is essential for Taiwan to seek means through scientific research to reduce future earthquake hazards.

Because of the extreme complexity involved in the earthquake processes, reliable earthquake prediction is not currently possible (Kanamori et al., 1997; Kanamori, 2003). Present technological advances in seismic instrumentation and in digital communication and processing permit the implementation of a real-time earthquake monitoring system. From the point of view of seismic hazards mitigation, RRS and EWS are becoming the practical and promising tools to reduce the loss caused by a damaging earthquake (United States National Research Council, 1991; Kanamori et al., 1997; Teng et al., 1997; United States Geological Survey, 1998; Wu, 1999; Allen and Kanamori, 2003; Lee and Espinosa-Aranda, 2003). A real-time strong-motion network was installed in Taiwan named Rapid Earthquake Information Release System (RTD) by the CWB for monitoring purposes since 1995. In order to maximize the use of data from this network, the CWB has utilized its RTD system as a basis for the development of RRS and EWS capabilities (Lee, 1995; Lee et al., 1996; Teng et al., 1997; Wu et al., 1997, 1998a, 1998b, 1999, 2000, 2001, 2002, 2003a, 2003b, 2003c; Wu, 1999; Wu and Teng, 2002, 2003). We shall first define the roles of these two systems under current development in Taiwan:

(1) A Rapid Reporting System (RRS) provides information (hypocenter, magnitude, intensity, ground shaking and potential damage) within about a minute after the event occurrence to populated areas and other sensitive locations. The RRS transmits this critical information electronically to emergency response agencies and other cognizant governmental agencies. These agencies can then take actions (some of which are pre-programmed) immediately after an earthquake has struck. The response

measures can include the dispatch of rescue missions to the likely areas of damage in a timely manner**.**

(2) An Early Warning System (EWS) forewarns an urban area of the forthcoming strong shaking, normally with a few sec to a few tens of sec of early warning time, i.e., before the arrival of the destructive S-wave part of the strong ground motion. Even a few seconds of advanced warning time will be useful for pre-programmed emergency measures for various critical facilities**,** such as the deceleration of rapid-transit vehicles and high-speed trains to avoid potential derailment, the orderly shutoff of gas pipelines to minimize fire hazards, the controlled shutdown of high-technological manufacturing operations to reduce potential losses, and the safe-guarding of computer facilities to avoid the loss of vital databases.

This RTD system (Fig. 1) uses a real-time strong-motion accelerograph network that currently consists of 82 telemetered strong-motion stations distributed across Taiwan, an area of 100 km x 300 km. Each station has 3-component force-balanced accelerometers with signals digitized at 50 samples per sec per channel at 16-bit resolution. The full recording dynamic range is ±2g, and a sensitivity sufficient to record M > 4.0 events at distance of 100 km or more. Currently, RRS of the CWB can offer information about one minute after an earthquake occurrence. Information includes earthquake location, its magnitude and shaking maps of Taiwan area. Rapid damage assessment can be also determined and issued by the RRS in the near future. By applying sub-network method approach, the EWS of the CWB can achieve earthquake reporting time about 20 sec. It will offer effective earthquake early warning for metropolitan areas located more than one hundred km from the epicenter. In this paper we will report the progress of the RRS and EWS in Taiwan.

2. Rapid Reporting System

Digital signals (of 3-channel strong-motion and 3-channel weak-motion) are continuously telemetered to the headquarters of the CWB in Taipei via 4,800 baud leased telephone lines. The incoming digital data streams are parallel processed by a group of computers. Whenever the pre-specified trigger criteria were met, the digital waveforms are stored in the memory and are automatically analyzed by a series of programs (Wu et al., 1998b). The results were immediately disseminated to governmental emergency response agencies electronically in many ways such as internet, FAX, pager, telephone on demand and mobile phone short message (Fig. 2). Results include earthquake location, local magnitude, and intensites of Taiwan area. Generally, the RRS of the CWB can offer information about one minute after an earthquake occurrence. The information gives an average error of 10 km in hypocentral location and an uncertainty of 0.3 units in local magnitude. Except basic information, more detailed information such as moment magnitude determination, ground motion calculation, and potential damage assessment will be analyzed by the RRS within few minutes**.** Moment magnitude or its equivalent must be determined for the RRS and EWS, even though this part of processing is most time-consuming. For any destructive earthquake must have magnitude M_w >6.5 for which M_L is known to be saturated.

2.1 **Large magnitude determination**

The CWB routinely determines local magnitude, M_L (Shin, 1993) using simulated Wood-Anderson seismograms (Kanamori et al., 1999) and a method developed by Richter (1935), we have found that for really large earthquakes (M >> 6.5) the M_L scale saturate, and difficulties again arise preventing from an adequate Mw determination. A practical empirical method is employed in the RRS of the CWB that can quickly derive an equivalent Mw for large crustal earthquakes based on the strong shaking in real time. Full strong motion waveform, we call "total effective shaking" instead of traditional maximum amplitude is used for magnitude determination.

To compute the total effective shaking embodied in the waveforms of the near-field acceleration recordings, we define an absolute-value acceleration integral $\sqrt{Es}$ such that:

$$\sqrt{Es} = \int_{Tp}^{Te} \sqrt{V(t)^2 + N(t)^2 + E(t)^2}\, dt \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

Here V(t), N(t), and E(t) are vertical, north-south, and east-west components of acceleration (in gal) of time (t), respectively. The integrand gives the absolute amplitude A of the vector sum of the 3-component accelerations. Upon integration, $\sqrt{Es}$ will have the unit of velocity, thus Es is proportional to seismic wave energy. Tp is the P-wave arrival time. Te is the end-of-event time of the significant strong-shaking duration, which is defined as the point of time when the acceleration amplitude A drops below 20% of the maximum amplitude (Amax) and remains there for 5 sec. The unit of Tp and Te is in sec. In part B of Figure 3, Amax is shown to be close to 500 gal. The end-of-event time Te occurs at about 40 sec after the P-arrival, which is defined to be the time when A has become 20% of Amax for more than 5 sec. Part C of Figure 3 shows $\sqrt{Es}$, the cumulative total effective shaking, that builds up as the strong-shaking continues. The integration is cut off at 40 sec for this case. The early cutoff is mainly for the interest of quickly completing the total effective shaking calculation so that the system can get on with the magnitude determination for the purpose of RRS. Indeed, after 40 sec for this example, the additional increment of wave energy is small and can be neglected for the present purpose of Mw determination.

With a total of 2506 strong-motion records recorded by Taiwan Strong Motion Instrumentation Program (TSMIP) network (Fig. 1) from 13 crustal events (Mw range from 5.8 to 7.6) as the input, the resulting regression attenuation relationship for $\sqrt{Es}$ is given by

$$\log(\sqrt{Es}) = 0.664 + 0.493 \cdot Mw - 0.001 \cdot R - 0.713 \cdot \log(R) + Si \qquad \ldots(2)$$

Here R is the hypocentral distance in km. Si is the ith site correction factor of the TSMIP station. The station site amplification factors of peak ground acceleration (PGA) were determined in a previous study (Wu et al., 2001). Where $\log(\sqrt{Es})$ is approximately normal distribution with mean 0.0 and standard deviation 0.155. It is interesting that Mw is given approximately by the value of log(Es).

In this study, the attenuation of log ($\sqrt{Es}$) and the site effects come out reasonably well through the regression analysis. Since the log (Es) is proportional to Mw in a simple manner, we shall rewrite equation (2) replacing Mw by Mew to reflect that a different process is used in the moment magnitude derivation:

$$Mew = -1.347 + 1.014 \cdot \log(Es) + 0.002 \cdot R + 1.446 \cdot \log(R) - 2.028 \cdot Si \quad \ldots.(3)$$

Here, Mew is derived empirically through an integration process by summing up the earthquake strong shaking absolute amplitude. The integrated quantity has a unit of velocity, which bears a simple relation to the total energy (in fact, log(Es) ~ Mew).

Figure 4 gives a comparison of the three magnitude values by plotting the Mew against a 45^0 Mew = Mw line, with the dashed lines giving one standard deviation values. The figure shows that M_L values (in solid triangles) are scattered about the 45^0 Mew = Mw line, and give a significantly lower value for the large Chi-Chi Mw7.6 event due to M_L saturation. The Mew values stay mostly well inside one standard deviation. The Mew value for the large Chi-Chi Mw7.6 event falls almost right on the mark with a standard deviation of 0.12. The differences between Mew and Mw are distributed in a small range from –0.25 to 0.16. This result shows the magnitude of large crustal earthquakes in Taiwan can be well determined from $\sqrt{Es}$, or from an integration of absolute amplitude over the strong **{-}** shaking period. This integration is fast and can be carried out in real-time. Therefore, the Mew determination is practical in the RRS operation.

Figure 5 shows data of the end-of-event times Te of the 2506 records used in this study. Except for the Chi-Chi mainshock, most of the end-of-event times have values between 15 and 30 seconds after the S-wave arrival. The end-of-event times of the Chi-Chi mainshock lasted more than 30 seconds after the S-wave arrivals, especially at large distances. For large earthquakes like the Chi-Chi event, due to the large rupture dimensions (100 km x 40 km) and results a long rupture times (~30 sec)**,** Te is necessarily longer. Even then, in a typical RSS operation, with a dense real-time strong-motion station network as shown in Figure 1, only stations with epicentral distances less than 60 km are involved in the $\sqrt{Es}$ calculation. The method presented here still can produce a reliable Mew (therefore an equivalent Mw) within about one minute.

2.2 Ground motion calculation

During a disastrous earthquake, the early assessment and timely reporting of the peak ground acceleration (PGA) and peak ground velocity (PGV) maps will be crucial in an effective emergency response operation. In this study, PGA and PGV attenuation relationships are deduced with data from the TSMIP database of the CWB. The resulting attenuation relationships for PGA and PGA (Wu et al., 2001) are given by

$$\log_{10}(PGA) = 0.00215 + 0.581Mw - \log_{10}(r_{rup} + 0.00871 \times 10^{0.5Mw}) - 0.00414r_{rup} \qquad \ldots(4)$$

$$\log_{10}(PGV) = -2.49 + 0.810Mw - \log_{10}(r_{rup} + 0.00871 \times 10^{0.5Mw}) - 0.00268r_{rup} \qquad \ldots(5)$$

where the PGA unit is cm/sec^2, the PGV unit is cm/sec, and r_{rup} is rupture distance in km.

The TSMIP stations cover almost all of the populated areas of the Taiwan. Therefore, estimating the TSMIP site ground motions will be very important for damage assessment. Generally, site effect is one of the important factors for predicting the ground motion. The TSMIP sites still have not been well classified (Lee et al., 2001). However, those stations have recorded many earthquakes. Thus, the TSMIP site correction S, can be determined empirically by averaging the residuals between the observed and predicted values as following

$$S = \exp\left(\frac{1}{n}\sum_{i=1}^{n}\ln\left(D_i / \overline{D}_i\right)\right) \qquad \ldots(6)$$

where D_i is either the observed PGA or PGV value, $\overline{D}_i$ is either the predicted PGA or PGV value obtained by the attenuation relationships. Thus, the TSMIP site peak ground motion can be expressed as $S \cdot \overline{D}_i$. Figure 6 shows the generalized PGA and PGV site correction contour maps of the TSMIP stations.

