Responses of the Earthquake Engineering Research Community to the Chi-Chi (Taiwan) Earthquake

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In the early morning of 21 September 1999, a devastating earthquake struck the central region of Taiwan. This earthquake became known as the "Chi-Chi" Taiwan earthquake. Immediately after the occurrence of the earthquake, the National Center for Research on Earthquake Engineering (NCREE) organized reconnaissance teams to investigate the damage in the earthquake-affected area. The purpose of this paper is to describe the inter-collaborations and actions that were taken by NCREE and the engineering research community. This paper also describes the damage situation from an engineering point of view that includes fault investigations, studies of strong ground motion characteristics, building and bridge damage investigations, geotechnical damage surveys, and lifeline damage investigations. The NCREE's emergency response decision support system and the HAZ-Taiwan earthquake loss assessment program are also described.
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INTRODUCTION

Taiwan is located at the active arc-continent collision region between the Luzon arc of the Philippine Sea plate and the Eurasian plate. The Philippine Sea plate is colliding onto the Eurasian continent at a rate of 7-8 cm/yr, generating high seismicity in this region. Most earthquakes in the western seismic zone are shallowly seated. On 21 September 1999, at 1:47 am local time (17:47 pm September 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 of the earthquake was located at 120.82°E and 23.85°N, near the town of Chi-Chi, Nantou County. The focal depth was 8.0 km. A surface rupture of about 105 km was observed along Chelungpu Fault with the largest measured vertical offset reaching more than 11 meters. After the major shock a total of 10,252 aftershocks were identified (as of 10 October 1999). Figure 1 shows the epicenters of the Chi-Chi earthquake and its aftershocks. The epicenters of disastrous earthquakes for the past 100 years in Taiwan are also shown in this figure. After the mainshock of the Chi-Chi earthquake, four aftershocks with magnitude greater than 6.5 were also identified.

As a direct result of this earthquake, 2,469 lives were lost, more than 700 people were severely injured, and over ten thousand buildings suffered damage at levels of moderate-to-collapsed. On the basis of the number of deaths, this was Taiwan's worst

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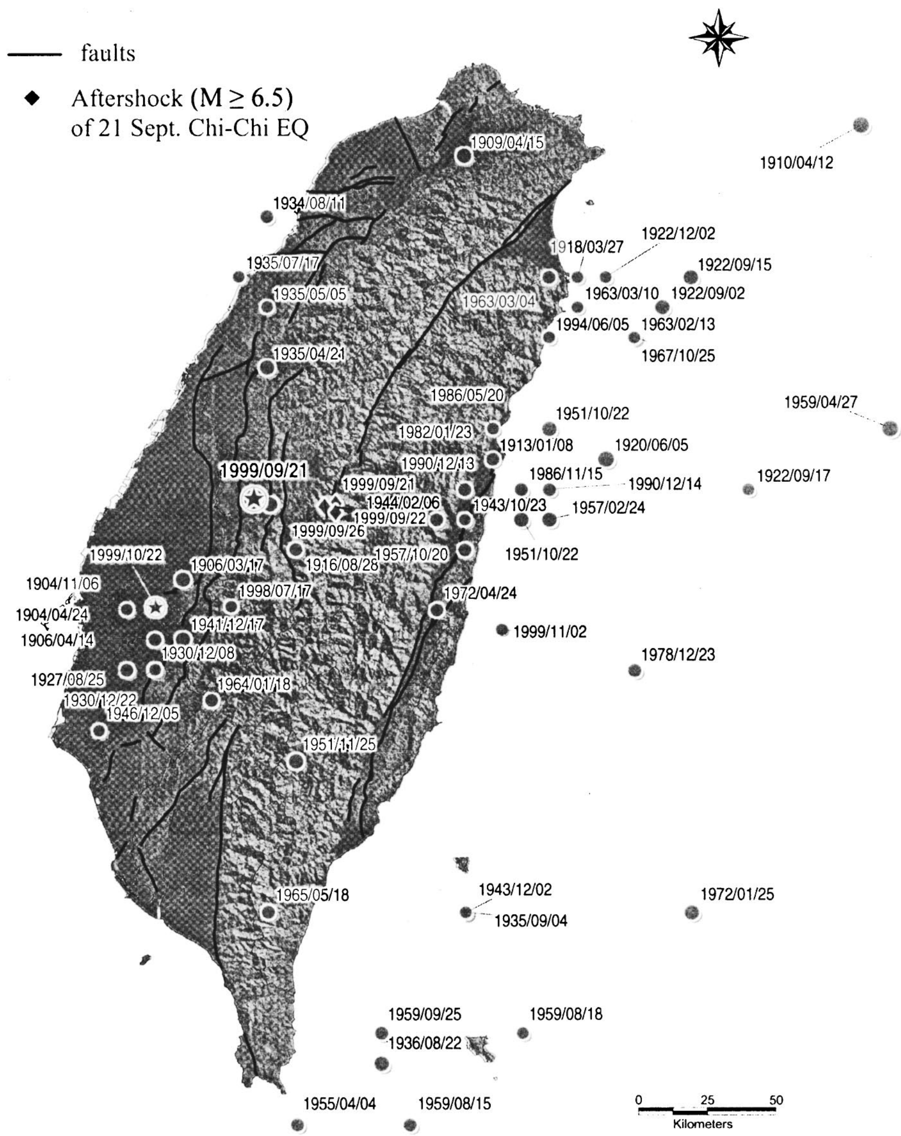

Figure 1. Distribution of epicenters of disastrous earthquakes in Taiwan since 1900. The epicenter of the 21 September 1999 Chi-Chi earthquake and three major aftershocks (M>6.5) are also shown. The epicenter of another earthquake, 22 October 1999, is also shown.

disaster since the Shin-Chu Taichung earthquake of magnitude 7.1 on 2 April 1935 in which 3,325 lives were lost. In addition, widespread destruction and disruption of lifelines, including roads and bridges, communication systems, water supply systems, gas supply systems, and electric power systems, had a significant economic impact.

Since 1982 the National Science Council (NSC) had launched three five-year research programs on earthquake hazard mitigation. At that time earthquake disaster miti-

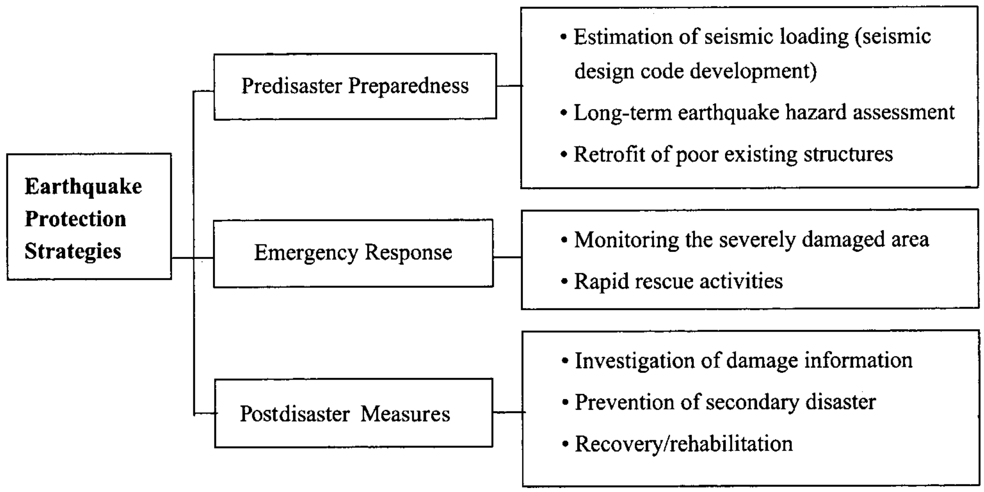

Figure 2. Flow chart showing the three major aspects of the earthquake protection strategies in Taiwan.

gation strategies in Taiwan were separated into three major categories: predisaster measures to construct safe structures, emergency measures after an earthquake aimed at life safety, and postdisaster management for restoration. Figure 2 shows the work items related to these three major categories. Under this natural hazard mitigation program, a National Center for Research on Earthquake Engineering (NCREE) was established in 1991 and began operating in 1997. It is a national research institute under NSC and National Taiwan University.

