Bulletin of the Seismological Society of America, 91, 5, pp. 1370–1376, October 2001

CWB Free-Field Strong-Motion Data from the 21 September Chi-Chi, Taiwan, Earthquake

by W. H. K. Lee, T. C. Shin, K. W. Kuo, K. C. Chen, and C. F. Wu

Abstract The Chi-Chi earthquake occurred at 17:47 on 20 September 1999 and is the largest earthquake (M_W 7.6) to have occurred on land in Taiwan in the twentieth century. This earthquake caused considerable damage and was named the "921 Chi-Chi Great Earthquake" by the Taiwan government, as the local date was 21 September. Because an extensive strong-motion instrumentation program in Taiwan was completed by the Central Weather Bureau (CWB) in 1996, over 30,000 digital strong-motion records have been obtained from the Chi-Chi earthquake and thousands of its aftershocks. These records form the largest set of strong-motion data recorded from a major earthquake since strong-motion seismology studies began in the 1930s. This data set is important to seismology and earthquake engineering because it includes over 60 recording sites within 20 km of the fault ruptures, which provides a five-fold increase of such near-field records available for the entire world.

A prepublication CD was made available in mid-December 1999, and the data on it have been used by many authors in dozens of articles published so far. Since then, we examined about 10,000 strong-motion records and conducted a first-order quality assurance procedure for all the records obtained on 20 September 1999, including the mainshock and hundreds of the early aftershocks. We performed extensive data processing for quality assurance and selected a total of 663 strong-motion data files from 441 accelerographs to construct strong-motion records up to 4-min long for the mainshock whenever possible. In this article, we present a brief description of the processed acceleration data from the Chi-Chi earthquake. The data set (about 500 megabytes) and an extensive 562-page report (documenting the data processing and results of the processed data) are archived on the attached CD in this Special Issue so that users can quickly access this valuable data set for their research.

Introduction

The Chi-Chi earthquake occurred at 17:47 on 20 September 1999 and is the largest earthquake (M_W 7.6) to have occurred on land in Taiwan in the twentieth century (Shin *et al.,* 2000). This earthquake caused considerable damage and was named the "921 Chi-Chi Great Earthquake" by the Taiwan government because the local date was 21 September. The Central Weather Bureau (CWB) in Taipei has the official duty of monitoring earthquakes in and near Taiwan and was fortunate to have completed an extensive instrumentation program in 1996 at a cost of about U.S. $40 million. Over 30,000 digital strong-motion records have been obtained from the Chi-Chi earthquake and thousands of its aftershocks. These records form the largest set of strong-motion data recorded from a major earthquake since strong-motion seismology studies began in the 1930s. This data set is important to seismology as well as to earthquake engineering because it includes over 60 recording sites within 20 km of the fault ruptures, providing a five-fold increase of such near-field strong-motion records from major earthquakes for the entire world.

For the mainshock, 441 digital strong-motion records were prepared and processed using 663 triggered data files recorded by 441 accelerographs. A total of 640 digital accelerographs were deployed at the free-field sites. However, 199 accelerographs did not record the mainshock due to various reasons, for example, some accelerographs were under repair, electricity to some sites was cut off due to construction, the internal battery of some accelerographs failed, or the trigger level of some accelerographs was set too high, and so on. There are also 55 strong-motion arrays (30–60 seismic channels) in operation in buildings and bridges, and 35 of these arrays recorded the mainshock. Although each strong-motion array has a three-component free-field accelerometer, these data are not included here. Also, several other institutions in Taiwan, especially the Academia Sinica, operate strong-motion instruments in Taiwan.

After the occurrence of the 921 Chi-Chi earthquake, it was clear that CWB had recorded the best (in quantity and quality) set of strong-motion data for a major earthquake since studies of strong-motion seismology began in the 1930s. An intensive effort was made to perform a first-order quality assurance procedure so that the data could be available for research as soon as possible. For practical reasons, the free-field strong-motion data from the Chi-Chi earthquake was placed as computer-readable files on a CD-ROM with explanatory notes. This task was completed on 6 December 1999, and a prepublication CD with a brochure (Lee *et al.,* 1999) was distributed free of charge for academic research. Since it was prepared in such a short time, we realized that much work remained. Due to funding and manpower limitations, preparation of the publication version (Lee *et al.,* 2001a) took another year.

