Taiwan Rapid Earthquake Information Release System

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INTRODUCTION

Interest in rapid access to earthquake information has grown enormously in the past few years (Gee *et al.*, 1996; Teng *et al.*, 1997; Wu *et al.*, 1997). In addition to satisfying the public and media needs, rapid notification programs provide valuable information for rapid earthquake disaster response, thereby mitigating the loss. Recognizing the importance of rapid earthquake information for seismic hazard mitigation, efforts to design and implement systems to provide rapid earthquake information have expanded over the last 10 years (Heaton, 1985; Nakamura and Tucker, 1988; Buland and Person, 1992; Romanowicz *et al.*, 1993; Bakun *et al.*, 1994; Espinosa Aranda *et al.*, 1995; Lee *et al.*, 1996; Shin *et al.*, 1996; Teng *et al.*, 1997; Wu *et al.*, 1997).

In 1989, a telemetered, digital, short-period seismograph network of 75 three-component field stations was installed in Taiwan (see Figure 1) using Teledyne Geotech 1-Hz short-period sensors (Teledyne S13). The signals are digitized at 12-bit resolution and telemetered using 4800-baud modems on leased telephone lines to the Central Weather Bureau (CWB) headquarters in Taipei. The incoming data are processed by Vax 6500/4400 computers with software written by the CWB staff for manual phase picking and earthquake location.

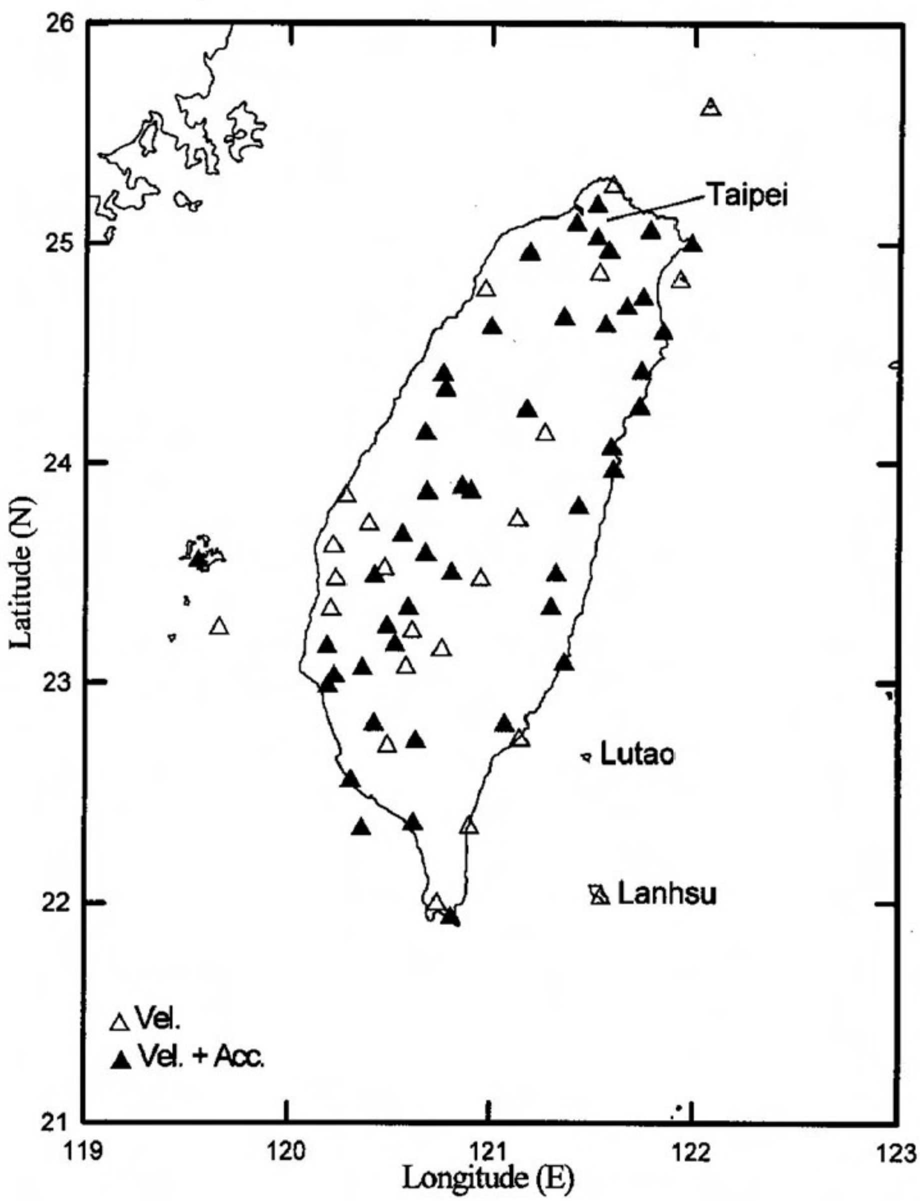
In 1991, a six-year program for strong-motion monitoring was initiated with the goal of installing an equivalent of 1,000 three-component, digital accelerographs in Taiwan. The full bandwidth of the leased telephone lines is 9600 baud. The telemetered short-period network uses only half of the bandwidth, a 4800-baud band, so there is another 4800-baud band available. Teng *et al.* (1994) suggested that by collocating a 3-component digital accelerograph at each of the short-period station sites, strong-motion data can be telemetered to the CWB Headquarters using part of transmit bandwidth without additional costs.

The CWB has defined a new set of specifications of digital accelerographs that must have digital signal stream output according to the digital seismic telemetry (DST) format proposed by E.R. Jenson of the U.S. Geological Survey (USGS), as outlined in 1992 (Lee, 1994a). Since the CWB procurement is by open bidding, three commercial accelerograph vendors have quickly produced such accelerographs. Software for data acquisition and processing of telemetered incoming signals was jointly developed by CWB and USGS. In the fall of 1994, CWB began the implementation of an automatic, real-time, telemetered network of digital accelerographs in Taiwan. In the May, 1997, 48 stations, each with 6-component signal output (3 velocity and 3 acceleration), were put into operation (Figure 1). Eventually, telemetered digital accelerographs will be placed at every short-period seismograph site.

In this paper, we describe the scientific rationale, the instrumentation, data processing, and system performance of the Taiwan Rapid Earthquake Information Release System (TREIRS).