Immediately after a strong earthquake, PGAs and PGVs of all of the RTD system stations are available at the CWB headquarters. The peak ground motion P at a TSMIP site can be estimated by

$$P = \overline{D} * S * \frac{Tobs}{Tcal} \qquad \ldots(7)$$

where $\overline{D}$ is either the predicted PGA or PGV value obtained by the attenuation relationships, Tobs is the observed value at the nearest RTD system station, and Tcal is the predicted value by the attenuation relationships with site correction at that RTD system station. Generally, the attenuation relationships and site corrections represent a statistically averaged effect. Every event possesses its own characteristics, such as the source radiation patterns and directivity effect. And the observed values from the RTD systemsupply such characteristics.

We use the extensive recordings of the Chi-Chi earthquake to test the estimation scheme outlined above. Figure 7B gives the “reality” – the PGA map based on observations from both the RTD system and the all 650 free-field TSMIP. Figure 7A shows the result of the estimation scheme outlined above**.** It gives a PGA map close to the observed PGA map given by Figure 7B. We conclude that our schemes are satisfactory in estimating the PGA and PGV values.

Since our primary objective is to estimate the TSMIP site ground motions within 2 minutes after occurrence of a felt earthquake in Taiwan region, the procedure presented in here represents a first-order determination of the ground motion intensity. We expect that the calculated PGA and PGV maps will be useful for earthquake emergency response operations.

2.3 Rapid damage assessment

Having the ability of near real-time damage assessment would benefit earthquake emergency response operations in Taiwan greatly. Thus, we established an empirical method of assessing the near real-time damage using the rapid reporting system in Taiwan. Relationships between peak ground velocity and damage rates (fatality rate, total and partial household collapsing rates) obtained in each township of Taiwan during the 1999 Chi-Chi earthquake were determined. We applied Kriging method to calculate the PGA and PGV values of the geometrical center of each township with assigned average PGA and PGV values. The averaged damage rates within different PGA and PGV ranges were used in the regression analysis. Logarithm regression of the damage rate with PGA and PGV values yielded roughly linear relation**{s}.** Figures 8 and 9 illustrate the regression relations of the observed and predicted damage rates (dots) with PGA and PGV values (solid lines), as the regressions were defined by:

$$\log_{10}(Fr) = -12.572 + 4.282 * \log_{10}(PGA) \pm 0.657$$

$$\log_{10}(Ct) = -10.118 + 4.146 * \log_{10}(PGA) \pm 0.508$$

$$\log_{10}(Cp) = -9.941 + 4.061 * \log_{10}(PGA) \pm 0.501$$

$$\log_{10}(Fr) = -9.360 + 4.315 * \log_{10}(PGV) \pm 0.341$$

$$\log_{10}(Ct) = -8.452 + 4.825 * \log_{10}(PGV) \pm 0.483$$

$$\log_{10}(Cp) = -8.007 + 4.452 * \log_{10}(PGV) \pm 0.541 \qquad \ldots\ldots(8)$$

where Fr, Ct, and Cp are rate percentages of the fatality, total and partial-collapsed households, respectively. PGA is the peak ground acceleration (gal). PGV is the peak ground velocity (cm/sec).

The distribution of the peak ground velocity can be mapped within minutes post-initiation of a strong earthquake by the rapid reporting system of the CWB (Wu et al., 2001). By correlating peak ground velocity with damage rates gathered by the rapid reporting system, a near real-time damage assessment can be issued, in addition to the epicenter, magnitude and intensity.

3. Early Warning System

The approach of the EWS was motivated by the experience of the 15 November, 1986 Hualien, Taiwan, earthquake of M_L 6.8 (or M_W 7.8). Although the epicenter of that earthquake was located near Hualien, the most severe damage occurred in the Taipei metropolitan area, about 120 km away. According to the travel times of past earthquakes in Taiwan, the shear waves traveling over this distance should take more than 30 sec. Thus, if a seismic monitoring system can reliably inform the location and magnitude within 30 sec of a large earthquake that could threaten an area, then several or more seconds of advanced warning will be available for emergency response (Lee, 1995; Lee et al., 1996).

Recently, the Mexico City Seismic Alert System successfully provided about 70 sec of advanced warning of the 14 September, 1995, Copala (Guerrero, Mexico) earthquake to the citizens of Mexico City (Espinosa-Aranda et al., 1995). This case applies to a rather unique situation in which the affected area is far away from the source area (about 300 km) so that a delay time of as much as 70 sec is available for event identification. Nonetheless, the Mexican experience represents an outstanding success in earthquake early warning. The Mexican system suffers some detection uncertainty due to the sparse coastal network used consisting of small number of stations.

Currently, the RRS of the CWB can routinely broadcast the location and magnitude of a strong earthquake as well as the distribution of intensity about 60 sec after the origin time of the earthquake. However, the 60 sec time lapse is still too long to be practical for earthquake early warning. Because of the elongated shape of Taiwan (about 350 km from north to south) and because most of the historical damaging events occurred in the middle and eastern offshore parts of the island, an effective warning time must be made less than 30 sec for it to be effective. For shortening the reporting of the RRS to achieve early warning function**.** Many studies include rapid magnitude determination, sub-network, and virtual sub-network approaches were developed by the CWB in recent years (Lee, 1995; Lee et al., 1996; Wu et al., 1998a, 1999; Wu and Teng, 2002).

3.1 **Rapid local magnitude determination**

Two major requirements for a seismic early warning system are the near real-time estimations of the earthquake location and magnitude. The first requirement on rapid location can be achieved readily in the 10-sec time window immediately following the first P-arrival. On the other hand, the second requirement of rapid determination of the earthquake magnitude would be more difficult because the shear wave trains may not be recorded completely within this time window, and, more importantly, since a damaging event is large, a M_w or its equivalent must be developed for damage potential assessment.

Thus, a method for quick M_w magnitude determination for large events needs to be developed. Many researchers (e.g., Nakamura, 1988; Grecksch and Kumpel, 1997; Tsai and Wu, 1997; Allen and Kanamori, 2003) have also tried to estimate magnitude from the initial portion of accelerograms, but large uncertainties are a major problem. Based on the current configuration of the RTD system and its monitoring area, we have developed an empirical method to reliably determine earthquake magnitude within 20 sec after the P-wave signals arrive at the nearest station.

Twenty-three sets of strong-motion data from moderate earthquakes ($M_L > 5.0$) in the Taiwan area are used to realize this goal. For earthquakes larger than M_L 5, epicenters can be reliably determined in about 15 sec after the arrival of the P wave from the nearest station**.** Figure 10 shows simulated Wood-Anderson seismograms from the 25 June, 1995 earthquake (M_L 6.5). In the beginning 10 sec, there are seven P phases and two S phases that can be used to locate the earthquake. The earthquake magnitude M_L cannot be determined in the same time frame due to incomplete recording of shear waves at some stations. However, the magnitude based on the first 10 sec of signal (M_{L10}) can be found to correlate with M_L (Fig. 11) as follows:

$$M_L = 1.28 * M_{L10} -0.85 \pm 0.13 \qquad \ldots(9)$$

By applying this method for magnitude determination that the CWB can determine epicenters and magnitudes with tolerable uncertainty in about 30 sec after occurrence of earthquakes and seismic early warning will become possible in Taiwan.

3.2 **Sub-network approach**

In order to explore the feasibility of an earthquake early warning system for Taipei, a prototype seismic early warning systems have been implemented in Hualien, about 120 km away. Through previous studies (Wu et al., 1997; Wu, 1999), we concluded that using a dense sub-network under RTD system is a good approach to shorten the reporting time, and thus gaining some earthquake early warning capabilities. Thus, a dense, real-time monitoring system with high-density station coverage in the Hualien area, and lesser density outside Hualien area (Fig. 12) was developed for testing earthquake early warning capability from sources in the Hualien area. The high-density station coverage in the Hualien was designed for recording shear waves to enhance magnitude determination and lesser density outside Hualien was for offering P arrivals to improve location quality.

For the 27 earthquakes occurred during August 1998 to April 1999, this system has successfully reported earthquake information in about 18 sec after the origin time with the location uncertainity under 10 km (Fig. 13). Therefore, it provided about 15 sec of early warning time before shear waves arrival in the Taipei urban area for Hualien area earthquakes.

3.3 **Virtual sub-network approach**

In an earlier experiment in Hualien, Taiwan, we have demonstrated that earthquake reporting time can be significantly shortened by using a smaller network (Wu et al., 1997, 1999; Wu, 1999). This leads to the design and configuration of a virtual sub-network (VSN) within the hardware system of the ongoing RTD network. The VSN**,** automatically configured by the monitoring system, is event-dependent and its configuration varies with time. By working with the VSN, we can substantially reduce the reporting time such that an effective earthquake early warning capability is becoming feasible.

In hypocenter and magnitude determinations, only stations close to the epicenter (less than 60 km) contribute crucial information. Within the framework of the RTD network, we choose to process only signals from a subset of the RTD stations that form a VSN network surrounding an event. As soon as the RTD is triggered by an event, the system automatically extracts a subset of the RTD input signal channels and configures a VSN with a 60-km radius centered on that event. Figure 14 also gives a number of possible VSN configurations; each normally consists of about a dozen stations. The extracted data stream for this event forms the basic VSN input data for the subsequent EWS work.

Signals of all stations within a 60-km radius are grouped and extracted through a Multi-IO-Board to form the VSN input, which will then be processed in parallel through the VSN software in a dedicated computer (Fig. 15). We have conducted a series of experiments to determine the optimum recording time for a 60-km radius network. Our results show that 10 sec is about the optimum. As soon, as the 10-sec waveforms are presented at the VSN system, they will be immediately processed to give simulated Wood-Anderson seismograms for magnitude determinations that, in turn, will generate an equivalent moment magnitude. Further reduction of this recording time will cause a significant reduction in the reliability and stability of the magnitude determinations, because insufficient length of large amplitude S waves is available. An increase of the recording time, on the other hand, will severely cut into the earthquake early warning time without a significant improvement on magnitude determination. The VSN system is programmed to continue the recording of the waveforms up to 10 sec after the first P arrival, then hypocenter and magnitude determinations will be carried out. Results are disseminated automatically to users through a Win/Popup Notification software. As a really large earthquake may have large dimensions and long rupture time, the above VSN processing can be repeated every few seconds to update the rupture escalation and event development. We shall incorporate this updating function into out future VSN software.

We have implemented the above VSN operation on the existing RTD network during the period from December 2000 to June 2001. A total of 54 earthquakes of magnitude M_L ranging from 3.5 to 6.3 were detected, real-time processed, and reported. This represents a 100% correct detection and reporting. If we assume that the off-line manual measurements give correct values, our VSN results give an average error of 4.2±7.3 km in epicenter, 4.5±5.5 km in focal depth, and an uncertainty of ±0.24 units in local magnitude. The reporting time Tr is 30-sec or less, with an average of about 22 sec.

4. Summary

For EWS, the CWB has achieved a short earthquake reporting time about 20 sec (Wu et al., 1998a, 1999; Wu and Teng, 2002)**.** This will offer earthquake early warning for metropolitan areas located more than one hundred km from the epicenter. For an event with the same location as the September 20, 1999 Chi-Chi, Taiwan, earthquake, the Taipei metropolitan area at 145 km**,** would have more than 20 sec of early warning time. Figure 16 shows the expected early warning times for an event like the Chi-Chi earthquake for all parts of Taiwan. The small triangles in Figure 16 give the locations of elementary schools, which essentially reflect the population density.

