The Chi-Chi, Taiwan Earthquake of September 21, 1999: Reconnaissance Report

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MULTIDISCIPLINARY CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
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MCEER

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The Multidisciplinary Center for Earthquake Engineering Research

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation (NSF) in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

Funded principally by NSF, the State of New York and the Federal Highway Administration (FHWA), the Center derives additional support from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

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Foreword

Over the years, MCEER has supported many rapid surveys and reconnaissance visits to areas hit by severe earthquakes. Observations in the field as soon as possible following a major earthquake are one of the important ways in which vital data can be gathered and important lessons learned. In order to realize our vision of "earthquake resilient communities," these often tragic events must be investigated to validate our collective knowledge and to discover new insight into success stories and failures.

Our multidisciplinary team members conduct their reconnaissance visits primarily to support and foster knowledge development within MCEER's research program. The mission of the research program is to investigate how advanced and emerging technologies can be adapted and implemented to reduce earthquake hazards. Research efforts focus on development and calibration of loss estimation methodologies, damage evaluation, detection and response technologies, and development of retrofit strategies for critical facilities (such as lifelines, buildings and their contents, and bridges). The time period immediately following a destructive earthquake offers a critical window of opportunity to determine more closely the "weak links," reasons for failure or unacceptable performance, and to observe the success stories.

The observations and recommendations made by our team members are presented in this report, for the benefit of people in seismic regions throughout the world. Only by absorbing the technical and institutional lessons from these events, and then further developing our understanding and potential solutions in the laboratory and in our communities, can the potential for future tragedies be reduced.

George C. Lee
Director, Multidisciplinary Center for
Earthquake Engineering Research

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Preface

In the early morning hours of September 21, 1999, a devastating earthquake struck the central region of Taiwan. This earthquake became known as the 921 earthquake or the "Ji-Ji" or "Chi-Chi" earthquake. The magnitude of the 921 earthquake was $M_S = 7.6$ (Richter scale) or $M_L = 7.3$ (the system used in Taiwan). There were two large aftershocks of $M_L = 6.8$ that occurred about 30 hours and 120 hours after the main shock. An $M_L = 5.3$ aftershock was recorded as late as 260 hours later causing collapses of already damaged structures. As of October 1999, the death toll stands at more than 2,400, with over 10,000 people injured. Approximately 10,000 buildings/homes collapsed and over 7,000 more were damaged. In addition, there was widespread destruction and disruption of lifelines, including roads and bridges, communication systems, water and gas supply systems, and electric power systems.

Shortly after the earthquake occurred, MCEER arranged to visit the devastated area through the National Center for Research on Earthquake Engineering (NCREE), located at the National Taiwan University in Taipei, Taiwan. NCREE hosted a workshop for MCEER researchers and others to identify short-term strategies/actions for post-earthquake restoration and research needs. MCEER researchers were paired with NCREE researchers with similar specialties, and the joint reconnaissance teams examined the earthquake's impact. Their initial observations and impressions are reported in the *MCEER/NCREE Response*, which can be accessed from our web site at *http://mceer.buffalo.edu/research/taiwaneq9_99/default.asp*. More comprehensive studies have since been carried out by NCREE. These reports are in Chinese, and are listed in the **Selected Bibliography** section of this report.

This report contains observations from this reconnaissance trip and workshop. It is the product of many authors representing several disciplines and, while not a final assessment of the topics addressed, represents a preliminary earthquake engineering evaluation of the natural, built and social environments. The observations and conclusions herein form a springboard for future collaborative research efforts between MCEER, NCREE and other colleagues, in our common goal to create earthquake resilient communities throughout the world.

Acknowledgments

This report and the reconnaissance effort which made it possible are a collaborative effort between many investigators and institutions. Sponsorship of these activities was provided primarily by the Earthquake Engineering Research Centers Program of the National Science Foundation and the Federal Highway Administration through the Multidisciplinary Center for Earthquake Engineering Research (MCEER). This support is gratefully acknowledged.

The authors wish to collectively acknowledge the support and cooperation of the people of Taiwan who so willingly provided assistance during a very traumatic time. Many had the kindness and willingness to freely share information and provide access to damaged facilities.

The authors also wish to acknowledge the generous assistance of many organizations, agencies and individuals who made their visit possible and whose employees gave freely of their time and expertise. Some of these organizations and individuals are listed below and others are identified in the body of the report. They include:

- Liang-Chun Chen, National Taiwan University
- Lan-Hung Chiang, National Taiwan University
- Lun-Chang Chou, Office of the National Science and Technology Program for Hazard Mitigation
- Tien-Yin Chou, GIS Research Center, Feng Chia University
- James D. Goltz, California Institute of Technology (as part of the EERI reconnaissance effort)
- Han-Wen Hsiao, Office of the National Science and Technology Program for Hazard Mitigation
- J.C. Hsu, NCREE Administrative Section Chief
- Jong-Tsun Huang, Department of Psychology, National Taiwan University
- Hung-Chih Hung, National Chung-Hsing University
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- Jenn-Tai Hwang, Department of Construction Engineering, National Taiwan University
- Mr. Sheng-Nan Lin, Taiwan Power Company
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- Ministry of Economic Affairs
- Jia-D. Shen, Graduate Student, University at Buffalo
- Dr. Chih-Hong Sun, Office of the National Science and Technology Program for Hazard Mitigation
- Taiwan Institute for Economic Research
- Chin-Yen Tsay, Vice Chairman, National Science Council

- Hung-Kai Wang, Institute of Building and Planning, National Taiwan University
- Sheng-Ming Wang, Office of the National Science and Technology Program for Hazard Mitigation
- Dr. C.P. Weng, National Science Council
- En-Chang Wu, National Taiwan University
- Mr. Wei Wu, Deputy Chief Engineer for Central Taiwan, Highway Bureau of the Ministry of Transportation and Communications
- Mr. James Yeh, Deputy Director General, Highway Bureau of the Ministry of Transportation and Communications
- Shin-Cheng Yeh, National Chi-Nan University

Section 1
Introduction

George C. Lee
Multidisciplinary Center for Earthquake Engineering Research
University at Buffalo, State University of New York

On September 21, 1999, at 1:47 a.m. local time (17:47 p.m. Sept. 20, UT), an earthquake of magnitude $M_L = 7.3$ and $M_w = 7.7$ took place in the central part of Taiwan. The epicenter was located at 120.82°E and 23.85°N near the town of Chi-Chi, Nautou County. The focal depth was 8.0 km. A surface rupture along the Chelungpu fault of about 105 km was observed, with the largest measured vertical offset reaching more than 9 meters. After the major shock, 10,252 aftershocks were identified (till October 10, 1999); four were greater than magnitude 6.5. As a direct result of this earthquake, over 2,400 lives were lost, more than 10,000 people were injured, over 10,000 buildings/homes collapsed and more than 7,000 suffered damage. This was Taiwan's worst disaster since the Shin-Chu Taichung earthquake of April 1935, where 3,325 lives were lost in a magnitude 7.1 earthquake (Loh and Tsay, forthcoming).

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) and the National Center for Research on Earthquake Engineering (NCREE) have enjoyed a long history of research collaboration, beginning in 1992, to investigate earthquake engineering issues of mutual interest. Over the years, many collaborative projects have been initiated, most notably in subject areas such as structural control, and evaluation and retrofit of lifelines, especially electric and power. Shortly after the earthquake struck Taiwan, the two Centers decided to use their collective knowledge and expertise to identify important short-term strategies/actions for post-earthquake restoration and research needs. A workshop was convened by Professor C-H. Loh, Director of NCREE, in Taiwan on October 3-5, 1999 to share information already collected, and identify teams for further reconnaissance. MCEER and NCREE researchers were paired together to focus on specific areas. The areas and participants were:

- Ground Motion Characteristics - C.H. Loh and George C. Lee
- Geotechnical Aspects - Thomas O'Rourke and M-L. Lin
- Damage to Critical Facilities - T.T. Soong and G. Yao
- Building Damage - Michel Bruneau and K.C. Tsai
- Bridge Damage - Ian G. Buckle, K.C. Chang and J-S. Hwang
- Lifeline Damage: Electric Power Systems - M. Shinozuka and G.Y. Liu
- Application of Remote Sensing - M. Shinozuka, George C. Lee and Z.J. Chen
- Economic Consequences - Stephanie E. Chang
- Emergency Response and Short-term Restoration - Paul J. Flores

- Development of a new system-related loss estimation methods for HAZ-Taiwan.
- Investigation of social and economic issues.

Representatives of the four Centers are planning to meet, together with other researchers, this fall in Taiwan to discuss the specific details of the research program.

The Chi-Chi earthquake not only helped to identify a very specific research agenda for collaboration between MCEER and NCREE, it provided an opportunity for MCEER and the PEER Center to coordinate expertise and work together. The earthquake was devastating to the people of Taiwan, but the positive outcome is that new research opportunities have been identified, our team efforts have been enhanced, and experts from a variety of earthquake hazard mitigation centers have been brought together.

1.1 References

Loh, C.H. and Tsay, C-Y. (forthcoming), "Responses of Earthquake Engineering Research Community on the Chi-Chi (Taiwan) Earthquake," submitted to *EERI Spectra.*

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Section 2
Geology and Tectonics of Taiwan

Chin-Hsiung Loh
National Center for Research on Earthquake Engineering
National Taiwan University

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Multidisciplinary Center for Earthquake Engineering Research
University at Buffalo, State University of New York

The island of Taiwan is located at a complex juncture between the Eurasian and Philippine Sea plates. North and east of Taiwan, the Philippine Sea plate subducts beneath the Eurasian plate to the north along the Ryukyu trench, while south of the island the Eurasian plate underthrusts the Philippine Sea plate to the east along the Manila trench. Taiwan, therefore, occupies an unstable region between these two subduction systems of opposite polarity. Seismicity is extremely active on this island. Taiwan can be divided into two major tectonic provinces, separated by a narrow, linear geographic feature known as the Longitudinal Valley. The western province, which comprises the major part of the island, is composed of Tertiary sediments that have undergone varying degrees of metamorphism and induration and is associated with the Eurasian continental shelf. Thus, tectonically, the Longitudinal Valley also assumes the role of a suture zone between the two plates.

The western province resembles a deformed miogeosyncline with clastic sediments more than 10 km thick deposited upon a pre-Tertiary metamorphic basement. It is usually divided into several physiographic sub-units based on rock type or on degree of deformation. Faults or other structural discontinuities often bound these units.

2.1 Correlation of Earthquake Activity with Geologic Structure

Few earthquakes can be unequivocally related to known geologic structures in Taiwan. The exceptions are those limited number of cases where surface rupture is known to have been associated with specific earthquakes. The locations of faults are shown in Figure 2-1. There are several surface displacements associated with historical earthquakes taken from Bonilla (1975, 1977); in western Taiwan: Meishan fault, March 17, 1906; Chihu and Tuntzchio faults, April 21, 1935; and Hsinhua fault, December 5, 1946. These faults are shown as heavy lines in Figure 2-1. Some high-angle reverse faults in central Taiwan have been recognized to be associated with large-magnitude earthquakes.

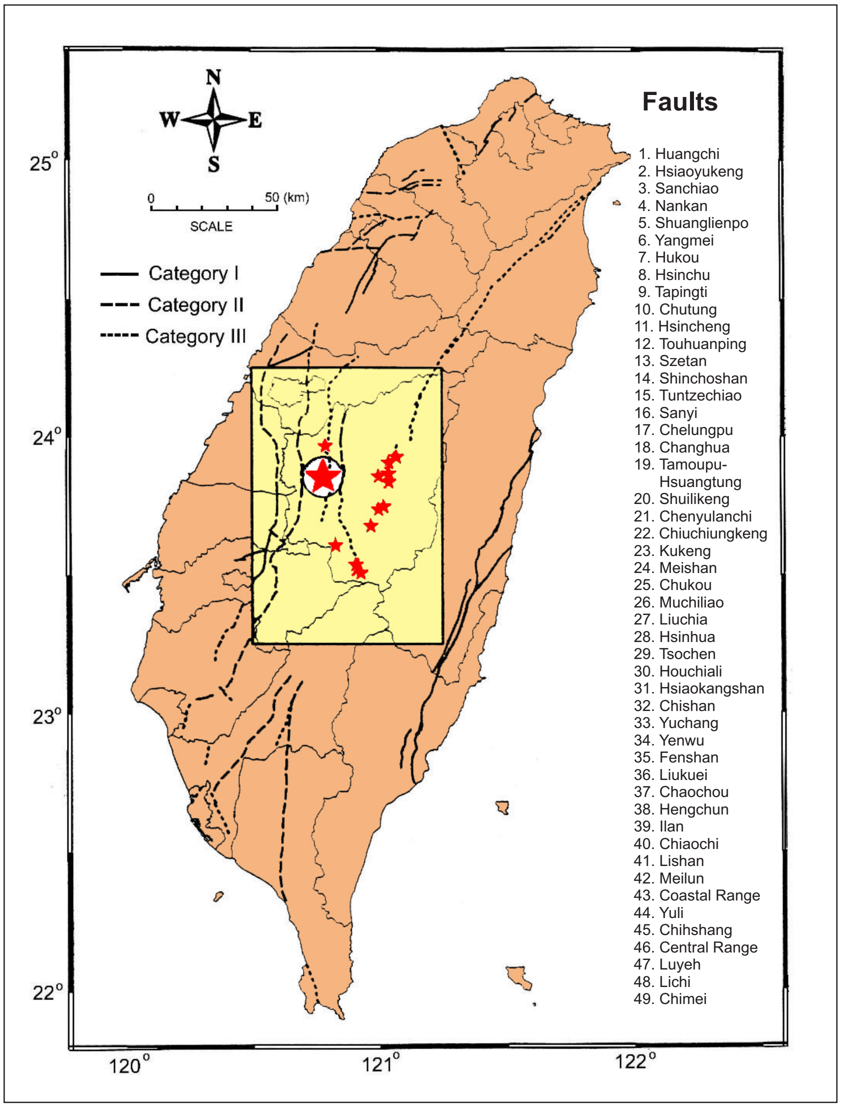


Figure 2-1 Active faults in Taiwan

2.2 Chi-Chi Earthquake

The Chi-Chi earthquake is believed to be associated with the Chelungpu and Shuangtung faults. These two faults are 10 km apart and subparallel. The hypocenter at Ji-Ji lies very close to the Shungtung fault and occurred at a depth of about 7 km, near the intersection with the Chelungpu fault. The faults are east-dipping high-angle reverse faults with a significant left-lateral strike-slip component. Traced northward, the Chelungpu fault joins or becomes the Sani fault. The Sani fault cuts the Pleistocene upper Toukoshan formation near the west end of its east-west portion, where the fault is interpreted as a right-slip fault. The Chi-Chi earthquake caused 7-8 meters of displacement along certain sections of the Chelungpu fault (see Section 3, Geotechnical Issues).

More than ten thousand aftershocks occurred. Figure 2-2 shows the time sequence of the aftershocks with magnitudes greater than 4.0 within six hours. The epicenters of these aftershocks are shown in Figure 2-3. It is noted that the epicenters of these aftershocks are almost all located in the eastern part of the Chelungpu fault. This is consistent to the fault system. Based on the strong motion data collected by the Seismology Center of the Central Weather Bureau, Figure 2-4 shows the attenuation of the intensity of this earthquake in terms of PGA values. Both two horizontal directions' PGA value are shown with the attenuation forms for comparison. The values of distance are calculated as the rupture distance. The figure shows good agreements between collected data and empirical forms.

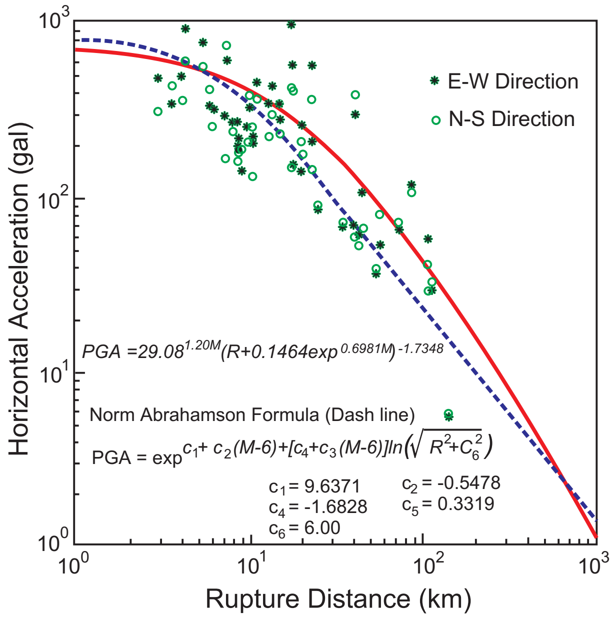


Figure 2-2 Time sequence of aftershocks within six hours, magnitudes greater than 4

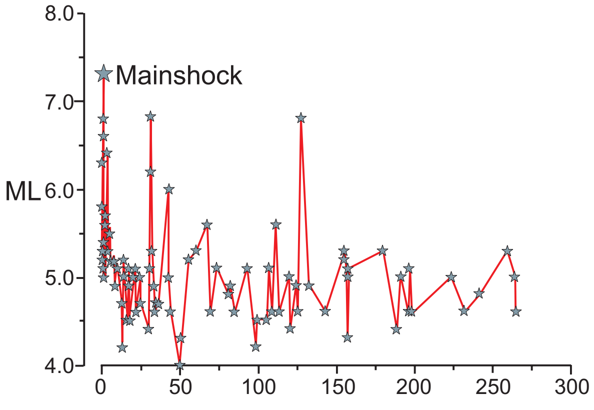


Figure 2-3 Epicenters of aftershocks

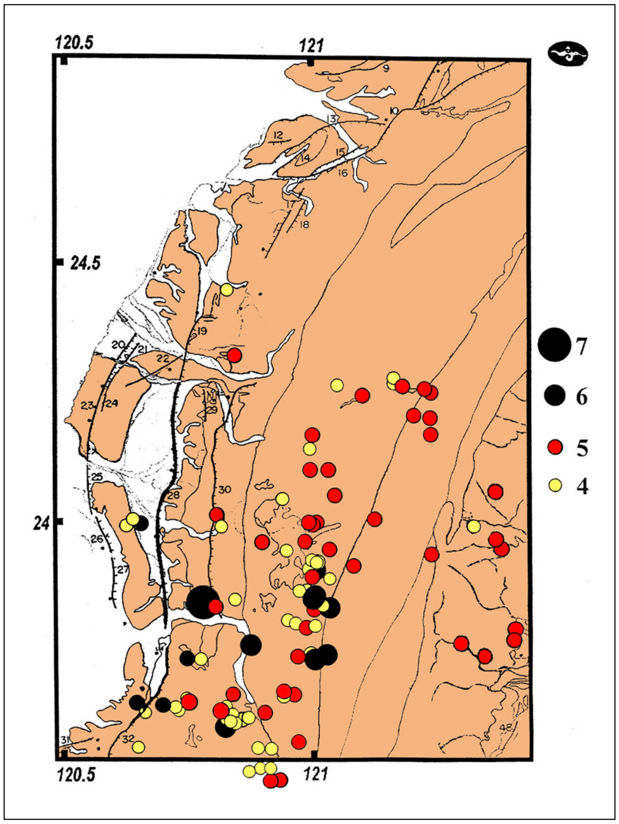


Figure 2-4 Attenuation of earthquake intensity in terms of PGA values

A previous study on the Chelungpu fault reported that the maximum magnitude of earthquake to be expected on this fault is about M_L=7.3. This predicted result was exact for the Chi-Chi earthquake that is associated to the Chelungpu fault system. The constant energy release model was used to estimate the maximum magnitude. The result is shown in Figure 2-5. Including the data caused by the Chi-Chi earthquake, the maximum credible earthquake magnitude will be about 7.5 local magnitude in the future.

2.3 Surface Fault Rupture

Due to the significant surface faulting along the Chelungpu fault (with rupture length of 105 km), it was necessary to exactly locate the surface fault ruptures. One month after the Chi-Chi earthquake, the location of the Chelungpu fault was identified and plotted on a 1/5000 topographic map, as shown in Figure 2-6. The displacement distribution along the fault is also shown in the figure. Field surveys indicated that the rupture of this earthquake generally followed the pre-existing fault scrap of the Chelungpu fault. The earthquake generated a rupture more than 105 km in distance and a maximum offset of 11 m (vertical) and 10 m (horizontal) in the northern part of the Chelungpu fault. Ground and geophysical surveys also showed that the shock resulted from reactivation of the Chelungpu fault. The rupture was generated by reverse strike-slip and normal movements, thus making it far more complicated than that of a simple fault. The rupture can be divided into three segments, each characterized by different orientation and sense of movement;

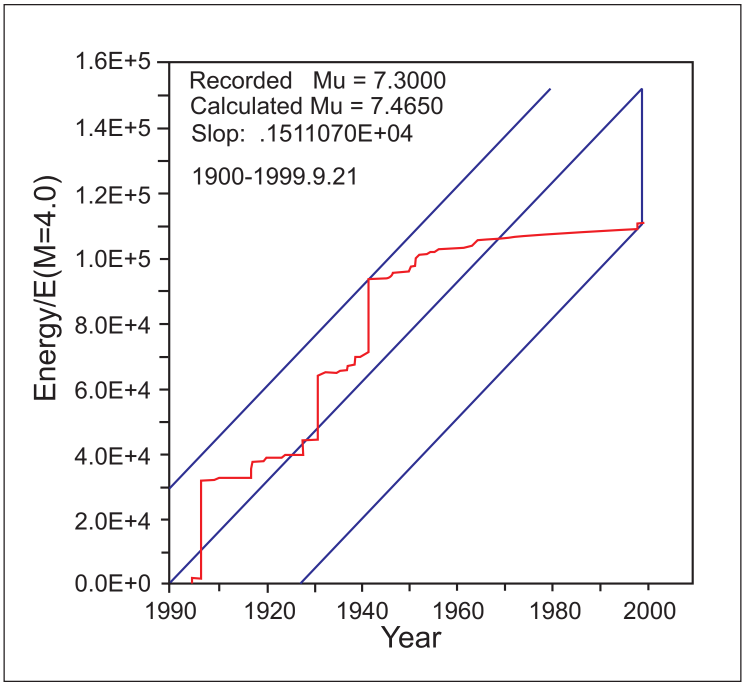


Figure 2-5 Maximum credible earthquake as estimated by the constant energy release model

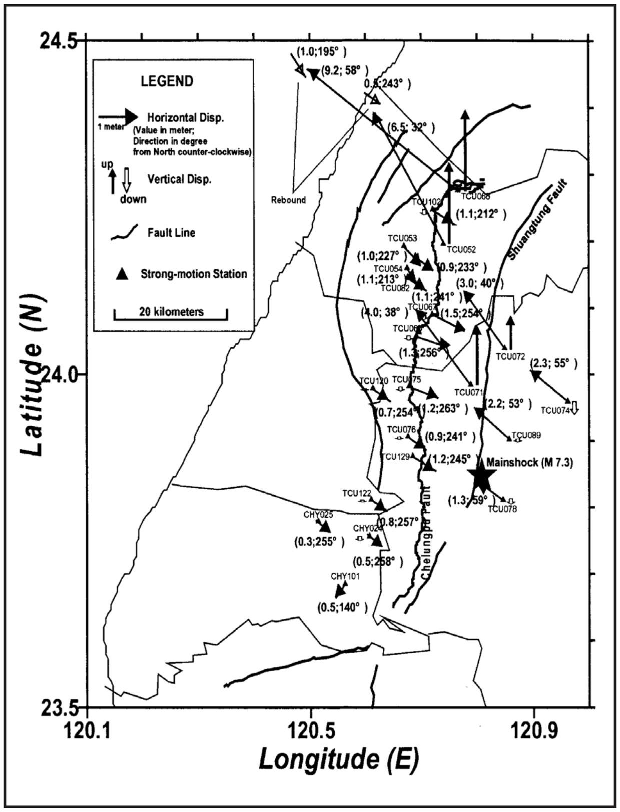
the northern segments were even generated by new faults not recognized before the Chi-Chi earthquake (Loh and Tsay, forthcoming).

2.4 Ground Motion Characteristics

Under the Taiwan Strong Motion Instrumentation Program (TSMIP), there are more than 650 strong motion observation stations distributed and maintained by the Central Weather Bureau, Ministry of Transportation and Communications, in Taiwan. About 70 percent of the observation stations were triggered for this earthquake. Analysis of the ground motion data included (Loh et al. 2000):

- PGA, PGV and PGD attenuation forms
- Spectral amplitude attenuation forms
- Response spectrum analysis (linear system)
- Near-field ground motion characteristics (pulse-like wave in velocity waveform)
- Distribution of PGA, PGV, and Spectral Acceleration (S_A) along the Chelungpu fault and in the earthquake affected area

It is important to note that much of the near-field ground motion data was recorded from this earthquake. The pulse-like velocity wave (with large amplitude and long period) was identified from some of the data collected from stations close to the fault, as shown in Figure 2-7. From the distribution of PGA and PGV along the fault, it was found that large PGA values were observed at both the southern and northern parts of the Chelungpu fault.



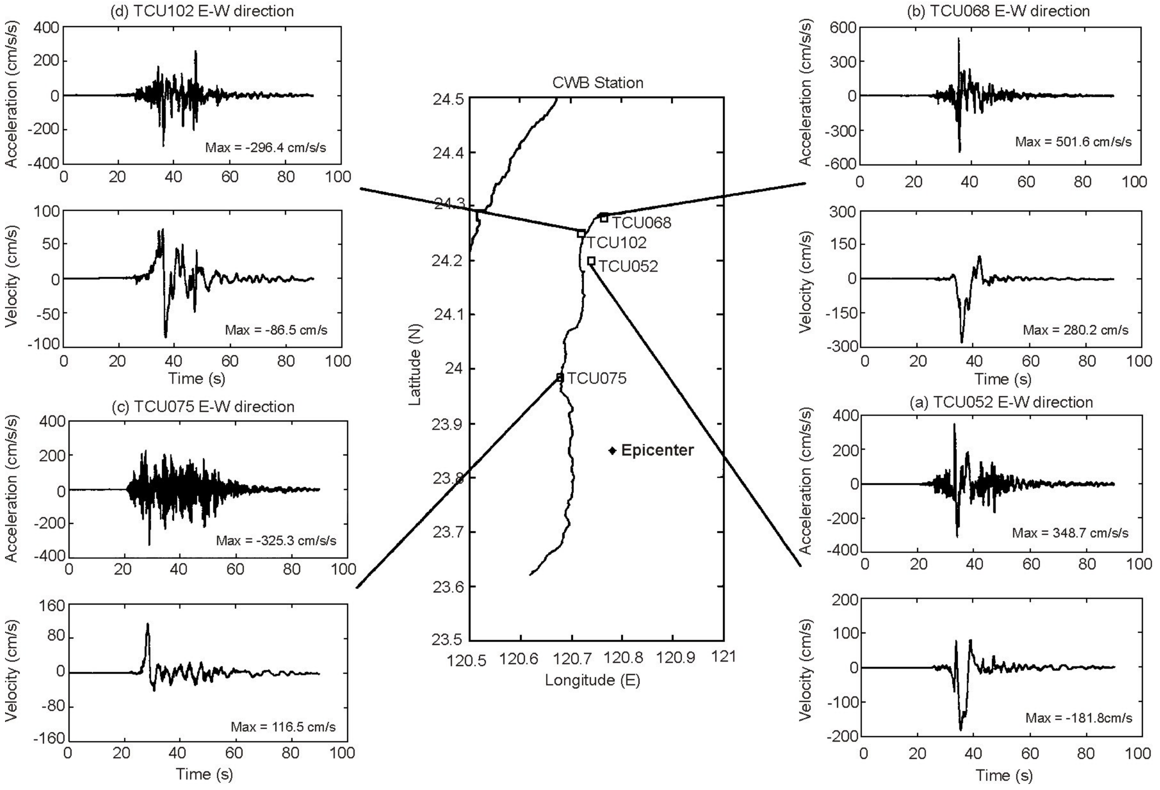
Loh and Tsay, forthcoming

Figure 2-6 Exact location of Chelungpu fault and the fault displacement distribution

Based on this newly collected data, the Taiwan seismic design code was re-evaluated. A code development committee was established to re-examine the seismic zone factor of the Taiwan building code. Figure 2-8 shows the revised Taiwan PGA attenuation form considering the data from the Chi-Chi earthquake. The difference between the revised PGA attenuation form and the original PGA attenuation form is not significant. After the Chi-Chi earthquake, a seismic hazard analysis (SHA) of the Taiwan area was performed considering the Chelungpu fault as an active fault (previously, the Chelungpu fault was designated as an inactive fault). Based on the results of the SHA, seismic zoning and zone factors were revised from four zones to two zones (Loh and Tsay, forthcoming).