We examined about 10,000 strong-motion records and conducted a first-order quality assurance procedure for all records obtained on 20 September 1999, including the mainshock and hundreds of early aftershocks. We performed extensive data processing for further quality assurance and selected a total of 663 strong-motion data files from 441 accelerographs to construct strong-motion records up to 4 min long for the mainshock whenever possible. In this article, we present a brief description of the processed acceleration data from the Chi-Chi earthquake. The article is a condensation of the article by Lee *et al.* (2001a), which has a very limited distribution. The data set (about 500 megabytes) and an extensive 562-page report (documenting the data processing and results of the processed data) are archived on the attached CD in this Special Issue so that this valuable data can be quickly accessed by interested readers worldwide.

Instrumentation and Station Information

The CWB operates several types of digital accelerographs (most of them are $\pm 2g$ full scale, 200 or higher samples per second, and 16-bit or better resolution with up to 20-sec pre-event recording). About 69% of the deployed accelerographs were manufactured by Geotech Instruments, about 25% by Terra Tech, and about 6% by Kinemetrics. Readers are referred to the manufacturers' web sites for further information about the accelerographs. All waveform data are stored as integers in unit of digital counts. Conversion to a physical unit, such as g, depends on the accelerograph model as shown below:

Model	Numbers Deployed	Full-Scale	Data Stored as	Digital Counts
A800	46	$\pm 1g$	12-bit integer	± 2048
A900 and A900A	393	$\pm 2g$	16-bit integer	± 32768
IDS and IDSA	163	$\pm 2g$	16-bit integer	± 32768
ETNA and K2	38	$\pm 2g$	24-bit integer	± 8388608

We asked the manufacturers to provide us with a brief description of their instruments. Geotech provided information about their accelerographs, which is summarized below. Terra Tech no longer exists as a company, and Kinemetrics referred readers to their Web site.

Accelerographs by Geotech Instruments (A800, A900, A900A)

The A-800 is a 12-bit digital data recorder and contains three Geotech Model S-110 accelerometers mounted orthogonally inside the cast aluminum base. Data are stored in CMOS static random-access memory (RAM) using a nondistorting format without data compression. The A-900 has all the features of the A-800 while being upgraded with a 16-bit analog-to-digital conversion unit (ADC), new Geotech DC force balanced accelerometers (FBA), and the capability to use a Global Position System (GPS) receiver for its time synchronization source. The A-900A is an improved version of the A-900 with modifications that provide for submersion to a limited depth, real-time serial data output, and accelerometers with improved performance.

All three units have an internal timing accuracy of ± 26 msec per 24 hr over the operating temperature range when not connected to an external timing reference. The time can be initially set by hand via a PC connected to the unit. By monitoring the 1 pulse per sec output from the unit and comparing it to a reference source, they can be synchronized to within ± 10 msec via the PC interface. On the A-900 and A-900A, a model GPS-1 receiver can be used to synchronize the internal timing. When enabled, these units will maintain continuous synchronization to absolute UTC time to within ± 1 msec at all times while the GPS is reporting a locked condition. For further information, visit Geotech Instruments at *http://www.geoinstr.com.*

Accelerographs by Terra Tech (IDS and IDSA)

The IDS accelerographs are 16-bit digital instruments with 250 samples per sec sampling. They are manufactured by Terra Technology Corp. Terra Tech was acquired recently by Refraction Technology, Inc. (*http://www.reftek.com*).

Accelerographs by Kinemetrics (ETNA)

The ETNA is a digital accelerograph with 18-bit resolution at 200 samples per sec. For further information, visit Kinemetrics at Kinemetrics, Inc. (*http://www.kinmetrics.com*).

Station Location, Site Classification, and Instrument Information

Locations of 441 accelerograph stations that recorded the mainshock are shown in Figure 1. Since some station sites have more than one accelerograph, there are 412 unique station sites. Station coordinates, site classification according to C. T. Lee (2001), and instrument information are given in Table 2 on the attached CD (Lee *et al.,* 2001b).