SCIENTIFIC RATIONALE

Regional and local telemetered seismic networks for earthquake monitoring have been in existence for many decades. In order to detect small earthquakes, most of these telemetered networks use short-period seismometers and are operated at high gains. Unfortunately, at short distance, these networks "saturate" for even moderate earthquakes, and the recorded waveforms are generally so severely "clipped" that their usage is mostly limited to the picking of the first *P*-arrival times and first *P*-motion polarities. In order to record the strong earthquakes on-scale, strong-motion accelerographs were deployed, mostly for engineering purposes and mainly operated in a non-telemetered mode.



▲ **Figure 1.** Map showing station locations of telemetered digital accelerographs and short-period seismographs (solid triangles), and telemetered digital short-period seismographs (open triangles) in Taiwan.

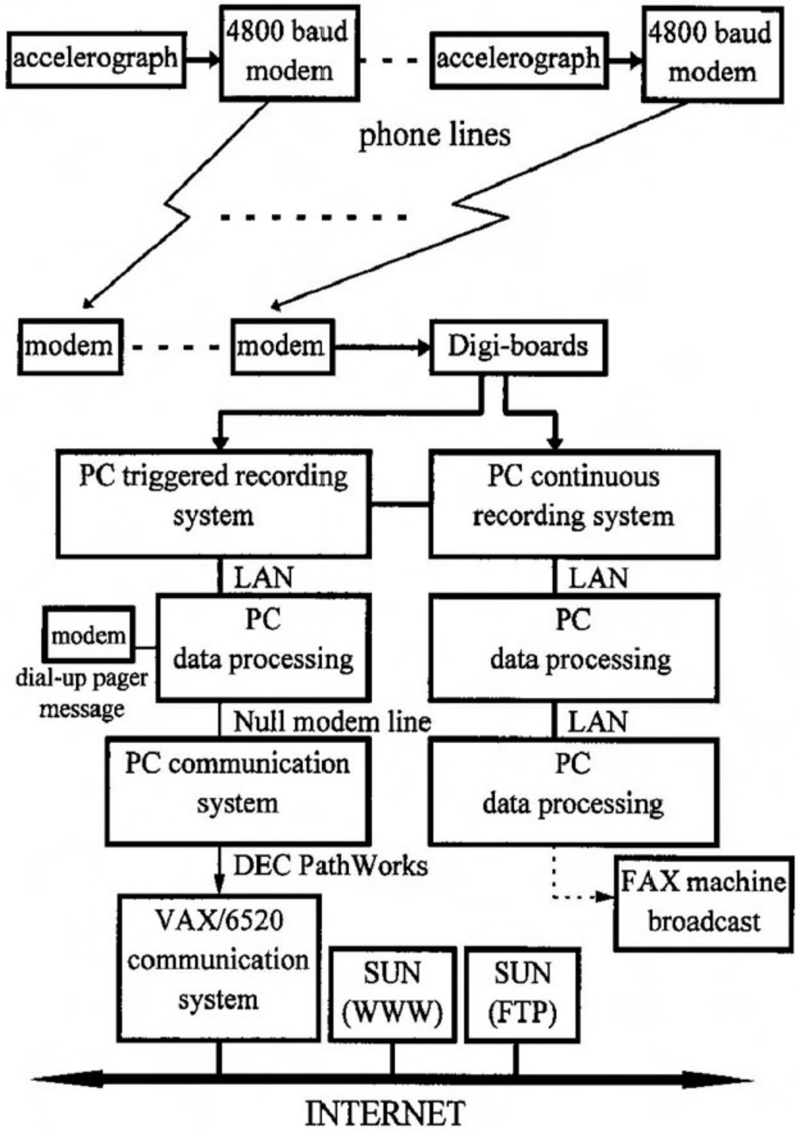
With the advance of modern digital accelerographs and digital communication, a real-time telemetered network of accelerographs can be implemented. As a result, rapid reporting of the occurrences of large earthquakes can be realized, with information such as the peak ground acceleration (PGA) quickly available for engineering assessment of potential damage inflicted on man-made structures. By speeding up the reporting time, an earthquake early warning system based on a telemetered network of accelerographs can be implemented if the impact area is at some distance from the source (Lee *et al.*, 1996).

INSTRUMENTATION

A modern digital accelerograph with digital data stream output is used at the field sites. A digitization rate of 50 sps with 3 channels is used in order to utilize the remaining 4800 baud of the CWB leased telephone line discussed earlier. Recording at a higher digitization rate of up to 200 sps is performed on-site for non-real-time analysis. When faster communication data rates on telephone lines become economical, higher than 50 sps sampling rate will also be considered. At the present time, a sampling rate of 50 sps is sufficient for the purpose of real-time monitoring and rapid reporting.

A block diagram of the hardware used for the TREIRS is shown in Figure 2. Two parallel PC systems are used for data acquisition and processing. One system is for continuous recording and the other for triggered recording.

The hardware cost is relatively inexpensive. A modern digital accelerograph costs about \$6,000 (US). A dual PC data acquisition and processing system costs about \$10,000 (US). The software required has been published (Lee, 1994b;



▲ **Figure 2.** A block diagram showing the hardware of the Taiwan Rapid Earthquake Information Release System (TREIRS).

1994c) and costs $500 (US). Telemetry can be implemented either by using leased telephone lines or FM radios (costing about $2,000 [US] for a pair).