For RRS, the RTD system can offer information about one minute after an earthquake occurrence (Teng et al., 1997; Wu et al., 1997, 2000) and distributions of

PGA and PGV can also be mapped within two minutes (Wu et al., 2001). The empirical relationships between PGA, PGV and earthquake losses were also determined (Wu et al., 2002, 2003a, 2003b). Thus, The RTD system can achieve near real-time damage assessment in Taiwan for earthquake emergency response operations.

We are encouraged by the development of RRS and EWS systems based on the successful experience of the RTD system. However, the earthquake early warning information is not yet available for immediate public release in the current system. We realize that the release of an earthquake early warning will not produce social benefits unless there is a comprehensive program to educate the public on how to respond to a warning message, as discussed by Espinosa-Aranda et al. (2003). However, CWB's RRS and EWS messages are routinely transmitted electronically to cognizant governmental emergency response agencies and critical public facilities.

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Figure Captions

Figure 1 Distribution of the 82 TREIRS stations and the 650 TSMIP stations.

Figure 2 A block diagram showing the hardware of the RTD system.

Figure 3 A sample strong-motion record using in our analysis:

(A) The EW component strong motion signal from the TSMIP station TCU078 for the 1999/09/20 17:47 Mw7.6 Chi-Chi, Taiwan earthquake, recorded at 5.5 km form the rupture.

(B) The absolute amplitude computed from three components.

(C) The integrated Es values determined in this study.

Also shown are in (B) the maximum amplitude (Amax) and the definition of end-of-event time (the vertical line at about 40 sec mark). See text for details.

Figure 4 The *Mew* and M_L data as plotted again a 45^0 line of *Mew* = Mw.

Figure 5 Distribution of the end-of-event times for 2506 records used in this study.

Figure 6 The PGA and PGV site correction factor contour map of the TSMIP stations.

Figure 7 Maps A and B show the Chi-Chi main-shock PGA distribution from the predicted values, and the observed values, respectively.

Figure 8 (A) Relationship between fatality rate and PGA; (B) Relationship between total household collapse rate and PGA; (C) Relationship between partial household collapse rate and PGA.

Figure 9 (A) Relationship between fatality rate and PGV; (B) Relationship between total household collapse rate and PGV; (C) Relationship between partial household collapse rate and PGV.

Figure 10 Simulated Wood-Anderson seismograms showing peak readings in the first 10 sec (open circle) and 50 sec (open diamond) after the arrival of the *P* wave at the nearest station.

Figure 11 Correlation between the actual M_L and tentative M_{L10} using the first 10-secsignals on an accelerogram after the arrival of the *P* wave at the nearest station.

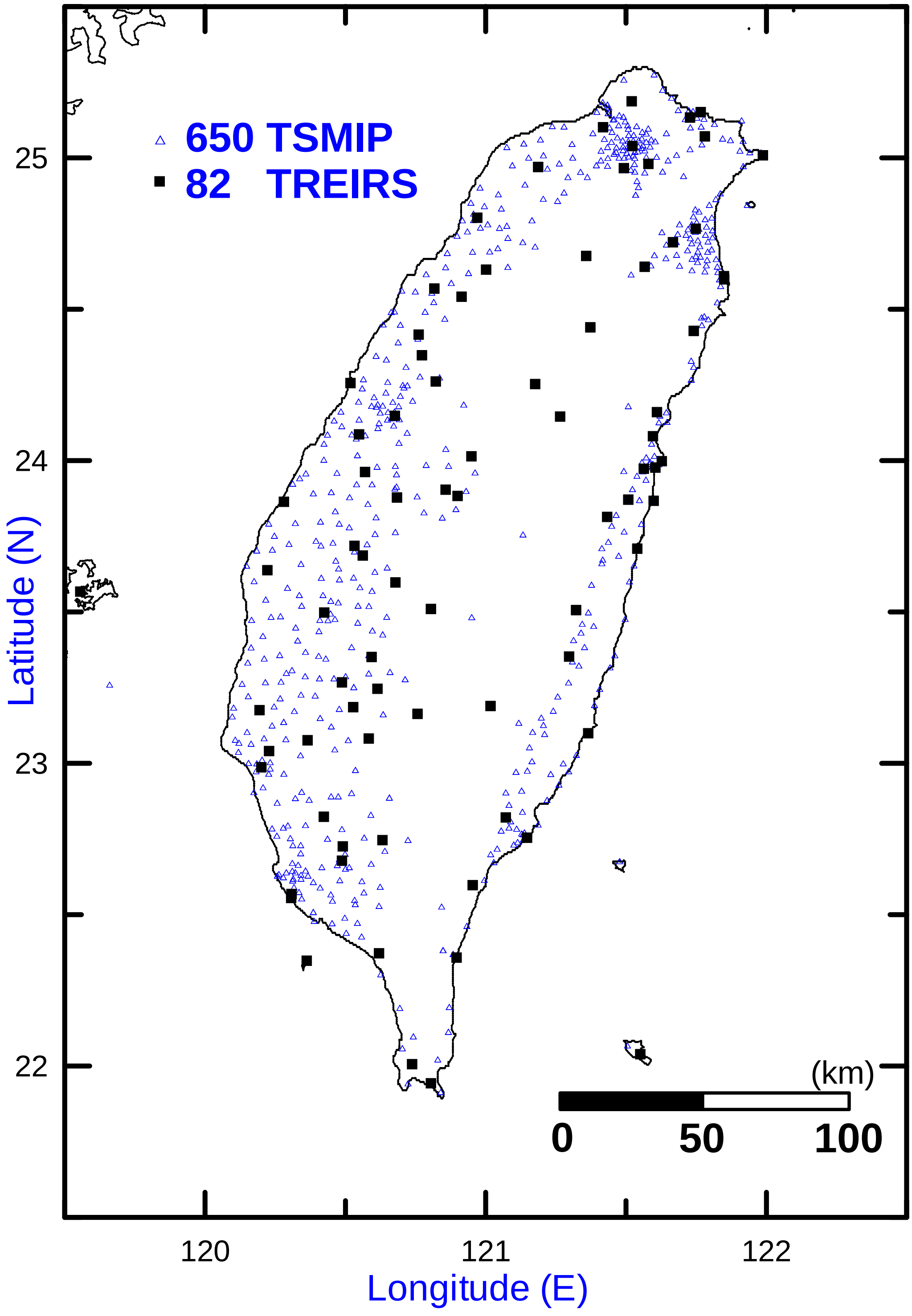
Figure 12 Station distribution of the Hualien sub-network.

Figure 13 Comparison of the automatic location and the manual location determined by the Hualien sub-network. The small solid squares are present the station location of this network.

Figure 14 Station distribution of the RTD system and sample VSN networks of 60-km radius configured by software from the RTD system. Each VSN network is centered at a hypothetical event in Taiwan. The star shows the 1999 Chi-Chi mainshock epicenter.

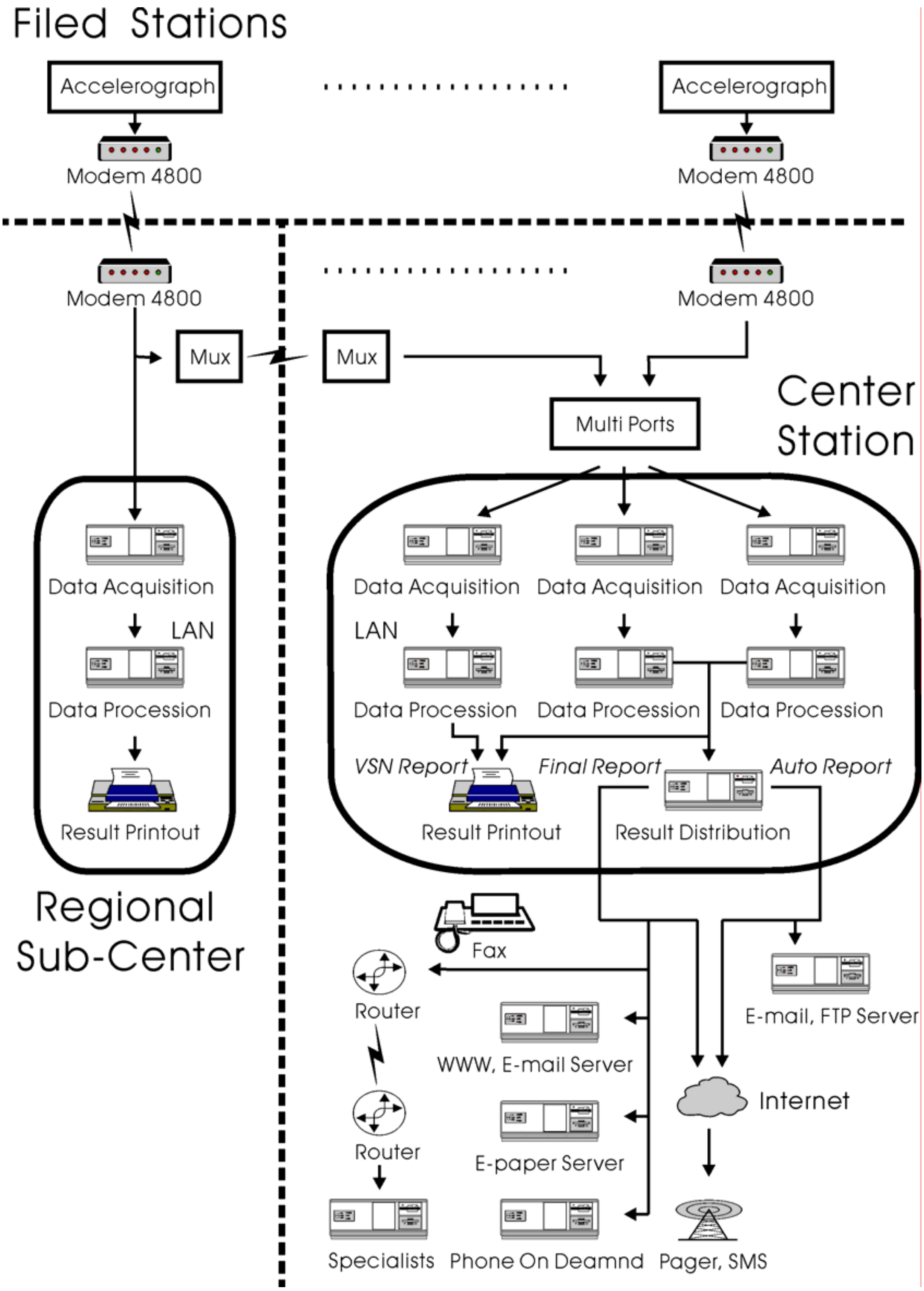
Figure 15 The RTD and VSN system hardware configuration.

Figure 16 Expected early warning times (indicated by circles) in Taiwan with respect to the occurrence of an event similar to the Chi-Chi earthquake of September 20, 1999. Triangles give the locations of elementary schools, which can be regarded as the population density of Taiwan.



