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A Free-Field Strong Motion Network in Taiwan: TSMIP

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ABSTRACT

The Central Weather Bureau has implemented the Taiwan Strong Motion Instrumentation Program (TSMIP) to collect high-quality instrumental recordings of strong earthquake shaking. Deployment of the accelerographs started in August 1992. By June 1997, 629 stations had been deployed. Each operating free-field station includes triaxial accelerometers, a digital recording sub-unit, a power supply and a timing system. Since the first installation in August 1992, this network has recorded 2482 earthquakes. The local magnitudes of these earthquakes ranged from 1.7 to 7.1 and thousands of high-quality digital accelerograms were collected. The quality of 16-bit data is shown to be much better than the conventional strong-motion data (either analog or 12-bit digital recordings). These new recordings provide an excellent database for making various earthquake engineering and seismological studies.

(Key words : Strong-motion network, TSMIP, Accelerograph)

1. INTRODUCTION

Beginning in the 1991 fiscal year, the Seismology Center of the Central Weather Bureau (CWBSC) embarked on the six-year seismic strong-motion instrumentation program, known as Taiwan Strong Motion Instrumentation Program (TSMIP; Shin, 1993). The main goal of the program is to collect high-quality instrumental recordings of strong earthquake shaking, both free-field and in buildings. These data are crucial for improving earthquake resistant design of buildings and for understanding the earthquake source mechanisms, as well as seismic wave propagation from the source to the site of interest, including local site effects.

Two types of digital strong-motion instruments are deployed throughout Taiwan, with special emphasis in nine metropolitan areas. One type is a triaxial accelerograph for recording free-field ground shakings. The other type is a multi-channel, central-recording, accelerograph array system for monitoring shakings caused by earthquakes in buildings and other structures. In the last five years, the CWBSC have installed a total of 629 free-field accelerographs and 51

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structural arrays. This paper describes the planning and current status of the free-field network. We hope the information presented in this paper will be useful to future users of the free-field data.

2. SELECTION OF ACCELEROGRAPH SITES

The Taiwan Strong Motion Instrumentation Program (TSMIP) is designed to enhance our ability to monitor strong earthquakes and to collect high-quality instrumental recordings of strong earthquake shaking. These data are crucial for improving earthquake resistant design of buildings and for understanding the behaviors of ground shakings. Effective reduction of life and property losses from strong earthquakes requires appropriate characterization of ground motions for building codes and earthquake resistant design. In order to meet these purposes, the selection criteria for the TSMIP accelerograph sites are set as follows : 1. In nine major metropolitan areas. 2. Near known fault zones. 3. At different geological sites: rock, soil and medium-stiff soil. 4. Near important construction or industrial sites or nuclear power plants. The program has selected and completed 629 free-field stations since August of 1992. The locations of these stations are shown in Figure 1.

Four types of site classification are designated, whenever possible, according to the U.S. Uniform Building Code (ICBO,1994) as follows :

S_1 : A soil profile with either:

(a) A rock-like material characterized by a shear-wave velocity greater than 2500 feet per second or by other suitable means of classification, or

(b) Stiff or dense soil condition where the soil depth is less than 200 feet.

S_2 : A soil profile with dense or stiff soil conditions, where the soil depth exceeds 200 feet.

S_3 : A soil profile 70 feet or more in depth and containing more than 20 feet of soft to medium stiff clay but not more than 40 feet of soft clay.

S_4 : A soil profile containing more than 40 feet of soft clay characterized by a shear wave velocity less than 500 feet per second.

The site classifications of free-field stations, as shown in Figure 1, were decided on by Dr. K. W. Kuo. In Figure 1, S_0 stands for a free-field station which has not yet been classified. (Kuo,1992, 1993, 1994)

3. TAIWAN STRONG MOTION INSTRUMENTATION PROGRAM (TSMIP)

The Taiwan Strong Motion Instrumentation Program (TSMIP) accelerograph network currently consists of 629 free-field stations. The locations of stations are shown in Figure 1. Except for in the Central Mountain Range, these free-field stations are irregularly spaced approximately 5 km apart.

The deployment of these instruments started in August 1992 with the majority being operational by December 1994. The CWBSC have completed instrument installation of 90 , 250

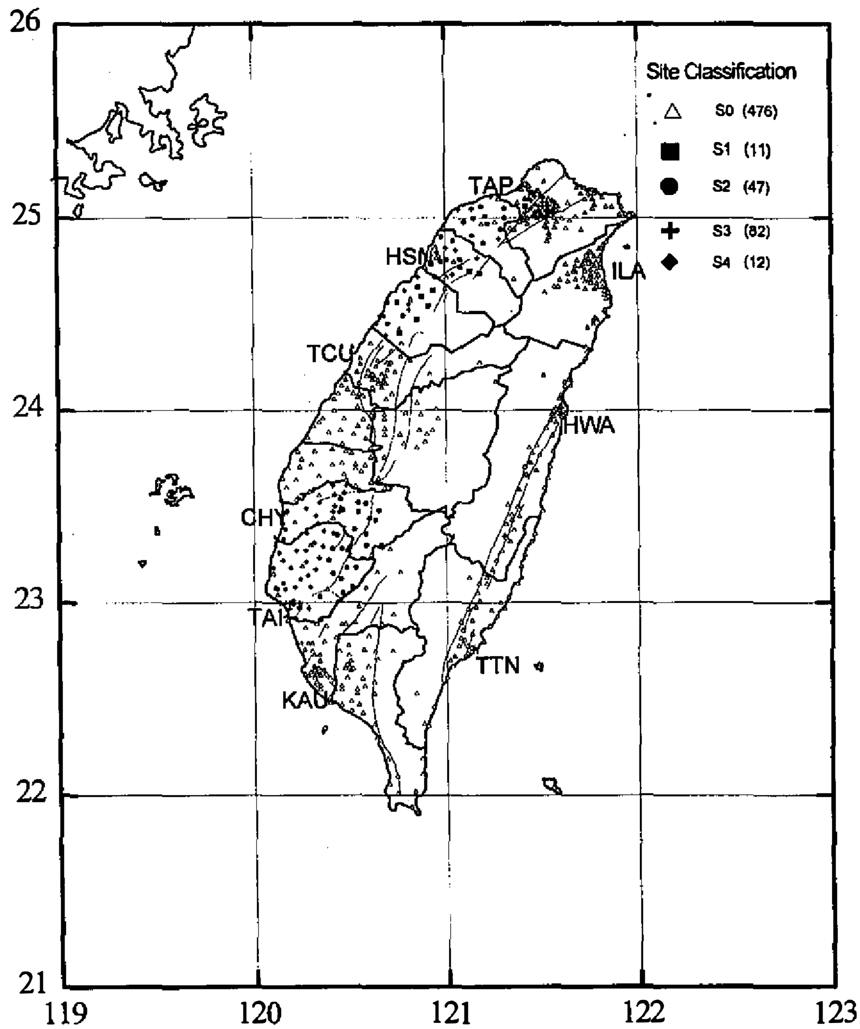

Fig. 1. The TSMIP free-field station distribution. Four types of site classification (S_1 ,S_2 ,S_3 ,S_4)were decided by Dr. K. W. Kuo according to the U.S. Uniform Building Code. S_0 stands for a free-field station which has not yet been classified.

and 230 sites in 1992, 1993, and 1994, respectively. By June 1997, 629 stations had been deployed. Each operating free-field station includes triaxial accelerometers, a digital recording sub-unit, a power supply and a timing system.

In order to handle the large work load to maintain so many free-field stations located all over Taiwan, the CWBSC has enlisted the help of the Institute of Earth Sciences at Academia Sinica , the Institute of Geophysics at National Central University, and the Institute of Seismology at National Chung-Cheng University to collect the recorded data.

4. INSTRUMENTATION

The primary purpose of the TSMIP accelerographs is to record infrequent large earthquakes at distances and locations of major scientific and societal significance. Attention is also given to collecting data from more frequent moderate-sized earthquakes.

