

Event Report



# Chi-Chi, Taiwan Earthquake

September 21, 1999 1:47 a.m. M7.6 23.8N 120.8E 7 km depth





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# The Chi-Chi Earthquake

The magnitude 7.6 Chi-Chi earthquake, and subsequent large aftershocks (four greater than magnitude 6.5), stunned all who live and work on the seismically-active island of Taiwan. Until now, the central and western parts of the island were considered less vulnerable to damaging earthquakes than the eastern region where the Eurasian and Philippine Sea plates collide. This is the most devastating earthquake since a magnitude 7.1 earthquake struck the Hsinchu-Taichung region in 1935, taking at least 3,500 lives.

The Chi-Chi earthquake struck shortly before 2 a.m., when people were sleeping. The Chelungpu Fault ruptured through hundreds of structures, and the earthquake generated thousands of landslides throughout the epicentral region. Damage was heaviest in the central counties of Taichung, Nantou, and Yunlin. Severe damage occurred in and around Taiwan's third largest city, Taichung (population 1 million), but very strong shaking was felt across much of the more densely populated northern region. The earthquake toppled two tall buildings in the capital city of Taipei (population 12 million), about 150 kilometers (90 miles) north of the epicenter.

The death toll surpassed 2,400 and more than 10,700 people were injured. Over 8,500 buildings were destroyed and another 6,200 were seriously damaged, a majority of which were reinforced concrete structures with poorly designed columns that failed at the first floor.

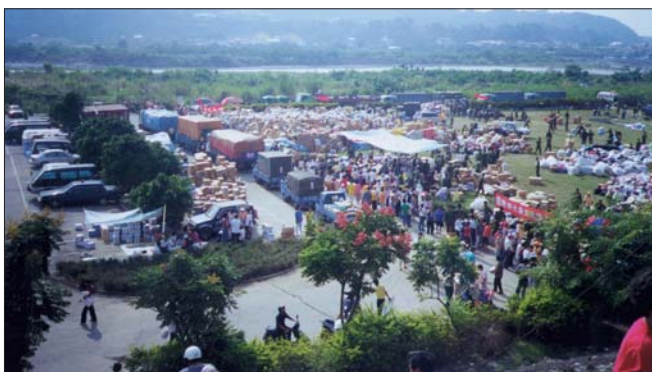
Unlike many other recent large-scale disasters in the United States, Japan, and Turkey, this earthquake was directly felt in the country's political power center. Government response was swift. Taiwan's investment



The September 21 earthquake's shallow epicenter was at Taiwan's geographic center and near Sun Moon Lake, a well-known vacation spot in Taiwan's less-populated central mountains.

in a sophisticated seismic network with real-time telemetry provided government officials with pager/fax read outs of the location, magnitude, and shaking intensities for the island's nine largest cities within two minutes after the earthquake. In the first hour, representatives of key central government ministries gathered at emergency headquarters in Taipei and response mobilization and implementation was both timely and effective.

More than 5,000 people were rescued from damaged or collapsed buildings. Most rescues were



As seen two days after the earthquake, public and private agencies used recreation fields along the river in Dungshu as a staging site for response and relief efforts.



This same site, seen one month after the earthquake, continued to serve as a disaster assistance headquarters for area residents.

County	Deaths	Injuries	Missing Persons	Rescues	Evacuations via Temp Rd.
Taipei Municipality	71	316	22	149	
Hsinchu City	2	4			
Taichung City	113	1,112		155	
Chiayi City		11		14	
Taipei County	39	145	7	192	
Taoyuan County	3	84			
Hsinchu County		4			
Miaoli County	6	196		34	
Nantou County	889	2,421	10	2,144	912
Taichung County	1,170	5,602	8	1,402	1,992
Changhua County	29	387		286	
Yunlin County	80	423		628	454
Chiayi County	2	5	4		1,327
Tainan County	1	1			
Ilan County		7			
<b>Total</b>	<b>2,405</b>	<b>10,718</b>	<b>51</b>	<b>5,004</b>	<b>4,685</b>

(Taiwan Ministry of the Interior, 10/21/99)

*Chi-Chi earthquake summary data*

performed by local fire agencies and organized teams of volunteers. Road and bridge failures, particularly in the remote mountain regions, presented the greatest response challenge. The government reports that 4,685 people were successfully evacuated from remote regions after temporary roads were constructed.

The Chi-Chi earthquake left an estimated 100,000 people homeless, and since less than 1% of the residential market has earthquake insurance, housing reconstruction responsibility rests largely with the victims and the central government. Public land in the central region has been set aside for temporary housing construction, and funding programs have been established to assist homeowners with repairs and reconstruction.

Overall economic losses are expected to be US\$10 to \$12 billion. A significant proportion of the estimated US\$600 million in insured losses will come from business interruption losses associated with the extensive power outage caused by the earthquake. The earthquake brought heavy damage to high-voltage transmission lines and nearly destroyed the Chungliiao substation, the critical link between the power-deficient northern part of the island and surplus supplies in the south. While temporary repairs have been made to reinstate island-wide operations, the system remains fragile and vulnerable to damage that could be triggered by additional earthquakes or storms.

In the aftermath of the earthquake, presidential candidates for the 2000 election initially halted their campaigns, but as time passes, they have begun to use the experience to illustrate policy and leadership

changes they would initiate if elected. For example, one candidate drafted disaster management recommendations, including the formation of a centralized response and recovery command center similar to the Federal Emergency Management Agency (FEMA) in the U.S., as well as a more localized approach to post-disaster damage and recovery needs assessment.

Since the earthquake, Taiwan's central government has been developing policies and plans for recovery and reconstruction. As of early January 2000, over 1,000 people were still living in tents, and the central government planned to have them moved by the end of the month. The final housing solution is yet to be defined. New maps have been prepared with construction setbacks from fault lines (similar to California's Alquist-Priolo zone requirements that preclude new development near surface fault rupture areas). The government also hopes to stimulate and diversify the economies of some of the hardest-hit towns and plans to incorporate larger urban renewal projects into the reconstruction efforts.