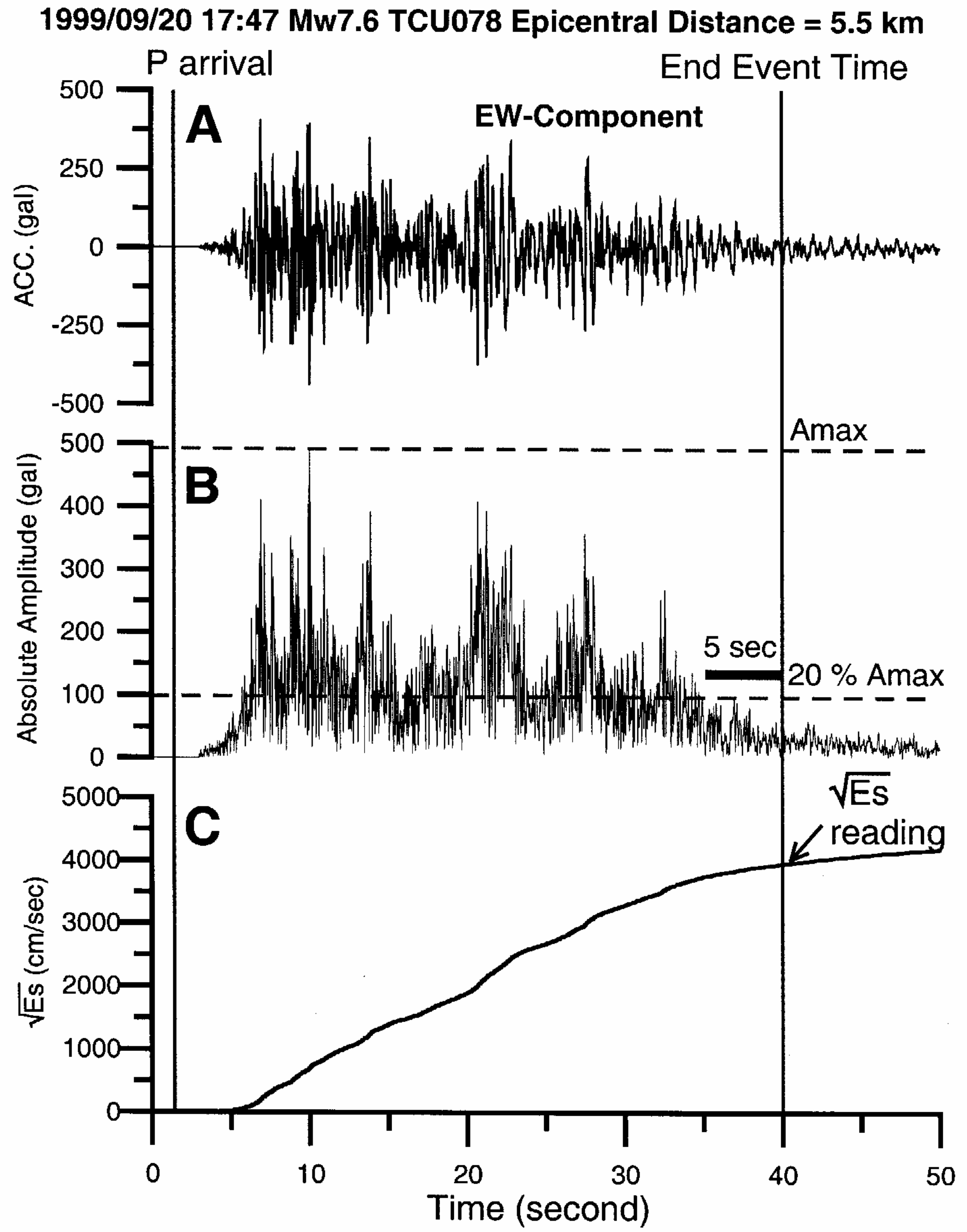
650 TSMIP
82 TREIRS
25
24
23
22
Latitude (N)
120
121
122
Longitude (E)
(km)
0
50
100

Figure 1



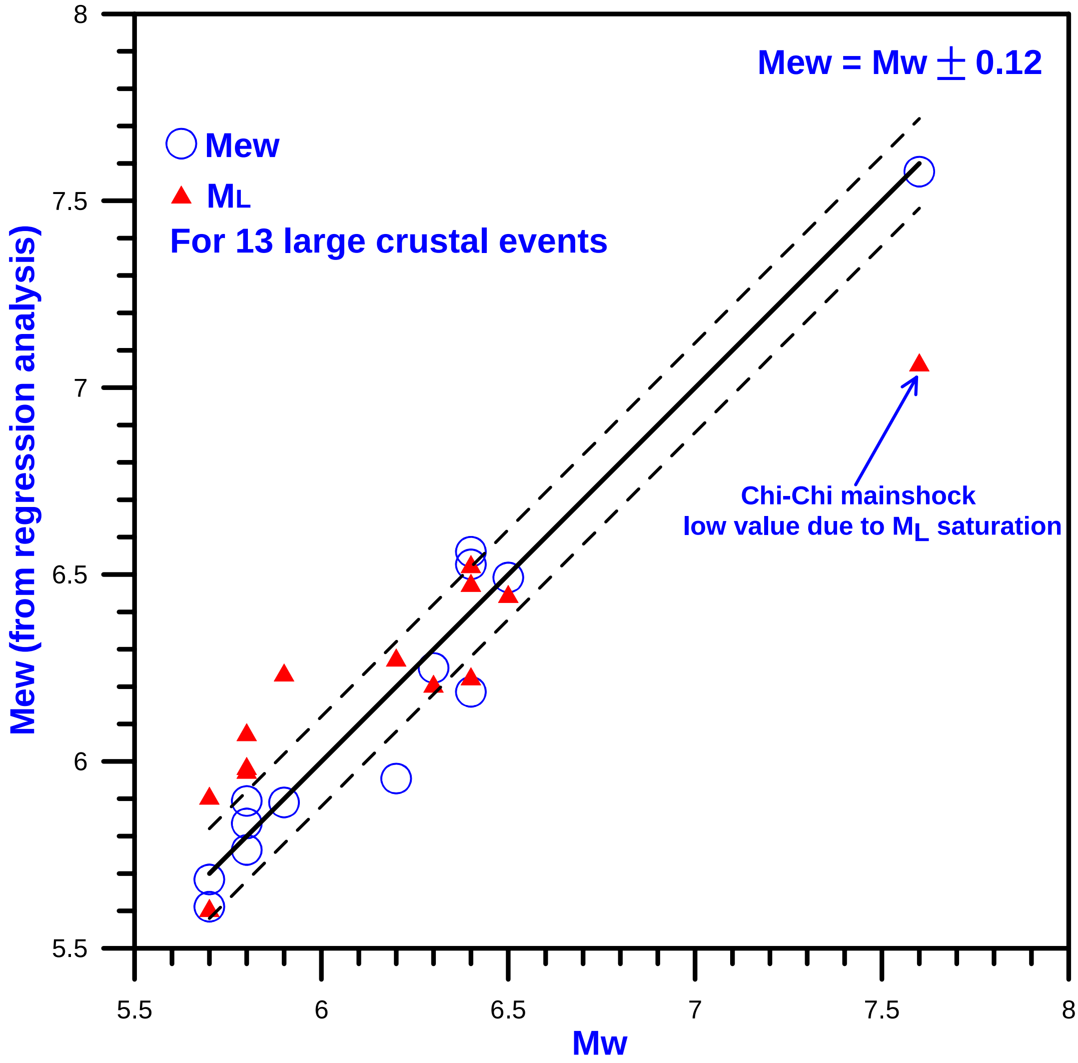
Filed Stations
Accelerograph
Accelerograph
Modem 4800
Modem 4800
Modem 4800
Modem 4800
Mux
Mux
Multi Ports
Center Station
Data Acquisition
LAN
Data Procession
Result Printout
Regional Sub-Center
Data Acquisition
Data Acquisition
Data Acquisition
LAN
Data Procession
Data Procession
Data Procession
VSN Report
Final Report
Auto Report
Result Printout
Result Distribution
Fax
Router
WWW, E-mail Server
E-mail, FTP Server
Router
Internet
E-paper Server
Specialists
Phone On Deamnd
Pager, SMS

Figure 2



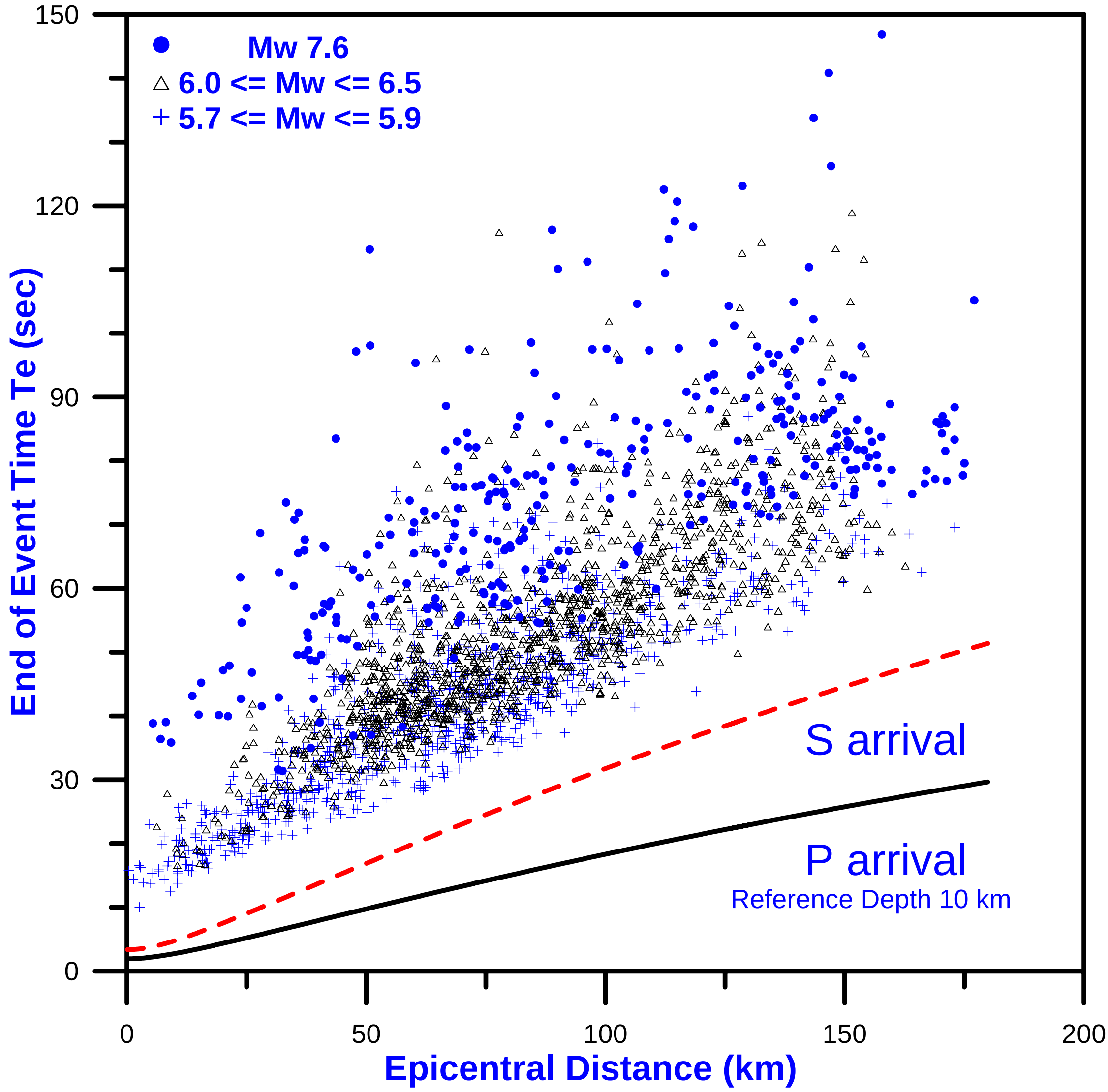
1999/09/20 17:47 Mw7.6 TCU078 Epicentral Distance = 5.5 km
P arrival
End Event Time
A
EW-Component
ACC. (gal)
500
250
0
-250
-500
B
Absolute Amplitude (gal)
Amax
5 sec
20 % Amax
400
300
200
100
C
√Es reading
√Es (cm/sec)
5000
4000
3000
2000
1000
0
10
20
30
40
50
Time (second)