Taking into account the relatively low likelihood of large earthquakes, the uncertainty in the location and time of these events, and the social significance of the recorded data, the following engineering and scientific requirements for the accelerograph are set :

The transducers for the accelerograph must respond accurately in the frequency range from DC to 50 Hz in order to record faithfully the near-source ground motion caused by large earthquakes. In order to record a wide range of earthquakes on scale, it is required that the complete system be digital and have at least 16-bit resolution.

The accelerograph is packaged in a single case which consists of three sub-units: the transducers (triaxial accelerometers), a solid-state digital recorder, and the battery power supply. The accelerograph can be connected via a user-supplied modem to a telephone line for remote interrogation and data downloading. These instrument features are further explained below.

4.1 Transducer Sub-Unit

Three orthogonally oriented, triaxial (two horizontal and one vertical) accelerometers are mounted internally inside the instrument case. Each transducer is a force-balance accelerometer with a full scale of 2 g. The dynamic range of the transducer is 96 dB. Its natural frequency is 50 Hz, and its damping is between 60%and 70%critical . Each transducer has a flat frequency response from DC to about 50 Hz, as shown in Figure 2 (Teledyne,1994; Terra, 1994). The instrument responses have been verified by shake-table tests (Teng et al., 1994).

4.2 Digital Recording Sub-Unit

The recording sub-unit consists of three channels with appropriate signal conditioning, A-D conversion, and solid-state memory. Absolute timing to within $\pm$ 5 msec of UTC can be maintained at all times by the accelerograph if an optional GPS timing device is used. In the event of losing the external GPS timing signals or for an accelerograph without a GPS timing device, the accelerograph is capable of maintaining absolute timing with a drift of less than $\pm$ 26 msec per day.

The recorder has 16-bit resolution which is equivalent to a 0.0598 gal/count for a 2g accelerometer. The ground motions sensed by the accelerometers are converted to digital voltage and stored in solid state memory. This recorder also provides adjustable pre-event and post-event memory. In the Taiwan Strong Motion Instrumentation Program(TSMIP), 20 seconds for pre-event memory and 15 seconds for post-event memory are typically programmed.

In the trigger algorithm, a band-pass filtered threshold was used. Although the setting of threshold level depends on the background noise of individual stations, a typical threshold is 0.2%of the full scale of 2g. Each of the three accelerometers is treated as an independent trigger or as one vote for more sophisticated settings of triggering. The recorder allows for use

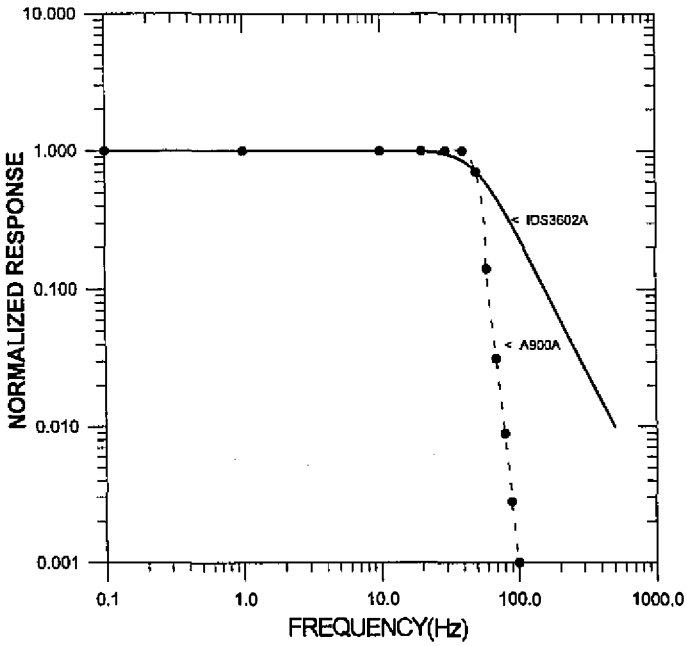

Fig. 2. The system response curves of the TSMIP accelerographs.

of multiple total votes to make the triggering even more flexible.

Since 1993 the accelerograph has been required to provide a serial stream of digitized 3-component ground acceleration data at 50 samples per second per channel for transmission by hardwire or by a suitable modem to a receiving station of the Central Weather Bureau Seismic Network (CWBSN) for realtime processing at all times.

4.3 Power Supply Sub-Unit

The accelerograph operates on an internal battery that can be recharged either from solar cells or from a 110V ± 20% AC power source. The average power consumption of the accelerograph when recording is less than 300 mA at 12V dc. The accelerograph also meets the following requirements: (1) Internal battery: 12 volt rechargeable, sufficient to operate the system on standby for a minimum of 1 day with a GPS timing device (or for a minimum of 2 days without a GPS timing device) and to record for 90 minutes without an external power source for charging. (2) If the external power source for the accelerograph is cut off for more than 2 days, the accelerograph is able to restart automatically and to function properly after the external power source is restored.

4.4 Shelter for Instrument

A typical station of the Taiwan Strong Motion Instrumentation Program (TSMIP) consists of a 125cm° × 125cm° × 10cm concrete pad and a fiberglass hut (see Figure 3) to provide shelter for the accelerograph. The accelerograph is bolted down near the center of the pad, and the coupling between the concrete pad and the ground is enhanced by eight 100-cm stainless steel rods. One end of these rods is cemented into the pad while the other end penetrates the ground as shown in Figure 4. The thin instrument pad is designed to minimize the soil-structure interaction effects of the pad on recordings.

5. TECHNICAL EVALUATIONS OF ACCELEROGRAPHS AND DATABASE MANAGEMENT

5.1 Technical Evaluation of Accelerographs

In order to purchase the accelerographs through competitive open biddings, five models of accelerographs were pre-qualified for the TSMIP.

During the 1992 fiscal year, 250 free-field accelerographs were purchased. Each bidder was required to submit, at his own expense, one unit of the production model of the accelerograph (with 1/4-g full-scale) for field tests. The three bidding models of accelerographs SSA-16 (Kinemetric), IDS-3602 (Terra Tech), and A900 (Teledyne Geotech) were placed on the same seismic pier at the HWA station of the CWB Seismic Network (CWBSN) in Hualien from

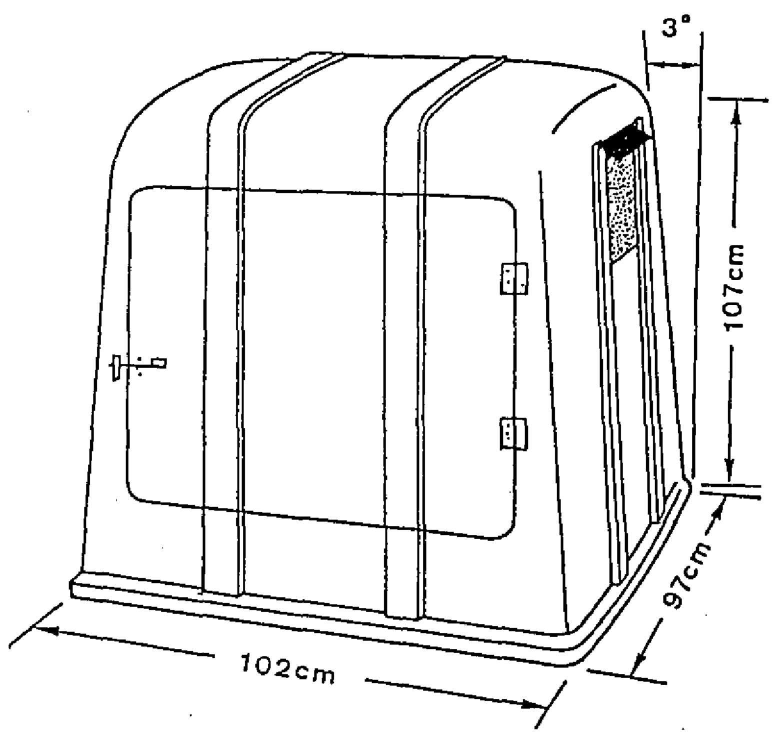

Fig. 3. A fiberglass hut provides shelter for the TSMIP accelerograph.

