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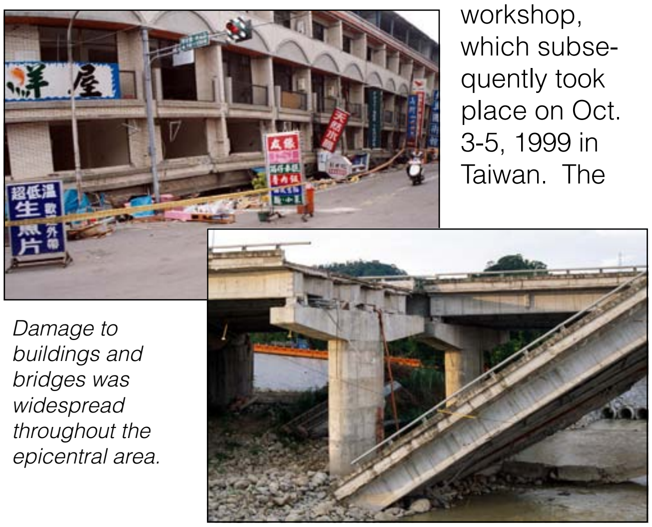
MCEER NCREE RESPONSE

PRELIMINARY REPORT FROM MCEER-NCREE WORKSHOP ON THE 921 TAIWAN EARTHQUAKE

by George C. Lee and Chin-Hsiung Loh

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 10 aftershocks greater than magnitude 6. Of these, an M_L = 6.8 occurred about 30 hours and 120 hours after the main shock, respectively. An M_L = 5.3 aftershock was recorded as long as 260 hours later causing collapses of already damaged structures. As of October 8, the death toll stands at more than 2,350. Over 8,700 people were injured, and dozens remain missing. Approximately 10,000 buildings/homes collapsed and over 7,000 more were damaged.

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 since 1995. Shortly after the 921 earthquake, we, as representatives of the two Centers, discussed the possibility of an MCEER-NCREE workshop, which subsequently took place on Oct. 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.



Damage to buildings and bridges was widespread throughout the epicentral area.

Surface faulting caused major damage to the Shih-kang Dam.

The workshop began with a briefing led by Professor Loh on the earthquake. This was followed by a brief presentation by Paul Flores, EQE, on short-term restoration strategies following the Northridge earthquake and by Mr. Tomio Saito, Director of Hyogo Prefecture in Japan, on Kobe's experience with short-term restoration strategies. The group then began its reconnaissance mission with a visit to Taichung. The next day was dedicated to reconnaissance, with MCEER and NCREE investigators paired together to focus on specific areas.

On the third day, participants made brief presentations concerning their field observations, discussed the mechanics of authoring reconnaissance reports, and identified additional individuals to contribute to the reports. Their preliminary reports are included in this issue of *MCEER/NCREE Response* and are also available on our web site at *http://mceer.buffalo.edu*. A more substantial reconnaissance report will be published in the coming weeks.

A Summary of Earthquake Reconnaissance Efforts of the Multidisciplinary Center for Earthquake Engineering Research

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GEOLOGY AND TECTONICS OF TAIWAN

by Chin-Hsiung Loh and George C. Lee

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-Teritary 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.

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 1. 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 1. Some high-angle reverse faults in central Taiwan have been recognized to be associated with large-magnitude earthquakes.

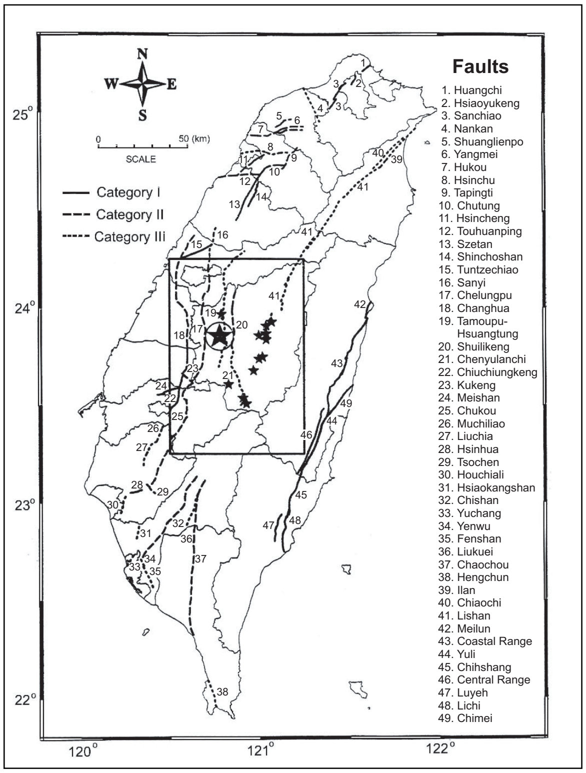


Figure 1. Active faults in Taiwan.

THE 921 EARTHQUAKE

The 921 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 joints 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 921 earthquake caused 7-8 meters of displacement along certain sections of the Chelungpu fault (see Geotechnical Issues on page 4).

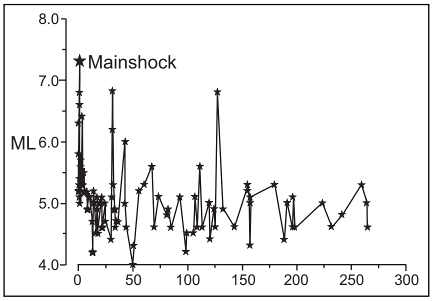


Figure 2. Time sequence of aftershocks within six hours, magnitudes greater than 4.

More than ten thousand aftershocks occurred. Figure 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 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 with the fault system. Based on the strong motion data collected by the Seismology Center of the Central Weather Bureau, Figure 4 shows the attenuation of the intensity of this earthquake in terms of PGA-values. Both two horizontal directions' PGA values 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.

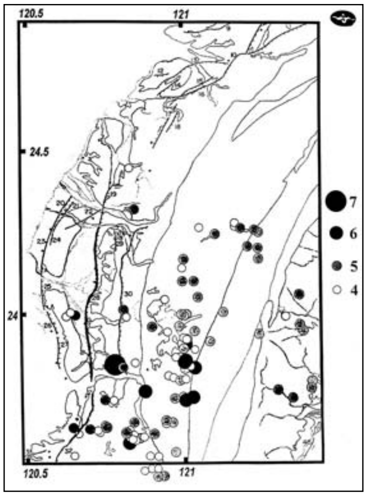
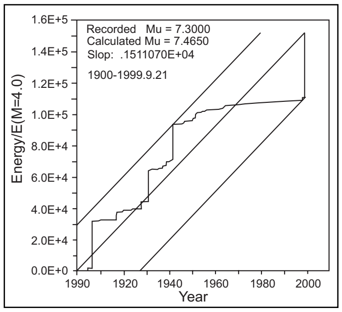


Figure 3. Epicenters of aftershocks.

