Learning from Earthquakes

The Chi-Chi, Taiwan Earthquake of September 21, 1999

On September 28, 1999, an EERI team arrived in Taiwan to survey the area affected by the earthquake. The team consisted of Team Leader Joe Uzarski, Structural Engineer, Oakland, CA; Michael O'Rourke, Co-Leader, Rensselaer Polytechnic Institute, Troy, NY; Norman Abrahamson, Pacific Gas & Electric Company, San Francisco, CA; Navin Amin, Middlebrook + Louie, San Francisco, CA; James Goltz, California Institute of Technology, Pasadena, CA; Ignatius Po Lam, Earth Mechanics Inc., Fountain Valley, CA; and Wen S. Tseng, International Civil Engineering Consultants, Berkeley, CA. This reconnaissance effort was greatly enhanced by collaboration with many other scientists, engineers and organizations. In appreciation of this, a special acknowledgment section appears on the last page. Contributors to this report were N. Abrahamson, N. Amin, J.P. Bardet, J. Goltz, I.P. Lam, J. Meyer, J. Moehle, M. O'Rourke, W.S. Tseng, and J. Uzarski.

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Introduction

A magnitude Mw 7.6 earthquake struck central Taiwan on September 21, 1999 at 1:47 a.m. local time (Figure 1). It was responsible for over 2,400 fatalities; more lives would have been lost if the earthquake had occurred during daylight hours. In the first few days following the earthquake, there were many major aftershocks, several over magnitude 6.5. Damage estimates, including calculations for lost productivity, range between US$20 and $30 billion. In recent centuries, large earthquakes have been most frequent on the eastern side of Taiwan, but this epicenter was near the center of the island, closer to the major population areas along Taiwan's west and north coasts. Taiwan has 22 million people, about two-thirds the population of California, and has a land area 9% of California's.

Seismology

The Chi-Chi earthquake was caused by the rupture of the Chelungpu fault. The main part of the fault is a north-south-striking thrust fault that dips about 30 degrees to the east. It is part of the western thrust zone that accommodates some of the crustal shortening caused by the collision of the Philippine Sea Plate and the Eurasia

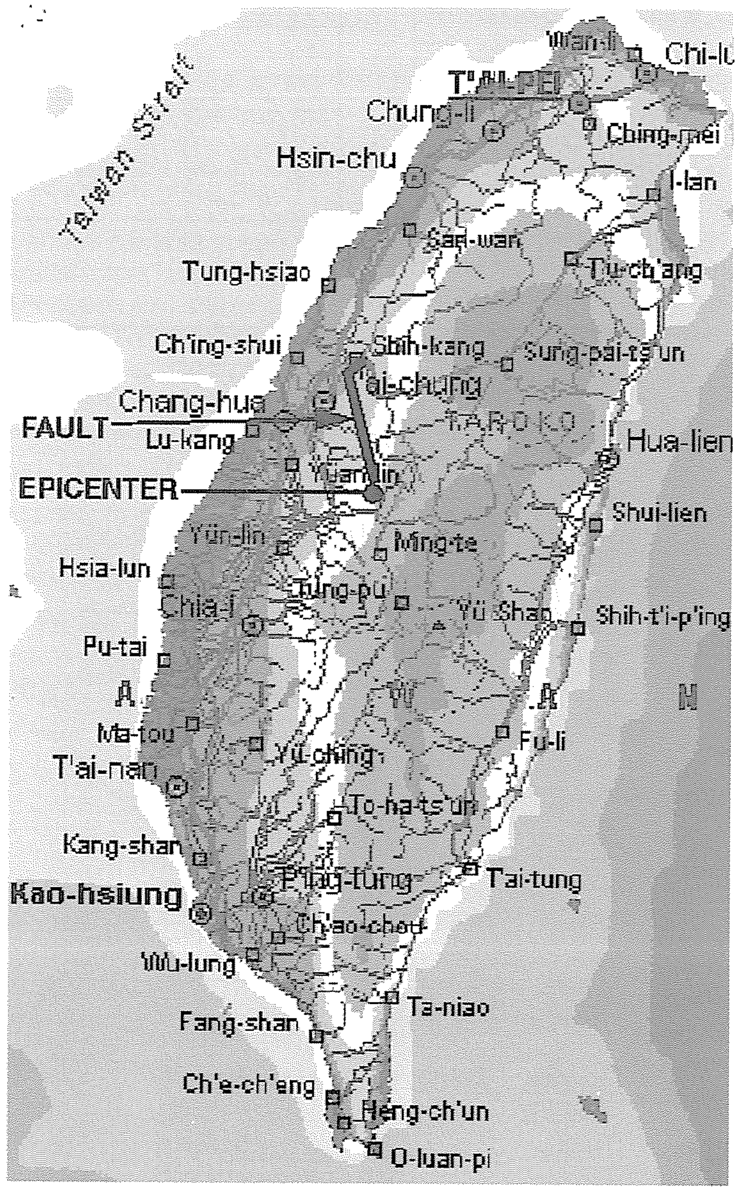

Figure 1 *- Map of Taiwan showing location of the epicenter and the Chelungpu fault.*

Plate. At the north end of the rupture, there is a sharp bend to the east and the fault rupture strikes nearly east-west. The total length of the rupture is about 80 km, with a down-dip width of about 40 km. The epicenter is located about 15 km from the south end of the fault. This earthquake had a very energetic aftershock sequence, with three ML>6.8 shocks in the first two weeks.

The Chelungpu fault was known to be an active fault, but it was assigned a low-to-moderate activity rate based on the lack of observed seismicity defining a fault plane. There are no geologic trenching data available to assess the activity rate of this fault. The rupture resulted in fault scarps 2 m to 3 m high along the southern end of the rupture and 4 m to 8 m high in the northern end, but some of the largest scarp heights include the effects of folding in the hanging wall. At the northern end, the complex east-west-striking rupture consists of multiple strands, including normal faulting steeply dipping to the north. This east-west strike has not occurred on a previously mapped active fault.