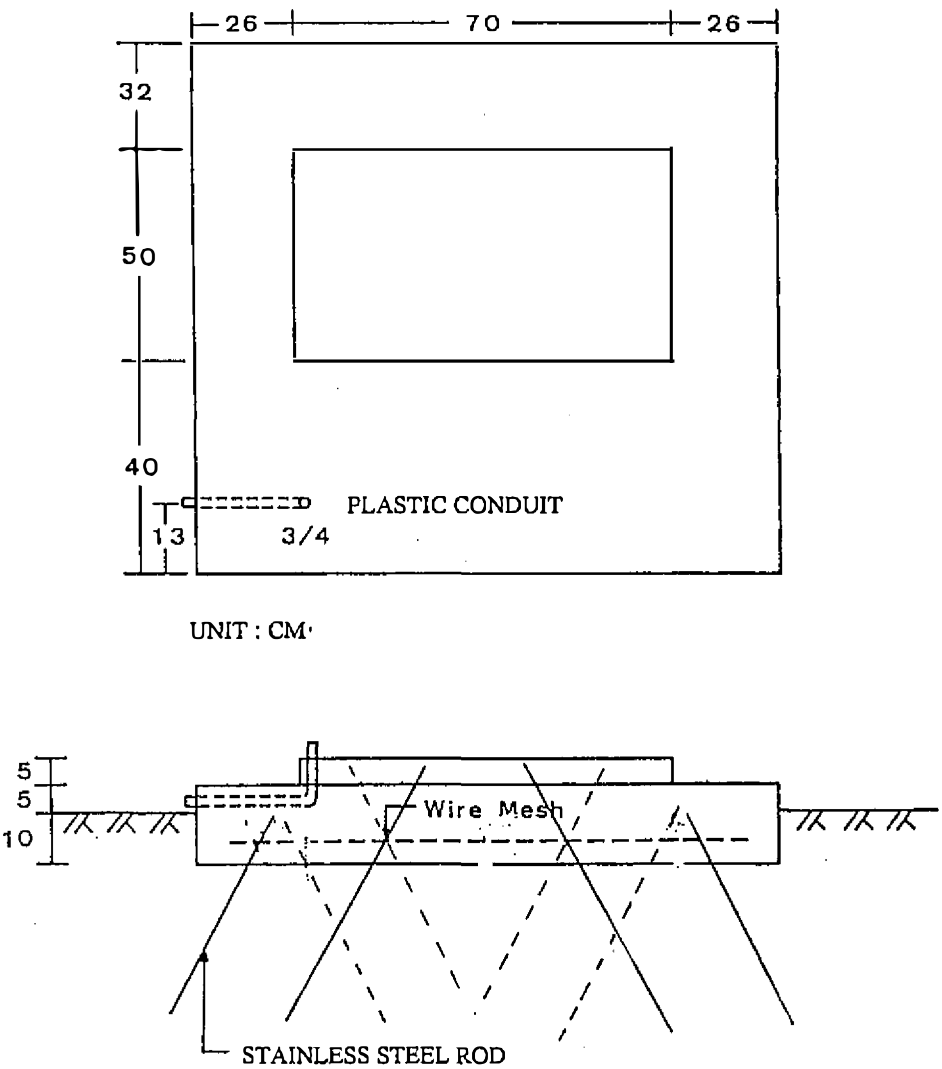

Fig. 4. The concrete pad for accelerograph installation.

September 21 to November 5, 1992. The field tests consisted of hardware checks on RAM memory capacity and the absolute timing system, as well as field performance tests on event triggering, calibration and tilt tests. The tests results were as follows: (1) The RAM memory of the three accelerographs met the requirements. (2) all three models of accelerographs provided a timing system with accuracy better than 5 msec. (3) event trigger test of the three accelerograph models were sucessfully triggered by eight events above magnitude 2.4. (Chiu et al., 1993)

In the 1993 fiscal year, CWB purchased 250 digital accelerographs which, in addition to the specifications specified by CWB in the 1992 fiscal year, also required realtime digitized data (RTD) stream output and a waterproof instrument case,. For the free-field accelerographs, two accelerographs were submitted for testing: Model A900A by Teledyne Geotech, and Model IDS3602A by Terra Tech. As a result, both submitted accelerographs were able to provide realtime digital data stream output that were acceptable to the USGS digital receiver under tests conducted at the USGS and both passed the waterproof test (submersion of each accelerograph in two to three-feet of water for two hours; Teng et al.,1994)

Comparison of the component and polarity conventions on accelerograms from the five models of accelerographs with the A800 accelerograph is given in Table 1. The characteristics of the six models of accelerographs is given in Table 2 (Liu,1993).

5.2 Hualien (HWA) Experiment

In order to test the performance of different types of accelerographs, the CWBSC installed six accelerographs (two A800s, one A900, two IDS3602s and one SSA16) at the Hualien seismic station during the period December 1992 to December 1993. Figures 5 and 6 show an example comparing the quality of accelerograms for an M 4.1 event. From the Fourier amplitude plots of the accelerograms , as shown in Figure 6, we can see the same trend at frequencies greater than 1 Hz. At lower frequencies, there are two groups of curves, one is for 12-bit A800 accelerograms, and the other is for 16-bit accelerograms. Figure 7 shows in linear scale the Fourier amplitude at frequencies below 1.0 Hz, with the two groups of curve evidently behaving very differently between different levels of resolution. False Fourier amplitude at low frequencies for the 12-bit records was due to sampling in the pre-event time windows of A800 accelerograms. It can be seen from the traces that the pre-event waveforms were step-like, as shown in Figure 5. The data resolution was 0.479 and 0.0598 gal/count for a 12-bit and a 16-bit accelerograph, respectively.

5.3 Data Quality

The CWBSC monitored the strong ground motion using SMA-1 accelerographs before 1990. The records were analog. Between 1990 and 1992 , the CWBSC installed 37 A800 accelerographs, to acquire intensity data from their PGA values, at CWB Seismic Network (CWBSN). These records were digital with 12-bit resolution. High resolution accelerographs (16-bit) have been deployed all over the TSMIP network since August 1992.

Since the first installation in August 1992, the TSMIP network has recorded 2482 earthquakes whose epicenters are shown in Figure 8. The local magnitudes of these earthquakes range from 1.7 to 7.1.

The TSMIP network can record a wide range of earthquakes on scale. Figures 9 and10 show two examples demonstrating the quality of TSMIP accelerograms for an M 1.7 event and an M 6.4 event, respectively. Due to dense distribution of accelerograph sites and high data resolution (16-bit), the network can record clear waveforms even for a magnitude as low as 1.7, as shown in Figure 9. The epicentral distances of the three recording sites were all less than 1 km. Judging from the global strong-motion database available so far, it is believed that the TSMIP will hardly ever go off scale and clip the strong-motion waveforms. Figure 10a shows the triaxial accelerograms from a M 6.4 event. The epicentral distance of the recording site was 10.5 km. It is interesting to point out that the highest peak acceleration in the EW component was 1,113 gals. Several seconds before the main shock there were a few foreshocks which were clearly recorded, as shown in the enlarged portion of the accelerograms in Figure 10b. Figure 11 shows the corresponding integrated velocity and displacement traces obtained by a routine integration algorithm with low-cut filtering at 0.12 to 0.16 Hz. No permanent displacements are noticeable. However, if we use a more elaborate integration algorithm (Chiu, 1998) on the same record, permanent displacements of nearly 1 cm are revealed on all three

Table 1. Component and polarity conventions of the CWBSC accelerographs.

TYPE	COMPONENT			POLARITY		
	CH1	CH2	CH3	V	N	E
A800	V	NS	EW	UP	UP	UP
A900	V	NS	EW	UP	UP	UP
A900A	V	NS	EW	UP	UP	UP
IDS-3602	V	NS	EW	UP	UP	DOWN
IDS-3602A	V	NS	EW	UP	UP	DOWN
SSA-16	EW	V	NS	DOWN	DOWN	UP

Table 2. Characteristics of six models of accelerographs.