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 is exact for the 921 earthquake that is associated with the Chelungpu fault system. The constant energy release model is used to estimate the maximum magnitude. The result is shown in figure 5. Including the data caused by the 921 earthquake, the maximum credible earthquake magnitude will be about 7.5 local magnitude in the future.



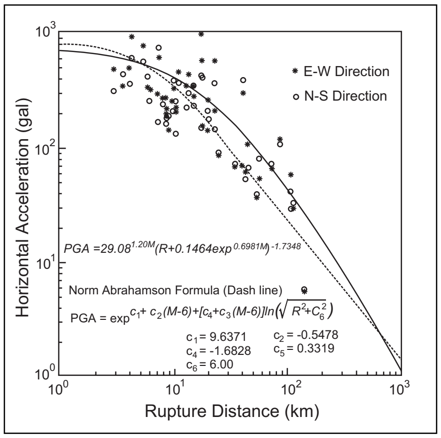


Figure 4 (top). Attenuation of earthquake intensity in terms of PGA values. Figure 5 (bottom). Maximum credible earthquake as estimated by the constant energy release model.

GEOTECHNICAL ISSUES

by Thomas D. O'Rourke and Meei-Ling Lin

The sources of permanent ground deformation of most importance during the 921 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 as the effects of landslides and surface faulting.

LANDSLIDES

There were literally scores of 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 2 to 5 m. A large proportion of the landslides were considerably deeper and broader. The largest landslides were located at Tsao-Ling Mountain near the village of Tsao-Ling and Jio-Feng Err Mountain near the village of Nangkang. 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 that are flooding the upstream river valleys. As water rises, there is the potential for overtopping and downstream flooding.

Figure 1a and b shows views of the landslide at its eastern and western margins, respectively. The landslide is at the location of previous landslides that occurred in 1941, 1942, and 1979. The landslide was generated primarily by failure of the Chin-Shui Shale Formation that underlies the Chao-Lan Sandstone (see Figure 1b). The shale is a friable, silty mudstone with weak cementation that deteriorates readily upon wetting and drying.

Recommendations for Short-Term Recovery

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. Debris flow hazards are especially severe because the earthquake has loosened and failed a considerable amount of soil and rock in addition to exposing deforested mountains and hillsides to the elements. 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.

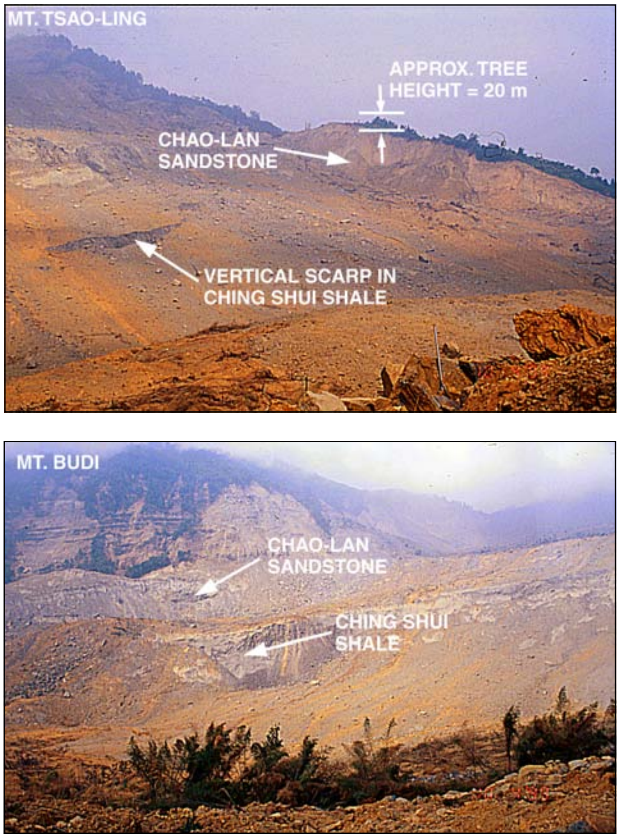


Figure 1a (top). Eastern and Figure 1b (bottom). Western boundary of Tsao-Ling landslide.

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 (see Applications of Remote Sensing, page 14).

SURFACE FAULTING

Some of the most notable ground failures associated with the 921 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 Tung-Feng Bridge and Shih-kang Dam, both of which spanned the Tachia Hsi 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 millions of cubic meters of water. This loss represents 40% of the raw water supply for Taichung County. Figure 2a is a photograph of the northern abutment area taken downstream of the dam, and Figure 2b is a photograph of the northern abutment from the vertically displaced southern part of the dam.

The effects of surface faulting in the 921 earthquake are broadly similar to the surface faulting effects of the August 17, 1999 Kocaeli earthquake in Turkey. Rupture of the Northern Anatolian fault during the Kocaeli earthquake caused a highway bridge to collapse and caused extensive damage to the main Turkish naval base in Golcuk. 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 921 and Kocaeli 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.

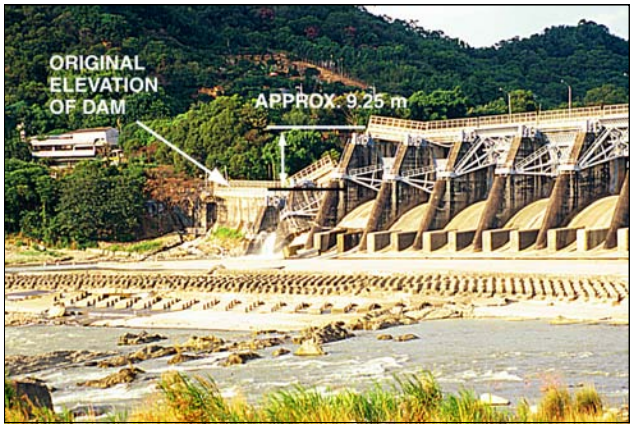


Figure 2a (top). View of northern end of Shih-kang Dam showing over 9 m of vertical offset at Chelungpu Fault and Figure 2b (bottom). View from uptrust side of Shih-kang Dam looking north.

Recommendations for Short-Term Recovery

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 re-use, 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.

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 California faults are controlled by state legislation, known as the Alquist-Priolo Act, that places substantial restrictions on new construction in active fault zones. Land use planning in Taiwan must take account of its high population density and limited options for land use. It will be advantageous to consider 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 were apparently not seriously damaged. This observation applies even to non-ductile concrete frames and unreinforced masonry structures. Similar observations have been made for the Kocaeli 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.

Damage to Critical Facilities

by Tsu T. Soong and George C. Yao

Critical facilities planned to be visited during the one-day reconnaissance tour included hospitals, schools, police stations and other public buildings. While we had opportunities to inspect damage in some of these structures, due to time limitations, it was decided to concentrate our efforts on hospitals. Three hospitals were chosen for their strategic value, extent of damage, and human and economic impact.