Due to the importance of natural hazard mitigation in Taiwan, the National Science and Technology program for Hazard Mitigation (NAPHM) was also developed under NSC. This organization also began to operate in 1997. The main objectives of NAPHM are as follows: (1) Establishment of hazard mitigation databases for research and operations, (2) Compilation of nationwide typhoon flood and earthquake hazard potential maps, (3) Establishment of methodologies for assessment of disaster risks and disaster scenario simulations, (4) Establishment of methodologies for development of a mitigation plan, and completion of such a plan for a selected pilot area, (5) Establishment of a hazard mitigation decision-support and information system.

Before the Chi-Chi earthquake, the information group of NAPHM had already prepared a GIS-based map for each county in Taiwan. Therefore, a GIS database for the disaster areas can be quickly assembled. In order to learn as much as possible from this disastrous event, within one week of the occurrence of Chi-Chi earthquake, professors and graduate students from different universities all over the country were organized by NCREE and NAPHM to form nine reconnaissance teams to investigate the damage situation and collect the scientific damage data. The lessons learned will be applied not only to the reconstruction of the impacted areas but also can be applied to other areas of simi-

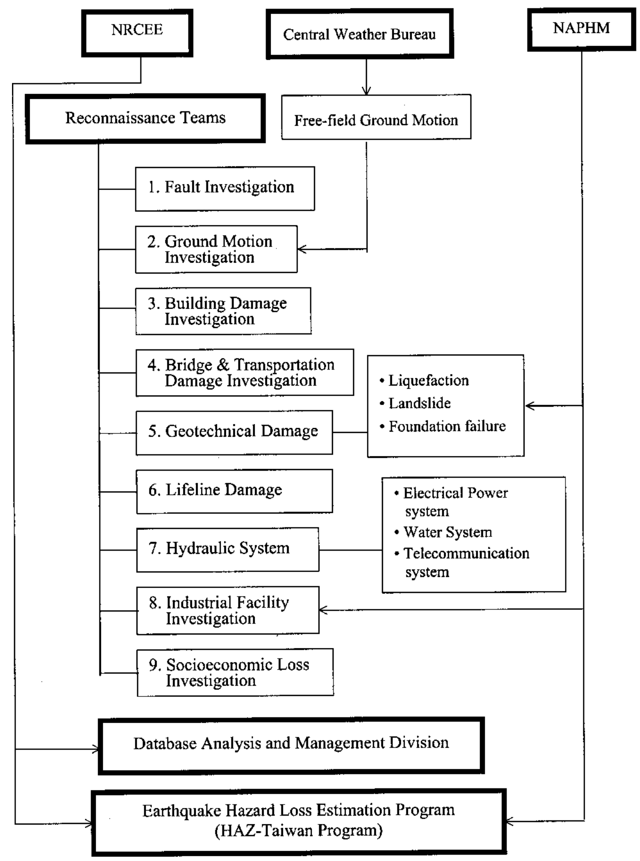

Figure 3. Framework for collaboration between NCREE, NAPHM, and the Central Weather Bureau for the seismic disaster management of the Chi-Chi earthquake. Nine reconnaissance teams were organized for Chi-Chi earthquake damage investigation.

lar seismotectonic environments. This paper describes the responses from the earthquake engineering research community after the Chi-Chi earthquake. The responses included investigations by reconnaissance teams and data management.

FRAMEWORK OF SEISMIC DISASTER MITIGATION MANAGEMENT IN TAIWAN

At the government level there are three organizations that are performing the seismic hazard mitigation research: Central Weather Bureau (CWB), NAPHM and NCREE. It is the responsibility of the National Science Council to be in charge of seismic hazard management. After the Chi-Chi earthquake reconnaissance teams were organized under NSC. The NCREE provided technical support and NAPHM provided information and data management. More than 1,200 scientists and engineers were mobilized to conduct systematic field surveys and to collect scientific data in order to learn as much as possible from this disastrous event (NCREE 1999). As shown in Figure 3, these teams included ground motion investigation, fault-induced surface rupture investigation, building damage investigation, bridge damage investigation, lifeline damage investigation, hydraulic facility damage, and socioeconomic loss investigation. Each team designed its own investigation format with the goal of entering data into electronic databases. Because CWB is in charge of the Taiwan Strong Motion Instrumentation Program (TSMIP), the free-field strong motion data was collected and distributed by this bureau. Through the Internet the collected free-field ground motion data was immediately passed to NCREE for detailed analysis. The NAPHM project office provided GIS-based information support for all the reconnaissance teams, particularly on the landslide and hydraulic investigation. In addition, the Chi-Chi Earthquake Database Analysis and Management System (CEDAMS) was established under NCREE that integrated damage investigation data and a data-processing module generated by NAPHM.

CEDAMS was established for the purpose of providing online analysis and management functions to the databases compiled by each reconnaissance team. All the damage data collected from survey teams was fed back to CEDAMS for detailed analysis. The data processing included (1) integration of damage investigation data including the strong ground motion data provided by Central Weather Bureau (CWB), (2) aerial photograph interpretation, (3) map making, and (4) disaster information compilation (GIS programs were used).

Since information management is the key to emergency response and GIS is the best tool to integrate disaster information, the system was developed using advanced information technology and WebGIS techniques. It was integrated in an Internet environment to allow access by both investigation teams and the general public. The system contains two parts: (1) Disaster Information Inquiry System; and (2) Earthquake Database Analysis and Management System. The first system serves the general public to provide disaster information. The second system was developed to provide spatial damage data analysis, cross-reference study, and statistical analysis of damage data to academic, engineering and government agencies for research as well as decision support needed by earthquake recovery activities. Database management mechanisms were also included in the development of the second system to provide online data uploading and downloading.

EARTHQUAKE RISK ASSESSMENT PROGRAM AND EMERGENCY RESPONSE DECISION SUPPORT SYSTEM

To support the reconnaissance teams in the field investigation, a GIS system and database for damage investigation were developed by NCREE and NAPHM.

EARTHQUAKE LOSS ESTIMATION METHODOLOGY

In 1997, in order to develop the seismic loss estimation program, NSC initiated a research project. The earthquake loss estimation methodology was originally developed for the Federal Emergency Management Agency (FEMA) by the National Institute of Building Sciences (NIBS) to provide a tool for developing earthquake loss estimates in the United States. It was called HAZUS97 (NIBS 1999). Based on the framework of HAZUS97, with the assistance of Risk Management Solutions, Inc. (Loh et al. 2000a),

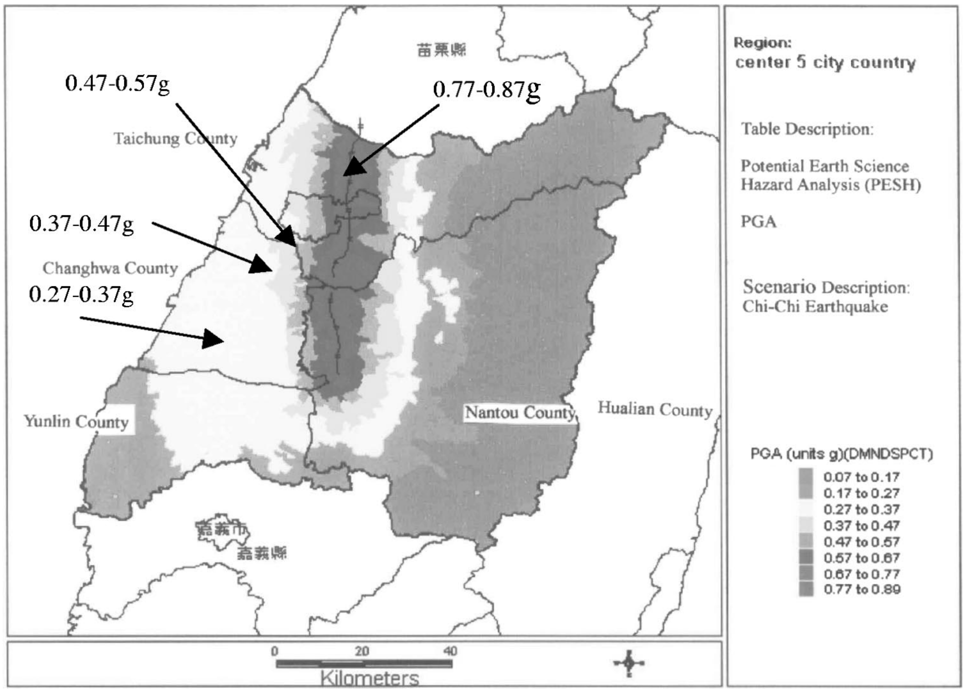

Figure 4. Simulation of PGA using the HAZ-Taiwan program in the central part of Taiwan for the 21 September 1999 Chi-Chi earthquake.

the NSC of Taiwan is developing a similar earthquake loss estimation methodology, called HAZ-Taiwan. The HAZ-Taiwan program includes potential earth science hazard analysis, inventory collection, direct physical damage estimation, and direct economic/ social loss and indirect economic loss estimation.