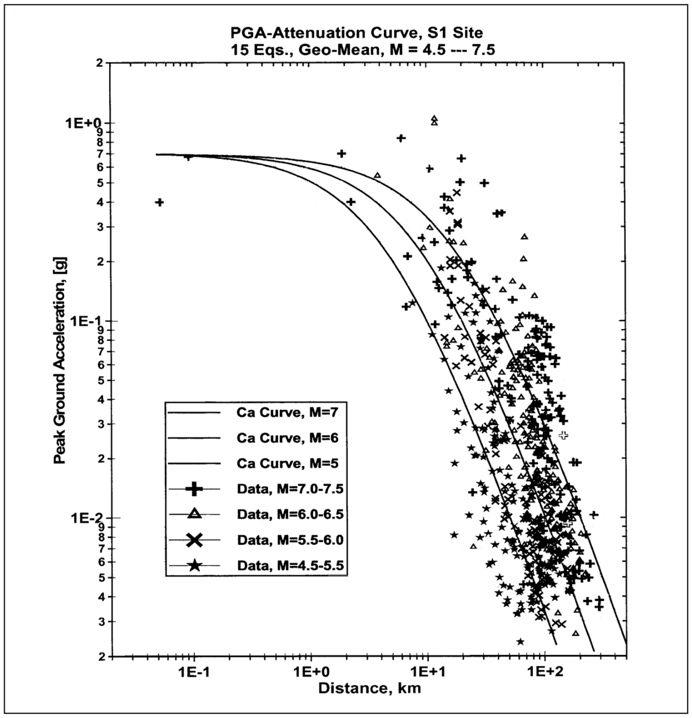
For reconstruction purposes, the design spectrum for near-field ground motion also needed to be developed. The elastic seismic demand of the current Taiwan Building Code (1997) is defined by the spectral acceleration $S_A = Z\,I\,C$, where Z is the zoning factor representing the seismic design level, I denotes the importance factor, and C is the coefficient of normalized spectral acceleration. The C-value did not consider the near-field ground motion characteristics. Based on the concept of UBC 97 and the ground motion data collected from the Chi-Chi earthquake, the near-fault factors of ground motion characteristics (N_A and N_V) have been incorporated to modify the seismic design spectrum for sites near the Chelungpu fault (see Figure 2-9).

Station	PGA (cm/s^2)	PGV (cm/s)	Distance (km)	PGV/PGA	Pulse duration (sec)
TCU052	348.7	181.8	2.34	0.521	5.54
TCU068	501.6	280.2	0.49	0.559	3.85
TCU075	325.3	116.5	0.43	0.358	3.08
TCU102	298.4	86.5	0.81	0.290	7.69



Loh and Tsay, forthcoming

Figure 2-7 Plot of ground acceleration and displacement from four stations along Chelungpu fault



Loh and Tsay, forthcoming

Figure 2-8 Plot of PGA attenuation (the Chi-Chi earthquake data is included) from Taiwan earthquake data (geometric mean was used)

2.5 References

Bonilla, M.G., (1975), "A Review of Recently Active Faults in Taiwan," U.S. Geological Survey Open File Report 75-41, 58 p.

Bonilla, M.G., (1977), "Summary of Quaternary Faulting and Elevation Changes in Taiwan," Geological Society of China Memoir 2, p. 43-55.

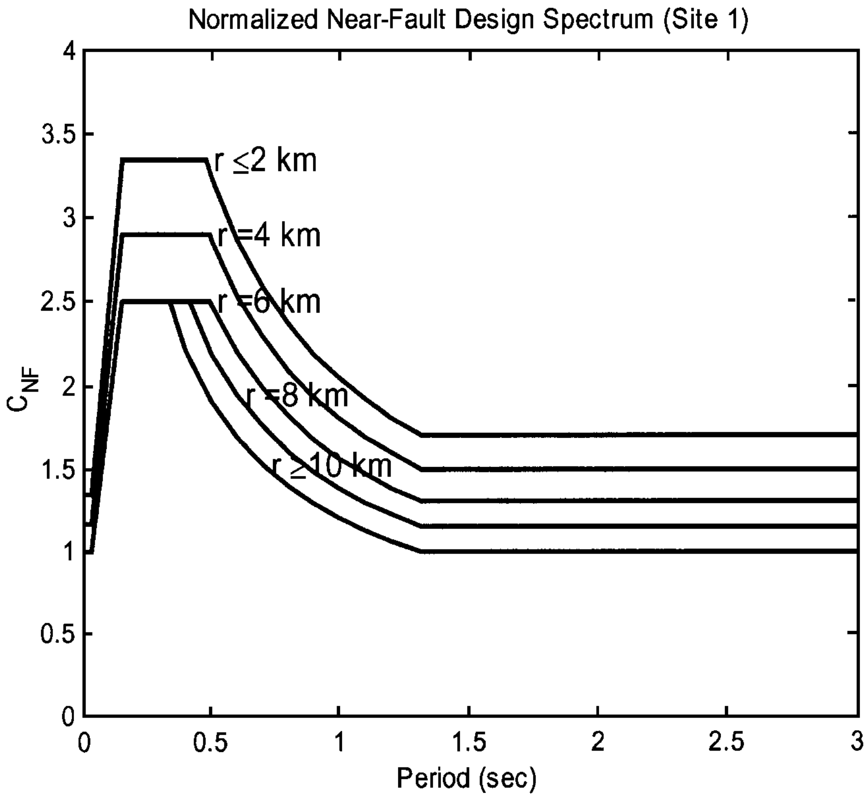
Loh, C.H., Lawson, R.S. and Dong, W., (2000), "Development of a National Earthquake Risk Assessment Model for Taiwan," *Proceedings of the 12WCEE,* New Zealand, January.

Loh, C.H. and Tsay, C.Y., (forthcoming), "Responses of Earthquake Engineering Research Community on the Chi-Chi (Taiwan) Earthquake," submitted to *EERI Spectra*.

Distance (km)	$r \leq 2$	$r = 4$	$r \geq 6$
N_A	1.34	1.16	1.0

Distance (km)	$r \leq 2$	$r = 6$	$r \geq 10$
N_V	1.70	1.30	1.0

Extremely Short:	$T \leq 0.03$ $C = N_A$
Very Short:	$0.03 \leq T \leq 0.15$ $C = N_A(12.5T + 0.625)$
Short:	$0.15 \leq T \leq T_1$ $C = 2.5N_A$
Moderate:	$T_1 \leq T \leq 1.315$ $C = 1.2N_V/T^{2/3}$
Long:	$1.315 \leq T$ $C = N_V$
	$T_1 = [1.2N_V/2.5N_A]^{3/2}$


Normalized Near-Fault Design Spectrum (Site 1)

Loh and Tsay, forthcoming

Figure 2-9 Seismic design spectrum considering near-field ground motion characteristics

Section 3
Geotechnical Issues: Restoration Strategies and Research Needs

Thomas D. O’Rourke
Cornell University

Jung-Feng Chang
Cornell University

Meei-Ling Lin
National Taiwan University

The geotechnical features that affect seismic performance during any earthquake may be divided into those that cause either permanent or transient ground deformation. Sources of permanent ground deformation include surface faulting, landslides, liquefaction, consolidation and settlement of unsaturated soils, and tectonic uplift and subsidence. Transient ground deformation includes the strong shaking and dynamic response experienced at various sites. From a geotechnical perspective, it involves the way by which soils and groundwater conditions at a given site affect the amplitude, frequency, and duration of shaking. Engineered facilities are often affected simultaneously by both permanent and transient deformation. Nevertheless, it is instructive to consider permanent and transient characteristics separately so as to concentrate on the complex geologic, materials, and geometric conditions that influence each phenomenon.

The sources of permanent ground deformation of most importance during the Chi-Chi earthquake are landslides and surface faulting. Although there was evidence of liquefaction in fills at the Taichung port facilities and in alluvial soils throughout the epicentral region, the influence of soil liquefaction on the built and natural environments was not as pronounced nor as significant as the effects of landslides and surface faulting.

3.1 Landslides

There were literally hundreds and thousands of landslides in the mountainous terrain within and adjacent to the epicentral area. Most slides were relatively shallow slips in residual soils, typically involving depths of 1 to 5 m. A large proportion of the landslides were considerably deeper and broader.

Figure 3-1 presents a map of the region of strongest ground shaking on which are shown locations of large landslides and landslides involving prolonged periods of road closure. Of special importance are the 27 km of Route 8, the Central Cross-Island Highway, which was blocked by scores of landslides between Kukuan and Techi. The severe and widespread nature of the landslides poses significant challenges for the reconstruction of this road. Not only is the highway important for east-west transportation of passengers and goods in central Taiwan, but it is critical for servicing the dams and hydroelectric facilities along the Tachia River.

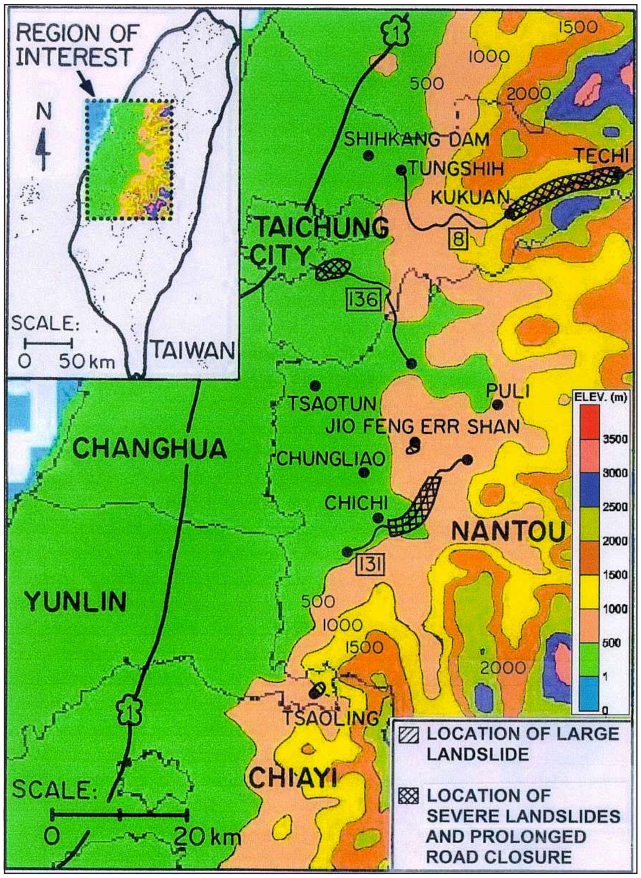


Figure 3-1 Map of earthquake-affected region with landslides and prolonged road closure sites

Figures 3-2 and 3-3 show aerial views of the landslides along Route 8. As indicated in the photos, there was substantial destruction of the highway, with relatively long sections of road both undermined by landslides and blocked by landslide debris. Figure 3-3 shows that the portal of one of the Route 8 tunnels was partially collapsed and was blocked by landslide debris.

Many provincial highways and county roads were disrupted by slope failures and/or blocked by landslide debris for several days to weeks after the earthquake because of landslides. For example, about 20 km of Provincial Highway 18 between Chichung and Shenmu and several km of County Roads 131 and 136 were still closed two weeks after the earthquake because of landslides. County Roads 131 and 136 are shown in Figure 3-1 as locations of severe landslides and prolonged road closure.

Figure 3-4 shows landslide scars typical of most soil and rock falls along the highway system in the mountains. The slides were relatively shallow, extending through the soil mantle into the weathered rock. Debris, cascading from higher elevations, blocked roadways in hundreds of locations.

Photograph by J.P. Bardet and J. Bray

Figure 3-2 Landslide along Route 8

Photograph by J.P. Bardet and J. Bray

Figure 3-3 Landslides and partial tunnel collapse along Route 8

Photograph by T.D. O'Rourke

Figure 3-4 Typical shallow landslides intersecting a mountain road

Figure 3-5 shows a landslide location near the Yun-Chia Tunnel in the Tsao-Ling area. Although some instances of tunnel collapse were reported along Route 8, most ground failures at tunnels were confined to soil and rock falls near tunnel portals.

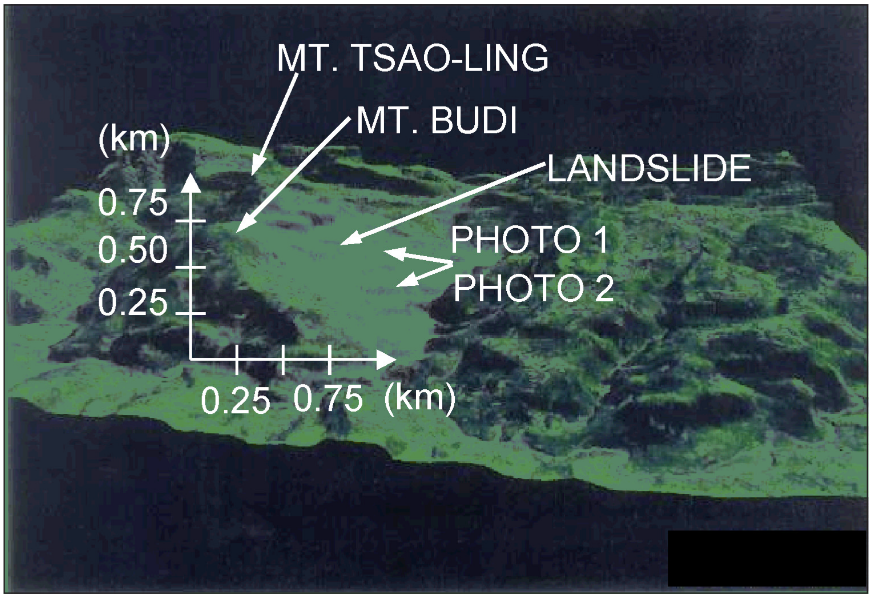
The largest landslides were located near the village of Tsao-Ling and Jio-Feng Err Mountain. These landslides mobilized millions of cubic meters of rock and soil that slid across adjacent rivers, creating large landslide dams. Blockage of the rivers was accompanied by the formation of lakes that are flooding the upstream river valleys. As water rises, there is the potential for overtopping and catastrophic downstream flooding.

Figure 3-6 shows a three dimensional view of the terrain at the Tsao-Ling landslide site that was developed with SPOT digital imagery. The use of remote satellite imagery to evaluate Chi-Chi earthquake effects is discussed in Section 8 of this report, and is used here to show the locations of ground-based photographs that were taken at the site of the landslide. Figures 3-7 and 3-8 show views of the landslide at its eastern and western margins, respectively.

Tsao-Ling is a site where significant landslide activity has occurred in the past (Hung et al.). A summary of the previous landslide activity at this location is provided in Table 3-1. Figures 3-9 and 3-10 show a plan and cross-sectional view, respectively, of the Tsao-Ling landslide site, based on the work of Hung et al. Figure 3-10 shows the approximate geometry of volumes of landslide material mobilized during the 1941 earthquake and subsequent heavy rainfalls in 1942 and 1979 (see Table 3-1).

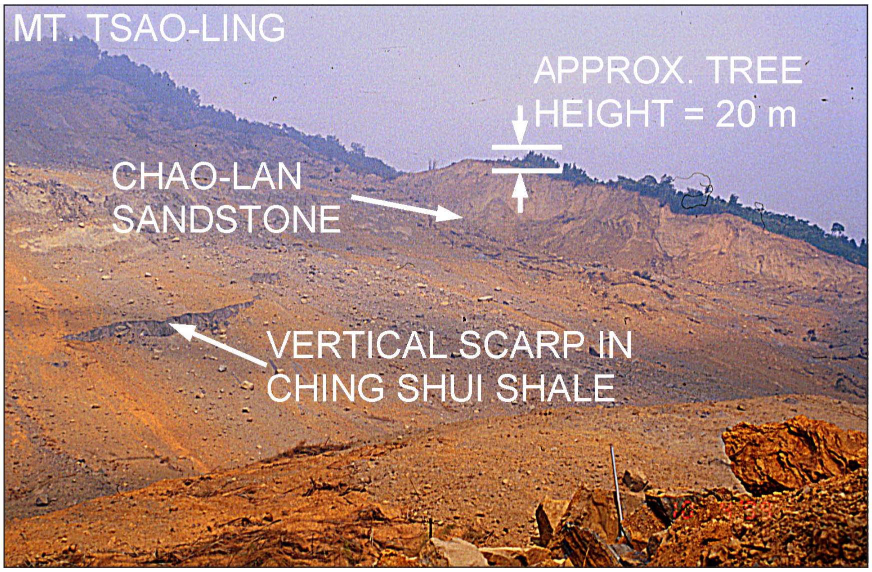
Photograph by T.D. O'Rourke

Figure 3-5 Landslide at portal of Yun-Chia Tunnel near Tsao-Ling



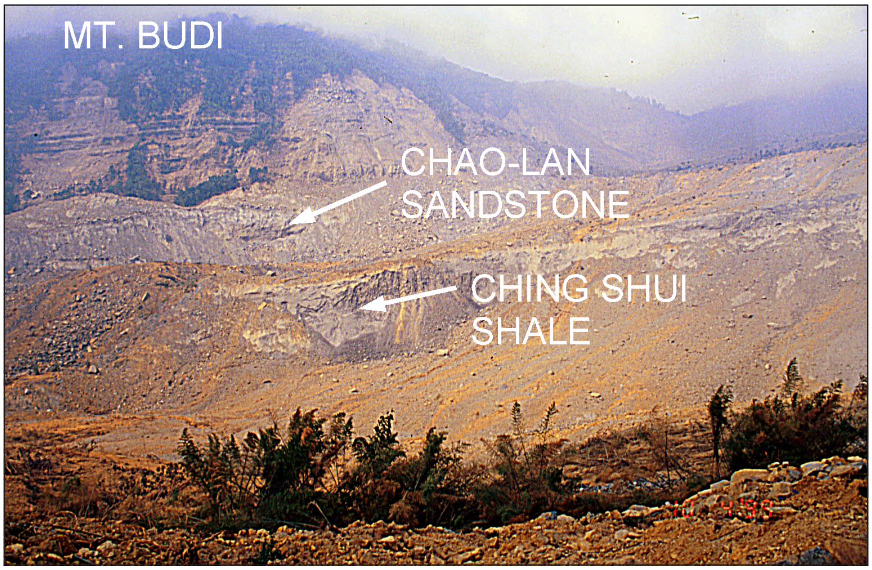
[redacted]

Figure 3-6 Three dimensional view of Tsao-Ling landslide developed from satellite imagery



Photograph by T.D. O'Rourke

Figure 3-7 Eastern boundary of Tsao-Ling landslide



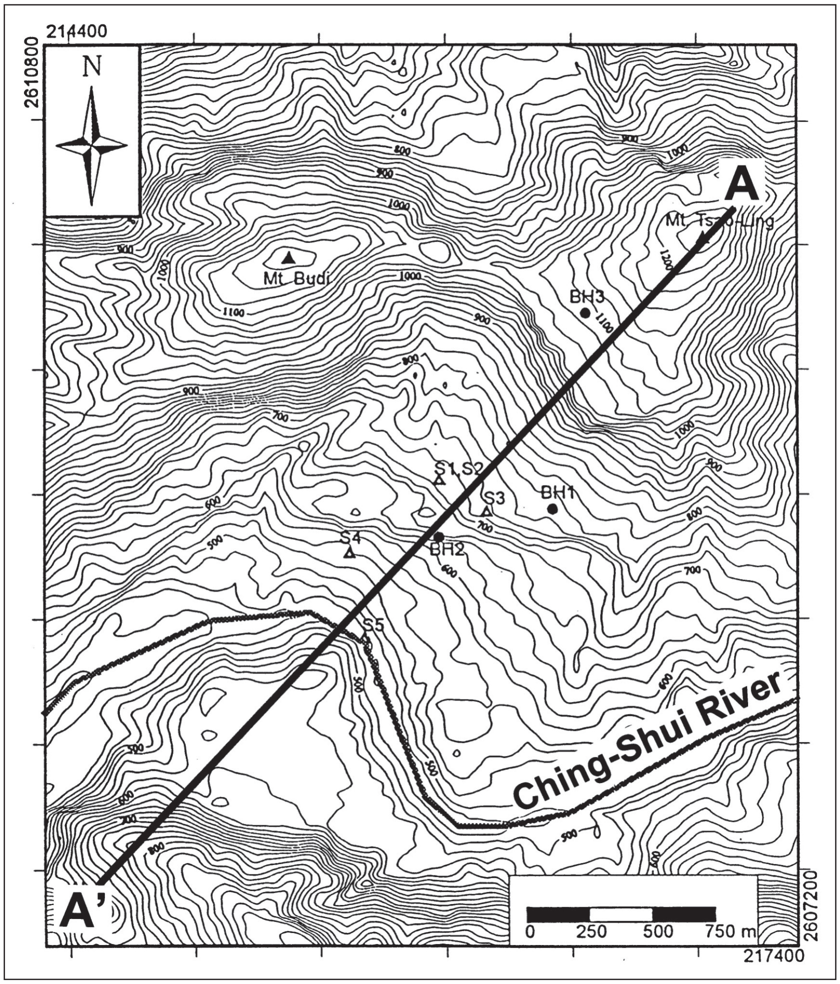
Photograph by T.D. O'Rourke

Figure 3-8 Western boundary of Tsao-Ling landslide

Table 3-1 Historical events involving the Tsao-Ling landslide site

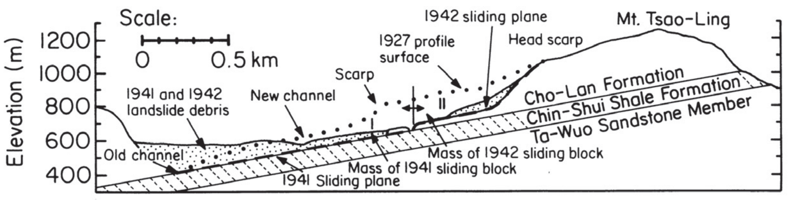
Date	Physical Process	Characteristics
June 6, 1862	Earthquake M = 6.0-7.0	Landslide and formation of a landslide dam that was eventually breached in 1898
December 17, 1941	Earthquake M = 7.1	Landslide and formation of 70 to 200 m high landslide dam, killing 36 people
August 10, 1942	3-day cumulative rainfall of 770 mm	Additional landslide of 100 million m^3, killing one person
May 18, 1951	5-day cumulative rainfall of 776 mm	Overtopping of 1941 landslide dam, killing 137 people
August 15, 1979	2-day cumulative rainfall of 327 mm	Landslide of 5 million m^3 and formation of landslide dam that was overtopped on August 24, 1979

Adapted from Hung et al., forthcoming

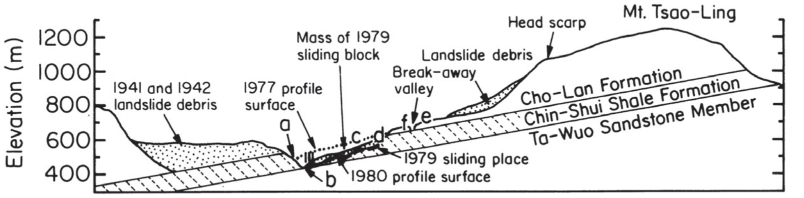


Hung et al., forthcoming

Figure 3-9 Topographical map of Tsao-Ling area



a) 1941 and 1942 Landslides



a) 1979 Landslides

Hung et al., forthcoming

Figure 3-10 Cross section A-A′ of 1941, 1942, and 1979

The landslide triggered by the Chi-Chi earthquake appears to have mobilized a volume of failed material similar to that involved in the 1941 earthquake. The landslide was generated primarily by failure of the Chin-Shui Shale Formation that underlies the Chao-Lan Sandstone (see Figures 3-8 and 3-10). The shale is a friable, silty mudstone with weak cementation that deteriorates readily upon wetting and drying. The shale exhibits very low compressive strength that is highly dependent upon time of submergence in water (Lin and Hung, 1982).

Landslides caused by the Chi-Chi earthquake have deforested large areas of the high, steep mountain slopes of central Taiwan. The soil and weathered rock that were once protected by a vegetative canopy in these locations are now exposed to precipitation, including heavy rain from tropical storms and typhoons. The threat, therefore, exists for additional landslides and debris flows to be triggered in substantial numbers. Because of the large deforested areas, increased vulnerability to landslides and debris flows will continue until the vegetative cover is re-established.

Landslides have had a very significant effect on two lifeline systems: the highway transportation network and the electric power grid. Both lifeline systems are important for earthquake recovery and the sustained economic well being of Taiwan.

A large portion of the electric power is generated in southern Taiwan and conveyed by means of 345 Kv transmission lines to the heavily populated and industrial areas of the north. Secondary distribution systems involve 161 and 69 Kv lines. There were numerous transmission tower failures in all voltage systems (see Section 7), many of which were in mountainous terrain where there was significant landslide activity.

3.1.1 Short-Term Recovery Needs

Plans are needed to deal with the landslide dams along the Ching-Shui and Wushi Rivers. Landslide dams in the 1940s and 1979 at the Tsao-Ling site and subsequent flooding when the dams were overtopped provide valuable data and experience with which to approach the problem. In developing a plan, it will be advantageous to calculate the volume of each landslide dam. Consideration should be given to the inflow rate, maximum volume of water stored, potential for accelerated filling due to tropical storms and typhoons, upstream and downstream flooding, and options to mitigate the problem. Mitigation options include, but are not limited to, partial excavation to reduce maximum impoundment levels, construction of overflow structures or diversion tunnels/conduits, blasting to release the water, and monitoring and eventual downstream evacuation.

An assessment of the remaining landslide and debris flow potential would be useful to identify communities and lifelines at risk from continued slope failure both within and downstream of the deforested mountain areas. Consideration should be given to how drainage features and flow paths have been altered by the earthquake.

Plans need to be formulated for the reconstruction of Route 8 that take account of the increased vulnerability to landslides associated with fractures and loosening of the weathered rock as well as its increased exposure to precipitation caused by the earthquake. The plans should balance risk mitigation related to control of future landslide activity with the need for rapid reinstatement of the road.

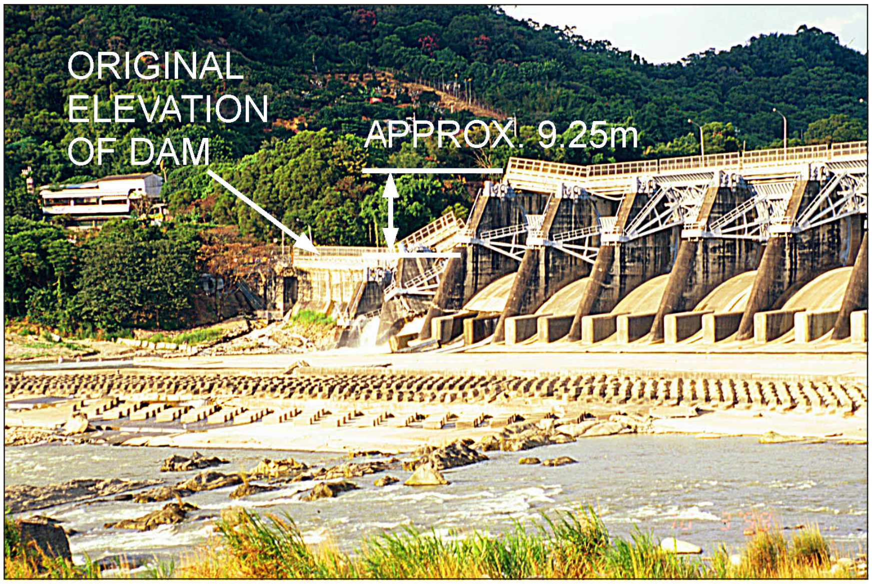
3.1.2 Research Needs

There is the need for a comprehensive decision support system to identify and rank landslide hazards and evaluate their impact on communities and lifelines. Whereas such a system should be calibrated for earthquakes, it should extend also to the influence of factors such as storms and floods. The opportunity exists for taking advantage of advanced remote sensing technologies and geographic information systems (GIS) to develop a graphical, multi-hazard approach to the problem.

3.2 Surface Faulting

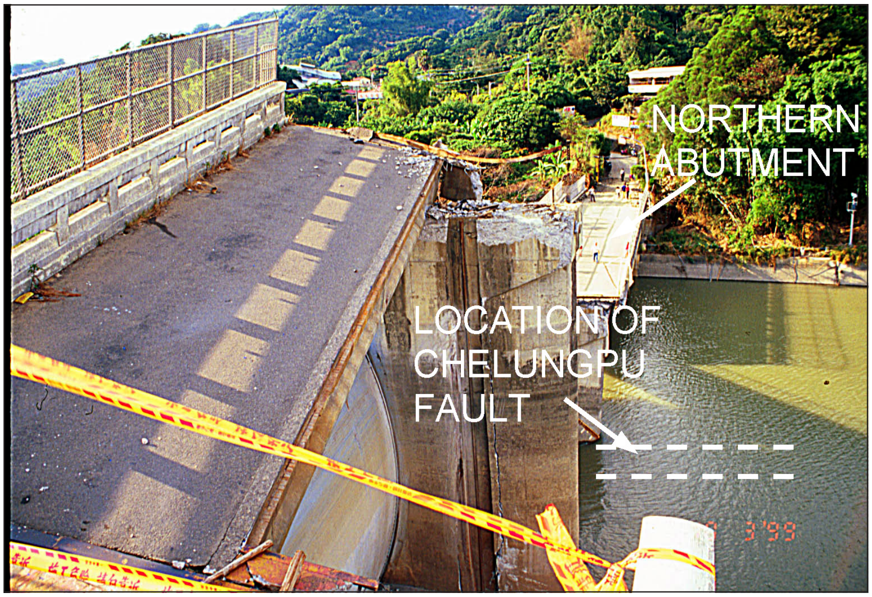
Some of the most notable ground failures associated with the Chi-Chi earthquake were related to the vertical and horizontal offsets generated by rupture of the Chelungpu fault. Vertical fault offsets in Feng Yuan were as high as 4 to 5 m, and were responsible for extensive building damage and collapsed structures. Surface faulting was also responsible for the failure of the Tong Fong Bridge and Shih-kang Dam, both of which spanned the Tachia River to the east of Feng Yuan.