Inventory

According to available information, there are 4,375 health care facilities within the six-county seismic affected zone, of which 165 are hospitals. Some suffered significant nonstructural as well as structural damage.

Hospitals Visited

The three hospitals chosen for more in-depth site visits were: the Christian Hospital and the Veterans Hospital in Puli, and Shiu-Tuan Hospital in Tsushan. All three are major health care facilities in their respective cities. The observations described below are based on interior as well as exterior damage inspections and on interviews with hospital officials.

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

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

CHRISTIAN HOSPITAL

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 (see Figure 1).

Damage

- New section sustained considerable damage from the main event on 9/21/99. Out of safety concerns primarily due to nonstructural damage (power outage[1], 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.
- The first floor of the building remains open and is being used for emergency care, patient registration and processing, command post, etc. (see Figure 2).

Consequences and Impact

- A major part of the hospital is 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 is underway. It was estimated that the interior will be restored and serviceable in two weeks.

VETERANS HOSPITAL

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-yr. old) and smaller buildings (see Figures 3 and 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 (Bldg. 2), along with those in Bldg. 1, were either moved to the older buildings or transferred to other VA hospitals. About 220 patients remain at the hospital.
- Considerable nonstructural damage in Bldgs. 1 and 2, including power failure, water damage, and equipment damage was observed. Bldg. 1 also sustained considerable structural damage, probably due to a lack of ductile detailing.

Consequences and Impact

- A major part of the hospital is 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.

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

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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.

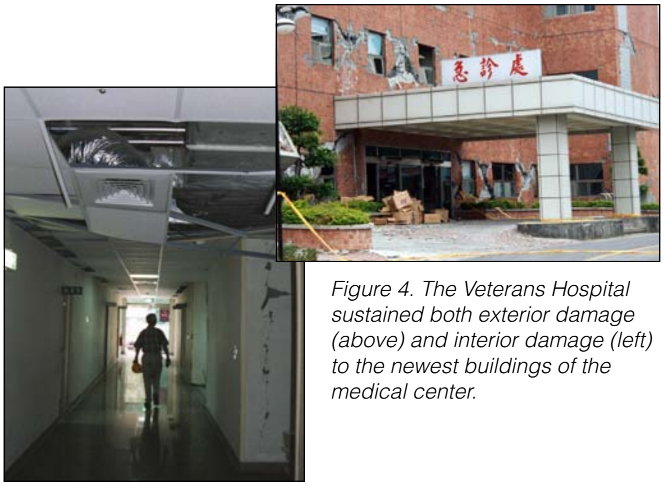


Figure 4. The Veterans Hospital sustained both exterior damage (above) and interior damage (left) to the newest buildings of the medical center.

- 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 is to be demolished or repaired remains to be determined. Bldg. 2 is expected to be repaired within two weeks.

SHIU-TUAN HOSPITAL

Shiu-Tuan Hospital is a 9-story, two-year-old RC building with a 400-bed capacity. It is privately owned and is the largest in Nantou County. The structure is situated about 120 m from the Tsa-Lung-Pu 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 (see Figures 5 and 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.

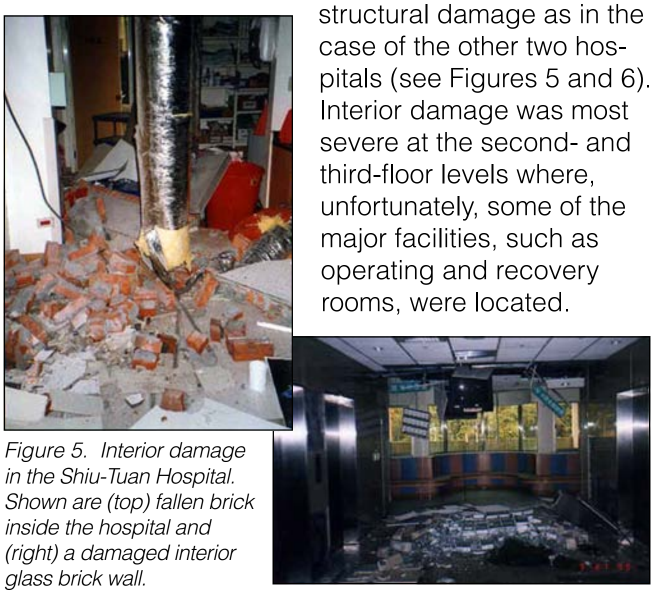


Figure 5. Interior damage in the Shiu-Tuan Hospital. Shown are (top) fallen brick inside the hospital and (right) a damaged interior glass brick wall.

- Hospital closed.

Consequences and Impact

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

Restoration

Repair is underway and the process may take one to two months. Funds for the repair remain to be found.

Figure 6. Damage to an exterior wall of the Shiu-Tuan Hospital in Nantou County.

OVERALL OBSERVATIONS

The damage to the three hospitals and its impact underscore the importance of addressing nonstructural issues. Performance of nonstructural components could be substantially improved, with attendant damage reduction, using rather simple and inexpensive means.

RECOMMENDATIONS FOR SHORT-TERM RECOVERY AND RESEARCH

- Review and improve current design and installation practices in nonstructural components.
- Develop effective retrofit strategies.
- Review and improve current nonstructural seismic provisions for hospitals and other critical facilities.

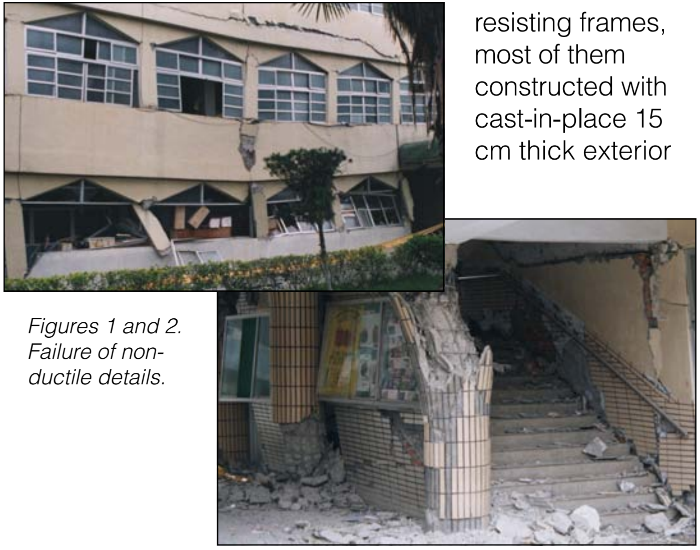
BUILDING DAMAGE

by Michel Bruneau and Keh-Chyuan Tsai

Preliminary data indicates that approximately 5,000 buildings totally collapsed as a result of this earthquake, with 8,000 others partially collapsed and countless others damaged to various degrees. While it will take considerable time and effort to inventory that 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.