Figure 3



Mew = Mw ± 0.12
Mew
ML
For 13 large crustal events
Chi-Chi mainshock
low value due to ML saturation
Mew (from regression analysis)
Mw
8
7.5
7
6.5
6
5.5
5.5
6
6.5
7
7.5
8

Figure 4



Mw 7.6
6.0 <= Mw <= 6.5
+ 5.7 <= Mw <= 5.9
S arrival
P arrival
Reference Depth 10 km
End of Event Time Te (sec)
Epicentral Distance (km)
0
30
60
90
120
150
0
50
100
150
200

Figure 5

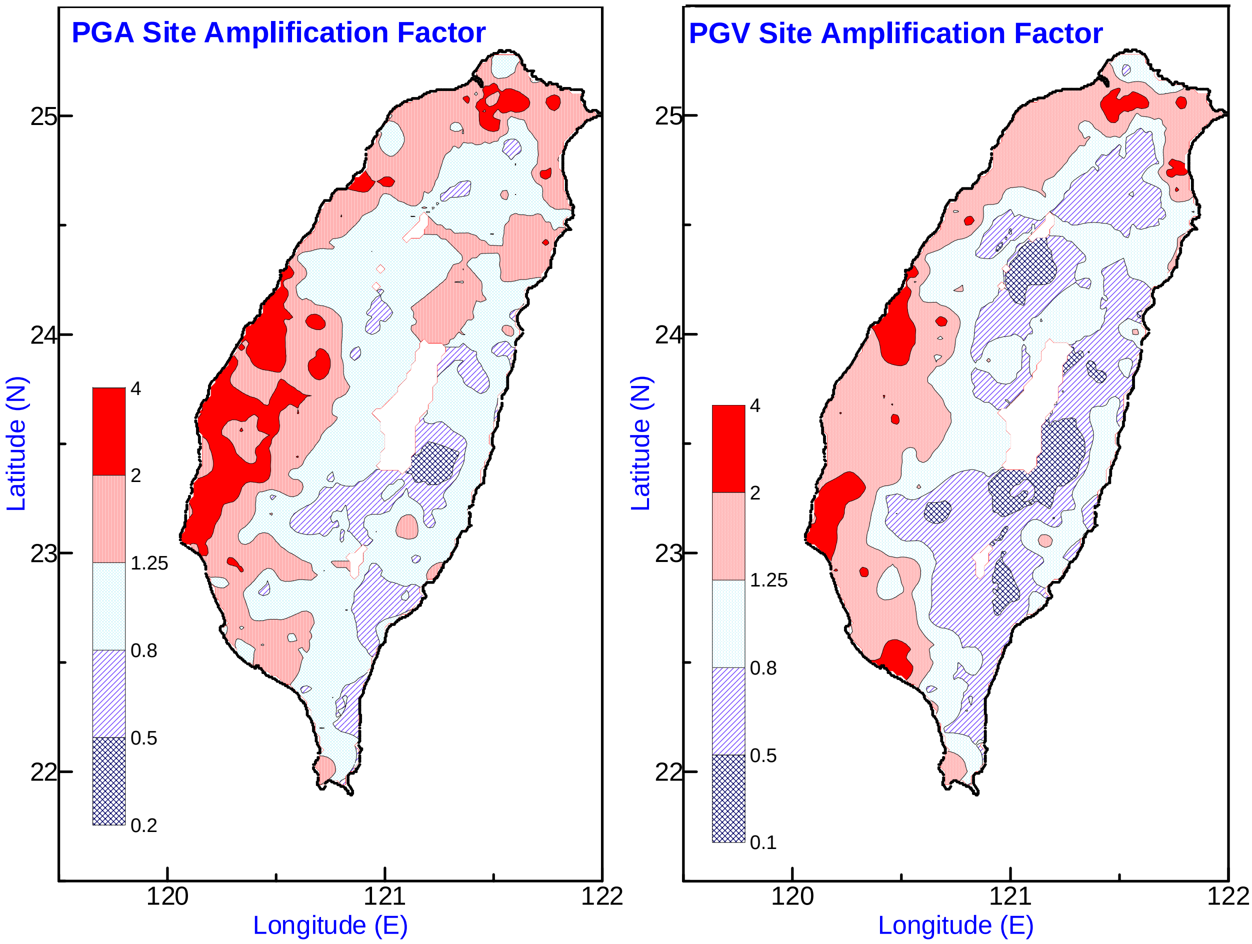

PGA Site Amplification Factor
PGV Site Amplification Factor
Latitude (N)
Longitude (E)
25
24
23
22
120
121
122
4
2
1.25
0.8
0.5
0.2
0.1

Figure 6

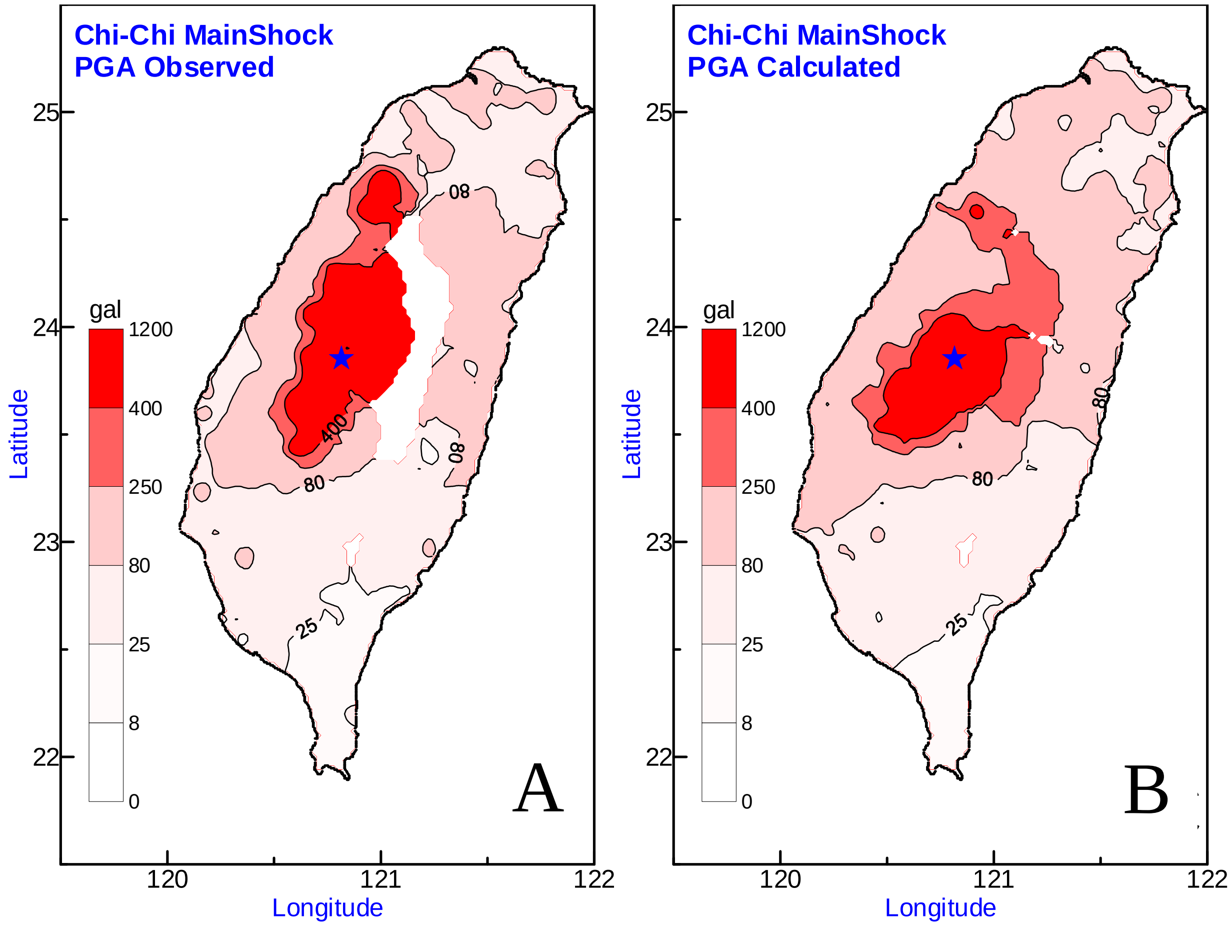

Chi-Chi MainShock
PGA Observed
gal
1200
400
250
80
25
8
0
Latitude
Longitude
25
24
23
22
120
121
122
80
400
25
A
Chi-Chi MainShock
PGA Calculated
80
25
B

