AIRCURRENTS

LESSONS LEARNED FROM THE 1999 CHI-CHI EARTHQUAKE—AND THEIR APPLICATION TO CALIFORNIA

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EDITOR'S NOTE: Ten years ago this month a magnitude 7.6 earthquake struck the island of Taiwan near the town of Chi-Chi (also Ji-Ji) in the western foothills of the island's central mountains. It was the most powerful earthquake to hit Taiwan in the last century. Nearly 2,500 people were killed and property damage was extensive. Because the Taiwan Strong-Motion Instrumentation Program—a comprehensive network of earthquake sensors—had recently been put in place throughout the island, the Chi-Chi earthquake produced the richest set of seismological data for a single event ever, both in quantity and quality. AIR senior scientist Dr. Khosrow Shabestari and principal scientist Dr. Bingming Shen-Tu describe the Chi-Chi earthquake's main features and how the seismological data it generated has been used by the Pacific Earthquake Engineering Research Center in partnership with the U.S. Geological Survey to develop new ground motion prediction equations—for California.

by Drs. Khosrow Shabestari and Bingming Shen-Tu

The island of Taiwan is the relatively recent creation of a complex geological interplay between the Eurasian Plate and the Philippine Sea Plate. The Philippine Sea Plate is pushing northwest into the Eurasian Plate at about seven centimeters (slightly more than 6 1/3 centimeters) a year. To the east of Taiwan (near the Ryuku Islands) the Philippine Sea Plate is subducting beneath the Eurasian Plate. At the same time, to the south along the Manila Trench, the Philippine Sea Plate is overriding the Eurasian Plate.

Consequently, Taiwan—lying as it does at the junction of this complex collision zone—is very active seismically. Four million years of this geologic activity has produced an island dominated by a spine of steep mountains down its center. To the east the mountains plummet sharply to the ocean; to the west they slope through foothills to a coastal plain that faces mainland China 160 kilometers away. Ninety percent of the Taiwan population lives in the west. Most seismic activity, large-magnitude earthquakes in particular, takes place in the rugged east and the north. And of the 43 earthquakes of magnitude 6.5 or greater that struck Taiwan in the 20th century, only five were relatively shallow events. The Chi-Chi earthquake was one of them.

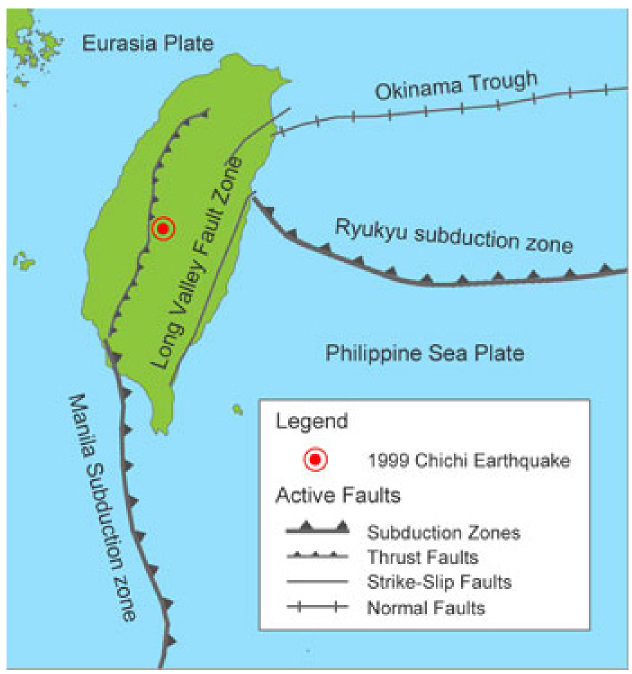

Figure 1. Tectonic Setting of Taiwan (Source: AIR)

CHI-CHI: THE 9-21 EARTHQUAKE

Early on the morning of September 21, 1999, the Chi-Chi earthquake—widely known in Taiwan as the 9-21 Earthquake—ruptured along a roughly 100-kilometer segment of the Chelungpu thrust fault that marks a boundary between Taiwan's western foothills and its western coastal plain. The earthquake's epicenter was near the town of Chi-Chi, which lies a few kilometers from one of the island's most picturesque tourist attractions, Sun Moon Lake (where a major temple collapsed). With a magnitude of 7.6 and a focal depth of just 8 kilometers, the earthquake caused damage as far away as Taipei—145 kilometers to the north northwest—where a number of multi-story buildings collapsed.

The rupture caused extremely strong shaking for perhaps forty seconds and created fault scarps nearly three meters high along its southern end and nearly 9 meters high in the north. The rupture zone itself was as much as 20 meters wide. One monitoring station in the north recorded a peak ground velocity (PGV) of more than 300 centimeters per second, the highest PGV ever recorded. Within the first hour of the rupture there were 296 aftershocks of magnitude 3.4 and higher. By the end of the first three weeks, there were over 10,000 aftershocks, six of them having a magnitude greater than 6.5.

