Geotechnical observations on the Tehuacan (Mexico) earthquake of June 15, 1999

Observations géotechniques suite au séisme de Tehuacan (Mexique) du 15 juin, 1999

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ABSTRACT: A brief description on the Tehuacan earthquake (M_w=7.0) of June 15, 1999 is presented. Geotechnical and structural issues related to this seismic event are commented, highlighting the first documented case of liquefaction in the Mexican Central Plateau, and the severe damage to churches or convents built from XVI to XIX centuries.

RÉSUMÉ: Cette communication décrit brièvement les caractéristiques du macroséisme de Tehuacan (Ms=7.0) du 15 juin 1999. Certains aspects géotechniques et structuraux de cet évènement sismique sont présentés. On décrit tout particulièrement en détail le premier cas documenté de liquéfaction sur le Plateau Central Mexicain ainsi que les dommages sévères soufferts par des églises et des couvents construits du XVIème au XIXème siècle.

1 INTRODUCTION

On June 15, 1999 at 20:42 h-GMT a large earthquake (m_b=6.3; M_s=6.5; M_w=7.0) struck the central region of Mexico. Its epicenter was located near the limit of the states of Puebla and Oaxaca, about 20 km southeast of Tehuacan, Puebla. The earthquake caused moderate to high intensities in some villages of the epicentral area, with damage to adobe dwellings. However, considerable and particular damage was produced to over 500 historical monuments, mainly catholic churches or convents built between the XVI and the XIX centuries, from the southern towns of Puebla, north Oaxaca, Tlaxcala and Morelos. This seismic event was felt with moderate to high intensity in the city of Puebla, the 5th largest of Mexico and 120 km far from the epicenter, although with few cases of structural or geotechnical damages in engineered constructions. The intensity in Mexico City was low, although people overreacted with fear, remembering the consequences of the Michoacan earthquakes on Sept. 19 and 20, 1985.

Of particular geotechnical interest, is the first time a documented case of liquefaction in the Mexican Central Plateau in know. Preliminary data on this phenomenon, as well as some evidences of site effects, source directivity and other geotechnical effects are reported in this paper. A broadband seismic network recorded seismic data, and strong-motion regional networks (city of Puebla and the valley of Mexico) captured accelerographic data.

2 LOCATION AND FOCAL MECHANISM

The epicenter of this earthquake was located at 18.20°N latitude and 97.47°W longitude at a depth of 92 km, according to the National Seismological Service of Mexico (SSN), Figure 1. On the other hand, the United States Geological Survey located the focus at 18.40°N and 97.45°W, 71 km. This intermediate-depth seismic event was associated (Singh et al. 1999) to a normal fault in the subducted Cocos plate, with a strike of 308° and a dip of 49°; these data based on local and regional records. Neither scar nor rupture plane in the ground surface was detected. This large earthquake is one of the most northern seismic events associated to the Pacific subducted zone, occurred inland Mexico.

Previous earthquakes in the region have succeeded, being the most recent those with a magnitude M_w=7.0 on 28-08-1973 [18.30°N and 96.53°W, 82 km] and 24-10-1980 [18.03°N and 98.27°W, 65 km].

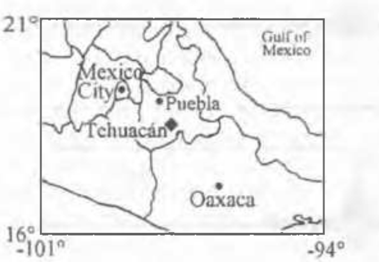

Figure 1. Epicenter for the 15-06-99 Tehuacan earthquake in Mexico.

3 STRONG GROUND MOTION

Strong-ground motions were recorded by the networks operated by the National University of Mexico, National Center for Disaster Prevention, Autonomous University of Puebla, SSN and the University of Nevada-Reno. Peak ground accelerations recorded at 38 seismic stations are depicted in Figure 2, against their focal distance, including some from Mexico City. For a lacustrine place in Mexico City, the peak accelerations at the surface and in a borehole in free field (60-m depth) are also included. It is clear the well known site effect for the soft clayey deposits of the city.

Of particular interest are the strong ground motion records from the network of the city of Puebla. Those recorded at PHPU station are displayed in Figure 3. In this case of soil profile, the vertical component is about 30% of the horizontal accelerations; however, this figure reaches up to 50% in firm deposits (BHPP station). Similar patterns were observed in Mexico City, Figure 4. This aspect of high vertical motions produced by inland-subduction mechanisms is an issue that should be of concern when defining the input motions for building seismic analyses.