*A partially collapsed reinforced concrete building in Dungshr. Approximately 15,000 buildings were heavily damaged or destroyed, the majority of which were mid-rise reinforced concrete structures.*

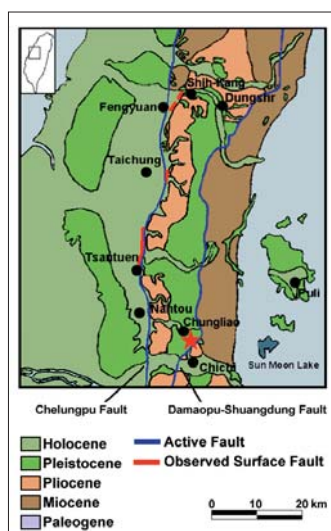
# The Earthquake and its Geologic Effects

The magnitude 7.6 Chi-Chi earthquake struck central Taiwan on September 21, 1999 at 1:47 a.m. local time. Locally known as the "921" earthquake, it ruptured 80 kilometers (50 miles) of the Chelungpu Fault, which flanks the western edge of Taiwan's central mountain range. The epicenter, located near the town of Chi-Chi, had a very shallow depth of 7 kilometers (4 miles). Ground shaking exceeded 1.0 g in many places and triggered hundreds of strong motion instruments across the island.

## RARE EVENT DESPITE FREQUENT EARTHQUAKES

Taiwan owes its formation, shape, and frequent rate of earthquakes to the complex interaction of the Eurasian and Philippine Sea plates. In a geologic time scale, the 35,563 square kilometer (13,731 square mile) island has virtually erupted from the ocean floor as the Philippine Sea Plate pushes northwestward into the Eurasian Plate at a rate of approximately 7 centimeters per year. Taiwan is divided longitudinally by a spine of very steep mountains that create an almost impenetrable barrier between the rugged and less populated eastern region and the gently sloping and highly developed western plains. Ninety percent of Taiwan's 22 million people live west of the mountains.

Large magnitude earthquakes in the eastern and



The reconnaissance team investigated approximately half of the 80-kilometer (50-mile) rupture along the Chelungpu Fault, which runs from Shih-kang in the north to Tungtou in the south.

north-eastern seismic zones dominate the island's high seismicity rates. Shallow depth (<20 kilometers) earthquakes generally occur in the less seismically active western region.

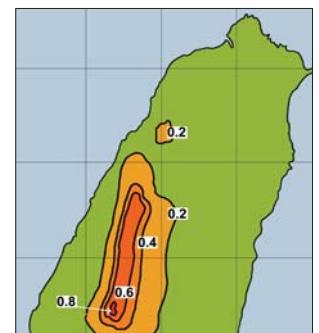
The island has more than 40 mapped active surface faults that generally trend north-south, parallel with the plate boundary. Most of these are thrust

(or low-angle reverse) faults, meaning that the block of land overhanging the fault plane moves up relative to the underlying block of land. Only five of this century's 43 earthquakes in Taiwan (magnitude 6.5 or greater) were surface fault events like the 921 earthquake, and much of the western portion of the island (including the Taichung area) is located in building design Zone 2, a moderate seismic area.

## STRONG GROUND MOTIONS ACROSS THE ISLAND

The Chi-Chi earthquake generated about 30 seconds of extremely strong shaking.

In general, ground motions near the fault trace and to the east of the rupture zone were significantly higher than areas west of the fault. Peak ground accelerations (PGAs) of 1.0 g to 1.2 g were recorded at the south



This reproduction of the Central Weather Bureau's preliminary shaking map shows intensities of 0.8 g or greater in the epicentral region.

rupture zone and 0.4 g were recorded at the north end. Ground motions in the north had shorter durations but much stronger velocities of more than 300 centimeters per second were recorded, as compared to the 40 to 60 centimeters per second measured at the south end.

The seismic moment (a measure of the energy released by the earthquake) was 10 times that of the 1995 Kobe, Japan earthquake and 50% greater than the 1999 Kocaeli, Turkey earthquake. There were more than 10,000 aftershocks, including three of magnitude 6.8 and one of magnitude 6.5, all of which were located to the east of the Chelungpu Fault.

There is some evidence that previous ground motion models for Taiwan may have underestimated actual site response. The fertile plains west of the Chelungpu Fault are known as the Taichung Basin, and the depth to bedrock is as much as 180 meters (600 feet). Although the role of local site response is still unclear, it appears that site characteristics may have influenced



*Ground deformation associated with the earthquake faulting destroyed these lightweight structures and formed a dam across the riverbed near Fengyuan.*

damage levels at some locations near the epicentral area. Likewise, Taipei City is also underlain by deep alluvial deposits and damages there may also have been caused by a "basin" effect.

#### **FAULT RUPTURES THROUGH MANY BUILDINGS AND LIFELINE SYSTEMS**

The Chelungpu Fault, a previously mapped and active fault trace, roughly follows the topographic break along the western edge of the central mountains. The north-south trending fault ruptured for over 80 kilometers (50 miles), from Shih-kang in the north to Tungtou in the south. The hanging wall of the thrust fault moved westward and upward by 1 to 2 meters (3 to 7 feet) along the entire length of the rupture. Tectonic warping, or folding, associated with the faulting caused additional upward ground deformations of 6 to 7 meters (20 to 23 feet), particularly in the northern reaches of the rupture.

In other earthquakes, most damage caused by fault displacements has typically been limited to areas close to the fault rupture. However, the tremendous ground deformation associated with this earthquake's faulting caused major destruction to buildings and lifelines across a wide zone, as much as 120 meters (400 feet) wide, along the entire rupture length. Damaged structures included schools, residences, dams, embankments, and bridges.