Fault rupture with a vertical offset exceeding 9 m was responsible for failure of the Shih-kang Dam and subsequent release of approximately two million m^3 of water. This loss represents 40% of the raw water supply for Taichung County. Figure 3-11 is a photograph of the northern abutment area taken downstream of the dam, and Figure 3-12 is a photograph of the northern abutment from the vertically displaced southern part of the dam.



Photograph by T.D. O'Rourke

Figure 3-11 View of northern end of Shih-kang Dam showing over 9 m of vertical offset at Chelungpu fault



Photograph by T.D. O'Rourke

Figure 3-12 View from upthrust side of Shih-kang Dam looking north

The effects of surface faulting in the Chi-Chi earthquake are broadly similar to the surface faulting effects of the August 17, 1999 Marmara earthquake in Turkey. Rupture of the Northern Anatolian fault during the Marmara earthquake caused a highway bridge to collapse and caused extensive damage to the main Turkish naval base in Gölcük. Recent major earthquakes, such as the 1994 Northridge and 1995 Kobe earthquakes, were not accompanied by surface faulting in heavily populated areas. The presence of severe surface faulting in both the Chi-Chi and Marmara earthquakes demonstrates how destructive and disruptive surface faulting can be, and encourages a more careful consideration of such effects along active faults in Taiwan and the U.S.

3.2.1 Short-Term Recovery Needs

The rupture of the Chelungpu fault differs at its northern end from the surface trace that was mapped and reported on the most recent active fault maps of Taiwan. The fault appears to turn sharply to the east just north of Feng Yuan where it intersects the northern side of the Shih-kang Dam. In the short-term, it is important to clarify the mechanism of fault rupture in this area and to define better the fault trace and its surface characteristics. Delineating the main fault rupture and establishing the occurrence of subsidiary ruptures, including coseismic movements on the nearby Tamoupu-Hsuangtung fault, are important for an improved understanding of both the near field transient and permanent ground deformations generated by the earthquake. Locating the active trace and strands of the Chelungpu fault is also important for evaluating various options with respect to restoration of the Shih-kang Reservoir.

Plans need to be made for recovery of the water supply in Taichung County. Of key importance for this restoration is a vulnerability assessment of the Shih-kang Reservoir site with respect to renewed movement of the Chelungpu fault. The reservoir is a critical facility, and relocation will be difficult, if not impractical. It may be important therefore to utilize as much of the current site as possible. Future use of the Shih-kang Reservoir requires careful consideration not only of the Chelungpu fault and subsidiary ruptures, but of the current elevation differential at site, relocation of all or part of the dam, and the reuse, if any, of existing undamaged portions of the dam.

Restoration of the Taichung water supply is a complex problem that requires a systems approach. For example, it may be advantageous to convey water from neighboring water sheds via new transmission pipelines, rather than rehabilitate the entire Shih-kang site. A comprehensive plan should include a full assessment of current earthquake damage to the reservoirs, treatment plants, and distribution network.

3.2.2 Research Needs

The destructive consequences of surface rupturing along the Chelungpu fault, which was identified as a relatively low risk Category II fault, raises important questions about hazard identification and siting of critical structures in the vicinity of active faults. Land use and development at active California faults are controlled by state legislation, known as the Alquist-Priola Act, that places substantial restrictions on new construction in fault zones. Although similar restrictions may not be appropriate in Taiwan because of its higher population density and limited options for land use, it will nonetheless be important to organize a more systematic approach to fault mapping, assessment of rupture hazard and risk, and potential establishment of zoning and siting guidelines, especially for critical structures.

Locations of underground pipelines crossing the Chelungpu fault provide excellent opportunities to evaluate the performance of such facilities subjected to varying levels of differential fault offset. Of special interest are welded steel pipelines for water trunk and transmission operations, high pressure natural gas and liquid fuel, and oil insulated electric cables. The pipeline age, diameter, wall thickness, type of steel, burial depth, crossing angle, and locations of adjacent bends and tees should be documented in addition to soil type, pipe condition, and repairs.

Reconnaissance observations have shown that many structures immediately adjacent to, but not located in, the path of fault rupture apparently were not seriously damaged. This observation applies even to non-ductile concrete frames and unreinforced masonry structures. Similar observations have been made for the Marmara earthquake. A systematic assessment of structures immediately adjacent to the Chelungpu fault, but not subject to permanent ground deformation, would help to clarify structural performance and apparent dynamic response very near the fault.

3.3 Transient Ground Deformation

There were approximately 100 strong motion instruments deployed throughout the epicentral region. The records will provide important data about near source strong motion characteristics, incoherency, differences between fault normal and fault parallel characteristics, and differences between fault hanging and foot wall motion characteristics. The substantial database of records also provides the opportunity to evaluate local site response effects. Of special interest are sites with nearby strong motion instruments on rock and soft soil deposits. Other instrumented sites of special interest include those with landslides, liquefaction, and topographic amplification.

The use of GIS-based data and graphical displays are encouraged to analyze the spatial distribution of strong motion. GIS patterns of peak acceleration, velocity, and other seismic parameters (e.g., spectral acceleration and velocity, Arias intensity, etc.) should be evaluated. It will be advantageous to superimpose the GIS strong motion patterns on GIS patterns of building damage that are being developed by the Information Group at National Taiwan University. Correlations should be explored between strong motion parameters and the intensity of building damage by structural type.

MCEER has substantial experience in developing GIS databases for pipeline damage caused by earthquakes. The spatial distribution of pipeline damage by type in terms of repairs/km has been found to be an effective index of seismic intensity. Opportunities exist for collecting similar data for the Chi-Chi earthquake and performing collateral evaluations of the GIS patterns of strong motion, building damage, and pipeline repairs.

3.4 References

Hung, J-J., Lee, C-T. and Lin, M-L., (forthcoming), "Tsao-Ling Landslide (Taiwan) Revisited," *Catastrophic Landslides,* Geological Society of America, S.G. Evans, editor.

Lin, M-L. and Hung, J-J., (1982), "The Influence of Moisture Content on Mechanical Properties of Some Sedimentary Rocks in Taiwan," *Proceedings of the Seventh Southeast Asia Geotechnical Conference*, Hong Kong, Nov., pp. 155-169.

Top Contents

Section 4
Critical Facilities

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Critical facilities include hospitals and health care facilities; schools; police, fire and emergency response stations; key government facilities; and key industries. They provide life saving functions and render emergency assistance to communities when a disaster strikes. It is thus particularly important that every effort be made to insure their safety and functionality during and after a disaster. In this section, damages to some of these facilities due to the Chi-Chi earthquake are assessed, together with their probable causes and impact. Possible corrective actions and research needs in mitigating the effect of a similar future disaster event on these critical facilities are addressed.

It is noted that damage information on many of these facilities is still being collected and processed at the time of this writing. Therefore, they should be considered incomplete and preliminary as reported in this section.

4.1 Hospitals

According to available information, there are 4,375 health care facilities within the six-county seismic affected zone, of which 165 are hospitals. Damage to hospitals can be grouped into the following three categories: (a) minor structural damage and minor nonstructural damage, (b) partial structural damage but serious nonstructural damage, and (c) serious structural damage. In the first category, evacuation of patients and staff was not required and the hospitals were capable of performing emergency care to earthquake victims. In the second, hospitals were rendered non-serviceable and time was required for restoration. This type of damage was prevalent in the areas close to the epicenter. For example, within the critical 48-hour period after the earthquake, close to 1,000 beds were lost for patient care in Nantou county alone. Serious structural damage, or the third category, was also evident in regions close to the epicenter, where major hospitals were closed, requiring either demolition or major repair.

While structural damage was widespread in the six-county affected area, nonstructural damage was found to be a major factor adversely affecting functionality of major hospitals. Common occurrences included fallen interior walls and ceilings, toppling, sliding or collision of medical and non-medical equipment, overturning of water and oxygen tanks, interruption of emergency power, and flooding due to pipe breakage. For a closer scrutiny, several hospitals were chosen for more in-depth site visits. In what follows, damage investigations made on October 5, 1999 at three major hospitals are summarized. The observations described below are based on interior as well as exterior damage inspections and on interviews with hospital officials.

4.1.1 Christian Hospital, Puli

A major facility in Puli and surrounding communities, the Christian Hospital is a 400-bed facility of reinforced concrete (RC) construction consisting of a new (about 4-yr. old) section and an old (about 20-yr. old) section (Figure 4-1).

Photographs by T.T. Soong

Figure 4-1 The Christian Hospital sustained considerable damage. Photos show (left) part of the exterior damage to the hospital; and (right) interior damage to partitions and ceilings.

Damage

- New section sustained considerable damage from the main event on 9/21/99. Out of safety concerns primarily due to nonstructural damage (water damage, equipment failure, etc.), the building was evacuated with patients housed in tents on the hospital ground. The building was immediately inspected and considered safe. Upon interior cleaning, patients were returned to the building.
- The building suffered significant nonstructural damage again from the 9/27/99 M6.8 aftershock. Patients were again evacuated and housed in temporary trailers with considerably reduced capacity (about 50 beds), with overflow transferred to other area hospitals.

Photograph by T.T. Soong

Figure 4-2 The first floor of the Christian Hospital remained open though the hospital suffered extensive interior damage.

- The first floor of the building remained open and was being used for emergency care, patient registration and processing, command post, etc. (Figure 4-2).

Consequences and Impact

- A major part of the hospital was non-serviceable primarily due to nonstructural damage.
- Drastically reduced capacity (10% of original) at a time when demand was the highest.
- Trauma to patients through two relocations.
- Drastically reduced services due to equipment damage.
- The lack of an earthquake emergency management plan probably made the situation worse.

Restoration

Restoration was underway. It was estimated that the interior would be restored and serviceable within two weeks.

4.1.2 Veterans Hospital, Puli

Another major hospital in Puli, the Veterans Hospital, is a 450-bed facility with two main RC buildings (the Medical Center and the Administration Center), built about three years ago and several older (about 25 years old) and smaller buildings (Figures 4-3 and 4-4).

Damage

- New buildings sustained considerable damage from the main event. The Medical Building (Bldg. 1) was closed and the patients in the Administration Building

Photograph by M. Bruneau

Figure 4-3 An overview model of the Veterans Hospital in Puli. The two white buildings are the newest and both sustained considerable damage.

Photographs by M. Bruneau

Figure 4-4 The Veterans Hospital sustained both exterior damage (left) and interior damage (right) to the newest buildings of the medical center.

(Bldg. 2), along with those in Bldg. 1, were either moved to the older buildings or transferred to other VA hospitals. About 220 patients remained at the hospital.
- Considerable nonstructural damage in Bldgs. 1 and 2, including power failure[1], water damage, and equipment damage. Bldg. 1 also sustained considerable structural damage, probably due to a lack of ductile detailing.

Consequences and Impact

- A major part of the hospital was non-serviceable due to both structural and nonstructural damage.
- Drastically reduced capacity (50% of original) at a time when demand was the highest.
- Trauma to patients due to evacuation.
- Drastically reduced services due to equipment damage.
- As in the case of the Christian Hospital, no earthquake emergency management plan appeared to be in place at the time of the earthquake.

Restoration

Whether Bldg. 1 was to be demolished or repaired remained to be determined. Bldg. 2 was expected to be repaired within two weeks.

4.1.3 Shiu-Tuan Hospital, Tsushan

The 9-story, two year old reinforced concrete (RC) Shiu-Tuan hospital has a 400-bed capacity. It is privately owned and is the largest in Nantou county. The structure is situated about 120 m from the Chelungpu fault with an uplift of approximately one meter at the site.

Damage

- Structurally intact, it suffered considerable nonstructural damage as in the case of the other two hospitals (Figures 4-5 and 4-6). Interior damage was most severe at the second- and third-floor levels where, unfortunately, some of the major facilities, such as operating and recovery rooms, were located. Patients were moved to open hospital ground and subsequently transferred to other hospitals.
- Hospital closed.

Consequences and Impact

- Trauma to patients due to evacuation and re-allocation.
- Hospital closed, making the largest hospital in this vicinity unavailable to patients and earthquake victims.
- Seven patients died due to stoppage of life-support system.

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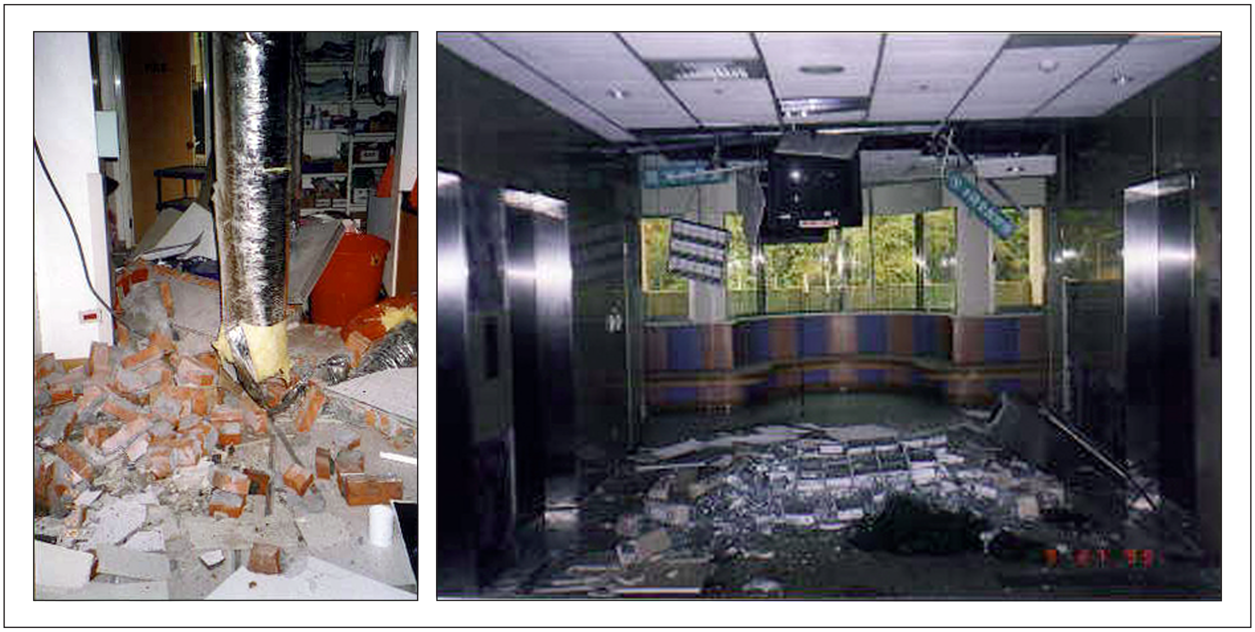
[1] The emergency generators also failed. They were located on the second floor of a separate building and, due to amplified acceleration on that floor, major components broke loose and rendered them inoperable.



Photographs by G. Yao

Figure 4-5 Interior damage in the Shiu-Tuan Hospital. Shown are (left) fallen brick inside the hospital and (right) a damaged interior glass brick wall.

Photograph by G. Yao

Figure 4-6 Damage to an exterior wall of the Shiu-Tuan Hospital in Nantou county

Restoration

Repair was underway and the process was expected to take one to two months. Funds for the repair remained to be found.

4.1.4 Summary

The damage to the three hospitals and its impact underscores the importance of securing medical equipment and protecting patients and staff from falling debris and overturning objects. As demonstrated in the case studies above, hospitals can be rendered non-serviceable and lives of patients can be lost due to failure of life support equipment in critical care areas. Table 4-1 is a compilation of nonstructural damage in the three hospitals highlighted in this section which, incidentally, could have been reduced or even avoided with inexpensive and easily implementable protective measures.

Table 4-1 Nonstructural damage in three surveyed hospitals

Cause of Disruption and Evacuation	Christian	Veterans	Shiu-Tuan
Backup Power Outage	X		X
Water Supply Outage	X	X	X
Gas Service Outage		X	X
Elevator Damage		X	X
Communications Failure	X	X	X
Falling Debris	X	X	X
Broken Piping, Water Leakage	X	X	X
HVAC Anchorage Failures	X	X	X
Mechanical Equipment Damage	X	X	X
Toppling of Gas, Liquid Storage Tanks	X	X	X
Medical Equipment Damage	X	X	X
Emergency Evacuation Plan Not in Place	X	X	X

4.2 Schools

School buildings sustained severe damage, reaching as far as the city of Taipei, 150 km from the epicenter. As in the 1998 Chia-Yi/Ruei-Li earthquake, the severity of damage to school buildings, as demonstrated in Table 4-2, again exceeded that of other structures due primarily to the commonality of their weaknesses in construction. The common problems associated with school buildings appeared to be, on the one hand, short-column effects which led to shear failure in columns and, on the other, eccentricity of most school buildings associated with cantilevered corridors at upper floors (Figure 4-7). It is estimated that restoration, repair and reconstruction costs associated with school buildings can reach US $1.3 billion (Ministry of Education, 1999a).

Table 4-2 Severity of damage to schools in Taiwan

Type of Institution	Total	Damaged	Damage Ratio (%)
Universities and Colleges	36	33	91.7
Technical Institutions	98	38	38.8
Normal Universities	13	8	61.5
High Schools	242	63	26.0
Middle Schools	715	168	23.5
Elementary Schools	2,557	488	19.1
Schools for the Disadvantaged	20	4	20.0
Total	3,681	802	21.8

Ministry of Education, 1999b

Photographs by T.T. Soong

Figure 4-7 Typical damage to schools due to short-column effect and eccentricity

According to a recent accounting made available by the Ministry of Education, a total of 786 schools were damaged by the earthquake and its aftershocks as listed in Table 4-3, of which 51 suffered complete collapse. Damage was heavily concentrated in Nantou and Taichung counties as illustrated in Table 4-4. In Nantou county, for example, 139 out of 186 elementary and middle schools, or approximately 75%, suffered damage serious enough that they had to be closed. This situation not only affected the education of students, but also made them unusable as evacuation and emergency response centers.

4.3 Police and Fire Stations

As in the case of schools and other public buildings, police stations and emergency response centers also sustained severe damage in the affected region (for example, see

Table 4-3 Damage to schools in Taiwan

City/County[1]	Universities and Colleges	Technical Institutes and High Schools	Middle Schools	Elementary Schools	Total
Taipei City	8	8	8	43	67
Taipei County	2	1	21	52	76
Yi-Lan County	0	3	1	4	8
Tou-Yuan County	2	1	1	7	11
Hsinchu City	2	0	5	9	16
Hsinchu County	0	1	2	10	13
Miu-Li County	2	4	20	59	85
Taichung City	11	9	19	37	76
Taichung County	3	15	14	39	71
Nantou County	6	11	10	42	69
Chang-Hwa County	3	10	26	46	85
Yu-Lin County	1	6	10	32	49
Chia-Yi City	0	9	7	16	32
Chia-Yi County	2	2	7	35	46
Tainan City	1	0	10	18	29
Tainan County	1	2	0	0	3
Others	3	1	6	39	49
Total	47[2]	83[2]	168	488	786[2]

[1] *Numbers for counties do not include those in cities within the counties.*

[2] *Inconsistencies between Tables 4-2 and 4-3 are probably due to different information sources.*

Ministry of Education, 1999a

Table 4-4 Severity of elementary and middle school damage

County	Total Collapse	Partial Collapse and Nonstructural Damage	Total
Nantou	30	109	139
Taichung	11	32	43
Neighboring Counties	10	41	51

Ministry of Education, 1999a

Table 4-5 Interim damage summary pertaining to police and fire stations

City/County	Severity of Damage				
	Total or Partial Collapse or Overturning	Serious Damage (Requiring Demolition or Retrofit)	Moderate Damage (Requiring Retrofit or Repairable)	Light Damage (Repairable)	No Damage
Nantou County	5	1	1	1	0
Taichung County	--	--	--	--	--
Taichung City	0	0	0	14	0
Miu-Li County	1	0	2	1	4
Chang-Hwa County	0	2	3	0	0
Yu-Lin County	--	--	--	--	--

NCREE, 1999

Photograph by T.T. Soong

Figure 4-8 Total collapse of Puli Town Hall

Figures 4-8 and 4-9). Damage report forms were sent to these units by NCREE investigators and those returned to date are summarized in Table 4-5.

4.4 Key Industrial Facilities

Of particular interest to the international business community was impact of the Chi-Chi earthquake on the output at the Hsinchu's Science Based Industrial Park, where about 30 firms produce a significant percentage of the world's semiconductors and silicon wafers. Damage to this facility and its global impact will be the focus of this section.

Hsinchu's Industrial Park, situated about 110 km from the epicenter, houses approximately 239 high-technology firms having important links to the world's computer and communications industry. Based on the types of products they produce, they can be grouped into

10 5 '99

Photograph by T.T. Soong

Figure 4-9 Heavily damaged Puli Police Station

the following: Integrated Circuit: 95, Computers and Peripherals: 44, Telecommunications: 36, Electro-optical: 35, Automation: 16, and Biotechnology: 13.

Power to the entire island was interrupted due to damage to the electrical transmission network and switching stations close to the epicenter, due to high-priority user status at the Hsinchu's Industrial Park. Power to the Park was restored to full capacity at 500,000 KV on September 25, 1999, four days after the earthquake. Even so, production loss at the facility was estimated to be around US $400 million, most of which incurred at the semiconductor and silicon wafer production facilities.

Overall damage at the facility has been light in comparison with those closer to the epicenter. Again, nonstructural and equipment damage stood out, including fallen ceilings, cracked walls and partitions, shear failure of columns, piping breakage, and equipment damage. Most of this damage was repaired rapidly and the entire industrial complex has been restored to its pre-earthquake production level. Table 4-6 lists damage survey results based on the returned survey forms to date.

Table 4-6 Damage survey at Hsinchu Industrial Park

<table>
<tr><th colspan="5">Forms Returned: 171</th></tr>
<tr><td>No Damage: 101
Percent of Total: 59%</td><td colspan="4">Damage Reported: 70
Percent of Total: 41%</td></tr>
<tr><td rowspan="4"></td><td>Damage</td><td>Light</td><td>Moderate</td><td>Serious</td></tr>
<tr><td>Cracks in Walls</td><td>55</td><td>11</td><td>0</td></tr>
<tr><td>Deformed Floors</td><td>8</td><td>3</td><td>0</td></tr>
<tr><td>Shear in Columns</td><td>5</td><td>0</td><td>0</td></tr>
</table>

NCREE, 1999

4.5 General Observations and Lessons Learned

4.5.1 *Seismicity*

Heavy damage to critical facilities in areas close to the epicenter was certainly in large part attributable to unanticipated high level of ground shaking in the region. For example, Nantou and Taichung counties, where most of the damage occurred, are located in seismic zone 2 with a design peak ground acceleration (PGA) specified at 0.23 g. On the other hand, the actual recorded PGAs in the region were in general higher than 0.35 g, and were as high as 0.92 g. Even accounting for an importance factor of 1.25 for public buildings, the design PGA values were considerably below those actually experienced, causing widespread damage to constructed facilities.

4.5.2 *Structural Damage*

Beyond high seismicity, several important factors contributing to observed structural damage to buildings, including critical facilities, have been identified and discussed in other parts of this report. Some have also been identified in this section. These include:

- Short-column effects leading to column shear failure.
- Eccentricity due to cantilevered corridors.
- Lack of ductile detailing.
- Column failures due to inadequately spaced stirrups, reinforcements, and splices.
- Soft-story induced failures.
- Unstable foundations and ground uplift.

However, in spite of these common ills, structural damage to critical facilities appeared to be heavier than those in other sectors. It has been speculated that this may be due to the nature of the bidding process associated with the construction of public and government owned buildings, where fixed-price design/built contracts are practiced. As reported in local news broadcasts, this practice invites abuse and encourages contractors to utilize substandard construction materials and circumvent accepted engineering practices in order to complete their projects under budget.

4.5.3 *Nonstructural Damage*

As highlighted in several parts of this section, the impact of nonstructural damage on the loss of functionality of critical facilities has been significant, leading to their inability to perform emergency and lifesaving services and, tragically, loss of lives. While seismic codes exist in Taiwan for buildings and bridges, there appears to be an absence of rational seismic provisions for nonstructural components. Ironically, seismic performance of nonstructural components can be substantially improved using rather simple and inexpensive means.

4.6 Research Needs and Recommendations

Research needs have been identified in other sections of this report in the areas of seismicity and some structural issues. The outstanding issue identified in the preceding section related to construction practices associated with public buildings needs to be critically reviewed. Revisions and modifications appear to be necessary in order to insure quality engineering and quality construction in the future.

Also of critical importance is the nonstructural issue. Stringent seismic design and installation guidelines need to be in place to insure not only structural integrity, but also functionality of critical facilities, which require protecting nonstructural components, as well as structures, from seismic damage under strong ground shaking as experienced in the Chi-Chi earthquake. A systematic development of these guidelines involves the following:

- Review and improve current design and installation practices in nonstructural components.
- Develop effective retrofit strategies for nonstructural components in existing critical facilities.
- Develop effective implementational procedures for existing facilities and new constructions.

4.7 References

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Section 5
Building Damage

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Preliminary data indicates that approximately 5,000 buildings totally collapsed as a result of this earthquake, with more than 4,000 others partially collapsed and countless others damaged to various degrees. There were 8,773 instances of structural damage recorded using the Building Damage Survey Form (ABRI, 1999; Building Technology Standards, 1974, 1982 and 1997) jointly prepared by the National Center for Research on Earthquake Engineering (NCREE) and the Architecture and Building Research Institute (ABRI). However, because each damage report filed for either an individual structure or for a block of consecutively connected buildings was counted as one instance of damage, the extent of damage was actually broader than implied by this survey. While it will take considerable time and effort to inventory the damage to a level of refinement that will allow formulation of a reliable critique of current building codes and practices, preliminary observations indicate that buildings that collapsed typically exhibited non-ductile reinforcing details compounded by detrimental building configurations.

The objective of this chapter is to provide an overview of the most common type of damage caused by this devastating earthquake, along with some recommendations for short-term recovery and long-term reconstruction as a result of these observations.

5.1 Building Characteristics and Building Codes

A large percentage of buildings that collapsed due to the Chi-Chi earthquake main shock or strong aftershocks were non-engineered one-to-three story reinforced concrete frame structures constructed with brick infill partitions and exterior walls. Many collapsed buildings had a pedestrian corridor and open front at the ground floor, and only one wall at the back of the building along the street direction. This type of building damage accounts for the majority of the complete building collapses near the epicenter due to severe ground shaking.

Many school buildings suffered extensive and severe damages. The “short-column” type of damage in these reinforced concrete structures is rather common in the direction parallel to the exterior corridor outside the classrooms, where small windows above partial-height infill shortened the effective length of almost all the columns.

However, in the affected area, more than two dozen modern high-rise apartment buildings overturned or collapsed. These were reinforced concrete moment resisting frames, most of them constructed with cast-in-place 15 cm thick exterior wall and 12 cm thick partition walls. These buildings were typically designed following requirements for moment resisting frames identical to the Uniform Building Code (UBC) used in the United States, albeit generally one edition behind the latest available at any given time. Table 5-1 provides a brief overview of the seismic force design requirements in Taiwan over the last 25 years. In Nantou county, where most of the damage occurred, the specified peak ground acceleration to consider for design is 0.23 g (for the 475 year return-period earthquake), which translates into a design coefficient, C_d, of approximately 0.11 g for short period structures. Incidentally, that coefficient was 0.05 g from 1974 to 1982, and 0.08 g from 1983 to 1996, before the higher aforementioned value was adopted in 1997. (Note that Nantou is located in Taiwan's Seismic Zone 2, and that design forces 22 percent and 43 percent higher are mandated in Seismic Zones 1A and 1B, respectively.) Alternatively, the code permits the use of a slightly larger seismic force to size members with some relaxation on the ductile detailing of the reinforcement, following what is prescribed in the UBC. Surprisingly, many of the buildings that collapsed were engineered and constructed in the last decade. However, none exhibited evidence of ductile detailing. Many of them appear to have tall floor and open plaza features on the ground level.

