

**PRELIMINARY REPORT ON THE GEOTECHNICAL
ENGINEERING ASPECTS OF THE JUNE 15 AND JUNE 21, 1999,
MÉXICO, EARTHQUAKES OF THE CHURCHES**

by

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1 INTRODUCTION

A seismic event of moment magnitude 7.0 (USGS) struck the central region of México on June 15, 1999, at 15:42 hours (20:42 GMT). The epicenter of the earthquake was located near the border of the states of Puebla and Oaxaca. A second event of moment magnitude 6.3 (USGS) was recorded on June 21, 1999, at 12:43 hours (17:43 GMT), also affecting the central region of México.

Figure 1.1 shows the location of the epicenters of these two seismic events, which together affected cities in the states of Guerrero, Hidalgo, México, Michoacán, Morelos, Oaxaca, Puebla, Tlaxcala, Veracruz and the Federal District.

The first event was felt in the Federal District (México City), approximately 250 km from the epicenter, where many people rushed into the streets alarmed by the vibrations felt in the buildings. More than 400 people required attention due to nervousness or anxiety, and two fatalities were reported due to heart attacks. The electric power was interrupted in some sectors of the city. The conventional telephone service was sporadically interrupted as well as the cellular phone service, but both were completely reestablished fifteen minutes later. Many pipe breaks and leaks were reported in México City.

Puebla City, located approximately 125 km from the June 15 epicenter, has a population of about 5 million and is home to more than 2,000 churches and temples. More than 100 of these structures were damaged by the seismic events. A four story building complex located in the downtown area was severely damaged, in an area where local soil conditions had led to prediction of significant amplification in earlier microzonation studies. The death toll in this city, the highest, was five.

In the states of Morelos and Hidalgo the damage was minor and mainly affected churches and historical monuments built in the 16th and 17th centuries. In the state of Tlaxcala only one fatality was reported; this due to a heart attack. The damage here was also minor and consisted of small landslides along road cuts, cracking of the old churches and houses, and a fire in a textile factory that resulted in one injury.

In the area investigated by the authors the most notable effects were concentrated in unreinforced masonry (URM) structures, such as churches and small adobe and cane houses, of which more than 7,000 were damaged.

The towns in the area surrounding the rupture plane are mostly small agricultural and mining towns where the damage was concentrated predominantly in URM structures, such as churches, houses, and rock walls. The bigger towns of Tehuacán, the closest to the epicenter, and Acatlán de Osorio, located approximately 60 km to the east of the epicenter, were affected in a similar manner.

According to the Attorney General of the State of Puebla, Carlos Arredondo Contreras, there were 15 fatalities due to the first event. The second earthquake caused no deaths. Table 1.1 presents the summary of damage induced by the earthquakes of June 15 and June 21, detailed per state.

TABLE 1.1 Summary of the damage in each state caused by the seismic events of June 15 and June 21, 1999

State	Damaged Houses	Deaths	Injuries
Distrito Federal	Unreported	2	Unreported
Guerrero	Unreported	1	Unreported
Oaxaca	3,476	Unreported	Unreported
Puebla	4,299	15	188
Tlaxcala	Unreported	1	1
Veracruz	70	2	5

A research team consisting of graduate students and faculty from the University of California at Berkeley (UCB) and the National Autonomous University of México (UNAM) performed a preliminary field investigation of seismic geotechnical issues under the sponsorship of the National Science Foundation (NSF) and the Pacific Earthquake Engineering Research Center (PEER). In Figure 1.2, the route followed by the research team is shown, with points of interest and strong-motion stations indicated.

2 SEISMOLOGICAL AND GEOLOGICAL OBSERVATIONS

According to the National Seismological Service of México (SSN), the focus of the seismic event registered on June 15, 1999, was located at 18.20° north latitude and 97.47° west longitude at a depth of 92 km. The epicenter was calculated at 30 km south southeast of the city of Tehuacán in the state of Puebla, approximately 55 km northeast of the city of Huajuapán de León in the state of Oaxaca. The United States Geological Survey (USGS) located the epicenter at 18.40° north latitude and 97.45° west longitude at a depth of 71 km. This discrepancy between SSN and USGS data made determining the distance to the rupture surface for attenuation calculations difficult.