INSTRUMENT MODEL	MANUFACTURER	NO.	YEAR OF DEPLOYMENT	CHARACTERISTICS OF ACCELEROGRAPHS				
				MEMORY SIZE	RECORDING TIME	SAMPLING RATE	DYNAMIC RANGE	REAL-TIME OUTPUT
A800	Teledyne Geotech	52	1991	1 MB	14 MIN	200 /S	72 dB	NO
A900		2	1992	2 MB	27 MIN	200 /S	96 dB	NO
A900		250	1993	6 MB	87 MIN	200 /S	96 dB	NO
A900A		150	1994	6.5 MB	90 MIN	200 /S	96 dB	YES
IDS-3602	Terra Tech	92	1992	2 MB	23 MIN	250 /S	96 dB	NO
IDS-3602A		100	1994	4 MB	90 MIN	250 /S	96 dB	YES
SSA-16	Kinemetric	2	1992	2 MB	28 MIN	200 /S	96 dB	NO

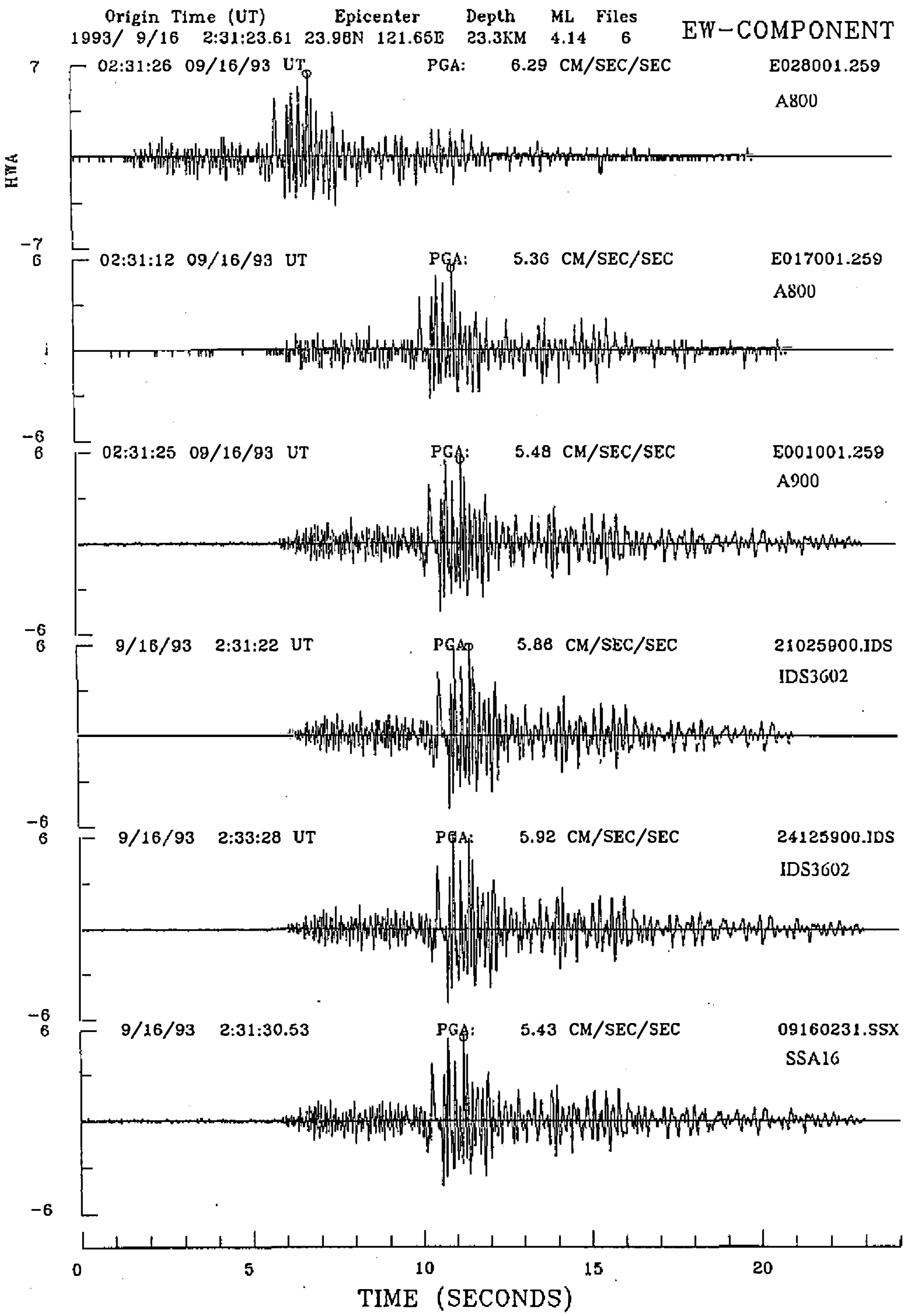

Fig. 5. Accelerograms of the EW component of an M 4.1 event.

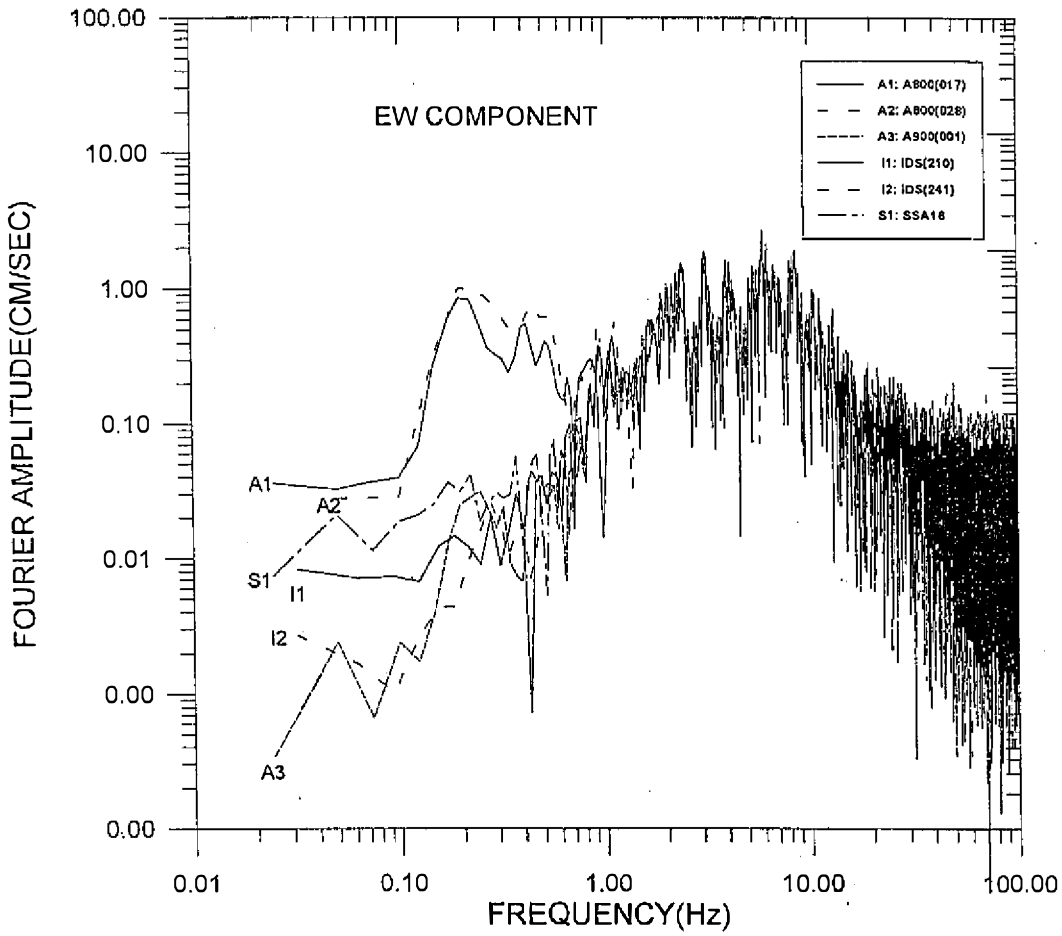

Fig. 6. Fourier spectra of the EW component of an M 4.1 event.

components, as shown in Figure 12. This case confirms the DC response of the accelerograph. The TSMIP has high instrument performance under strong ground motion. For example, Figure 13 shows the locations of triggered stations during the earthquake of June 5, 1994 (ML=6.4). The epicenter is shown in the figure by a solid star. At the time of the 6/5/94 earthquake, recordings were obtained from 214 of the 293 operational accelerograph sites, as shown in the figure by solid circles. Except for those instruments which were shut down due to external power failure, approximately 90%of the TSMIP accelerographs were successfully triggered at a PGA level of 8gals which was about twice the triggering level of most units.