4 SOURCE DIRECTIVITY AND ATTENUATION OF GROUND MOTION

Singh et al. (1999) consider that source directivity occurred towards NW, along the strike of the fault. This conclusion is based on the different duration of the intense part of the ground motion, for different seismic stations around the epicenter. The larger accelerations and the more intense damage towards NW of the epicenter can be related to this directivity effect, at least in part.

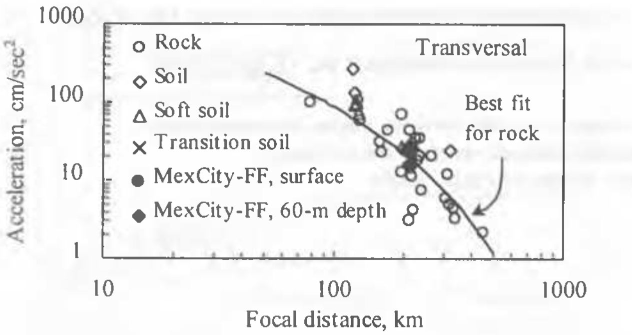

Figure 2. Peak ground accelerations and focal distance for the Tehuacan earthquake on June 15, 1999.

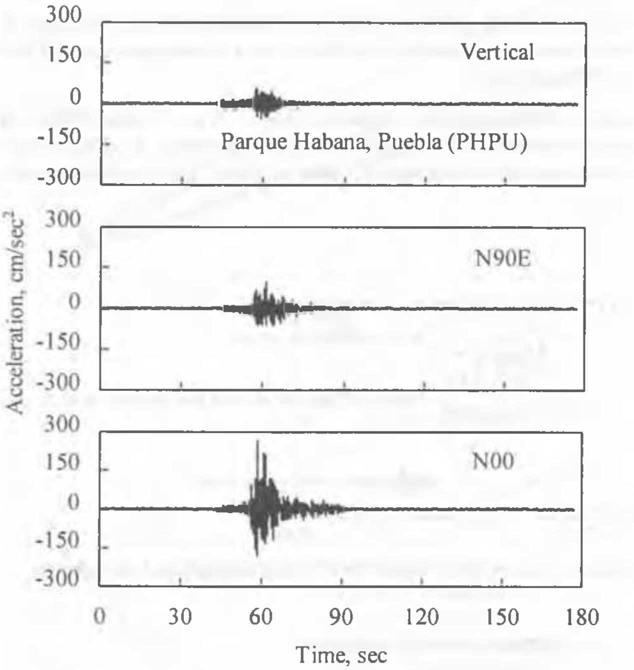

Figure 3. Strong motion records due to Tehuacan earthquake in soil site in Puebla, PHPU station (after Alcántara et al. 1999).

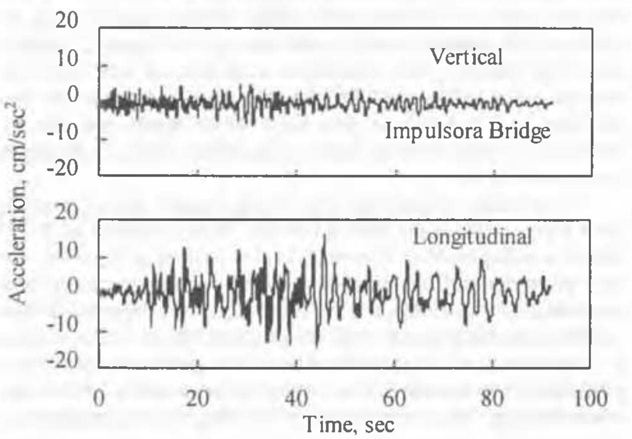

Figure 4. Strong motion records due to Tehuacan earthquake in a free-field 60-m depth borehole at Lake Zone in Mexico City.

Attenuation relationships are well known for those earthquakes from shallow, thrust events occurring along the Pacific coast, which indeed induce high intensities in the Valley of Mexico. However, there is not a relationship available for intermediate-depth Mexican earthquakes. When we plot the available data for the Tehuacan earthquake in a relationship like the above mentioned of similar magnitude, an interesting conclusion can be drawn: normal-faulting events provoke somewhat higher maximum accelerations than shallow thrust events. Even for medium focal distances on rocky sites, larger maximum accelerations in the vertical direction were recorded for the Tehuacan earthquake, than the usual values for the frequent earthquakes from the Pacific coast.