Figure 7

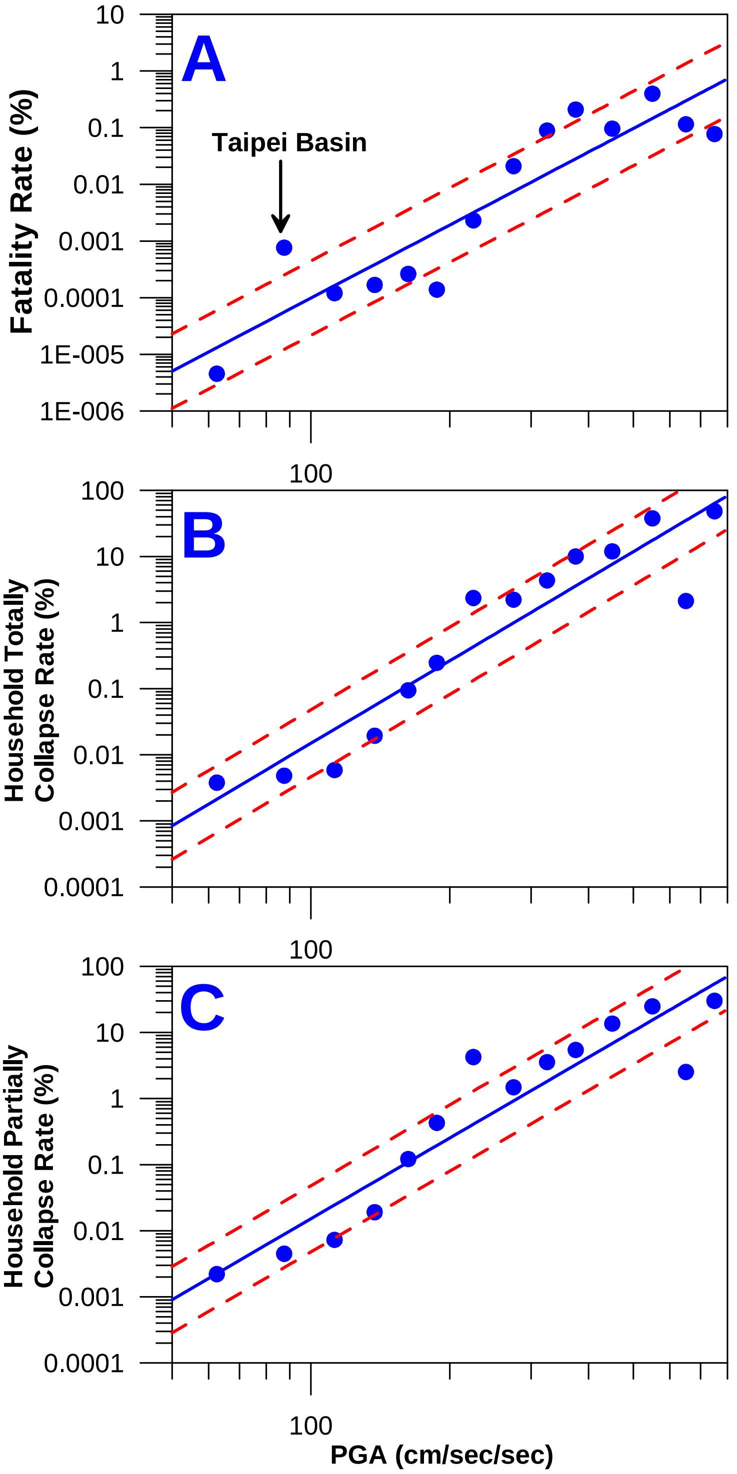

A
Taipei Basin
Fatality Rate (%)
10
1
0.1
0.01
0.001
0.0001
1E-005
1E-006
100
B
Household Totally Collapse Rate (%)
100
10
1
0.1
0.01
0.001
0.0001
100
C
Household Partially Collapse Rate (%)
100
10
1
0.1
0.01
0.001
0.0001
100
PGA (cm/sec/sec)

Figure 8

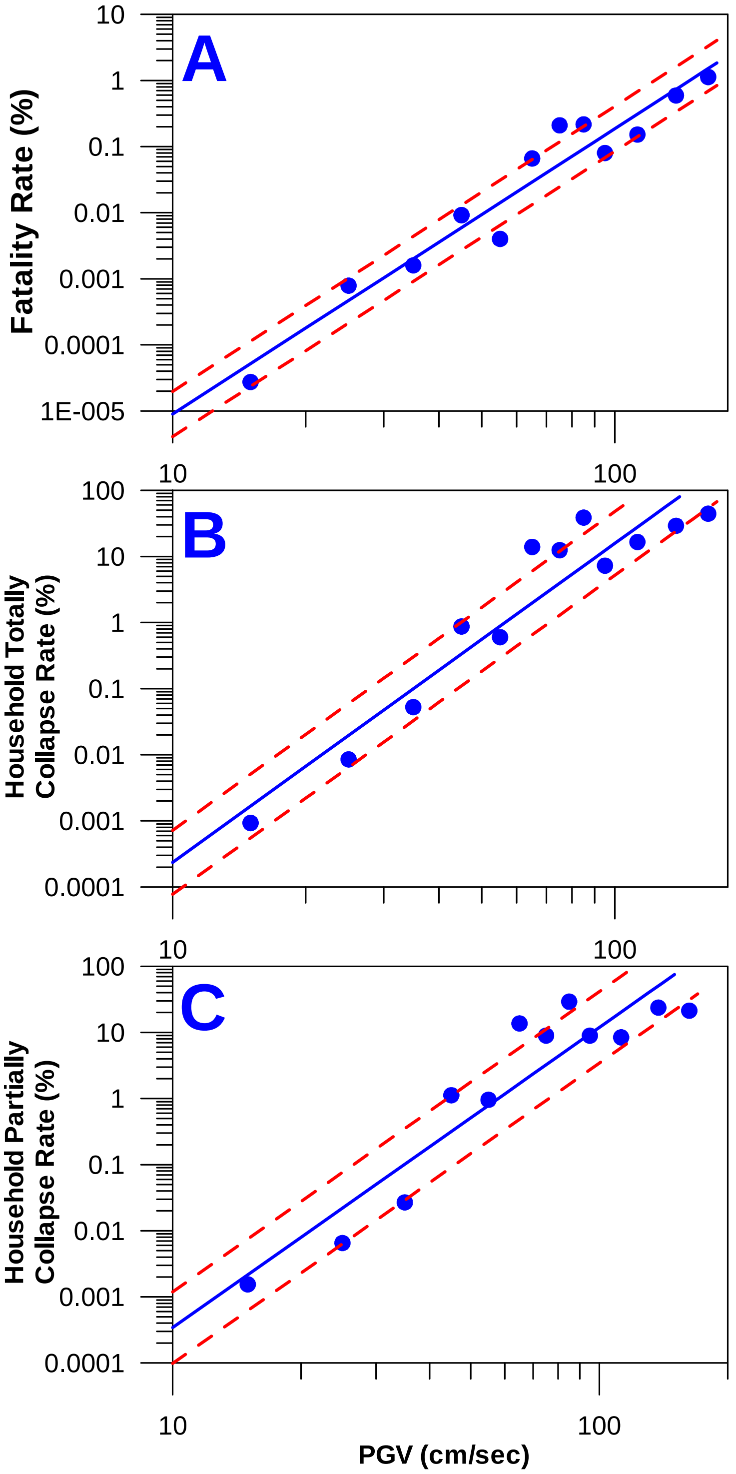

A
B
C
Fatality Rate (%)
Household Totally Collapse Rate (%)
Household Partially Collapse Rate (%)
10
1
0.1
0.01
0.001
0.0001
1E-005
100
10
100
PGV (cm/sec)

Figure 9

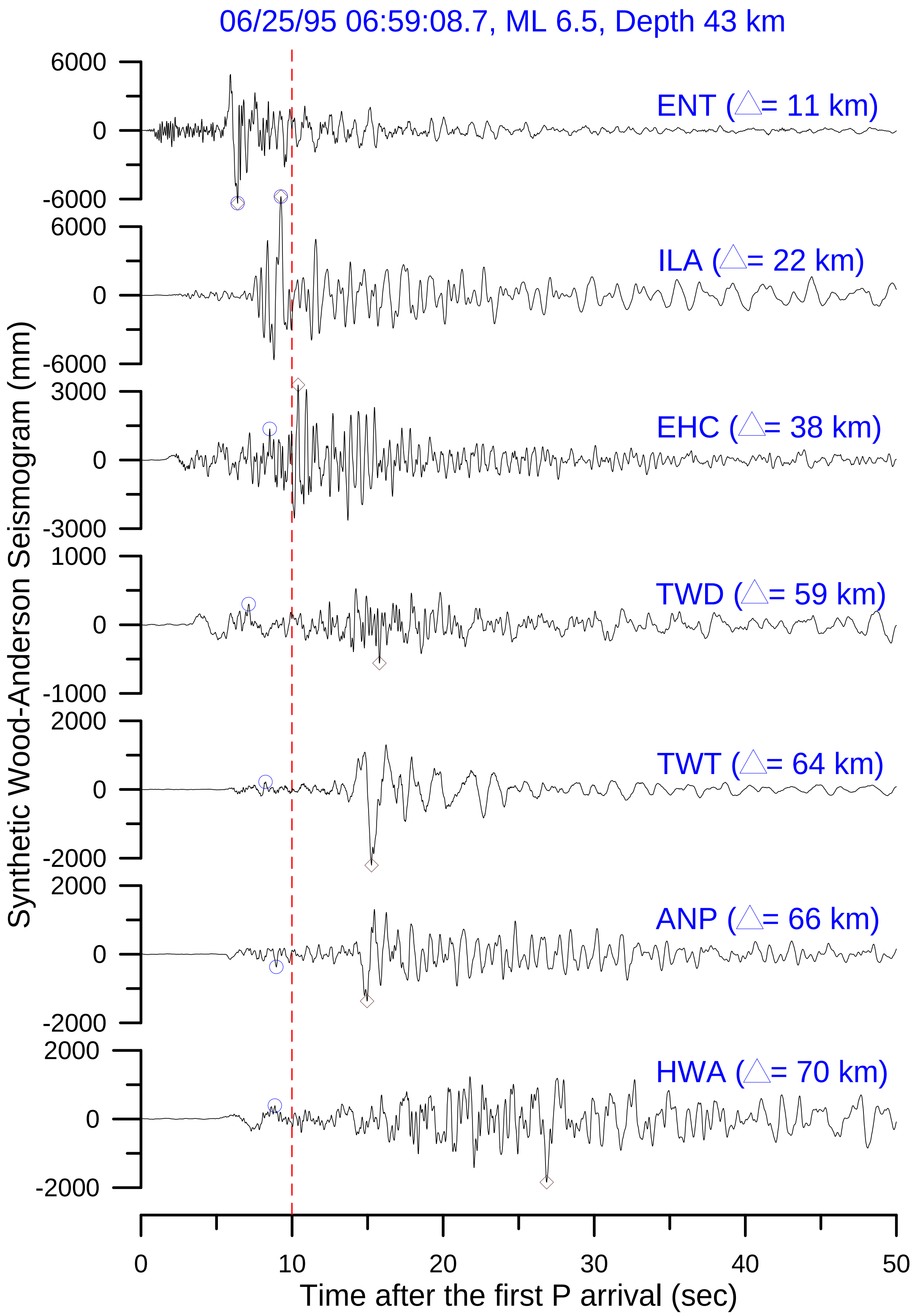

06/25/95 06:59:08.7, ML 6.5, Depth 43 km
ENT (△= 11 km)
ILA (△= 22 km)
EHC (△= 38 km)
TWD (△= 59 km)
TWT (△= 64 km)
ANP (△= 66 km)
HWA (△= 70 km)
6000
0
-6000
3000
-3000
1000
-1000
2000
-2000
Synthetic Wood-Anderson Seismogram (mm)
0
10
20
30
40
50
Time after the first P arrival (sec)