A second strong event with a moment magnitude of 6.3 (USGS) occurred on June 21 at 12:43 hours (17:43 GMT). According to SSN the focus was located at 18.09° north latitude and 101.78° west longitude at a depth of 42 km. The USGS published data locating the second event at 18.34° north latitude and 101.49° west longitude with a depth of 50 km.

The June 15 event occurred in a complex region of normal and reverse faults with a regional tectonic mechanism associated with the subduction of the Cocos plate under the North American plate. The Cocos plate moves towards the northeast and subsides under the Pacific Coast of México, producing events like the September 19, 1985, earthquake that caused significant damage in México City. This plate subduction also leads to the formation of the Trans-Mexican Volcanic Belt.

The hypocenter determined by the USGS was used to locate the hypocenter-to-site (i.e. source-to-site) distance of the June 15, 1999 event. The rapid moment-tensor solutions for this earthquake suggest that this event was complex, consisting of two sub-events, separated by several seconds (e.g. <<http://www.neic.cr.usgs.gov/neis/FM/previous/9906.html>>). The fault mechanism was that of a normal fault. The strike of the potential rupture plane was approximately 310 degrees and dipped to the north or south at about 45 degrees. This type of fault rupture mechanism is not unusual for this area of Central Mexico.

The following regional geology descriptions correspond to the central and southern portions of the state of Puebla that were surveyed by the research team. The central region, in which Puebla City is located, can be characterized by the predominance of relatively young (upper tertiary and quaternary) volcanic structures of diverse types and textures such as basaltic flows, tuffs and ashes created successively by many volcanoes during the Cenozoic period. The southern portion of the state, in which the June 15 focus was located, and in which the cities of Tehuacán and Acatlán de Osorio are located, is composed of a combination of metamorphic, igneous and sedimentary rocks affected by intense erosion. The structure of this zone is characterized by normal and reverse faulting with a predominant northwest strike and a predominant dip toward the northeast.

3 STRONG GROUND MOTION

3.1 Attenuation Relationships:

The $M_w = 7.0$ event on June 15, 1999, in central México, generated a number of strong-motion recordings over a variety of geologic site conditions, including free-field soil and rock as well as motions from various instrumented structures. Attenuation of the horizontal Peak Ground Acceleration (PGA) with distance, shown in Figure 3.1, was developed using 18 rock, 2 transition/soil, and 9 soil site recordings at strong-motion stations located throughout the affected region. This information was provided by UNAM, the Autonomous University of Puebla (BUAP), and the National Center for Disaster Prevention of México (CENAPRED), as shown in Table 3.1.

The rock sites on which the strong-motion recording stations are located correspond to 1997 Unified Building Code (UBC) Site Classes B-C, with most rock sites appearing to be soft and weathered rock (UBC Site Class C). The soil sites correspond to UBC Site Classes C-D, with most soil sites being UBC Site Class D.

Table 3.1 Strong-motion data for the June 15, 1999, earthquake.