#### **EXTENSIVE GROUND DEFORMATION ALTERS LANDSCAPE**

Strong ground motions on the landmass east of the Chelungpu Fault generated more than 1,800



*Landslides caused most of the more than 600 road disruptions, limiting access to remote mountain villages for more than a week and hampering emergency operations throughout the epicentral region.*

landslides throughout the central mountain region. Two phenomenal landslides occurred near the epicenter. In one, a large section of mountain slid 2 to 3 kilometers (1 to 2 miles) and swept away everything in its path, including entire villages. The other slid down more than 100 meters (330 feet), damming up a river and forming an artificial lake. Several villages were abandoned when water was impounded behind the new rock dam. A similar dam was formed by a landslide in a 1941 earthquake, which eventually ruptured and caused catastrophic flooding.

#### **LIQUEFACTION EFFECTS ARE LIMITED**

Liquefaction was confined mostly to areas along riverbanks and levees. Only a few sand boils (a key sign of liquefaction) were identified. The most severe liquefaction-induced damage occurred at the port of Taichung. The port is about 20 years old, built in four stages on reclaimed ground. The water table is less than 2 meters (7 feet) below the ground surface, yet ground remediation work at the time of construction appears to have withstood the strong shaking. Only four of the port's 45 berths sustained damage and were out of service due to liquefaction effects.

Ground subsidence also contributed to bridge damage at a few locations. Bridges crossing waterways near Yuanlin and Wufeng were damaged when the ground settled by as much as 1 meter (3 feet). Ground settlement also caused damage to 300 houses in a residential neighborhood, with up to 1 meter of settlement reported.

# Residential and Commercial Buildings

The Chi-Chi earthquake and subsequent aftershocks destroyed approximately 8,500 buildings and significantly damaged another 6,200. Damage was heaviest in the central Taiwan counties of Taichung, Nantou, and Yunlin. In the central mountain city of Puli, approximately 50% of commercial buildings in the downtown area were severely damaged or collapsed. An estimated 60,000 housing units have been destroyed and another 50,000 need repair.

## ALTHOUGH CODES RESEMBLE U.S., CONSTRUCTION PRACTICES DIFFER

Taiwan has fairly uniform building and construction types. Most are reinforced concrete buildings with unreinforced brick masonry partitions and infill walls, particularly in the heavily impacted region. There are almost no hollow clay tile, reinforced masonry, or woodframe buildings in Taiwan. Structural steel is used for some of the newer high rise construction. Almost all the buildings in Taiwan are less than 100 years old, and only a few older, one-story adobe structures remain today.

Taiwan's building code is similar to the Uniform Building Code (UBC) used in the western U.S. Most of central and western Taiwan (the heavily impacted area) is in Zone 2, corresponding to a region of moderate seismicity. The substantial ground motions measured in this earthquake suggest that the codes may need to require higher seismic design standards.

In Taiwan, buildings greater than 50 meters (165 feet) tall are subject to a peer review process to ensure adequate structural design. These are typically office or apartment buildings made of reinforced concrete or structural steel (single or dual moment-resisting frames). Buildings between 10 and 50 meters (30 to 165 feet) tall have strict engineering standards, but are not subject to peer review. Buildings less than 10 meters tall are constructed according to prescribed code provisions. Inspections for most buildings less than 50 meters tall are done by architects, not by structural engineers.



*The non-ductile concrete frames in many buildings' first floors collapsed when they were unable to withstand the lateral earthquake forces.*

## WEAK FIRST FLOOR COLUMNS CAUSE LOW AND MID-RISE BUILDING DAMAGE

Damage to low and mid-rise buildings (less than 8 stories high) was quite extensive and caused a majority of the earthquake's fatalities. Most collapsed buildings were reinforced concrete frame buildings with brick infill walls, typically accommodating commercial uses on the first floor with residences above. Most damage was caused by poor, non-ductile concrete detailing and soft story conditions.

While brick infill is not designed to be part of the earthquake load resisting system of a building, it nevertheless adds strength and stiffness, unless it is isolated from the concrete frame. In Taiwan, the brick infill is often discontinued on the street side in order to provide open commercial areas and covered pedestrian walkways on the ground level. Until recently, many cities in Taiwan required this "arcade" style of construction, and during the building boom of the 1980's, cities often gave bonuses (e.g. higher densities or increased heights) for adding arcades. Unfortunately, this discontinuity in the brick infill created weak first stories and torsional irregularities. The non-ductile concrete frames in the buildings' first floors collapsed when they were unable to withstand the lateral earthquake forces. Buildings with brick infill on the ground level were often severely damaged, but seldom collapsed.

Since 1982, concrete building standards in Taiwan have included ductile steel reinforcement requirements that specify the quantity and placement of steel reinforcements in order to eliminate non-ductile (brittle) failures. Similar detailing requirements were added to the UBC in the western U.S. following the 1971 San Fernando earthquake. Although these detailing requirements are part of Taiwan's code, they often were not implemented in construction.

Little fire damage occurred in the 921 earthquake. Buildings are typically clad with tiling or stone veneer, which offers good fire resistance. Furthermore, natural gas use is limited. Heating systems are fueled by electricity and bottled propane gas is widely used for residential cooking.

#### WEAK COLUMNS ALSO TOPPLE HIGH-RISES

The Chi-Chi earthquake significantly damaged many high rise (8 stories or greater) buildings, and in some cases caused spectacular collapses. More than 15 buildings in this height category completely collapsed, all of which were less than 50 meters (165 feet) tall. No buildings more than 50 meters high collapsed. A number of these failures occurred in the area extending from Taichung to Fengyuan, but also



*Spalling on the exterior veneer exposed salad oil cans in the concrete beams of this newly constructed reinforced concrete building in Nantou City.*

included two as far away as Taipei. As with the shorter buildings, most damage was caused by the catastrophic non-ductile failure of first-story columns. Soft story conditions (from open areas in the first story) also contributed to the damage, particularly concentrating damage in the first-story columns.

