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Strong-Motion Instrumentation Programs in Taiwan

T. C. Shin
Central Weather Bureau, Taipei, Taiwan
Y. B. Tsai
National Central University, Chung-li, Taiwan
Y. T. Yeh
Kao-Yuan Institute of Technology, Kaohsiung, Taiwan
C. C. Liu
Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan
Y. M. Wu
Central Weather Bureau, Taipei, Taiwan

1. Introduction

Taiwan is located on the Circum-Pacific seismic belt. On the east side of Taiwan, the Philippine Sea plate subducts beneath the Eurasian plate at the Ryukyu trench, while at the south end of Taiwan, the South China Sea lithosphere subducts eastward under the Philippine Sea plate. The active convergent margin, connecting these two subduction zones, is characterized by rapid crustal deformation, regional-scale crustal faulting, and high seismicity. The densely populated western Taiwan, with high-rise buildings as a consequence of developing economy, is vulnerable to increasing earthquake hazard. Therefore, earthquake research has a high priority in Taiwan and considerable amounts of resources have been devoted to seismic instrumentation in general, and strong-motion instrumentation in particular.

Many disastrous earthquakes have occurred in the past, the most recent one being the 1999 Chi-Chi earthquake (Teng *et al.*, 2001). About 2500 people died and 300,000 were left homeless. The importance of strong-motion instrumentation has long been recognized, and we will summarize here the history of the strong-motion instrumentation programs in Taiwan. The earlier instrumentation programs were conducted primarily by the Institute of Earth Sciences, Academia Sinica, and have been mostly research oriented (Tsai, 1997; see also Report of the Institute of Earth Sciences under China (Taipei) in Chapter 79). The later efforts, involving an order-of-magnitude increase in the number of instruments, were conducted primarily by the Central Weather Bureau.

2. Strong-Motion Instrumentation Program by IES

2.1 Strong-Motion Accelerographs Network (SMA)

An islandwide strong-motion network was deployed by the Institute of Earth Sciences (IES), Academia Sinica, beginning in 1974, and by 1983, this network consisted of 72 stations. The instruments used were the standards at that time, i.e., the SMA-1s. The first strong-motion record obtained by this network was in April 1976. The purpose of this network is mainly to study earthquake source, structure responses, attenuation of ground motions, and risk analysis. By 1990, accelerographs of this network increased to 79, as a mix of analogy and digital recording units. Most of them were installed on free-field sites, while some were on the man-made structures. Most of those free-field stations were installed on the populous plain areas. After 1990, all stations of this network have been continuously upgraded to force-balance accelerometers with 16-bit resolution. Numbers of accelerograph stations on plain areas were reduced, and new stations were installed in the Central Range Mountain

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of Taiwan. The total number of stations in this network is currently 74. The purpose of the new installation is to study the topographic effects and attenuation behavior of strong motion in the mountainous area (Huang, 2000). Leaders of this project include Y. B. Tsai (1974–1978), C. S. Wang (1979–1980), Y. T. Yeh (1981–1992), and B. S. Huang (1992–present).

2.2 Strong-Motion Accelerograph Array in Taiwan, Phase 1 (SMART-1 Array)

SMART-1 Array was set up in Lotung in 1980 and closed at the end of 1990. This was a cooperative project between the Institute of Earth Sciences, Academia Sinica and University of California, Berkeley. The SMART-1 Array consisted of a central site and accelerographs in three concentric circles, with radii of 200 m, 1 km, and 2 km, respectively. Each circle had 12 evenly spaced sensors. All 43 accelerographs were tied to a common time base, with timing to better than ± 0.01 sec. Each accelerograph consisted of a triaxial force-balance accelerometer, capable of recording ± 2 g, connected to a digital event recorder that uses a magnetic tape cassette for recording. The accelerographs were triggered on either vertical or horizontal acceleration at an adjustable preset threshold. Signals were digitized with a 1-bit resolution at 100 samples per second. Each recorder had a digital preevent memory that stored the output signals from the force-balance accelerometer for approximately 2.5 sec before trigger. Such accelerographs had an obvious advantage of providing synchronous time history of the ground-motion acceleration. Hence, we could perform spatial and temporal correlation across the whole array. The recorded data on digital cassettes were played back at the central laboratory and transferred onto a regular 9-track magnetic tape in ASCII format. During the playback, a seismologist scanned the digital signals displayed on a minicomputer console and made corrections for glitches, gaps, time code errors, and offsets in DC level. A regular magnetic tape containing edited data was available for further analysis only hours after the recording, whereas the analog recording/processing commonly used at that time would take days to digitize and process (Tsai and Bolt, 1983). Many research papers were published using the SMART-1 data (e.g., Loh *et al.*, 1982; Abrahamson, 1988).