Liquefaction occurred in many places, especially along river banks and levees. Sands from liquefaction sites at Taichung Port were thrown nearly 150 meters from the waterfront. Landslides were widespread; nearly 2,000 were documented. One, about 32 kilometers south of the epicenter, tumbled more than 3 kilometers, sweeping away everything before it, including houses, cars and roads.

EXTENSIVE DAMAGE

It was fortunate that the earthquake happened when it did, at 1:47 in the morning, local time. Cooking fires had been put out hours before (there were few post-event fires). Children were in their beds rather than in school; 786 school buildings were destroyed or badly damaged. The Taichung County Junior High School lay directly on the fault. Its outdoor running track was pushed up over two and a half meters, and its three floors—empty of children at the time—collapsed in pancake fashion.

Immediately following the earthquake all power on the island was down. Power stations and power lines—355 high-voltage transmission towers alone—received significant damage. In Taichung (only 24 kilometers

Figure 2. Toppled Building in Chi-Chi (Source: AIR)

from the epicenter) several high-rise apartment buildings collapsed, killing and injuring several hundred people. More than 3,200 buildings in the city were destroyed. More than 1,250 were killed in Taichung and its surrounding county of the same name.

Just north of Taichung—about 48 kilometers from the epicenter—the Shih-kang Dam failed. It supplied about 50% of the area's water. The earthquake lifted one section of the dam 10 meters, causing three of its 18 concrete abutments and spillways to collapse. Across the countryside Chi-Chi uplifted roads, downed bridges, tore through embankments, and broke up other infrastructure lifelines: water pipes, gas lines, water treatment plants, river levees, road and rail tunnels, railway tracks.

Figure 3. Partial Collapse of Shih-kang Dam (Source: AIR)

Altogether, the Chi-Chi earthquake was responsible for nearly 2,500 fatalities, another 11,500 injured, and more than 100,000 houses destroyed or severely damaged. More than 100,000 people were made homeless. Property loss was estimated at more than US$ 11 billion. Were the Chi-Chi earthquake to recur today, AIR estimates that insurable losses would exceed US$18 billion. Insured losses, however, would be considerably lower due to low earthquake take-up rates; AIR estimates that insured losses would approach US$ 2 billion.

Figure 4. Soft Story Collapse in Chi-Chi (Source: AIR)

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STRONG GROUND MOTION DATA COLLECTION

Because of Taiwan's high seismicity, an island-wide seismic monitoring network was put in place as early as the 1970s. That was a 25-station analog system comparable to the U.S. Geological Survey standard of the time. In the early 1990s, the Central Weather Bureau (CWB), which has responsibility for earthquake hazard determination and warning in Taiwan, decided to blanket the island, particularly metropolitan areas, with modern digital strong-motion instruments.

At the time of the Chi-Chi earthquake, the "Taiwan Strong-Motion Instrumentation Program" consisted of more than 650 modern digital free-field strong-motion stations and another nearly 150 earlier-installed digital and analog stations. But Chi-Chi event was unique not only because of the extent to which it was recorded, but also for the confluence of four important factors: large magnitude, considerable rupture length, high peak ground accelerations and, perhaps most importantly, proximity of the monitoring stations to the actual rupture. Chi-Chi's magnitude was 7.6, its rupture length was more than 100 kilometers, and it produced many high PGA measurements—including some approaching 1 g.

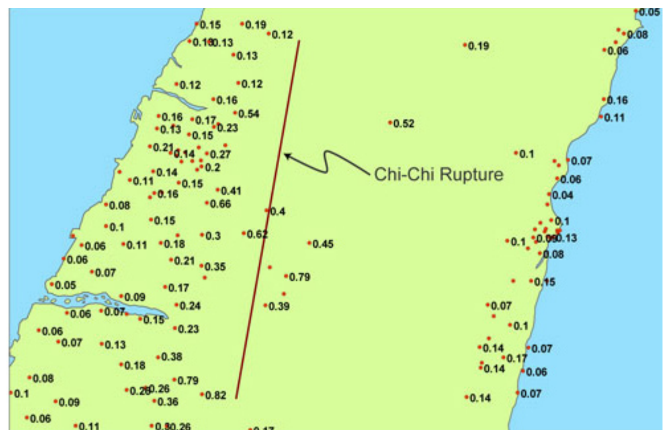

Figure 5. Sample Recorded PGA Measurements from the Chi-Chi Earthquake

At least equally important, when the earthquake struck, the sensor network was also able to provide emergency and other officials with pager and fax read-outs of the location, magnitude, and shaking intensities for the island's nine largest cities—all in less than two minutes.