Station	Organization	Site Type	Hypocentral Distance (km)	MHA1 (g)	MHA2 (g)	MVA (g)
CAIG	SSN	ROCK	354	0.004	0.004	0.004
CUIG	SSN	ROCK	229	0.009	0.011	0.007
HUIG	SSN	ROCK	336	0.015	0.012	0.006
OXIG	SSN	ROCK	182	0.029	0.032	0.017
PLIG	SSN	ROCK	238	0.020	0.018	0.015
PNIG	SSN	ROCK	245	0.003	0.003	0.003
PPIG	SSN	ROCK	166	-	0.046	0.036
TUIG	SSN	ROCK	346	0.004	0.003	0.002
YAIG	SSN	ROCK	200	0.054	0.072	0.028
ZIIG	SSN	ROCK	460	0.002	0.002	0.002
RABOSO	UNAM	ROCK	132	0.146	0.111	0.103
CHILA	UNAM	ROCK	104	0.100	0.103	0.067
PHPP	UNAM	ROCK	128	0.037	0.059	0.031
CUER	CENAPRED	ROCK	226	0.044	0.046	0.018
PBPP	BUAP	ROCK	131	0.126	0.104	0.065
BHPP	BUAP	ROCK	136	0.060	0.059	0.034
CUP5	UNAM	ROCK	229	0.012	0.012	0.008
ACPD	UNAM	ROCK	327	0.005	0.005	0.003
DFRO	UNAM	TRANSITION	232	0.028	0.029	0.014
PENR	UNAM	TRANSITION	217	0.031	0.028	0.023
PHPU	UNAM	SOIL	128	0.106	0.284	0.057
SRPU	BUAP	SOIL	130	0.220	0.134	0.073
CAPP	BUAP	SOIL	132	0.105	0.074	0.046
UAPP	BUAP	SOIL	128	0.111	0.097	0.066
CUT2	UNAM	SOIL	295	0.011	-	-
PCJR	UNAM	SOIL	229	0.024	0.028	0.010
SCT2	UNAM	SOIL	229	0.030	0.031	0.013
TLHB	UNAM	SOIL	211	0.023	0.026	0.017
ACAD	UNAM	SOIL	327	0.023	0.025	0.011

BUAP: Autonomous University of Puebla

CENAPRED: National Center for the Prevention of Disasters of Mexico

SSN: National Seismological Service of Mexico

UNAM: National Autonomous University of Mexico

A series of North American attenuation relationships were plotted with the collected ground motion data. The Toro et al. (1997) Central and Eastern North America "Gulf" hard rock attenuation relationship appeared to represent the trends of the recorded data well, although the PGA values were slightly underestimated by this hard rock

relationship. It is important to clarify that this attenuation relationship was defined for hard rock with an average shear wave velocity of 1800 m/s at the surface (i.e. UBC Site Class A) and uses the Joyner-Boore definitions of distance.

Figures 3.1a and 3.1b show the Youngs et al. (1997) intraslab attenuation relationship for rock (UBC, Type B) and soil (UBC, Types C and D) sites respectively, which is consistent with the conditions encountered at the ground motion stations. This attenuation relationship was developed for intraslab earthquakes associated with subduction zones using data that includes, among many others, the 1973 Mexican event listed in Table 3.2 as well as other Central Mexico earthquake events. The distance parameter used by this attenuation relationship is closest distance to the rupture, however, Youngs et al. (1997) do use hypocentral distance when the fault plane geometry is not available. Hypocentral distance was used in lieu of the distance to the rupture, as the rupture plane geometry had not been clearly defined for the June 15 event at the time of this report. This substitution is consistent with Youngs et al. (1997) and is not considered to introduce a significant error due to the great source-to-site distance of the recordings.

As shown in Figure 3.1, recorded peak horizontal accelerations were significantly higher on “soil” sites than on “rock” sites, and the highest recorded PGA was 0.28 g at the PHPU soil site.

3.2 Site Effects in Puebla City:

The geologic configuration of Puebla City according to Ruiz and Juarez (1996), is presented in Figure 3.2. The following basic structures can be differentiated:

- a) Very fractured limestone (Kc) geologic units of 20 cm in thickness appear in the southern limit of Puebla City.
- b) Basaltic lava (Qbt), frequently covered by lime-sandy tuff of yellowish color, generally compact, occurs in the hills to the south (Tepozochitl and Tolttepec) and to the east of the city, as well as in the hills of Loreto and Guadalupe.
- c) Basaltic clinker (Qc) located in the northwestern portion of the city and a volcanic cone formed by basaltic clinker of reddish color.
- d) Interstratified volcanic tuff with deposits of fluvio-lacustrine origin (Qtl) that transitions from clays to even-rolling stones appear randomly distributed around the city.
- e) Deposits of travertine (Ql), a banded, very dense material deposited by calcite springs, are located in the zone of Rancho Colorado, in the surroundings of Cerro de la Paz, in the bathing Resort of Agua Azul and in the Historical Center. These deposits happen to occur at different depths and in strata of variable thickness.
- f) Alluvial deposits (Qal), mainly composed of muddy sands, appear along the Alseseca, San Francisco, and Atoyac rivers.

