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Quick and Reliable Determination of Magnitude for Seismic Early Warning

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Abstract This article reports efforts toward using real-time earthquake monitoring by the Taiwan Central Weather Bureau to meet the needs of seismic early warning. Twenty-three sets of strong-motion data from moderate earthquakes ($M_L > 5.0$) in the Taiwan area are used to demonstrate the feasibility of 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 at the nearest station. 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 related to M_L as follows:

$$M_L = 1.28 * M_{L10} - 0.85 \pm 0.13.$$

Our results show that the real-time strong-motion system routinely used by the Central Weather Bureau can be used to determine epicenters and magnitudes in about 30 sec after occurrence of earthquakes in Taiwan. Such information hopefully can be used to reduce damage to society.

Introduction

From the view of seismic hazards mitigation, an early warning system is becoming one of the promising tools to reduce the loss caused by a damaging earthquake. Recently, a real-time strong-motion network was installed in the Taiwan area by the Central Weather Bureau (CWB) for monitoring purposes. In order to maximize the use of data from this network, a rapid earthquake information and early warning system is under active development. The aim of the system is to provide a warning time from a few to tens of seconds before the actual strong ground shaking caused by a large earthquake begins. The information will be useful to minimize property damage and loss of lives in metropolitan areas. Such an approach was motivated by the painful 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 tell the location and magnitude within 30 sec of a large earthquake that could threaten the area, then several seconds of advanced warning will be available for emergency response, such as slowing down rapid-transit vehicles and high-speed trains to avoid potential derailment, orderly shutoff of gas pipelines to minimize fire hazards, controlled shutdown of manufacturing operations to reduce potential loss, and safe-guarding computer facilities to save vital information.

The basic idea of an earthquake warning system for San Francisco was proposed 130 years ago by Cooper (1868). A modern approach for a computerized seismic alert network was published by Heaton (1985). In Japan, a method for earthquake early warning has been employed in bullet train operations for more than 20 years (Nakamura, 1989). 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 latest development of the Taiwan Rapid Earthquake Information Release System (TREIRS) has been presented recently in a series of published articles (Teng *et al.*, 1997; Wu *et al.*, 1997a, 1997b, 1997c). Currently, the system 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 part of the island, the effective warning time should be less than 30 sec.

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 because based on the Central Weather Bureau Seismic Network (CWBSN) station distribution (Fig. 1), at least six *P* and *S* phases will be available to locate an event in the 30-sec time window. 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. Thus, a method for quick magnitude determination needs to be developed.

Grecksch and Kumpel (1997) estimated magnitudes using the rise time of the first complete peak, the predominant period, and the related Fourier amplitude of the initial part of strong-motion signals. However, with this approach, the magnitude uncertainty can reach as much as ±1.35 for a single accelerogram and ±0.5 for more than eight accelerograms. Other researchers (e.g., Nakamura, 1988; Tsai and Wu, 1997) have also tried to estimate magnitude from the initial portion of accelerograms, but large uncertainties are still a major problem. Based on the current configuration of the CWBSN and its monitoring area, we present in this article an empirical method to reliably determine earthquake magnitude 20 sec after the *P*-wave signals arrive at the nearest station. This approach uses a real-time accelerograph network of 52 stations (Fig. 1) to locate and to determine the magnitude and intensity of an earthquake. The results can be further improved with the prediction of peak ground acceleration to achieve the goal of earthquake early warning.