A large percentage of buildings that collapsed due to the main shock or strong aftershocks are non-engineered one-to-three stories reinforced concrete frame structures constructed with brick in-fill 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 (see Figures 1 and 2). 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 windows above half-height in-fill shortened the effective length of almost all the columns.

However, in the affected area, more than two dozen modern 10- to 15-story apartment buildings overturned or collapsed (see Figure 3). These were reinforced concrete moment resisting frames, most of them constructed with cast-in-place 15 cm thick exterior walls 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 published. 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 of 22% and 43% 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 in the ground level. Current seismic force requirements are given in Table 1.



Figures 1 and 2. Failure of non-ductile details.

Figure 3. Failure of new construction.

Commonly encountered were failed columns with widely spaced stirrups (unconfined plastic hinge zone), splices with inadequate development length or located in the hinge region, light or non-existent joint transverse reinforcement, stirrups with 90°, etc. Strong-beam weak-column systems 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 translated into a lower structural stiffness and strength, leading to "soft-story" mechanisms (see Figure 4).

Most steel buildings have been constructed in the last decade. Steel frame buildings are quite common

Table 1. Seismic force requirements in Taiwan.

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

for buildings taller than 25 stories in Taichung City, about 50 km northwest of the epicenter. Damage to steel buildings had not been reported at the time of this writing, beyond the collapse of a few old light warehouses typically having small built-up columns. However, experience in post-earthquake investigations shows that such damage can take much longer to surface; steel structures being generally hidden and covered by fire proofing. Brace fractures and other damage observed to bin and tank supports in many aggregate-producing plants suggests that non-ductile details also exist in steel structures in Taiwan.

Lessons Learned

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 non-structural 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 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.

Conclusions and Recommendations for Short-Term Recovery

- Given the extensive damage suffered by reinforced concrete buildings that clearly exhibit 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.

- Seismic zonation maps must be critically reviewed to reassess 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.

- 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 having soft stories and an open front. This requires the establishment of priorities, timetables, 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 buildings (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.

Figure 4. Failure due to soft first story.

BRIDGE DAMAGE

by Ian G. Buckle, Kuo-Chun Chang and Jenn-Shin Hwang

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 kms of road remained closed, and another 400 kms, while open to traffic, were subject to delay and capacity restrictions (Figure 1).

Many hundreds of bridges are located in the 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.

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 new cable-stayed bridge. Table 1 gives a summary of the pertinent data for these ten bridges. Figure 1 shows their approximate locations on Routes 3, 129 and 149, and their proximity to the epicenter at Chi-chi and the Chelungpu fault. 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 0.4 g), and average fault dislocations of approximately 1.5 m horizontally and 3 m vertically.

Figure 1. Highway closures and bridges with significant damage in Taichung and Nantou counties.

Table 1. Partial list of bridges with significant[1] damage.

Bridge ID	Bridge Name	Route No.	Date of Construction/ Widening	Type	Spans	Total Length (m)
1,	Tong-tou	149	1980	RC[2]	4 x 40 m	160
2.	Ming-tsu	3	1990	RC	28 x 25 m	700
3.	Mao-luo-shi	3	1999	Steel/RC[3]	8-span segment	
4.	Wu-shi	3	1981/83	PC[4]	18 x 34.7 m	624
5.	E-jian	129	1972	RC	24 x 11 m	264
6.	Tong-fong	3	1962/88	RC	22 x 26 m	572
7.	Shi-wei	3	1994	PC	3 x 25 m	75
8.	Ji-lu		1999	Cable-stayed	2 x 150 (?) m	300 (?)
9.	Bei-feng[5]	Located downstream of Shih-kang dam across Tachia Hsi				
10.	Chang-geng[5]	Located upstream of Shih-kang dam across Tachia Hsi				

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
5. Not visited in this reconnaissance effort, data not available at this time

Damage to these ten bridges 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, and fault rupture. Figures 2, 3, 4, and 5 illustrate some of this damage.

LESSONS LEARNED

The following set of lessons learned includes new lessons, not previously seen so clearly, and some old lessons that are to be remembered.

- Fault rupture, directly under or between bridge foundations, is a catastrophic event and span collapse is inevitable if the dislocations are large.

Figure 2 (below). Failure of the back-wall of the south abutment of the Ming-tsu bridge (Route 3), leading to the unseating of adjacent spans. Figure 3 (right). Shear crack in Pier 1 of the Wu-shi bridge (Route 3).

- 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.
- 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.

RECOMMENDATIONS FOR SHORT-TERM RECOVERY

Recovery strategies can be divided into three classes:

- Immediate post earthquake period (1 to 90 days).
- Reconstruction of collapsed or crippled structures (3 to 12 months).
- The construction of new structures (1 year onwards).

The urgent need to reopen closed highways, immediately following a damaging earthquake, requires emergency powers to command the resources to construct bypasses around bridges with collapsed spans, erect shoring, reinstate bearings, fill and resurface settled approaches, and erect temporary bridging (e.g., Bailey bridges). All of these options are common sense and self-evident to bridge engineers and emergency management personnel.

However, when design commences for the replacement structures (the reconstruction phase), it is not always clear how to proceed. It is unlikely that the causes for collapse and sustained damage will be fully understood and agreed at this time. Yet the design process cannot wait until all the answers are known and must proceed. It is therefore recommended that a conservative strategy be adopted for the reconstruction phase, to minimize the risk of repeating past deficiencies. For example, seat widths may be arbitrarily increased, 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.

As agreement is reached on the causes of damage, and improved design methodologies developed, the conservatism in the above approach might be relaxed, and the bridge design code revised for all future construction. A moratorium on new construction might be considered until the revised code is available. But this may take several years to complete, and an interim set of guidelines might be preferred instead of a moratorium. Such a set of guidelines might be based on the conservative procedures used for the reconstruction phase.

Figure 4 (right). Rigid-body rotation of Pier 10 due to ground failure under the E-jian bridge (Route 129). Figure 5 (below). Tilting of Pier 2 and subsequent collapse of three spans of the Shi-wei bridge (Route 3).

LIFELINE DAMAGE: ELECTRIC POWER SYSTEMS

by Masanobu Shinozuka, Gee-Yu Liu and Chin-Hsiung Loh

The September 21, 1999 earthquake in Taiwan 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.

Regarding the 345 KV transmission system (Figure 1), a significant number of transmission towers suffered from structural problems, and were tilted and displaced causing a large number of transmission lines to fail (marked with an X in Figure 1). This in turn caused the initial blackout throughout the middle and north of Taiwan. In addition, 161 KV (Figure 2) and 69 KV transmission systems in the affected area also suffered from similar failures. 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 yard and the north yard) that were both significantly damaged. 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 1, and hence the functional loss of these yards was at least partially responsible for the post-earthquake power interruption.

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.