5.4 Database Management

Thousands of high-quality digital accelerograms have already been collected by the TSMIP from the 2482 earthquakes occurring in the last few years. These new recordings provide an

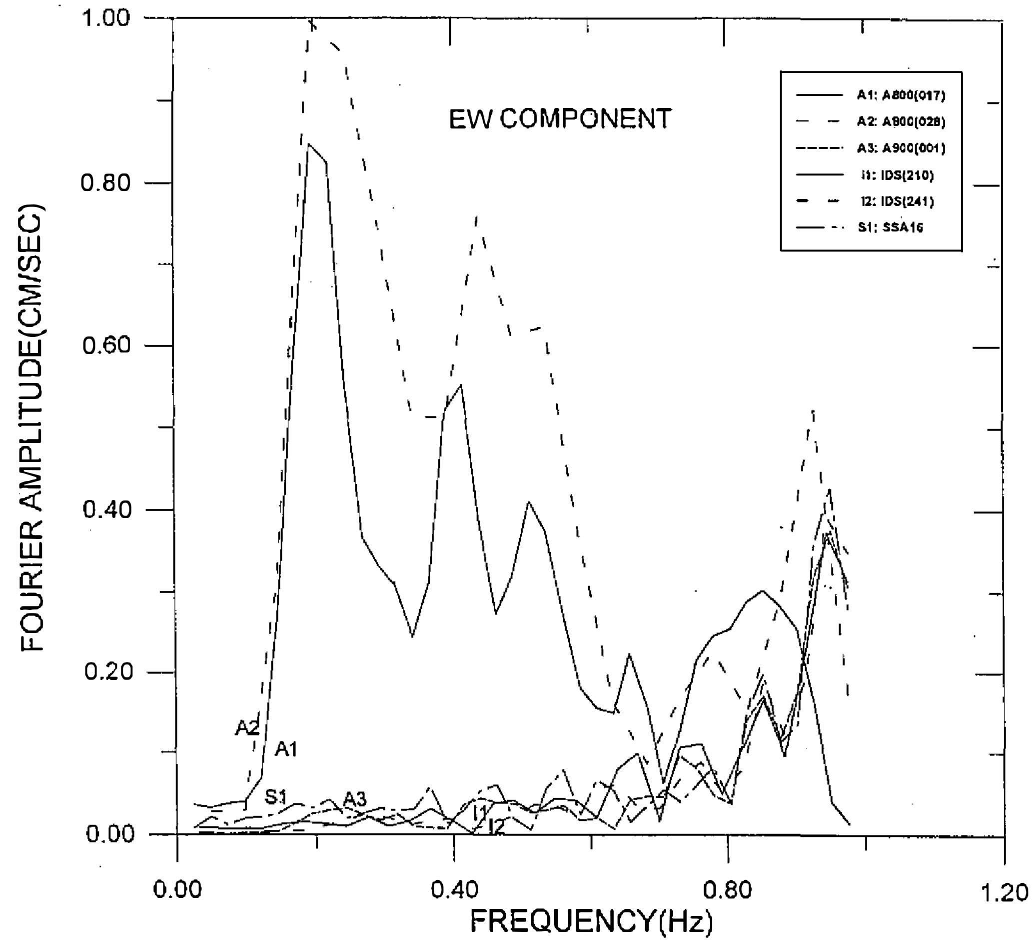

Fig. 7. Linear-scale plot of the Fourier spectra of the EW component of an M 4.1 event.

excellent database for making various earthquake engineering and seismological studies.

The recorded data are either written directly in the SUDS format, or in another format with a conversion routine to convert the data to SUDS format. The SUDS format is required so that the data recorded by different models of accelerograph are compatible with the IASPEI Software Library.

The CWBSC has printed an annual bulletin since June 1998. The bulletin provides the following data :(1) site information and instrument deployment of all stations, including station code, station name, location, elevation, instrument type, instrumental serial number, installation date etc; (2) all earthquake parameters that were recorded in the year , including original time, epicenter, focal depth, magnitude, PGA of three components; (3) the original accelerograms of all three components, i.e., vertical, north-south, and east-west components, for large earthquakes; (4) brief reports of damaging earthquakes. Users who are interested in

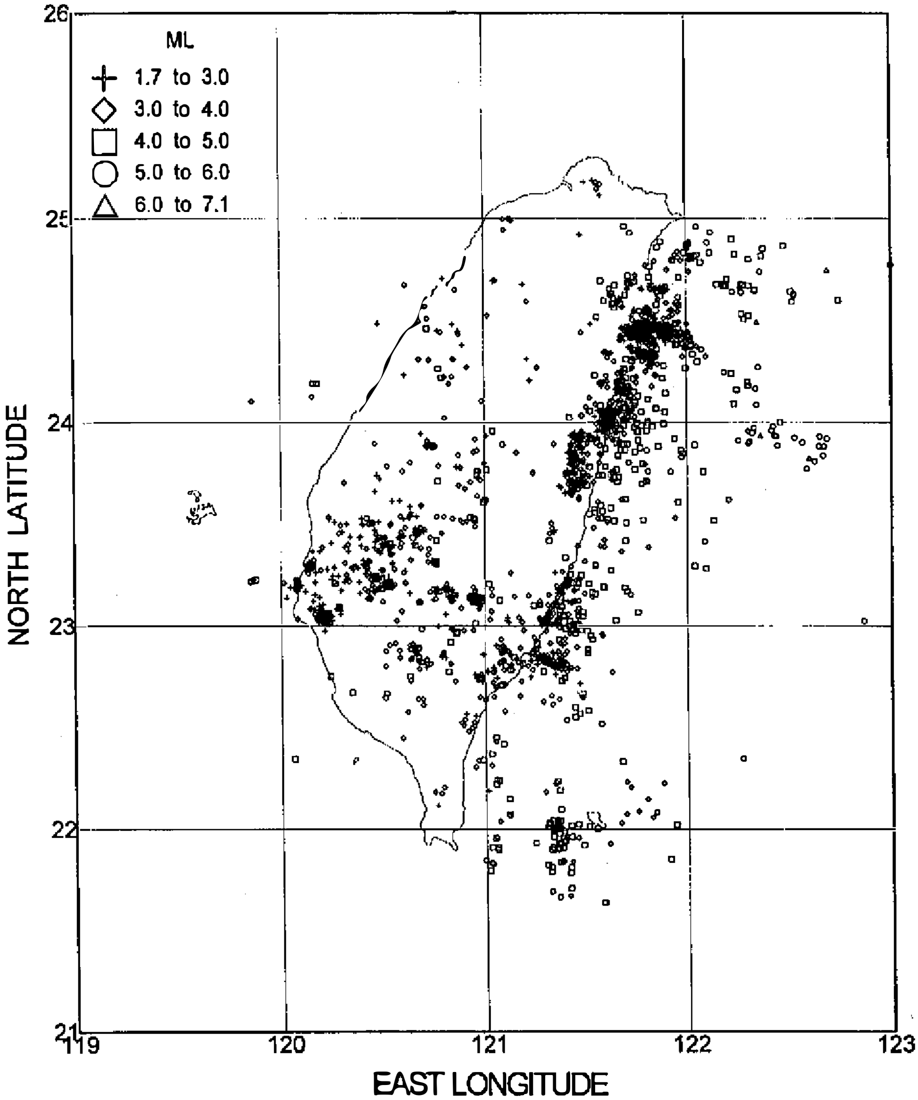

Fig. 8. The locations of recorded earthquakes from the TSMIP stations from 1992 to 1997.

the original strong motion data or annual bulletin can acquire them by contacting the service center of the CWB.