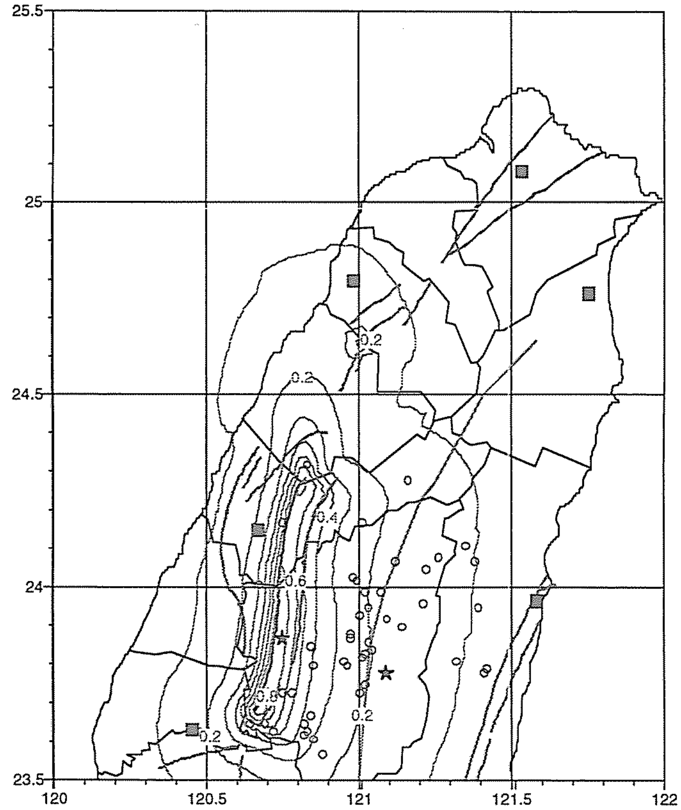

Figure 2 - Preliminary Shake Map. The official agency for monitoring earthquakes in Taiwan is the Central Weather Bureau.

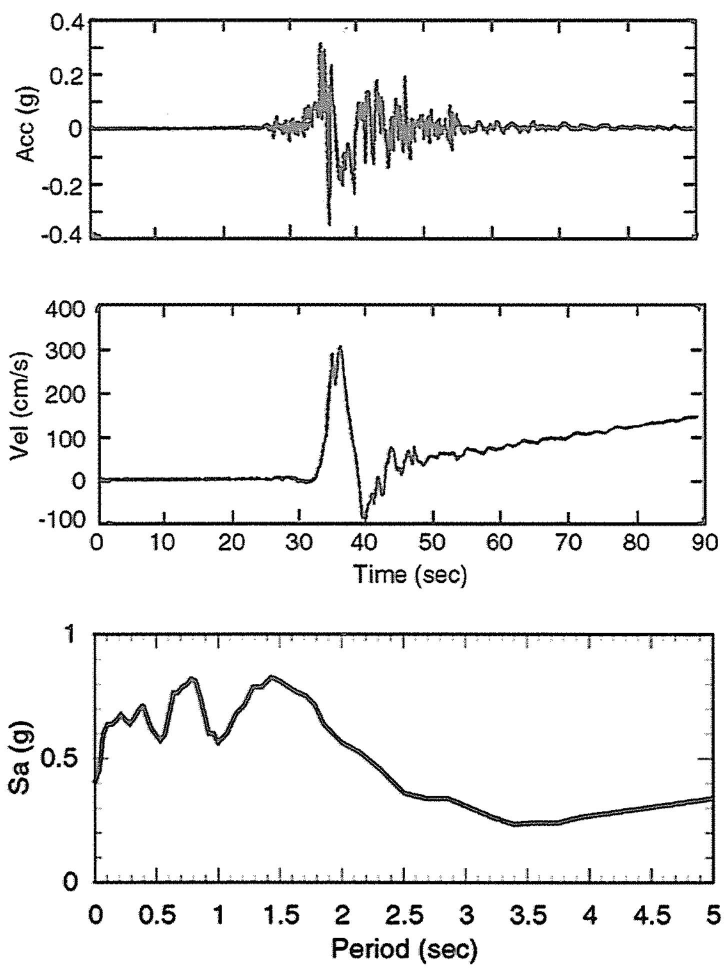

Figure 3 - Time history and response spectra.

Beginning in 1990, the Central Weather Bureau (CWB) installed an extensive network of about 600 free-field strong-motion instruments, as well as 39 in buildings and 16 on bridges. In addition to the CWB stations, the Institute of Earth Sciences has about 400 free-field instruments. With this extensive instrumentation, the Chi-Chi earthquake is well-recorded; it has provided a significant increase in the number of strong-motion recordings from large crustal earthquakes.

The horizontal peak ground accelerations (PGA) from the Chi-Chi earthquake were larger than median PGAs predicted by the attenuation relations used to develop Taiwan's building code; however, they are lower than the median PGAs predicted by crustal attenuation relations commonly used in California. The average horizontal PGAs from the Chi-Chi earthquake recorded at distances less than 20 km are about 30% below the median PGAs based on commonly used attenuations in California. The PGAs on the vertical component, about 60% of the horizontal component at distances less than 10 km, were also lower than the median V/H ratios predicted for near-fault locations from standard attenuation relations used in California.

A preliminary PGA shake map (Figure 2) was created by first developing an event-specific attenuation relation and then spatially smoothing the residuals. While the peak accelerations were largest at the southern end of the rupture, the peak velocities were larger at the northern end of the rupture. Station TCU068, located near the bend in the rupture, recorded a ground motion with peak velocity of about 300 cm/s, which is the largest peak velocity ever calculated. The time history and response spectra for this station are shown in Figure 3.