5 GEOLOGY AND SITE EFFECTS IN PUEBLA

According to a geotechnical compilation (Auvinet 1976), the basement of the city consists of Cretaceous limestone. Overlying these sediments a sequence of mixed volcanic (tuffs, mainly) and alluvial deposits are present, Figure 5. As a result of the volcanic activity related to the formation of the Mexican Volcanic Belt, reddish basaltic scoria forms a small hill to the east of the city, and outcrops of basalt and tuffs are evident to the south and west. Different rivers cross the city, leaving alluvial deposits with gravel and silty sand layers. Lacustrine deposits with alluvium and volcanic tuffs are also erratically distributed throughout the city.

Significant site effects were detected in the city of Puebla, considering the accelerographic data recorded at four stations located on rock, in comparison with those of two stations placed on soil profiles. In terms of peak ground accelerations between the PHPU (soil) and the BHPP (rock) stations, an amplification factor of 4.8 was reached. Comparing the response spectra at BHPP with another in the travertine area, the ratio between ordinate spectra is larger than 4, for periods between 0.45 and 1 sec. Spectral ratios of weak motion data (microtremors) were obtained by Chávez-García et al. (1995) in different places in the city. They determined predominant periods T_o between 0.5 and 1.1 seconds, and amplification factors between 2 and 7.

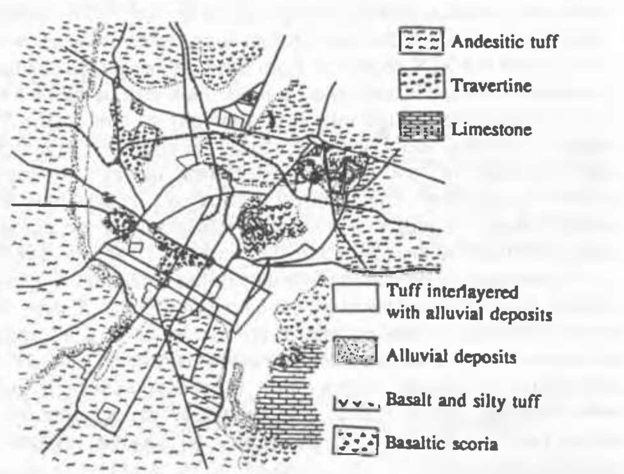

Figure 5. Geological map of the city of Puebla, including large avenues for reference (after Chávez-García et al. 1995).

6 GEOSEISMIC ZONING OF THE CITY OF PUEBLA

Auvinet (1976) gathered geological and reduced geotechnical information in order to define a geotechnical zoning of the city. Chávez-García et al. (1995) advanced a microzoning map based on seismic and geotechnical information. They carried out microtremor measurements in 39 places within the urban zone, and captured information with a temporal seismograph network. They proposed four zones, considering the dominant period as the key factor. However, Romo & Ovando (1995) have drawn attention on the fact that to the natural period of the ground, we must add its capacity to amplify the seismic movements, related to a reference hard site. Considering this, they suggest the plot of Figure 6 as an option for a geoseismic zoning.

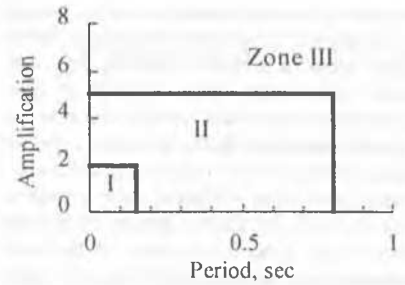

Figure 6. General proposal for geoseismic zoning of a region [after Romo & Ovando, 1995].

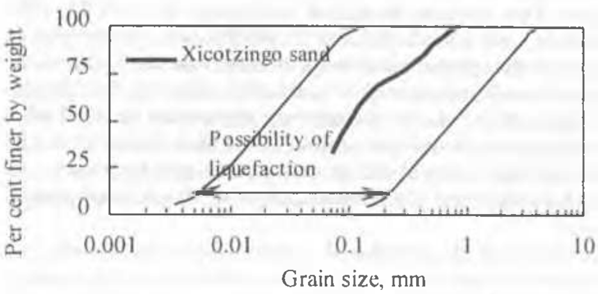

Figure 7. Grain-size distribution of Xicotzingo silty sand, Tlaxcala.