Deficiencies in steel reinforcement details included: (1) a lack of adequate column confining steel, (2) a lack of 135-degree hooks on the confining steel, and (3) slicing of all vertical steel reinforcement at the same location in the column, directly above floor levels.

In the initial days of the disaster, a few tall building collapses mounted concern that poor construction practices had caused an unnecessary number of fatalities. Mangled in the debris were rows of salad oil cans embedded in collapsed concrete beams. Contractors and engineers quickly responded that cans are commonly used to save on concrete when creating thicker beams for architectural purposes. Although skepticism still exists, this practice could in fact be similar to U.S. practices of using styrofoam to fill architectural voids. Nonetheless, many architects and building contractors have been prosecuted for illegally borrowing licenses from high-rated architects and building contractors. Some were restricted from leaving the country because of violation suspicions following the earthquake.



*The combined vertical weight of the building and earthquake overturning forces exceeded the load-bearing capacity of the columns, completely toppling some buildings, such as this one in Dali.*

# Public and Industrial Facilities

The Chi-Chi earthquake inflicted heavy damage on the island's public facilities, particularly schools and municipal buildings. Industrial damage was extensive, but relatively light when compared to the overall impacts on residential and public sectors of the economy.

## HEAVY LOSSES TO SCHOOLS AND PUBLIC FACILITIES

The Chelungpu Fault ruptured through the elementary and junior high schools in Wufeng and considerable public attention has focused on the conditions of Taiwan's schools and public facilities. In all, 43 schools in Nantou and Taichung counties were completely destroyed (and have since been demolished) and a total of 700 schools nationwide were damaged in some way. The government estimates that the total reconstruction will likely cost US\$150 million. The Taiwan Red Cross has committed more than US\$15 million to rebuild 14 elementary and junior high schools in the epicentral region. Plans are to convert a Wufeng junior high school into an earthquake memorial museum, and to find another suitable campus location nearby.



*A pancaked classroom building on a junior high school campus in Wufeng.*

Since many of the damaged schools were of similar design and vintage, concerns have been raised about whether the higher design standards for schools and other critical public facilities were actually followed. Fifty-one police stations in Taichung, Nantou, and Yunlin counties were destroyed and the buildings of 10 fire departments have been deemed hazardous, with limited entry. The National Chi-Nan University located in the town of Puli was so badly damaged that the campus was closed and students have been relocated to Taiwan National University.

## INDUSTRIAL IMPACTS RELATIVELY LIGHT

About 9,000 industrial plants in 53 industrial parks around the island reported some amount of damage, yet the overall impact on Taiwan's basic industries and export-leading high technology industry was relatively light. However, if the epicenter had been further north or south, the industrial sector would have sustained significantly more direct physical and indirect business interruption losses.

Little building damage was experienced at the Hsinchu Industrial Park, which is located 70 kilometers (40 miles) southwest of Taipei, at the heart of Taiwan's semiconductor



*The 4-story reinforced concrete city administration building in Puli also suffered a pancake collapse.*

manufacturing sector. Equipment damage was minimal with one clear exception. At the Park's semiconductor manufacturing facilities, the 921 earthquake and subsequent strong aftershocks knocked the high-precision quartz fusing devices out of alignment. Production at most facilities was drastically reduced by the earthquake-induced power outage and remained below capacity until spare parts arrived from Japan and other countries.

Industrial damage was heaviest in the three central counties of Taichung, Nantou, and Yunlin, which contain 19,000 factories and account for 22.8% of Taiwan's industrial capacity. Light industrial and precision machining industries employ about 350,000 workers, or 6.3 % of the island's total workforce. The average daily gross product for the three-county region is reportedly US\$170 million.

Industrial damage was sporadic and relatively light within the city of Taichung. A distribution warehouse

collapsed onto trucks parked at a loading dock. South of Wufeng, a concrete ready-mix plant was completely destroyed, and concrete delivery trucks parked nearby were thrown onto an adjacent riverbank. In Puli, the reinforced concrete buildings at a rice wine brewery suffered significant damage and industrial vessels collapsed, and business here is expected to be interrupted for many months.

#### PORT DAMAGED BY GROUND SETTLEMENT

The port of Taichung is one of four ports that handle international trade in Taiwan, and is second in size to Taiwan's port of Kaohsiung in the south. As much as 4 feet (1.2 meters) of ground settlement was observed, and liquefaction and ground subsidence seriously damaged four of the port's 45 berths. All crane facilities at the affected berths appeared undamaged, but were slightly tilted along with the supporting structures. Earthquake-induced sloshing seriously

damaged 10 of 11 large steel molasses tanks at the port. Storage silos on deep-pile foundations sustained little or no damage. Repair is likely to exceed US\$150 million and is expected to take many months.



*As much as four feet of ground settlement was observed along the entire length of a wharf (approximately 1,000 meters, or 3,300 feet) at the port of Taichung.*



# Infrastructure Impacts

Civil infrastructure systems are essential to the robust functioning of a modern society. As distributed systems, their very nature makes them vulnerable to natural hazards, particularly widespread ground failures as observed in this event.

## HEAVY DAMAGE TO ROADWAYS AND BRIDGES

Surface faulting and extensive ground deformation severely impacted roads and bridges throughout Taichung, Nantou, Chiayi, and Yunlin counties.

East-west travel across the island was significantly hampered, and many central mountain villages were inaccessible as landslides closed highways and roads for several weeks. Emergency access was often limited to helicopters and walking.