Geotechnical Effects

Fault Rupture: Surface rupture (observed along about 60 km) was the most dramatic aspect of this earthquake. There were large vertical offsets and the surface ruptures were not straight but generally curved, as is typical in thrust faults due to the dip of the fault. Rupture was most dramatic at a concrete gravity dam that extends across the Tachia River near the town of Shih-Kang, about 50 km north of the epicenter. It passed directly beneath one end of the dam and caused severe damage (Figure 4). The offsets were roughly 10 m vertical and 2 m horizontal. Prior to this earthquake, the Chelungpu fault was not mapped at this site.

Figure 5 shows surface rupture at a water filtration plant located near Feng-Yuan. The figure also shows a water pipe, originally straight, which was bent 90 degrees and buckled by the large forces exerted by permanent ground distortion. Most buildings across the street (not directly within the fault rupture zone) showed no apparent damage (see Figure 6), in contrast to severe damage within the 15-20-m-wide rupture zone. This suggests that ground motion associated with permanent fault offset occurred slowly compared to dynamic shaking. These observations were common.

Landslides: Numerous landslides and rock-falls destroyed the highway transportation systems and isolated the communities in the central mountain areas of Taiwan. There were two enormous landslides at Tsaoling and Nankang, 30 km south and 13 km north of the Chi-Chi epicenter, respectively. The debris flow of the Tsaoling landslide traveled a distance of 2-3 km, carrying with it buildings, roads and cars, and destroying everything in its path (Figure 7). Thirty-four persons were killed. A new road had to be constructed on top of the landslide for the rescue effort. The debris flow of the Tsaoling landslide dammed the valley and formed an artificial lake; the new dam may rupture during the forthcoming monsoon, and could devastate downstream localities. Such a

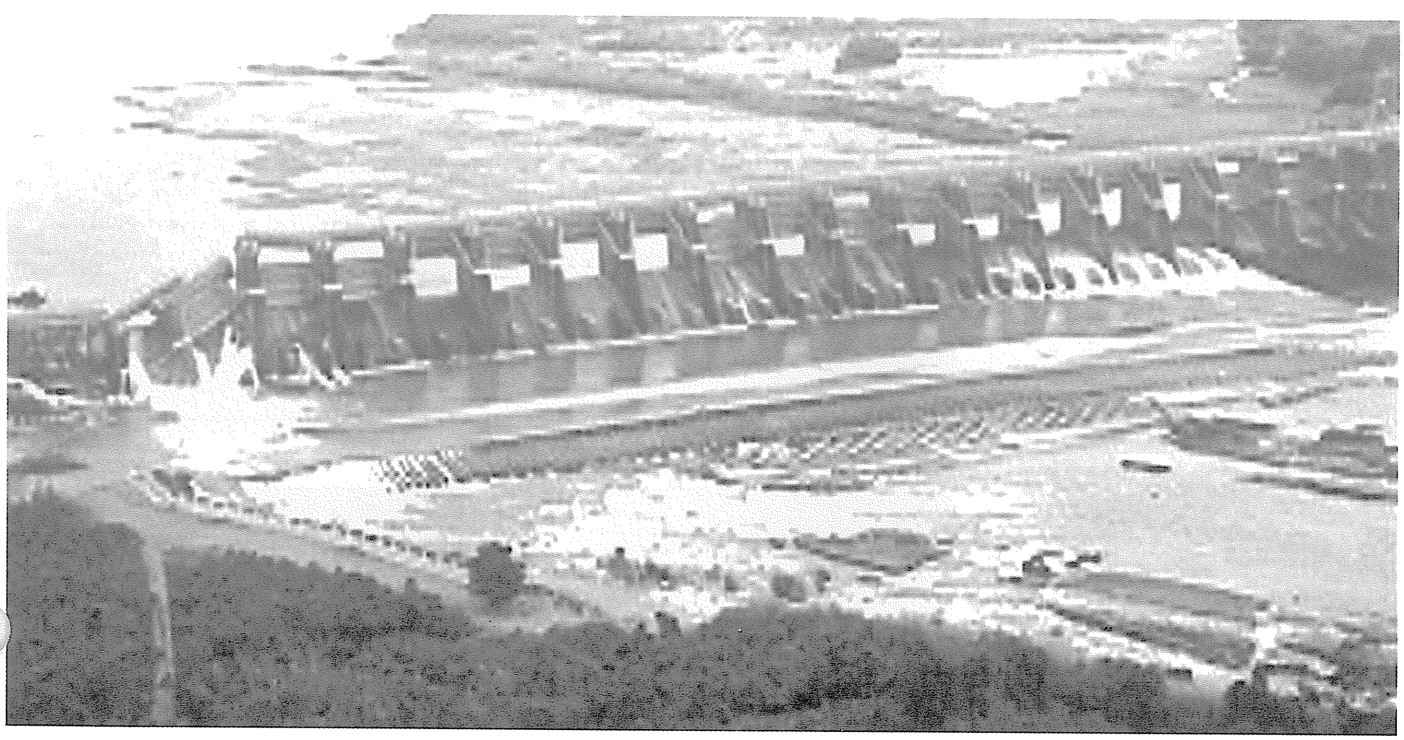

Figure 4 *- Fault surface rupture across Shih-Kang Dam.* (Photo: J.P. Bardet)

Figure 5 *- Fault surface rupture at a water filtration plant near Feng-Yuan.* (Photo: I.P. Lam)

catastrophic rupture of a landslide-caused lake occurred after the 1941 Taiwan earthquake.

Liquefaction: Liquefaction damage was reported at isolated locations. It was significant at Yuanlin—there was widespread settlement of building foundations, and water wells were completely filled by sand from sand boils. Liquefaction also led to settlement, failure, and lateral spread of levees, and movements at bridge abutments at river crossings. However, many bridges remained functional, despite signs of liquefaction and lateral spread close to the bridge foundations.