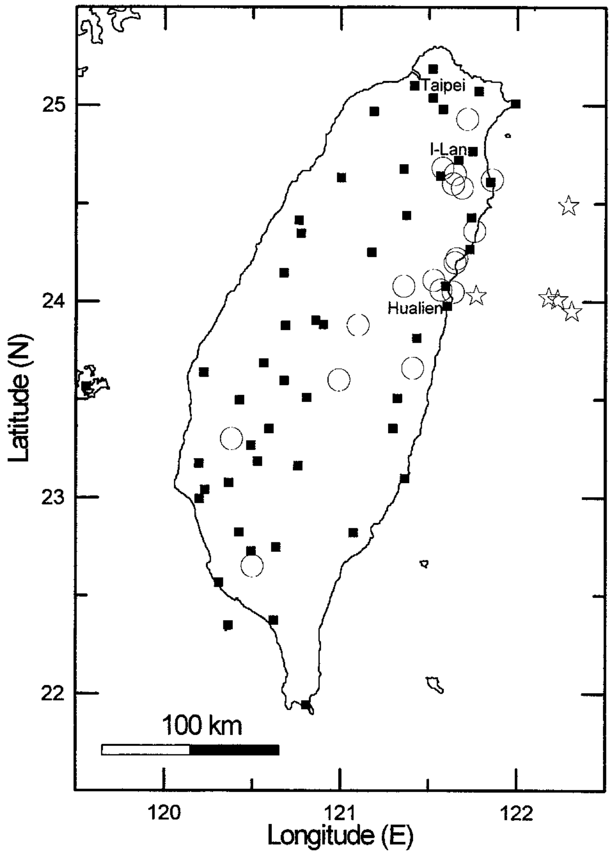

Figure 1. Stations of the Taiwan real-time strong-motion network (solid squares) and epicenters of selected earthquakes (open circles for gap $\leqq$ 180° and open stars for gap > 180°) used in this study.

Instrumentation

The CWB of Taiwan has deployed a modern digital accelerograph network. The network headquarters receives a continuous digital data stream input from 52 strong-motion stations on a real-time basis. At a digitization rate of 50 samples/sec, three channels of strong-motion data take up the 4800-baud band of the CWB leased telephone lines, whereas an additional 4800-baud band is used for transmitting short-period velocity data. A flow chart of the accelerograph network data processing is shown in Figure 2. For rapid earthquake information release, the incoming data are processed by the software package XRTPDB, written by Tottingham and Mayle (1994). Whenever a set of prespecified trigger criteria is met, digital waveforms are saved and analyzed by a series of programs for automatic phase picking using an algorithm similar to those developed by Allen (1978, 1982) and McEvilly and Majer (1982), and for automatic earthquake location (Wu *et al.*, 1998). The local magnitude (M_L) is calculated by simulating the Wood–An-

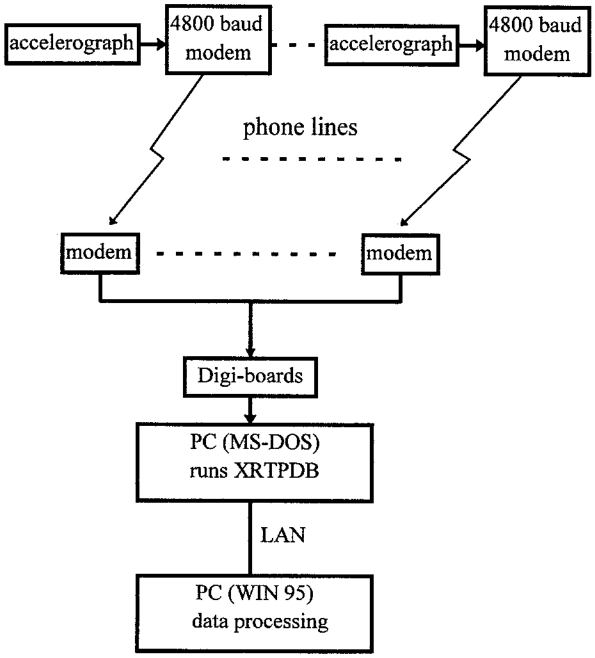

Figure 2. Block diagram showing the data processing system of the real-time strong-motion network of Taiwan.

derson seismograms from accelerograms and the attenuation correction factors determined by Shin (1993). Testing of the system began in January 1995. Thus far, more than 500 events have been recorded and processed. The results have proved that the system is capable of reporting earthquake information within 60 sec after their origin time (Wu *et al.*, 1997b).

Data Analysis and Results

The 23 larger and better-located events were selected for use in this study (Fig. 1 and Table 1). The selection criteria were $M_L > 5.8$ and gap $< 275°$ or $M_L > 5.0$ and gap $< 180°$, where gap represents the azimuthal range around an epicenter without station coverage in the location process (Lee and Lahr, 1975). The events occurred in 1995 and 1996 and were widely felt in Taiwan. A prerequisite for good magnitude determination is to have a reliable earthquake hypocenter location. Figure 3 shows the hypocenter coordinate adjustments as function of time determined by the autolocation process for the 18 events with gap $< 180°$ listed in Table 1. In general, the earthquake hypocenter location becomes stable in about 10 sec after the nearest station receives the P-wave arrival. During the same time frame, the magnitude adjustment fluctuates and decreases significantly as the shear waves at more stations become available (Fig. 4). After about 20 to 30 sec of the first P arrival, the magnitudes become stable for most of the 18 earthquakes.