Figure 10

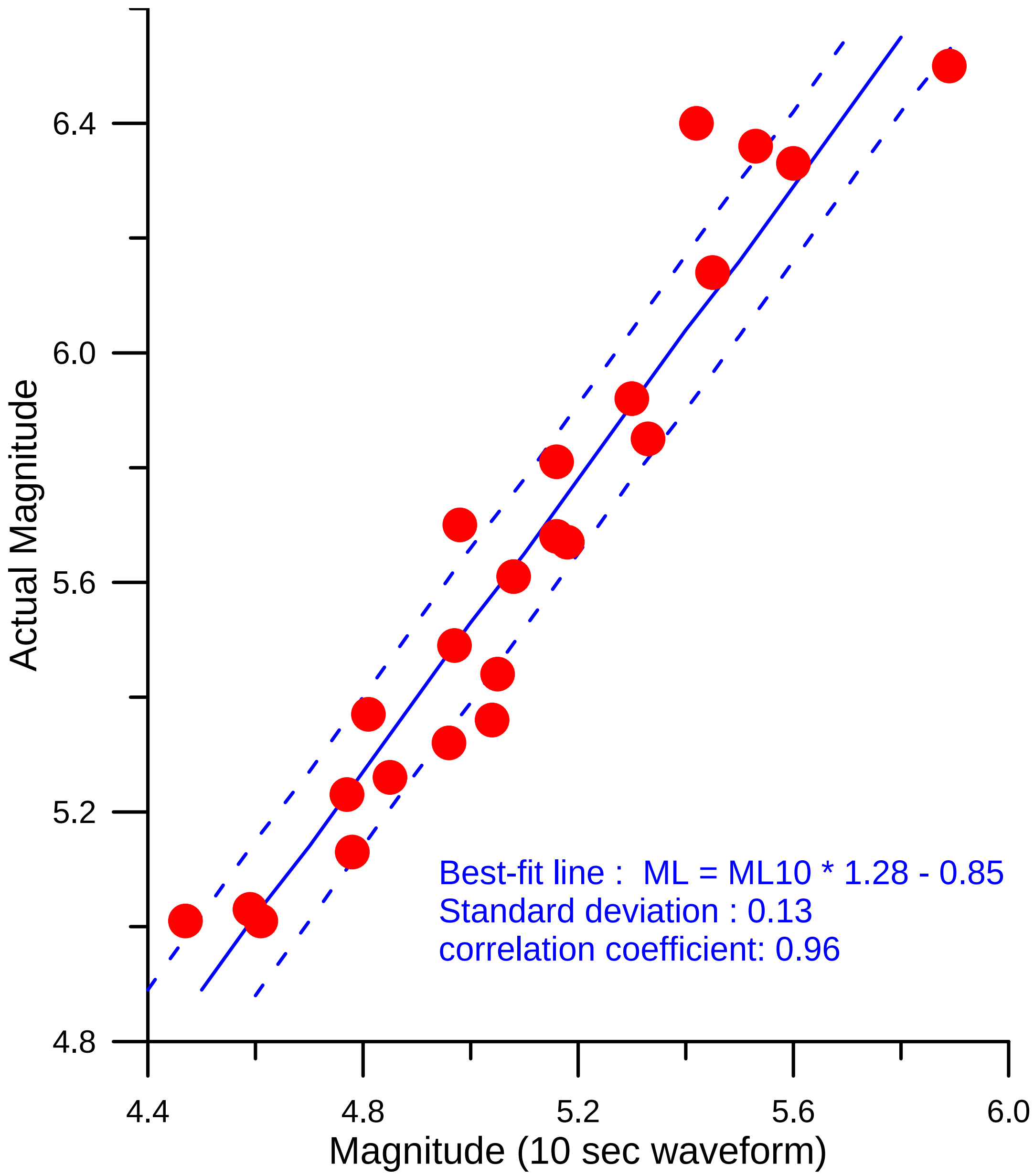
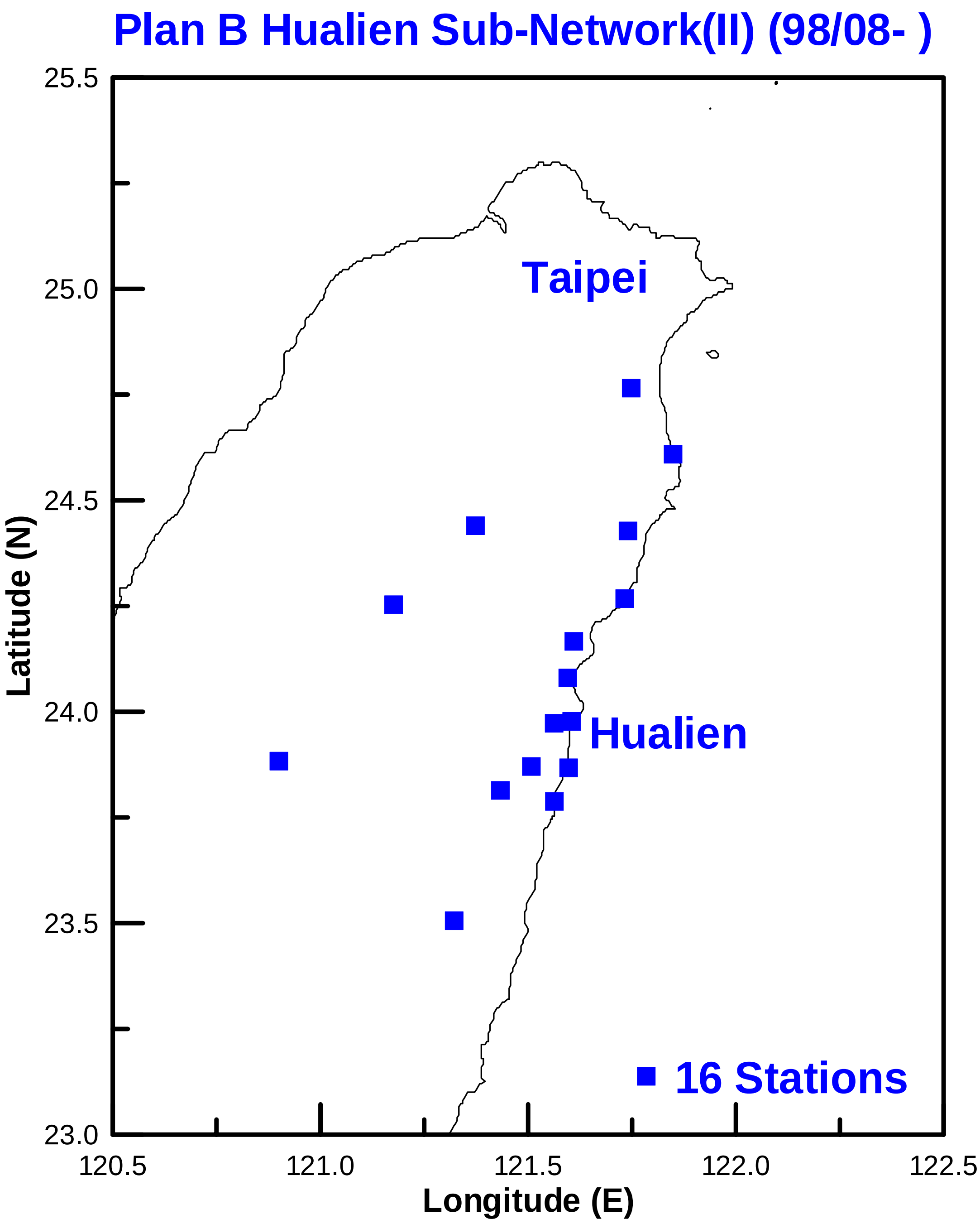

6.4
6.0
5.6
5.2
4.8
Actual Magnitude
4.4
4.8
5.2
5.6
6.0
Magnitude (10 sec waveform)
Best-fit line : ML = ML10 * 1.28 - 0.85
Standard deviation : 0.13
correlation coefficient: 0.96

Figure 11



Plan B Hualien Sub-Network(II) (98/08-)
25.5
25.0
24.5
24.0
23.5
23.0
Latitude (N)
120.5
121.0
121.5
122.0
122.5
Longitude (E)
Taipei
Hualien
16 Stations

Figure 12

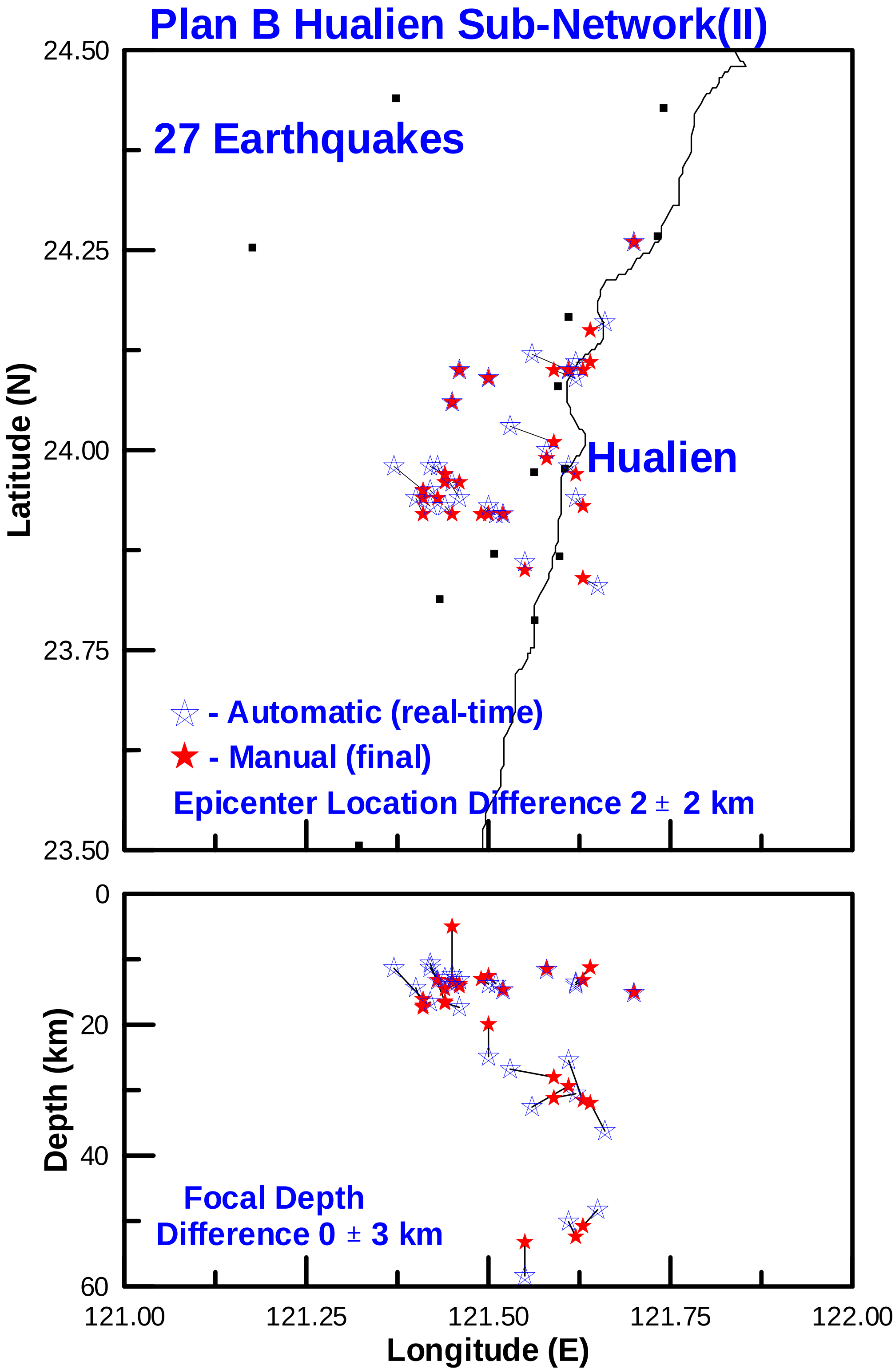
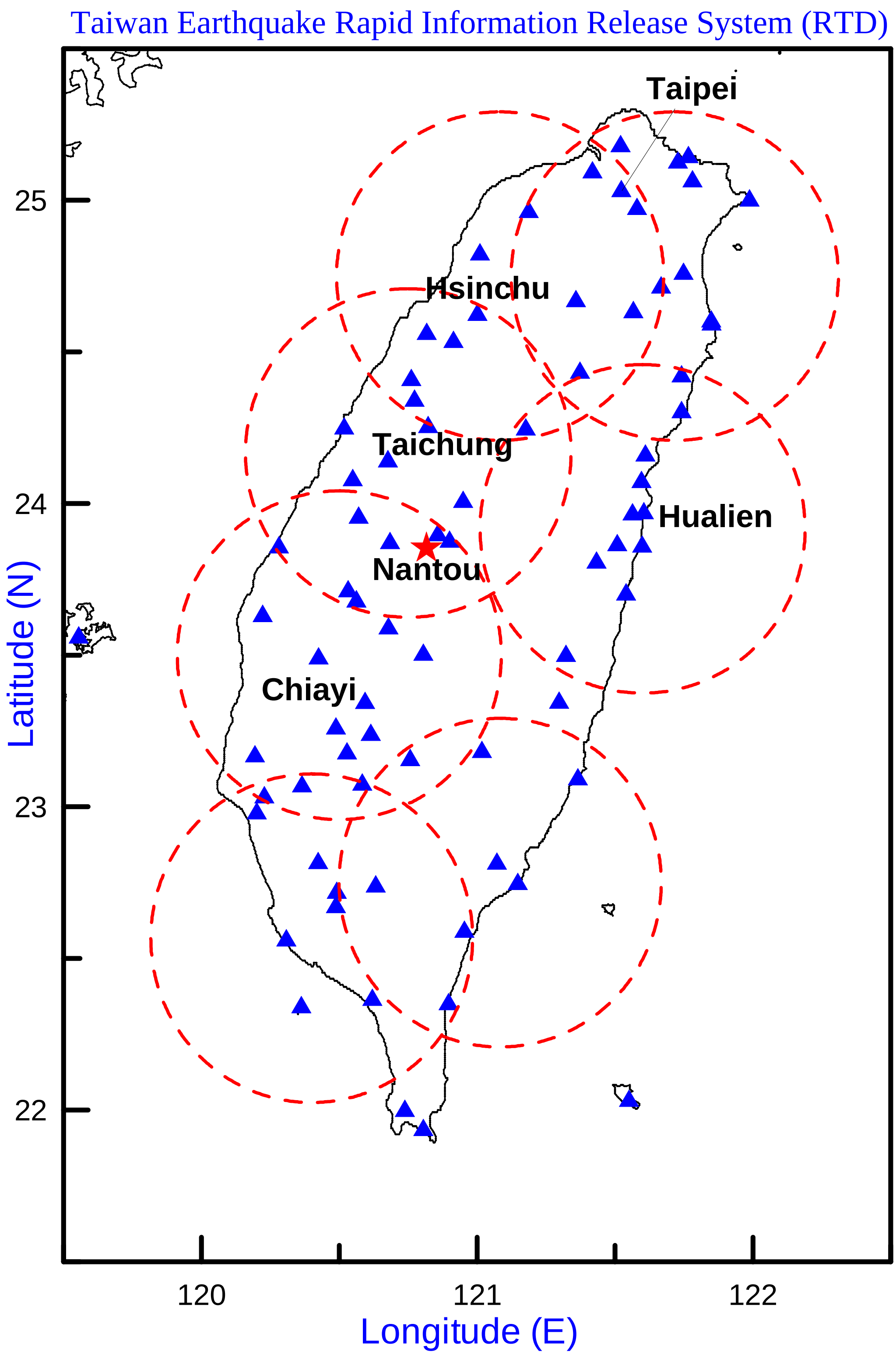