The Taichung Harbor on the west coast (55 km from the epicenter) also suffered liquefaction damage, but performed well and remained functional. This harbor, only about 25 years old, has a total of 40 piers. Ming-Jeh Kuo, Deputy Commissioner of Taichung Harbor, indicated that Piers 1 through 5 (constructed using reinforced concrete rectangular caissons) were damaged. The undamaged piers were pile-supported (with both vertical and battered piles). Liquefaction of hydraulic fill behind the concrete caissons caused widespread settlement of the pavement behind the piers and caused as much as 2 m of backfill settlement (Figure 8). Cargo-handling cranes were tilted and ren-dered inoperable. A cement silo supported on piles had no apparent damage, but a mat-supported reinforced concrete building adjacent to the silo was damaged by differential settlement of the foundation. Ten out of 11 cylindrical steel-shell tanks used for molasses storage were also damaged at the Port of Taichung. During the earthquake, the tanks were almost full, and the sloshing of the heavy liquid crumpled their tops.

Buildings

Brick and concrete are the most common building materials. Most structures are built using reinforced concrete framing. Unreinforced brick partitions and walls, even in recent construction, are very common. No hollow clay tile was observed. Structural steel and metal deck are used for tall buildings. Wood frame or reinforced masonry structures are rare. Some single-story older buildings are constructed using adobe blocks. Buildings over 50 m (about 12-14 stories) require a special peer review during the plan approval process.

Figure 6 *- Undamaged building with unreinforced brick walls immediately adjacent to fault rupture.* (Photo: Uzarski)

Figure 7 - *Large-scale landslide at Tsaoling involving a large debris flow moving 2-3 km.* (Photo: J.P. Bardet)

The Taiwan Building Code (TBC) was revised in 1974, 1982 and 1996. The 1982 TBC requires ductile detailing of reinforced concrete frames similar to the American Concrete Institute and Uniform Building Codes (UBC) of 1982 vintage. The majority of the damaged buildings were designed in accordance with the 1982 Taiwan Code. The 1996 TBC is similar to the 1994 UBC. The island of Taiwan is divided into four seismic zones. Nantou, Taichung and the Taipei area are in the moderate seismic zone.

Single-Story Houses: In rural areas, traditional one-story, 30-80-year-old residences are constructed of unreinforced masonry or adobe with weak mortar and with wood roofs. In areas of intense ground shaking, these buildings performed poorly and caused a number of deaths. They constitute a low percentage of the housing units.

Arcade Buildings: Arcade style buildings are very common in Taiwan, and many of them were damaged (Figure 10). These buildings have open fronts at the street with covered pedestrian walkways created by the second-story framing. Usually, the street level is commercial or parking and the upper stories are residential; this style creates an undesirable soft story at the lowest level. Three- and four-story arcade buildings are common, but in the more densely populated areas, heights up to 12 stories are not unusual. The Taipei city government is now considering a ban on new buildings with walkway arcades along major roads and in commercial districts.

The TBC code has a special section for structures that do not exceed 10 m or three stories in height. This section allows reinforced concrete frames with unreinforced brick walls to be constructed using prescriptive provisions; i.e., engineering calculations are not required. First the unreinforced masonry walls are erected with deliberate spaces for concrete columns that will be installed subsequently. This method reduces formwork for the concrete columns to just two sides. The reinforced concrete frames are cast integrally with the unreinforced brick walls, forcing the masonry to resist seismic loads.

Mid-Rise Buildings: In urban areas, a substantial percentage of the residential units are in reinforced concrete apartments of 12-15 stories. A number of these buildings collapsed in Taichung City, Feng-Yuan, Dali, and Taipei County (Figure 9). Typically, they are cast-in-place, special moment frame structures utilizing all frame lines in both directions. They generally have spread footings. Some of the towers have subterranean parking garages. The exterior walls and the shaft walls are reinforced concrete, approximately 10 cm thick. These are considered nonstructural walls and

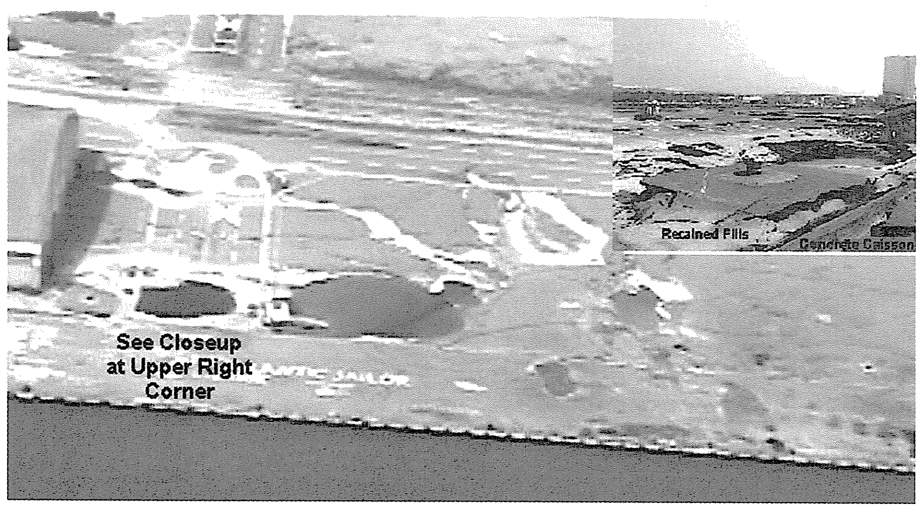

Figure 8 - *Settlement behind laterally displaced caisson sections at Berth 1, Port of Taichung.* (Photo: J.D. Bray)