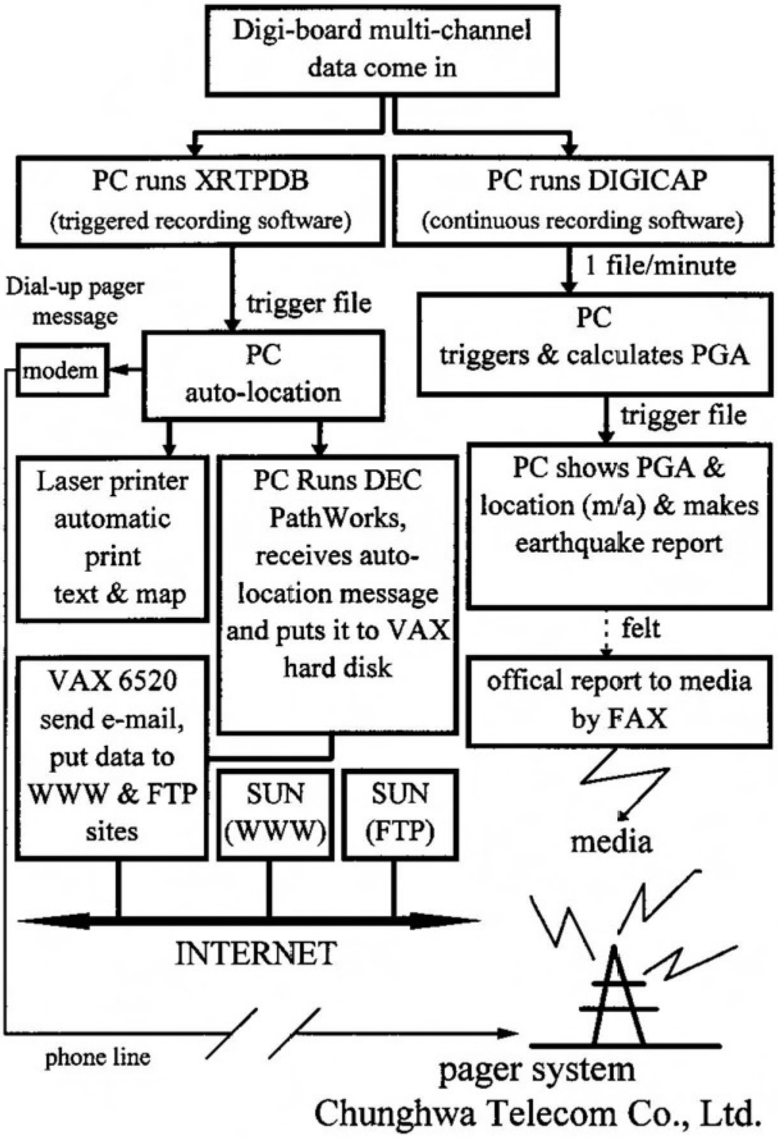
DATA PROCESSING

A flow chart for the data processing is shown in Figure 3. For the rapid earthquake information release system, the incoming data are processed by a software XRTPDB written by Tottingham and Mayle (1994). Whenever a set of pre-specified trigger criteria are met, digital waveforms are saved and analyzed by a program for automatic phase picking, with an algorithm similar to that given by Allen (1978; 1982), and McEvilly and Majer (1982) and for automatic earthquake location. Results are disseminated in four different ways, namely, through e-mail, World-Wide Web, FTP sever, and pager system (Wu *et al.*, 1997).

The incoming data are also processed by a second PC system. The data are continuously recorded at 1-minute intervals per file by a software DIGICAP written by Mayle (1995). Each one-minute file is then subjected to automatic triggering, phase picking, earthquake location, and PGA calculation. The results are included in a routine manner in an earthquake report for official announcement.

SYSTEM PERFORMANCE

Taiwan Rapid Earthquake Information Release System (TREIRS) had been operational since March 3, 1996. While most $ML > 4.0$ earthquakes were recorded by TREIRS, only the events having P (or S) arrivals from six stations have been processed. During the one-year operation, there were 54 events that were automatically identified (see Table 1), in which three events were retriggered due to the effects of the coda signals of big earthquakes. This problem has been corrected by the installation of a new version of the association algorithm to avoid retrigger on the same event. This retrigger problem has also been reported in the UC Berkeley system



▲ **Figure 3.** A flow chart showing the data processing of the TREIRS.

(Gee *et al.*, 1996). We believe that when our test period is over and the magnitude threshold is raised to report only significant events, the retrigger problem will no longer exist.

Response Time

The response time is defined in this paper as the time interval from the earthquake origin time to the time the system provides the location and magnitude results (reporting time). Based on the 24 earthquake reports of Table 1, we found the response time to be a linearly increasing function of the average hypocentral distance of the first 6 stations nearest to the epicenter (Figure 4), as follows:

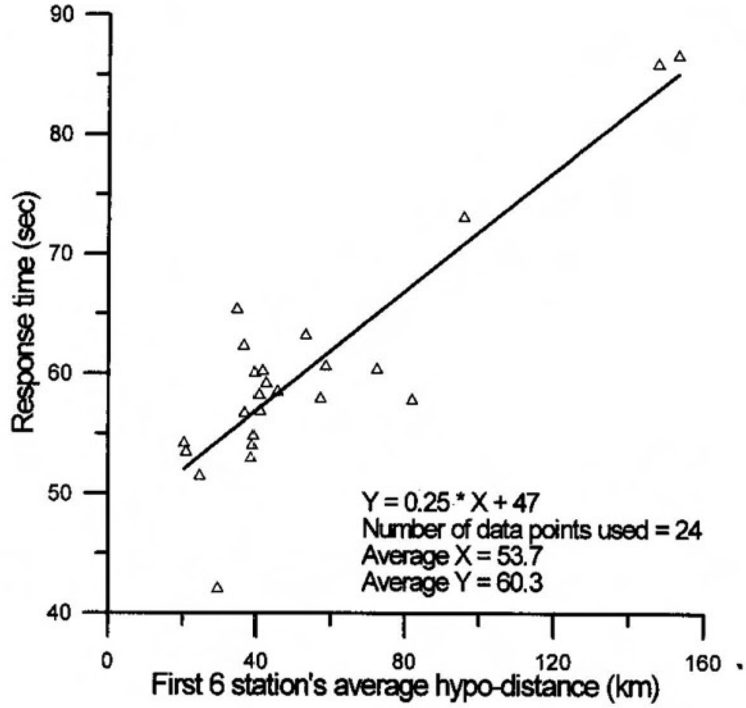
$$Tr = 0.25 \cdot \overline{D} + 47$$

Tr is the response time, $\overline{D}$ is the average hypocentral distance of the first 6 stations nearest to the epicenter.

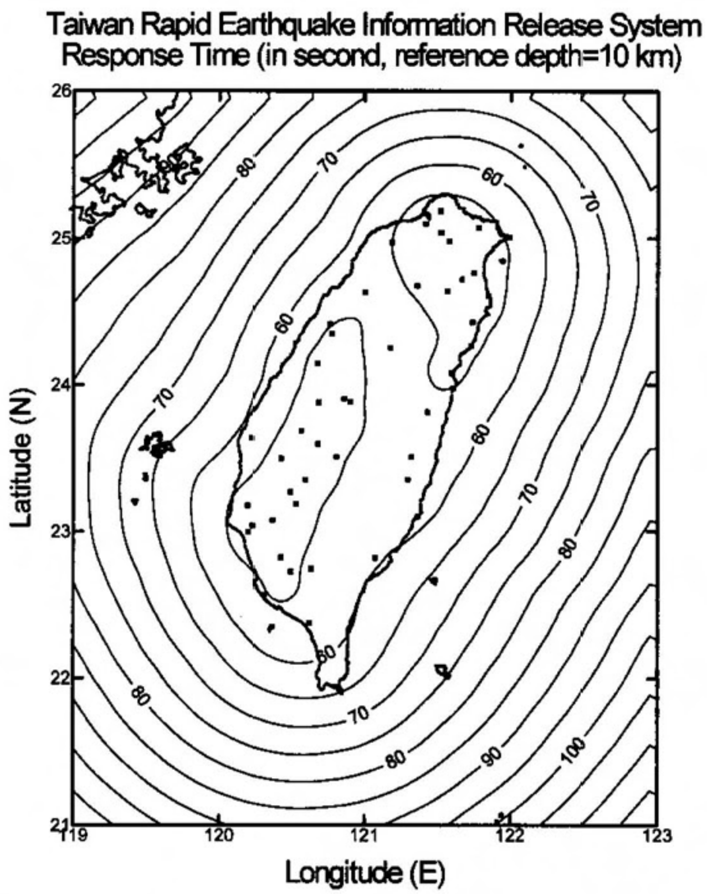
The response time varied from about 42 s to 88 s, with an average of about 60 s.