Table 5-1 Seismic force requirements in Taiwan

Year	Seismic Base Shear	Remarks
1974	V_W=ZKCW	Z = 1.25, 1.0, 0.75 K = 0.67, 0.8, 1.0, 1.33 C_{max} = 0.10, W=D+0.25L
1982	V_W=ZKCIW	Z = 1.0, 0.8, 0.6 K = 0.67, 0.8, 1.0, 1.33 I = 1.0, 1.25, 1.5 C_{max} = 0.15, W=D
1997	$V = \frac{ZICW}{1.4\alpha_y F_u}$	Z = 0.33, 0.28, 0.23, 0.18 I = 1.0, 1.25, 1.5 C_{max} = 2.5, W=D α_y = 1.2 (WSD), α_y=1.5(USD) $F_u \approx$ 2.9, 2.5, 2.1

5.2 Structural Damage

5.2.1 Fault Displacements

One of the significant features of the Chi-Chi earthquake is its large surface fault lateral and vertical displacements, as reported in Section 2. Buildings constructed across faults typically cannot survive the relative displacements that occur at their foundation due to fault movements, and the buildings in Taiwan were not different in that perspective. Examples of buildings destroyed by fault movements are shown in Figure 5-1. While roads can be repaired quickly by placing fills and repaving across significant vertical fault offsets, as shown in Figure 5-2, buildings obviously cannot be easily repaired, particularly when large displacements have afflicted them with considerable damage. Inexpensive concepts to construct buildings across faults have not been developed to date, and the best strategy remains to avoid building at such locations. Unfortunately, this presupposes the availability of reliable maps of active fault locations, and legislation that effectively prevents constructions across such faults. Generally, these are still largely unavailable except in the most active seismic areas.

Photographs by K.C. Tsai

Figure 5-1 Damage to buildings straddling fault line

Photographs by M. Bruneau

Figure 5-2 Road was originally level, uplifted by fault rupture, and repaved to restore service

Numerous instances of geotechnical failures that had an impact on the seismic performance of buildings were also observed, such as settlement due to liquefaction (Figure 5-3); however, these are not discussed in this chapter.

Photograph by K.C. Tsai

Figure 5-3 Damage due to settlement caused by liquefaction

5.2.2 Soft Stories

Investigation teams following every major earthquake in the later half of this century have seen their share of buildings with concentrated severe damage at their first story. As large open first floors have evolved as a key architecture feature over that period, first floors typically have lower strength and stiffness compared to the other floors. This discontinuity in the structural and nonstructural system results in the observed concentration of damage at the weaker or more flexible story. Unless specific measures are taken by the engineers to counteract this effect, which is possible but sometimes difficult as it must account for the contribution of structural as well as nonstructural elements, this type of damage, commonly called “soft-story damage,” is likely to occur. Examples of buildings that have suffered extensive soft-story damage, or collapse, are shown in Figures 5-4 to 5-8. The buildings in Figure 5-4, of very similar configuration, illustrate clearly the “soft-story” damage concentration concept and progression toward collapse.

In Taiwan, as in many other countries, the problem is often compounded by irregular structural configuration. Large openings on the street side, for garage doors, store windows, or other purposes (Figures 5-5 to 5-6), lead to a significantly weaker and more flexible structural frame than on the back-side where walls with few openings are generally found. This structural eccentricity accelerates the soft-story damage on the street side, often resulting in toppling of the building toward the street (Figure 5-7), or toward the intersection in the case of buildings located on street corners and thus having two open sides (Figure 5-8). Note that buildings in Taiwan often project over the sidewalk, which is one common architectural feature that increases this structural eccentricity.

Photographs by M. Bruneau

Figure 5-4 Large sway in progression toward collapse (left) and building failure due to soft first story (right)

Photograph by M. Bruneau

Figure 5-5 Soft-story failure of building having numerous large openings at first story on street side

Photographs by M. Bruneau

Figure 5-6 Damage due to irregular structural configuration

Photographs by M. Bruneau

Figure 5-7 Damage due to soft first story on street side of buildings, causing them to topple toward the street

Photographs by M. Bruneau

Figure 5-8 Buildings located on street corners toppled toward the intersection as a result of soft-story damage

5.2.3 *Strong-Beams/Weak-Columns*

Strong-beam weak-column systems, apparently common in Taiwan, might have resulted in numerous story collapses following excessive column damage. This was particularly frequent in the first story of buildings, as the larger openings and higher story height there translate into a lower structural stiffness and strength, leading to "soft-story" mechanisms. However, strong-beam weak-column conditions were also observed at all the stories of many buildings.

5.2.4 *Short Columns*

In a mode of behavior in some ways similar to that resulting from the strong-beam weak-column condition, severe column damage and failures have occurred when partial-height nonstructural partitions have been used. These partitions typically "trap" the columns, preventing the development of their normal flexural behavior over their height, rather allowing them to only deform over their free-height (i.e., the length of the column not surrounded by partitions). As a result, although the shorter length of the trapped column would make it possible to resist higher lateral forces before the flexural strength of the column is reached, the shear strength of a short column is often first reached and typical non-ductile shear failures ensue.

In other instances, although trapped columns may develop flexural plastic hinging instead of shear failures, it remains that damage in columns is not desirable. The partial height infills thus promote the strong-beam weak-column behavior described earlier. Examples of such failures are shown in Figure 5-9 for a column having moderate stirrup spacing that provided sufficient transverse reinforcement, along with a favorable column geometry, to prevent this shear failure. Also note on that figure the conspicuous asymmetric column cover concrete in that instance.

Photographs by M. Bruneau

Figure 5-9 Damage due to trapped columns having "moderate" stirrips spacing

5.2.5 Non-Ductile Detailing

During major earthquakes, survival of even the most symmetric well-proportioned buildings may not be possible in the absence of ductile detailing reinforcement. Following the Taiwan earthquake, many examples of non-ductile details were noted, such as widely spaced stirrups (unconfined plastic hinge zone) in failed columns, splices with inadequate development length or located in the hinge region, light or absence of joint transverse reinforcement, stirrups with 90°, etc.

Figures 5-10 to 5-14 illustrate some examples of such undesirable detailing practices. The columns shown in Figure 5-10 had widely spaced stirrups and were therefore poorly confined, which led to their rapid degradation in the hinge region. Poor transverse reinforcement detailing also led to the shear failure and soft-story failure of the building shown in Figure 5-11. A closer look at another building that experienced soft-story failure and shown in Figure 5-12 revealed the presence of poor detailing, with columns bars spliced in the joint region. An example of total absence of transverse joint reinforcement (among other things) is shown in Figure 5-13. And, of course, some buildings suffered from many (if not all) of the above deficiencies, as shown in Figure 5-14.

Photographs by M. Bruneau

Figure 5-10 Damage to column having widely spaced stirrups and trapped by a partition

Photograph by M. Bruneau

Figure 5-11 Shear failure of columns

Photographs by M. Bruneau

Figure 5-12 Example of collapsed building with column bars spliced within the joint

Photographs by M. Bruneau

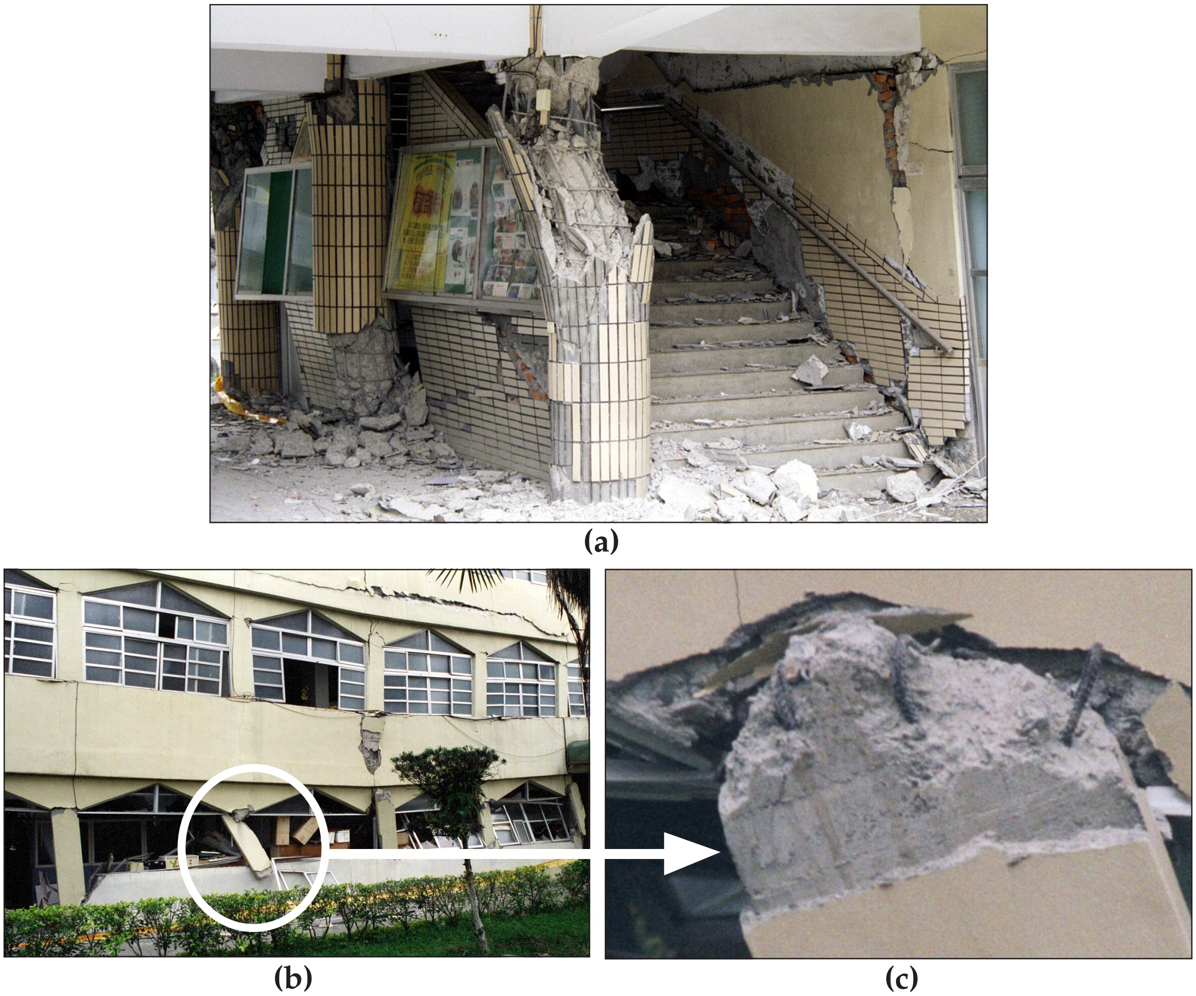
Figure 5-13 Example of collapsed building having no transverse joint reinforcement

Photographs by M. Bruneau

Figure 5-14 Damage due to poor detailing

5.2.6 Compatibility of Deformations

This earthquake also provided reminders of the significance of recognizing compatibility of deformations during the design process. Some engineers, when conducting structural analysis and design of buildings, systematically de-couple the structural elements that are part of the lateral-load resisting system from the others intended to solely provide gravity-load resistance. While this is convenient, it is important to verify that the gravity-load resisting structural element can displace without undesirable damage to the same maximum seismic-induced lateral drifts calculated for the lateral-load resisting system. Even in buildings having the most ductile lateral-load resisting systems, failure to perform this verification may jeopardize the ability of the structure to sustain its gravity loads, with dire consequences. Damage to the building shown in Figure 5-15 illustrates this behavior. The large residual lateral displacement of the first floor due to column damage is clearly visible on that figure. The small columns between windows along the


(a)

(b)

(c)

Photographs by M. Bruneau

Figure 5-15 Example of damage to gravity-only columns (i.e. columns assumed not part of lateral load resisting system); (a) residual drift; (b) circled area is a typical gravity-only column; (c) close up view

façade of that school building were visibly not detailed to carry lateral load, as evidenced by the poor anchorage of the column reinforcement into the joint. Consequently, the columns failed in the manner illustrated, with the reinforcement pulling out of the joint and leaving the column precariously hanging. Although this building suffered from non-ductile detailing of the lateral-load resisting systems, similar large residual deformations have been observed in the past in ductile structures.

5.2.7 Impact of Infill Walls

In many instances, the contribution of nonstructural partitions to seismic response apparently had a positive impact. Although generally neglected by the designer while considering lateral-load resistance, the use of reinforced concrete as infills stiffens and strengthens the structure. In some cases, the greatly enhanced supplied strength may have more than overcome the increased demand resulting from the lower structural fundamental period of vibration. This could explain why so many buildings survived where strong shaking peak ground acceleration exceeded 0.3 g. Unfortunately, in many cases, only a few such walls or partitions existed at the ground level, which proved fatal when ductile reinforcing details were not implemented.

Good examples of this behavior are shown in Figures 5-16 and 5-17. Figure 5-16 shows the typical X-type shear cracks that were observed and would be expected when windows such as the one present in this building locally weakens a reinforced concrete shear wall. In this case, the cracks intersected a column at its mid-height, exposing its reinforcement and damaging it in a way that would otherwise not occur in a moment frame. This illustrates how infills can completely change the structural behavior of a structure, from the moment-frame conceived by the engineer and intended in the original design, to a shear wall system. When such infill walls extended over the entire building height, including ground level, collapse was typically avoided, as shown in Figures 5-16 and 5-17.

Photograph by M. Bruneau

Figure 5-16 Damage due to infill walls at ground level

Photographs by M. Bruneau

Figure 5-17 Hospital with severe damage to nonstructural infill walls but minor (cosmetic) damage to structural elements

In other instances where large columns were used, as shown in Figure 5-17, these columns only suffered minor cosmetic damage in spite of extensive infill damage. In such cases, although the infills may not have totally prevented undesirable frame behavior, they stiffened the more flexible frames and provided energy dissipation, thus significantly contributing to seismic survival.

Infills that were not adequately tied to the surrounding frames, even though they may have partly contributed in the manner described above, were not as effective, and were sometimes dislodged by out-of-plane seismic excitations. Figure 5-18 illustrates one such infill panel that fell outward as a result of being poorly tied to its surrounding frame. Another example is shown in Figure 5-19 in a building adjacent to one that completely collapsed as

Photograph by M. Bruneau

Figure 5-18 Out-of-plane collapse of an infill panel poorly tied to the surrounding frame

a result of damage at that same story. Note however, that although this absence of continuity between the infills and frame did not help, discontinuous infills are not inferred to have been the cause of the observed collapse. These buildings suffered from many other poor detailing practices, as shown in Figure 5-20.

Photographs by M. Bruneau

Figure 5-19 Severely damaged building complex; (top) out-of-plane collapse of third story infill wall; (bottom) collapse due to poor detailing practice

Photographs by M. Bruneau

Figure 5-20 Collapse due to poor detailing practice

Infills also played a significant role in helping poorly detailed reinforced concrete buildings survive during the Marmara (Turkey) earthquake that occurred approximately one month prior to the Chi-Chi earthquake. However, damage comparisons show the advantages of reinforced concrete infills (used in Taiwan) over the unreinforced masonry infills (used in Turkey). In the latter case, the brick infills failed in a brittle manner, leading to a sudden drop in strength without ductile response. Reinforced concrete infills, on the other hand, contributed in a more stable manner to the energy dissipation, and transfer of the seismic demands to the frames was more gradual.

5.2.8 Steel Structures

In Taiwan, most of the steel buildings were constructed in the last ten years. Steel frame structural systems are quite common for buildings taller than 25 stories. In order to cost-effectively satisfy the seismic and wind force requirements, moment resisting frames (MRFs) coupled with concentrically or eccentrically braced frame (EBF) dual systems are very popular. In these steel buildings, most of the beams are built-up wide flange sections of A36 or A572 grade 50 steel, while the columns are built-up box sections of A572 grade 50 steel. In most cases, moment connections were made at each beam-to-column joint. Most of the beam-to-column connections have bolted web and welded flange details in which run off tabs and backings are left in place after the flange welds. In some of these connections, the beam web was welded to the shear tab. The most common welding field practice is SMAW using E7016 electrode. In some cases, FCAW procedures have been employed in the field using E70T-7 NR311 electrodes.

In Taichung City, about 50 km northwest of the epicenter, where the recorded peak ground accelerations obtained from the main shock range between 0.2 and 0.3 g, several tall steel buildings have been constructed in the past decade. During the Chi-Chi earthquake, there were two steel buildings under construction, one 14-story (MRF) department store (Figure 5-21) and one 45-story (MRF/EBF dual system) office/hotel tower. Before the earthquake, most of the steel frames in these two buildings had been completed and the concrete slabs were poured. However, fire proofing, window walls and partitions were not installed yet and all the steel beam-to-column joints were still visible following the earthquake. Note that the 14-story building adopted the typical details described above and the 45-story structure employed reduced beam sections with radius cut details. Detailed inspections conducted for these two buildings following the earthquake indicated no apparent connection damage.

Photographs by C.M. Uang

Figure 5-21 14-story steel building under construction with undamaged moment-resisting steel frames

Except for the collapse of a few old light metal structures (Figure 5-22), damage to steel buildings had not been reported at the time of this writing. However, experience in other post-earthquake investigations shows that such damage takes much longer to discover, as steel members and joints are generally covered by fire proofing or architectural finishing. Further investigations are required in order to confirm the extent of the damage to steel buildings in the severely shaken regions.

Brace fractures and other damage was observed to bin and tank supports in many aggregate-producing plants. Damage to the elevated bins shown in Figure 5-23 illustrate well the typical progression of failure observed in many such structures. First, as shown in Figure 5-23b, fracture of non-ductile braces developed at their bolt holes. Because net section fracture occurs before gross section yielding of the brace, this occurs without any effective global structural ductility. Without braces, the remaining structure now behaves as a moment frame, but its column-to-beam connections do not have the details and strength (let alone the ductility) necessary to resist the seismically induced forces. As a result, significant damage occurs at the column connections (e.g., Figure 5-23c), and collapse ensues. These non-ductile details and damage observations from industrial facilities suggest that similar non-ductile details may also exist in steel buildings in Taiwan, but no such buildings have been reported to suffer damage.

Photographs by M. Bruneau

Figure 5-22 Collapse of non-ductile light metal structures

(a)

(b)

(c)

Photographs by M. Bruneau

Figure 5-23 Collapse and damage of non-ductile steel structures supporting elevated industrial bins

5.2.9 Other Issues (Nonstructural Damage, Unreinforced Masonry Buildings, Retrofit)

Although the amount of structural damage that has resulted from this earthquake can be overwhelming, nonstructural damage issues were also important, and are discussed in Section 4. Figure 5-24 is provided here simply to remind the reader of the significance of nonstructural damage in preventing safe egress, either both due to internal damage (e.g., suspended ceiling collapses) or external damage (e.g., failure of canopy over an exit door).

Unreinforced masonry was often used in small villages. Behavior of these non-engineered buildings constructed using bricks of miscellaneous quality (for example, standard clay brick for exposed finishes and mud-bricks for walls hidden by stucco finishes, as shown in Figure 5-25) varied considerably. The two buildings shown in Figure 5-25 were approximately 15 feet from each other; one survived with cosmetic damage, the other collapsed.

Finally, it appears that no buildings had been seismically retrofitted prior to the Chi-Chi earthquake, as this practice was not given a high priority by owners and policy makers. It is anticipated, however, that this will change during and after the major reconstruction effort in Taiwan.

Photographs by M. Bruneau

Figure 5-24 Examples of interior and exterior nonstructural damage that may prevent safe egress; collapse of suspended ceiling (left) and collapse of canopy above an exit door (right)

Photographs by M. Bruneau

Figure 5-25 Cosmetic damage (left) and complete collapse (right) of unreinforced masonry structures located 15 feet apart

5.3 Recommendations for Short-Term Recovery

In the perspective of the damage reported herein,, the following recommendations are made for consideration during the initial recovery period:

1. Given the extensive damage suffered by reinforced concrete buildings that clearly exhibited a lack of ductile detailing, it is essential that steps be taken to ensure that only ductile details be used in all new constructions and in the repair of damaged structures. Furthermore, until further research findings become available, buildings having "soft-story" characteristics should not be allowed in new constructions.

   In light of the fact that some of this knowledge is currently present in the enacted codes, it seems that efforts must be directed, through education, professional development, and legislation as appropriate, to ensure a better understanding and enforcement of capacity design principles and full implementation of ductile detailing.

2. Seismic zonation maps must be critically reviewed to re-assess the national seismic risk and desired earthquake protection levels. This simultaneously entails a critical reassessment of the design-spectra in light of the new data.

3. The extensive vulnerability of the existing building inventory, as revealed by this earthquake, must be addressed before other equally destructive earthquakes strike again in the country. Particular attention should be paid to buildings with soft stories and open fronts. This requires the establishment of priorities, timetable, policies and criteria for seismic retrofit. It is not fiscally possible to retrofit all structures in cities having extensive building inventories, but key post-emergency building (such as hospitals and other critical facilities) require special measures to ensure that they will be made available. In that perspective, passive energy dissipation

systems (such as those developed in Taiwan or abroad) could play an important role and are worthy of consideration.

5.4 Conclusion

Findings from this earthquake concur with those from prior events, emphasizing the need for stringent enforcement of implementation of ductile detailing requirements. All failure modes observed are well known and have been extensively described in the past.

In many instances, the contribution of nonstructural partitions to seismic response apparently had a positive impact. Although generally neglected by the designer while considering lateral-load resistance, the use of reinforced concrete as infills transformed the structural system from moment frames to shear walls, and the greatly enhanced supplied strength may have more than overcome the increased demand resulting from the lower structural fundamental period of vibration. This could explain why so many buildings survived in regions where strong shaking peak ground accelerations occurred. Unfortunately, in many cases, only a few such walls or partitions existed at the ground level, which proved fatal when ductile reinforcing details were not implemented.

5.5 Significance to North America

It is worthwhile to emphasize that building damage similar to what was observed in Taiwan is also expected to occur in North America. Indeed, while ductile design requirements have long been codified, and although many buildings are being constructed in compliance with these requirements, there remains an enormous inventory of existing buildings designed and constructed prior the enactment of these provisions. For example, buildings having non-ductile reinforced concrete frames, typically constructed in the 1960's and earlier, still constitute the majority of the building infrastructure in North American cities exposed to a significant seismic risk, even in California. The situation is even worse in those parts of the continent where recognition of the seismic threat is more recent, particularly in those cities that have yet to recognize this risk and adopt earthquake-resistant design provisions.

Furthermore, while the issue of building damage due to large surface faulting has faded from attention in recent years, it remains that many buildings in North America have been constructed straddling a major fault. Legislation that prevents building construction within specified fault distance (as done in California) is relatively recent, and far from widespread. These issues will require further consideration.

Finally, this earthquake, which occurred in Taiwan's Seismic Zone 2 (whereas Zones 1A and 1B are rated as being more severe), serves as a reminder of the dangers of underestimating the severity of the earthquake risk. As the last damaging earthquake fades from memory, there is a tendency to "forget" the seismic risk. While the risk does not decrease, awareness and perceptiveness does. This is particularly typical in those parts of North America where the last damaging earthquakes pre-date the current century. There, responsible engineers must resist the various pressures frequently encountered to make the earthquake risk "disappear" through various strategies. This is particularly important in those regions where low probability but high intensity seismic events are possible.

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Section 6
Performance of Highway Bridges

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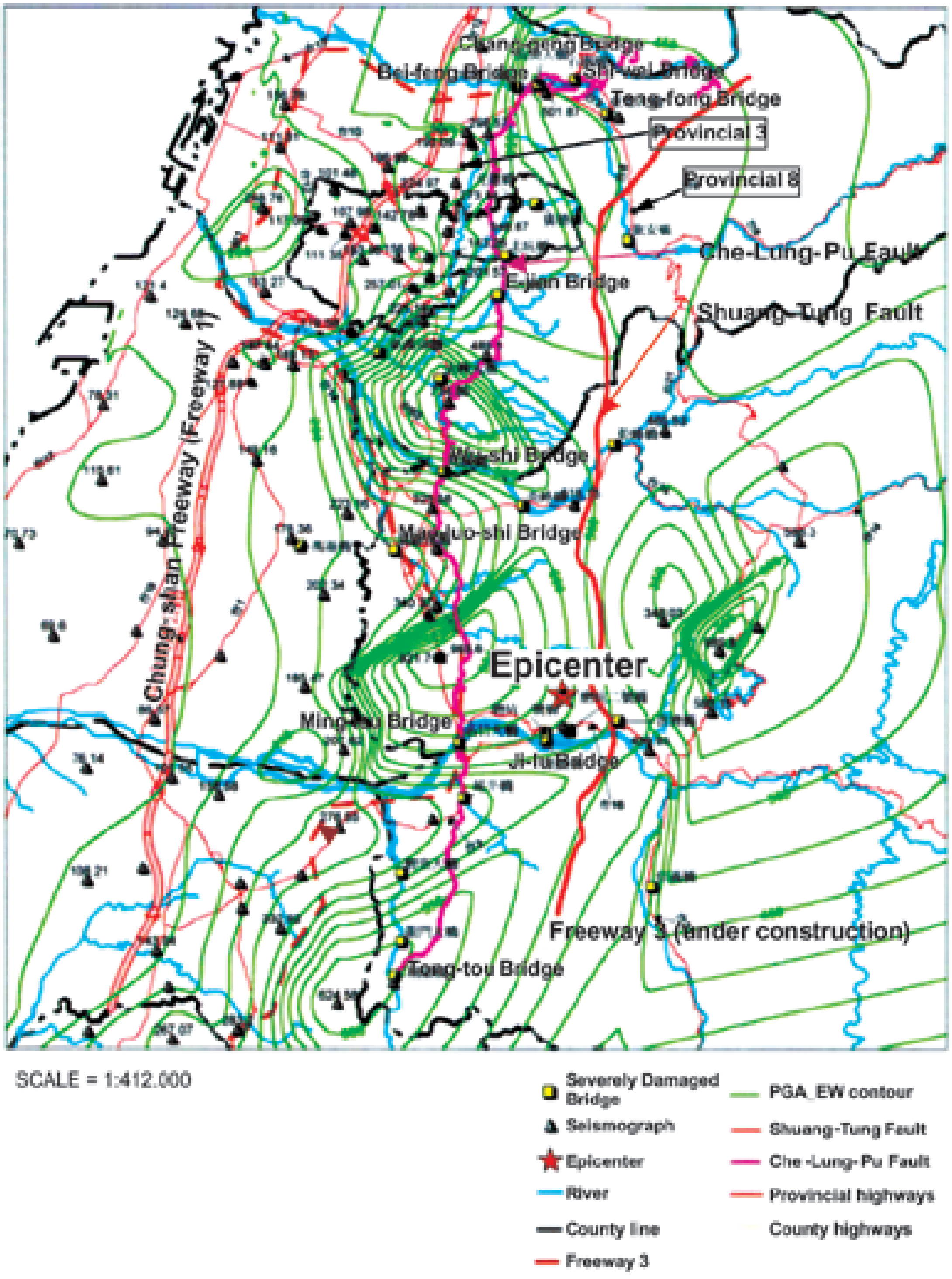
Highway damage was widespread throughout Taichung and Nantou counties due to fault rupturing, collapsed or crippled bridges, landslides, soil settlement and slope failures. Ten days after the earthquake, 45 km of road remained closed, and another 400 km were subject to delay and capacity restrictions (Figure 6-1).

Many hundreds of bridges are located in Taichung and Nantou counties, but most escaped serious damage and suffered only minor distress such as the settlement of approach fills behind abutment back-walls. But approximately 10% of the bridge inventory experienced moderate-to-major damage and those most seriously affected range from 3-span to 28-span structures, including simply supported reinforced concrete slab-and-girder superstructures, continuous steel plate-girders and long-span cable-stayed girders.

Figure 6-1 shows major routes, location of severely damaged bridges, and active faults. Also shown are the seismic measuring stations and the PGA's recorded during the earthquake. For example, Route 3 is a major north-south highway running the length of Taiwan from Taipei in the north to Pingtung in the south. There are approximately 65 bridges on this route as it passes through Taichung and Nantou counties. Five of these bridges suffered collapsed spans or were extensively damaged, such that the safety of the structure was in jeopardy, requiring closure pending demolition or significant repair. Another five bridges on county and city highways experienced similar distress, including one cable-stayed bridge under construction. Figure 6-1 shows the approximate locations of these bridges on Routes 3, 129 and 149, and their proximity to the epicenter at Chi-Chi and the Chelungpu fault. It will be seen that all ten structures are within 10 km of the fault and most are within 5 km. Seven are located directly on the causative fault or on one of its numerous branch faults. All are considered to be in the 'near field' and thus subjected to intense ground motions both horizontally (up to 1 g) and vertically (up to 0.6 g), and average fault dislocations of approximately 1.5 m horizontally and 3 m vertically.