3.3 Microzonation of Puebla City:

Puebla City has a long history of seismic events in part because its proximity to the Trans-Mexican Volcanic Belt. An overview of the frequency of significant ground motions in the region is presented in Table 3.2. Due to Puebla's seismic history, considerable effort has been focused on developing a microzonation of Puebla City (Chávez-García et al., 1995). Ruiz and Juárez (1996), proposed the seismic microzonation map shown in Figure 3.3, based on analysis of microtremor data using Nakamura's (1989) technique, and small refraction studies.

Table 3.2 Historic Seismicity of the city of Puebla, Ruiz & Juárez (1996), after Figueroa (1974).

Date	Magnitude	Modified Mercalli Intensity
25-08-1611	7.5	VI
30-07-1667	7.0	VII
16-08-1711	7.5	VIII
22-11-1837	6.5	VI
03-03-1845	6.0	VII
03-10-1864	7.0	IX
19-07-1882	7.5	VII
24-05-1959	6.8	VII
28-08-1973	7.0	VIII

According to this microzonation, four zones can be differentiated. Zone I considered rock and shallow firm soil (limestones and basalts) with low predominant period, T_p , around 0.1 to 0.3 seconds. Zone II consists of travertine outcrops. In Zone III where surficial units consist of alluvial deposits and volcanic tuff, with T_p around 0.8s, in which Chávez-García et al. (1995) found a potential amplification factor of up to 10 based on microtremor results. Zone IV consists of compressible soils, with T_p of up to 2.5s. The largest values of T_p (2 to 2.5s) appear to the NE, in sands and silts. In the basalt outcrop this value decreases to 0.1s. On average, T_p is smaller in tuffs than that of the mixtures of tuff and alluvial deposits.

3.4 Effects of the June 15, 1999, Earthquake on the City of Puebla:

The June 15 event occurred about 125 km to the southwest of Puebla City. Even though 8 strong motion instruments exist in the city (see Figure 3.3) the motion only registered on 6 of them; BHPP (Barranca Honda), CAPP (Central de Abasto), PBPP (Paseo Nicolas Bravo), PHPU (Parque la Habana), SRPU (San Ramon Castillotla) and UAPP (Zona Universitaria) as shown in Table 3.3.

The maximum accelerations recorded were 0.28g and 0.22g, registered in the PHPU and the SRPU strong motion instruments, respectively. The instrument BHPP located in rock registered 0.06 g. Figure 3.4 shows the baseline corrected acceleration-time history and corresponding acceleration response spectrum registered at the PHPU

station (soft tuff), and the acceleration-time history registered at the BHPP station, which is located on basaltic rock. It can be seen that the excitation energy of the soil record is concentrated around a period of 0.8 to 1.2 seconds (with a predominant period, T_p , of 0.85 seconds). According to the microzonation, the predominant period of the ground is around 0.8 seconds or larger, and this correlation of periods could explain why the major effects of the earthquake were localized in the downtown zone. When compared to neighboring rock station recordings, significant site amplification (PGA_{soil} / PGA_{rock} of about 4 using the PHPU and BHPP stations respectively; Alcántara et al., 1999) was observed in the City of Puebla.