Before the Chi-Chi earthquake, the potential earth science hazard analysis module of the HAZ-Taiwan program had already been developed. Two days after the earthquake, using the HAZ-Taiwan program, the potential earth science hazard analysis was performed and generated an estimated PGA distribution in the GIS system. Figure 4 shows the estimated PGA distribution for the Chi-Chi earthquake in the central part of Taiwan. Although the result of the simulation was not consistent with the actual ground motion, it provided an estimated distribution of PGA along the Chelungpu Fault before the ground motion data was collected and available. This information was passed to the Ministry of Interior before all the free-field strong motion data along Chelungpu Fault were collected from CWB strong motion arrays. The emergency response committee used this preliminary information for postdisaster management, including emergency response and prevention of secondary disaster.

DATABASE DEVELOPMENT

To develop the damage investigation database, tables were created based on input from the reconnaissance teams and questionnaires designed by each field survey group.

The field survey data were input to the tables by each group as they collected it in the field. The database was sent back to each field survey group for verification and quality check after integration with the spatial and ground motion data by the information system division of NCREE.

The "spatial data input system" for Chi-Chi earthquake disaster information had been developed using WebGIS techniques on the Internet. The data were integrated using a Microsoft SQL Server database and ArcView GIS software. The survey data from nine groups were processed for integrating with spatial and attribute data in a GIS. There are about 12,000 data items using approximately 150 megabytes compiled in the Chi-Chi earthquake database. For the building damage data, there are approximately 5 to 8 gigabytes if the database includes four to six pictures of each survey point and approximately 15 to 20 gigabytes if the database includes the data processing results such as aerial photos, SPOT images, digital maps, and the data set of the disaster area.

EMERGENCY RESPONSE USING GIS

Before the Chi-Chi earthquake, the information group of NAPHM had already prepared a GIS base map for each county in Taiwan. Three weeks later, after the occurrence of Chi-Chi earthquake, the information group of NAPHM sent two GIS teams to the Emergency Response Center located in Taichung and Nantou counties to help emergency response officers organize damage information. The GIS database for the disaster areas was quickly assembled and copied on to CD-ROM for GIS experts to bring to the local emergency response center in Taichung and Nantou counties. Earthquake damage locations were identified and digitized on the GIS database. Attributes related to the damage descriptions were keyed in, and photographs scanned and attached to the damage locations. The local government of the earthquake-affected area and the Earthquake Management Center of the Central Fire Protection Administration fully used these data to inform disaster management.

INVESTIGATION OF SURFACE FAULT RUPTURE

Due to the significant surface faulting along the Chelungpu Fault (with a rupture length of 105 km), it was necessary to locate precisely the surface fault ruptures. A land survey team was organized to investigate the surface rupture. One month after the Chi-Chi earthquake, the exact location of Chelungpu Fault was identified and was plotted on the 1/5000 topographic map, as shown in Figure 5. Based on the GPS data and recorded free-field strong ground motion data, the distribution of permanent ground displacement along the fault is also shown in the figure.

The quake generated a rupture more than 105 km in length and a maximum offset of 11 m (vertical) and 10 m (horizontal) on the northern part of the Chelungpu Fault. Ground and geophysical surveys also showed that the shock resulted from reactivation of the Chelungpu Fault. This rupture initiated near the epicenter and propagated to both the north and south directions along the fault. The rupture was generated by the combination of reverse, strike-slip and normal movements, particularly on the northern part of the

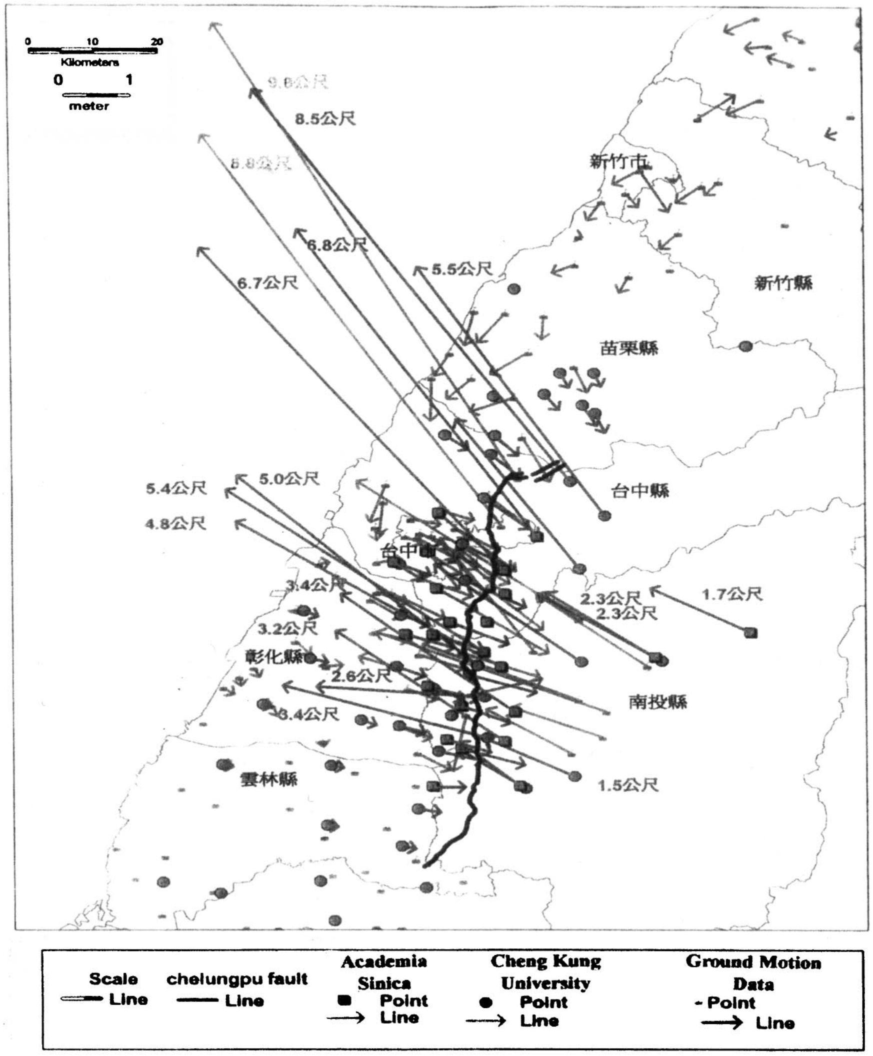

Figure 5. Exact location of Chelungpu Fault. The permanent offset of ground, calculated from strong motion instrumentation and GPA, is shown by arrow. The length of the arrows indicates the amount of permanent displacement in meters (Lee and Tsai 1999).

fault. The rupture can be divided into three segments, each characterized by different orientation and sense of movement. In addition, the northern segments were generated by new faults not recognized before the Chi-Chi earthquake.

The location of fault rupture was mapped on a GIS 1/25,000 scale topographic map. These data were immediately sent back to each reconnaissance team to locate the structural damage in relation to the fault line. Field surveys indicated that the rupture of this earthquake generally follow the pre-existing fault scarp of the Chelungpu Fault.

For the purpose of city planning in the earthquake-affected counties, a detailed land survey along the surface fault ruptures was also conducted within four months after the occurrence of Chi-Chi earthquake. This land survey covered a 40-meter width on the foot wall side and a 60-meter width on the hanging wall side along the fault. The result of the fault survey was plotted on a 1/1000 topographic map that included all the damaged and undamaged structures as well as detailed ground surface deformation along the 100-meter- wide belt of the fault. This information has provided valuable data for the reconstruction and replanning of the severely damaged area along the surface rupture area.