Table 6-1 summarizes information about these and other major highway bridges damaged by the earthquake. Damage included overturned bearings; shear failures in columns, pier walls, and caissons; joint failures in column-to-girder connections; loss of support for both normal and skewed simple and continuous girders; cable fracture; abutment back-wall failure; and foundation failures due to slope instabilities, liquefaction,



National Center for Research on Earthquake Engineering

Figure 6-1 Bridges with significant damage in Taichung and Nantou counties

Table 6-1 Partial List of Bridges with Significant[1] Damage

Bridge ID	Bridge Name	Route No.	Date of Construction/ Widening	Type	Spans (m)	Total Length (m)	Damage Mode
1.	Tong-tou	149	1980	RC[2]	4 x 40	160	Collapse
2.	Ming-tsu	3	1990	RC[2]	28 x 25	700	Collapse
3.	Mao-luo-shi	3	1999	Steel/RC[3]	8-span segment	500	Column
4.	Wu-shi	3	1981/83	PC[4]	18 x 34.7	624	Collapse/ Column
5.	E-jian	129	1972	RC[2]	24 x 11	264	Collapse
6.	Tong-fong	3	1962/88	RC[2]	22 x 26	572	Girder/ Column
7.	Shi-wei	3	1994	PC[4]	3 x 25	75	Collapse
8.	Ji-lu	Local	1999	Cable-stayed	2 x 150	300	Pylon/ Bearing
9.	Bei-feng	129	1959	_____	5.7	5.7	Deck/ Abutment
10.	Chang-gang	Local	1987	_____	25	300	Collapse
11.	Pi-feng	Local	1991	_____	25	300	Collapse
12.	Guang-long	Local	1986	_____	28	56	Deck/ Abutment
13.	Guan-de	Local	1977	_____	20	60	Collapse
14.	Long-an	129	1986	_____	35	280	Column
15.	Cheng-feng	136	1986	_____	25.6	184	Column/ Abutment
16.	Yan-feng	14	1984	_____	35	455	Column
17.	Pu-ji	16	1979	_____	35	105	Pier Cap
18.	Hsing-shi-nan	127	1994	_____	50	500	Column/ Bearing
19.	Yan-ping	3	1986	_____	13	78	Abutment
20.	Hsin-yi	21	1981	_____	29	180	Column
21.	Long-men	53	1982	_____	40	480	Collapse
22.	Li-yu	53	1988	_____	39	546	Bearing
23.	Ping-lin	6	1969	_____	25	500	Collapse/ Column
24.	Mo-keng No. 1	16	1996	_____	14.6	14.6	Abutment
25.	Mo-keng No. 2	16	1996	_____	40	40	Abutment
26.	Da-feng	105	1992	_____	_____	_____	Deck

Notes:

1. *Significant damage is defined as one or more collapsed spans, and/or extensive structural damage that jeopardizes the safety of the bridge requiring closure until repaired or replaced.*
2. *RC = Reinforced concrete superstructure*
3. *Steel/RC = Steel superstructure/reinforced concrete substructure*
4. *PC = Prestressed concrete superstructure*

and fault rupture. Brief descriptions of the damage to the first ten bridges listed in the table are given in this section. A comprehensive evaluation of damage to all the bridges listed in Table 6-1 is provided by Chang et al., 1999 (in Chinese). It is noted that the observations made in this chapter are preliminary and subject to change as additional data becomes available.

6.1 Observations

6.1.1 Tong-tou Bridge

All four simply supported spans of the *Tong-tou bridge* on Route 149, (Figure 6-2) collapsed due to shear failures in the single column bents comprising the three river piers (Figure 6-3). These columns were supported on large diameter caissons, which extended well above the river bed thus shortening the overall height of the columns themselves. The columns appeared to have been shear critical but did not fail simultaneously. Instead, one probably failed before the other, leading to an asymmetrical collapse of spans 2 and 3

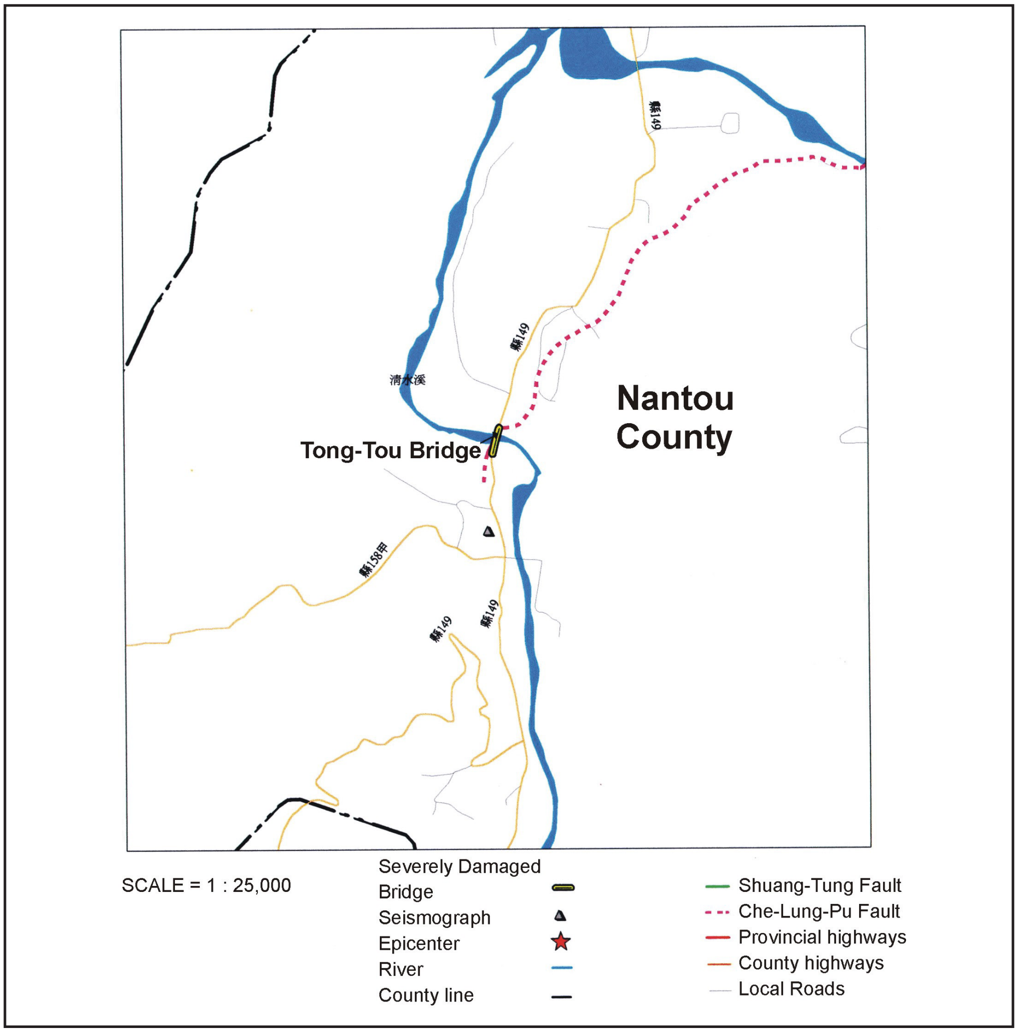


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Figure 6-2 Location of Tong-tou bridge

Photograph by Ian G. Buckle

Figure 6-3 Collapse of the Tong-tou bridge due to shear-critical columns

(one fell upstream and the other downstream of the bridge centerline). In addition, the northern abutment suffered considerable structural damage that appears to have been due to large earth movements arising from either fault rupturing or ground failure behind the abutment, or both. Significant settlement of the approach pavement occurred (Figure 6-4).

Photograph by Ian G. Buckle

Figure 6-4 Failure of the approach-fill behind north abutment of Tong-tou bridge

6.1.2 Ming-tsu Bridge

Constructed in 1990, the *Ming-tsu bridge* on Route 3 comprises 28, 25 m spans for a total length of 700 m. Figure 6-5 shows that the fault rupture passed the southern end of the bridge and caused eight of these spans to collapse (Figure 6-6). Although the superstructure comprised multiple spans of simply supported girders, they had been made continuous by a cast-in-place reinforced concrete deck slab which was continuous over intermediate bents. Thus the bridge was a series of continuous segments, and at least two of these segments collapsed at the south end of the structure. At the time of our site visit, the northern-most segments had been demolished and only the southern segment remained 'standing'. Whereas liquefaction may have been responsible for pier tilting and collapse of the northern segments, the spans in the southern segment became unseated when the southern abutment failed. During strong longitudinal motion the superstructure impacted the back-wall of the south abutment, which was unable to arrest the motion. The wall and its back-fill failed and were driven back about 0.5 m into the back-fill, followed by the superstructure (Figure 6-7). This longitudinal movement was sufficient to cause unseating of the adjacent spans comprising this segment.

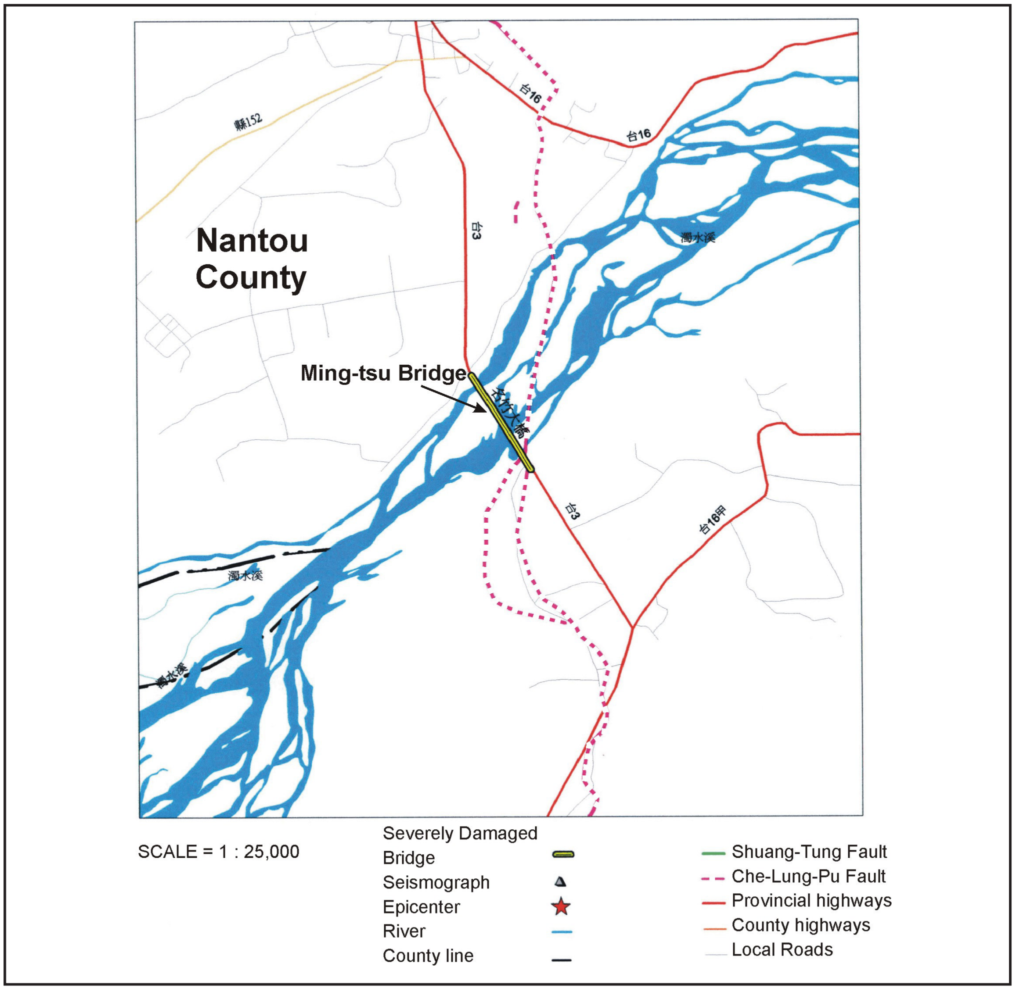

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Figure 6-5 Location of Ming-tsu bridge

Photograph by Ian G. Buckle

Figure 6-6 Ming-tsu bridge after removal of many of the collapsed spans

Photograph by Ian G. Buckle

Figure 6-7 Failure of the back-wall and back-fill behind south abutment of the Ming-tsu bridge, leading to the unseating of adjacent spans

6.1.3 *Mao-luo-shi Bridge*

The *Mao-luo-shi bridge* on Route 3 is a multiple-span viaduct comprising a set of continuous segments, each constructed from steel plate girders supported on concrete, single-column bents. In one 8-span segment (Figure 6-8), four of these bents are 'C–bents' where the column is eccentrically connected to the cross-girder. Although there were no collapsed spans in this viaduct, all of the eccentric connections showed distress, particularly in the column. Shear cracking was evident in the upper third of each column and increased in severity with increasing eccentricity (Figure 6-9). Despite the absence of gross deformations in the superstructure, the cross-girders were been temporarily shored and the bridge closed until permanent repairs could be made.

Photograph by Ian G. Buckle

Figure 6-8 Mao-luo-shi bridge, showing single-column concrete bents supporting continuous steel girders

Photograph by Ian G. Buckle

Figure 6-9 Typical distress in an eccentric, column-to-cap beam connection in the Mao-luo-shi bridge

6.1.4 *Wu-shi Bridge*

The *Wu-shi bridge* on Route 3 (Figure 6-10) is in fact two bridges on a parallel alignment (Figure 6-11). Both are 18 spans long for a total length of 624 m. The first bridge was constructed in 1981 and the second one, two years later, in 1983. Both were of similar design (simple spans supported on wall-type piers) with one exception. The piers of the second bridge were not as wide as those of the first and in some cases (e.g., at Pier 3) they were about one-half of this width. Despite the fact that both bridges experienced similar ground motions, they failed in different ways. Ground failure occurred behind and under the northern abutment of both bridges, triggered by fault rupture parallel to the abutments. Soil deformation at the base of these wall-abutments was approximately 0.3 m towards the river. There was similar ground deformation under the first and second piers, but of lesser magnitude (perhaps 0.2 m). The two bridges accommodated this movement in different ways, as described below.

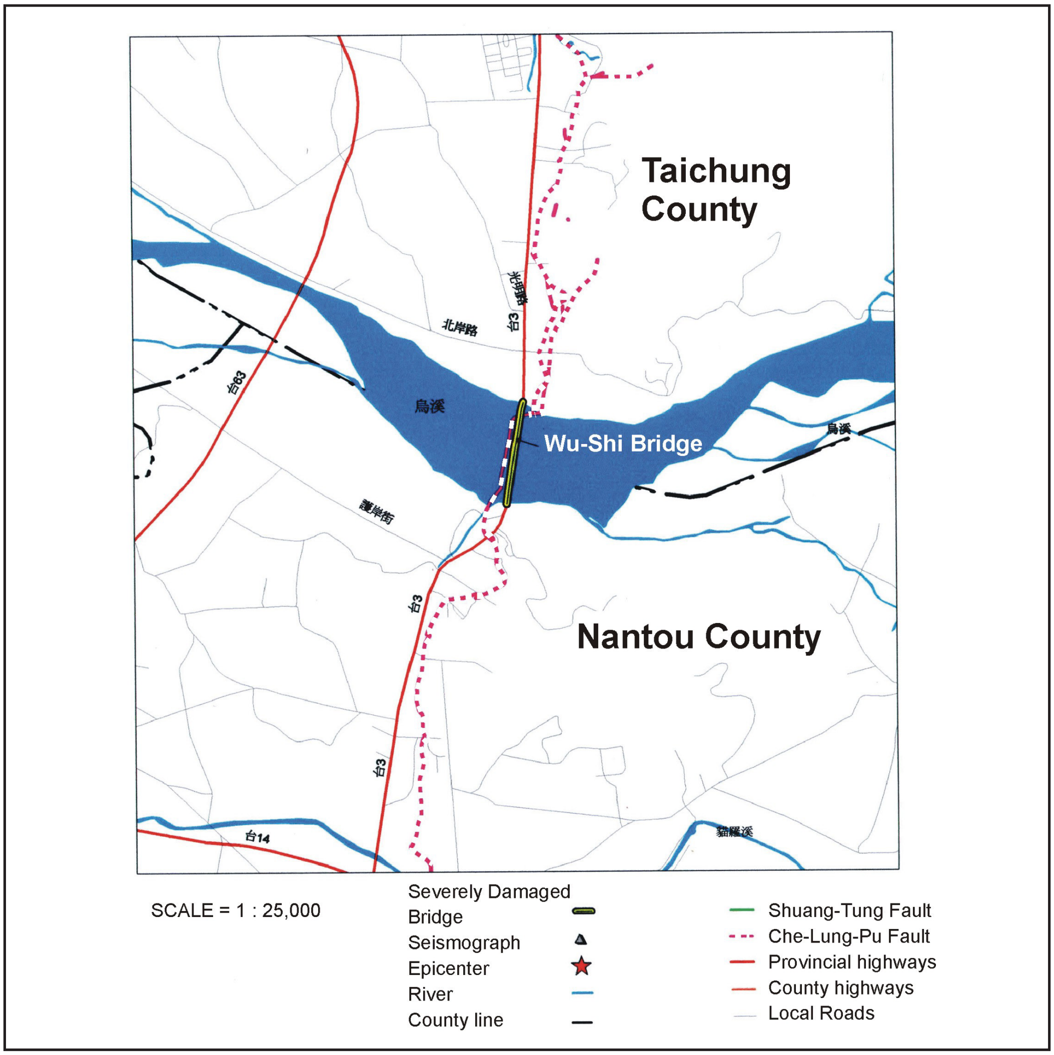

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Figure 6-10 Location of Wu-shi bridge

Photograph by Ian G. Buckle

Figure 6-11 Collapsed span in the Wu-shi bridge (east)

In addition to the ground failure, there was strong ground shaking transverse to both bridges, which caused massive shear failures in the first five piers and/or caissons of the second bridge (Figure 6-12). This did not happen in the first bridge, possibly due to the greater shear capacity of its wider columns. Instead, the first two spans of this bridge became unseated at Piers 1 and 2, due to the movement of these piers towards the river. Lesser soil deformations were experienced at the remaining piers and these were accommodated at the pier caps without unseating. But the shear keys at these caps were heavily damaged due to the transverse motion, and at Pier 2 they failed completely (Figure 6-13). As a consequence, although the superstructure was not unseated at this pier, it came to rest with a permanent transverse offset and with the outside girder overhanging the pier cap. In the second bridge, the longitudinal movement of the foundations under Piers 1 and 2 did not lead to span collapses. Instead, this movement was accommodated within the plane of the massive shear cracks in both piers. Examination of these cracks showed longitudinal offsets of about 0.15 m (in addition to large vertical and transverse offsets), which was sufficient to allow the girders to remain on their seats.

Photograph by Ian G. Buckle

Figure 6-12 Shear failures in the columns and caissons of the Wu-shi bridge (west)

Photograph by Ian G. Buckle

Figure 6-13 Diaphragm and shear key failures at Pier 2 of the Wu-shi bridge (east)

6.1.5 E-jian Bridge

Constructed in 1972, the *E-jian bridge* on Route 129 has 24, 11 m spans providing a total length of 264 m. The superstructure comprises a pair of simply supported, reinforced concrete, double-T girders. Each pier is an unreinforced concrete wall on a spread footing. The structure was being widened at the time of the earthquake and new piers had been constructed, but at a different spacing than for the original bridge. During the earthquake, fault rupturing occurred under the north abutment with about 1.5 to 2 m of uplift (Figure 6-14). Consequently, twelve spans collapsed from the northern abutment to the center pier of the bridge (Figure 6-15). The remaining twelve spans to the south abutment remained standing with little apparent damage. Examination of the collapsed girders showed little distress and the field evidence suggests that collapse was due to large movements of the pier foundations towards the center of the river channel. At or near the abutment, where uplift occurred, these unreinforced piers were crushed, or snapped at mid height, but the remaining piers moved as rigid bodies towards the river or rotated with their footings due to slumping

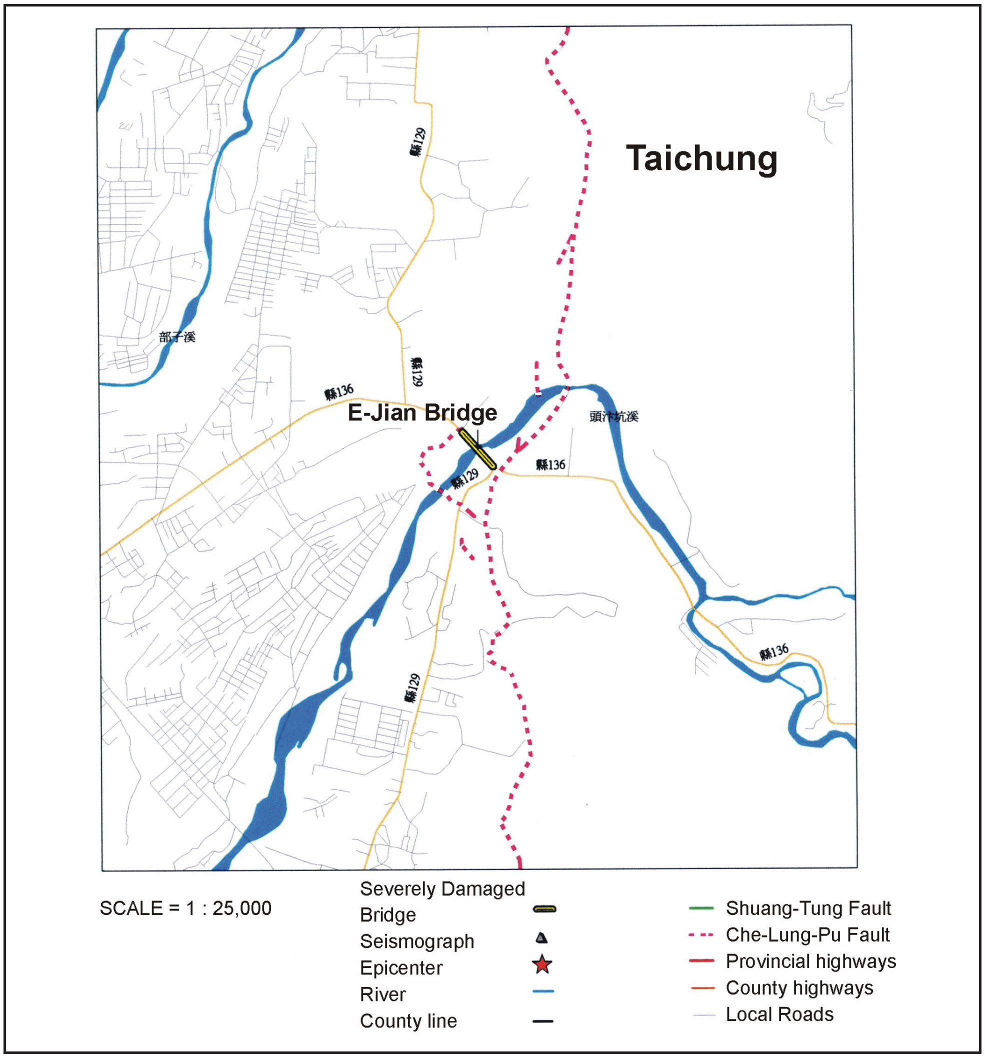

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Figure 6-14 Location of E-jian bridge

Photograph by Ian G. Buckle

Figure 6-15 Collapsed spans of the E-jian bridge due to massive ground movement towards the river (left)

and flow of the uplifted material (Figure 6-16). In doing so, the piers were driven in under the adjacent 'downhill' span while unseating the adjacent 'uphill' span. Corresponding overhangs of the superstructure girders occurred, which at Pier 9 measured 3 m. There is little evidence of residual displacements in the southern half of the bridge (which remains standing), and this appears to confirm the scenario that the collapses were due to gross movements of the northern foundations rather than unseating due to structural vibration. The extent of these movements appears to have been of the order of 5 m near the abutment, decreasing to about 3 m near the river channel.

Photograph by Ian G. Buckle

Figure 6-16 Tilting of Pier 10 of the E-jian bridge due to ground movement towards the river (left)

6.1.6 *Tong-fong Bridge*

The 22-span *Tong-fong bridge* on Route 3 was originally constructed in 1962 and widened in 1988. It is in fact three parallel bridges, each of total length 572 m. The spans are simply supported reinforced concrete girders resting on bearings at each pier cap. During the earthquake, the bearings at Piers 1 and 2 were dislodged due to strong transverse motion, and significant shear cracking and spalling occurred in Pier 5 of the downstream bridge. Within 13 days of the event, the bearings had been replaced with elastomeric bearings and the bridge reopened to traffic. This bridge is expected to be replaced.

6.1.7 *Shi-wei Bridge*

The *Shi-wei bridge* on Route 3 was reconstructed in 1994 as a pair of 3-span bridges on single column bents. Each span is 25 m long and comprises five simply supported prestressed concrete girders and deck slab. Each is supported on elastomeric pads with shear keys for transverse restraint. Due to the fault crossing through the northern end of the bridge (Figure 6-17), two spans in one bridge and one span in the second bridge collapsed when the

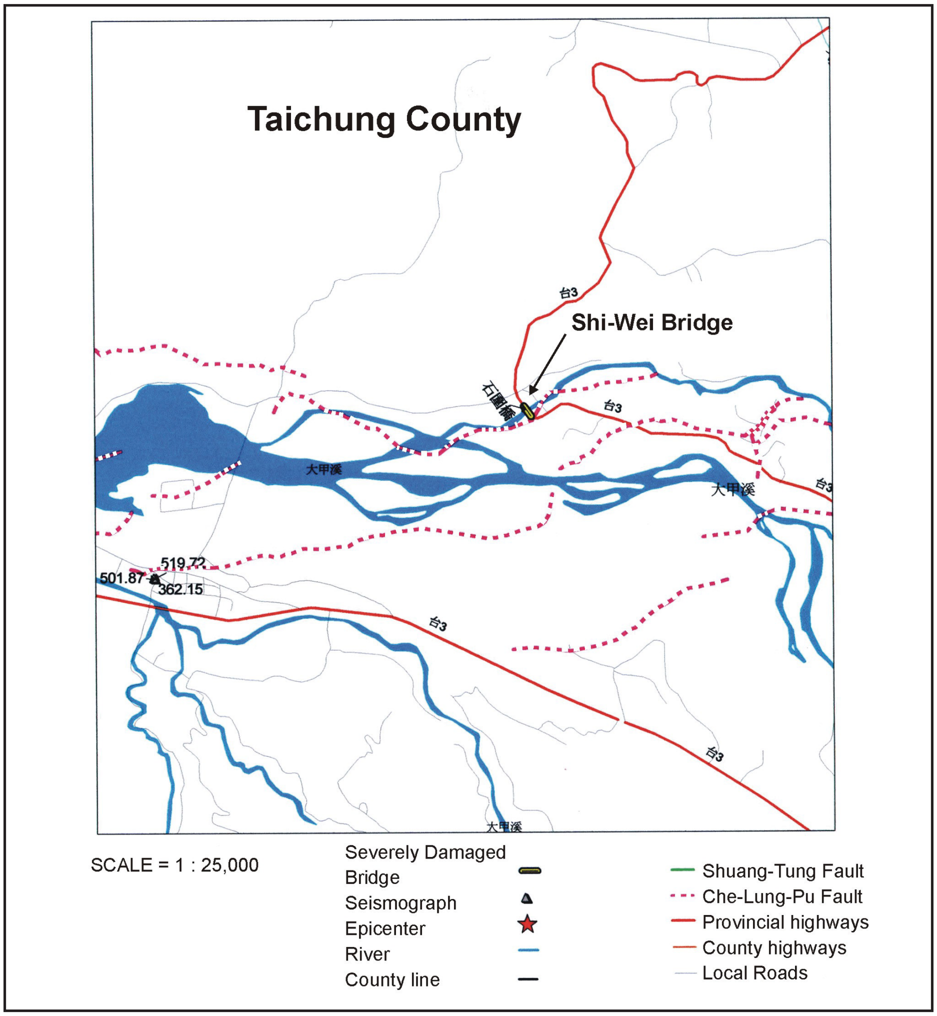

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Figure 6-17 Location of the Shi-wei bridge

second pier (column and caisson) in both bridges tilted away from the abutment by approximately 10 to 15 degrees (Figure 6-18). There was no sign of abrasion on the vertical faces of either column to indicate sliding of the span down the face of the column. It therefore appears that titling happened first, followed by the 'free' fall of the end spans. The reason for the collapse of the middle span of the second bridge is not so clear, but it may have been due to the skewed nature of this span (Figure 6-19). Since the bridge is curved, there are angle changes between the straight girders in adjacent spans at common piers and thus the middle span, of both bridges, has skewed supports. Such spans are known to exhibit excessive in-plane displacements due to rigid body rotations of the spans about a vertical axis during strong earthquakes. Unless generous seat widths are provided, collapse is likely. The fact that the middle span of the second bridge did not collapse may have been because it is on the 'inside' of the curve with shorter girders, and the displacements due to skew would not have been as large.

Photograph by Ian G. Buckle

Figure 6-18 Collapse of the middle span of the Shi-wei bridge and tilting of Pier 2 (right); span to the right has also collapsed

Photograph by Ian G. Buckle

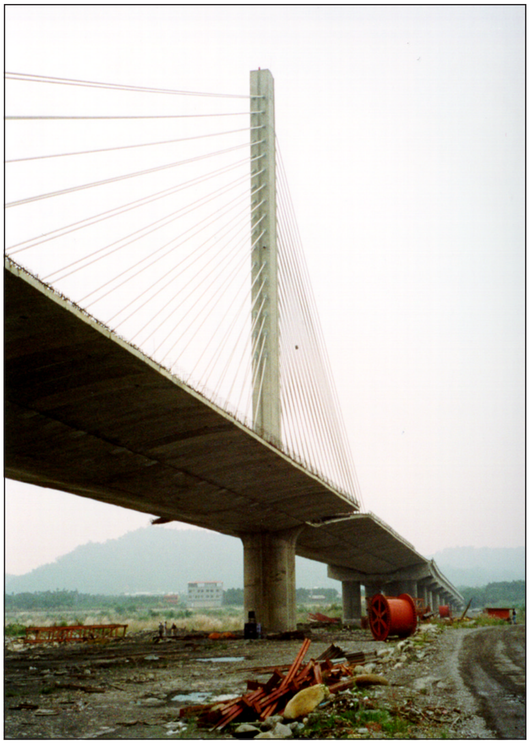
Figure 6-19 Shi-wei bridge showing curvature and skewed alignment of superstructure girders

6.1.8 Ji-lu Bridge

The *Ji-lu bridge* is a cable-stayed bridge under construction across the Chu-shui Hsi, one of the largest rivers in Taiwan (Figure 6-20). Simply supported approach spans at both ends lead up to the two-span, single-tower structure that is approximately 240 m long. The concrete superstructure is symmetrically supported by 17 pairs of parallel cables from each side of the tower.