2.3 Lotung Large Scale Seismic Test Array (LSST)

The LSST program was set up for evaluating the soil-structure interaction effects and the backfill effects. These effects are important in seismic design of nuclear reactor facilities. A quarter-scale and a 1/12-scale model of the nuclear reactor containment structure were constructed inside the SMART-1 Array on October 1985. It was closed at the end of 1990, the same time that SMART-1 Array had completed its mission. The LSST program was a joint project between the Taiwan Power Company (Taipower) and the Electric Power Research Institute of USA (EPRI), under the management of H. T. Tang. Under a contract of Taipower, IES installed and maintained the instruments, as well as carried out data collection, reduction, and analysis. In the initial phase, four types of sensors were installed in the fields for data acquisition: the surface accelerometer, the downhole accelerometer, the structural response accelerometer, and the interfacial pressure transducer. These sensors were triaxial type, except the pressure transducer. The output of all accelerometers and pressure gauges was transmitted by hard wire to the central recording unit and was recorded on cassette tapes. These tapes were then processed and transcribed onto 9-track tapes using the ASCII format.

2.4 SMART-2 Array

The SMART-2 strong-motion array was deployed by IES in the northern part of the Longitudinal Valley in Hualien in December 1990, and was fully operational in 1992 (Chiu *et al.*, 1994). It consists of 45 Kinemetrics SSR-1 instruments as surface stations and two sets of downhole subarrays. All sensors used in this array are force-balance accelerometers. This array is designed to study the rupture process of the seismic fault and the characteristics of near-source ground motions. Furthermore, the high-quality data from SMART-2 may be used for research in seismology and earthquake engineering (e.g., Huang and Chiu, 1996).

Chiu *et al.* (1995) studied the coherency of ground motions based on the SMART-2 data and compared it with the results of the SMART-1. A comparison of coherency functions for both vertical and horizontal motions from a magnitude 5.5 earthquake recorded by the SMART-2 indicated no significant difference in the range of 1 to 10 Hz for separation distance of 400, 800, and 1500 m.

2.5 Hualien Large Scale Seismic Test Array (HLSST)

Since 1993, EPRI and Taipower have sponsored a dense multiple-element array, the HLSST network, located at the Veteran's Marble Plant of Hualien within the SMART-2 deployment area of northeastern Taiwan. This is an international joint project operated by IES with the objectives of investigating the behaviors of soil-structure interaction during severe earthquakes and verifying the validity of various analysis methods using the strong-motion records. To serve this purpose, a one-quarter-scale cylindrical reactor model and a cylindrical liquid-storage-tank model were constructed in Hualien, a high-seismicity region. The cylindrical liquid-storage-tank model was closed in July 1998.

2.6 Downhole Accelerometer Arrays in the Taipei Basin (DART)

A research project, "Integrated Survey of Subsurface Geology and Engineering Environment of the Taipei Basin," was proposed in early 1990s to collect data for the purposes of engineering construction, groundwater management, ground subsidence prediction, study of the basin effects of seismic waves, and geological sciences. This project has been sponsored by the Central Geological Survey (CGS), Ministry of Economic Affairs since August 1991. CGS contracted the study of the basin effects on seismic waves to IES, which proposed the DART program, in which one site was installed per year to analyze the variation of seismic waves propagating from the basement to ground surface. Each site includes one free-surface accelerometer and some downhole sensors. These force-balance accelerometers are connected to a PC-based central recording system or a K2 digital recording system with GPS timing and position information.

Wen *et al*. (1995) studied basin effects using a dense strong-motion array in Taipei Basin. Their results showed that site amplification is frequency dependent. They also indicated that both horizontal peak ground acceleration and the spectral ratio in low-frequency band are closely correlated with the geological structure of Taipei Basin.

3. Strong-Motion Instrumentation Program by CWB

In the late 1980s, Y. B. Tsai proposed an extensive strong-motion instrumentation program for the urban areas in Taiwan. Since the Central Weather Bureau has the official responsibility to monitor earthquakes in the Taiwan region, the Taiwan Strong-Motion Instrument Program (TSMIP; see Shin, 1993) was successfully implemented during 1991–1996.