Table 3.3 MHA and Duration registered in Puebla City Strong-Motion Instruments System

Station	Location	Site Type	Latitude	Longitude	MHA1 (g)	MHA2 (g)	MVA (g)
BHPP	Barranca Honda	Basaltic Rock	19.109	-98.227	0.06	0.06	0.03
CAPP	Central de Abastos	Compressible Soil	19.089	-98.188	0.11	0.07	-0.05
PBPP	Paseo Nicolas Bravo	Medium Compressible Soil	19.046	-98.208	0.13	0.10	0.07
PHPU	Parque la Habana	Tuff interlayered with alluvium ?	19.040	-98.167	0.11	0.28	0.06
SRPU	San Ramon Castillolta	Basalt and silty Tuff ?	18.965	-98.260	0.22	0.13	0.07
UAPP	Zona Universitaria	Low Compressible soil	19.002	-98.202	0.11	0.10	0.07

The baseline corrected acceleration, velocity, and displacement time history for the motion recorded in the PHPU ground motion instrument is presented in Figure 3.5. Preliminary analysis shows that the significant duration, D_{5-95} , of the PHPU soil record was about 38 seconds. The ratio of PGV/PGA was around 83 cm/s/g at the PHPU site. The site amplification of the intensity of ground motions along with the relatively long duration and periodic nature of the motion may help explain the concentration of damage in Puebla. The ground shaking in Puebla, which is located at an epicentral distance of about 125 km, was sufficient to cause damage to old colonial structures, such as churches, and houses constructed without any structural reinforcement. The ground shaking also adversely affected some medium-height modern buildings (4 to 5 stories). Most of the damage was moderate, although 3 buildings collapsed in downtown Puebla.

Site effects were also observed in Acatlán de Osorio, a town located approximately 50 km west of the epicenter, which suffered a substantial amount of damage. In México City, located around 200 km from Puebla City, shaking levels were low, but clear site effects were observed. Figure 3.6 shows the uncorrected acceleration time history recorded at the Secretaria de Comunicaciones y Transportes, SCT (located on soft clay) and UNAM (located on rock) strong ground motion instrument. Amplification of accelerations by a factor of about 3 can be observed, as can the clearly longer-period nature of the motions at the soft clay site.

4 OTHER GEOTECHNICAL CONSIDERATIONS

The geotechnical considerations presented hereafter correspond principally to the damage observed by the reconnaissance team at sites along and near the roads that connect the cities of Puebla, Tehuacán, Huajuapán de León, Acatlán de Osorio, Izúcar de Matamoros, Atlixco, Tepexi de Rodríguez, San Juan de Ixcaquítla and Huamantla, as is shown in Figure 1.2, as well as a limited number of reports /observations made by others.

4.1 Effects of Ground Motions on Some Structures:

Collapse of a four-story building, shown in Figure 4.1, occurred in downtown Puebla. The collapse of this structure may be attributed, in part, to local soil conditions and site amplification as discussed in Section 3.4. An adjacent building was severely affected as well, as shown in Figure 4.2. This structure had a street level garage that collapsed due to column shear; apparently no punching or settlement occurred. These buildings are located in the double hatched portion of the microzonation map (Figure 3.3) for which significant amplification of ground motion was predicted. They are also located within 1 km of the PHPU station that recorded amplified ground motions in Puebla. These buildings were part of a four building, four story complex of which two were completely leveled, one was sheared without collapse, and the remaining building showed little damage. No one was killed in these buildings.

Figure 4.3 shows a 5 m deep, unbraced open excavation for the placement of a sewer line. This site is also located in the double hatched zone on the microzonation map, but did not show any evidence of failure or displacement. At the time of the June 15 earthquake, workers were inside the excavation.

Old structures were particularly hard hit during the events of June 15 and June 21. Figure 4.4 shows the Carolino building of downtown Puebla. The interior structural damage seen is indicative of damage that most URM structures in the Puebla and Oaxaca regions experienced. Figures 4.5 and 4.6 show the typical damage that many of the churches in the affected region experienced. In nearly every town, regardless of how small the population is, there is a church similar to the churches seen in these two figures. With unerring regularity, these churches were damaged during the strong ground shaking. Even in the towns least affected by the tremors, where all other structures emerged unscathed, the churches often had some sort of damage.

An interesting example of “local site effects” is the damage to the church in the town of Cholula, approximately 10 km west of Puebla City. Figures 4.7 and 4.8 show the damage that occurred to this 16th century church that is built on an ancient stone pyramid. The severe damage may be attributed, at least in part, to topographic amplification of ground motions due to the pyramid.