The structure was virtually complete at the time of the earthquake; only the guardrails and a section of the superstructure remained to be completed. During construction, a gap had been created in the superstructure at the base of the tower to accommodate the construction crane. But although the crane had been dismantled, the gap had not been filled at the time of the earthquake.

Damage to the structure included a fractured cable, flexural and torsional cracking at the base of the tower and in the superstructure, and vertical and lateral pounding of the superstructure into the 'abutment' substructures (Figures 6-21, 6-22, and 6-23). These substructures provide the transition between the cable-stayed spans and the approach spans and consist of two-column bents with a cap beam. It is not clear why this structure should suffer such distress, but the missing section of the superstructure (Figure 6-22) and the loss of one cable would lead to unbalanced loads and reduced stiffness, which in turn would generate asymmetric response and potentially large excursions of the girder in both torsion and in-plane flexure. Furthermore, the severity of the ground motions, particularly in the vertical direction, could have been responsible for the vertical pounding at the abutments, as evidenced by shear cracks in the abutment cap beams (Figure 6-23).



Photograph by Ian G. Buckle

Figure 6-20 Ji-lu cable-stayed bridge; empty cable socket visible mid-height of the tower

Photograph by Ian G. Buckle

Figure 6-21 Damage at bent cap of south abutment, Ji-lu bridge; bent cap wall has been knocked off

Photograph by Ian G. Buckle

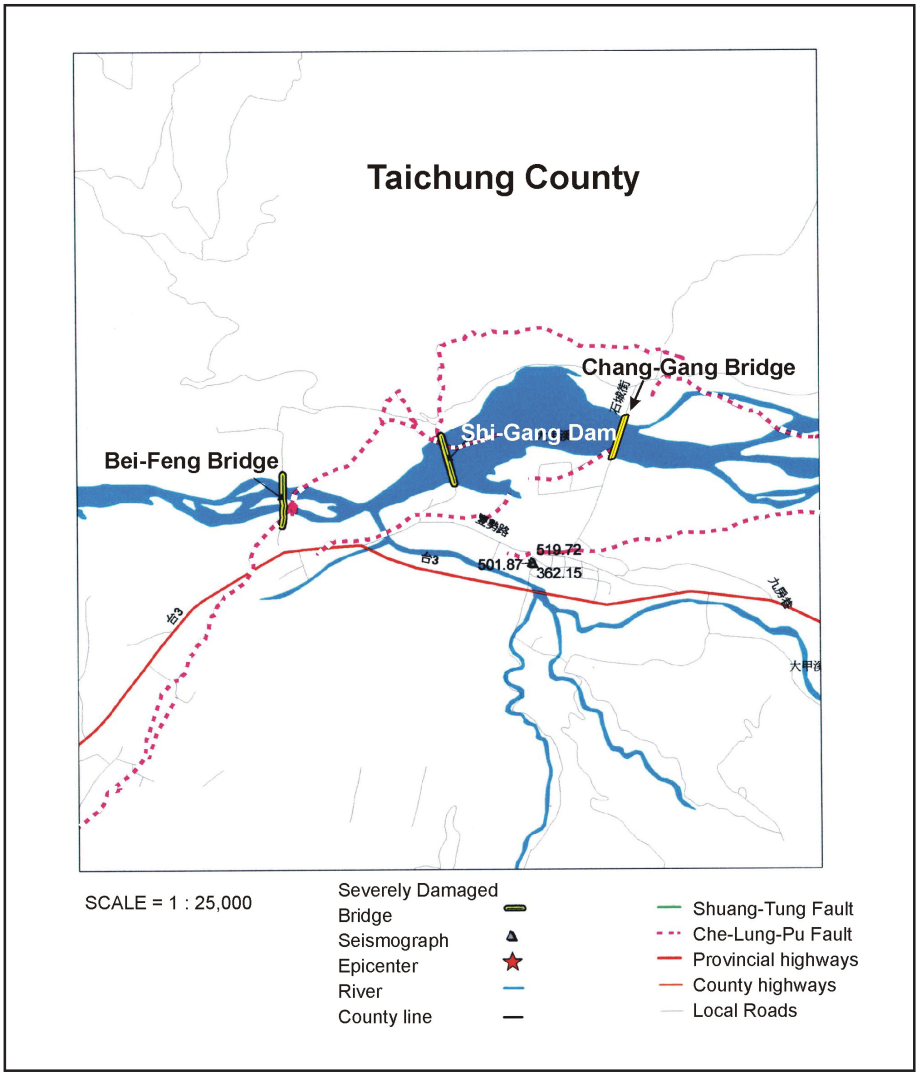
Figure 6-22 Damage to the soffit of the main girder near the pylon of the Ji-lu bridge; missing cantilevered section (right) had not been placed at time of the earthquake

Photograph by Ian G. Buckle

Figure 6-23 Pounding damage and shear cracks in the bent cap of the north abutment of the Ji-lu bridge

6.1.9 Bei-feng and Chang-gang Bridges

The *Bei-feng and Chang-gang bridges* are both located near the Shih-kang dam on the Tachia River (Figure 6-24). They are long, multiple span, simply supported bridges similar to those described above. Both suffered collapsed spans due to fault rupture at or near their abutments (Figures 6-25 and 6-26).



National Center for Research on Earthquake Engineering

Figure 6-24 Location of Bei-feng and Chang-gang bridges

Photograph by J. Shen

Figure 6-25 Collapse of end spans of Bei-feng bridge due to abutment and bent failures triggered by fault dislocations. Vertical offset of fault is seen crossing the river immediately upstream.

Photograph by J. Shen

Figure 6-26 Collapse of span of Chang-gang bridge due to unseating of girders triggered by fault dislocations

6.2 Lessons Learned

The following is a preliminary set of lessons to be learned from this earthquake:

- Fault rupture, directly under or between bridge foundations, is a catastrophic event and span collapse is inevitable if the dislocations are large.
- Near-field ground motions are intense and extremely punishing on bridge structures, particularly older bridges that have not been designed to modern codes.
- Long-span bridges are vulnerable in near-field sites, especially those still under construction.
- Ground failures precipitate structural failures.
- Engineered abutment back-walls and back-fills are essential to prevent span collapses even for continuous bridges.
- Generous seat widths are excellent insurance against unintended actions such as ground failure and rotation in skewed spans.
- Shear failures must be avoided in piers.
- Engineered shear keys are required to prevent spans falling transversely from pier caps.
- Load paths through column-to-girder joints must be specifically detailed, particularly for eccentric connections.

6.3 Recovery Progress

Past earthquakes have shown that there at least three phases to recovery:

- Execution of urgent repairs and the construction of bypasses under emergency conditions (say the first 90 days).
- Replacement of crippled structures (say 3 to 12 months).
- Retrofit of existing bridges, and revision of design codes for new bridges, based on lessons learned (say 1 year onwards).

The first phase was well advanced in the Nantou and Taichung counties by the first week in October (two weeks after the earthquake). Bypasses had been constructed (Figure 6-15), shoring erected (Figures 6-8 and 6-9), Bailey bridges installed, overturned bearings reinstated, and settled approach fills repaved. Only about 45 km of highway remained closed at the beginning of October and these were mainly roads in the mountainous regions of the two counties where extensive landslides had yet to be cleared.

Progress in the second phase will be slower because it requires the design of replacement structures before the reasons for the damage are fully understood and agreed. Conservative designs are therefore expected in the interim, so as to minimize the risk of inadvertently constructing a new set of vulnerable structures. Design earthquakes are expected to be increased, seat widths made larger, shear keys strengthened for elastic response, shear and confining steel increased in columns, skew supports removed (or seat widths further increased to allow for skew), eccentric column to cross-girder connections eliminated, sacrificial spans installed in bridges that cross active faults, and site specific hazard analyses performed for critical bridges, including long-span bridges.

An emergency law was imposed by the Central Government in October so that related government agencies could take necessary measures for rapid recovery. But the speed of the recovery varied widely. For example, two bridges, the Long-men and Li-yu, were rebuilt and open to traffic eight months after the earthquake. But the reconstruction of many other collapsed bridges is only now getting underway (eleven months after the earthquake), despite the designs being completed at the same time as Long-men and Li-yu. These variations appear to reflect differences in policies and political priorities within local jurisdictions.

The Long-men Bridge (figure 6-27) is a 500 m long, 8.6 m wide bridge with 13 spans of PC box girders with reinforced concrete piers and pile foundations. The Li-yu Bridge is very similar, at 575 m long, 8.6 m wide, with 15 spans. Both bridges were opened to traffic on 5/31/2000, after 123 days and 131 days, respectively, total construction time.

Photographs by K.C. Chang

Figure 6-27 Long-men Bridge after earthquake (left) and after reconstruction (right)

It is too early to estimate the implication of this experience on Taiwan's retrofitting program for existing bridges, and its design code for new bridges (the third phase). However, the lessons learned are expected to significantly affect both of these activities, not only in Taiwan, but also in seismically active regions through out the world.

6.4 References

Chang, et al., (1999), *The Comprehensive Reconnaissance Report of the 921 Chi-Chi Earthquake: Bridges*, National Center for Research on Earthquake Engineering, December (in Chinese).

The authors wish to acknowledge the generous assistance provided by the Highway Bureau of the Ministry of Transportation and Communications, to this reconnaissance effort. Specifically, the assistance of Mr James Yeh, Deputy Director General, and Mr Wei Wu, Deputy Chief Engineer for Central Taiwan, is gratefully acknowledged.

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Section 7
Lifeline Damage: Electric Power Systems

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The Chi-Chi earthquake severely impacted Taiwan Power company's ability to transmit and distribute electric power to its customers. The authors visited Taiwan Power Company on October 4 (3:30-5:00 p.m.) where Mr. Sheng-Nan Lin, Chief Engineer, and his staff briefed us on the state of damage, repair and restoration of the system. The highlights of the briefing are provided below, followed by the authors' interpretations, observations and tentative recommendations for short-term actions.

7.1 Overview of Damage to Electric Power Systems

Regarding the 345 Kv transmission system, a significant number of transmission towers suffered from structural problems, and were tilted and displaced (Figure 7-1) causing a large number of transmission lines to fail (marked with an X in Figure 7-2). This in turn caused the initial blackout throughout the middle and northern areas of Taiwan. In addition, 161 Kv (Figure 7-3) and 69 Kv transmission systems in the affected area also suffered from similar failures. Figure 7-4 shows a damaged transmission tower and Figure 7-5 shows a temporary tower standing next to one that was damaged.

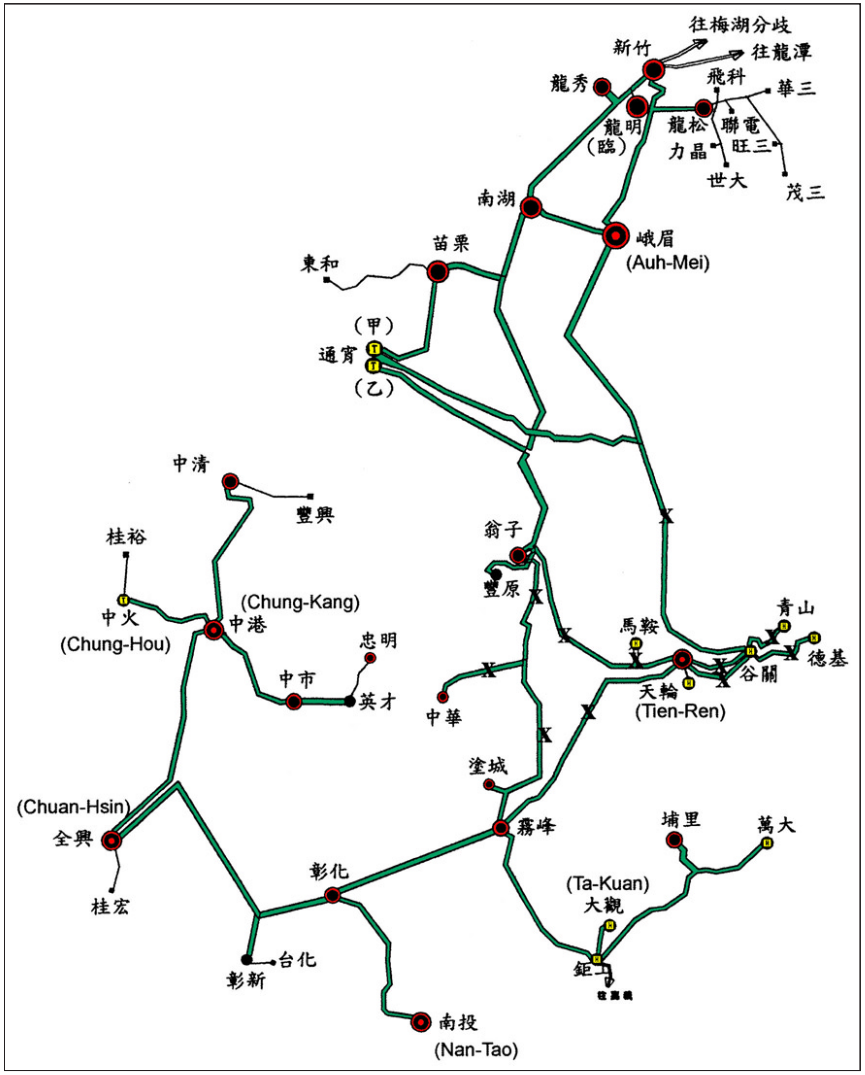
Some substations and switchyards were also damaged, although the impact of their damage on the entire power system was much less direct than the failure of transmission and distribution systems. A notable exception was the two switchyards at Chung-Liaw (the south

Photograph by G-Y. Liu

Figure 7-1 Transmission tower tilted and deformed

Courtesy of Taiwan Power

Figure 7-2 345 Kv electric power transmission system



Courtesy of Taiwan Power

Figure 7-3 161 Kv electric power transmission system

Photograph by G-Y. Liu

Figure 7-4 Transmission tower with top portion collapsed

Photograph by G-Y. Liu

Figure 7-5 Failed transmission tower replaced by a temporary tower

Table 7-1 Damage sustained by electric power facilities

Facility	Number
Hydro Power Stations	7
Thermal Power Stations	2
Transformer Stations	
1. 345 Kv	5
2. 161 Kv	6
3. 69 Kv	13
Transmission Lines	
1. Major Switchyard	1
2. Circuits	
345 Kv	28
161 Kv	30
69 Kv	21
3. Towers	
345 Kv	355
161 Kv	155
69 Kv	83
Distribution Lines	
1. Power Poles	
Broken	678
Fallen	773
Tilted	2,571
2. HV Switches	164
Underground Switches	44
3. Main Line Breakage	4,560
Customer Line Breakage	20,108
HV Cable Breakage	32,957/m
4. Pole-mounted Transformers	1,039
Box Transformers	93
Station Transformers	15
Underground Distribution Room (Flooded)	7
Office Buildings	30
Death Tolls	2
Water Supply	
Checker Dam	1
Purification Plants	30
Service Offices	12
Affected Customers	360,000

Shih, 1999

yard and the north yard) that were both significantly damaged. Figures 7-6 and 7-7 show some of the damage observed at the Chung-Liaw switchyard. Figure 7-8 shows similar damage at Tien-Lui substation between Chung-Liaw and Lung-Tan (see Figure 7-1). In fact, the loss of 53 potential transformers, 46 lightening arresters, and many bushings on buses, in addition to other equipment, rendered the yards inoperational. The functionality of these two yards is pivotal to power transmission in Taiwan, as can be seen from Figure 7-1, and hence the functional loss of these yards was at least partially responsible for the post-earthquake power interruption. Table 7-1 shows a summary of damage sustained by Taiwan Power's systems and facilities (Shih, 1999). Table 7-2 further breaks down the transmission tower failure to different modes (Shih, 1999).

Table 7-2 Failure of transmission towers

	Collapsed	Tilted	Deformed	Foundation Failure	Foundation Displacement	Total
345 Kv	1	9	55	271	19	355
161 Kv	9	4	9	131	4	155
69 Kv	3	16	3	64	2	83

Shih, 1999

As for repair and restoration, effort was made to transmit power from southern Taiwan to the north, which is highly dependent on the power generated in the south and elsewhere. This was done first by systematically completing emergency repair of transmission/distribution lines, substations and generating stations that were initially damaged, and then transmitting the power by bypassing the Chung-Liaw switchyards. The rationing of electric power to industry customers was lifted at the time of this writing (October 5, 1999) and it is expected that restrictions imposed on residential customers will also be lifted on October 10, 1999, a few days earlier than targeted. Construction of the third 345 Kv transmission line between Chung-Kang and Auh-Mei may be accelerated due to the government emergency decree that resulted from this earthquake. However, it was reported that other options are also under consideration by Taiwan Power, for example, to construct additional power generating plants serving primarily regional areas, which may provide a socio-economically more viable solution to the need of enhancing its network reliability and redundancy.

7.2 Recommendations for Short-Term Recovery

The following observations and tentative recommendations seem to be in order for short-term actions:

1. A large number of transmission tower failures were apparently due to the fact that they are constructed, obviously by necessity, over rugged mountainous areas with steep slopes susceptible to ground failure. It might be well advised to design, construct, and retrofit tower foundations with this in mind.

Photograph by G-Y. Liu

Figure 7-6 Damage at Chung-Liaw switchyard

Photograph by G-Y. Liu

Figure 7-7 Failure of 345 Kv gas insulated line due to liquefaction induced settlement

Photograph by G-Y. Liu

Figure 7-8 Damage at Tien-lun substation

2. Enhanced measures of seismic protection, including base isolation, for generating plant equipment, switchyards and substations appear to be equally important.

3. A systems analysis capability should be developed for both pre-event estimation of seismic reliability of transmission and distribution networks, and socioeconomic decision support to optimize post-event recovery and restoration processes.

While item 1 above would be an interesting joint project for the immediate future, the current MCEER-NCREE collaborative research is already addressing items 2 and 3.

7.3 References

Shih, Ban-Jwu, Editor, (1999), *The Comprehensive Reconnaissance Report of the 921 Chi-Chi Earthquake - Lifeline Systems*, National Center for Research on Earthquake Engineering.

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Contents

Section 8
Applications of Remote Sensing

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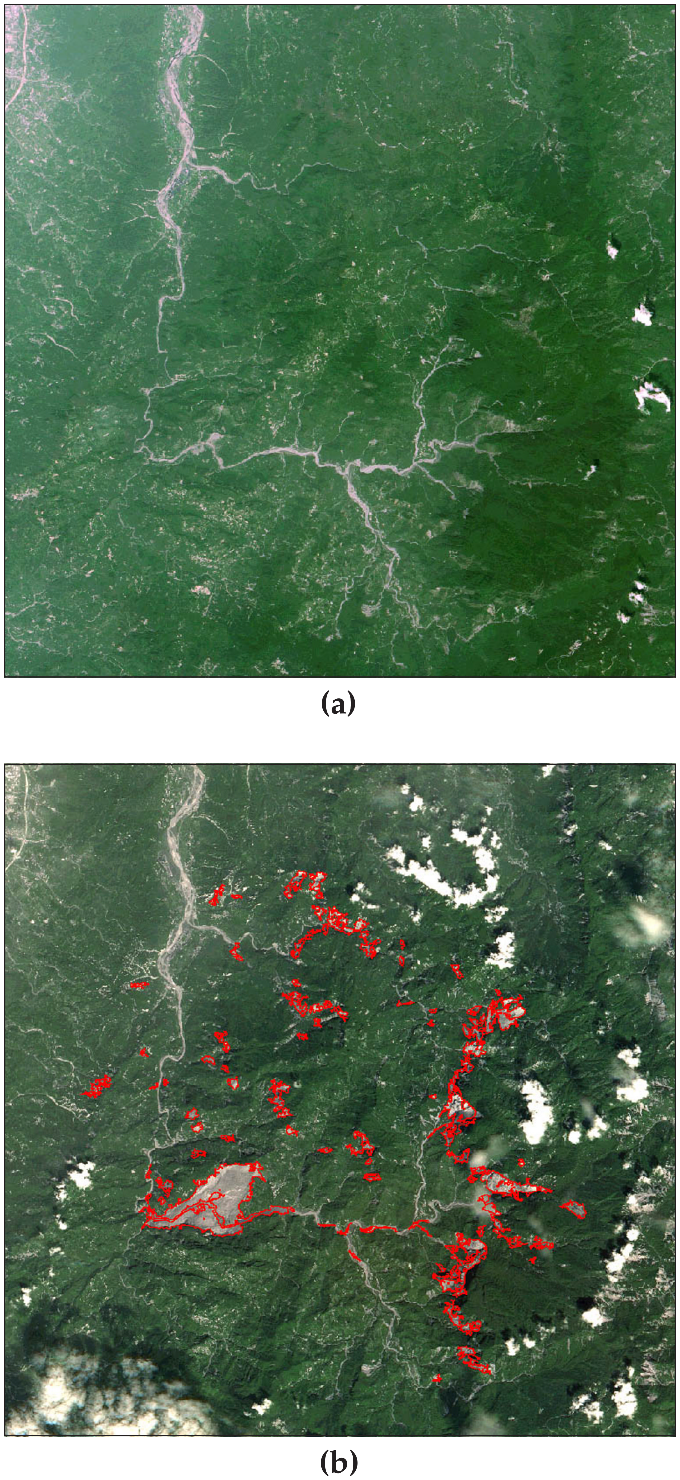
Applications of remote sensing for assessing the impact of earthquakes on the natural and built environment are a recent innovation, and it is useful, particularly when combined with geographical information systems (GIS). The MCEER-NCREE team, accompanied by Dr. C.P. Weng of National Science Council, visited the Center for Space and Remote Sensing Research at the National Central University in Chung-Li on October 4, 1999, where Professor G. Liu, the Center Director, and Professor A.J. Chen, Principal Investigator of Ground Receiving Station funded by National Science Council, briefed and provided the team with the following items:

1. Hard copies of the ortho-rectified and coregistered SPOT images with resolution of 6.25 m before and after the earthquake (April 1 and September 27, 1999, respectively) over a band of the affected area.

2. Images of a 25 km x 25 km area 50 km south of Taichung (distance approximate) including Tsao-Lin before and after (Figure 8-1) the earthquake (April 9 and September 27, 1999, respectively). The image after the event identifies locations and sizes of landslides by making use of NDVI (Normalized Difference in Vegetation Index). Figure 8-1b clearly shows the landslide locations caused by the earthquake. Three-dimensional images of a smaller area were constructed before and after (Figure 8-2) the event (March 6 and September 27, 1999, respectively), utilizing an existing topographical map together with SPOT images.

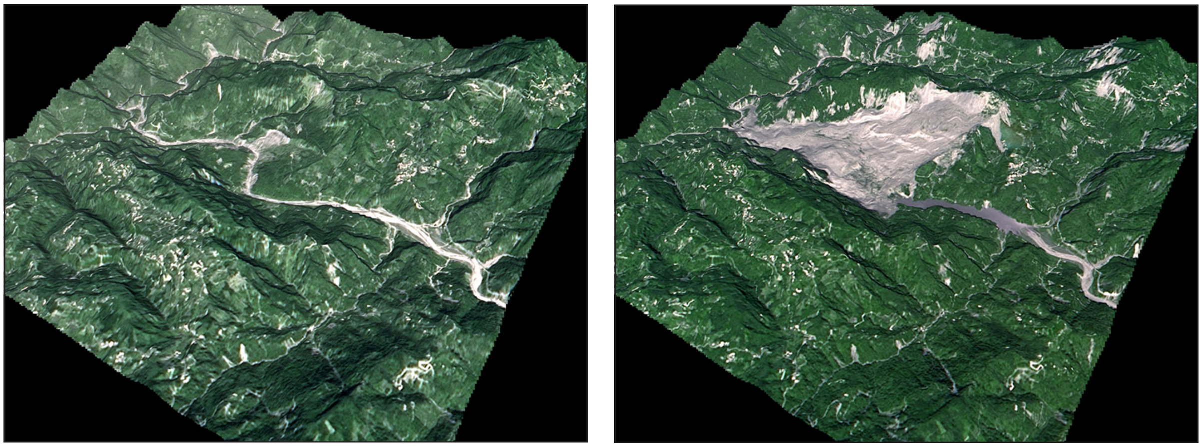


(a)

(b)

Center for Space and Remote Sensing Research,
National Central University

Figure 8-1 SPOT image of a 25 km x 25 km area 50 km south of Tai-Chung (a) before the event (distance approximate); (b) landslide areas identified after the event



(a) (b)

Center for Space and Remote Sensing Research, National Central University

Figure 8-2 3-D images of a landslide area near Tsao-Lin before (a) and after (b) the event

Enlarged SPOT images at the site of failure of the Shih-kang dam after and before the event are shown in 8-3a and b, respectively. In the center of Figure 8-3a, the bottom of the man-made lake behind the Shih-kang dam is shown exposed due to the discharge of water from the lake through the water gates damaged by the earthquake, while the lake bed was covered by water before the earthquake as shown in Figure 8-3b.

The MCEER-NCREE team also visited the Office of the National Science & Technology Program for Hazard Mitigation on October 6, 1999 and met with Professor C. L. Yen, Program Director and Professor C. H. Sun, Group Leader of Information Systems, who briefed the team on their effort in supporting the search and rescue as well as emergency response activities. The effort consisted of utilizing their GPS-compatible GIS capability visualizing the seismic damage experienced in each focused area. This capability made it possible for Professor Yen's office to produce the map in Figure 8-4, where a GIS map combined with post-earthquake aerial photos of the damaged buildings is shown. This is an important capability to efficiently provide the near ground truth verification needed under emergency conditions in near real-time. The same capability also makes it possible to fuse GIS and aerial photos to make the needed geographical information more complete with the aerial photos provided by the Council of Agriculture, Taiwan.

(a)

(b)

Center for Space and Remote Sensing Research,
National Central University

Figure 8-3 Images of Shih-kang Dam area after (a) and before (b) the event

災情彙整管理決策支援系統(四)

圖四：台中縣大里市

National Science and Technology Program for Hazards Mitigation

Figure 8-4 GIS map and aerial photos.

8.1 Recommendations for Short-Term Recovery

The following recommendations are made relevant to short-term actions for recovery and restoration:

1. Stereoscopic aerial photos taken by the Council of Agriculture should be acquired throughout the affected area in order to establish the near ground truth before demolishing or restoring damaged structures.

2. Before and after SAR images from ERS Satellite should be obtained from the Center for Space and Remote Sensing Research for severely damaged areas to validate their usefulness for the analysis pertinent to the earthquake disaster assessment.

3. Most importantly, collaborative research to enhance the present state-of-the-art of HAZ Taiwan should be initiated between MCEER-NCREE as a joint effort with Dr. Chen's and Dr. Yen's programs. MCEER has a long history of cutting edge research on and implementation of pre-event damage assessment and post-event response, recovery and restoration. In particular, use of advanced technologies such as GIS, GPS, and satellite/airborne optical and SAR imagery, has been extensively studied at MCEER in the context of earthquake disaster mitigation. The proposed collaborative effort will establish a milestone in directing the traditional earthquake engineering into the age of the new millennium.

Section 9
Economic Impacts[1]

Stephanie E. Chang
University of Washington

From the standpoint of economic impacts, the Chi-Chi earthquake can be considered a major natural disaster. The earthquake not only caused serious loss to the economy of central Taiwan, but had measurable national repercussions as well. Physical damage from the earthquake has been estimated at some US $14 billion (NT $449 billion). Taiwan had not experienced a disaster of this scale in recent memory.

Damage was concentrated in Taichung city and Nantou and Taichung counties in central Taiwan. This region accounts for close to 3 million people, or some 13 percent of Taiwan's population. It spans urban areas as well as remote mountainous regions and numerous rural towns. Major industries in this area, such as agriculture and tourism, and to a lesser extent manufacturing, suffered significant damage. The destruction of housing stock and large displacement of population has also hindered economic recovery. In addition to property loss, deaths and injuries, over 100,000 people were displaced from their homes (Figure 9-1).

Photograph by S. Chang

Figure 9-1 Roadside tents provide temporary shelter in Chusan, Nantou county

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[1] This report is based primarily on information gathered in the first 2 months after the earthquake. An exchange rate of US $1=NT $32 was used to convert those figures that were not originally reported in U.S. dollars.

Power outage lasting for 1-2 weeks affected a much broader area, including not only most of central Taiwan but also the northern region of the island, where Taipei city and much of the country's industrial activity are located. Power outage caused substantial disruption to the key electronics and high-tech manufacturing sectors, but much of the immediate production losses were able to be made up through overtime work. Table 9-1 provides an overview of earthquake losses for some of the more heavily hit industries in Taiwan.