Figure 5 shows simulated Wood–Anderson seismo-

Table 1
Earthquake Data Used in This Study

Origin	Time	Lat. (N)	Lon. (E)	Depth (km)	*N*sta	Gap	M_L	M_{L10}
01/10/95	07:51:16.12	23.66	121.41	15	12	170	5.23	4.77
02/23/95	05:19:12.15	24.22	121.66	18	25	139	6.33	5.60
03/24/95	04:13:52.14	24.62	121.86	79	24	180	5.81	5.16
04/03/95	11:54:47.98	23.95	122.31	16	25	230	5.92	5.30
04/24/95	10:04:01.52	24.65	121.65	63	28	60	5.44	5.05
06/25/95	06:59:08.74	24.58	121.69	43	36	84	6.50	5.89
07/07/95	03:04:48.29	23.88	121.10	15	28	49	5.61	5.08
07/14/95	16:52:47.89	24.36	121.76	6	23	178	5.70	4.98
08/20/95	09:25:05.36	24.68	121.58	55	23	55	5.13	4.78
10/31/95	22:27:08.11	23.30	120.38	8	25	88	5.37	4.81
12/01/95	03:17:04.86	24.60	121.64	45	33	65	5.85	5.33
12/18/95	16:17:54.49	24.05	121.64	19	33	173	5.68	5.16
12/20/95	23:56:37.09	24.03	121.77	33	30	194	5.26	4.85
01/22/96	19:22:59.33	24.93	121.72	64	29	108	5.32	4.96
03/05/96	14:52:29.00	24.01	122.23	4	40	224	6.36	5.53
03/05/96	17:32:11.50	24.02	122.18	7	40	221	6.14	5.45
05/28/96	21:53:24.61	24.11	121.53	17	34	88	5.36	5.04
06/09/96	01:30:27.91	24.06	121.57	45	29	106	5.03	4.59
07/06/96	01:27:09.08	22.65	120.50	36	22	88	5.49	4.97
07/29/96	20:20:56.94	24.49	122.29	59	30	253	6.40	5.42
10/09/96	09:29:11.02	23.60	120.99	3	31	44	5.01	4.47
11/26/96	08:22:23.95	24.20	121.65	20	33	145	5.67	5.18
12/15/96	18:56:27.07	24.08	121.36	63	35	51	5.01	4.61

*N*sta: Number of recording stations.

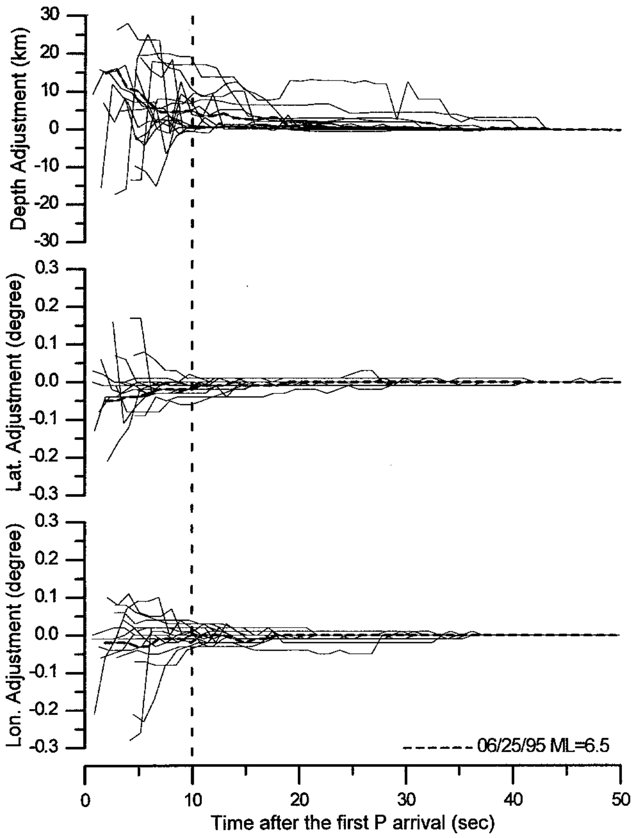

Figure 3. Hypocenter coordinate adjustments for the 18 events as function of time from the arrival of the P wave at the nearest station.