EMPIRICALLY PREDICTED GROUND MOTIONS AND CHI-CHI GROUND MOTIONS

Strong motion seismology uses sensors (such as accelerometers and geophones) to record and measure the large-amplitude ground motions caused by earthquakes—and also the reaction of various structures to those motions. The data are used to analyze the fault motions that produced the earthquake and also to help determine the likely strong shaking patterns of possible earthquakes in the future. The findings from these analyses are used to upgrade building codes, design earthquake-resistant structures, and to help devise emergency plans and relief needs.

Usually, however, an earthquake does not accommodate scientific inquiry by choosing to occur near a sensor. Not uncommonly, strong motion data is spotty, incomplete and most likely recorded at some distance from the actual event. Equations have therefore been developed to describe (or, predict) ground shaking caused by earthquakes. These ground motion prediction equations are based on cumulative empirical data derived from seismic events all around the world (although most data has come from events in California). The basic assumption made in these efforts is that ground motions from earthquakes in tectonically similar regions should themselves be similar.

Very soon after the Chi-Chi data became available, it was determined that the observed Chi-Chi ground motions differed from the motion predicted by the standard equations—to a degree greater than could be attributed to expected earthquake-to-earthquake variation.[1] Short-period motions from the Chi-Chi earthquake generally were smaller than the predicted motions by factors averaging about 0.4 for periods less than 1-2 seconds. This result was the same regardless of what prediction equation was used and whether it was assumed that the site was underlain by rock or by soil. On the other hand, the observed motions came closer to the values of the predicted motions—and even exceeded them—for the very longest periods.

In other words, close to the earthquake epicenter (where the period was less than 1-2 seconds) large-amplitude strong ground motion was roughly 40% of what had been expected. Farther away (where the period was four seconds or more), strong ground motions were about the same or even greater than what would have been predicted by the existing ground motion prediction equations.

Researchers attribute the cause of this discrepancy (between predicted findings and observed findings) to the fact that the Chi-Chi earthquake was a shallow crustal event whose rupture plane extends to the surface. The composition and material of the upper crustal structures at very shallow depths (near to ground surface), is not as dense as at greater depths. This absorbs high-frequency contents of seismic energy. Consequently, the amplitude of short period ground motion caused by earthquakes whose faults break the earth's surface is less than that of quakes whose rupture planes remain many kilometers below the surface.

CHI-CHI DATA AND THE NEXT GENERATION ATTENUATION RELATIONS PROJECT

The Chi-Chi findings contributed to seismologists' determination to develop new ground motion prediction equations (see the AIR Currents article Ground Motion Prediction—The Next Generation for a detailed discussion). A formal effort to do this began in the year 2002 when the "Next Generation of Attenuation Relations (NGA) Project" was launched. The NGA Project was a five-year applied research program led by the Pacific Earthquake Engineering Research Center (headquartered at the University of California, Berkeley) and partnered with the USGS, the Southern California Earthquake Center, and several similar organizations.

The chief task of the NGA was to develop improved ground motion attenuation relations for shallow crustal earthquakes in the western United States and similar active tectonic regions. To accomplish this goal, major effort was put into evaluating, updating, and expanding the earlier strong ground motion database. The extensive Chi-Chi data figured prominently in this effort.

The new database that was used to develop the NGA equations consists of 173 shallow crustal earthquakes ranging in magnitude from 4.2 to 7.9. The earliest took place in 1952, the most recent in 2003. Because of the quality demanded of the data, most were in California; 53 were in other countries. The Chi-Chi earthquake actually accounted for six of these, since five of the Chi-Chi aftershocks of M5.9 and above were included as separate events.

Indeed, the extraordinarily comprehensive Chi-Chi data constituted a major share of the database. For example, of the entire set of 173 earthquakes, only ten were of M7.0 or above, one of which was the Chi-Chi earthquake. Data on the Chi-Chi earthquake came from as many as 380 seismic stations. The next largest data source was a 1999 earthquake in California (the Hector Mine earthquake) that was able to provide data from 82 stations.

As suggested previously, the use of ground motion data from international events to construct ground motion prediction equations for California is appropriate because near-field earthquake ground motion is not very sensitive to regional geological differences, but is instead mostly controlled by the source rupture details. Seismological studies of the Chi-Chi earthquake indicate that it had source mechanisms and rupture details similar to those of crustal earthquakes in the western United States.

CONCLUSION

The Chi-Chi earthquake was without doubt a catastrophe for the people of Taiwan. But it did provide a wealth of information that has contributed significantly to an increased understanding of earthquake strong ground motion and, ultimately, to how the built environment is likely to respond to such motion. That enhanced understanding is being used to inform the development of building codes in Taiwan—and in other tectonically active places in the world.

1 SEE, FOR EXAMPLE, BOORE, DAVID M. (2001); COMPARISONS OF GROUND MOTIONS FROM THE 1999 CHI-CHI EARTHQUAKE WITH EMPIRICAL PREDICTIONS LARGELY BASED ON DATA FROM CALIFORNIA, BULLETIN OF THE SEISMOLOGICAL SOCIETY OF AMERICA, 91, 5, PP. 1212-1217

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