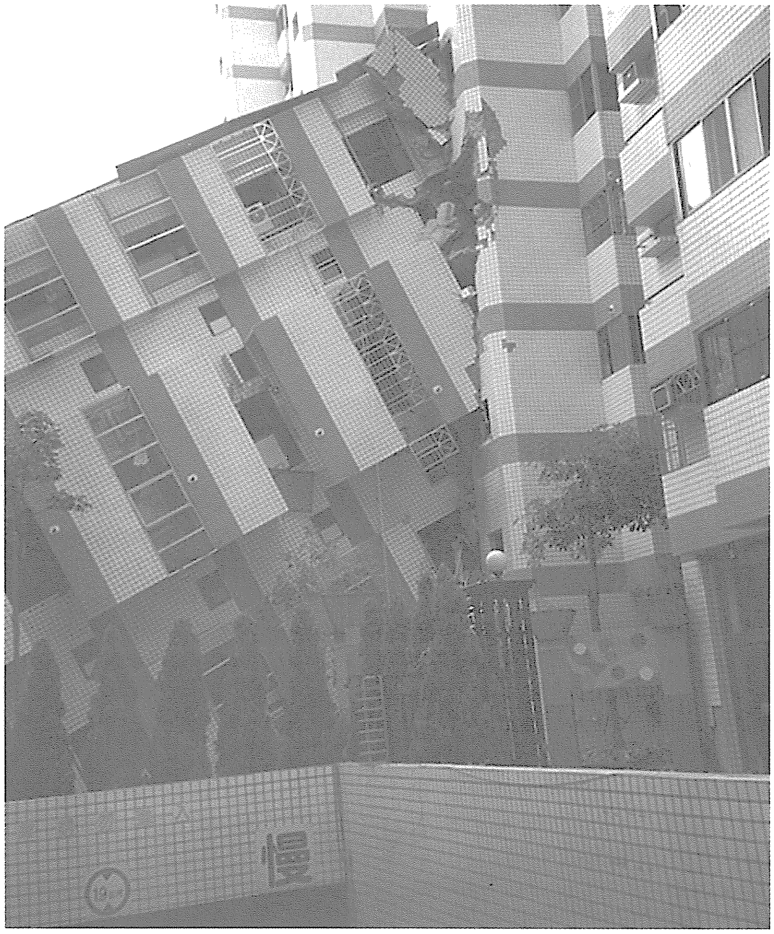

Figure 9 *- Soft-story collapse of a mid-rise apartment building, Dali.* (Photo: Meyer)

are not included in the seismic design. Interior, nonstructural partitions are single-wythe unreinforced clay brick masonry. Typically, the nonstructural "curtain" wall does not extend below the second floor. Many of the exterior walls have a thin, hand-set veneer granite directly attached to the concrete with a cement-sand mortar. The buildings are generally less than ten years old, and many are less than five years old.

Building regulations require peer review for structures greater than 50 meters in height, which may account in part for the abundance of 12-15-story buildings (just under 50 meters in height). Another regulation allows additional area or floors if open space for public use is provided at the street level (Figure 12). This encourages tall, open first stories which, combined with the cast-in-place curtain walls at upper levels, leads to buildings with soft first stories. Most design drawings include ductile detailing provisions, but in observed damaged columns, implementation of ductile detailing was deficient.

A significant number of the mid-rise apartment buildings suffered dramatic failures, generally from loss of stability at the first story. Typical observed detail deficiencies included insufficient column ties, lack of cross ties, 90-degree rather than 135-degree hooks on the ties, and splices with inadequate length, located at floor levels and with inadequate confinement and no staggering (see Figure 11). From a configuration standpoint, the cast-in-place curtain walls above the first stories, coupled with the detail defects found in the columns, account for the dramatic failures of these buildings. In general, these failures were not the result of foundation failure.

Despite the dramatic failures, most mid-rise buildings performed well, although there was damage to the nonstructural exterior reinforced concrete walls and unreinforced masonry partitions. Typical damage consisted of large (up to 5 cm wide in many cases) classic diagonal shear cracks in the exterior walls, cracked and failed interior masonry partitions, and little damage to the concrete moment frame members.

Figure 10 *- Double pancake of four-story building. Only two stories remain.* (Photo: Uzarski)

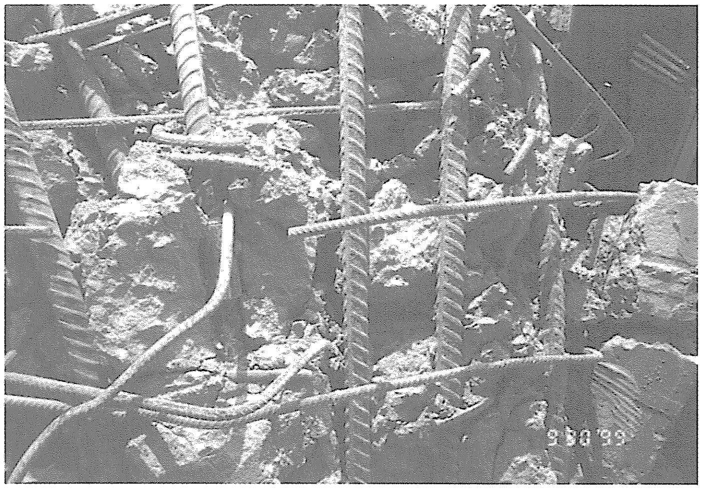

Figure 11 - Typical deficient column details: ties with 90-degree hooks instead of 135-degree hooks, excessive spacing of ties, and inadequate transverse cross ties. (Photo: Amin)

The global stability of these buildings appeared to be unimpaired, although debris from the masonry partitions caused some obstruction for egress and some degree of falling hazard, and the partition movement jammed some doors. Pieces of the thin granite broke off and fell.

High-Rise Buildings: The team did not receive any reports of collapse or severe damage to high-rise buildings (20 stories or more), but there were reports and observations of minor damage to facades and some movement at the construction joints at floors. Many of Taiwan's recent high-rise buildings (generally over 25 stories) are constructed with structural steel. The buildings under construction were moment frame with steel girders and steel box columns infilled with concrete. Moment connections are pre-Northridge style with steel back-up bars and runoff tabs left in place. A welding process with E7016 electrodes was used for field welding.

Seismic Assessment Teams

Damage assessments in the Tung-Shih area were performed by civil and structural engineers from Taipei who volunteered for two or three days on a rotating basis. The engineers were quartered in ten-person tents at the emergency camp set up by the army. Engineers were given yellow armbands and hard hats. Local block leaders—who act in an official capacity for the local government in various matters—transported the engineers to the neighborhood being assessed and accompanied them to each residence. The block leaders greatly aided the efficiency of the assessment effort because they knew all the residences in their "block" as well as the residents. The residents were eager to have the assessing engineer walk thoroughly through their houses, whether the damage was light or heavy.

