Learning from Earthquakes

The Tehuacan, Mexico, Earthquake of June 15, 1999

On June 29, 1999, an EERI team visited the area affected by the Tehuacan earthquake of June 15, 1999. The team was composed of Julio Ramirez, Team Leader, of Purdue University, West Lafayette, Indiana; Santiaco Pujol of Purdue University, and James Miller of Degenkolb Engineers, San Francisco, California.

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Introduction

The June 15th Tehuacan earthquake was reported by the Mexico National Seismological Service (SSN) to have occurred at 20:42:05 h GMT (15:42:05 local time). The epicenter was located approximately 20 km SW of Tehuacan and 55 km NE of Huajuapan de Leon in the state of Oaxaca (Figure 1). The focal coordinates were Latitude 19.20 degrees North and Longitude 97.47 degrees West, the depth was between 60 (Harvard CMT, Instituto de Geofisica, UNAM) and 80 km (University of Michigan), with several additional values in between. The earthquake magnitudes are mb=6.3 (USGS), Ms=6.5 (USGS), MI=6.7 (UNAM), and Mw between 6.7 (Tokyo) and 7.0 (Harvard).

The earthquake caused damage in villages near the epicentral region, and in larger cities in the state of Puebla: Tehuacan, Cholula, Atlixco, and Puebla, the capital. Damage was also reported in the states of

![Figure 1 - General view of the epicentral area. (Map: G. Aguilar and S. Pujol)](image-url)
Tlaxcala, Guerrero, Oaxaca, Veracruz and Morelos. The state of Puebla has an area of 33,997 km² and a population of approximately 4.1 million.

Geosciences

Large earthquakes in the subducting Cocos plate result in significant damage to villages of the Mexican highlands, or altiplano. Between 1864 and 1999, there were ten earthquakes in this region with magnitudes greater than M=6.5, and at least seven with a depth comparable to the June 15th quake. The events are all associated with the movement of the Cocos plate beneath this section of the North American continent. Because this type of earthquake is relatively common in this part of Mexico, seismic-resistant designs throughout the region ought to consider the near certainty that structures will experience such an event.

An indication of directivity of the source towards the NW was noted from the durations of the NS component of accelerograms recorded at hard (rock) sites located within 230 km of the hypocenter (Figure 2). A visual examination of the accelerograms in Figure 3 indicates that the duration of the intense part of the ground motion at sites RABO, YAIG, and PLIG is smaller than at sites PNIG, OXIG, and LIVIG. The duration at CHFL, the site closest to the epicenter, falls in between these two extremes. In general, the duration is short at stations located NW of the epicenter, suggesting a NW directivity.

The acceleration data on hard (rock) sites, available at the time of this report, yielded the isoacceleration map shown in Figure 4. The acceleration data collected by Alcantara Nolasco et al. (1999) for the City of Puebla is given in Table 1. Figure 5 shows the accelerograms for two stations: PHPU (soil), registering the highest peak ground accelerations (279 gals, or cm/s/s) in Puebla, and BHPP (rock).

Geotechnical Aspects

The earthquake generated a number of strong-motion recordings over a variety of geologic site conditions, including free-field soil and rock, and from various instrumented structures. Attenuation of the horizontal peak ground acceleration (PGA) with distance is shown in Figure 6, which was developed using 18 rock, two transition/soil, and nine soil site recordings at strong-motion stations located throughout the affected region. This information was provided by UNAM, BUAP, and CENAPRED, and compiled by Pestana et al (1999).

The rock sites on which the strong-motion recording stations are located correspond to 1997 Unified Building Code (UBC) Site Classes B-C. Most rock sites appeared to be soft and weathered rock (Class C). The soil sites correspond to
UBC Site Classes C-D, with most being Class D. As shown in Figure 5, recorded peak horizontal accelerations were significantly higher on soil sites than on rock sites. The highest PGA was 0.28g at the PHPU soil site.

Figure 6 also shows the Youngs et al. 1997 intraslab attenuation relationships for rock (UBC Class B) and soil (UBC Classes C and D) sites. These attenuation relationships were developed for intraslab earthquakes associated with subduction zones using data from, among many others, several Central Mexico earthquakes. The primary distance parameter used in this attenuation relationship is the closest distance to the rupture; however, the hypocentral distance is used when the fault plane geometry is not available. Hypocentral distance was used in Figure 6 because the rupture plane geometry had not been clearly defined at the time of this report. This distance definition does not introduce a significant error due to the great source-to-site distance of the recordings.