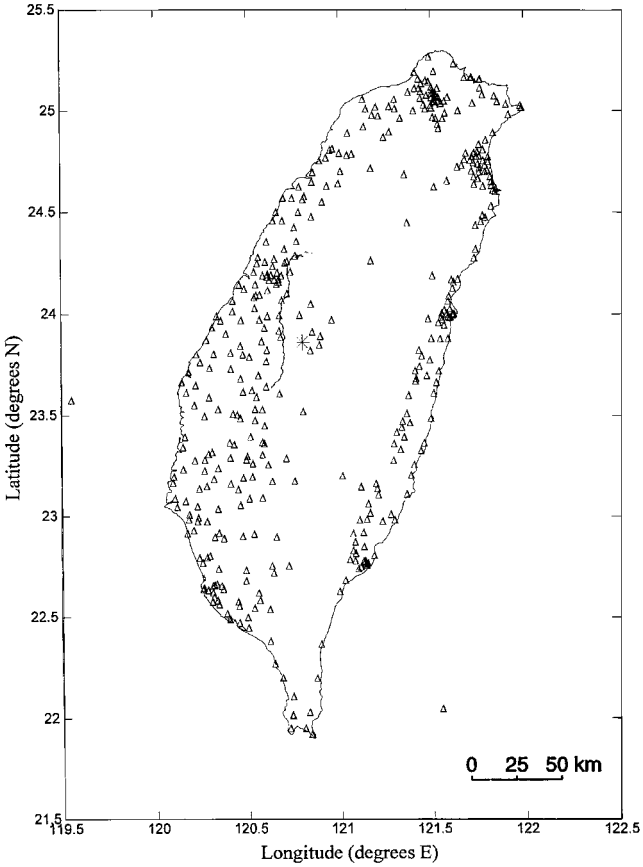

Figure 1. Locations of 441 accelerograph stations that recorded the mainshock (shown as *). Surface ruptures on the Chelungpu fault are shown to the left of the mainshock.

Preparation for the Publication Version

It is well known that a large collection of data from hundreds of instruments requires extensive quality assurance, because to err is human. In this case, the data collection was also complicated by 4 distinct types of accelerographs, each having a different data format. A first-order quality control check was performed on the recorded free-field strong-motion data in the preparation of the prepublication CD as described by Lee *et al.* (1999).

Assurance of Data Quality

The CWB strong-motion data were collected by four academic groups (under the direction of Mr. Chun-Chi Liu of Academia Sinica, Prof. Gwo-Bin Ou of National Chung Cheng University, and Prof. Chien-Ying Wang and Prof. Kuo-Liang Wen of National Central University). The collected data were centralized at the CWB headquarters, and the CWB staff provided the strong-motion data recorded by the CWB free-field accelerographs on three CDs to the first author. These were raw data taken from the accelerographs of four types: Models A800, A900, and A900A of Teledyne Geotech, Models IDS and IDSA of Terra Tech, and Model ETNA of Kinemetrics.

Approximately 10,000 strong-motion records were collected from about 450 digital accelerographs at the free-field sites during a time period of about 6 hr 13 min from the Chi-Chi mainshock, that is, from about 17:47 through 24:00 of 20 September, 1999 UTC. An earthquake will trigger an accelerograph recording (up to a prespecified maximum length, typically 90 sec long) if its waveform amplitudes exceed a certain threshold level. Since there were hundreds of aftershocks immediately after the mainshock, up to 128 triggered records could be obtained from an accelerograph until the memory storage of the accelerograph was full. Some of the triggered records are overlapping because there are pre-event memory (up to 20 sec) before the triggered time. Several quality control tasks were performed on the recorded data to assure data quality. The principal tool we used was an interactive computer program called SMQC written by Doug Dodge for performing quality assurance tasks (see section C of the report by Teng and Lee, [2000]).