Structures were tagged with green, yellow and red tags similar to the procedure in California. The general intent is similar to the Applied Technology Council, ATC 20, wording—"no restrictions," "limited entry," and "do not enter," respectively—although the actual wording on the tags is different. The assessing engineer completed a form that included the owner's name, address of structure, type of tag, and a brief description of the damage. These forms were turned in at the camp, but enforcement of restrictions

Figure 12- View of a partially collapsed 15-story building (less than 50 m high). Reinforced concrete with infill brick partitions. Beam column joint failure at facade.

(Photo: Amin)

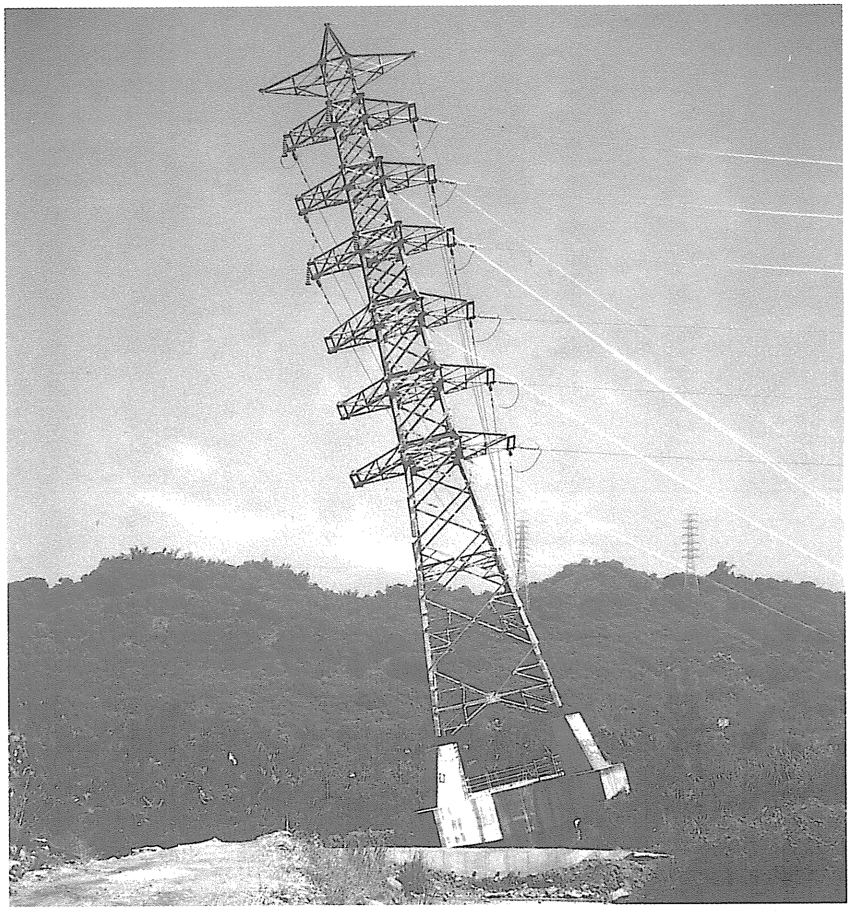

Figure 13 - Leaning transmission tower. (Photo: Tseng)

to entry at red-tagged buildings was lax. People used red-tagged buildings during the daylight hours or removed belongings from red-tagged buildings, including those with total first-story collapse.

Lifelines

Water Supply System: Taiwan Water Supply Corporation (TWSC) is the sole provider of water in Taiwan, except to Taipei (where service was not interrupted). TWSC has water storage and treatment facilities distributed throughout the country. There are three primary sources for the TWSC water supply: impounded surface water (i.e., dams) accounts for about 60%, and ground water wells and direct diversion from rivers account for 25 and 15%, respectively. There are about two dozen water treatment plants in the system and about 32,000 kilometers of water transmission and distribution pipe.

The supply system and a treatment plant in the epicentral region suffered significant damage. The fault rupture beneath the Shih-Kang Dam (50 km from the epicenter) caused severe damage and cut off the water supply from the reservoir. Fault rupture through a water treatment plant in Feng-Yuen (50 km from the epicenter) rendered the plant inoperable. In addition, the earthquake resulted in a large number of leaks or breaks in the transmission and distribution network. Apparently, there was little damage to the hundreds of above- or below-ground concrete storage tanks within the TWSC system, nor were there reports of damage to, or sanding of, ground water wells.

Damage to the Shih-Kang dam (Figure 4) reduced the water supply for Taichung City and County by between 40% and 50%. The Feng-Yuen water treatment plant consists of settling basins, finish water reservoirs and associated underground piping, all of which were damaged. A number of pools in one settling basin used baffles in the treatment process. The submerged baffles were displaced due to sloshing. The sloshing was so severe that some baffles actually flipped out of their individual pools and ended up on the ground outside the settling basin.

Portions of the reinforced concrete roofs over the finished water reservoirs collapsed. The fault rupture passed directly through one corner of the plant. The vertical offset at the fault trace was about 4 m, and the horizontal offset was in the 1 m to 2 m range. These offsets were large enough to sever four steel pipelines, with diameters of 400, 1100, 1500 and 2000 mm, which traversed the fault.

In Nantou County, earthquake damage—primarily to distribution piping—resulted in outages of up to one week in cities and towns. In the countryside, restoration of service was slower due to damage to access roads and bridges. In Taichung County, about eight in ten customers were without water services immediately after the event, and restoration of full service took one month or more. During the restoration period, temporary water supply to those affected was from emergency storage tanks supplied by tanker trucks and fire tenders.