Site effects were evaluated for the City of Puebla with the data recorded at six strong-motion stations (Table 1). According to Chavez-Garcia et al. (1995), the ground in this region consists of a soft tuff interlayered with alluvial deposits. The predominant period, obtained from microtremor studies and Nakamura’s (1989) technique, was approximately 0.8 seconds. The corresponding acceleration response spectra of the PHPU station record show energy concentration around a period of 0.8 to 1.2 seconds (the predominant period was 1.1 seconds).

Preliminary analysis shows that the significant duration, DS-95, of the PHPU soil record was about 40 seconds. The ratio of peak ground velocity to peak ground acceleration PGV/PGA was around 83 cm/s/g at the PHPU site.

When compared to neighboring rock station recordings, significant site amplification was observed in the City of Puebla: PGA (soil)/PGA (rock) of about 4, e.g. using the

<table>
<thead>
<tr>
<th>Station Code</th>
<th>Station Name</th>
<th>Soil Type</th>
<th>Station Coordinates</th>
<th>Peak Ground Accelerations (gal)</th>
<th>Orientation C1-C2-C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHPP</td>
<td>Barranca Honda</td>
<td>Basaltic Scoria</td>
<td>Lat: 19.11 N</td>
<td>Lon: 98.23 W</td>
<td>C1: 58.8 , C2: 33.4 , C3: 58.3</td>
</tr>
<tr>
<td>CAPP</td>
<td>Central de Abasto</td>
<td>Soil Compressible</td>
<td>Lat: 19.09 N</td>
<td>Lon: 98.19 W</td>
<td>C1: 44.9 , C2: 72.7 , C3: 103.2</td>
</tr>
<tr>
<td>PBPP</td>
<td>Nicolas Bravo</td>
<td>Soil Med.</td>
<td>Lat: 19.05 N</td>
<td>Lon: 98.21 W</td>
<td>C1: 63.7 , C2: 123.2 , C3: 102.3</td>
</tr>
<tr>
<td>PHPU</td>
<td>La Habana</td>
<td>Soil</td>
<td>Lat: 19.04 N</td>
<td>Lon: 98.17 W</td>
<td>C1: 56.1 , C2: 104.5 , C3: 279</td>
</tr>
<tr>
<td>SRPU</td>
<td>San Ramon</td>
<td>Not Class.</td>
<td>Lat: 18.97 N</td>
<td>Lon: 98.26 W</td>
<td>C1: 71.3 , C2: 216 , C3: 131.3</td>
</tr>
<tr>
<td>UAPP</td>
<td>C. U.</td>
<td>Soil Low</td>
<td>Lat: 19.00 N</td>
<td>Lon: 98.20 W</td>
<td>C1: 64.4 , C2: 94.9 , C3: 108.8</td>
</tr>
</tbody>
</table>

Table 1 - City of Puebla peak ground acceleration data from records of the main shock. (Alcantara Nolasco et al.)
roadways in the states of Puebla and Oaxaca, affecting traffic to varying degrees.

Some ground cracking was observed in the town of Acatlan de Osorio and north along the road to Izucar de Matamoros. Liquefaction was observed in the altiplano of the state of Tlaxcala, some 20 km northwest of the City of Puebla. Sand boils were visible over part of a large cornfield. The liquefied soil was a non-plastic silty sand of volcanic origin, with 28% passing the #200 sieve. However, there was little significant soil liquefaction, which is not surprising given the dry season and moderate levels of shaking. Several cases of poor structural performance were apparently due to settlement of loose superficial soils or fills.

Structural and Nonstructural Damage

The earthquake caused significant damage in south Puebla, north Oaxaca, and south Morelos. Structural damage was observed in PHPU and PBPU stations (Alcantara et al., 1999). This site amplification of ground motion amplitudes, along with the relatively long duration and periodic nature of the motion, may help explain the concentration of damage in Puebla, at an epicentral distance of 110 km. Site effects were also observed in Acatlan de Osorio, a town located approximately 50 km west of the epicenter. The damage occurred almost exclusively to structures in the sediment-filled valley; structures founded on rock in the surrounding foothills fared well.