SEISMIC MONITORING AND GROUND MOTION CHARACTERISTICS

At the beginning of 1990, CWB began to install a seismic network that includes 73 stations around Taiwan area. Digital telemetry and digital recording of three-component high- quality force balanced accelerometers were used for seismic monitoring operations. The Taiwan Rapid Earthquake Information Release System (Lee and Shin 1997) can routinely release the location and magnitude of a strong earthquake as well as the distribution of intensity about 60 seconds after the occurrence of an inland earthquake. In addition, there are more than 600 free-field strong motion observation stations distributed and maintained by the Central Weather Bureau, Ministry of Transportation and Communications, Taiwan. About 70 percent of the observation stations were triggered for this earthquake.

After the earthquake two teams were immediately dispatched to collect the data from the stations named "TCU" and "CHY" because they were close to the disaster area. The recorded ground motion data were immediately passed to NCREE for analysis. Analysis of the ground motion data included (1) PGA, PGV, and PGD attenuation relationships, (2) spectral amplitude attenuation relationships, (3) response spectrum analysis (linear system), (4) near-field ground motion characteristics (pulse-like wave in velocity waveform), and (5) map products including distribution of PGA, PGV, and spectral acceleration (Sa) along the Chelungpu Fault and in the earthquake-affected area.

The map products were passed to the damage investigation teams to develop the structural damage level with respect to ground motion intensity. The attenuation relationships were used to reassess the seismic hazard of Taiwan. It is important to note that a significant amount of 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 6. For the near-fault ground motion, a large PGV/PGA ratio was identified (between 0.3 and 0.5). From the distribution of PGA and PGV along the fault, it was found that large PGA was observed at the southern part of the Chelungpu Fault and large PGV was observed at the northern part of the Chelungpu Fault (Loh et al. 2000b).

The contour map of PGA, PGV, and spectral amplitude were prepared by the information management group and immediately passed to the field reconnaissance teams for damage investigation. The relationship between the structural vulnerability curves and the PGA (or PGV) of this earthquake will be established.

Input Near-Fault Ground Motions

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

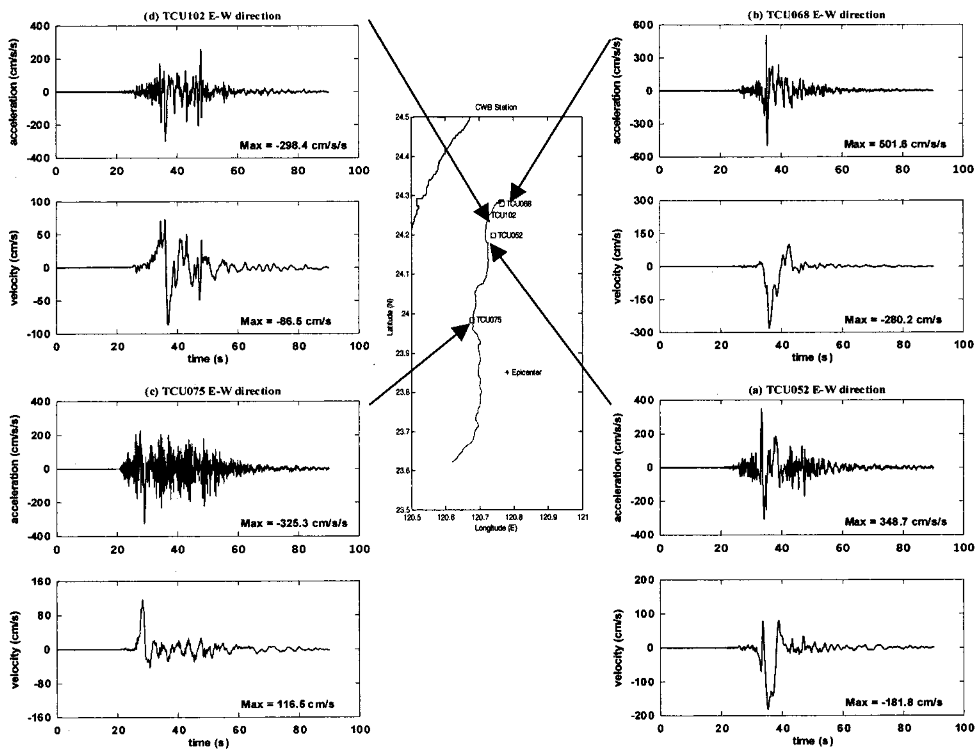

Figure 6. Plots of ground acceleration and velocity wave forms from four stations (TCU052, TCU068, TCU075, and TCU102) along Chelungpu Fault. The PGV/PGA ratio and pulse duration is also shown in the table.

For emergency recovery of civil infrastructure, the Taiwan seismic design code was re-evaluated immediately. A code development committee was established to re-examine the seismic zone factor of the Taiwan building code. Figure 7 shows the revised Taiwan PGA attenuation relationships with the consideration of the data from the Chi-Chi earthquake, i.e.,

$$y(g)=0.02968\exp[1.20M][R+0.1464e^{0.6981M}]^{-1.7348} \quad (1)$$

The difference between the revised PGA attenuation relationships and the original PGA attenuation relationships is not significant. After the Chi-Chi earthquake a seismic haz-

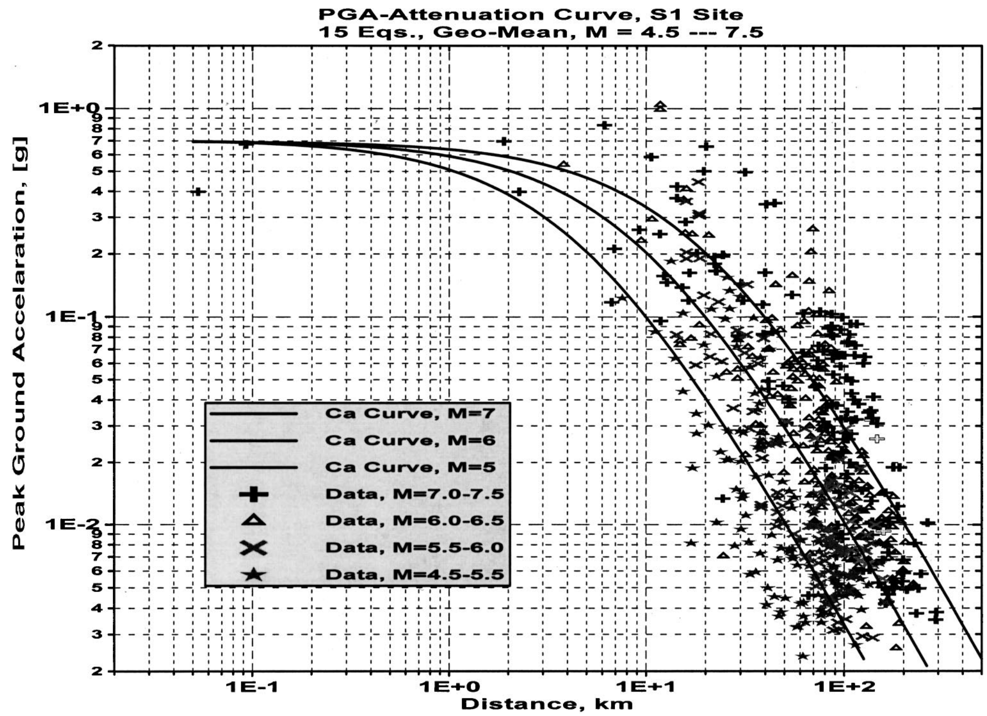

Figure 7. Plot of revised PGA attenuation (the Chi-Chi earthquake data are included) from Taiwan earthquake data (Geometric mean was used). The "Ca Curve" indicates the regressed PGA attenuation relationship using the Campbell form (Jean and Loh 2000).

ard analysis (SHA) was also performed with the consideration of the Chelungpu Fault as one of the active faults in Taiwan (previously, the Chelungpu Fault was designated as a fault that is not very active). Based on the results of the SHA, the seismic zoning and zone factor were revised. Figure 8 shows the comparison between the old and new seismic zoning and zone factor in Taiwan. The result was immediately passed to the Ministry of Interior to revise the code for use in emergency recovery construction.