6. CONCLUSIONS

The Taiwan Strong Motion Instrumentation Program has provided a high-quality strong motion database for improving the earthquake resistant design criteria for buildings, and for

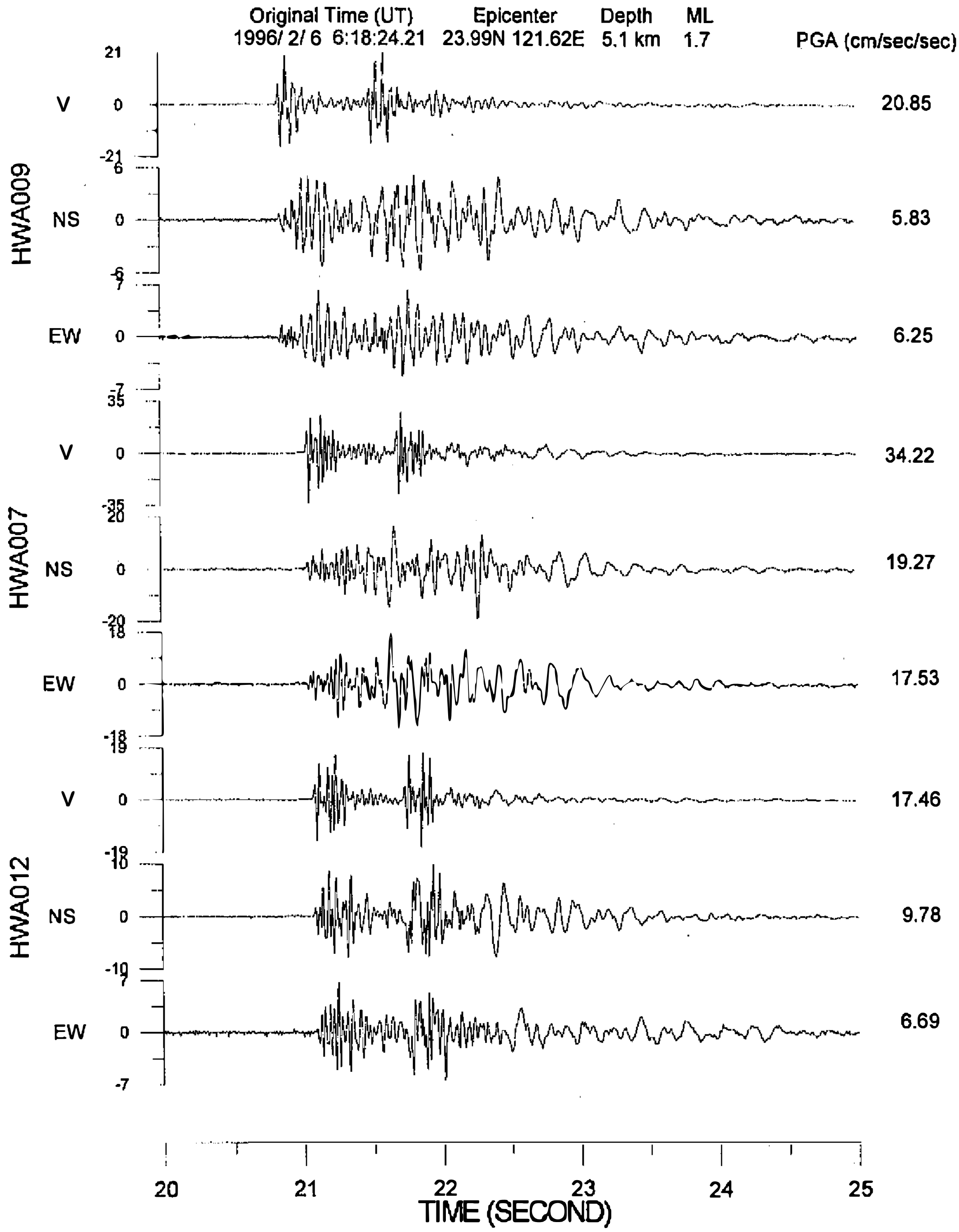

Fig. 9. A sample three-component accelerogram of the TSMIP database for an M 1.7 event.

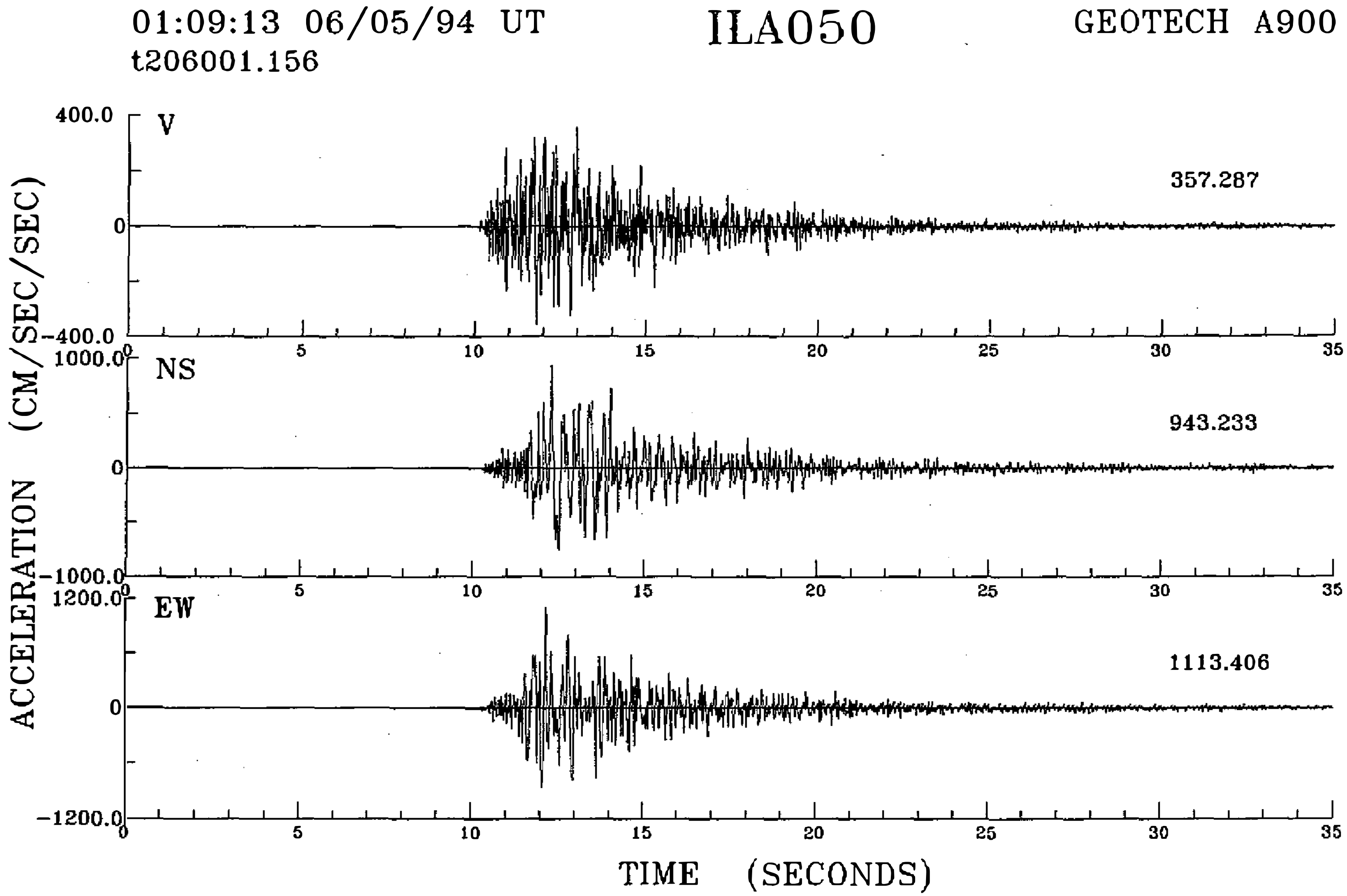

Fig. 10a. A sample three-component accelerogram of the TSMIP database for an M 6.4 event.