Once earthquake source parameters and regional intensity data become available, this information is sent to WWW and FTP servers and broadcast by e-mail and pager system. In general, users in the Taiwan region can usually receive an e-mail or pager message in 2 minutes. Users outside the Taiwan region can receive e-mail in 3 minutes (Teng *et al.*, 1997; Wu *et al.*, 1997). Based on the response time function from the 24 events, we can calculate the earthquake response time for Taiwan (see Figure 5). For shallow earthquakes (focal depth = 10 km) occurring on the island of Taiwan, the TREIRS' calculated response times are all less than one minute.

The response time is calculated from the earthquake origin time. But the seismic system does not know about the occurrence of an earthquake before the *P* phase arrives at the first station. So, we define an "effective response time," the



▲ **Figure 4.** The earthquake response time versus the first six stations' average hypocentral distance nearest to the epicenter.



▲ **Figure 5.** Contour shown the earthquake response time of the TREIRS calculated in this study from the events of Table 1.

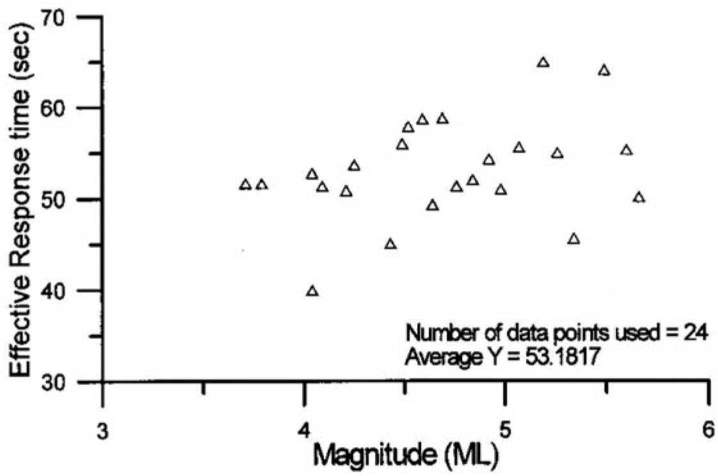
TABLE 1.
A list of 54 earthquake reports broadcasted by the Taiwan Rapid Earthquake Information Release System (TREIRS).

		Auto-picking				Manual-picking					
Date	Origin Time	Lat. (N)	Lon. (E)	Depth (km)	M_L	Lat. (N)	Lon. (E)	Depth (km)	M_L	Reporting Time	Tr (s)
03/05/96	14:53:35.3	23.99°	122.30°	8	6.5	24.01°	122.23°	4	6.4		
03/05/96[a]	14:54:05.1	24.44°	121.31°	0	6.0						
03/05/96	17:33:31.0	24.02°	122.16°	5	6.1	24.02°	122.18°	7	6.1		
03/05/96[a]	17:33:31.0	23.90°	122.26°	29	6.4						
03/05/96	21:19:53.5	23.02°	121.38°	3	4.9	23.02°	121.39°	8	5.0		
03/11/96	01:29:30.9	24.91°	122.16°	102	4.7	24.89°	122.04°	110	4.3		
03/26/96	15:42:11.7	24.26°	121.89°	33	4.5	24.28°	121.81°	38	4.6		
04/07/96	16:55:39.1	23.47°	120.65°	0	5.1	23.47°	120.67°	2	5.0		
04/19/96	07:26:23.7	23.71°	121.79°	32	4.8	23.69°	121.82°	35	4.8		
05/26/96	07:36:45.1	24.56°	121.67°	60	4.5	24.53°	121.64°	60	4.6		
05/27/96	18:36:40.3	24.19°	121.56°	18	4.1	24.20°	121.55°	15	4.1		
05/28/96	21:53:24.5	24.10°	121.53°	18	5.5	24.11°	121.53°	18	5.4		
05/29/96	21:56:16.1	22.73°	120.67°	36	4.9	22.77°	120.65°	27	4.9		
06/09/96	01:30:28.5	24.03°	121.60°	48	5.0	24.06°	121.57°	46	5.0		
07/06/96	01:27:06.7	22.63°	120.27°	4	5.5	22.65°	120.50°	36	5.5		
07/21/96	05:11:59.8	24.47°	122.56°	48	4.9	24.52°	122.42°	67	5.0		
07/29/96	20:20:58.8	24.48°	122.31°	60	6.3	24.49°	122.29°	60	6.4		
07/29/96[a]	20:20:57.9	24.52°	122.47°	38	6.5						
08/05/96	18:41:17.0	23.22°	121.70°	25	4.9	23.21°	121.49°	44	5.0		
08/06/96	03:19:55.4	23.57°	121.58°	27	4.2	23.57°	121.52°	25	4.3		
08/10/96	06:23:08.7	24.07°	122.31°	0	5.7	23.88°	122.62°	330	5.9		
09/05/96	23:42:10.2	21.68°	121.44°	40	7.0	21.90°	121.40°	5	6.7		
09/15/96	23:01:03.5	24.24°	121.61°	14	4.2	24.24°	121.66°	16	4.3		
10/09/96	09:29:13.3	23.62°	121.01°	17	4.9	23.61°	121.01°	17	5.0		
10/13/96	08:35:04.1	24.12°	121.81°	26	4.4	24.12°	121.79°	27	4.7		
10/19/96	19:16:07.2	23.15°	120.52°	27	4.6	23.18°	120.49°	12	4.5		
11/01/96	18:07:36.4	24.51°	121.64°	43	4.7	24.52°	121.61°	46	4.9		
11/05/96	05:39:03.3	23.73°	121.35°	15	4.3	23.69°	121.43°	12	4.5		
11/07/96	07:26:23.6	24.29°	121.71°	43	4.6	24.30°	121.73°	43	4.5		
11/14/96	01:39:16.1	23.38°	122.07°	40	5.3	23.42°	122.08°	13	5.4	01:40:14	58
11/14/96	01:43:42.5	22.93°	120.68°	0	4.6	22.92°	120.68°	6	4.6	01:44:48	66
11/16/96	00:22:46.4	23.27°	120.21°	0	4.4	23.25°	120.26°	8	4.5	00:23:38	52
11/26/96	08:22:25.2	24.16°	121.68°	21	5.7	24.20°	121.65°	21	5.7	08:23:22	57
11/30/96	06:33:43.1	23.89°	121.42°	20	4.2	23.86°	121.45°	17	4.2	06:34:38	55
12/01/96	16:06:29.0	23.85°	121.39°	22	4.0	23.85°	121.39°	21	4.2	16:07:26	57
12/03/96	22:41:58.9	24.25°	121.69°	12	4.1	24.26°	121.66°	25	4.3	22:42:52	57
12/15/96	08:10:51.8	24.46°	121.90°	8	4.0	24.47°	121.90°	6	4.1	08:11:34	42
12/15/96	18:56:29.5	24.08°	121.36°	58	5.0	24.08°	121.36°	63	5.0	18:57:30	60
12/21/96	16:05:24.0	24.78°	122.75°	103	5.2	24.74°	122.98°	83	5.4	16:06:50	84
12/23/96	08:53:13.7	23.92°	121.42°	19	4.3	23.87°	121.53°	21	4.5	08:54:12	58
12/25/96	13:36:01.7	24.67°	121.74°	7	3.8	24.68°	121.73°	7	3.9	13:36:56	54