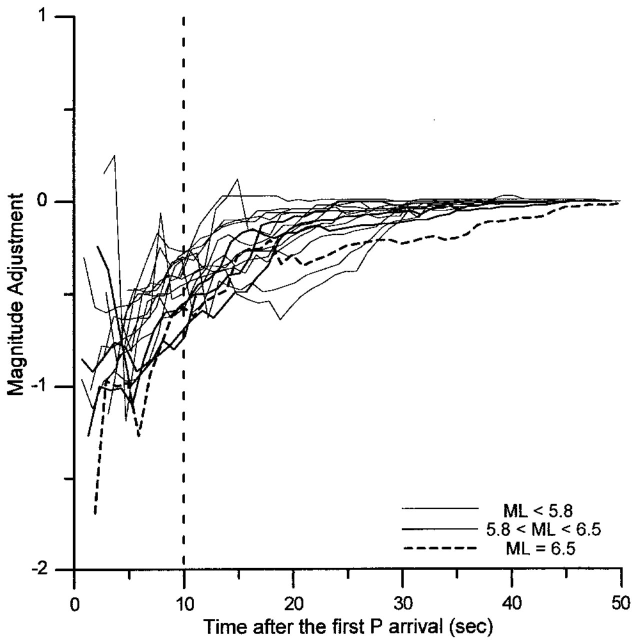

Figure 4. Magnitude adjustments for the 18 events as function of time from the arrival of the P wave at the nearest station.

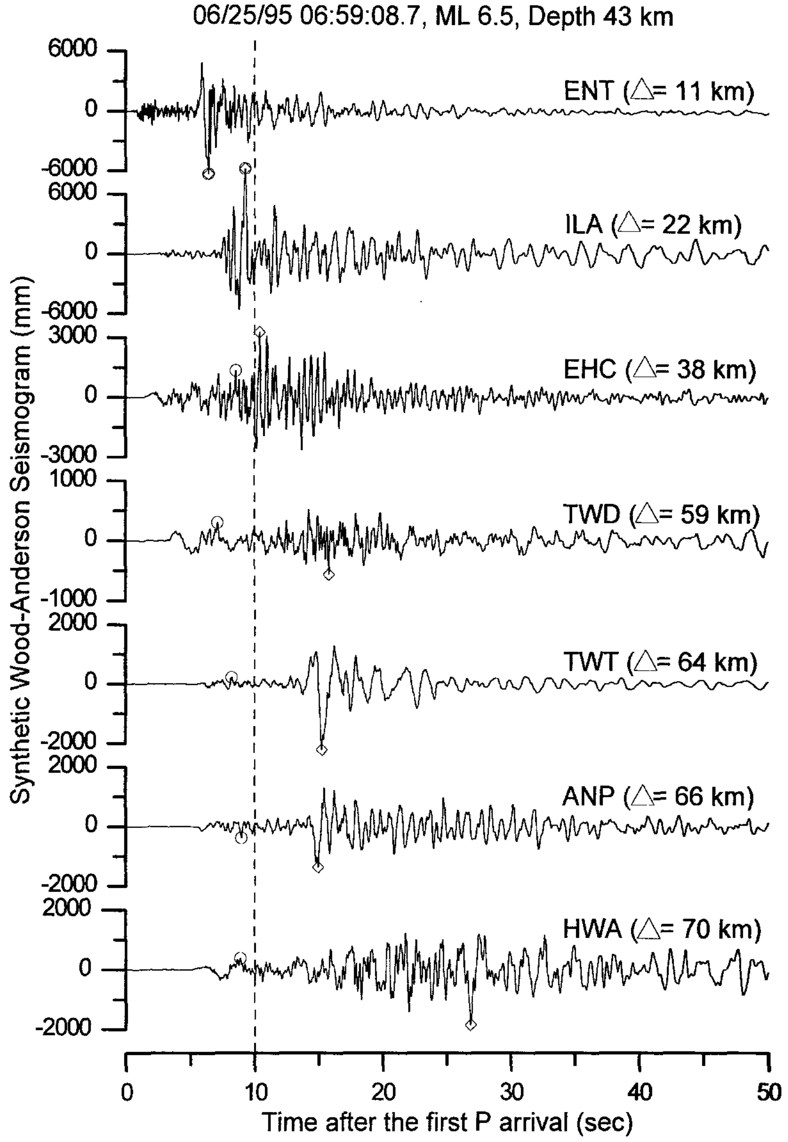

Figure 5. Simulated Wood–Anderson seismograms showing peak readings in the first 10 sec (open circle) and 50 sec (open diamond) after the arrival of the *P* wave at the nearest station.

grams 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 location results are reasonably good, as judged from the location adjustments for this event shown in Figure 3 (dashed lines). The determination of local magnitude depends on both the peak amplitudes of Wood–Anderson seismograms and the epicentral distance. Figure 4 shows the magnitude adjustments for this event (dashed line). The large variation in magnitude adjustments is due to the fact that such a large event has triggered more distant stations that have not yet provided complete shear wave information in the beginning time window used for calculation of the magnitude.