Header Information

Although information about the unit serial number, station name, coordinates, timing device, and so on are encoded in the header of each strong-motion data file, we found many errors. Because this header information must be entered manually by a technician, it is easy to make mistakes. We corrected many errors using a master file of station information maintained at the CWB headquarters. We devoted a considerable amount of time in building up a reliable master file of station information, especially with respect to station coordinates and timing, as described next.

Station Coordinates

We found many errors in the station coordinates that were entered into the accelerographs and recorded in the header of the strong-motion data files. After the Chi-Chi earthquake, the CWB staff reread the station coordinates from their field maps (scale 1:25,000). We took about half of these revised coordinates and plotted them on 1:25,000 maps. We compared the plotted locations against the 1:25,000 published maps and verified the results. About 20 station locations, which were in doubt, were further verified by the CWB staff. In addition, we obtained GPS-surveyed coordinates of schools conducted by the Ministry of Education. Since most of the CWB free-field accelerographs are located in schools, we compared our coordinates to the GPS-surveyed coordinates and assumed agreement if the difference in distance was less than 250 m. We allow this difference because the school's reference point is not the same as the accelerograph site in that school. Station coordinates with site classification (according to C. T. Lee, [2001]) and instrument information are given in Table 2 on the attached CD (Lee *et al.,* 2001b).

Absolute Timing

Most of the CWB free-field accelerographs were purchased during the period of 1991–1995 before a GPS timing device became the standard means for providing accurate timing in accelerographs. However, the importance of absolute timing was recognized by CWB. The GPS timing devices were installed in the newer accelerographs, and some of the older accelerographs were upgraded with a GPS timing device. Unfortunately, these upgrades were being carried out when the Chi-Chi earthquake occurred. Because only a fraction of the CWB free-field accelerographs were equipped with a GPS timing device, timing for most of the strong-motion records is approximate, as it is based on the accelerograph's internal clock. The internal clock is initialized manually and is no better than about 1 sec initially. Since it is easy to enter the initial time incorrectly, and since the internal clock drifts, timing for most of the strong-motion records is only approximate.

Even for the stations with a GPS timing device, timing may still be uncertain. For example, the default for the A900/A900A accelerographs is to use the internal clock, and some accelerographs with a GPS timing device were not set correctly to override the internal clock. Even if an accelerograph was set correctly, GPS synchronization occurs only every 2 hr (the default). The recorded data file does not have information about the status of time synchronization. However, the file header contains information on whether or not the 1-sec pulse of GPS is being received.

More detailed information about the GPS timing status is available from the IDSA accelerographs. Data files recorded by the ETNA accelerographs contain detailed information about GPS timing status and on the time drift of the internal clock.

After careful examination of the file header information of the original strong-motion records and with generous support from the manufacturers, we identified 39 accelerographs (equipped with a GPS timing device) that had absolute timing during the Chi-Chi mainshock. A listing of these accelerographs with station and instrument model information are given in Table 3 on the attached CD, and their locations are shown in figure 2 of Lee *et al.* (2001a), also on the attached CD(Lee *et al.,* 2001b).

Time Corrections

We developed a method to assess the quality of timing for the CWB strong-motion records. The Chi-Chi mainshock and 84 aftershocks were carefully timed, and a simultaneous inversion for locations and velocity corrections were performed using a version of the VELEST program by Kissling (1992), which is based on a technique originally developed by Aki and Lee (1976). We then computed the theoretical *P*-arrival time with our picked *P* time. For the 39 accelerographs with GPS timing devices which were identified previously, we found close enough agreement in the times to convince us that these accelerographs had reliable absolute times. For the remaining accelerographs with GPS timing devices, we could not tell, or we concluded that the absolute timing was not reliable.

For accelerographs that do not have GPS timing devices or bad GPS timing, we made time corrections only if necessary and possible. If the *P*-time residual was larger than 1 sec for accelerographs at epicentral distance less than 50 km or larger than 2 sec at epicentral distance less than 100 km, and so forth, we made a time correction such that the theoretical *P* time is the same as the picked *P* time. In other words, we use the *P*-time residual as the clock correction for these accelerographs. By this method, we believe that the timing for most of the processed CWB strong-motion records (for the Chi-Chi main shock) is good to 1–4 sec depending on the epicentral distance of the accelerographs (the larger the distance, the larger the uncertainty).