a. retrigger

TABLE 1. A list of 54 earthquake reports broadcasted by the Taiwan Rapid Earthquake Information Release System (TREIRS).											
		Auto-picking				Manual-picking					
Date	Origin Time	Lat. (N)	Lon. (E)	Depth (km)	M_L	Lat. (N)	Lon. (E)	Depth (km)	M_L	Reporting Time	Tr (s)
12/25/96	21:52:19.3	24.36°	122.08°	0	4.8	24.25°	122.17°	13	5.0	21:53:20	59
01/05/97	10:34:23.2	24.64°	122.24°	0	5.5	24.65°	122.32°	25.8			
01/05/97	18:41:01.3	23.27°	122.77°	29	5.5	23.04°	122.68°	36	5.6	18:42:28	88
01/18/97	17:13:46.8	24.14°	122.44°	0	5.6	23.97°	122.51°	7	5.6	17:15:00	73
01/20/97	05:53:03.4	24.15°	121.70°	39	4.8	24.13°	121.79°	30	4.8	05:54:02	59
01/26/97	19:18:03.9	24.10°	121.67°	25	4.6	24.09°	121.63°	25	4.6	19:18:58	54
01/28/97	04:09:11.6	24.44°	121.78°	26	4.5	24.44°	121.78°	26	4.5	04:10:14	57
02/02/97	17:45:50.4	24.69°	121.73°	5	3.7	24.70°	121.72°	8	3.9	17:46:44	56
02/09/97	21:42:28.7	23.53°	121.63°	25	4.7	23.53°	121.64°	26	4.7	21:43:32	63
02/10/97	16:50:17.9	24.19°	121.68°	19	5.1	24.19°	121.69°	24	5.1	16:51:18	60
02/27/97	15:44:44.7	23.95°	121.58°	27	4.9	23.91°	121.70°	20	4.9	15:45:44	59
03/22/97	23:37:42.0	24.45°	121.77°	9	4.5	24.45°	121.76°	9	4.5	23:38:40	58
03/24/97	23:32:23.7	24.17°	121.65°	28	5.3	24.19°	121.64°	25	5.2,	23:33:24	60

a. retrigger



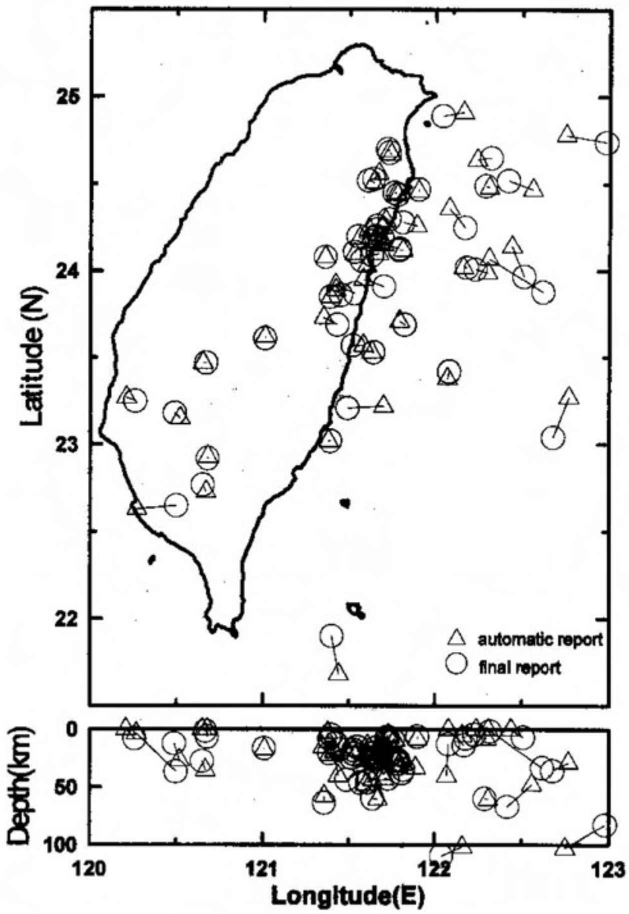
▲ **Figure 6.** Earthquake effective response time versus magnitude.

time between the first *P* arrival and the system reporting time. In general, the effective response time is independent of earthquake location and magnitude (see Figure 6), but it is related to the system performance. The TREIRS' average effective response time is 53 s. This means that for the occurrence of a regional earthquake, the TREIRS can provide earthquake source parameters and regional intensity information about 53 s after the first station receives the P arrivals.