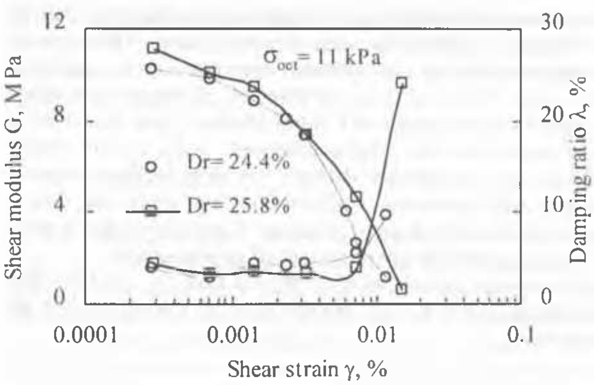

Figure 8. Shear modulus and damping ratio against the corresponding cyclic shear strain, for the Xicotzingo silty sand.

7 LIQUEFACTION

In the southern region of the State of Tlaxcala, about 20 km to the NW of the city of Puebla, liquefaction was detected close to the riverbanks of the Zahuapan River, which downstream is known as the Balsas River. The affected area that is located about 140 km from the epicenter is characterized by cornfields in a rural zone, then, the effect of this phenomenon was minor. However, the occurrence of liquefaction by itself is an important fact. It was very surprising to learn that liquefaction developed in the Central Plateau. Indeed, it is the first time that liquefaction is documented in the Puebla-Tlaxcala Valley, which is close to the Valley of Mexico. The authors are not aware of a previous event to this altitude (about 2200 m on the sea level) in Mexico.

The silty sand that came out through cracks and little "volcanoes" is a dark material, coming from a deposit that presumably was originated by an eruption of the relatively near Popocatepetl volcano. The grain size distribution curve of a representative sample is shown in Figure 7. A uniform silty sand with a high content of non-plastic silt-size particles, is quite clear. Considering all the samples, 28% to 45% by weight is finer than the No. 200 mesh. The variations of the shear modulus and damping ratio with the shear strain of the silty sand are depicted in Figure 8. The rapid reduction with distortion in the dynamic rigidity of the soil skeleton, reflects its high liquefaction susceptibility.

8 STRUCTURAL AND GEOTECHNICAL DAMAGE FROM THE EARTHQUAKE

An isoseismic map of this earthquake was prepared by Singh et al. (1999) based on the modified Mercalli intensity scale, making use of reports of civil protection authorities and newspaper accounts. At least 17 people died, most of them in the State of Puebla.

Considerable damage was reported in unreinforced adobe dwellings in some villages of the epicentral area. The largest and more important damage was observed in more than 500 historical monuments of the States of Puebla, Oaxaca, Tlaxcala and Morelos. Catholic churches and convents built from XVI to XIX centuries suffered the collapse of vaults, cupolas and bell towers, Figure 9. Damage is associated mainly to flexural effects in arches and vaults built with unreinforced masonry, and to previously damaged monuments, which were poorly repaired after the 1973 and 1980 earthquakes.

Most of the damage in the city of Puebla was concentrated in the travertine deposits area of the downtown. Peak accelerations of about 120 gals were recorded over there, while 50 gals seems to be a typical value at "hard sites" in the city. Accordingly, as it has happened in Mexico City and other cities through the world, the damage distribution in the city of Puebla was associated to site effects.

Full collapse of three of five buildings (soft story with slender reinforced concrete columns, and two stories with masonry walls) occurred in downtown, Figure 10. The site is close to the ancient alluvial deposits of the San Francisco River, which is conducted by underground pipes now. The relatively high flexural and shear demands at the ground floor were combined with a soft story wherein abrupt change in its stiffness occurs. In this site, some columns of the ground floor penetrated the ground surface, Figure 10b and 10d. The type of foundation is unknown, but presumably it should be a concrete isolated footing. This penetration could be the consequence of a foundation failure, for which a possible very loose saturated alluvial deposit could be propitious. Lateral movement of the building was not appreciated; so, the penetration of a failed column with some lateral movement must be considered less probable. No evidence of liquefaction was found at or nearby the site.

Figure 9. Cupola failure in San Agustin church, downtown Puebla, and extensive cracking at the bell towers of the Ocotlán Basilica, Tlaxcala.

Some landslides were reported (Pestana et al. 1999) along road cuts and natural hills; most of them with a relatively superficial mechanism, affecting the road traffic to various degrees. Only a relatively large landslide occurred in the foothills of "La Malinche" mountain, 120 km far from the epicenter, disrupting an aqueduct and interrupting the water supply to some towns for several days.

The intensity in Mexico City was very low. No major damages were reported; only a low masonry wall was turned over. However, as has occurred previously, people overreacted with fear to this earthquake, according to past experiences, but mentioning that it was felt different to other usual earthquakes (those generated close to the Pacific coast).