Generally speaking, Figure 4 indicates that larger events have larger magnitude-adjustment values than smaller events in the beginning 30-sec time window. A couple of small events also have large magnitude adjustments between 15 and 30 sec after the first *P*-wave arrival due to error in the automatic location. Therefore, even though the location becomes stable at about 10 sec after the first *P*-wave arrival, our system is not effective to determine the final local magnitude within this time period. However, since small earthquakes generally have smaller adjustments and large earthquakes have larger adjustments in the beginning time window, it seems that there is a relationship between the final magnitude and the tentative magnitude determined in the beginning period. To test this concept, we cut off the waveforms of the 23 events at 10 sec after the *P*-wave arrival at the nearest station, then located the events manually to reduce the magnitude bias caused by the automatic location error, and simulated the Wood–Anderson seismograms to determine tentative magnitude values, which we call M_{L10}. Figure 6 shows that M_{L10} and the actual local magnitude (M_L) are linearly related. The equation of the corresponding least-squares line is

$$M_L = 1.28 * M_{L10} - 0.85 \pm 0.13. \qquad (1)$$

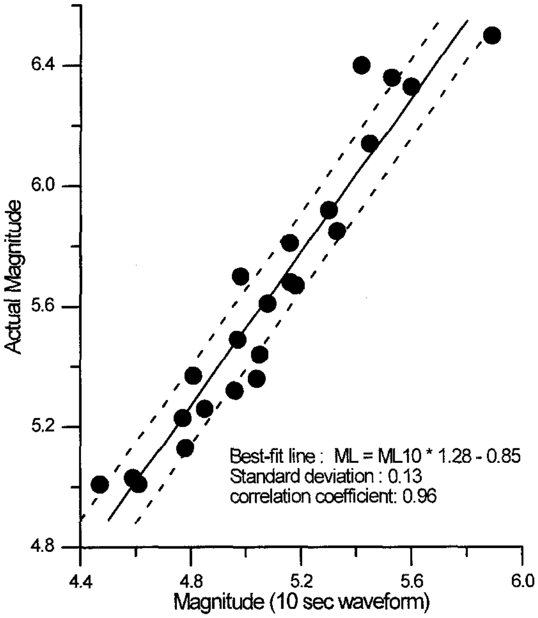

Figure 6. Correlation between the actual M_L and tentative M_{L10} using the first 10-sec signals on an accelerogram after the arrival of the P wave at the nearest station.

The correlation coefficient has a high value of 0.96. The slope of 1.28 clearly indicates that small earthquakes have smaller adjustments and big earthquakes have bigger adjustments at 10 sec after the first P arrival. Such quick and reliable information about an earthquake magnitude can be very useful for early warning to regions located beyond about 30 km from large earthquakes.

Discussion and Conclusions

A data acquisition PC in our system runs XRTPDB in trigger mode. Typically, an earthquake will trigger the system at 1 to 2 sec after the nearest station receives the first P-wave arrival because of a relatively dense network coverage. If we set the continuous recording time after triggering at 8 sec, we can get the first 10-sec waveforms after the first P-wave arrival. Using a fast Pentium II PC, we only need about 3 to 5 sec for autolocation processing. Thus, we can determine the hypocenter and magnitude of an earthquake simultaneously within 15 sec after the P-wave arrival at the nearest station.

Two examples are shown in Figure 7. In the first case, the 18 December 1995, M_L 5.7 earthquake (Table 1) was located in the Hualien area. The Taipei area is 115 km away.