Thirty of the 590 inspected bridges on the island sustained damage. Of those, five bridges collapsed, nine bridges required major emergency repairs to sustain traffic, and 16 bridges were damaged but rated safe. Nearly all bridges in Taiwan are constructed with simply-supported, pre-stressed concrete girders. Construction quality is generally good and damage has not been attributed to poor construction.

Most of the collapsed bridges were located on the provincial highway Tai-3, which runs north-south through Taichung and Nantou counties, and coincides with an extensive part of the Chelungpu Fault rupture. Most were constructed before more stringent seismic requirements were implemented. Bridges constructed over the fault were severely damaged by the rupture, even those built recently. The fault rupture tended to push the road bed up, unseating it from the spans. Several bridges near the fault collapsed when the embankment behind the bridge abutment moved significantly.

Damages due to differential movement along bridges temporarily closed many roads, but few of these damages were severe. Most required temporary repairs in order for limited transportation to resume. Permanent roadway repairs will take several months to complete, especially in the seriously affected Taichung and Nantou counties.



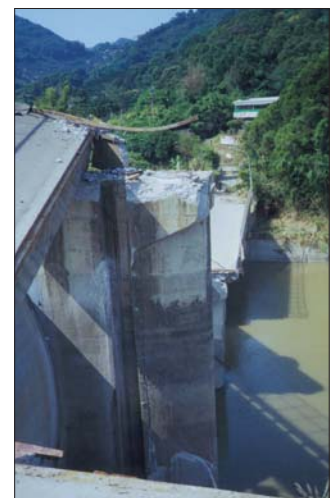
*On Tai-3 near Wufeng, the Chelungpu Fault rupture sheared through a bridge column, causing several spans to collapse.*

## RAILWAY DAMAGE LIMITS TRANSPORT

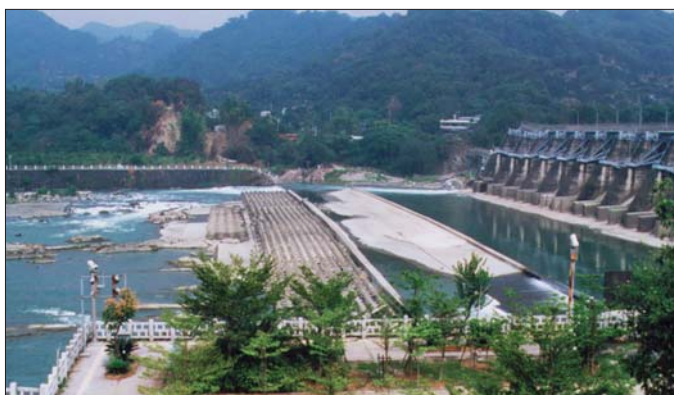
Ground deformation damaged the tracks of the island's major north-south railroad near Taichung. Passenger and freight transport was significantly affected. Temporary repairs reopened the system within a few weeks after the earthquake, but travel delays continue and permanent repairs will take significantly longer to complete.

## WATER SYSTEM DAMAGE HURTS CENTRAL REGION

The 921 earthquake disrupted service to more than 80% of the region's 5 million water customers, and a full recovery will take several months. The Shih-kang Dam, which supplies 40% to 50% of the water consumed in the Taichung area, is nearly 25 years old, and was apparently built without knowledge of the faults. The dam failed when vertical fault displacements on both sides of the dam caused large relative ground motions between individual piers. Faulting and associated ground deformation raised one portion of the dam by nearly 10 meters (30 feet), causing three of the 18 concrete piers



*Vertical ground displacements due to earthquake faulting caused three piers to collapse on the northern end of the Shih-kang Dam.*



*Vertical ground displacements associated with earthquake faulting have raised the overall ground elevation around the Shih-kang Dam, exposing areas that were once covered by water.*

and spillways to collapse. The resulting reservoir discharge did not inundate downstream uses, but the water supply was interrupted for some time.

Two of the regional system's 25 water treatment plants are located in the epicentral area, near Fengyuan. One of these plants was located adjacent to the fault rupture and sustained severe damage. A roof also collapsed on a 5-meter (17-foot) deep reservoir pool.

The water system also includes more than 32,000 kilometers (20,000 miles) of pipe. The fault crossed a major transmission pipe leading from the Shih-kang Dam to Taichung, and the 1/2 inch thick steel pipe was significantly deformed by the fault uplift. It will be difficult to assess how much damage occurred in the water transmission system in the epicentral region.

#### ELECTRIC SYSTEMS DAMAGE AFFECTS ENTIRE ISLAND

Taiwan's electric power system, run by the state-owned Taiwan Power Company (Taipower), supplies over 10 million customers on the island. There are 69 power plants with a total installed power capacity of 26,680 megawatts (MW).

Residents of Taipei who were awake at the time of the earthquake were given a few seconds of advance notice when a widespread power blackout preceded the earthquake's motions. The outage, which was nearly island-wide, had three main causes:

- A transmission tower carrying 2 of 4 critical lines linking the central and northern sections of the island's power grid collapsed

- The Chungliiao substation, a major hub in the island's high voltage transmission network that directs 45% of the north's power demand, sustained heavy ground shaking of 1.0 g, which completely destroyed equipment in the southern switchyard and activated a very large landslide that damaged over half of the site and snapped an incoming transmission line
- Two nuclear power plants located in the northern part of the island, though sustaining no significant damage and experiencing ground shaking at only 0.3 g, tripped due to overall system imbalance and were shut down for nearly a week after the event

Additional power generation and transmission facilities throughout the epicentral region sustained considerable damage, and all hydrogenerating capacity in the island's system was lost for more than 10 days. The switchyard at the Tienlun hydroelectric plant was almost completely destroyed, and the generator, water pipelines, and penstocks suffered some damage. The dam at the Sun Moon Lake reservoir in Nantou County also sustained damages. Without the hydropower for regulating frequencies across the island-wide power grid, the electrical system was unstable for some time.