There was landsliding throughout the region, with superficial sliding the primary mechanism. Other sliding mechanisms observed were rock toppling, rock sliding, block sliding, and raveling. Large landslides occurred on the slopes of "Cerro el Pinal" and "Cerro la Malinche," approximately 120 km northwest of the epicenter. The La Malinche slide disrupted an aqueduct and interrupted the water supply to the surrounding towns for several days. Other slides deposited debris on the

Figure 5 - Accelerograms for PUEBLA-PHPU station (soil) and for PUEBLA-BHPP (rock). (Pestana et al.)

Figure 6 - Peak ground acceleration vs. distance for the 6/15/99 seismic event and the Youngs et al. (1997) rock attenuation relationship. (Pestana et al.)
There was generally damage at the upper level of the towers, cracking between the towers and adjacent walls (Figure 7), longitudinal cracking on the underside of the vaulted masonry roofs and masonry arches, and dome cracking. In some cases there was complete collapse of the domes, vaults and bell towers.

The churches performed poorly relative to other types of buildings, considering the moderate ground accelerations of this earthquake. Damage observed in palaces and other historical monuments was no doubt worsened by the lack of adequate maintenance on these buildings.

The churches were built in three categories of buildings: (1) historic buildings (churches, convents, monuments); (2) houses; and (3) engineered buildings. In other states—including Mexico and its capital, Mexico City—the damage was light and mostly restricted to nonstructural elements.

Historic Buildings: The largest and most prevalent damage was to over 700 historic buildings in the six states reporting damage. This region is rich in Catholic churches, convents, and palaces built between the 16th and 19th centuries. The structural system of most churches consists of a vaulted masonry roof that is supported by side walls and stone arches spanning the church width. Large interior pilasters and exterior buttresses along the side walls support the arches vertically and horizontally. At the crossing or bay in front of the sanctuary, a masonry dome is located; at the rear of the church, opposite the sanctuary, there are usually one or two towers. The main floor is typically constructed at grade.

All the building elements are very thick—the walls appeared to be as much as four feet thick—and constructed of solid unreinforced stone or brick masonry. In general, the mortar was hard and appeared to be in good condition. Several of the churches had a common orientation, with the longitudinal axis running in the east-west direction, and the sanctuary located on the eastern end. Most of the observed damage in the churches corresponded to seismic forces in the transverse direction of the church, or the north-south direction.

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Housing Units: Most significant residence damage was observed in adobe houses that usually have walls without any type of horizontal or vertical reinforcement. Roofs are commonly made of logs that support heavy clay tiles. A typical failure mode was the appearance of vertical cracks at the corners of the house leading to the out-of-plane failure of the walls (Figure 8). At the time of...
Surveys of several reinforced concrete structures revealed damage related to easily recognized deficiencies: captive columns, abrupt changes in the stiffness of the structures along their heights (soft stories), and poor detailing. In three buildings, severe structural damage was caused by the interaction between columns and discontinuous masonry walls. “Captive columns” are common in school buildings, where the need for light and ventilation leads to the use of large windows that run from column to column in simple reinforced concrete frames. Masonry walls at the bottom of these windows confine the columns partially (Figure 11).

Two buildings of a Puebla condominium complex collapsed. Each building was supported by a reinforced concrete frame with four stories and, in these two buildings, the first level was used for parking. Masonry walls used as partitions stiffened the structures in the upper three stories. The “softer” first-story seems to have resulted in the structures’ collapse (Figure 9).

Two-story brick masonry housing units also suffered serious damage. These generally have small vertical and horizontal, lightly reinforced concrete elements (columns and beams) with infill walls of extruded brick masonry units. In Ciudad Serdan, Puebla, 44 units of this type showed severe damage associated with inadequate walls and poor quality construction.

**Engineered Buildings:** Relatively few cases of major structural damage to engineered buildings were reported. However, over 1000 schools were reported damaged in six states, with 12 of these schools severely damaged. Nine hospitals were damaged, four in the City of Puebla alone. Some had to be closed due to nonstructural damage which, in some instances, led to a significant down time for emergency surgical and laboratory units.