Electric Power System: Power outages occurred immediately. In Taipei (150 km from the epicenter), the power went out even before the city began to shake. Taiwan Power Company (Taipower), a state-owned utility, is the sole supplier of electric power in Taiwan. Although the power generation facilities remained largely operational, there was substantial damage to substations and high-voltage transmission towers. In northern Taiwan there was a 24-hour outage, while service to the southern part of the island was mostly unaffected. After electricity was partially

Figure 14 - The fault ruptured beneath the I-Jiang Bridge, about 30 km NNW of the epicenter. (Photo: Moehle)

restored, mismatches between demand and capacity caused rolling blackouts in the north for more than a week after the event. Uninterrupted restoration of full power was anticipated within one month of the quake.

The Chung-Liao substation, less than 10 km from the epicenter, was severely damaged by a combination of strong shaking and permanent ground deformation effects. Damaged substation components included circuit breakers, lightning arrestors, ceramic insulators, gas-insulated line relays and gas circuit switches. Emergency repairs involved installing a bypass transmission line around the station. Full restoration of this substation is not expected for several months.

Many high-voltage transmission towers were damaged; some collapsed, while others tilted or settled due to ground deformation. One example of transmission tower damage due to fault rupture was observed near the town of Ming-Chien (Figure 13), about 10 km from the epicenter. The scarp, with an approximate 2 m vertical offset, skirted the edge of the tower's concrete foundation pedestal. This caused the tower to tilt roughly 20 degrees from vertical. Some of the lines had snapped due to rotation of the tower and were repaired by splicing. As an emergency measure, the tower was temporarily stabilized by ground-anchored guy wires.

Taipower operates five fossil fuel plants, two hydroelectric plants and three nuclear plants. Another nuclear plant is under construction in northern Taiwan. According to Taipower, all nuclear power plants were undamaged. All three have seismic instruments set to trigger at 0.01 g. The two nuclear plants in northern Taiwan (170 km from the epicenter) recorded peak horizontal accelerations at the containment base of around 0.04 g, but both of them were tripped off by damage to the 345KV transmission grid, not because of ground shaking. No seismic measurements were taken at the third nuclear plant at the southern tip of the island (epicenter, 205 km) because ground motion greater than 0.01 g was not detected. Operations at the southern plant were not interrupted. Only one fossil-fuel power plant was damaged; it consisted of one boiler in a six-unit oil-fired plant located near the Port of Taichung (epicenter, 50 km).

Highway Bridges

The reconnaissance team visited 11 sites at which bridges suffered damage. These do not represent all the damage to highway bridges, but they do include the sites of major damage identified by the Taiwan Highway Bureau and the Expressway Corporation.

Design and Construction Practice: Most of the bridges observed in the epicentral region were constructed of pre-stressed I-girders supported with or without bearings on reinforced concrete piers. Design provisions, which presumably governed their design and construction, are set forth in the *Standard Specification for Highway Bridges of Taiwan.* Those specifications are based mainly on the *American Association of State Highway and Transporation Officials (AASHTO)*

Figure 15 *- The Jyi-Luh cable-stayed bridge, about 10 km SW of the epicenter, was under construction and sustained significant damage.* (Photo: Moehle)

Standard Specifications. In particular, the first edition of the Taiwan specifications, published in 1960, was based on the 1953 AASHTO specifications; the 1987 edition was based on the 1977 AASHTO specifications; and the 1995 edition was based on the 1992 AASHTO specifications.

Damages: Some bridges failed due to fault rupture beneath or adjacent to them. Rupture through a bridge was identified in three cases; rupture immediately adjacent was identified as a cause of a fourth collapse, and rupture was suspected in connection with the collapse of a fifth bridge. Given the magnitude of fault offsets, significant damage and collapse were not surprising.

The U-Shi Bridge, located about 20 km NW of the epicenter, consisted of two parallel structures—the East Bridge constructed in 1981 and the West Bridge constructed in 1983. The superstructure comprised 18 spans of prestressed I-girders supported on reinforced concrete pier walls. The deck had an expansion joint at the north abutment, continuous joints for the next two piers, and another expansion joint over the third pier. Fault rupture passed through the foundation of the third pier, with an offset of approximately 1.5 m vertical.

Damage included unseating of the prestressed spans of the East Bridge near the north abutment. The West Bridge is supported by smaller cross-section piers, which failed. The first and second piers, containing approximately 0.0025 vertical reinforcement ratio, sustained apparent shear failures involving nearly complete fracture of the cross section along a failure surface. The third pier had cracking indicative of torsion failure. The damage patterns are consistent with rigid-body deformation involving in-plane rotation of the bridge deck.

The fault ruptured beneath the I-Jiang Bridge (Figure 14), about 30 km NNW of the epicenter. This structure comprised 24 spans (11 m each), simply supported without bearings on reinforced concrete pier walls. When the rupture passed between the first and second piers from the northwest abutment, the first pier rose approximately 3 m relative to the second pier. In its final rest position, the deck overhangs the pier wall by approximately 4 m. It seems unlikely that the deck moved that distance slowly, because had it done so, it would have fallen to the ground after a relatively small movement as it became unseated at one end. It seems more likely that the span was propelled at a high velocity before coming to rest in this final position.

All four spans collapsed in the Toong-Tour Bridge, near the southern end of the fault rupture about 25 km SW of the epicenter. The bridge consisted of prestressed I-girders supported on circular-cross-section piers; the base of the piers apparently had been enlarged after initial construction to reduce damage from debris flowing down the river. The north abutment was severely damaged, with apparent movement toward the river. It is plausible that this movement, perhaps coupled with longitudinal shaking, resulted in the observed longitudinal shear failures of the piers protruding from the enlarged lower portions.

The reconnaissance team also examined viaducts under construction linking Expressways 1 and 3 near Taichung. The bridges comprised box girders supported on bearings, which connected to reinforced concrete bridge piers through short reinforced concrete pedestals. These pedestals proved to be the weak links in the load path, with several of them spalling. Some bents in the system were of monolithic superstructure-substructure construction, and apparently had no damage.