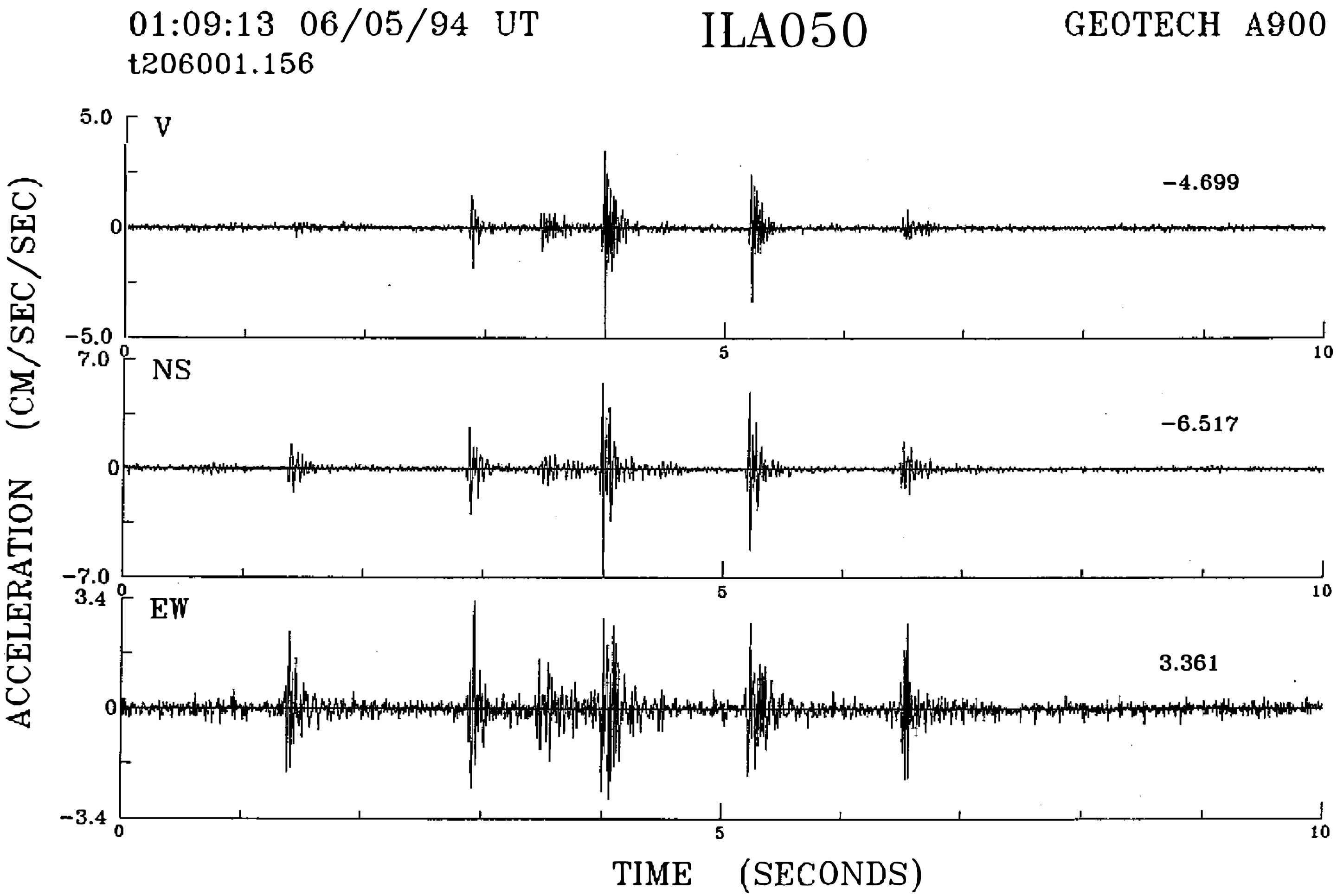

Fig. 10b. The enlarged portion of the accelerograms in Figure 10a several seconds before the main shock.

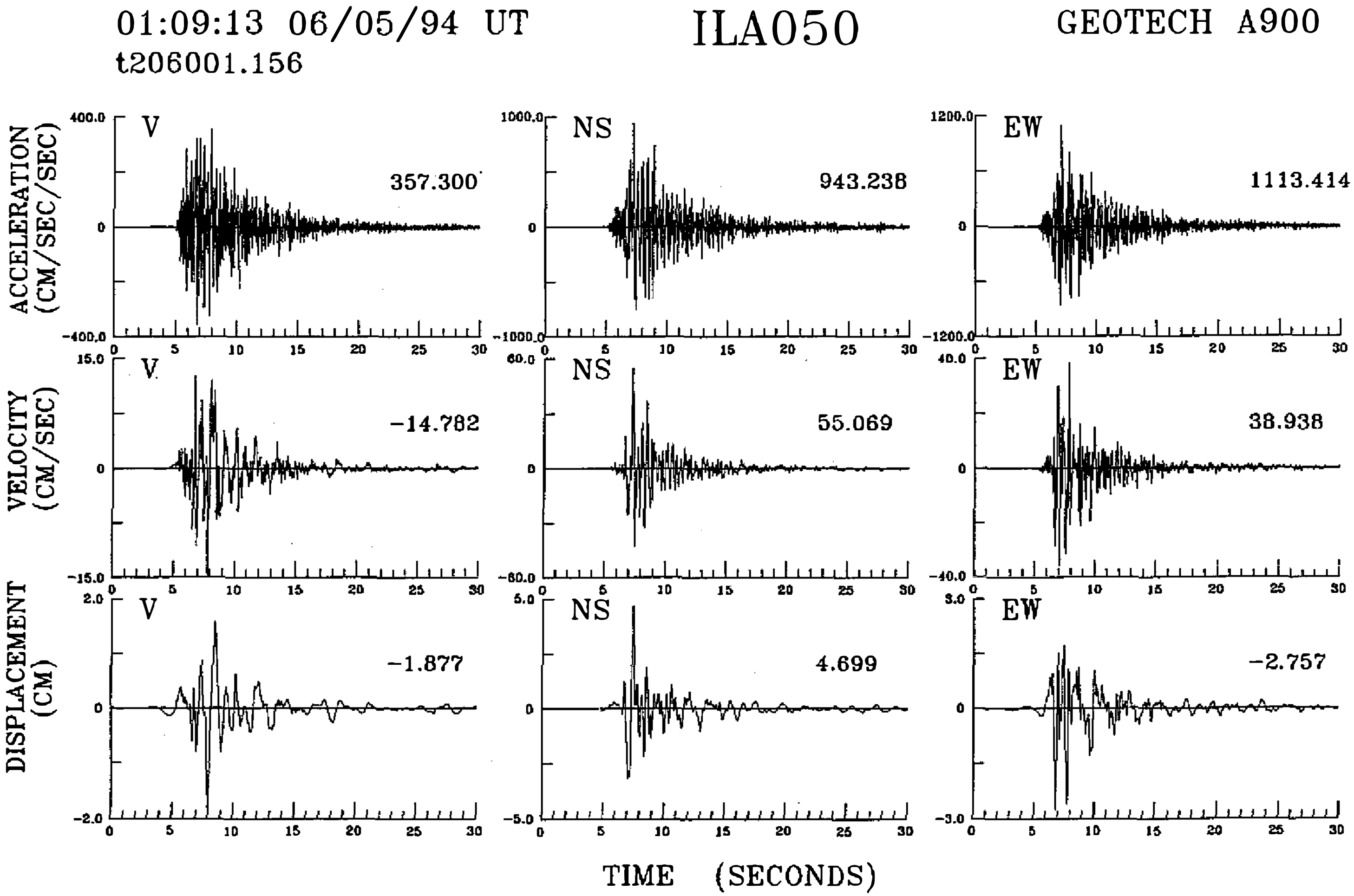

Fig. 11. Integrated velocity and displacement waveforms in Figure 10a by a routine integration procedure with low-cut filtering. No permanent displacements are recovered.