The main goal of this program is to collect high-quality instrumental recordings of strong ground shaking from earthquakes, both at free-field sites and in buildings and bridges. These data are crucial for improving earthquake-resistant design of buildings and bridges 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 were deployed throughout Taiwan in this program, with special emphasis in nine metropolitan areas. One type is a digital triaxial accelerograph for recording free-field ground shakings (Liu *et al*., 1999). The other type is a multichannel (32 or 64 channels), central-recording, accelerograph array system for monitoring shakings caused by earthquakes in buildings and other structures (Lee and Shin, 1997). By the end of 2000, a total of 640 free-field accelerographs and 56 structural arrays had been deployed. Locations of the free-field accelerographs are shown in Figure 1, and locations for the building arrays are shown in Figure 2.

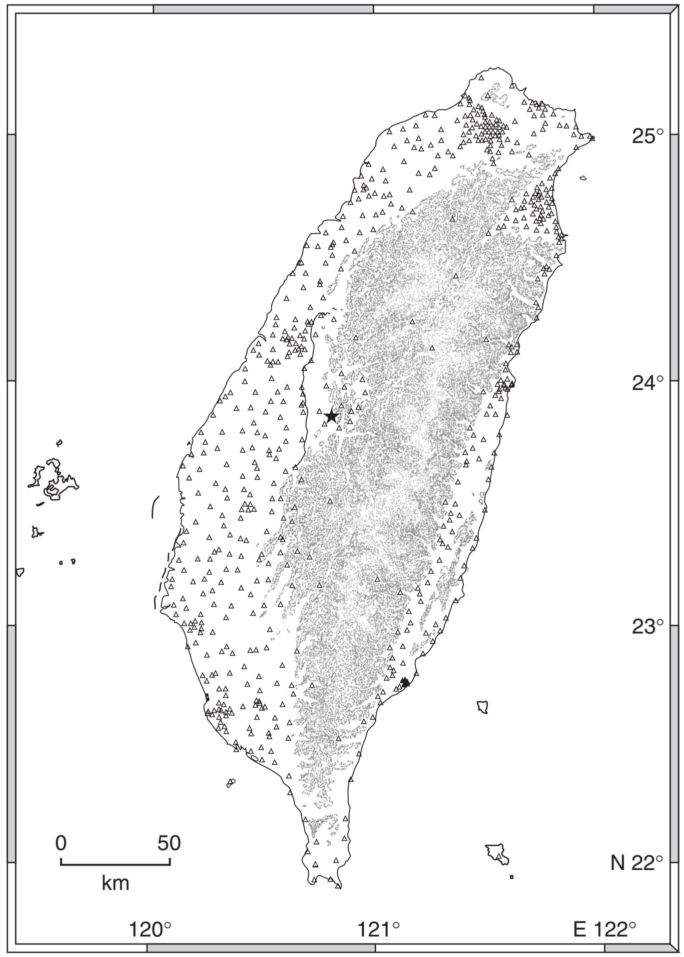

FIGURE 1 Locations of the CWB free-field, three-component, digital accelerograph stations. The star indicates the location of the Chi-Chi earthquake. Surface ruptures extending about 80 km north–south are shown to the left of the epicenter.

4. The Taiwan Rapid Earthquake Information Release System

The desire for seismological observation in real time has long been recognized, and significant advances have been made during the past decade in many countries (Kanamori *et al*., 1997). The idea of an islandwide early earthquake warning system using the existing telemetry in Taiwan was first proposed by T. L. Teng in the early 1990s. The Taiwan Rapid Earthquake Information Release System (RTD) is based on a simple hardware/software design first introduced by Lee *et al*. (1989), and was subsequently improved and refined (Lee, 1994; Lee *et al*., 1996; Shin *et al*., 1996; Teng *et al*., 1997; Wu *et al*., 1997, 1998, 1999). The RTD system consists of 61 telemetered strong-motion accelerographs in Taiwan (Fig. 3). Digital signals are continuously telemetered to the headquarters of the Central Weather Bureau (CWB) in Taipei via 4800-baud leased telephone lines. Each telemetered signal contains three-component seismic data digitized at 50 samples per second and at 16-bit resolution. The full recording range is ± 2 g. The incoming digital data streams are processed by a computer program called XRTPDB (Tottingham and Mayle, 1994). Whenever the prespecified trigger criteria are met, the digital waveforms are stored in memory and are automatically analyzed by a series of programs (Wu *et al.*, 1998).