Plan B Hualien Sub-Network(II)
27 Earthquakes
Hualien
- Automatic (real-time)
- Manual (final)
Epicenter Location Difference 2 ± 2 km
Latitude (N)
24.50
24.25
24.00
23.75
23.50
Depth (km)
0
20
40
60
Focal Depth
Difference 0 ± 3 km
121.00
121.25
121.50
121.75
122.00
Longitude (E)

Figure 13



Taiwan Earthquake Rapid Information Release System (RTD)
Taipei
Hsinchu
Taichung
Hualien
Nantou
Chiayi
25
24
23
22
Latitude (N)
120
121
122
Longitude (E)

Figure 14

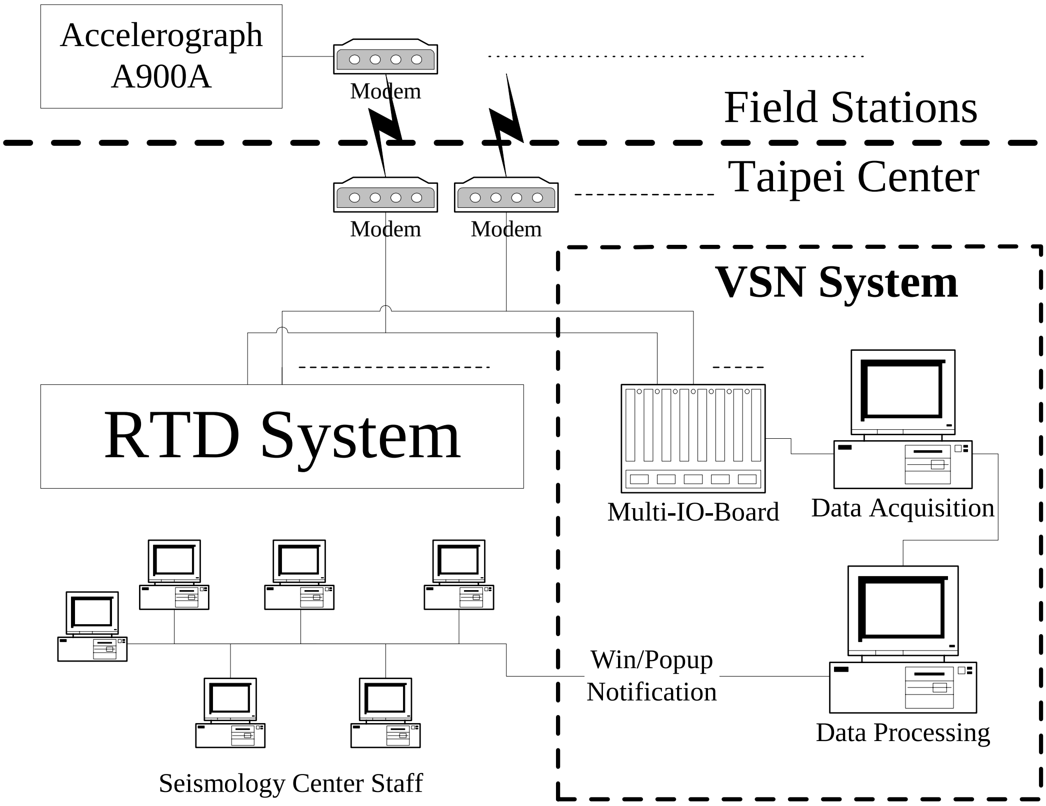

Accelerograph
A900A
Modem
Field Stations
Taipei Center
Modem
Modem
VSN System
RTD System
Multi-IO-Board
Data Acquisition
Win/Popup
Notification
Data Processing
Seismology Center Staff

Figure 15

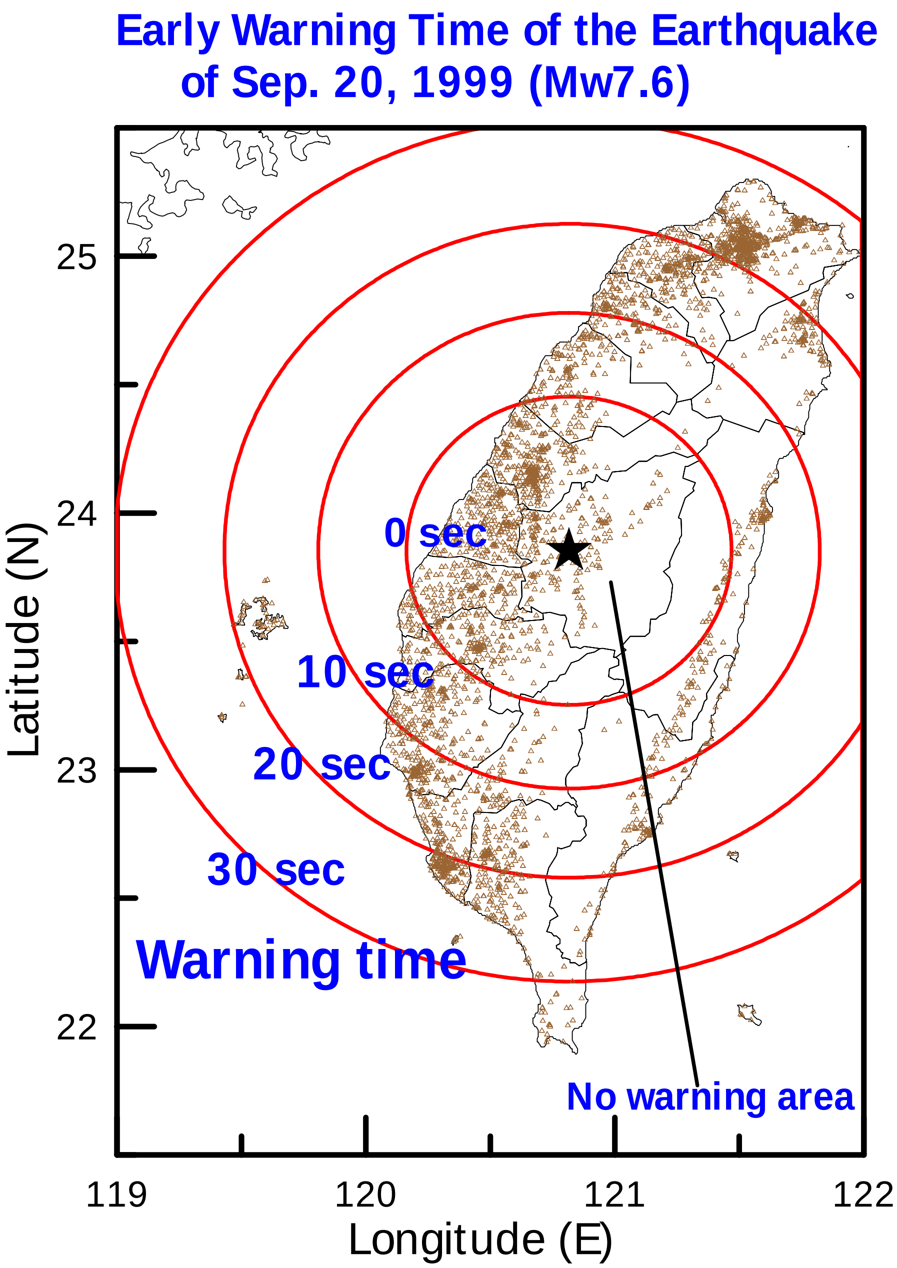

Early Warning Time of the Earthquake
of Sep. 20, 1999 (Mw7.6)
0 sec
10 sec
20 sec
30 sec
Warning time
No warning area
25
24
23
22
Latitude (N)
119
120
121
122
Longitude (E)

Figure 16