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 spectral acceleration $S_A = ZIC$, where Z is the zone factor representing the seismic design level (as discussed in the previous section), I denotes the importance factor, and C is the coefficient of normalized spectral acceleration. The C-value, in the current Taiwan building code, did not consider the near-fault ground motion characteristics. Based on the SEAOC blue book (SEAOC 1996), with the consideration of near-fault ground motion data collected by the CWB strong motion array, the near-fault factors of ground motion characteristics (N_A and N_V) have been incorporated into the modified seismic design spectrum for sites near the Chelungpu fault. Figure 9

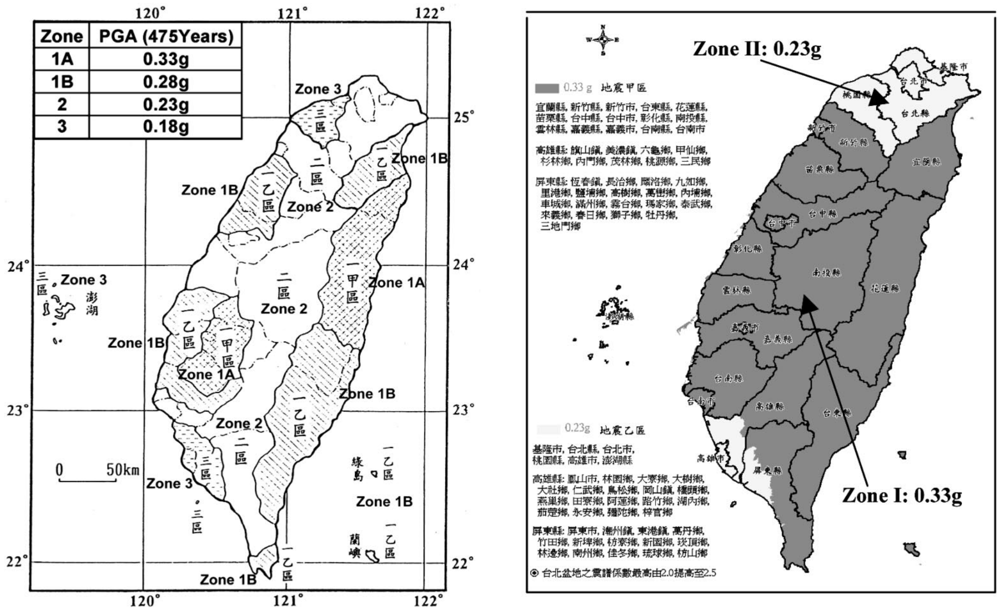

Figure 8. (left) Seismic zonation of Taiwan before Chi-Chi earthquake (four zones), and (right) revised seismic zonation in Taiwan after Chi-Chi earthquake (two zones) (NCREE Report No. 10).

Distance (km)	$r \leq 2$	$r = 4$	$r \geq 6$	Distance (km)	$r \leq 2$	$r = 6$	$r \geq 10$
N_A	1.34	1.16	1.0	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	$1.315 \leq T$ $C = N_V$
$T_1 = [1.2N_V / 2.5N_A]^{3/2}$	

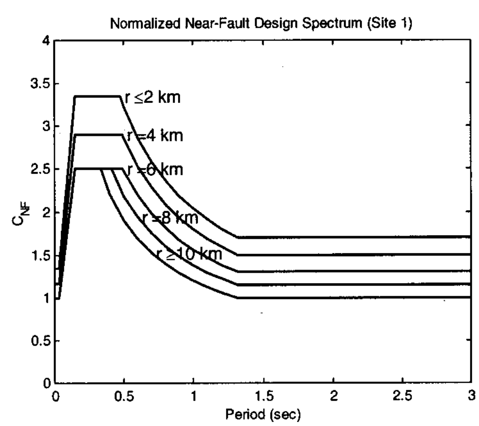

Figure 9. Near-fault seismic design spectrum for site with different distance (r) to the fault. The NA and NV values are also shown with respect to distance (Chai et al. 2000).

shows the normalized spectrum coefficients with the modification of near-fault ground motion characteristics (Chai, Loh and Chen 2000). The result of the analysis was passed to the recovery and reconstruction committee.

INTERPRETATION OF BUILDING DAMAGE

The distribution of building damage was determined from field survey data and plots of the damage data on the 1/5000 scale topographical map. Building damage was classified into five categories by the building damage survey team: Collapse, Severely leaning and tilting, Severe damage, Moderate damage (extensive cracks), and Minor damage (usable building with small cracks). Widespread damage to old reinforced concrete (RC) structures was reported after this earthquake, particularly in low-rise RC structures designed with pre-1974 building codes. After the field survey, the features of building damage were identified:

1. Five typical failure modes were found:
    a. "Soft" first story or overturning moment (due to large open space at ground level),
    b. Short column failure (particularly for school buildings),
    c. Inadequate arrangement of the structural system, which included improper open space design in the lower level of building and improper basement design of tall buildings in the basement of parking are
    d. Building across the fault, and
    e. Liquefaction-induced settlement of the buildings.
2. Structural detailing problems (failure in lap splices).
3. Three-story or four-story dwellings with commercial operations in the soft first story had few interior walls to resist lateral loads, thereby sustaining partial or total collapse.
4. Construction of reinforced concrete frame in Taiwan includes both pure frame construction and frame-wall construction. The frame-wall construction must be included in the design in order to prevent the use of nonstructural walls as frame-wall systems.

The building damage survey data was fed back to the data management center and was plotted in relation to the fault rupture, as shown in Figure 10. The damage survey indicated that the total number of the damaged reinforced concrete buildings had reached 50% of the structural damage recorded in the survey report. According to the report, about 75% of the damaged RC buildings are one- to five-story buildings, and 52% of these damaged low-rise buildings are classified as severely damaged. The report also indicated that approximately 84% of the RC damaged structures are buildings with pedestrian corridors (not properly designed in beam-column joint).

Based on the degree of damage classification of building structure in HAZUS, four building damage classifications were specified: complete collapse, extensive damage, moderate damage and slight damage. With these classifications the vulnerability curves

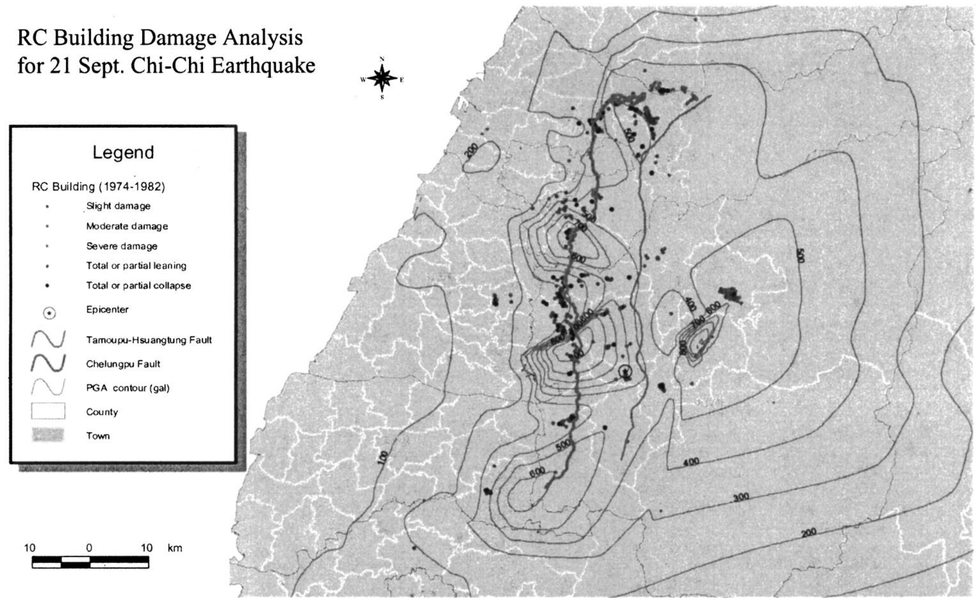

Figure 10. Damage distribution of reinforced concrete buildings (constructed in the period between 1974–1982) along Chelungpu Fault. PGA contour lines are also shown (NCREE Report 1999).

of building structures were also developed from the building damage data. The damage data for mid-rise reinforced concrete buildings were selected for analysis. First, define the Damage Ratio (DR) as the number of damaged buildings at a specific spectral acceleration value divided by the total number of damaged buildings in that category. Figure 11a and 11b show the cumulative damage ratio with respect to a specific spectral acceleration for mid-rise reinforced concrete buildings constructed before 1974 and between 1974 and 1982, respectively. Figure 11 does not represent the fragility curves of building structures. It only reflects the building damage situation in that particular area.