Transmission line damage was also extensive. In all, 355 high-voltage transmission towers were damaged. The remote locations of most lines in the central region hampered damage assessment and temporary repairs. Permanent transmission line repairs are expected to take 2 to 3 years to complete.



*Clean-up underway at the Tienlun switchyard, nearly one month after the earthquake. Similar heavy damage that occurred at the Chungliiao substation was already cleaned up by this time.*

# Power and Business Interruption

In 1998, Taiwan exported US\$110 billion in products and services, 35% of which was related to its semiconductor industry. Taiwan currently supplies 12% of the global Dynamic Random Access Memory (DRAM) market, while also supplying 33% of the market's non-memory chips. The Chi-Chi earthquake provides an extraordinary opportunity to examine the critical linkages between electric power damage, restoration priorities, and consequences for business interruption and economic recovery.

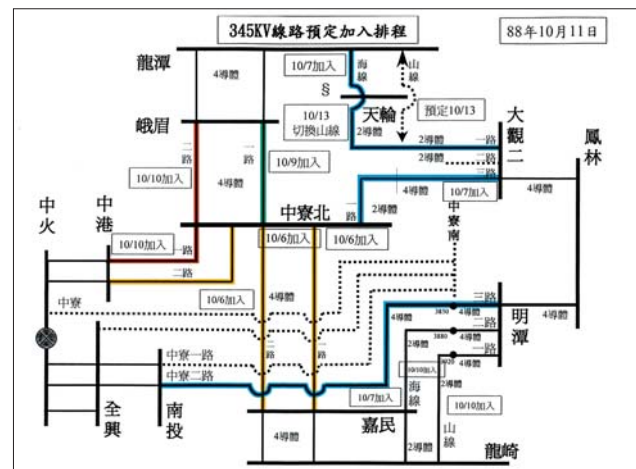
## ISLAND-WIDE POWER GRID QUITE FRAGILE

Rapid development in northern Taiwan in recent years increased power load demand by approximately 6% annually, but new power generating facilities have not come on line as quickly as needed. Currently, the northern third of the island has a daily deficit of more than 3,800 MW, amounting to 45% of the power demand for Taipei and the northern part of the island. This power must be transferred north from generating plants in the central and southern parts of the island, and is carried on transmission lines going through central Taiwan's Chungliiao substation. Twenty-two high voltage lines pass through Chungliiao, making it one of the most critical electric power nodes in the world.

Taiwan's single, island-wide grid is vulnerable to disruption when a single key power line goes down. System imbalances and associated voltage drops are common, particularly in the north where industrial users reportedly experience outages on a monthly basis. At the time of the earthquake, Taipower was still managing repairs and its public response to an island-wide power outage that occurred in July 1999 when the tower on one major high-voltage line collapsed during a storm.

## SYSTEM DAMAGE ASSESSED AND RESTORATION PRIORITIES SET

When the earthquake hit, all power in the northern and central part of the island was quickly lost, and only 5,000 MW were circulating in the southern portion of the system. Taipower initiated emergency



As part of the restoration plan, the undamaged equipment at the Chungliiao substation was carefully mapped and temporary routings were designed to get power through the station again and headed north. The pink, yellow, and blue shading illustrate restored transmission routes through the central region and to the north.

response coordination at its headquarters in Taipei and quickly assessed system damages using microwave communications to interact with regional offices. The central region, which was critical to the island-wide restoration process, sustained the heaviest damages.

A plan to restore power was selected the day after the earthquake, calling for accelerating efforts already underway (prior to the earthquake) to build a transmission bypass around Chungliiao and link another, undamaged substation with the main transmission lines in order to transfer more power northward. It also called for construction of two temporary towers to replace the two circuits on a high-voltage tower that collapsed.

Restoration priorities included the military, critical infrastructure facilities (e.g. airports, transportation, water, and power), emergency-related facilities (e.g. police/fire stations and hospitals), and key industrial facilities. Large-scale industries [with consumption greater than 1,000 kilowatts (kW) per day] had priority for uninterrupted power supplies. Smaller industries (below 1,000 kW) and households were rationed according to geography. Northern residents and smaller businesses (including those in Taipei and Hsinchu) were placed on mandatory rolling outages of 7 hours per day for three weeks after the earthquake.

System power restoration proceeded gradually over the weeks following the earthquake. Plants came back on line, temporary transmission towers were constructed, and routes were slowly restored.

## SIGNIFICANT IMPACTS AT THE HSINCHU SCIENCE PARK

The 600 hectare (1,500 acre) Hsinchu Science Park accounts for over 50% of Taiwan's total semiconductor sales and about 35% of its computer-related sales. The Park is one of two technology-based and academically-linked science parks in Taiwan and has almost doubled in size in the past five years. It accounts for about 8% of Taiwan's national and international trade. Over 75,000 employees work for the 280 businesses that reside within the Park.

Businesses at the Park use a total of approximately 500 MW of power each day. Semiconductor manufacturers are particularly heavy power users, since their operations run around the clock. The chip building process takes about two weeks, and an uninterrupted power supply (UPS) is critical to avoiding contamination of in-process production and recalibration of sensitive manufacturing lines.

Although the Park sustained very little direct physical damage, the power outage was immediate and business production quickly drew to a halt. Most semiconductor plants had at least one emergency power generator that was quickly engaged to help shut down plant operations and provide a minimal power supply. A few plants had also invested in expensive UPS systems that provided them with added protection for production inventories in process when the earthquake struck.