Details of the timing correction information are given in Table 4 on the attached CD (Lee *et al.,* 2001b). If absolute timing is important, users should use the corrected start time for strong-motion data files as: Start_Time + Time_Cor, where Start_time is the original recorded file start time and Time_Cor is the time correction. If Time_Cor is zero, then either the accelerograph has absolute timing with a working

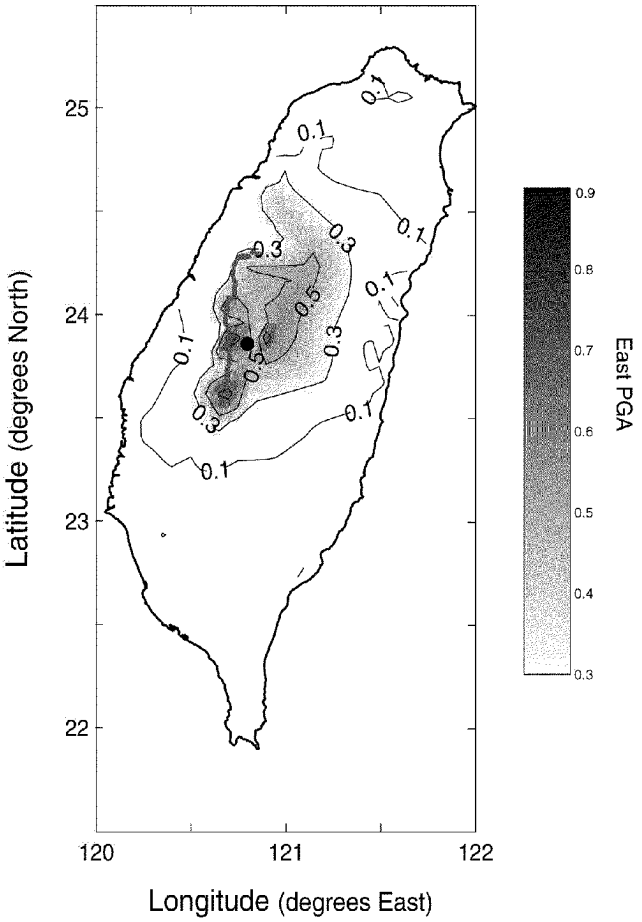

Figure 2. Contour map of PGA values in *g* (E–W component) for the Chi-Chi mainshock.

GPS timing device or the *P* residual is within the expected error range. If Time_Cor is blank in Table 4 on the attached CD (Lee *et al.,* 2001b), this means that we could not pick the first *P* arrival because the accelerograph was triggered late.

DC-Offset Corrections and Peak Ground Acceleration Values

Whenever possible, we have removed the direct-current offsets (based on the pre-event data) in the processed strong-motion records. We then determined the peak ground acceleration (PGA) values in units of *g* (981 cm/sec^2) from the processed strong-motion records. The details are given in Table 5 on the attached CD (Lee *et al.,* 2001b), and contoured maps of PGA values for the Chi-Chi mainshock are shown in Figure 2 (EW component), Figure 3 (NS component), and Figure 4 (Vertical component).

Contents in the Attached CD

For documentation purposes, we included all relevant data files, including those that have defects, such as spikes, bad data channel(s), late triggering, and soon, on the attached CD (Lee *et al.,* 2001b). Users should select the data files that are appropriate for their needs. For example, if a user wishes to use the data for picking *P* arrivals in an earthquake location study, then one should use only the data files that have absolute timing.

We classify the recorded data files into four quality groups. Since the recorded strong-motion data are based on a triggering algorithm, a main concern is whether the record has pre-event data and whether the record is long enough to cover the entire duration of the ground shaking at that station. In addition, we are concerned whether the record has defects (e.g., spikes, or a component was not recorded), and whether the record has absolute timing. In general, QA-class records are the best and can be used for any studies. The QB-class records are the next best, except most of them do not have absolute timing. The QC-class records cover the principal strong motions but may not have adequate preevent data and/or post-strong-motion data. The QD-class records have some defects; they are included here for completeness and should not be used for most studies. Since most A800 accelerographs have a colocated A900 or A900A accelerograph, the user should use the A900 or A900A data files whenever possible.