The Jyi-Luh cable-stayed bridge (Figure 15) across the Choshun River, about 10km SW of the epicenter, was under construction and sustained significant damage. The bridge deck had not been completed near the pylon, and closure joints at both ends of the stayed deck had not yet been placed, leaving the structure in a relatively vulnerable condition. The soil around the supporting bents had apparently liquefied, and may have permitted some to settle and rotate. The shear keys at both ends of the stayed spans apparently had translated laterally approximately two meters, gouging the supporting bent cap and inducing severe shear cracking. The pylon spalled to expose the core concrete and reinforcement over approximately two meters in height; splitting of the concrete around the core was evident nearly to the height of the lowest cables. One cable had sustained anchorage failure and was lying on the bridge deck.

Societal Impacts

Deaths and Injuries: According to the Taiwanese Ministry of the Interior (10-21-99), there were 2,405 fatalities and 10,718 injuries, approximately 1,000 of which were serious enough to require hospitalization. Casualties were heavily concentrated in three jurisdictions: Taichung County, Nantou County and Taichung City. These accounted for 85% of all injuries and 90% of all fatalities. In Taipei, Taiwan's largest city (150 km from the epicenter), there were 71 deaths and 316 injuries.

Displaced Persons: The number of persons displaced from their homes in the earthquake is very difficult to ascertain, but estimates published in the English-language Taiwanese newspapers most frequently mentioned 100,000. Information compiled by the Taiwanese Ministry of the Interior on residential damage reveals that 31,534 housing units were destroyed and 25,506 units were seriously damaged. Given these figures, a displaced population of 100,000 seems likely to be an underestimate. Further, the frequency and magnitude of aftershocks and concerns about safety impelled many people to abandon otherwise undamaged homes for outdoor shelter. That shelters were in dispersed locations and took different forms also contributed to difficulty in accurate counts.

Emergency Response: Based on observations in the field and reports from government agencies, voluntary organizations and residents of the impact areas, the government response was reasonably timely and generally effective. Government actions were only one element of the overall response, and the contributions of volunteers and significant involvement by the private sector were crucial. International assistance took the form of search and rescue teams, cash and donated materials.

Receipt of rapid information from Taiwan's sophisticated seismic network played an important role in early situation assessment at the national government level. Key officials were paged within two minutes of the main shock with seismic information including the earthquake magnitude, location, and shaking intensities for the large cities. Upon notification that the earthquake was over magnitude 7 and located in central Taiwan, ministry officials assembled at the National Fire Headquarters in Taipei at 2:30 a.m. The Vice President, who has

***Figure 16** - Rescue worker searches for survivors in collapsed building, Taipei.*
(Photo: Tomohide Atsumi, Osaka University)

responsibility for emergency response at the national level, joined this meeting at 3:30 a.m. Communications were established with local agencies and the emergency response was initiated.

Taiwan's instrumentation network capabilities are comparable to those now under development in southern California. Data from this seismic network were used in response mobilization, but mapped data on intensity distribution, aftershock warnings or advisories, and follow-up public information would also have been helpful to emergency response organizations. The real-time intensity mapping capability currently available in Taiwan could be enhanced, and an outreach program to promote the use of these maps for emergency response decision making could be implemented.

According to documents provided by the Interior Ministry, there were 5,004 rescues (10-21-99). Rescues in Nantou (2144), Taichung (1402), and Yunlin (628) Counties account for 83% of all those officially reported. In addition, extensive landslides and earthquake damage to roads and bridges in Taichung, Chiayi, Nantou and Yunlin Counties isolated 4,685 people. International search and rescue teams accounted for six live rescues. Military personnel, active in many response activities, also carried out search and rescue missions, and assumed much of the responsibility for recovering the dead.

To achieve greater coordination of response and recovery efforts and to expedite disaster assistance, on September 25th the central government declared a six-month State of Emergency (expiring on March 24, 2000). The decree facilitated the following actions: redirection of budgetary allocations to the response effort and issue bonds; use of public and private property (including land, buildings, and equipment) as deemed necessary; assignment of the Army to disaster response and recovery tasks; establishment of severe penalties for unwarranted price hikes for necessities; and the waiving of certain fees and legal requirements.

The locations at which victims found shelter were difficult to assess, as were the number of people displaced from their homes. Agencies of government, including cities and county governments, established shelters, as did the Army. The shelters were located at schools and other public buildings in the disaster areas, and were serviced by local government agencies, the military 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.

Economic Impacts: Estimates of overall losses in the earthquake were not available from government agencies in Taiwan, but an article which appeared in the *Asian Wall Street Journal* (10-5-99) placed the cost to rebuild damaged buildings and infrastructure at US$8 billion. When other damage, such as that to utilities, is added to the impact of indirect economic losses, particularly lost production due to electric power outages, the overall loss may approach US$20 to US$30 billion. The industries most affected by the earthquake are the computer hardware and components industry, tourism, agriculture, and banking sectors.

Conclusions

Buildings up to 15 stories (50 m total height) suffered the most seismic damage, including collapses. However, compared to the total stock of such buildings, and considering the magnitude of the earthquake, the percentage of damage was small. The damage to these buildings could be attributed to the soft first story created by the "open space" policy, or to poor construction practices leading to lack of ductile detailing. Other possibilities include lack of field inspection by qualified structural engineers and, in some cases, the directionality of the seismic motions. When additional information is available, site response may correlate with observed damage.

One of the challenging questions from this earthquake is whether the reinforced concrete building frames would perform well if the nonstructural walls were replaced with walls isolated from the structure or constructed of deformable materials so that they would not resist appreciable loads (as with the gypsum board partitions in U.S. construction).

In light of the estimated ground shaking intensity, it was surprising and encouraging that the majority of bridges in the epicentral region, not described here, had limited damage. While the collapsed bridges in some cases created travel delays, alternative routes were available for travel through the region, on apparently undamaged bridges.

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More photos and links to other excellent websites can be found at http://www.eeri.org.