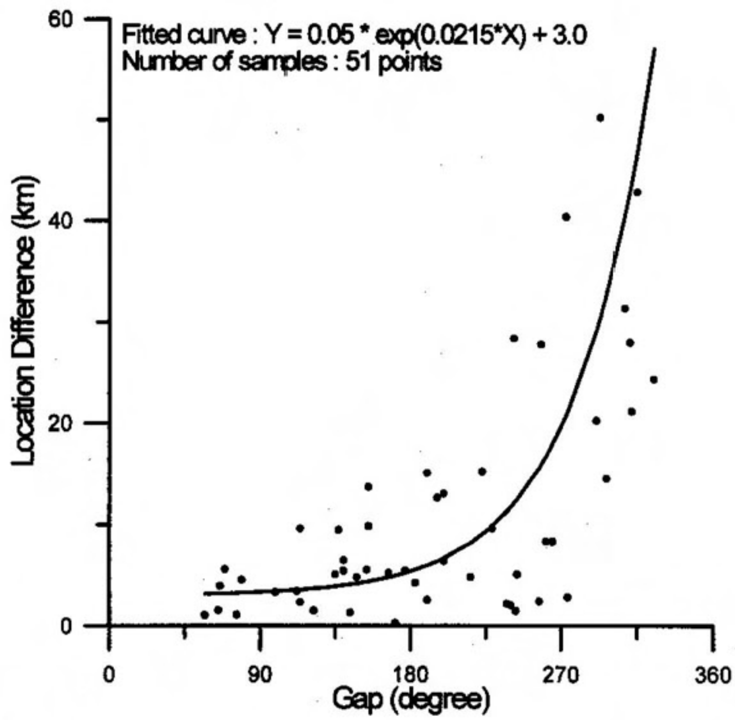
Location difference between automatic and manual picking

As a comparison, the epicenters and focal depths of 51 earthquakes from March 5, 1996 to March 24, 1997 as determined by the TREIRS automatic location system versus off-line manual locations are shown in Figure 7. The average difference in epicenter location is about 7.4 kilometers, and the average difference in focal depth is about 7.0 kilometers. The difference between automatic and manual locations of the TREIRS depends on the station coverage gap (Lee and Lahr, 1975). The relationship between the location difference and the station coverage gap can be fitted with an exponential curve (see Figure 8). Generally speaking, when the station coverage gap is smaller than 225°, the location difference is less than 15 kilometers.

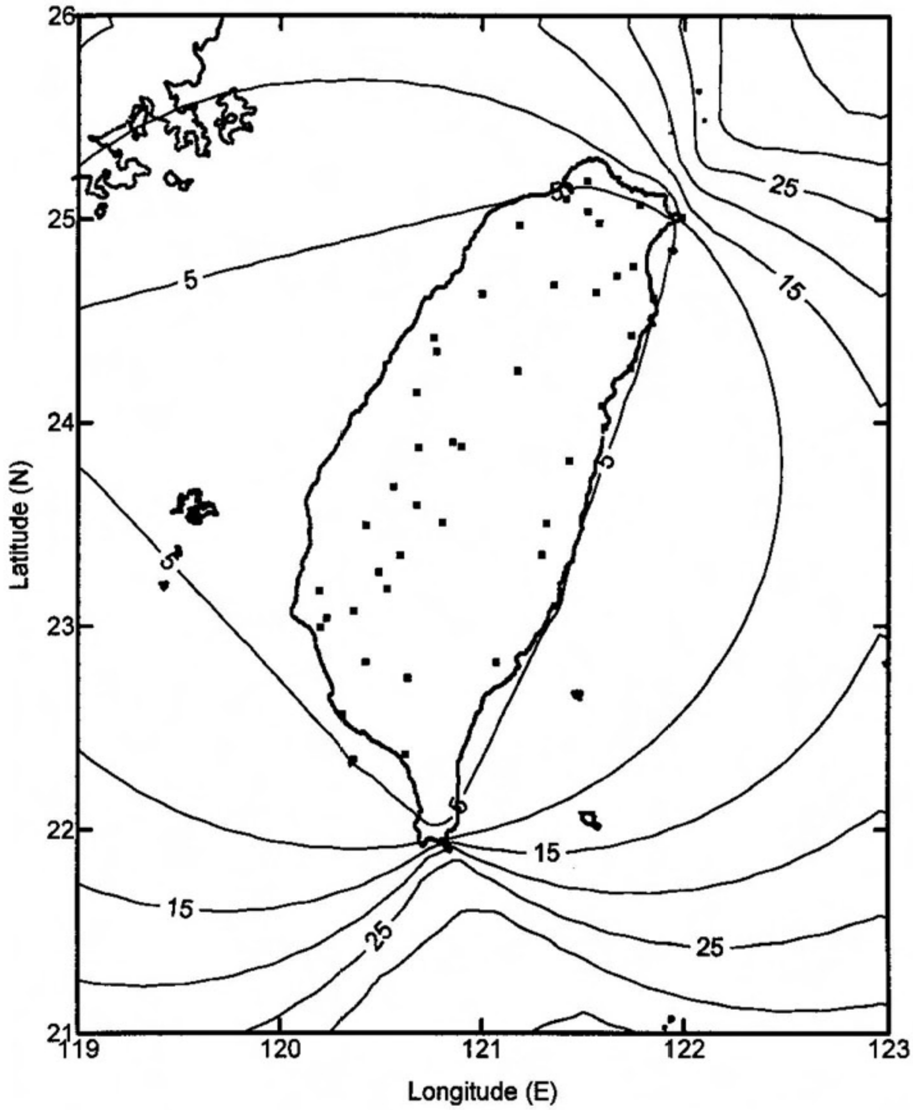
The theoretical difference between automatic and manual event location for the Taiwan region was calculated based on the fitted exponential curve of Figure 8 and the given 48-station TREIRS (see Figure 9). It shows that the location



▲ **Figure 7.** Location differences of 51 earthquakes determined by automatic and manual picking.



▲ **Figure 8.** The relationship of the TREIRS location difference between automatic and manual picking and the stations' coverage gap.



▲ **Figure 9.** Calculation of the location difference between automatic and manual picking estimates by the TREIRS in this study (units in km).