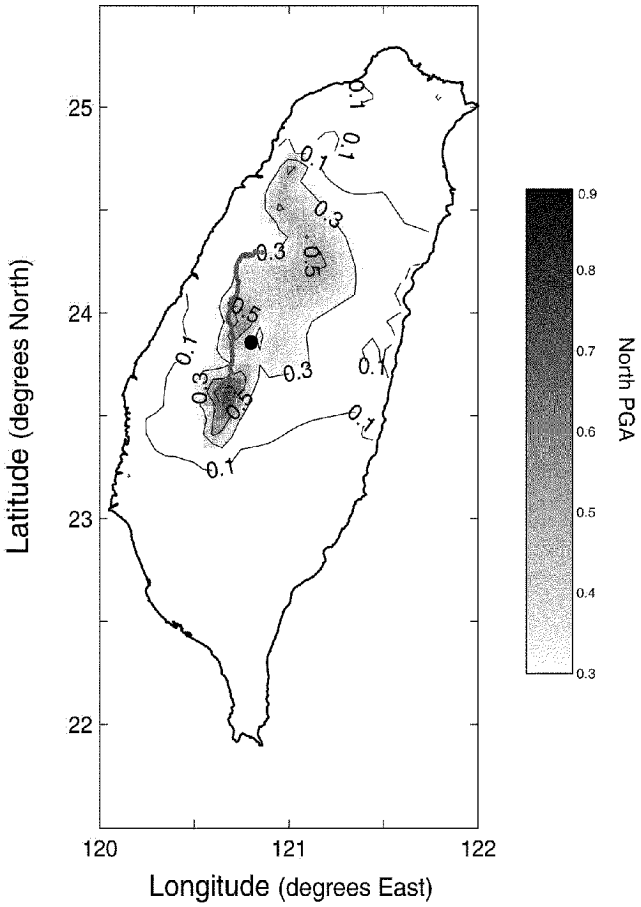

Figure 3. Contour map of PGA values in *g* (N–S component) for the Chi-Chi mainshock.

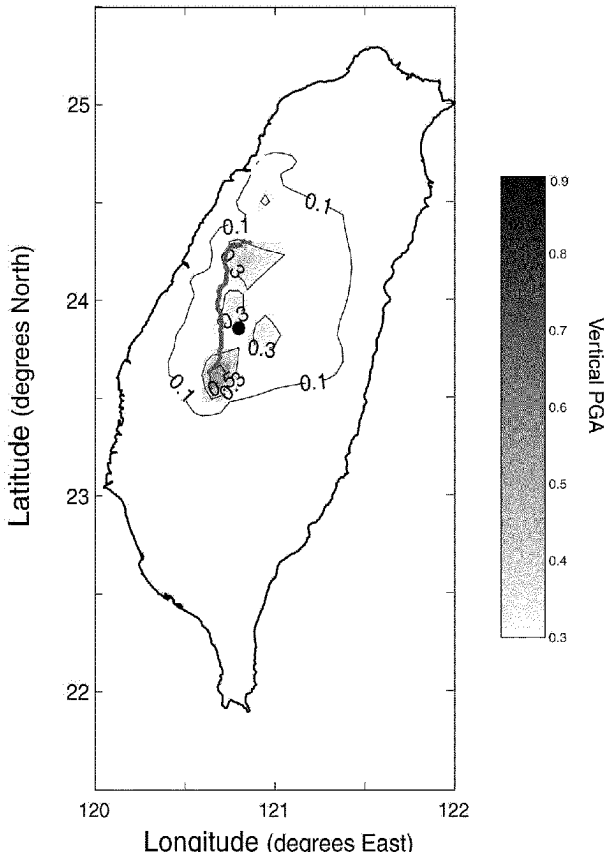

Figure 4. Contour map of PGA values in *g* (vertical component) for the Chi-Chi mainshock.