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

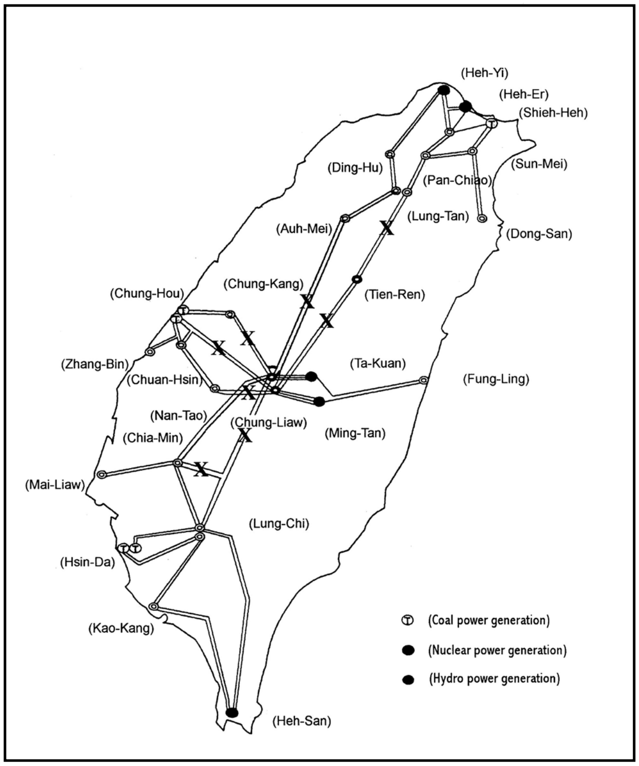


Figure 1. 345 KV electric power transmission system.

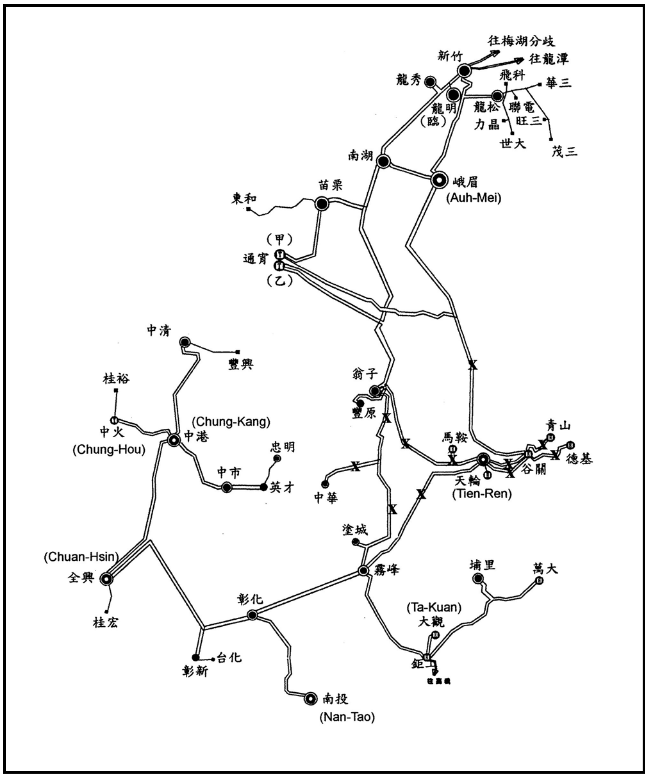


Figure 2. 161 KV electric power transmission system.

ground failure. It might be well advised to design, construct, and retrofit tower foundations with this in mind.

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.

MCEER NCREE RESPONSE

A full-color version of this publication is available via MCEER's web site at http://mceer.buffalo.edu. The web site also features numerous photographs of the area taken by the reconnaissance team. Links to other sites containing information about the earthquake are provided.

APPLICATIONS OF REMOTE SENSING

by Masanobu Shinozuka, George C. Lee, Zhe-Jung Chen and Chin-Lien Yen

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 orthorectified 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 Tai-Chung (distance approximate) including Tsao-Lin before (Figure 1) and after (Figure 2) 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 2 clearly shows the landslide locations caused by the earthquake. Three-dimensional images of a smaller area were constructed before (Figure 3) and after (Figure 4) the event (March 6 and September 27, 1999, respectively), utilizing an existing topographical map together with SPOT images.

3. Enlarged SPOT images at the site of failure of the Shih-kang dam after and before event (Figures 5 and 6,

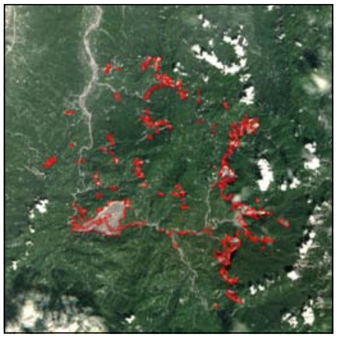


Figure 1 (left). SPOT image of a 25 km x 25 km area 50 km south of Tai-Chung before the event (distance approximate). Figure 2 (right). Landslide areas identified after the event.

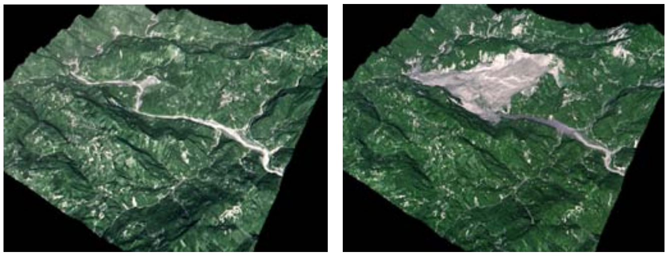


Figure 3 and 4. 3-D images of a landslide area near Tsao-Lin before (left) and after (right) the event.

respectively). In the center of Figure 5, 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 6.

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 such a map as in Figure 7 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.

Figure 5 and 6. Images of Shih-kang Dam area after (top) and before (bottom) the event.

Figure 7. GIS map and aerial photos.

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.

ECONOMIC CONSIDERATIONS

by Stephanie E. Chang

From an economic standpoint, the "921" earthquake is a major disaster that has not only caused serious damage to the economy of central Taiwan but will have national repercussions as well. The disaster region includes five cities and counties in central Taiwan, of which Nantou and Taichung counties and Taichung city were most severely hit. This region accounts for nearly five million people, or one-fourth of Taiwan's population. It spans urban areas (Taichung) as well as remote mountainous regions and numerous rural towns. Power outage lasting for 1-2 weeks affected a much broader area, including most of central and northern Taiwan (where much of the industrial activity, as well as Taipei city, are located). In the areas of heaviest damage, agriculture and agricultural processing (e.g., tea), tourism, and wine production are important economic sectors. All of these suffered major damage to facilities. The destruction of housing stock and large displacement of population will also hinder economic recovery. Taiwan had not experienced a disaster of this scale in recent memory.