Table 9-1 Loss to industrial sectors from the Chi-Chi earthquake[(a)]

Sector	Preliminary Loss Assessment
Textiles Manufacturing	Facilities mostly concentrated in Taipei, Taoyuan (in the north), and the southern region of Taiwan. Damage was mostly caused by stoppage of electricity, especially in the central region in factories which produced synthetic fabrics. Some other textile factories had backup electricity and so were not seriously affected.
Machinery Manufacturing	50% of facilities found in central region. Considerable damage.
Electronic Parts Manufacturing	Chip companies suffered considerable loss caused mostly by stoppage of electricity and the time required to recalibrate machinery that had been shifted. On average, each company lost 5-7 days' worth of production value.
Restaurants and Tourism	Business negatively impacted; loss was greatest for the tourist sites and hotel industry in the central region.
Banking	Loss had mostly to do with bank facilities and with loans on houses that collapsed. In the future, the proportion of bad loans will increase.
Insurance	Payouts will increase, but the industry had reinsured to manage risk; therefore, loss was not great overall.

Note: (a) Abstracted and translated from ITIS (1999) report dated 9/30/99.

The earthquake curtailed the growth rate of Gross Domestic Product (GDP) in 1999 by about 0.2 to 0.5 percent, but losses appear to be limited to the short-term. Losses in September were to some extent made up by extra production in October. Stimulus from reconstruction activity is anticipated in 2000. However, while losses to the overall national economy lasted about one month, the heavily impacted region and certain local industries will likely require several months or even years to recover.

Subsequent sections of this chapter discuss in detail damage estimates, regional economic impact, national economic impact, and reconstruction finance. The chapter concludes with a summary of observations and recommendations.

9.1 Damage Estimates

As of one month after the earthquake, over 57,000 homes in 56 towns and cities had been certified as completely or partially destroyed (China News, 10/17/99). This represents about 8 percent of total homes in the disaster region.[2] Note that these figures pertain to

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[2] Based on number of households in Taichung city and Taichung and Nantou counties, as reported in the 1995 Census (DGBAS, 1996). These areas accounted for over 90 percent of the housing damage.

housing units rather than buildings, which may contain multiple units. Of these damaged homes, some 55 percent were "completely" and 45 percent "partially" destroyed. These assignments are linked to disaster assistance eligibility (see below) and appear to have been made by local government representatives, rather than engineers. As a result, they may or may not provide an accurate assessment of damage.

Loss estimates varied widely in the weeks following the disaster. As shown in Table 9-2, early estimates ranged from NT $100 billion to NT $1 trillion, and reports were often ambiguous as to whether these figures pertained to property loss only or also included business interruption loss to damaged and undamaged firms. As more complete information became available, estimates stabilized and became more specific and detailed. The most recent estimate puts property loss at US $14 billion (NT $449 billion).[3] This is equivalent to 5 percent of Taiwan's gross domestic product (GDP).

Table 9-2 Loss estimates by source and date[(a)]

Source	Date of Estimate	Loss Estimate (US$ billion)	Loss Estimate (NT$ billion)	Notes
KMT Party	9/21/99	3.1	100	
Taiwan Institute for Economic Research (TIER)	9/27/99	31.3	1,000	includes production loss
Institute of Economics at Academia Sinica [(b)]	10/5/99	7.8	250	includes indirect loss
Directorate General for Budget, Accounting and Statistics (DGBAS)	10/14/99	9.1	292	
National Government	10/28/99	14.0	449	

Notes:
(a) As reported in China News issue from date of estimate, except where noted
(b) Chien, 1999

With reference to an earlier estimate of US $9.1 billion (NT $292 billion), the government reported that roughly 70 percent consisted of building-related damage while the remainder pertained to industrial, agricultural, and transportation damage. Another report had placed repair cost to transportation and communications infrastructure at about US $319 million (NT $10 billion), roughly half of which pertained to rebuilding the Central Cross-Island Highway (The Taiwan Economic News, 9/30/99). Overall, damage to highways was estimated at US $269 million (NT $8.6 billion), to railways at US $10 million (NT $320 million), and to Taichung harbor at US $39 million (NT $1.25 billion).

9.2 Regional Economic Impact

9.2.1 Economy of the Disaster Region

The disaster-impacted region spans both urban and rural, mountainous areas in central Taiwan. The vast majority of the damage and casualties occurred in Nantou county,

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[3] More recent estimates put the losses variously at US $11.5 billion (Goltz et al., forthcoming) in terms of direct and indirect losses, and US $10.7 billion (Shaw, 2000) in terms of direct property loss.

Taichung county, and Taichung city (Table 9-3), which are collectively referred to here as the "disaster region." Fatalities and structural collapses did, however, occur as far away as Taipei city. The disaster region includes 2.7 million people, or 13 percent of Taiwan's population. Within this region, the Taichung metropolitan area has been growing rapidly in population in the last several years while rural Nantou county has been declining in relative terms.

The structure of the economy also varies substantially within the disaster region. Table 9-4 indicates employment for selected sectors in the disaster region and Taiwan as a whole. The economy of Taichung city is quite diversified in trade and services, while Taichung county contains many small and medium-sized manufacturing firms. In Nantou county, agriculture (especially tea cultivation) and tourism are the major industries.

Table 9-3 Population and loss for disaster region

Region	Population in 1995[a]	Annual Pop. Growth Rate, 1990-1995[a]	Deaths in the 921 Earthquake [b]	Multi-family Buildings Destroyed[b]
Taiwan	20,788,000	10.0%	2,405	26,831
Disaster Region	2,744,000	--	2,172	26,344
Nantou County	524,000	5.3%	889	19,320
Taichung County	1,378,000	23.3%	1,170	6,528
Taichung City	842,000	22.7%	113	496

Notes:
(a) 1995 Census (DGBAS, 1996)
(b) Ministry of the Interior (10/21/99), as cited in Goltz (1999)

Table 9-4 Sectoral employment in the disaster region[a]

Region	Total Employment (thousands)	% Reg. Empl. in Agriculture	% Reg. Empl. in Manufacturing	% Reg. Empl. in Trade
Taiwan	8,589	10%	29%	20%
Disaster Region	1,118	10%	29%	20%
Nantou County	210	26%	19%	18%
Taichung County	558	9%	37%	17%
Taichung City	350	3%	23%	27%

Note:
(a) Data from 1995 Census (DGBAS, 1996)

9.2.2 Losses to Agriculture

The agricultural sector sustained some important losses due in part to landslides as well as shaking, particularly to structures and infrastructure such as greenhouses, irrigation facilities, and roads (Figure 9-2). According to the Council of Agriculture, some US $44 million (NT $1.4 billion) in crop losses were incurred, including 14 percent of the disaster-impacted area's 21,000 hectares of tea crop (Liu, 1999). In the area around Luku village in Nantou county, as much as one-third of the tea farms were damaged. According to a field study by the Taiwan Institute of Economic Research, agricultural damage was concentrated in the epicentral region, particularly in areas with steep slopes (TIER, 1999). That study concluded that while agricultural production would be affected in the first six months after the earthquake, complete recovery could be expected within one to two years.

Photograph by S. Chang

Figure 9-2 Damaged farm structures outside Chusan, Nantou county

9.2.3 Losses to Tourism

Prior to the earthquake, Nantou county had been Taiwan's foremost destination for domestic tourism. Centered around Sun Moon Lake, this tourist area was well-known for beautiful scenery, resorts and other attractions. The earthquake caused severe damage to numerous tourism sites, hotels and access roads (China News, 10/31/99). All 18 hotels around Sun Moon Lake were damaged, four of them collapsing. Occupancy rates at local hotels fell to 30 percent or less after the earthquake. The Tourism Bureau of the Ministry of Transportation and Communications estimated damage to public tourism facilities throughout Taiwan at US $18.4 million (NT $589 million). Loss estimates from the Taipei Travel Industry Association were much higher: including damage to all tourist facilities as well as business interruption loss in the first month after the disaster, the tourism industry may have suffered US $281 million (NT $9 billion) in total losses. Moreover, the image of central Taiwan as a disaster region is also keeping many tourists away, even as facilities begin to reopen. Based on a field study, the Taiwan Institute of Economic Research suggested that the regional tourism industry would be severely affected for at least several months (TIER, 1999).

9.2.4 Losses to Regional Industry and Commerce

In the industrial and commercial sectors, it appears that overall, damage was limited and recovery could be essentially completed within one to two months. Most of the industrial damage occurred along the fault, rather than in the epicentral region (TIER, 1999). Damage to factories was for the most part minor, although there was more damage to commercial structures (Figure 9-3). According to the TIER report, industrial production losses were largely caused by disruption of water and electric power service, but surveys by the Ministry of Economic Affairs (MOEA) did find significant damage to localized industry (MOEA, 1999; China News, 10/20/99). The earthquake damaged facilities in several government-administered industrial parks in central Taiwan. About one quarter of companies in the major industrial parks sustained serious damage, with small and medium-size businesses producing metal products, machinery, and plastic goods being hit the hardest. One survey found that about 40 percent of manufacturers in Taichung and Nantou counties suffered some degree of loss.

Photograph by S. Chang

Figure 9-3 Structural collapse destroying ground-floor store in Ji-Ji, Nantou county

Local manufacturing, for the most part, recovered within one month. The MOEA survey of Taichung and Nantou counties found that 83 percent of manufacturers had resumed some level of production within two weeks, and 97 percent within a month. On average, manufacturers resumed normal levels of operation in about 24 days. Recovery was faster in Taichung and Nantou cities, where industrial production returned to normal within about three weeks of the disaster. Even in most of the more severely damaged towns, some 95 percent of production capacity had been regained within this time frame. However, in the Chusan and Nankang areas in Nantou county, recovery was estimated at only 80 percent. The TIER study similarly found that production had recovered to 90 percent of normal levels by mid-October (TIER, 1999).

Although regional manufacturing was able to recover quite rapidly, industries such as retail trade and services which depend upon regional demand are likely to suffer losses for a longer period of time. Their recovery will be aided by the inflow of disaster assistance to the region in the coming months, but it is nonetheless constrained by the disruption of activity in agriculture and tourism and the consequent effects on local incomes and consumption.

9.3 Impact on National Economy

9.3.1 Electric Power Outage and High-Tech Industries

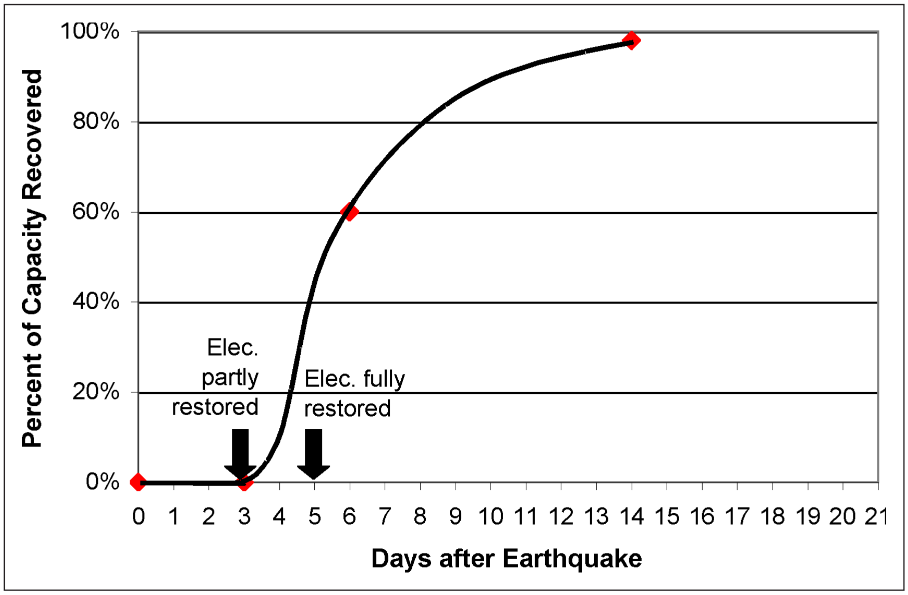
One of the most significant economic issues arising from the disaster has been the impact of electric power outage on high-tech industries associated with the Hsinchu Science and Industrial Park in northwestern Taiwan, often referred to as the country's "Silicon Valley." Taiwan is the fourth largest supplier of semiconductors in the world, accounting for 12 percent of world production and providing components for many large computer manufacturers in the U.S. It is also the world's leading producer of laptop computers. The electronics industry, including semiconductors, makes up one-third of Taiwan's exports, and exports are a main driver of the national economy.

Power outage caused approximately 10 days' worth of production stoppage at Hsinchu and other industrial parks. This outage would have been longer had Taipower not instituted power rationing schemes that gave priority to the industrial park at Hsinchu, along with hospitals and other critical facilities (see Section 7).

Speculation of ensuing computer components shortages caused global prices for some types of computer chips to escalate after the disaster. Some overseas companies dependent upon supplies from Taiwan, such as Hewlett-Packard, Apple, Compaq, and Dell, announced minor revenue impacts due to the earthquake. However, the credibility of such claims has been questioned by industry analysts who attributed the shortfalls to problems unrelated to the earthquake (Arnold, 1999).

Industrial park management at Hsinchu estimated that the earthquake caused up to US $313 million (NT $10 billion) in losses at the park, including equipment damage, loss of work in progress, and productivity reduction (Engbarth, 1999). Acer Inc., an important supplier to IBM, reported that the earthquake might cause it to miss fourth-quarter 1999 shipments of laptop computers by some 10 percent (Flannery, 1999). The two largest chip producers, Taiwan Semiconductor Manufacturing Company (TSMC) and United Microelectronics (UMC) Group, reported that revenues in September dropped 13 percent from August. While TSMC's initial loss estimates had been much higher, it later revised them downward since the power outage was shorter than had been anticipated (Bickers, 1999). Most of the loss was covered by insurance.

The electronics and high-tech manufacturers demonstrated considerable resiliency in the disaster, making use of generators during electricity rationing periods and working considerable overtime, including over a holiday. Recovery was aided by continuing high global demand for their products. TSMC was able to start some production by the third day after the earthquake (Bickers, 1999). Power was fully restored on the fifth day and recovery was essentially complete within two weeks. Figure 9-4 shows an approximate restoration curve for the semiconductor producer. In the end, TSMC reportedly missed less than one percent of its September orders (Arnold, 1999).



Based on data from Bickers (1999) and Huang and Kuo (1999)

Figure 9-4 Inferred restoration curve for Taiwan Semiconductor Manufacturing Co. (TSMC)

9.3.2 Effect on GDP, Employment and Other Macroeconomic Indicators

The disaster had a noticeable but limited impact on the national economy. Many macroeconomic indicators showed losses in September and, to a lesser extent, October. The Taiwan economy overall recovered in about a month, and some of the initial business losses were able to be made up through overtime work. Reconstruction spending should begin to exert some short-term stimulus in late 1999 or early 2000.

The disaster appears to have curtailed Taiwan's 1999 GDP growth rate by 0.2-0.5 percent, with later estimates tending toward the higher end of the range. The central government eventually revised its pre-disaster growth rate forecast of 5.74 percent down to 5.3 percent (MOEA, 1999; China News, 9/24/99 and 10/28/99). In the third quarter of 1999, GDP grew by 5.1 percent over the previous year, in comparison with 6.6 percent in the second quarter (China News, 11/20/99). The government anticipates that GDP growth would rise to 6.0 percent in 2000 as reconstruction gets underway.[4]

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[4] More recent information indicates that the 1999 economic growth rate was reduced by 0.3 percentage points due to the earthquake, to 5.48%. This included a 0.5 percentage point reduction from output loss counter-balanced by a 0.2 percentage point increase from reconstruction stimulus (Shaw, 2000).

Much of the GDP loss appears to derive from the business interruption caused by electric power outage to central and northern Taiwan, rather than directly from damage to structures. The Taiwan Stock Exchange was closed for one week, largely due to power outage (China News, 9/29/99). Information on over 400 large companies on the Stock Exchange indicated total structural and equipment damage of US $59 million (NT $1.9 billion), goods inventory loss of US $66 million (NT $2.1 billion), and sales loss of US $247 million (NT $7.9 billion). For these companies, at least, business interruption losses vastly outweighed the cost to repair or replace damage. However, it is unclear if these initial estimates took into account the ability to make up loss through overtime work once damage was repaired.

More detailed data on industrial production also show that plant and equipment damage represented only a fraction of total loss. A survey of 6,000 industrial facilities[5] across Taiwan conducted by the Ministry of Economic Affairs found that 27 percent of them had suffered some degree of damage, with total physical damage estimated at US $406 million (NT $13 billion) (MOEA, 1999). However, 54 percent of those surveyed reported some reduction of revenue due to the disaster. Firms indicated that half of the revenue loss derived from reduction of work time, such as from electric power disruption, rather than from damage to plant or equipment. Much of this loss may be readily made up through overtime work. Revenue loss was reportedly some US $2.2 billion (NT $69 billion), or one percent of annual revenue, most of this occurring in September. These figures suggest that for these manufacturers, overall revenue loss was five times greater than property damage.

MOEA reported that industrial production in September dropped 4.9 percent from August. While this still represented a 3.5 percent increase from the previous year, it was less than the eight percent increase that had been expected without the earthquake (China News, 10/22/99). Industrial production quickly recovered in October, increasing 10.1 percent over September or 7.5 percent over the previous year (Chen, 1999b).

Taiwan is a major exporter of textiles, electronics and high-technology goods, machinery, metals, agricultural products, and high-technology items. Taiwan's export volumes were noticeably impacted by the earthquake (MOEA, 1999). Exports grew by 0.9 percent over the previous year in September, far less than the 10.4 percent average growth for the preceding three months. However, information from the first half of October showed a 23.5 percent increase, and exports for all of October grew 13.2 percent over the previous year (Chen, 1999a; Kuo, 1999). This suggests that much of the September loss was being made up in October through overtime work. MOEA surveys also found that orders for export goods were minimally impacted, further suggesting that the earthquake's impacts on export volumes would be short-lived.

Employment impacts were less pronounced at the national level. According to the Directorate General of Budget, Accounting and Statistics (DGBAS), the earthquake caused a loss of 42,000 jobs and affected the jobs of 125,000 workers (China News, 10/26/99). Taiwan's unemployment rate in September declined to 3.1 percent from 3.2 percent in

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[5] Probably firms in Ministry-supported industrial parks, although this is not clear from the report.

August, but this was still higher than the 3.0 percent rate a year earlier. Both the labor force size and first-time job seekers decreased in September. Nantou county in particular suffered considerable job loss due to temporary closure of wine factories and tourism facilities (Taiwan News, 10/3/99).

In terms of other economic indicators, consumption decreased in the end of September as households refrained from luxury spending in the disaster atmosphere. Government revenues also suffered; in September, personal income taxes fell by 11 percent from the previous year (China News, 10/12/99).[6] However, the earthquake appears to have had little impact on consumer prices, with the exception of building material prices which rose about three percent after the disaster (China News, 11/6/99).

9.4 Reconstruction Finance

Perhaps the most important economic issue in the medium-term pertains to reconstruction finance. Taiwan, having little experience with major natural disasters, did not have a reconstruction financing system or policy in place before the earthquake. Few property owners subscribed to earthquake insurance, which is tied to fire insurance coverage. Some one percent of fire policies included earthquake provisions, and these were more prevalent among businesses than households. Latest estimates indicate US $480 million (NT $15.4 billion) in property insurance claims, a figure that will undoubtedly rise (Taiwan News, 10/7/99). In the aftermath of the disaster, the government has been struggling to determine appropriate financial support mechanisms, and announcements have been revised several times.

The latest package consists of a combination of grants and loans. Table 9-5 summarizes relief grants that are being offered by the central government to the disaster victims.

Table 9-5 Government disaster relief grants program

Category of Compensation	Compensation (NT$)	Compensation (US$)
Death of Family Member	1 million	31,300
Serious Injury	200,000	6,250
Completely Destroyed House	200,000	6,250
Partially Destroyed House	100,000	3,100
Temporary Shelter Need	Temporary housing or NT$3,000 rent subsidy per person per month	Temporary housing or US$94 rent subsidy per person per month

Executive Yuan of Taiwan government (9/28/99)

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[6] According to more recent information, government revenue loss in 1999 and 2000 due to the earthquake reached NT $36.8 billion (US $1.15 billion) (Shaw, 2000).

Low-interest (3%) and no-interest loans with a 20-year term are being offered to households and businesses for reconstruction. Owners of homes that had been partially or completely destroyed are eligible to purchase public housing on favorable terms, although this scheme has been contended by the mayor of Taipei, where public housing is much in demand (The China Post, 10/8/99). In addition, the central government negotiated with commercial banks to urge them to forgive outstanding mortgages on damaged property. While highly contentious, it appears that several banks have agreed to take over these mortgage debts. According to one report, this includes mortgages on the damaged structures and excludes land, and households are eligible if they rebuild or purchase a new home (China News, 10/16/99). Another report indicated that only those who planned to rebuild in the same location were eligible; for others, the repayment schedule would be delayed by five years (Namgyal, 1999). It is likely that the banking sector will suffer substantial losses as a result of the disaster. The agricultural credit cooperatives, which had already faced some financial difficulties before the earthquake, are in a particularly dire situation.

The national government estimated that it would need some US $5 billion (NT $160 billion) for its reconstruction fund (China News, 10/26/99). The Executive Yuan has allocated US $1.6 billion (NT $50 billion) for low-interest lending to damaged industries (MOEA, 1999). The government plans to finance the fund by borrowing from the postal savings deposit system and government-owned banks, drawing from a reserve fund, issuing new bonds, instituting a 2-year freeze on government employee salary increases, and diverting proceeds from a special lottery which had been planned to seed the new national pension system. Proceeds from the lottery diversion in the first three months of 2000 are estimated to yield US $25 million (NT $800 million) (China News, 10/16/99). The government has also been soliciting private sector sponsorship of reconstruction projects for over 100 damaged school buildings (China News, 10/30/99).[7]

9.5 Observations

A number of observations, lessons, and preliminary conclusions can be drawn regarding economic issues in the restoration process:

- Although total losses were not as great as in other recent earthquakes such as Northridge and Kobe, they were more severe in relative terms. The disaster caused measurable though not severe loss for about one month to the national economy.
- In this disaster, the geographic and sectoral scope of economic disruption vastly exceeded the scope of direct property and human loss, largely due to lengthy electric power outage to northern Taiwan.
- Power disruption may have caused more GDP loss than damage to plants and equipment. At least for some sectors, notably manufacturing, revenue losses were much larger than the costs to repair damage, largely due to power outage.

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[7] More recent information indicates that the central government had approved NT $12.14 billion (US $379 million) in emergency relief expenditures and had estimated reconstruction expeditures at NT $138.7 billion (US $4.3 billion) about two-thirds of which would be financed by public debt and one-third by budgetary diversions and savings. A new national insurance scheme is under study (Shaw, 2000).

- Prioritization schemes for electric power restoration are possible and can be used to give priority to critical economic sectors and/or facilities.
- For central Taiwan, agriculture and tourism will be bottleneck sectors in the economic recovery. Tourism may be particularly slow to recover, as image problems will need to be overcome even after physical repairs are completed.
- Earthquakes can cause significant loss to the agricultural sector.
- The counties and townships hardest hit by the disaster will require several years and substantial government assistance to recover.
- Reconstruction financing is a contentious issue and it appears that the banking industry may suffer substantial losses due to both loan defaults and debt forgiveness policies imposed by the central government.
- Earthquake insurance will provide a minimal source of reconstruction finance.
- This disaster has demonstrated the need for pre-disaster planning and policy development with respect to issues of disaster relief, reconstruction finance, mitigation, and reconstruction prioritization.

9.6 Recommendations

Based on the author's observations and discussions with professionals in Taiwan, the following short-term restoration strategies and research needs are identified:

- Promote use of information technology to support restoration decision-making — It appears that there exists a major gap in terms of a reliable data collection system for disaster damage and loss on the part of the government. The resulting lack of credible loss estimates could only cause confusion as to how much, where, and what kinds of disaster assistance are needed. Other sectors, notably academia, are stepping in to help address the problem. New information technologies, such as the web GIS disaster decision-support system being developed by the Office of the National Science & Technology Program for Hazards Mitigation, can potentially serve a critical role in centralizing and disseminating information about the disaster. An exchange of experience and ideas with the U.S. (and Japan) could be mutually beneficial in this regard.
- Identify particularly vulnerable and critical economic sectors, and develop special strategies for them — If potential bottleneck sectors in the economic recovery are identified and special assistance provided, overall recovery may be hastened.
- Conduct research on electric power outage and associated economic impact to Hsinchu Science and Industrial Park — Taiwan's experience could be very instructive to the U.S. in terms of understanding the vulnerability of high-tech industries, the economic consequences of electric power outage, and possibilities for strategically prioritizing power restoration to reduce economic loss. Research on this question would have to be conducted in the near-term, before information and consciousness about the issue disappear.
- Conduct research on societal and economic impact and needs with reference to the current large survey being sponsored by NCREE — Researchers in Taiwan are mobilizing a large survey effort to collect social and economic data on this disaster. The survey is scheduled for completion in November 1999. Potentially fruitful

exchanges may be made with disaster researchers in the U.S. on survey design, findings, and transferable lessons.

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Section 10
Emergency Response and Short-Term Restoration [1]

Paul J. Flores
EQE International

The social and economic consequences from the Chi-Chi earthquake that impacted central Taiwan were significant. As of December 1999, Republic of China (ROC) government sources report that approximately 10,000 buildings collapsed and another 7,500 suffered some level of damage, over 2,400 persons were killed, more than 10,000 were injured, of which approximately 1,000 required hospitalization, 39 remain missing, 4,540 had to be rescued from rubble and debris, and over 100,000 were displaced from their homes.

As compared to some other recent events like the 1995 Kobe and 1994 Northridge earthquakes, where the damage was highly concentrated, the effects from the Chi-Chi earthquake were widespread, covering an area of about 50 kilometers long and 20 kilometers wide. A five county area including the city of Taichung experienced the greatest damage and casualties. The widespread nature of the damage and the extensive disruption to the island's transportation system, made the emergency response to the disaster extremely difficult. These same factors have also posed some significant challenges during the government's short-term restoration efforts.

10.1 Emergency Response

The ROC did not have large-scale disaster response or recovery plans in place at the time the earthquake occurred. The National Fire Fighting Administration (NFFA), under the Ministry of the Interior, has responsibility for the management of most emergencies affecting Taiwan. The NFFA has generally been capable of handling small to medium size emergencies or disasters, but it lacks the authority and resources to cope with a disaster at the scale of the Chi-Chi earthquake. The focus of the NFFA's emergency plans has been on fire and flood incidents, the typical disasters affecting Taiwan. Taiwan has not experienced a disaster the size of the Chi-Chi earthquake in historic time. Without that experience, the need for special emergency plans to effectively manage a catastrophic earthquake

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[1] The author had the opportunity to visit the epicentral area of the Chi-Chi earthquake in central Taiwan on two different occasions. The first was a reconnaissance trip and workshop during early October 1999, sponsored by the Multidisciplinary Center for Earthquake Engineering Research (MCEER), University at Buffalo, State University of New York and the National Center for Research in Earthquake Engineering (NCREE) of Taiwan. The information collected during that trip provided the basis for the assessment of the government's emergency response and short-term restoration activities. The second visit was a workshop and field trip during December 1999, sponsored by Taiwan's National Science Council and NCREE. The purpose of the second workshop was to provide the Taiwan government with recommendations on short-recovery strategies and preparedness for future earthquakes. The information gathered during the second visit included working sessions with government representatives involved in the management of the recovery effort and academics conducting socioeconomic research. This second visit provided the opportunity to assess progress in the recovery and collect more up to date information on impacts and governmental actions.

disaster seems to have been overlooked. Nevertheless, the government's overall emergency response to the Chi-Chi earthquake seems to have been expeditious, but to a large extent improvised.

The government's utilization of Taiwan's extensive seismographic network greatly contributed to the expedient emergency response. Taiwan has a sophisticated digital seismic network with real-time information capability much like the network now being developed in southern California under the TriNet project. Taiwan's network has been in place since 1996 and is operated and maintained by the Seismology Center of Taiwan's Central Weather Bureau (CWB). The mainshock magnitude, location and strong motion data for the Chi-Chi earthquake were determined and communicated via pagers, fax and the internet (e-mail, www and FTP servers) within 102 seconds after the event origin time. Not all 60 stations reported due to loss of the system's T-1 line during the earthquake. This line links stations in central Taiwan with the CWB processing center in Taipei. The earthquake's magnitude and location were determined by 12 stations in the northern and southern areas of the island. In addition to the provision of earthquake source data, the system also rapidly generated an instrumental intensity map and a shaking intensity map.

Receipt of rapid information from the network played a key role in early situation assessment at the national government level. The Director of the NFFA is a priority recipient of information from the CWB. Upon notification that the earthquake was over magnitude 7 and located in central Taiwan, the NFFA Director convened the Ministry of the Interior's "Emergency Action Team" and summoned nine other key ministers. By 2:30 a.m., all of the summoned ministers were present at the NFFA headquarters, which became the "921 Earthquake Central Action Center." The purpose of this center was to identify and begin the implementation of priority emergency actions. The first priority of the gathered ministers was to coordinate search and rescue efforts and address the disruption to the telecommunication systems, primarily due to extensive electrical power outages, and land transportation, due to the collapse of several major bridges and landslides. The disruption to the telecommunications and transportation systems greatly impeded the government's initial emergency response efforts. Later that day, a "Front Command Center" was also established in Taichung City to coordinate local government emergency actions. The following is a summary of emergency measures the government implemented immediately following the earthquake.