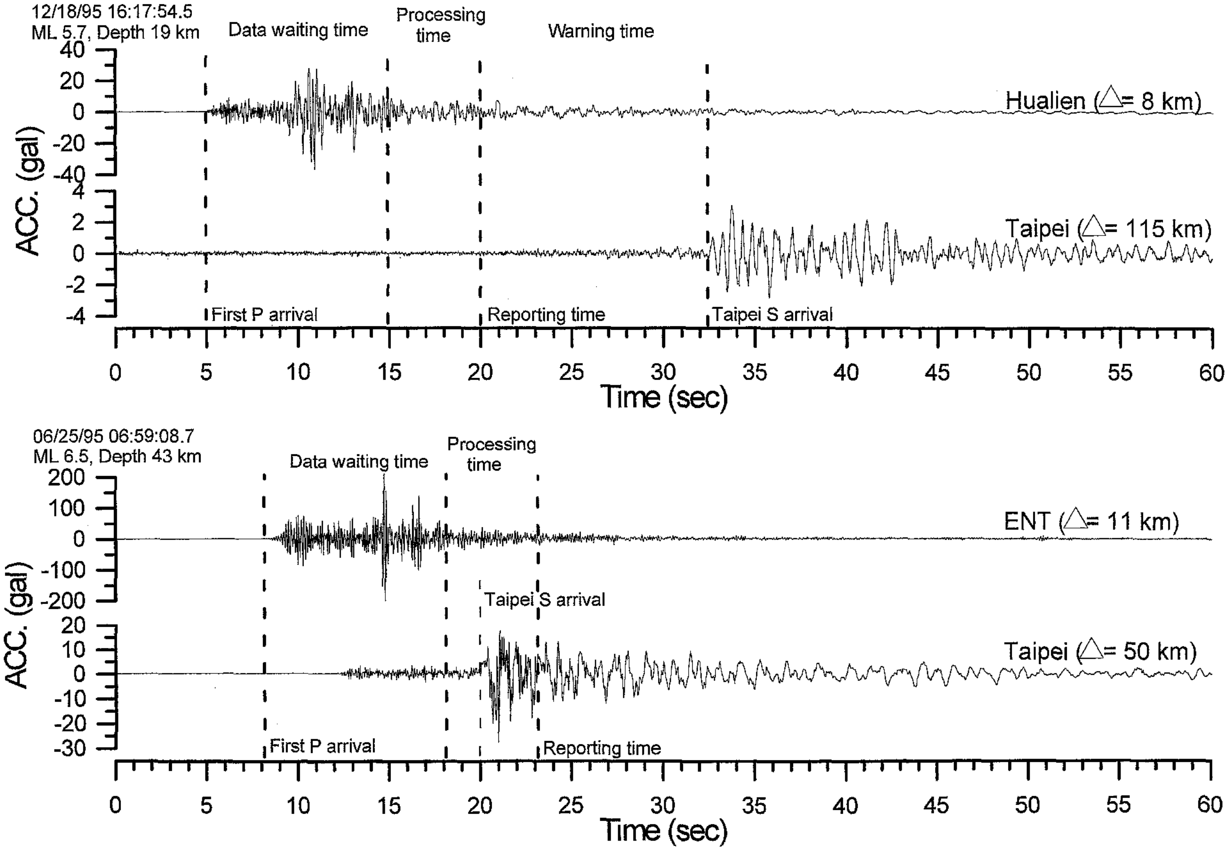

Figure 7. Two examples of real-time accelerograms showing recording and processing times to determine the earthquake location and magnitude for seismic early warning for Taipei City.

The *P* wave arrived at the nearest station 5 sec after the origin time. The earthquake information can be reported in 20 sec. Therefore, warning information can be issued about 12 sec in advance of the *S*-wave arrivals at the Taipei area. In the second case, the epicenter of the 25 June 1995, M_L 6.5 earthquake is located at about 40 km depth and only about 50 km away from the Taipei area. In this case, because of the short epicentral distance, the *S* wave arrived at the Taipei area while the information was being processed. Therefore, in cases like this, it is not possible to provide an early warning.

In summary, we have demonstrated the feasibility of using the real-time accelerograph network in Taiwan for early warning. It is possible to reliably determine the hypocenter and M_L magnitude of a large earthquake in about 30 sec after its initiation. The empirical method for magnitude determination proposed in this article can provide quick and reliable determination of an earthquake magnitude, which is important for seismic early warning. The results obtained in this study are based on the current system routinely used by the CWB. Obviously, the configuration of a seismic network, including the number of stations and the density of station distribution, is important to perform such tasks. Understanding the regional seismicity, in particular, the distribution of potentially damaging earthquakes, can guide the optimal layout of a network for seismic early warning.

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