OBSERVATIONS

As of this writing, government and other agencies are still in the process of gathering data on the extent of damage caused by the earthquake. Early estimates of loss varied substantially, from NT $100 billion (US $3.1 billion) to NT $1 trillion (US $31 billion), the latter being equivalent to 10% of gross domestic product (GDP) and including both damage and business interruption. The most recent estimate is a total economic loss of NT $250 billion (US $7.8 billion). Repairs to transportation and communications infrastructure are reported at about NT $10 billion (US $31 million).

The disaster is widely anticipated to have a noticeable but not severe impact on the national economy. The central government anticipated that 1999 GDP growth would be dampened to 5.5%, as compared to a pre-disaster forecast of 5.74%. Much of the expected 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. Over 400 large companies on the Stock Exchange reported total structural and equipment damage of NT $1.9 billion (US $59 million), goods inventory loss of NT $2.1 billion (US $66 million), and sales loss of NT $7.9 billion (US $247 million). For these companies, at least, business interruption losses vastly outweighed the cost to repair or replace damage. However, it is unclear how much of the sales loss can be made up through overtime production.

One of the most significant economic issues arising from the disaster has been the impact of electric power outage on high-tech industries at the Hsinchu Science-based 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% of world production and providing components for many large computer manufacturers in the U.S. 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. As it was, speculation of ensuing computer components shortages led some overseas companies such as Hewlett-Packard to anticipate slight revenue losses. Global prices for some types of chips escalated. Industrial park management at Hsinchu estimated that the earthquake caused up to NT $10 billion (US $313 million) in loss to businesses at the park.

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. Only some 1% of property owners subscribed to earthquake insurance, which is tied to fire insurance coverage. Latest estimates indicate about NT $15.4 billion (US $480 million) in property insurance claims to date. 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 1 summarizes relief grants that are being offered by the central government to the disaster victims.

Low-interest (3%) and no-interest loans with a 20-year term are being offered to households and businesses for reconstruction. The government plans to finance these measures by drawing from the postal savings deposit system, issuing new bonds, and diverting proceeds from a special lottery which had been planned to seed the new national pension system. Owners of homes that had been partially or completely destroyed are eligible to purchase public

Table 1. 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

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

housing on favorable terms, although this scheme is controversial in Taipei, where public housing is much in demand. In addition, the central government has been negotiating with commercial banks to urge them to forgive outstanding mortgages on damaged property. While highly contentious, it now appears that the banks have agreed to take over the mortgage debts for those persons who plan to rebuild in the same location; for others, they will defer the repayment schedule by five years. 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.

Preliminary Conclusions

A number of preliminary conclusions can be made regarding economic issues in the restoration process:

- In this disaster, the geographic and sectoral scope of economic disruption vastly exceeded that of direct property and human loss, largely due to lengthy electric power outage to northern Taiwan.
- Prioritization schemes for electric power restoration are possible and can be used to give priority to critical economic sectors and/or facilities.
- 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.
- 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.

Recommendations for Short-Term Recovery

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. The resulting lack of credible loss estimates could only cause confusion as to how much, where, and what kinds of disaster assistance are needed. 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 quickly, before information disappears.
- **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 to be completed in November 1999. Potentially fruitful exchanges may be made with disaster researchers in the U.S. on survey design, findings, and transferable lessons.

Sources: *This brief report is based on numerous media sources from 9/21/99-10/8/99 (including the Asian Wall Street Journal, China News, Far East Economic Review, Financial Times, New York Times, Taiwan News, Taipei Times, and Wall Street Journal), as well as information from the National Fire Administration and discussions with academic researchers and professors. An exchange rate of US $1 = NT $32 was used in this report.*

EMERGENCY RESPONSE AND SHORT-TERM RESTORATION

by Paul J. Flores and James D. Goltz

The social-economic consequences from September 21, 1999 earthquake were significant. According to Taiwan government sources, more than 2,350 persons were killed, over 8,700 were injured, of which approximately 1,000 required hospitalization, 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 921 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 will also present some significant challenges for the government's short-term restoration of efforts.

EMERGENCY RESPONSE OBSERVATIONS

Taiwan did not have large-scale disaster response or recovery plans in place at the time the earthquake occurred. The responsibility for the management of most emergencies affecting Taiwan is assigned to the National Fire Administration (NFA), Interior Ministry. The NFA did have in place emergency plans and programs, but their focus is on fire and flood incidents, the more typical disasters affecting Taiwan. Events of this size do not seem to have presented any major problems in the past so the need for special plans to effectively manage a catastrophic earthquake disaster seems to have been overlooked. Nevertheless, the government's overall emergency response to the 921 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 California under the TriNet project. This system 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 921 earthquake were determined and communicated via paging, fax and the internet (e-mail, www and FTP servers) in 102 seconds after the event origin time.

Receipt of rapid information from the network played a key role in early situation assessment at the national government level. The Director of the National Fire Administration, part of the Ministry of the Interior, is a recipient of information from the CWB, communicated by pager. Upon notification that the earthquake was over magnitude 7 and located in central Taiwan, ministry officials assembled at the National Fire Headquarters at 2:30 a.m. The first priority of the gathered ministers was to address 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, since these disruptions were greatly impeding the government's initial emergency response efforts. The following are other emergency response observations. Figures 1, 2 and 3 illustrate some aspects of this response.

Source: Tomohidi Atsumi, Osaka University

Figure 1. Stadium in Taichung City was used as an emergency staging area.

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 with rescue and recovery operations were residents of the impacted communities and victims themselves who accomplished rescues prior to the arrival of organized teams. Organized search and rescue teams included organized volunteers and local fire agency personnel in the hours immediately following the earthquake. Upon mobilization of the armed forces in the afternoon of 9-21,

Source: Tomohidi Atsumi, Osaka University

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

units joined existing search and rescue teams in the affected counties. Within 24 hours, international search and rescue teams representing 21 countries arrived and were assigned to locations by the National Fire Administration.

Shelter and Mass Care

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. Agencies of government including cities and county governments established shelters, as did the army. These shelters were located at schools and other public buildings in the disaster areas and were serviced by local government agencies and voluntary organizations. Services included security provided by local police and army units, meals prepared by volunteers and sanitary facilities, medical care, counseling and other services provided by government agencies and volunteers. There were also numerous unofficial tent encampments in open spaces, public parks, parking lots and in front of homes and residential buildings damaged in the earthquake (as well as undamaged homes).

Source: Tomohidi Atsumi, Osaka University

Figure 3. Tents such as these provided immediate shelter for the displaced population.

Emergency Medical

On September 26, the Department of Health announced a six-month response medical program by establishing a medical services bureau in each of the 27 townships designated as damaged areas. Under the plan, one medical institution per township (e.g., medical center, military hospital or one of the local health authorities) was given responsibility for providing or coordinating medical services. The services provided include medical care and information gathering on diseases found in the designated area.