### POWER RESTORATION AT THE PARK WAS A COOPERATIVE EFFORT

Representatives of the semiconductor plants and other members of the Park's power quality improvement



*The newly-opened cogeneration plant is an independent power producer and a valuable auxiliary power source for several semiconductor businesses in the Hsinchu Science Park.*

committee agreed to a power rationing and supply scheme for all businesses in the Park within hours after the earthquake. The Park's newly-opened cogeneration plant, an independent power producer (IPP), agreed to provide a continuous supply of 80 MW to semiconductor plants in the Park's newest phase 3 development area (about half of the normal demand for businesses in this part of the Park). Taipower also agreed to initially provide 40 MW of continuous power, which was rationed out to businesses in phase 2 of the Park. All of the Park's semiconductor plants, located in phases 2 and 3 of the Park, were therefore able to have a limited, but continuous, power supply to keep some production going.

All plants with emergency power generating capabilities also agreed to run their equipment continuously in order to provide additional capacity at each site. It was agreed that businesses in the Park's phase 1 area would not receive power until Taipower's normal supply to the Park (500 MW) was restored. Taipower's supply to the Park slowly ramped up over the days and weeks ahead, as the system was restored.

### ALTERNATIVE POWER SOLUTIONS SOUGHT

The worldwide chip shortage of 1999 was exacerbated by the power disruption caused by the 921 earthquake. However, while business interruption losses will be high, most businesses also expect these losses will be offset by the unexpected and dramatic increase in chip prices that occurred in the second half of 1999.

Semiconductor businesses are increasing their dynamic UPS and emergency generating capacity. Some businesses are considering placing more of their critical manufacturing operations outside of Taiwan, and larger plants are also considering proposals to construct small cogeneration plants at their facilities.

The Hsinchu Science Park Administration and Taipower have also been constructing additional substations to help stabilize power supplies within the Park. The Park cogeneration plant also plans to increase capacity by an additional 250 MW in the next few years.

# Financial and Economic Loss

Taiwan's central government estimates total financial and property losses from the Chi-Chi earthquake at US\$10 to \$12 billion. Direct property losses are expected to be US\$8 to \$9 billion of the total losses, while indirect business interruption losses are estimated at US\$2 to \$3 billion. Newspaper accounts indicate that the manufacturing sector is expected to have the highest business interruption losses of US\$1 to \$2 billion, followed by the service, utilities, and agriculture sectors, respectively.

## SLIGHT DECREASE IN 1999 GDP WILL BE OFFSET BY 2000 INCREASES

Preliminary estimates are that the total losses from the 921 earthquake amount to 3.3% of Taiwan's gross domestic product (GDP) and will result in a 0.5% decrease in the island's forecasted GDP for 1999. A 5.32% overall growth rate was originally predicted for 1999, and forecasters expected that the signs of the earthquake's negative impact would emerge in the fourth quarter of 1999. The earthquake initially caused the US\$3.4 billion Taiwan stock market to plunge, but the market gradually moved back toward its strong pre-earthquake level.

1999 reductions in GDP are expected to be offset in 2000 with a growth forecast of 6.05%. Domestic consumption is expected to grow by nearly 6% and domestic investment due to post-earthquake

reconstruction is expected to have a nearly 9% growth rate (almost double 1999's rate).

## INSURED LOSSES ARE LOW

Insured losses are estimated to only be about US\$600 to \$750 million, and most of this payment will go to manufacturing industries for business interruption losses associated with the extensive power disruption. The claims are expected to mostly pass through to global reinsurance companies, with local insurance companies only retaining about 10% to 25% of the insured losses. In addition, nearly one month after the earthquake, about 1,200 life insurance claims had been filed, totaling US\$60 million.

## GOVERNMENT SELF-FINANCES RECOVERY

In December 1999, Taiwan's central government established a Community Renewal Fund, which for an estimated period of five years, will serve as the financial mechanism for the 921 earthquake reconstruction program. Taiwan's Ministry of the Interior will be in charge of the fund and local city and county governments will submit proposals for reconstruction funding. It is designed as a special-purpose fund that can also generate its own revenue. The exact level of funding will be defined in the Reconstruction Bill now under consideration.

Taiwan's Central Bank has appropriated US\$3 billion for low-interest, long-term loans to aid victims in housing reconstruction, and the total compensation payout is expected to be near US\$540 million. Relief allowances are set based on the damaged state of buildings, which has placed significant importance on the government's damage determination process. The central government sent out at least 700 experts to double-check building damage appraisals. Government relief policies stipulate that residents of buildings declared "totally collapsed" can receive approximately US\$6,500 in relief allowances, and residents of buildings declared "partially collapsed" (seriously damaged) are eligible for half of this amount.



*A completely overturned high-rise apartment building in Dali. Taiwan will have to come to terms with apparent code and construction practice deficiencies in the months ahead.*



*The Chelungpu Fault rupture and associated warping damaged buildings, infrastructure, and roads in Fengyuan. New maps have been prepared with construction setbacks from fault lines (similar to California's Alquist-Priolo zone requirements).*

The government is also now offering publicly-financed housing built in 1998 in Nantou County at a 30% discount to earthquake victims. This discount puts the average price tag at a locally low rate of US\$60,000, but the response has been less than expected. Newspapers highlight the "disconnect" between the government's damage compensation amounts and the real costs of rehousing.

Disputes over building declarations have been increasing, and local government officials have complained of threats by residents to declare undamaged buildings as unsafe so occupants can receive the government loans. Local officials are also being criticized for delays in funding distribution. In mid-October, government accounting offices estimated that the central government had released US\$430 million to local governments, but less than one-third had actually made it into the hands of eligible recipients. This figure is higher than newspaper surveys at the time, which estimated that nearly 80% of those eligible for government aid had yet to receive any funds or money.

The areas hardest hit by the quake also have an estimated US\$225 million in agricultural losses. As a result, a central agricultural bank has been proposed

to help absorb the local credit departments that are currently operating with negative net values.