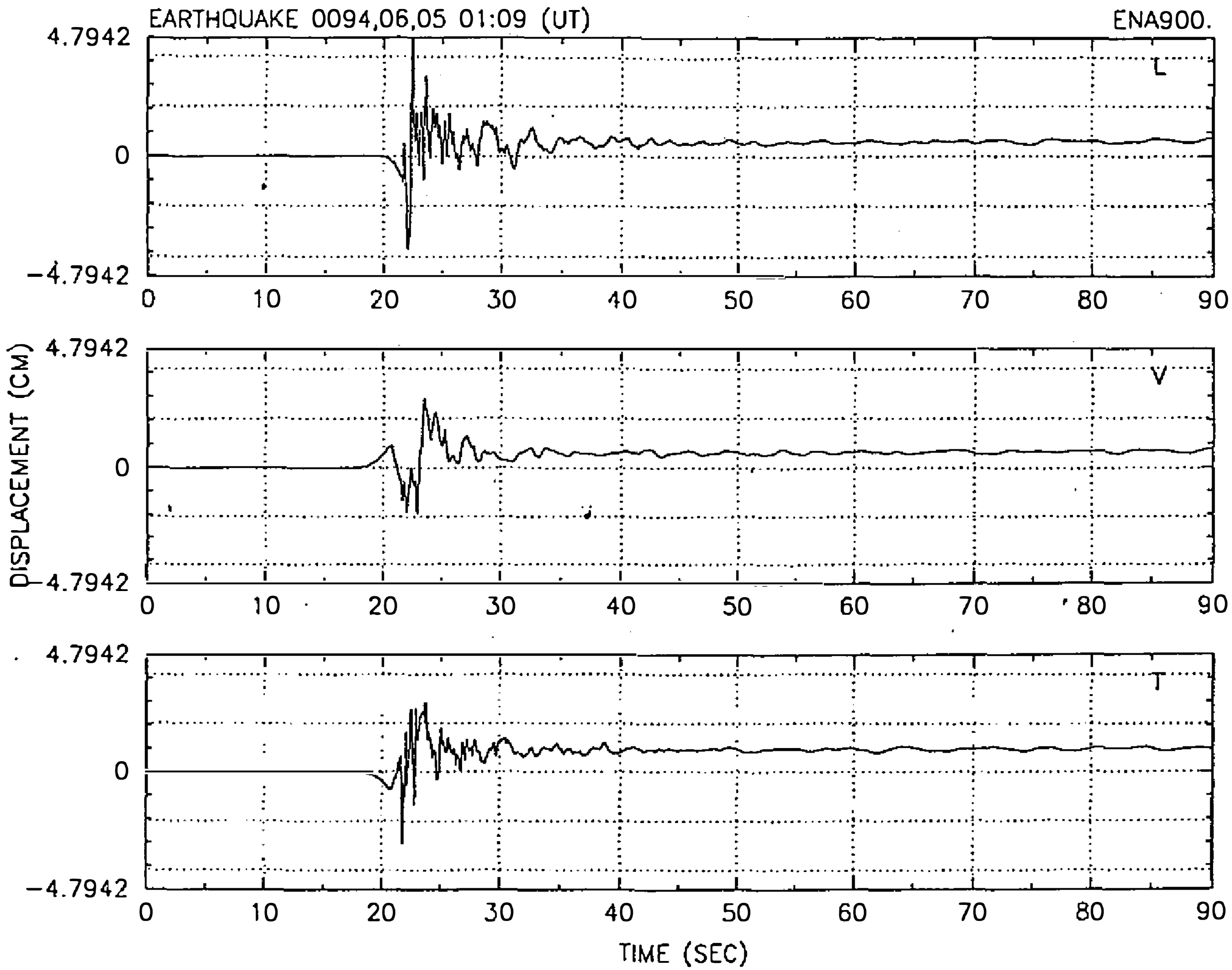

Fig. 12. Integrated displacement waveforms in Figure 10a by a stable integration procedure (Chiu, 1998) which reveals permanent displacements on all three components.

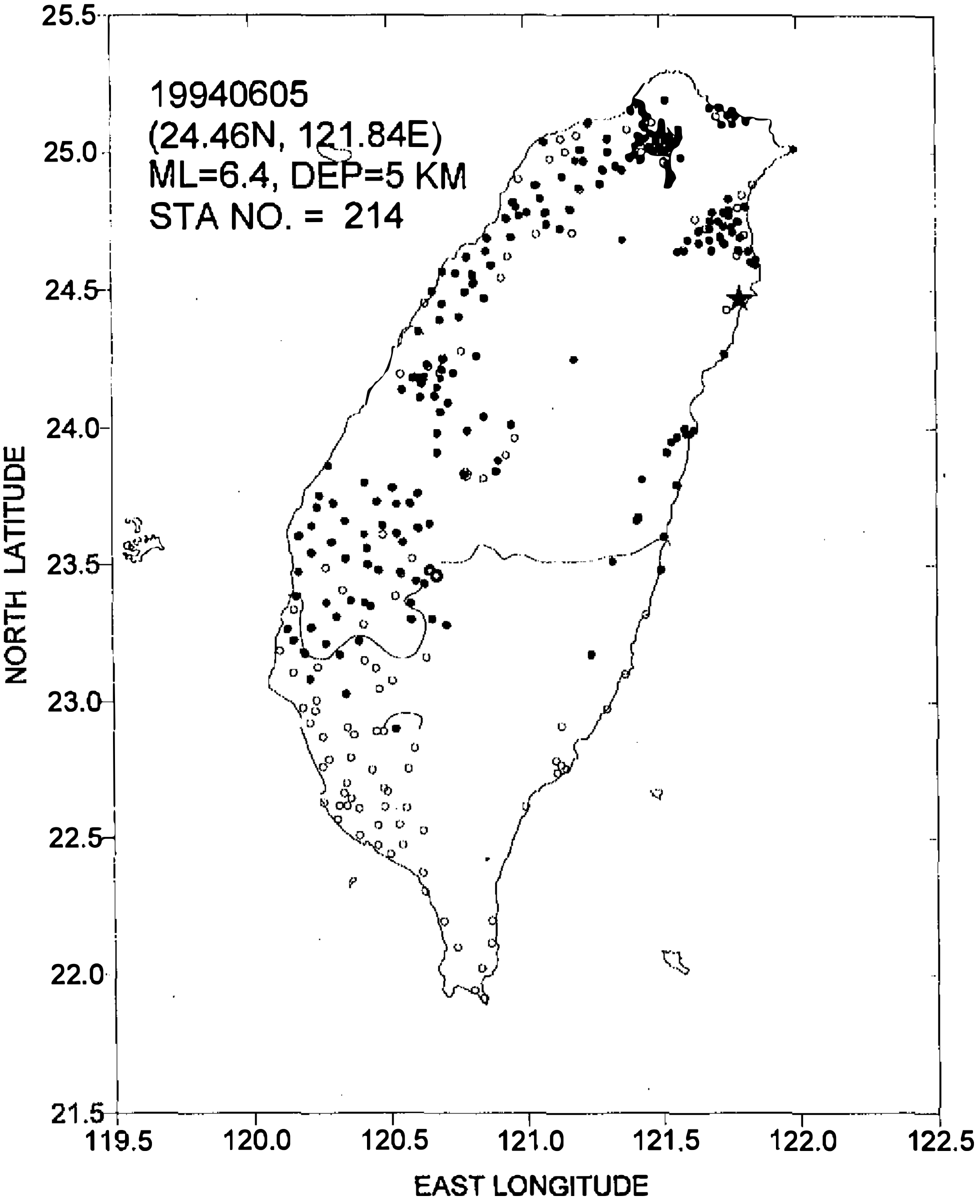

Fig. 13. Locations of triggered stations during the June 5, 1994 (ML=6.4) earthquake.

studying the earthquake source mechanisms as well as seismic wave propagation from the source to sites of interest, including local site effects.

The quality of 16-bit data is significantly better than the conventional strong-motion data(either analog or 12-bit digital recordings). Thousands of high-quality digital accelerograms have been collected from many earthquakes occurring in Taiwan during the last few years. These new recordings provide an excellent database for making various earthquake engineering and seismological studies.

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