SHORT-TERM RESTORATION OBSERVATIONS

Once life-saving operations, such as search and rescue and emergency medical services, are well underway the next major item of business for the government is the setting of priorities for short-term restoration activities and initiating on-going communications with impacted citizens. The ROC seemed to have established priorities very quickly, and in a widely circulated public information poster, these priorities were presented to the public.

What seemed to be lacking were specific details on how these priorities were to be implemented. On October 5, 1999, a “Five Year Reconstruction Plan” was announced. 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;
- Phase 3) during March 2000 and September 2004, the reconstruction plans will be implemented.

Taiwan’s lack of experience in managing large disasters and the non-existence of disaster assistance programs prior to the 921 earthquake, will most certainly prolong the recovery effort. Already, the central government seemed to be experiencing major coordination problems between its ministries and other levels of government. An organizational structure that fully integrates the rebuilding plans and efforts of all government agencies and volunteer organization will need to be established.

The following are additional observations on short-term restoration activities:

Temporary Route Recovery

A number of major transportation routes were disrupted to due to bridge collapses or landslides. The government moved very fast in providing temporary alternative routes to maintain linkages between populations centers and minimize the disruption to the movement people and goods.

The government's utilization of Taiwan's extensive seismographic network greatly contributed to the expedient emergency response.

Temporary Housing

The government seemed to have legitimate concerns about the length of time the shelter and mass care centers established by the armed forces and/or volunteer groups can be adequately sustained. It is recognized that some form of temporary housing will need to be provided. Japan has already promised to donate 2,000 prefabricated houses, used during the post-Kobe earthquake reconstruction, to help with this need. While the government is planning to provide temporary housing, it has reservations on whether the displaced population will take advantage of this resource. An alternative being explored is the utilization of a high number of vacant housing units under government ownership.

PRELIMINARY CONCLUSIONS

A few preliminary conclusions can be made regarding Taiwan's emergency response and short-term restoration activities.

- The utilization of the Weather Bureau'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 921 earthquake. On the other hand, other information derived from the networks, such as ground motion maps, could have also aided government officials in estimating damage and social 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.
- 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.
- The government's emergency route recovery program was expeditious and effective in maintaining key transportation links and minimizing disruption to the movement of people and goods.

RECOMMENDATIONS FOR SHORT-TERM RECOVERY

1. The experience from the 921 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 development of emergency response plans and disaster assistance programs needs to be given high priority.

2. The application of real-time seismic information and the utilization of new technologies such as loss estimation and GIS was already being pursued by universities, the National Center for Research on Earthquake Engineering, the National Science and Technology Program for Hazards Mitigation and other institutions. These efforts need to be accelerated and further research in the loss estimation should be high priority.

3. The almost nonexistent insurance coverage of residential and commercial properties has put most of the recovery financing burden on the government and lending institutions. The government needs to seriously look into expanding the role of insurance in disaster financing. Research on this issue should be given very high priority.

4. Financing the rebuilding of commercial and residential properties poses the greatest challenge to the government and lending institutions. Financing programs will need to be well thought out since these will most likely serve as the basis for the government disaster assistance programs that will need to be institutionalized as part of an overall disaster preparedness program.

OBSERVATIONS AND IDEAS FOR THE FUTURE

by George C. Lee and Chin-Hsiang Loh

The 921 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 sections of this report co-authored by investigators from both NCREE and MCEER. Several reconnaissance teams have also issued technical observation reports (for example, the NSF-supported team, the EERI team, and others). In this section, the authors reflect on their observations of the damage from the 921 earthquake and its affect 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, and physical infrastructure systems for which post-event actions may begin. They are offered for the public and the government as Taiwan faces restoration challenges following the 921 earthquake.

OBSERVATIONS

1. If the epicenter of the 921 earthquake had been located just 50 miles either North or South of the Taichung/Nantou area, the devastation to Taiwan's economy and 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, 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 921 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.

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 (unconfirmed) remain standing in and around the epicenter and they all need critical assessment of the damage sustained. 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. 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.

> ***The opportunity exists today to carry out careful loss estimation and risk assessment studies.***

3. The current emergency management and restoration organizational structure was swiftly and rapidly established immediately after the earthquake. It 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 block diagram of the hierarchy, such a 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, and to update their coordinated efforts in mitigation and emergency preparedness, including training and practice for emergency professionals. 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, 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 re-establishment, the top-down approach must be coupled with the bottom-up efforts of the participation of a 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. One action to enhance the bottom-up effort is to define the responsibilities of elected district administrators (county executives, town supervisors, etc.) to maintain inventory of the physical environment in the district and be knowledgeable of the issues making the district more resilient.

4. One of the most pressing issues in short-term restoration is that of construction quality. 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.

5. The short- and long-term research needs identified by the 921 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 921 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 921 earthquake.

This article is an excerpt from a longer paper entitled "Some Human and Institutional Perspectives of the 921 Earthquake in Taiwan: Lessons Learned." The entire paper is on MCEER's web site at http://mceer.buffalo.edu.

SELECTED BIBLIOGRAPHY

by Laura Taddeo

The following bibliography is a selected listing of items available through the University at Buffalo libraries. The list provides an overview of available materials and is meant to be a starting point for further reading. Additional materials can be obtained by contacting the MCEER Information Service.

OVERVIEWS

"Historical Earthquakes and the Seismograms in Taiwan," by Pao Hua Lee in **Historical Seismograms and Earthquakes of the World.** San Diego: Academic Press, Inc, 1988.

"Seismic Zoning on Ground Motions in Taiwan Area" by Chin-Hsiung Loh and Wen-Yu Jean in **Seismic Behavior of Ground and Geotechnical Structures.** Rotterdam: A.A. Balkema, 1997, pages 71-79.

"Seimic Hazard and Uncertainty Analysis of the Taiwan Area," by Chin-Hsiung Loh and Fwu-Shing Baw in **Soil Dynamics and Earthquake Engineering**, volume 11, number 8, 1992, pages 497-508.

"Some Aspects of Seismicity in Taiwan Region," by Jeen-Hwa Wang, Y-Ben Tsai, and Kou-Cheng Chen in ***Proceedings of the CCNAA-AIT Joint Seminar on Research for Multiple Hazards Mitigation; National Cheng-Kung University, January 16-19, 1984.*** Edited by Leon Ru-Liang Wang and Maw Shyong Sheu. Tainan, Taiwan: National Cheng-Kung University, 1984, pages 562-580.

Catalogue of the Earthquakes in Taiwan from 1604-1988, Technical Report IES-R-661 by S.N. Cheng and Y.T. Yeh. Taipei, Taiwan: Institute of Earth Sciences, Academia Sinica.

STUDIES ON PREVIOUS EARTHQUAKES

"The 16 September 1994 earthquake in the Taiwan Strait and its Tectonic Implications," by Honn Kao and Francis T. Wu in **TAO: Terrestrial, Atmospheric and Oceanic Sciences**, volume 7, issue 1, March 1996, pages 13-29.