#### RECONSTRUCTION POLICY EMERGES

Although the plans are still evolving, the central government has outlined objectives for relocating victims off of unstable lands, and incorporating larger urban renewal projects into the reconstruction efforts. For example, the central government has identified more than 47,000 hectares (116,000 acres) of land in the central region that could be eligible for land swaps. The land swap plan aims to offer alternative land to residents whose houses have been classified as "uninhabitable" because of ground instability. The hard-hit commercial banking industry was boosted by the plan announcement, since their burden on existing land loans would also transfer to more stable and developable land areas.

As of the beginning of January 2000, more than 1,000 people were still living in tents, and though the final housing solution was yet to be determined, the government hoped to have them moved by the end of the month. The central government also hopes to stimulate and diversify the economies of some of the hardest-hit towns.

# Consequences and Implications

As Taiwan's 2000 presidential campaign heats up, the central government and residents face some difficult recovery challenges, including:

- Rebuilding more than 80,000 housing units and a building stock that is largely uninsured (Taiwan's residential earthquake insurance market penetration rate is less than 1%)
- Rebuilding the extensively damaged public facilities and public infrastructure systems throughout the epicentral region
- Deciding whether or not reconstruction will be permitted on unstable hillsides and in fault rupture areas
- Reevaluating the island's earthquake risk probabilities and management practices in light of lessons from this event (an event which exceeded all previous maximum magnitudes predicted for this part of the island)

## LESSONS FOR RECONSTRUCTION FINANCING

Taiwan's overall transition, however, is graced with a remarkable asset – capital. Compared to Los Angeles following the 1994 Northridge earthquake or Japan following the 1995 Kobe earthquake, or even more dramatically, Turkey following the 1999 earthquakes, Taiwan's central government has favorable economic conditions to help facilitate recovery. The central government has little debt burden, critical economic sectors are booming, and future outlooks are also positive. For example, Taiwan's electronics industry made a remarkable recovery from the recent Asian financial crisis. Taiwan's total electrical and electronic product exports reached US\$19 billion (a 13% increase over 1998). This earthquake will provide a critical global case study for how healthy economies perform in disaster recovery.

## LESSONS FOR GLOBAL RISK MODELING

The Chi-Chi earthquake and subsequent large aftershocks are the best recorded seismic events in



*Most of Taipei's 12 million residents live in dense neighborhoods of predominantly reinforced concrete buildings. The city is also exposed to high seismic risk from active faulting in the region, as well as its close proximity to the highly-active offshore plate boundary.*

world history. In 1990, Taiwan instituted a national program that installed more than 1,000 strong motion instruments within 5 years. The 921 earthquake activated instruments at more than 700 free-field acceleration sites, as well as in 39 buildings and 16 bridges. The earthquake provided 65 near-field (< 20 kilometers from the epicenter) ground motion records, five times the total number that existed for magnitude 7 or greater events in the world before now. Prior to the 1999 earthquakes, there were only eight (the 1999 Kocaeli, Turkey earthquake generated an additional five recordings).

The wealth of ground motion data resulting from this event is likely to substantially influence ground motion modeling and seismic design code standards worldwide as data is processed and analyzed in the months and years to come. Evidence from this and other recent earthquakes suggests that peak ground velocity may be a more critical predictor of building damage than other ground motion measures.

## LESSONS FOR SEISMIC DESIGN PRACTICES FOR BUILDINGS AND LIFELINES

While ground shaking is the primary cause of most earthquake-related damage, the 921 earthquake, like the 1999 Turkey earthquakes, illustrated the severe building and lifeline damages that earthquake faulting



*This major semiconductor manufacturing facility is located in the newest phase 3 of the Hsinchu Science Park.*

can cause. They have also shown that surface deformation associated with large fault ruptures can be difficult to predict. A dam, power substation, bridges, and other lifelines across the fault suffered fatal damages and the costs to rebuild will significantly impact the nation's economy. Redundancy and a systems approach seem to be among the few ways of guaranteeing critical infrastructure functionality after earthquakes.

The Chi-Chi earthquake emphasized the importance of code compliance procedures. In many instances, ductile detail requirements already in Taiwan's code simply had not been implemented in the buildings' design and construction.

The earthquake also highlighted some extraordinary variations in the performance of similar building types. In some instances, one building collapsed, while nearly identical adjacent buildings sustained no visible damage.

The complexity of the rupture process, ground motion propagation, soil conditions, and building performance inherently limit the validity of any initial conclusions that might be drawn. However, comprehensive post-earthquake damage inventory data and statistical explanations will be essential to completing the picture and improving seismic design and risk modeling capabilities.

## LESSONS FOR POWER-RELATED BUSINESS INTERRUPTIONS

If the epicenter of the Chi-Chi earthquake and subsequent large aftershocks had been closer to the north, damage to the island's high-tech industries and associated impacts on global markets would have been much greater. Unlike any event before, the Taiwan earthquake has illustrated modern industry's significant power dependencies, the cascading costs and effects of power-related disruptions in production, and the need for sufficient redundant power supplies to safely shut down operations.

The Hsinchu Science Park businesses were able to coalesce on a rationing plan and unite in negotiations with Taipower on power needs following this disaster. Without unified representation, high-tech industries in other parts of the world (such as in Silicon Valley, CA, Fairfax County, VA, or the research triangle in North Carolina) might be placed in a competing situation with power suppliers following a catastrophic disaster. The Taiwan earthquake illustrates the need for power suppliers and customers to work together in pre-disaster planning and improving system reliability. Rebates for small on-site emergency and continuous power generating capabilities, as well as rate adjustments for better load management, are just a few of the schemes that power companies may want to consider in order to keep their power-dependent industrial customers.

Following this earthquake, Taipower hopes for a reduction in negative public attitudes toward constructing additional transmission lines and completing a fourth nuclear power plant located at the northern end of the island. The plant, currently under construction, has a planned capacity of 2,700 MW and would help eliminate the island's system-wide power imbalance. It is also likely that this disaster will accelerate privatization efforts that have been underway since Taiwan passed legislation to deregulate the electric power industry on the island.

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