10.1.1 Mobilization of Military Forces

The Ministry of Defense played a major role in the immediate emergency response. The ministry immediately established an Emergency Command Center to consolidate military relief resources that included a large staging area in Taichung city (Figure 10-1). The military forces provided a variety of emergency relief functions. These included the deployment of showering stations and other much needed services for survivors, the establishment of organized shelter centers, the emergency repair of bridges and roads, the provision of security in the hard-hit areas, the deployment of mobile medical teams for treating victims, the assemblage of temporary housing units, the demolition of severely damaged buildings that posed significant safety hazards, and the distribution of potable water. The immediate decision to utilize the military resources tremendously contributed to the government's expedient response.

Photograph by T. Atsumi

Figure 10-1 Stadium in Taichung city was used as staging area by the military

10.1.2 Urban Search and Rescue

Search and rescue activities were intense during the first seven days of the disaster and were accomplished by a number of agencies, organizations and individuals. The first to respond were residents of the impacted communities and the victims themselves who accomplished rescues prior to the arrival of organized teams. Within a few a hours after the earthquake, those involved in search and rescue operations expanded to include local professional and voluntary fire brigades, police personnel, and civil search and rescue teams (Figure 10-2). The first international search and rescue teams arrived at 4:00 p.m. on the same day of the earthquake and were immediately integrated into the overall effort. In all, 21 countries sent search and rescue teams to assist in the operations.

10.1.3 Mass Care and Shelter

The number of locations where victims found shelter is as difficult to assess in this earthquake as the number of people displaced from their homes. Local government agencies and the military established official emergency shelters throughout the impacted areas, as did religious volunteer groups. These shelters were located at schools and other public buildings and municipal parks. The services provided at these shelters included security provided by local police and military units, meals prepared by volunteers, sanitary facilities, medical care, and counseling. Typical of the larger "official" shelter sites was the Vocational Technical High School in Taichung (Figure 10-3). This location sheltered approximately 1,100 persons in tents arranged around the grounds of the high school and

Photograph by T. Atsumi

Figure 10-2 Urban search and rescue operations dominated the initial emergency response

athletic fields. Local restaurants provided an organized feeding program with support and coordination by the city of Taichung. Aid stations with various supplies, services and referrals was organized and staffed by military personnel and volunteers. Residents whose homes were undamaged or had sustained only minor damage erected their own shelters in close proximity to their homes, entered these buildings during the day but preferred to spend nights outside in tents (Figure 10-4).

Photograph by J. Goltz

Figure 10-3 Mass care and shelter center set up on the grounds of the Vocational Technical High School in Taichung city

Photograph by T. Atsumi

Figure 10-4 Services being provided at an official shelter

10.1.4 Emergency Medical Care

On the afternoon following the earthquake, the Emergency Medical Care Network of Central Taiwan established a "Medical Care Rescue Command Center" to organize and coordinate emergency medical resources and services. The center mobilized and deployed trained medical personnel from hospitals in the north and south parts of the island and imported the medical supplies and instruments needed to treat the injured.

The earthquake caused significant structural and nonstructural damage to many of the region's health care facilities, impacting on-going medical care (see Section 4). To ensure the continuation of health care services in the region, on September 26 the Department of Health announced a six-month medical assistance plan and established a medical services bureau in each of the 27 townships impacted by the earthquake. The plan was designed to provide free medical care for patients without health insurance. Medical institutions providing care in the damaged areas were assured that the Bureau of National Health Insurance would reimburse them for providing free medical care to victims. The plan also established a health maintenance program that included information gathering on diseases found in the impacted area and the monitoring of sanitary conditions. The plan also provided the on-going coordination of the volunteer services of approximately 3,000 doctors, nurses, paramedical personnel, social workers, mental health professionals and medical administrators that were initially brought in from other parts of Taiwan and other nations.

10.1.5 Emergency Response Observations and Recommendations

The experience from the Chi-Chi earthquake has hopefully raised the awareness of government officials and the general public of the social and economic impacts that large earthquakes can cause. Certainly, there is more concern now for a similar damaging earthquake that could impact Taipei. There is a great need for all levels of government in Taiwan to institutionalize earthquake preparedness and mitigation programs.

The utilization of the CWB's extensive array of seismographic stations contributed to the government's expedient emergency response by providing immediate information on the magnitude and location of the Chi-Chi earthquake. On the other hand, other information derived from the networks, such as ground motion maps, could have also aided government officials in rapidly estimating damage and social and economic impacts.

The government's immediate response to the earthquake would have been more effective if it was guided by pre-existing emergency plans that were well understood and exercised. The military's apparently effective response was due to its highly disciplined command and control system. Civil agencies must also have such structured plans to guide their actions during a major disaster.

As a result of the many lessons that have been learned from the Chi-Chi earthquake, the Government of Taiwan is reconsidering the adoption of the Disaster Prevention and Relief Act. In 1995, the Act was introduced in the Legislative Yuan, but it was not passed into law. In the aftermath of the Chi-Chi earthquake, the Act has been reintroduced, with modifications based on the lessons learned from the disaster. According to most of the government officials interviewed, the Act is on a fast track toward being adopted. Deliberations on the Act will soon be taking place in the Legislative Yuan. The following recommendations are offered for consideration during the Legislature's deliberation process.

- Taiwan should consider adopting a Standardized Emergency Management System (SEMS) that can effectively integrate and coordinate the emergency response and recovery activities of all levels of government and the private sector, including volunteer organizations. The SEMS utilized by the State of California and the U.S. Federal Emergency Management Agency can provide a good model that can be easily modified to meet the specific needs of the ROC.
- Integrate into the new emergency management system that the Act will establish advanced technologies such as real-time loss estimation methods, including the utilization of ground motion maps produced by the CWB's seismic monitoring network, rapid damage assessment capabilities using remote sensing, and Geographic Information Systems (GIS) for organizing and displaying natural hazards and damage assessment data. The National Science and Technology Program for Hazards Mitigation (NAPHM) is rapidly developing many of these advanced technologies, some of which are being utilized in current recovery efforts.
- Initiate a research effort to objectively evaluate the effectiveness of the Emergency Measures immediately undertaken after the earthquake and the programs proposed under the five-year Post-Earthquake Rebuilding Plan. The purpose of the research would be to assess the effectiveness of the emergency measures and disaster assistance implemented by the government to identify those that worked well and should be instituted as part of the emergency management system the Disaster Prevention and Relief Act will establish.

10.2 Disaster Recovery and Reconstruction

In most disaster situations, once the life-saving operations, such as search and rescue and emergency medical services, are underway the next major item of business is setting priorities for short-term restoration and long-term reconstruction activities. As a first step in this process, five days after the earthquake, President Teng-Hui Lee declared a six-month state of emergency and issued an Emergency Decree "to empower the government to override some laws and statutes and quickly mobilize resources to deal with the consequences of the disaster." The decree covered the city of Taichung and the five counties suffering the greatest damage. A key feature of the decree was to lift the ceiling on government bond issues to raise the necessary recovery funds.

The presidential decree allowed the Taiwan government to quickly establish short-term restoration priorities, and in a widely circulated public information poster, these priorities were presented to the public. The government's top restoration priorities are summarized in Table 10-1.

Table 10-1 Short-term restoration priorities

- Provide monetary compensation for deaths, injuries and for those whose homes were destroyed in the earthquake.
- Provide temporary houses for those displaced.
- Set up an emergency fund for assistance centers and for local government disaster relief in the disaster area.
- Provide special mortgage loans for those displaced.
- Reduce taxes and interest rates on existing loans for those displaced.
- Provide emergency medical service and control the spread of diseases.
- Provide safety inspection of buildings.
- Provide daily necessities including food, water and electricity.
- Stabilize retail prices.
- Set up an organization to accept donations.
- Reopen schools and provide psychological counseling for students.
- Set up special telephone numbers for disaster-related services.
- Set up a special disaster relief account.
- Dispatch the army to assist in disaster recovery.
- Maintain environmental hygiene.
- Assist unemployed workers in the disaster area to find new jobs.
- Establish a list of the injured and dead.
- Provide assistance to children and the elderly who lost family members in the disaster.
- Provide traffic information and a special postal service.

To meet the priority of compensating for deaths and injuries, the government plans to compensate families with NT $1 million (US $31,000) for every member that died in the earthquake and NT $200,000 for those that were seriously injured.

On October 5, 1999, the central government announced the establishment of a five year Post-Earthquake Reconstruction Plan (PERP). The plan is divided into three phases:

- Phase 1: Between the beginning of October and the end of November 1999, reconstruction plans will be developed for the five county disaster area;
- Phase 2: Between December 1999 and February 2000, the reconstruction plans will be finalized and reconstruction units established; and
- Phase 3: During March 2000 and September 2004, the reconstruction plans will be implemented.

The Council for Economic Planning and Development (CEPD) had the responsibility for drafting the PERP which contains four elements: 1) the restoration of infrastructure, 2) the rebuilding of industry, 3) the rehabilitation of lives, and 4) the renewal of communities. The first year's cost of the reconstruction work proposed in the plan is estimated to be NT $80 billion (US $2.5 billion) to be funded by the issuance of bonds.

Local governments will have the primary responsibility for the implementation of the "community renewal" element of the PERP. According to those involved in the development of the PERP, "this will be the most complicated part of the whole plan." The goal is to rebuild and revive damaged communities, taking particular account of the geographical characteristics, cultural features, the wishes of the local residents and a host of other relevant factors. In addressing this element of the plan, a major issue has surfaced in which Taiwan medical professionals have little experience: "psychological and mental rehabilitation." To date, those involved in dealing with aspects of disaster recovery have been staff and graduate students from the Psychological Departments of the National Taiwan University, the National Chen-Chih University, and the Chung-Yuan University. Considerable attention is now being given to this issue, which many see as a potential impediment to the renewal process if not appropriately addressed.

To implement the PERP, the Post-Earthquake Reconstruction Commission was established as unit under the Public Construction Commission (PCC), Executive Yuan. The commission is composed of 14 task groups and maintains a branch office in the city of Taichung.

10.2.1 Resettlement of Displaced Individuals and Families

The earthquake caused the "total collapse"[2] of 50,000 housing units (both single and multifamily) and the "partial collapse"[3] of another 47,000 units. It is, therefore, not surprising that the first task group to be established was the one assigned to deal with issues related

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[2] Total collapse, as defined by the PCC, are buildings that show major cracks or excessive tilt and must be demolished.

[3] Partial collapse, as defined by the PCC, are buildings that have more than 1/3 of their roofing area damaged or the cost of restoration is more than 50% of the replacement cost.

to the resettlement of displaced individuals and families. The resettlement program developed by this group consists of several major components.

Building Safety Assessment

The building safety assessment process implemented is very similar to the one used in California (ATC-20) in which all inspected buildings are posted with green, yellow and red placards to notify owners and the general public. As of October 28, 1999, 57,750 buildings had been inspected and 15,311 had been classified as red, 12,782 as yellow, and 24,657 as green.

Resettlement Measures

As part of the resettlement program developed by the task group, individuals or families whose homes were totally collapsed will be given a grant of NT $200,000 (US $6,250) and those with a partial collapse will be given a grant of NT $100,000 (US $3,100).

Additionally, these individuals or families will be offered three resettlement alternatives: 1) purchasing government-built housing units at a 30 percent discount, 2) moving into temporary housing (assembled housing) for one year, or 3) applying for a rental allowance of NT $3,000 for one year. The popular choice seems to be the temporary housing alternative since government housing has to be bought and even with the 30 percent discount, the units are considered to be small and of lower quality. The rental allowance alternative is equally unpopular since vacant rental housing units are often not near a family's existing neighborhoods. The temporary housing settlements that the author visited were very pleasant and had a neighborhood feel to them (Figure 10-5). A total of 5,092 temporary housing units will be eventually assembled. Even so, the government is very concerned about the temporary housing sites. Of particular concern is the anticipated reluctance of those residing in these sites to move out after the one-year time limit.

Photograph by P. Flores

Figure 10-5 Temporary housing site in Taichung county

As of mid-December, 200,000 resident households had applied for the rental allowance program and 1,300 had applied for the purchase of government-owned housing units.

The long-term resettlement strategies contained in the PERP consist of providing impacted households with "preferential loans" to rebuild or renovate damaged housing. There will be two types of loans for rebuilding: 1) interest free loans for less than NT $1.5 million, and 2) three percent loans ranging from NT $150-350,000 and 20 year repayment schedule. Renovation loans will be provided at three percent for NT $1.5 million per household and 20 year repayment schedule. For households holding previous mortgages on a damaged property, the government will extend payment of the principal for five years and reduce the interest to one percent. For those households whose homes were totally or partially collapsed and have an active mortgage loan, eight government-owned banks will bear a structural fraction of the loss (i.e., excluding the mortgage land value).

Demolition

To address the serious public safety issues that damaged buildings posed and to prepare for the long-term reconstruction, a major demolition program was initiated soon after the earthquake. The military was tasked with the demolition of all severely damaged buildings of five stories or less. As of the end of October 1999, 25,262 buildings had been demolished. The PCC is in charge of demolishing buildings of more than five stories. As of the same date, 121 buildings fell into the latter category, of which 62 have already been demolished (Figure 10-6). Debris from demolished structures was taken to several sites throughout the impacted area for disposal (Figure 10-7).

Photographs by P. Flores

Figure 10-6 Demolition of severely damaged multi-family apartment complex

10.2.2 Restoration of Public Facilities

Under the PERP, the PCC has been tasked with the restoration work of public facilities. This will be a tremendous undertaking considering the scope of the task at hand:

- The repair or replacement of national and provincial highways, and urban and rural roads. As of mid-December 1999, the PCC had implemented an exemplary

Photograph by P. Flores

Figure 10-7 Debris from demolition work was brought to sites like this for disposal

emergency route recovery program that re-established key transportation links to minimize disruption to the movement of people and goods.

- The restoration of reservoirs, dikes, embankments, regional flood prevention and drainage structures. The restoration work underway at the Shih-kang Dam that failed due to surface faulting exemplifies the monumental work that lies ahead (Figure 10-8).

Photograph by P. Flores

Figure 10-8 Restoration work underway at Shih-kang Dam

- The repair or replacement of national colleges and universities, and public secondary and elementary schools (Figure 10-9).
- The repair or replacement of central and local government buildings and facilities.
- The restoration of farming, forestation, fishery, and livestock husbandry facilities.

Photograph by P. Flores

Figure 10-9 Damage to secondary school in Wu-feng Hsiang City, Taichung County

10.2.3 Recovery and Reconstruction Observations and Recommendations

The Taiwanese government is in the process of initiating its five-year PERP. This provides an opportunity to apply the lessons that have been learned thus far and the experience being provided by the international community in the implementation of the many programs that the plan proposes.

1. The reconstruction of destroyed residential and commercial property will challenge a government that has had little experience in managing large scale disasters. The tendency will be to rebuild quickly at the expense of constructing safer structures, improving the urban environment, and providing for ample community participation. This tendency is not specific to Taiwan and is prevalent in any major disaster anywhere in the world. An important factor in this process will be the provision of temporary housing and commercial space.

2. Local government has been assigned an important role in the rebuilding process. Under the PERP, local government has been given the responsibility for implementing the Community Renewal Element. Many of these local governments, particularly townships and villages, do not have the experience, resources, or technical capabilities to effectively carry out this responsibility. A Local Government Technical Assistance Program should be established by the central government to assist municipalities to effec-

tively implement their assigned responsibility including the development of a recovery planning model that can effectively integrate community participation.

3. The psychological impacts from this disaster cannot be underestimated and it must be understood that these effects will be long-lasting. For that reason, the Taiwanese Government should give equal attention to psychological recovery as it will to physical rebuilding. Research must address the role of cultural differences in psychological response to disasters. Since most of the prior psychological work on natural disasters has been conducted primarily in North America, research must address how the Taiwanese culture influences emotional, cognitive, social, and physical responses to earthquakes.
4. A very small percentage of households and small businesses affected by the Chi-Chi earthquake were covered by insurance. This situation has led to the government becoming the insurer of last resort. It is understandable why the government had to take on this role. The caring of victims will always be a priority with any government anywhere in the world. However, it is equally important that this role does not become the precedence for future disasters. The approach taken for providing disaster assistance to victims of the earthquake can serve as a disincentive for hazard mitigation because the government will be expected to make all victims whole in the future whether or not they have made any effort to reduce their exposure to disasters. Research should be undertaken to explore how government, in partnership with lending institutions and the insurance industry, can expand the role of insurance in future recovery financing structures.

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Section 11

Human and Institutional Perspectives of the Chi-Chi Earthquake

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The Multidisciplinary Center for Earthquake Engineering Research (MCEER) and the National Center for Research on Earthquake Engineering (NCREE) have had a research collaboration agreement to carry out fundamental earthquake engineering research in areas of mutual interest. A number of joint studies in the general area of seismic response control began after the first workshop in 1995. A second workshop was carried out in April 1999 in which two additional research projects were added (remote sensing applications, and protective systems for bridges). NCREE has a brand new research laboratory funded by Taiwan's National Science council. It is located at the National Taiwan University in Taipei. The lab has served as a focus point for many international professional reconnaissance teams since the earthquake, and provides updated information about this earthquake on the web (*http://www.921ncree.gov.tw*).

Shortly after the Chi-Chi earthquake, discussions between the authors led to the idea of an MCEER-NCREE workshop, which took place on October 3-5, 1999 in Taiwan. The purpose of the workshop was to identify important short-term strategies/actions for post-earthquake restoration and research needs, including specific cooperative projects for investigators from both centers to work as teams based on the 921 experience (see Section 1).

This chapter summarizes the observations and reflections of the authors after the three-day workshop in Taiwan with respect to the societal and government responses of the Chi-Chi earthquake. The authors are of the opinion that this earthquake not only destroyed a segment of Taiwan's physical landscape (Figures 11-1 and 11-2), but also made a significant impact to the society and government. Taiwan, like the U.S., is lucky because it hasn't experienced a major destructive earthquake with large number of death tolls in recent memory. This Chi-Chi earthquake presents a reminder and an opportunity for the people and government in Taiwan to begin a serious effort to establish more resilient communities against future earthquakes.

Photograph by M. Bruneau

Figure 11-1 Surface faulting caused major damage to the Shih-kang Dam

Photograph by M. Bruneau

Figure 11-2 Newly constructed buildings suffered severe damage

11.1 The Public

Earthquake ground motions are felt by people living throughout Taiwan. Thus, the term “earthquake” is a familiar one. However, an earthquake of the magnitude of 921 has not happened in recent history. To many people, an earthquake amounted to the swaying of buildings and the development of cracks on a wall. Occasionally, the roof of some houses collapsed. The building code in Taiwan provides for reasonable design guidelines (the most recent update to the guidelines was made in 1997). Based on historical data and measurements made by strong motion instrumentation programs, the Taichung/Nantou area is classified as a region of moderate intensity with a design peak horizontal acceleration of 0.23 g. The Chi-Chi earthquake generated a horizontal force of more than four times this maximum design criterion. It is thus easy to see why so many buildings and bridges collapsed (Figure 11-3). Psychologically, the public in the area was accustomed to earthquakes, but not one of such destructive magnitude, occurring in built-up areas.

Photograph by J. Shen

Figure 11-3 Damage to buildings and bridges was widespread throughout the epicentral area

The public showed tremendous spirit as they worked together to save lives and help each other with the basic needs to survive in the days following the earthquake. After a day to two, many began to complain that the government was too slow in its rescue and relief efforts. As a few more days passed and people were forced to accept the loss of a loved one whose body had not yet been located, these complaints of ineptitude and inefficiency were understandably intensified. Nonetheless, it seemed that the government was actually quite swift and effectual in its response to the event, given its magnitude. At the same time, many people praised the efforts of military personnel and international emergency response teams, even though such help was limited in its effectiveness by the scarcity of critical information such as local area maps, building blueprints, and other such data. The disaster management effort at the regional and local level was clearly unprepared for this disaster.

In speaking with a variety of individuals, one can see that this earthquake has had an enormous impact on the way the public views the importance of building safety and location of both workplace and residences. In the short three-day visit, questions regarding these issues were the most frequently raised by the general public. Now is the time in Taiwan to emphasize public education on earthquake hazards and mitigation measures.

A well-educated public will affect improvements in policy regarding mitigation and preparedness for earthquake and other natural hazards. In the past, real estate properties for many are the means to become rich. The landslides, the disappearance of the lake (reservoir), and the interrupted skylines in the city caused by the Chi-Chi earthquake had elevated the awareness of the public to treasure the small island shared by 22 million people (Figure 11-4). One may expect that environmental conservation and protection will be emphasized. Activities such as illegal pumping of fresh ground water for growing seafood (sinking land surface level) will be condemned by the public.

Photograph by J. Shen

Figure11-4 The beautiful historic site of Lin's Garden was completely destroyed

11.2 The Government

On the national level, the government seems to have responded well. It was certainly not possible to satisfy all those affected by the earthquake. However, many of the complaints stemmed from lack of preparedness rather than lack of emergency action. Within hours of the initial main impact, the national government announced policies for relief, short-term restoration and an organized interagency structure for efficient execution of rescue efforts. By September 28th (one week later), there were 17 major policies implemented, including hotlines, information and health centers, temporary housing, disaster relief funds and materials, and others (see Section 10).

However, a lack of earthquake disaster preparedness at both the national and local levels was evident. To varying degrees, this state of affairs exists everywhere in the world with respect to unexpected natural disasters. Because the occurrence of devastating earthquakes is probabilistic in nature, the consequences of such events are often not taken seriously by both the government and its constituents. In recent decades, the professional communities and government in Taiwan have made significant progress to mitigate earthquake hazards by, for example, funding the Strong Motion Instrumentation Programs at the Central Weather Bureau of the Ministry of Transportation and Communication, and funding earthquake and earthquake engineering research projects by the National Science Council including the establishment of NCREE. The Ministry of the Interior and the various structural engineering professional organizations have also been active in updating building codes and the ministry of Education has been investing in human resources development and earthquake engineering facilities at the universities. Additionally, a National Science and Technology Program for Hazard Mitigation was established several years ago to coordinate the development of national hazard mitigation strategies.

All these efforts have been carried out by many talented researchers and administrators. They now beg the question "What difference did these programs make in the communities where the earthquake struck?" Other than building code improvements for recently built structures, very little can be said about how the investment of tax money improved the preparedness and resiliency of the communities. It seems that a systems approach involving multiple agencies and professionals at all levels from national to local must be designed and implemented. An effective institutional structure for earthquake hazard mitigation is needed to develop well-prepared communities. It is important, however, to distinguish between a comprehensive block diagram of relevant components (which is easy to draw) and a properly functioning hierarchy of agencies (which makes decisions at each level in a manner consistent with the overall system objectives).

11.3 Some Lessons Learned and Recommendations for Possible Actions

An earthquake resilient community should have three elements at its core:

1. Properly developed codes for the physical infrastructure and high quality professional practice in planning, design, construction and maintenance.

2. An informed and participating public.

3. An institutional infrastructure system prepared for mitigation and response.

All three of these points require long-term sustained commitment from both the government and its citizens.

The Chi-Chi earthquake offers a chance to learn from "real world experience." Many issues related to earthquake engineering, from both the research and practical sides, have been addressed in other reports co-authored by investigators from both NCREE and MCEER (see Section 12). Several reconnaissance teams have also issued technical observation reports (for examples, the NSF-supported reconnaissance team, the EERI reconnaissance team, etc.). In this section, the authors reflect on their observations of the damage from the Chi-Chi earthquake and its effect on the local people, their community and government infrastructure and the level of public knowledge on issues of earthquake hazard preparedness. Other reconnaissance reports have paid special attention to earthquake engineering research opportunities and the importance of long-term professional practice dealing with the physical world. The following observations are made from the total perspective involving human, institutional as well as physical infrastructure system. They are offered for the public and the government in Taiwan as they face the restoration challenge after the Chi-Chi earthquake.

1. If the epicenter of the Chi-Chi earthquake had been located just 50 miles either north or south of the Taichung/Nantou area, the devastation to Taiwan's economy and the quality of life would have been much worse. To the north, the high-tech industrial park in Hsin-Chu and the political and economic center Taipei would have been struck; to the south, the center of heavy industry and manufacturing KaoHsiung could have been destroyed or seriously damaged. Eventually, these areas will be hit with a major earthquake. The opportunity exists today to carry out careful loss estimation and risk assessment studies for these areas. Ground motion information, geotechnical and structural design information all exist in sufficient quantities to conduct credible analyses of possible earthquake scenarios. These results could have a significant impact on the general public, elected officials and other decision-makers and stakeholders in Taiwan. Many individuals and organizations have gained financially from the booming real estate market of the past several decades – these groups will surely be supportive of such studies while the Chi-Chi earthquake is fresh in the population's collective memory. This type of study would allow for some quantification of the vulnerability of critical regions in Taiwan and could serve as the focus for a sustained effort in public education.

   Many individuals directly impacted by the earthquake require psychological help, for which the government has implemented a program. Often, survivors of critical events (drunk driving car crash, recovery from a terminal disease, etc.) become the best crusaders. These individuals may be provided with adequate understanding of the issues involving earthquake preparedness so that they can contribute to the public education task.

2. There is an immediate need for reliable methods of evaluating the extent of damage to a structure so that proper decisions can be made with regard to retrofit/repair/replacement of the structure. More than 7,000 damaged buildings remain standing in and around the epicenter and they all need critical assessment of the damage sustained (Figure 11-5). This is a significant opportunity to begin accumulating the knowledge about "building damage" by developing an "expert system" or standardized system of measures for non-destructive building evaluation. Of high priority is the evaluation of essential infrastructure buildings such as command centers, hospitals, manufacturing complexes and critical lifeline systems such as water, electrical power networks and bridges (Figure 11-6). An additional research effort to explore advanced technologies for deployment and implementation of emergency response, communication and rescue is also appropriate at this point, based on the lessons learned. There are many other long-term research opportunities in earthquake engineering that will not be addressed in this article.

Photograph by T.T. Soong

Figure 11-5 Reliable methods to evaluate the extent of damage are needed

3. The current emergency management and restoration organizational structure should be replaced gradually by a long-term institutional infrastructure which involves agencies at all government levels concerning all types of hazards. But beyond a simple box diagram of the hierarchy, such system requires thoughtful implementation. One very important element is the appointment of the proper individuals at key positions in the various agencies (an Emergency Response Corps - the ERC). In an emergency situation, these individuals of the ERC are the connecting nodes of the system of agencies. They must be well versed in and loyal to the overall strategic and tactical aims of the system because they may be called upon to make decisions on short notice without the ability to consult either their superiors or their subordinates. These individuals would need to meet regularly, say twice a year, to review the emergency operating plan that should exist, and to update their coordinated efforts in mitigation and emergency preparedness. An institutional infrastructure for multiple hazard mitigation and response may be organized differently consistent with a country's own system and culture. The system in the United States (Congressional hearings and actions, the NEHRP agencies,

Photograph by M. Bruneau

Figure 11-6 Damage to the Veteran's Hospital in Puli reduced its capacity to about 50% at a time when demand was highest

the lead agency FEMA and its regional office, etc. and how they function) can be used as a starting point for development.

In general, a functioning institutional infrastructure system is much more difficult to establish than to reconstruct the physical infrastructure system. The latter may be targeted to complete in three or five years if resources are available. Emergency response and short-term actions require a top-down approach. But for long-term reestablishment, the top-down approach must be coupled with the bottom-up efforts of the participation of well-educated public. The government must consider the current emergency management organizational structure as the beginning of a sustained pursuit, not as a one-shot event.

4. One of the most pressing issues in short-term restoration is that of construction quality (Figure 11-7). This has always been an ill-defined factor that makes the evaluation of existing damaged facilities more difficult. It also becomes a factor of importance in the time immediately following an earthquake, as reconstruction begins. Other issues such as public education, research, institutional effectiveness and building code improvements are longer term efforts. However, working with the real estate and construction industry can and should begin immediately with the restoration efforts. A workshop might be organized to review the current practice in building inspections (see item 2 above) and construction monitoring. Additional guidelines or recommendations would be issued as necessary. Building inspection and construction quality assurance should be examined from the overall perspective of planning, design, construction, decision-making processes (in the case of public works) and cost.

Photograph by J. Shen

Figure 11-7 Construction quality both prior to an earthquake and during the reconstruction phase is an important issue

5. The short-term and long-term research needs identified by the Chi-Chi earthquake indicate that most of the research programs of MCEER and NCREE, particularly those involving current and potential joint MCEER-NCREE research efforts in loss estimation and risk assessment, in developing retrofit strategies for critical facilities (water and electric power networks, medical facilities and bridges) and in application of advanced technologies in structural response mitigation and emergency responses can benefit from the real world experience of the Chi-Chi earthquake, and at the same time make a contribution to the state-of-the-art of earthquake engineering practice both in Taiwan and U.S. We look forward to a success story resulting from this center-to-center cooperation enhanced by the Chi-Chi earthquake.

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