Northern Taiwan Earthquake, November 15, 1986: An EQE Brief, February 1987, by Hai-Chow Lee. San Francisco: EQE Incorporated, 1987.

"A Study on the Great Eastern Taiwan Earthquakes of 1951 and the Distribution of Great Earthquakes in Taiwan," by Cheh-Yi Su in **Bulletin of the International Institute of Seismology and Earthquake Engineering,** volume 21, 1985, pages 177-194.

CODES/ZONING

"Seismic Hazard in Taiwan," by Yeong Tein Yeh and Chin-Hsiung Loh in **Practice of Earthquake Hazard Assessment.** Denver, Colorado: International Association of Seismology and Physics of the Earth's Interior (IASPEI), 1993, pages 231-238.

"Taiwan," by Yohchia Chen and Julius P. Wong in **International Handbook of Earthquake Engineering: Codes, Programs, and Examples.** New York: Chapman & Hall, 1994, pages 447-453.

SEISMOLOGY/GEOLOGY/GEOTECHNICAL ISSUES

An Introduction to the Active Faults of Taiwan by Hui-Cheng Chang, et al. Taipei, Taiwan: Central Geological Survey, MOEA, 1998.

"Large Earthquakes and Crustal Deformation Near Taiwan," by Silvio K. Pezzopane and Steven G. Wesnousky in **Journal of Geophysical Research**, volume 94, number, B6, June 10, 1989, pages 7250-7264.

"Seismotectonics of Taiwan," by Y. B. Tsai. **Tectonophysics**, volume 125, issue 1-3, 1986, pages 16-37.

"Source Geometry and Slip Distribution of the April 21, 1935 Hsinchu-Taichung, Taiwan Earthquake," by Bor-Shouh Huang and Yeong Tein Yeh in **Tectonophysics**, volume 210, number 1/2, August 30, 1992, pages 77-90.

"Focal Mechanisms of Recent Large Earthquakes and the Nature of Faulting in the Longitudinal Valley of Eastern Taiwan," by Francis T. Wu, et al. in **Proceedings of the Geological Society of China**, volume 32, number 2, April 1989, pages 157-177.

LIFELINES/BRIDGES/BUILDINGS

"Seismic Assessment and Renovation Study for Highway Bridges," by C.C. Chern, et al. in ***Structural Engineering in Natural Hazards Mitigation: Proceedings of Papers Presented at the Structures Congress '93; Irvine, California, April 19-21, 1993.*** Edited by A.H-S. Ang and R. Villaverde. New York: American Society of Civil Engineers, 1993, pages 881-886.

"A Knowledge-Based Design System for the Design of Freeway and Highway Bridges in Taiwan," by Chen-Cheng Chen, Ching-Churn Chern and Chen-Ji Chen in **Proceedings of the International Workshop on Civil Infrastructure Systems: Application of Intelligent Sysytems and Advanced Materials on Bridge Systems; National Taiwan University, January 10-12, 1994. (NCEER-94-0019).** Buffalo, New York: National Center for Earthquake Engineering Research, July 1994, pages 205-214.

"Bridge Planning, Design Philosophy and Expectations in the Taiwan Area National Expressway," by C.H. Kuo and C. F. Lee in **Proceedings of the International Workshop on Civil Infrastructure Systems: Application of Intelligent Sysytems and Advanced Materials on Bridge Systems; National Taiwan University, January 10-12, 1994. (NCEER-94-0019).** Buffalo, New York: National Center for Earthquake Engineering Research, July 1994, pages 29-47.

"Seismic Behavior of Yuansan Freeway Bridge in Taipei," by Ching-Churn Chern and Yue-Poa Hwang in **Proceedings of the US-Korea Joint Seminar/Workshop on Critical Engineering System; Seoul, Korea, May 11-15, 1987.** Edited by Chang-Koon Choi and Alfred H.S. Alfredo. [Publisher and place of publication unknown], volume 1, 1987, pages 365-376.

"Seismic Hazard Analysis of Taipei Metropolitan Rapid Transportation Chung-Ho Line in Taiwan," by Hui-Mi Hsu, Kuo-Ping Chang and Jin-Tsuen Yang in **Proceedings of the Fifth International Conference of Seismic Zonation; Nice, France, October 17-19, 1995.** Nantes, France: Ouest Editions, 1995, volume 1, pages 366-373.

"Seismic Design of 50-Story Shin Kuan Insurance Building," by H. M. Liao, Joseph Penzien, and Jiang-Yang Tsai in **Proceedings of the CCNAA-AIT Joint Seminar on Research and Application for Multiple Hazards Mitigation; Taipei, April 11-15, 1988.** Edited by Franklin Y. Cheng and Yeong Tein Yeh. Taipei, Taiwan: Institute of Earth Sciences, Academia Sinica, volume 1, April 1988, pages 399-414.

MITIGATION

"The Population, Earthquake Disasters and the Problem of Reducing Earthquake Risk in the Taiwan Island," by Liu Guangxia in **Journal of Natural Disasters (Ziran Zaihai Xuebao)**, volume 1, number 2, April 1992, pages 94-101. (In Chinese, includes English abstracts).

On the Earthquake Prevention and Emergency Response for the General Public in Taiwan, by Chang-Ping Chiou. Taipei: National Taiwan University, Center for Earthquake Engineering Research, 1985.

"Design and Implementation of Earthquake Early Warning Systems in Taiwan," by W.H.K. Lee, T.C. Shin, and T.L. Teng in **Proceedings of the Eleventh World Conference on Earthquake Engineering**. Oxford, England: Pergamon, Disc 4, 1996, paper number 2133.

WEB SITES/LINKS TO INFORMATION

National Earthquake Information Center(NEIC): Earthquake Bulletin
Web Address: *http://wwwneic.cr.usgs.gov/neis/bulletin/99_EVENTS/990920174719/990920174719.HTML*

USGS: Reports on the ChiChi (Taiwan) Earthquake
Web Address: *http://caldera.wr.usgs.gov/*

NCREE: JiJi Earthquake. (In Chinese)
Web Address: *http://921.ncree.gov.tw/.*

EQE International: Field Investigation Team to Taiwan
Web Address: *http://www.eqe.com/revamp/taipei2.htm.*

EQE Reconnaissance Team in Taipei, Taiwan
Web Address: *http://www.eqe.com/revamp/taipei9.htm.*

GEES: The Preliminary Report of the National Science Foundation Geotechnical Earthquake Engineering Reconnaissance
Web Address: *http://rccg03.usc.edu/RecentEQ/Taiwan/LinksTW.htm.*

NISEE: National Information Service for Earthquake Engineering
Web Address: *http://nisee.ce.berkeley.edu/taiwan/.*

IRIS: Special Event Page - Taiwan Earthquake
Web Address: *http://www.iris.washington.edu/DOCS/taiwan.htm.*

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