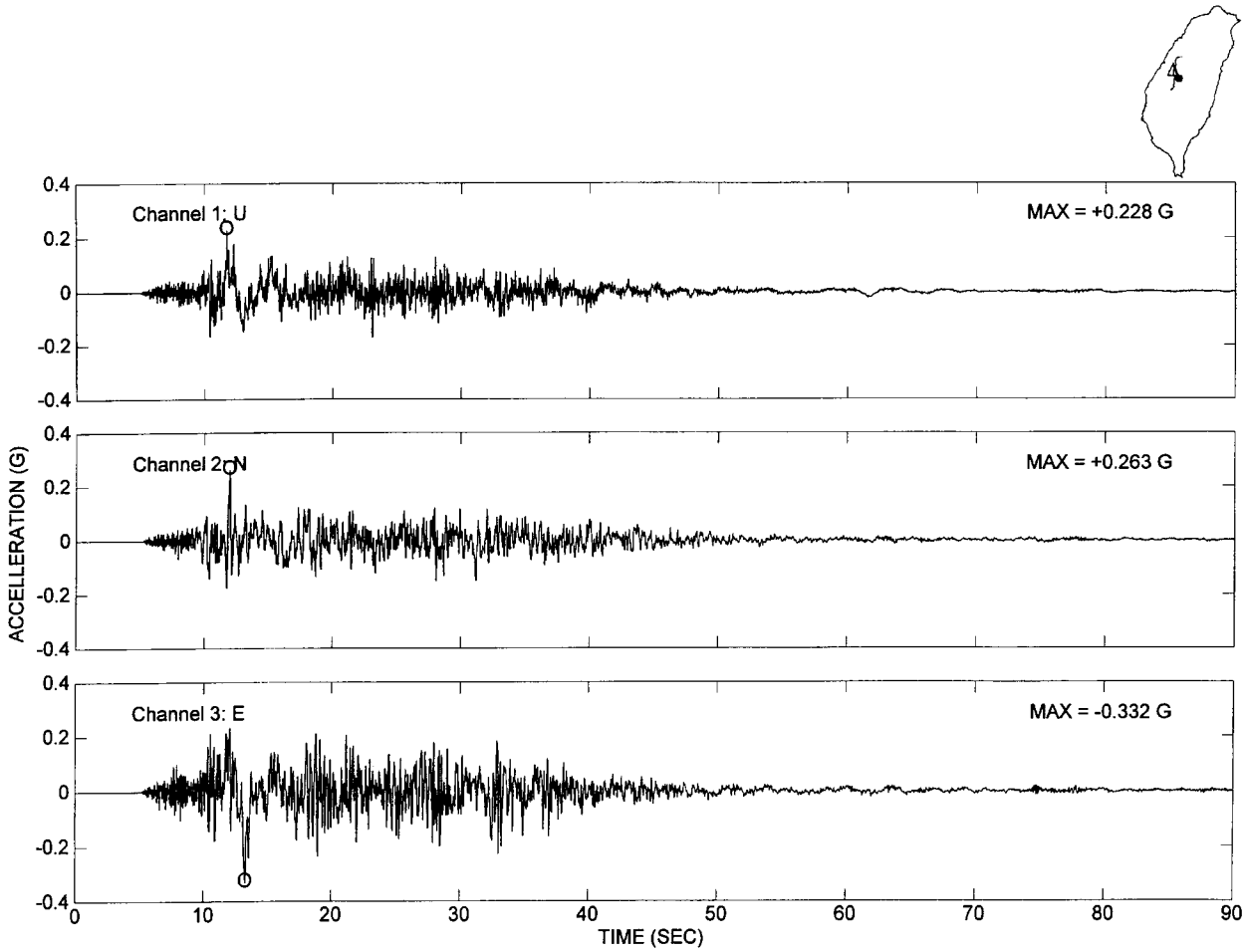

Figure 5. Record QA-14: File QT173000.263 at station TCU075 (Code, T075), Site Class, D. Lat. = 23. 9827° N, Kong. = 120. 6778° E, elev. = 96 m, distance = 18.4 km, model A 900, S/N = 173, fullscale = 2G.

There is a "readme" file and six directories containing the data files described in this article on the attached CD. Details are given by Lee *et al.* (2001b).