9 COMPARISON OF THIS EVENT WITH COASTAL EARTHQUAKES

For comparison of the Tehuacan earthquake with other coastal earthquakes of similar magnitude, we chose the accelerographic data recorded on a piled box foundation, at ground surface level, in Mexico City (Mendoza et al. 1999). The January 11, 1997 earthquake (M_w=7.2) was also a normal-faulting event (depth≈ 35 km) located close to the State of Michoacan coast [18.09°N, 102.86°W], precisely below the rupture area of the Michoacan earthquake of September, 19, 1985. Although this event occurred to a focal distance of about 450 km, that doubles that one for the Tehuacan earthquake, its magnitude is a little higher than for this

Figure 10. a) Story building with soft story in downtown Puebla, b) & c) Collapse of a building similar to a); and, d) close-up of the penetrated corner column in the ground for the building b).

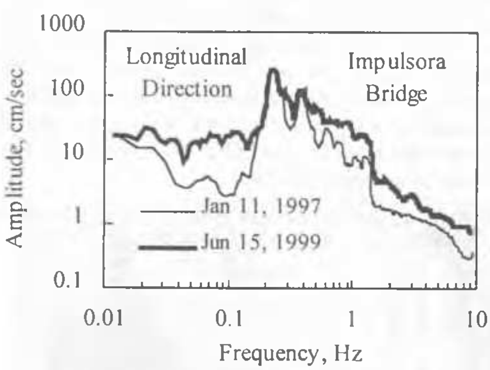

Figure 11. Fourier spectra for the Tehuacan and a coastal earthquakes, recorded on a piled box foundation in the Lake Zone of Mexico City.

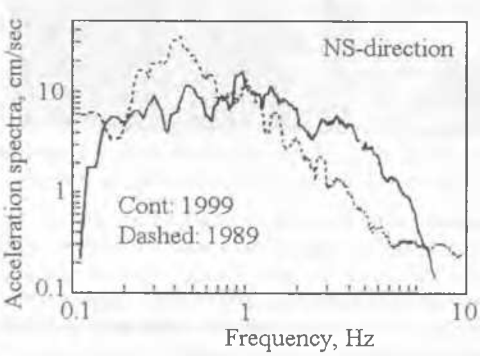

Figure 12. Fourier spectra for the Tehuacan and a coastal earthquakes, recorded in free field at the Hill Zone (CU station) of Mexico City (after Singh et al. 1999).

one; in any case, the interest is to inspect their spectral shapes, which are shown in Figure 11. In the Fourier spectra of the two earthquakes, a peak amplitude is observed at a frequency of about 0.23 Hz; however, the amplitude decay at higher frequencies in the deeper 1999 event is less marked than for the coastal earthquake. So, higher amplitudes at higher frequencies developed during the Tehuacan event. It is worth noticing that very similar maximum spectral amplitudes were reached in both earthquakes. The fact that these maximum values occur at the same frequency in the piled foundation, lends to support that its dynamic motions are greatly influenced by local site conditions.

The above comparison shows how different source mechanisms affect the response of a soil-foundation system in the soft clayey deposits of Mexico City. Detailed studies on the soil-structure interaction phenomena are in progress. In order to learn more about the ground motion in the Valley of Mexico due to two different sources, a similar comparison was made by Singh et al. (1999), but including data for the Ciudad Universitaria station in Mexico City, which is representative of free field on hard ground. They selected the coastal earthquake of April 25, 1989 (M_w=6.9) with a focal distance of 305 km. As can be seen in Figure 12, the spectral amplitudes for this event are higher at the range of low frequencies (0.25 to 0.6 Hz), decaying for frequencies higher than 1 Hz. On the contrary, the spectra for the Tehuacan earthquake shows low amplitudes at low frequencies, and relatively high levels of energy delivered at high frequencies, as should be expected from intermediate to deep-seated-seismic events.

10 CONCLUSIONS

A brief recount of preliminary seismic and geotechnical data for the Tehuacan earthquake was presented here. This normal-faulting intermediate-depth seismic event showed source directivity to the NW, provoking considerable damages to historical monuments in four states of Central Mexico. This directivity in combination with site effects, produced in the city of Puebla moderate and concentrated damage, precisely in those masonry buildings with inadequate wall confinement. Only one case of improper behavior in a set of buildings is speculated that it might be related to a deficient performance of its foundation.

Of particular geotechnical interest is that for the first time, liquefaction occurs in the Mexican Central Plateau during this earthquake.

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