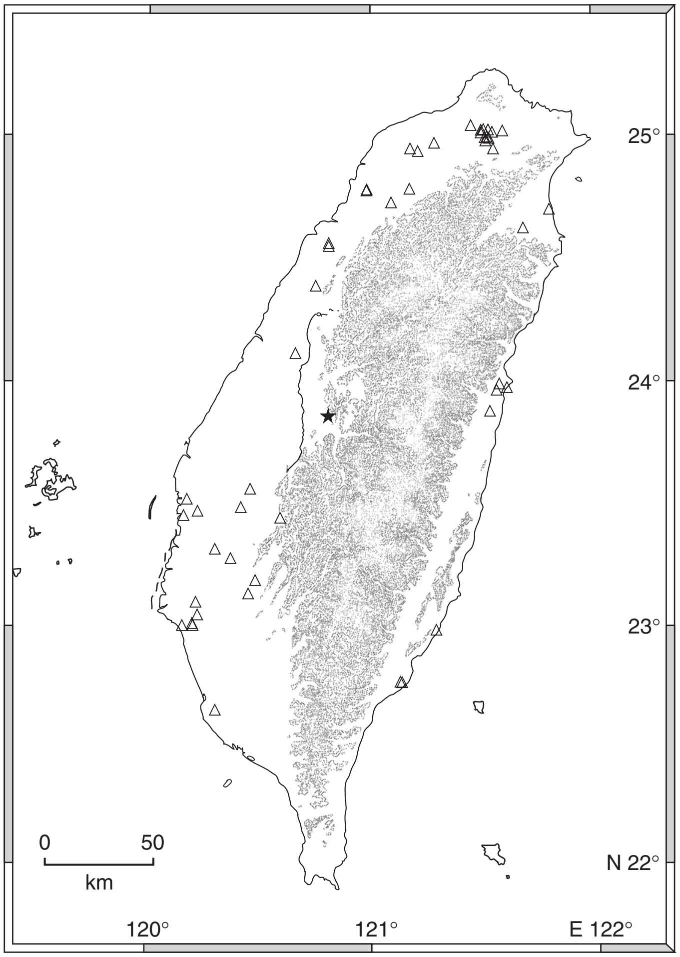

FIGURE 2 Locations of the CWB structural strong-motion arrays in buildings and bridges. The star indicates the location of the Chi-Chi earthquake. Surface ruptures extending about 80 km north–south are shown to the left of the epicenter.

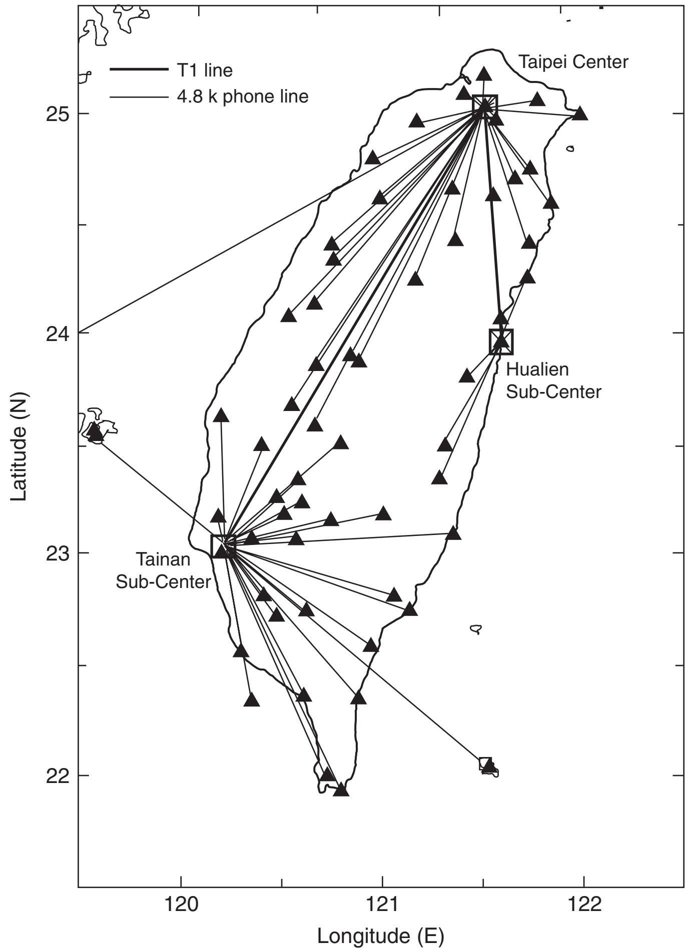

FIGURE 3 Map showing the telemetered stations of the Taiwan Earthquake Rapid Information Release System (RTD).