![Figure 9 - Soft story damage in Condominio 3 Oriente, Puebla. (Photo: S.Pujol)](image)

![Figure 10 - Column shear failure at the school of medicine of La Benemerita Universidad Autonoma de Puebla. (Photo: Alcocer et al.)](image)

![Figure 11 - School damage in Atlixco, Puebla. (Photo: S. Pujol)](image)
to wastewater pipelines. Telephone service was lost in some areas, but was restored in a few hours. No damage related to fire was noted. Six bridges were reported damaged in the affected area (Figure 13). Some roads were temporarily closed due to landslides. Figure 14 shows a slide reactivated during ground shaking, typical of the slides seen along road cuts.

Social Impacts

In the states of Puebla and Oaxaca, many rural communities were affected. Amongst them, San Mateo Ozolco and Acatlan de Osorio suffered the most. The damage to housing units in these communities was observed to be more concentrated, whereas in the larger urban settlements, such as the City of Puebla, it tended to be more scattered. A reduction in labor because of the people displaced in this event was estimated to be around 20% for the City of Puebla. A month after the earthquake, local and federal authorities announced a budget of U.S. $75 million for the reconstruction.

Emergency Response: In the rural communities, the initial search and rescue was carried out by the local residents. A few hours after the event, military personnel joined the efforts, as specified in the national emergency plan DN-III-E. The deaths and injuries caused by the quake—17 dead and 197 injured in Oaxaca and Puebla—did not place a large burden on the emergency medical and rescue services.

Emerging Issues: The damage caused by the event indicates that a more effective public policy for earthquake hazard mitigation needs to be implemented in Mexico. In particular, the construction practices in urban centers do not offer sufficient protection in the case of individual housing units. Approximately 80% of these units are built without considering seismic resistance (Eibenschutz and Duarte, 1991). It is further questionable that the avenues for reconstruction of the housing units provide sufficient assurance that seismic vulnerability will be reduced; the amount of money available is often not sufficient, and the affected population sometimes will exchange financial resources and construction materials in order to satisfy other needs (Macias, 1997).

**Figure 12** - Inadequate joint detailing.  
(/**Photo: S. Pujol/**)

All the severely damaged structures showed clear signs of poor detailing. The most impressive example may be that in the School of Medicine of La Benemérita Universidad Autónoma de Puebla (Figure 10). The first-story column lacked adequate transverse reinforcement (6.4mm diameter stirrups were observed, spaced at about the effective depth of the column).

Other problems noticed in the surveyed structures include use of small 90° hooks in stirrups, small cover and corrosion, poor location of reinforcement splices, and welding of architectural elements to reinforcing bars. Figure 12 shows the joint of a reinforced concrete frame. Notice the presence of splices and the lack of hoops.

**Observations on Lifelines**

Limited damage to lifelines was reported; where electricity was lost, or gas leaks reported, the damage was repaired in a matter of hours. Very little damage was reported to water systems, and there was no damage to the highway bridge (Figure 13).
Lessons Learned

Five conclusions are presented below based on initial observations of the earthquake's effects.

1) Because the affected region has experienced frequent earthquakes similar to or more intense than the June 15, 1999 earthquake, it is essential to enforce appropriate design codes and other risk-reduction measures. This strategy is critical for buildings such as schools, where there are structural shortcomings, and hospitals, which deserve special attention to avoid the nonstructural damage that required their evacuation in several cases.

2) Site effects were found to have contributed to the damage resulting from this earthquake.

3) The damage to historical buildings was extensive; portions of them sometimes collapsed completely. It is fortunate that the earthquake occurred at a time when many of these structures—especially churches—were empty. The problems associated with either earthquake risk reduction or repair of such structures are complex and involve many sectors of society.

4) Failure in nonstructural elements such as unreinforced masonry parapets and walls caused a significant percentage of the casualties, injuries and economic loss related to this event.

5) The considerable damage to low-income housing units also reveals the need to address this problem in a systematic manner.

References


Chavez-Garcia et al. (1994) "Microzonificacion Sismica de la Zona Urbana de la Ciudad de Puebla." Informe Tecnico del Instituto de Ingenieria UNAM, 0996-T9111, February.


Figure 14 - Reactivated landslide on the road from Tehuacan to Huajapan de Leon. (Photo: Pestana et al.)