INTERPRETATION OF BRIDGE DAMAGE

Based on the damage survey of bridge structures, the following major damage modes were identified:

1. displaced bearings, unseated girders and settlement of the approach slab,
2. shear failures in columns and pier walls,
3. abutment back-wall failure,
4. joint failures in column-to-girder connections,
5. foundation failures due to soil liquefaction, and
6. fault rupture induced collapse of the superstructure.

The evolution of seismic design codes of bridges in Taiwan can be traced back to

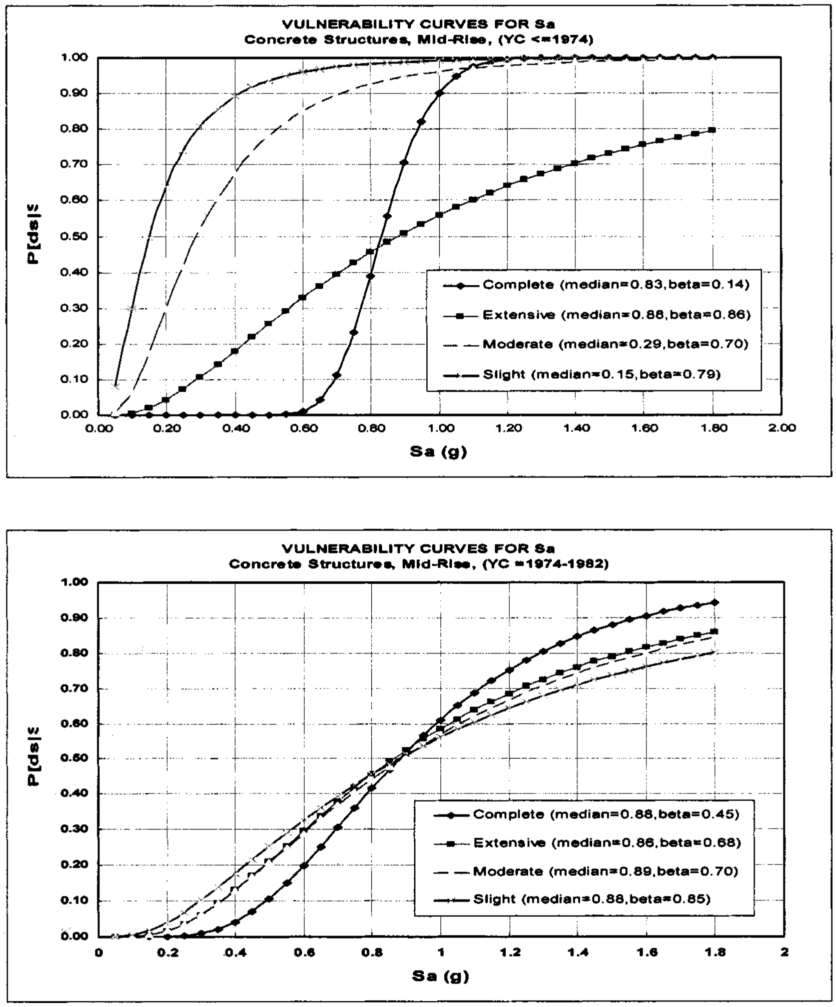

Figure 11. Vulnerability curves generated from building damage survey data of the Chi-Chi earthquake. The top figure indicates vulnerability curves for mid-rise RC buildings constructed in the period before 1974, and the bottom figure indicates mid-rise RC buildings constructed in the period of 1974–1982 (Loh 2000f).

1960. The "Engineering Design Code for Highway Bridges" was announced by the Ministry of Transportation at that time, but the code contained no specific guidelines for seismic design. In 1987, the revised highway bridge design code included seismic resistant concepts, geological site characteristics, and dynamic amplification factors. For the Chi-Chi earthquake, approximately 20% of bridges in the affected area suffered minor to major damage (Chang et al. 2000). To investigate the damage situation, a total of five damage states were defined for highway system components (similar to the damage criteria provided by HAZUS). The corresponding failure mechanisms are shown in Table 1 and defined as follows: none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4),

Table 1. HAZUS damage states and corresponding failure mechanisms

HAZUS damage state	Failure mechanisms
No damage (ds1)	First yield
Minor damage (ds2)	Cracking, spalling
Moderate damage (ds3)	Bond, abutment backwall collapse
Extensive damage (ds4)	Pier concrete failure
Complete damage (ds5)	Deck unseating, pier collapse

and complete (ds_5). Figure 12 plots the relationship between damage state and estimated PGA for bridges (most of them were simply supported bridges) in the affected area during the Chi-Chi earthquake (Loh et al. 2000c, Loh et al. 2000d).

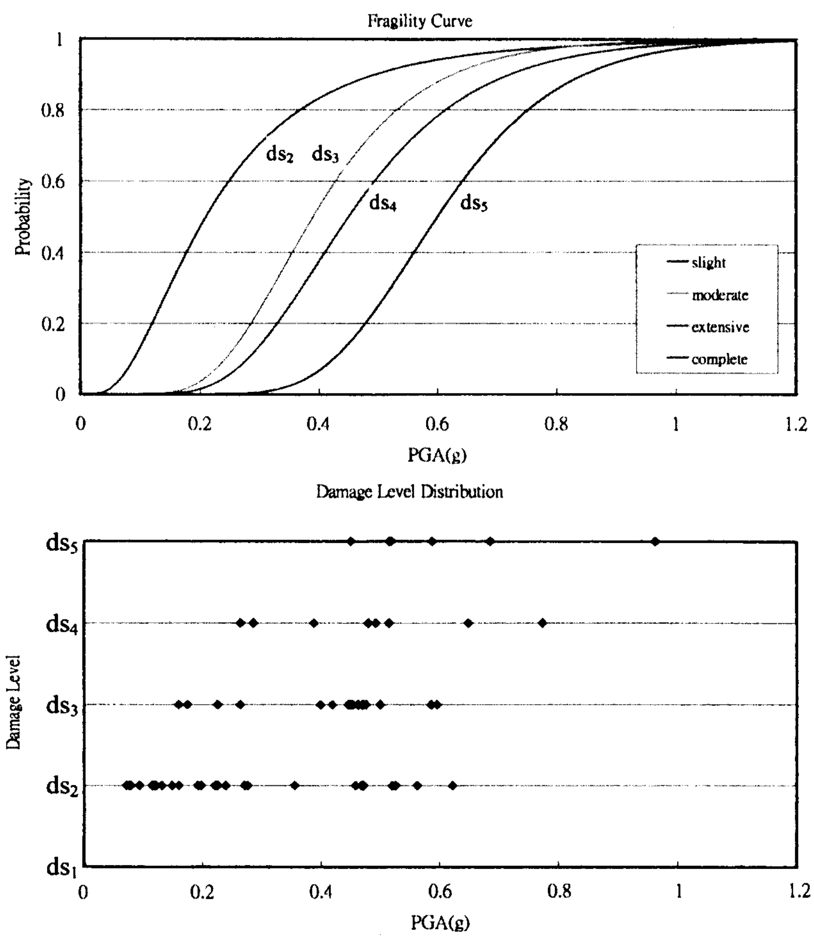

Figure 12. Plot of the developed fragility curves for simply supported bridges in Taiwan based on the damage data from the Chi-Chi earthquake. The bottom plot shows the relationship between bridge damage state and PGA (Loh and Huang 2000c).