The results are immediately disseminated to emergency response agencies electronically in four ways, namely, by e-mail, World Wide Web, fax, and a pager system (Fig. 4).

5. The Chi-Chi Earthquake of September 21, 1999

The Chi-Chi earthquake occurred at 1:47 on September 21, 1999 (Taiwan local time) or at 17:47 on September 20, 1999 UTC. It was the largest ($M_w = 7.6$) earthquake to have occurred on land in Taiwan in the 20th century. For the main shock, 441 digital three-component, strong-motion records were successfully retrieved by the Taiwan Central Weather Bureau (CWB) from about 640 accelerographs deployed at the free-field sites. These preliminary strong-motion data from the Chi-Chi main shock were released on December 13, 1999, in the form of a prepublication data CD (Lee *et al*., 1999). During the first 6 hours after the main shock, about 10,000 strong-motion records were recovered, and since then another 20,000 records were obtained. This is by far the best-recorded major earthquake in the world. There are over 60 three-component strong-motion records within 20 km of the fault ruptures.

A preliminary report of this earthquake is given in Shin *et al.* (2000), and a detailed report of the processed free-field acceleration data is given in Lee *et al*. (2001a). These data are also archived in Lee *et al.* (2001b). Characteristics of the strong ground motion are given by Tsai and Huang (2000). At the time of the earthquake, the Taiwan Rapid Earthquake Information Release System (RTD) automatically determined the location and magnitude for the main shock and prepared a shake map within 102 seconds after the earthquake's origin time. This information was then sent out by a pager-telephone system, by an e-mail server, and by fax. Its performance during the Chi-Chi earthquake and numerous strong aftershocks has been documented in Wu *et al.* (2000).

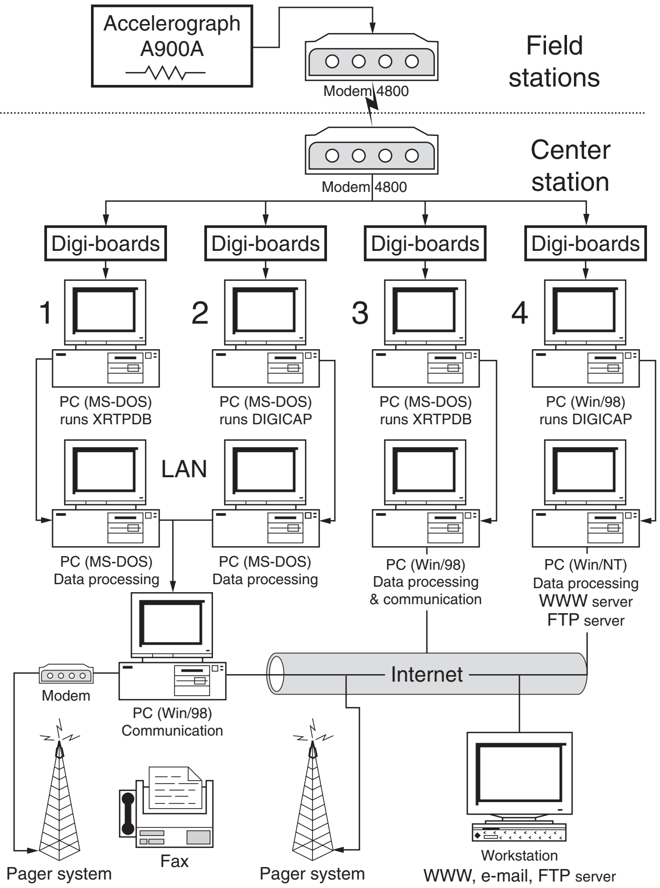

FIGURE 4 A block diagram showing the hardware of the RTD system.

6. Concluding Remarks

The Chi-Chi earthquake clearly demonstrated the usefulness of the extensive strong-motion instrumentation in Taiwan for purposes of emergency response and research in seismology and earthquake engineering. Readers are referred to several special issues and proceedings on the Chi-Chi earthquake (e.g., BERI, 2000; Loh and Liao, 2000; Wang *et al*., 2000; Teng *et al.*, 2001).

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