The most severely affected town that the authors visited was Acatlán de Osorio, located approximately 50 km west of the June 15 epicenter. Site effects were prominent in this town, with the most damage occurring to structures in the sediment filled valley and little or no damage to the structures located on rock in the foothills. Figure 4.9 shows the type of damage that was common in the downtown region. On certain streets many houses were reduced to rubble such as the one shown. Figure 4.10 shows a relatively modern two-story structure that was destroyed.

Damage to a bridge, shown in Figures 4.11 and 4.12, was observed on Highway 135 north of Tehuacán. Four bridges are located within 3 km of each other along this stretch of highway. The only bridge to be structurally damaged was one supported by three columns. This bridge experienced 15 cm of displacement in the lateral and longitudinal directions. Settlement of the approach embankments was identified by large tension cracks in the embankment shoulders. The three nearby undamaged two column bridges had the same orientation and were located in similar topography, yet experienced negligible damage.

4.2 Landslides:

Figure 4.13 shows shallow landsliding that occurred on the slopes of Cerro el Pinal. Larger landslides occurred on the flanks of the extinct volcano, Cerro la Malinche. These slides damaged the aqueduct that supplies water to the town of Ixtenco in the State of Tlaxcala, effectively cutting off the water supply for several days.

A series of small rock falls occurred along road cuts in the proximity of Tehuacán. Small slides were common along the cut slopes adjacent to roads in the vicinity of the epicenter. These failures included rockslides, rock toppling, block sliding of both earth and rock, and surficial raveling. In the states of Puebla and Oaxaca, sliding deposited debris on the roadways causing traffic delays and road closures. Figure 4.14 shows a larger reactivated slide located on the route from Tehuacán to Huajuapán de León. Figure 4.15 shows tension cracks parallel to the mountainous road that extends from the city of Acatlán de Osorio to Izúcar de Matamoros.

4.3 Ground Failure:

Surface expression of fault rupture was not seen along the path followed by the reconnaissance team. Lateral cracks in the earth, not associated with surface rupture, were observed in the backyard of a house in the city of Acatlán de Osorio in the state of Puebla, as shown in Figure 4.16. These appeared to be related to poor performance of relatively loose surficial soil or fill.

4.4 Soil Liquefaction:

Liquefaction occurred in the highlands (“altiplano”) of the State of Tlaxcala, about 20 km northwest of the City of Puebla. Sand boils, shown in Figure 4.17, were observed throughout a large area in a cornfield. The liquefied soil was volcanic in origin,

a non-plastic silty sand with 28% passing the #200 sieve. There were no observations of significant soil liquefaction affecting structures, which is not surprising given the dry season and relatively moderate levels of shaking. Several cases of poor structural performance, apparently due to cyclic densification/settlement of loose surficial soils or fills were noted.

4.5 Performance of Earth Structures:

Not many earth dams are built in the state of Puebla; the water demand is mainly supplied by groundwater in underlying aquifers. “Valsequillo” is a small rockfill dam located to the south of the city of Puebla, as shown in Figure 1.2. The embankment has a maximum crest height of approximately 25 m. Inspection of the 2H:1V upstream and downstream slopes of the embankment showed no evidence of cracking or displacement.

The solid-waste of many of the cities and towns in the proximity of the epicenter is eliminated by incineration in the open field. The solid-waste landfill of the city of Puebla, Chiltepeque, is a modern facility with side slopes of 3H:1V and a base liner system. During the landfill inspection of this site no signs of either major instability or localized failure were observed in the slopes. The solid-waste landfill of the City of Tehuacán also showed no evidence of seismically-induced deformations.

4.6 Miscellaneous:

According to the Red Cross, 35 people were trapped and one died in a mine at San Antonio Atexcac, in the State of Veracruz. In Tehuacán, another report claims that several people were trapped in a quarry due to a landslide. Many schools reported damage, but the authors saw very little in the way of geotechnical or structural related issues associated with these reports.

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