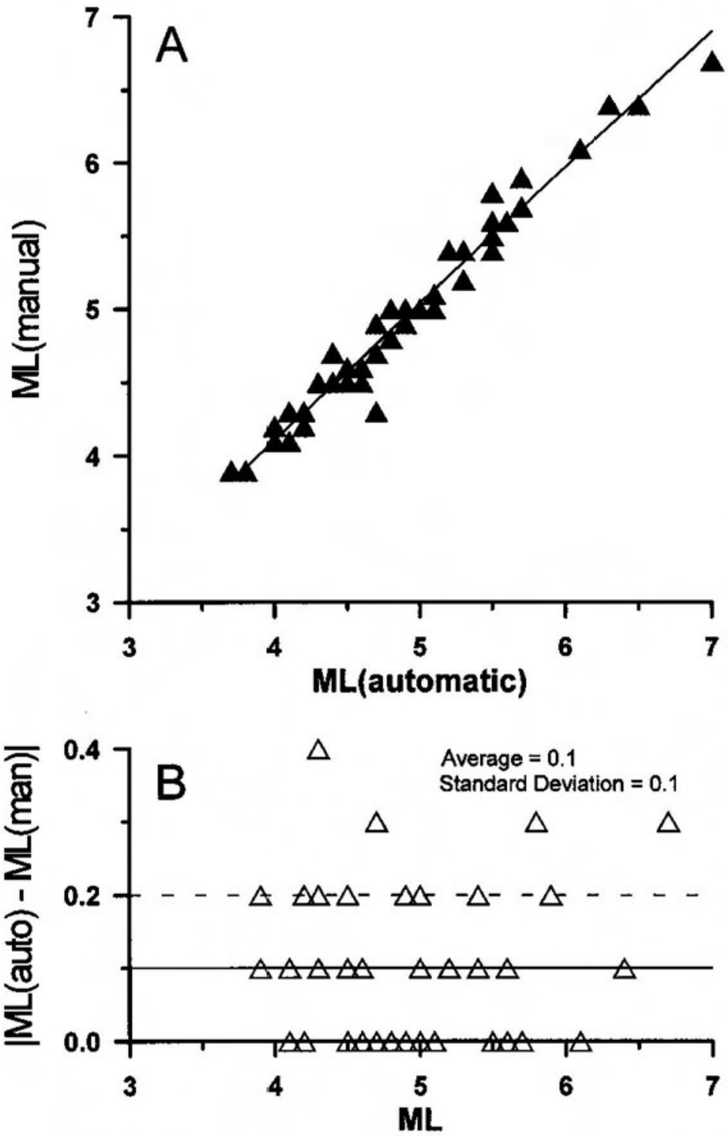
difference is smaller than 5 kilometers when an earthquake occurs on Taiwan and in the Taiwan strait. The location difference varies from 5 to 15 kilometers in the offshore area east of Taiwan. The northern and southern offshore areas have larger location differences as well as the location errors due to the geometry of the TREIRS station distribution.

The relationship between the location quality and the station coverage gap can be fitted with an exponential curve. The station coverage gap relates to the station distribution. The station distribution is limited by the geometry of the island of Taiwan, and most of the felt earthquakes occur in the eastern and offshore areas of Taiwan. Therefore, further improvement can be achieved if the stations on the small islands, Lanhsu and Lutao southeast of Taiwan are added.

Figure 10 shows the TREIRS magnitude difference of the 51 earthquakes obtained by automatic and manual location from March 5, 1996 to March 24, 1997. The magnitude differences vary from 0.0 to 0.4 with an average of 0.1 and a standard deviation of 0.1. The magnitude differences are smaller than 0.2 for most of the earthquakes.

DISCUSSION

The response time is a function of the nearest station's hypocentral distance because the starting time is counted from the earthquake original time. On the other hand, the effective response time is independent of the stations' hypocentral distance because the starting time is counted from the time when the first *P* wave arrives at the nearest station. The effective response time is almost a constant for a seismic system, since it depends on the speed of the computers' CPUs, the number of stations, the system setup parameters, and the software used. The effective response time of the TREIRS is about 53 s. It consists of three time delays:

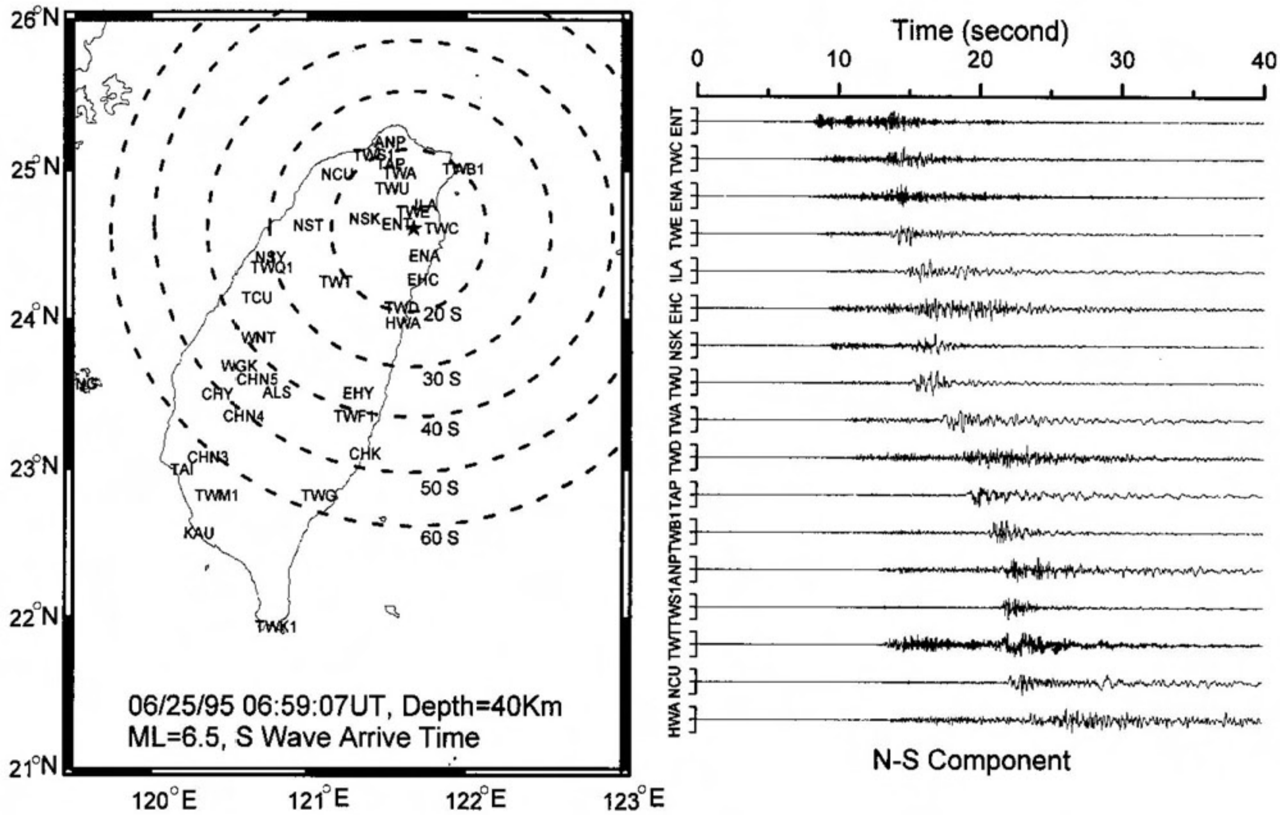


▲ **Figure 10.** Magnitude relationship (A) and difference (B) of 51 earthquakes determined by automatic and manual picking.