Conclusions

Extensive seismic instrumentation in most countries is usually carried out in response to a disastrous earthquake. We are fortunate that the extensive seismic instrumentation in Taiwan (including about 1200 modern digital accelerographs installed at free-field sites and in building and bridges) was carried out before the disastrous Chi-Chi earthquake. As a result, CWB obtained a very large set of strong-motion data before and after the earthquake. The total number of digital strong-motion records obtained by CWB from the accelerographs at the free-field sites is about 60,000 in the 10-year period from 1991 to 2000. It is comparable in volume to all the available strong-motion records obtained elsewhere in the world since studies of strong-motion seismology began in the 1930s. This extensive strong-motion instrumentation program was first proposed by Yi-Ben Tsai, and implementation and operation have been carried out by a large group of people.

Since only a limited amount of information can be published on paper, we have placed about 500 megabytes of data on the attached CD of this Special Issue (Lee *et al.,* 2001b). This allows us to archive a detailed report/CD (Lee *et al.,* 2001b), which has a very limited distribution. The detailed report contains plots of all the accelerograms archived (an example is shown in Fig. 5). We believe that such accelerogram plots will let any researcher browse the available strong-motion records and retrieve the desired data files on the attached CD quickly.

Acknowledgments

We thank Chun-Chi Liu, Gwo-Bin Ou, Chien-Ying Wang, and Kuo-Liang Wen for supervising the data collection in the field. We are grateful to Dave Boore and Ken Campbell for suggesting many improvements in the manuscript. The first author of this work (W.H.K.L.) was supported by the Central Weather Bureau, Taipei, Taiwan, under Grant CWB 89-2e-05.

References

Aki, K., and W. H. K. Lee (1976). Determination of three-dimensional velocity anomalies under a seismic array using first P arrival time from local earthquakes, *J. Geophys. Res.* **81,** 4381–4399.

Kissling, E. (1992). "VELEST" computer program, Institute of Geophysics, ETH, Zurich, Switzerland.

Lee, C. T., C. T. Cheng, C. W. Liao, and Y. B. Tsai (2001). Site classification of Taiwan free-field strong-motion stations, *Bull. Seism. Soc. Am.* **91,** no. 5, 1283–1297.

Lee, W. H. K., T. C. Shin, K. W. Kuo, and K. C. Chen (1999). CWB *Free-Field Strong-Motion Data from the 921 Chi-Chi Earthquake,* Volume 1, digital acceleration files on CD-ROM, prepublication version (6 December 1999), Seismology Center, Central Weather Bureau, Taipei, Taiwan.

Lee, W. H. K., T. C. Shin, K. W. Kuo, K. C. Chen, and C. F. Wu (2001a). CWB *Free-Field Strong-Motion Data from the 921 Chi-Chi Earthquake,* processed acceleration files on CD-ROM, Strong-Motion Data Series CD-001, Seismological Observation Center, Central Weather Bureau, Taipei, Taiwan.

Lee, W. H. K., T. C. Shin, K. W. Kuo, K. C. Chen, and C. F. Wu (2001b). Data files from CWB free-field strong-motion data from the 21 September Chi-Chi, Taiwan, earthquake, *Bull. Seism. Soc. Am.* **91,** no. 5, CD supplement.

Shin, T. C., K. W. Kuo, W. H. K. Lee, T. L. Teng, and Y. B. Tsai (2000). A preliminary report on the 1999 Chi-Chi (Taiwan) earthquake, *Seism. Res. Lett.* **70,** no. 1, 24–30.

Teng, T. L., and W. H. K. Lee (2000). Annual Report to the Central Weather Bureau on Earthquake Early Warning System and Implementation of the Strong Motion Instrumentation Program, November, 2000.

Southern California Earthquake Center
University of Southern California
Los Angeles, California
whklee@ix.netcom.com
(W. H. K. L.)

Seismological Observation Center
Central Weather Bureau
64 Kung-Yuan Road, Taipei, Taiwan
(T.C.S., K.W.K., K.C.C., C.F.W.)

Manuscript received 7 April 2001.