Lessons learned from bridge damage are listed as follows:

1. Fault rupture, directly under or between bridge foundation, is a catastrophic event and span collapse is inevitable if the ground displacements are large.
2. Near-field ground motions are intense. It is necessary to develop the seismic design code for bridges to consider the characteristics of near-field ground motion (pulse-like wave in the velocity wave form). Generous seat widths are excellent insurance against the action of pulse-like waves, and shear keys are required to prevent spans falling transversely from the pier caps.
3. For restoration and retrofit of bridge structures, the following design concepts can be considered: (a) enhancement of ductility (i.e., increase deformation ductility), (b) enhancement of strength (i.e., increase stiffness or strength), (c) application of base-isolation systems to bridge structures (i.e., increase energy absorbing ability).
4. Capacity design procedures and ductile details are necessary to prevent collapse during large earthquake. Multilevel performance criteria and corresponding design strategies are necessary for important bridges.

GEOTECHNICAL DAMAGE INVESTIGATION

Large-scale landslide and slope failure occurred within the focal distance of about 60 km. Huge landslides at Chao-Ling and Mt. Joi-Fun-Ell-Shan and huge slope failures at Guru-Guan and Mt. Joyen Shan were reported. These landslides mobilized millions of cubic meters of rock and soil that slid across adjacent rivers, creating large landslide dams. River blockage, especially at Tsao-Ling, was accompanied by the formation of lakes and flooding of the upstream river valleys. As water rose, there was the potential for overtopping and downstream flooding. Although emergency spillways have been constructed to prevent overtopping and possible breaching, dam failures may still occur due to large inflows into the impoundment during rainy seasons. As a result, the downstream valleys will have serious inundation, compromising the safety of people and properties. Simulation of the inundation potential of downstream valleys of the landslide lakes based on hydrologic and hydraulic studies was conducted immediately. Upstream hydrologic analysis is employed to describe the rainfall-runoff characteristics for the corresponding watersheds.

Serious soil liquefaction in earthquake-affected areas was observed. Significant soil liquefaction occurred in widespread areas during the earthquake including Miaoli, Taichung, Changhua, Yuanlin, Nantou, and Jiayi. Typical liquefaction-related phenomena such as sand boiling with water ejection from the ground, lateral spreading, flow failure, and damage to building foundations were very common in these areas. Since soil liquefaction and associated lateral spreading caused settlement or differential settlement at the foundation of structures, serious damage was induced. The Yuanlin area is identified as one of the largest areas of liquefaction. A deterministic approach was used to evaluate the liquefaction potential of these areas.

Field investigation of soil liquefaction was conducted at designated areas reporting liquefaction and ground subsidence. Soil liquefaction can only occur if specific ground

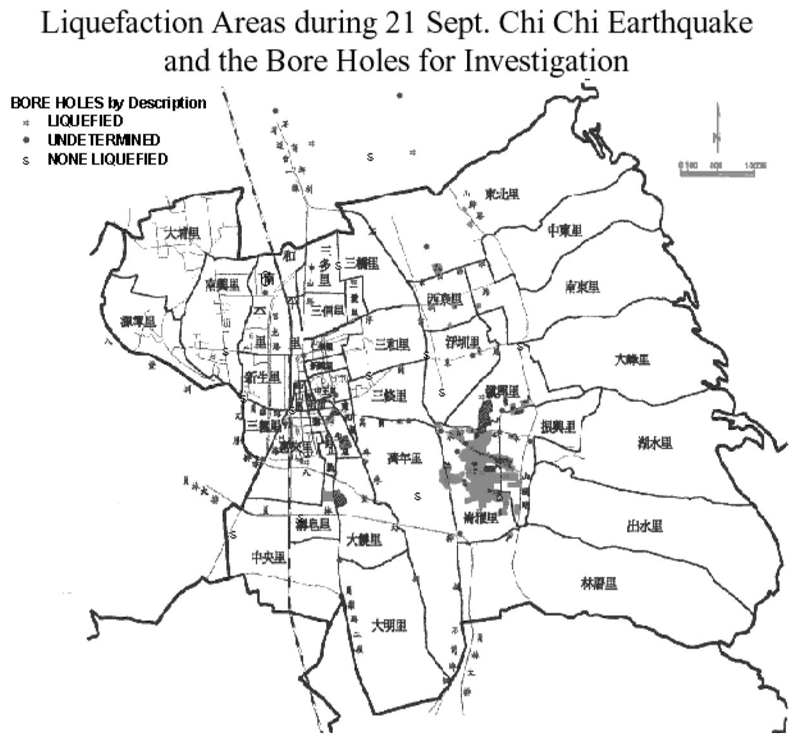

Figure 13. Liquefaction area in Yuanlin and the distribution of borehole locations at Yuanlin. Shaded areas indicate subsidence regions (Moh and Associates 2000).

conditions exist, therefore there is no clear relationship between the distribution of reported liquefaction site and the fault. For research on liquefaction potential, NSC performed detailed site investigations in the Yuanlin area. Data from a total of fifty boreholes were collected in the liquefied area, as shown in Figure 13. A single seismic time history was collected from the CWB strong motion array data near the liquefied area. The data were used to analyze the liquefaction potential. Seed's method and the Tokimatsu and Yoshimi method were used in this study. Once the probability of liquefaction at each soil layer was estimated, the liquefaction potential at a site, P_L, could be determined using the following weighting scheme along the depth of each site:

$$P_L = \int_0^{20} p_L(z) \cdot W(z)dz \Big/ \int_0^{20} W(z)dz \qquad (2)$$

where $P_L(z)$ is the liquefaction probability at depth z. $W(z)$ is the weighting function along the depth ($W(z)=1-0.05z$). It indicated that at depth greater than 20 meters the liquefaction probability is equal to zero. Figure 14 shows the estimated probability of liquefaction along the depth of soil deposit at BH-026 site (Seed et al. 1975). Comparison of the estimated liquefaction potential using different methods is also presented.

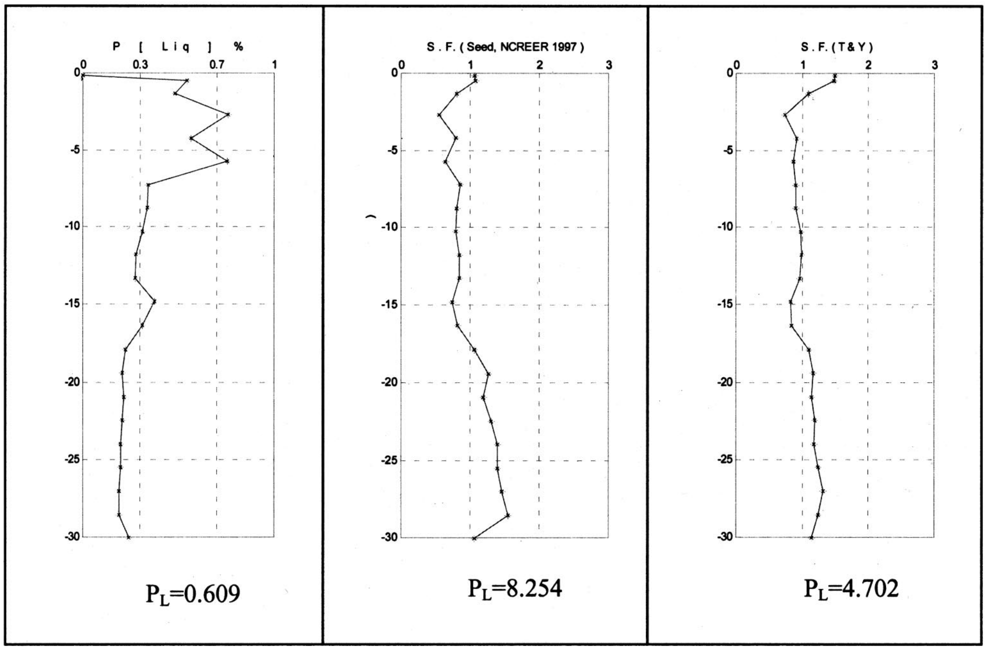

Figure 14. Comparison of the estimated liquefaction potential (PGA=0.19g, M=7.5) at BH-026 station by using three different methods: Probabilistic analysis (Loh and Shen 2000e), Seed method and T-Y method. The estimated P_L value from each method is also presented.

DAMAGE INVESTIGATION OF LIFELINE SYSTEMS

Damage surveys of lifeline systems included electric power systems, natural gas systems, communication systems, and water and sewer systems. Damage to lifeline systems was severe but tolerable. The damage investigation of water supply system in the earthquake- affected area was found that most of the significant damage was concentrated on the northern part of Chelungpu Fault. From the distribution of peak ground velocity (PGV) significant PGV value was observed on the northern part of Chelungpu Fault where severe damage of water supply system was observed. The fragility curves of the water supply system were also generated and expressed the repair rate with respect to PGV value.