- For most earthquakes the system triggers at 1 s–3 s after the *P* wave arrival at the nearest station.
- Even if a trigger condition is declared, the system still records waveforms for about 40 s–45 s.
- The data processing time on a Pentium-120 PC needs about 6 s–8 s for 48 stations, based on 50 sps, 3 components, and 80-s records.

For these time elements, the first delay is hard to improve, but the second and third delays can be improved. The second delay means that after the trigger condition is declared, the system continues to record signals for 40 s–45 s. The reason for this is that most stations will receive *S* phases within 40 s–45 s after triggering. In general, the station's peak ground acceleration (PGA) occurs a few seconds after the first *S* phase arrives. This portion of the station's *S* waveform can be used to calculate intensity and to simulate a Wood-Anderson seismogram (Richter, 1935) for calculating local magnitude (Shin, 1993). In the concept of an early warning system, the determination of magnitude is necessary, but a real-time determination is not crucial for either small events or for events at large distance. In this paper, we suggest that the continuous recording time can be shortened from 40 s–45 s to 15 s–25 s. For example, in the case of the June 25, 1996 $M_L = 6.5$ earthquake, there were more than 10 stations received *S* phases by 20 s after the origin time (see Figure 11). Those stations can be used to make a decision of earthquake hypocenter and magnitude.

The third delay due to the data processing time depends on the number of stations and record lengths. If the number of stations and the record lengths are suitably decreased, this can effectively shorten the data processing time. For exam-



▲ **Figure 11.** The *S* wavefronts of the June 25, 1995 M_L = 6.5 earthquake and waveforms.

ple, for 16 stations, with 3 components, 50 sps, and 40-s long record, the data processing time needs be only 3 s–4 s. Based on these two considerations, a shortened response time can be realized by a sub-net method. Each sub-network could consist of about 15 stations, an example of which is shown in Figure 12. At 15 s–25 s after the occurrence of an earthquake, almost all the stations of the sub-network will have already received *S* phases. The system can then stop waveform recording and start to do location processing. About 2 s–3 s later, the system can calculate the source parameters. We are confident that 30-s earthquake reporting can be achieved by using the sub-network method.

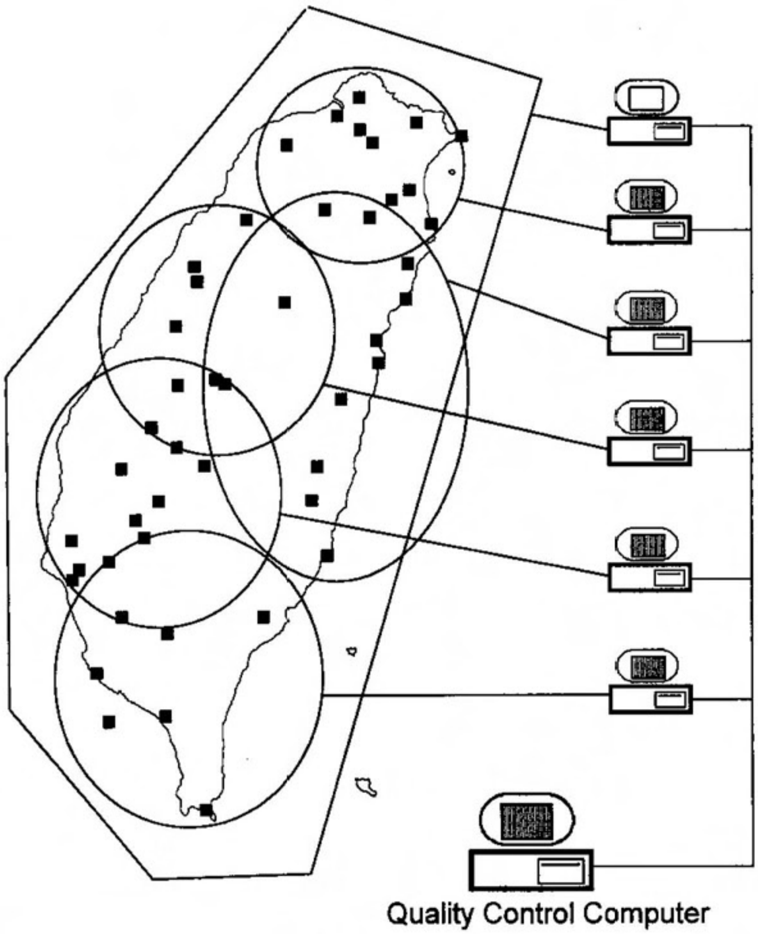
Location quality is a function of the station coverage gap, and a sub-network covers an area smaller than the regional network. Offshore earthquakes generally have a large station coverage gap, and the regional network will have better location quality and intensity observation but a slower response time than a sub-net. Therefore, the combination of a group of sub-networks and the regional network is necessary in the future to optimize the operation of the TREIRS. After further improvement we hope to have a preliminary result within 30 s for any sub-network and the final result within 1 minute for the regional network.

In an earlier paper (Teng *et al.*, 1997), we showed that using the recorded PGA by the TREIRS to define an area enclosed by 100-gal contour, we could use the center of this contoured area to find the effective epicenter. The size of this area, through an empirical relationship, gives the effective magnitude. In that process, the effective epicenter and effective magnitude can be determined within 20 s–30 s of the first *P*-wave arrival. This method can be applied to a very large, damaging event. The PGA contours also give a near real-time strong-motion map critically needed for emergency response in disaster relief and damage mitigation.

CONCLUSIONS

We have deployed an inexpensive, real-time, telemetered accelerograph network in Taiwan, which is capable of on-scale recording and rapid reporting of large earthquakes. This is possible because (1) functionally common modern digital accelerographs with digital stream output are available, (2) existing leased telephone lines for the telemetered short-period seismograph network have excess capacities for an additional 4800-baud transmission for each field station, and (3) a common software platform has been established by the IASPEI Software Library published by the International Association of Seismology and Physics of the Earth's Interior (IASPEI).

In this paper, our results show that we have achieved earthquake location and magnitude determinations in about one minute after the earthquake origin times. We are confi-



▲ **Figure 12.** A diagram showing the combined system of the local and regional seismic networks.

dent that a 30 s earthquake reporting time can be achieved by (1) redefining the first *P*-arrival as the starting time, and (2) by using the concept of sub-networks in the future. This paper and another paper of this series published previously (Teng *et al.*, 1997) essentially pave the way for an earthquake early warning system to be put in operation in Taiwan.

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