The only exception was damage to the electric power system. The loss of the extra-high voltage transmission system, including 28 345 KV-lines and the Chung-Liaw switchyard, caused the worst blackout event ever in Taiwan. In addition, strong ground shaking and soil liquefaction at Chung-Liaw switchyard caused foundation displacement and subsidence, and damaged equipment severely. Landslides and ground failures damaged the 345 KV transmission towers in the mountain areas. As a result, power transmission lines were severely damaged, causing interruption of power transmission from the south to north. The whole middle and north of Taiwan experienced blackout immediately after the earthquake, which lasted for two to three days. Based on the damage survey the following observations are made:

1. A large number of transmission tower failures were apparently due to the fact that they are constructed over rugged mountain areas with steep slopes susceptible to ground failure. Retrofit tower foundations at these areas are necessary. The earthquake-induced slope stability issue also needs to be studied.
2. Because of lack of redundancy in the power transmission system, a system analysis capability should be developed for pre-event estimation of the seismic reliability of transmission and distribution networks.
3. Enhanced seismic protection, including base isolation for generating plant equipment and substations appear to be important.

CONCLUSIONS

The purpose of this paper is to describe the immediately response from NCREE and NAPHM after the Chi-Chi earthquake. The application of real-time seismic information and the utilization of new technologies such as earthquake loss estimation and GIS to the investigation of damage data helped to quickly make data available. The response from NCREE and the project office of hazard mitigation was described. Data management from reconnaissance teams and its application were summarized. The preliminary investigation of the damage data as well as the follow-up information collected from the Chi-Chi earthquake can be used for a better understanding of this earthquake and its impact to the engineering communities. The following conclusions are drawn:

1. For emergency response and the postdisaster measures, the strong motion data collected from this earthquake provides a very useful message. It is very efficient to have one organization (CWB) in charge of the strong motion data collection. Strong motion data immediately released through the Internet to research institutes and reconnaissance teams can help the emergency response and recover teams make the right decisions. From an engineering point of view, these particular earthquake strong ground motion data with near-field ground motion characteristics have to be taken into consideration in the revision of seismic design standards, particularly the treatment of surface ruptures caused by fault activities. Seismic zonation maps must be critically reviewed to reassess the national seismic risk and desired earthquake protection levels.
2. The development of an emergency response plan and disaster assistance program (such as HAZ-Taiwan Program) needs to be accelerated and further researched. There is a great need for all levels of government in Taiwan to institutionalize earthquake preparedness and mitigation programs. Based on the result of structural damage investigations, the fragility curves of buildings, bridges and buried pipelines need to be developed. These curves can reflect the true structural situation. These fragility curves can be implemented to the HAZ-Taiwan earthquake loss estimation program.
3. Based on experiences in the Chi-Chi earthquake damage investigations, it was found that GIS and GPS can play a very important role in large-scale disaster management. Earthquake damage information can be quickly assembled into GIS databases for emergency response decision support. GIS can also integrate

information coming from various sources and present the whole picture of the damage situation. The progress of the rescue information can also be tracked by the GIS.

4. The extensive vulnerability of the existing building inventory, as revealed by this earthquake, must be addressed before other equally destructive earthquakes strike again in Taiwan.

REFERENCES

Applied Technology Council, 1985. *Earthquake Damage Evaluation Data for California, ATC-13*, Redwood City, CA.

Chai, J. F., Loh, C. H., and Chen, C. Y., 2000. Consideration of the near-fault effect on seismic design code for sites near the Chelungpu Fault, *J. Chin. Inst. Eng.* **23** (4), 447–454.

Chang, K. C., Chang, D. W., Tsai, M. H., and Sung, Y. C., 2000. Seismic performance of highway bridges, *Earthquake Engineering and Engineering Seismology* **2** (1), March, 55–77.

Jean, W. Y., and Loh, C. H., 2000. Seismic design implications of 1999 Taiwan Chi-Chi earthquake, *Proceedings of 1st Int. Conf. on Structural Stability and Dynamics*, Taipei, Taiwan.

Lee, W. H. K., and Shin, T. C., 1997. Real time seismic monitoring of buildings and bridges in Taiwan, *Proceedings of 1st Int. Conf. on Structural Health Monitoring* (edited by F. K. Chang), Stanford University, Technomic Pub. Co., Lancaster, PA, September, 777–787.

Lee, C. T., and Tsai, Y. B., December 1999. National Central University, private communication.

Liao, W. I., Loh, C. H., Wan, S., Jean, W. Y., and Chai, J. F., 2000. Dynamic response of bridges subjected to near-fault ground motions, *J. Chin. Inst. Eng.* **23** (4), 455–464.

Loh, C. H., Lawson, R. S., and Dong, W., 2000a. Development of a national earthquake risk assessment model for Taiwan, *Proceedings of 12th WCEE, New Zealand*, January.

Loh, C. H., Lee, Z. K., Wu, T. S., and Peng, S. Y., 2000b. Ground motion characteristics of the Chi-Chi earthquake of 21 September 1999, *Earthquake Eng. Struct. Dyn.* **29**, 876–897.

Loh, C. H., and Huang, Y. J., 2000c. Seismic fragility analysis of highway bridges, *Proceedings of Int. Conf. on Monte Carlo Simulation*, Monaco, June.

Loh, C. H., Wan, S., and Chang, Y. W., 2000d. Seismic demands of bridges subjected to near-fault ground motion, *Proceedings of 2nd Int. Workshop of Mitigation of Seismic Effects on Transportation Structures*, September, 54–64.

Loh, C. H., and Shen, J. C., 2000e. Evaluation of liquefaction potential using field data: Probabilistic aproach, *Proceedings of Int. Workshop on Annual Commemoration of Chi-Chi Earthquake*, **III**, 95–106.

Loh, C. H., 2000f. Lessons learned from Chi-Chi (Taiwan) earthquake, *Proceedings of Kobori Symposium*, Kyoto, November.

Moh and Associates, 2000. Liquefaction Evaluation of Yuanlin Area—Phase 1, *Technical Report No. 773-1-1*, Taipei, Taiwan, April.

NCREE Report, *Reconnaissance Report on 921 Chi-Chi Earthquake*, Dec. 1999. Vol. 1: Geoscience investigation, (P. I.: Prof. C. Y. Huang of NTU). Vol. 2: Ground motion study, (P. I.: Prof. K. L. Wen of NCU). Vol. 3: Geotechnical investigation, (P. I.: Prof. M. L. Lin of NTU & NCREE). Vol. 4: Building damage investigation, (P. I.: Prof. K. C. Tsai of NTU & NCREE). Vol. 5: Transportation system investigation: Bridges, (P. I.: Prof. K. C. Chang of NTU & NCREE). Vol. 6: Lifeline damage investigation, (P. I.: Prof. B. T. Sheh, of NTUST).

Vol. 7: Hydraulic system damage investigation, (P. I.: Prof.: M. S. Hsu of NTU). Vol. 8: Industrial facility damage investigation (P. I.: Prof. C. C. Lin of NCHU). Vol. 9: Social economic impact investigation (P. I.: Prof. H. C. Wang of NTU). Vol. 10: Lessons learned from the 921 Chi-Chi earthquake: An integrated recommendation, (P. I.: Prof. C. H. Loh of NTU & NCREE) Summary Report.

National Institute of Building Sciences, 1999. *Earthquake Loss Estimation Methodology—HAZUS97 Technical Manual*, National Institute of Building Sciences, Washington, D.C.

Seed, H. B., Arango, I., and Chan, C. K., 1995. *Evaluation of Soil Liquefaction Potential During Earthquake, Report No. EERC 75-28*, Earthquake Engineering Research Center, University of California, Berkeley.

Seismology Committee, Structural Engineers Association of California (SEAOC), 1996. *Recommended Lateral Force Requirements and Commentary*, Appendix-C, San Francisco, CA.

Tsai, K. C., Hsiao, C. P., and Bruneau, M., 2000. Overview of building damages in 921 Chi-Chi earthquake, *Earthquake Engineering and Engineering Seismology* **2** (1), 93–108.

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