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Sudden soil subsidence in Mexico City due to strong ground motions

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ABSTRACT: During strong ground motions earthquakes, soil deposits of lacustrine origin, like those of Mexico City (MC), experience shear stresses produced by seismic waves that are added to the ones due to the static loads. In that situation the soil mass is heavily stressed to values larger than its yielding stress σ'_Y, and consequently starts to settle after the earthquake.

However, sudden subsidence induced by strong ground motions of soils deposits rich in biogenic silica (diatoms), such as the ones of MC; it is a little known phenomenon. The occurrence of the latter has come forward in MC during the 1957, 1985 and 2017 large magnitude earthquakes.

Experimental results to study the mentioned phenomena are presented herein. The study included Mexico City soils samples under one-dimensional cyclic loading conditions, the results indicate that the yielding stress, σ'_Y and stress history are key parameters in the behavior of the soil samples tested.

1 INTRODUCTION

The behavior of Mexico City subsoil during three strong ground motions earthquakes such as the ones occurred on July 28, 1957, September 19, 1985 and recently on September 19, 2017, offered an exceptional opportunity for observing a singular phenomenon: the sudden settlements of constructions located on its subsoil during the occurrence of those earthquakes.

During seismic loading, soil layers are subjected to cyclic shear stresses with different amplitudes and frequencies that might induce transient and permanent deformations. The buildings located on top of these soil layers may have a significant damage due to settlements. Thus, the seismic behavior of any saturated soil, from sand to clay, might experience significant strains or strength loss that can contribute to ground deformations or instability during earthquakes. As a consequence of this, the constructions located on top of these soil layers may suffer a significant damage due to settlements.

Settlement of saturated clay soils induced by cyclic loading has been a topic of interest for several researchers (e.g. Fujiwara et al. 1985; Hyodo et al. 1988; Ohara and Matsuda 1988; Yasuhara & Andersen 1991; Sato et al. 2018).

In the case of loose saturated fine sands, the loss of shear strength is attributed to the increase in pore pressure due to the tendencies of the soil particles to re-arrange into a denser state, which is a direct consequence of the release of contacts between particles following the decrease of the effective confining pressure. Loose saturated fine sands are susceptible to liquefaction. Concerning the behavior of saturated clays subjected to seismic loading, excess pore pressure is produced as well. As time proceeds, the accumulated excess pore pressure dissipates and so the ground settles. In clayey soils, their interparticle forces prevent separation of particles and therefore, the loss of shear strength is generally less dramatic than in loose saturated fine sands.

There is an intermediate case, silty-clay or clayey-silt soils, these types of clayey materials may be vulnerable to severe strength loss as a result of earthquake shaking. Criteria for identifying liquefiable fine-grained soil has been proposed (Seed & Idriss 1982; Bray & Sancio 2006) based on the amount of clay minerals as a better indicator to soil´s susceptibility to liquefaction. Hence, the higher plasticity index, the lower the susceptibility to liquefaction.

2 THE SUBSOIL OF MEXICO CITY

Mexico City soils (MCS) are made of a complex mixtures of crystalline minerals and amorphous material that challenges a simple nomenclature; they are made of heterogeneous volcanic and lacustrine sediments with microfossils (diatoms and ostracods) and organic matter (Díaz-Rodríguez et al. 1998). The grain size distribution of MCS corresponds to silty clays or clayey silts. The natural water content is very high (w ≈ 220 – 420). The plasticity index I_p, often exceeds 300%, and the compression index Cc can be as high as 10.

The subsoil of Mexico City is interbedded with sands and volcanic glass layers up to a depth of about 200 m. The upper sequence (7 to 30 m depth) is characterized by very high void ratio (e ≈ 5 – 10) due to the presence of diatoms, the skeletal remains of microorganisms that thrived in the nutrient–rich lakebed (Díaz-Rodríguez et al. 1998).

The normalized strength properties of the MCS vary with the yield stress and also with the diatom content (Díaz-Rodríguez & Santamarina 2001; Díaz-Rodríguez 2011). While the friction angle of soils decrease, as the plasticity index increases, the high plasticity of MCS presents a friction angle comparable in magnitude to those of sands (Díaz-Rodríguez et al. 1992a). Another feature of soils with high diatom content is the low excess pore water pressures under undrained shearing, both monotonic and cyclic (Díaz-Rodríguez & López-Molina 2009, Díaz-Rodríguez 2011). Furthermore, significant degradation of this diatomaceous soil only occurs once cyclic shear stresses exceed about 80 percent of the static undrained strength (Díaz-Rodríguez 1989).

The behavior of MCS is essentially elastic even for shear strains as high as 0.1%, and has unusually low hysteretic damping (Díaz-Rodríguez 1992b), which leads to a high potential of amplification of seismic waves arriving from epicentral distances of hundreds of kilometers of the so-called Valley of Mexico. Hence, the role of MCS in the performance of buildings during seismic events is undisputed.

3 OBSERVATIONS OF SUDDEN SUBSIDENCE DURING LARGE MAGNITUDE EARTHQUAKES IN MEXICO CITY

3.1 *The July 28, 1957 Guerrero earthquake (M_w = 7.6)*

A destructive subduction interplate type earthquake of magnitude M_w = 7.6, occurred at 2:40:12 Mexico City time, the epicentral parameters of the U.S. Geological Survey are 17.055°N, 99.092° W, 37.8 km depth. Several MC buildings collapsed and other were seriously damaged. Among others, Zeevaert (1973) briefly described the effect of so-called Guerrero 1957 earthquake on the settlement of a heavy building placed on an undercompensated foundation (Figure 1). This figure shows the evolution of the vertical displacements of several foundation points of the building, before and after the 1957 earthquake. From this figure, it can be concluded that the building was practically stable before the earthquake, however, there was a sudden settlement during the occurrence of the earthquake, the building also continued to settle after the earthquake. The study of this case concluded that the static shear stresses, added to the dynamic shear induced during the earthquake of 1957, produced that the ultimate shear strength of the silty clay deposit was reached; therefore, partial damage took place in the soil skeleton structure, giving as a result an increase in the compressibility of the material that produced the compression phenomenon observed.

3.2 *The September 19, 1985 Michoacán earthquake (M_w = 8.0)*

The 19 September 1985, Michoacán (a subduction interplate) earthquake of magnitude M_w = 8.0, occurred at 13:17: 48 Mexico City time. The epicentral parameters are 18.19°N, 102.53°W, 27.9 km depth (NEIC). The event occurred along a part of the Cocos-North American plate boundary identified as the Michoacan seismic gap.

It is important to mention that the September 19, 1985 Michoacán earthquake caused many buildings, located in the lake-zone of Mexico City, to tilt and undergo settlements, sometimes of very large magnitudes. It is considered that several buildings sank and tilted due to the local

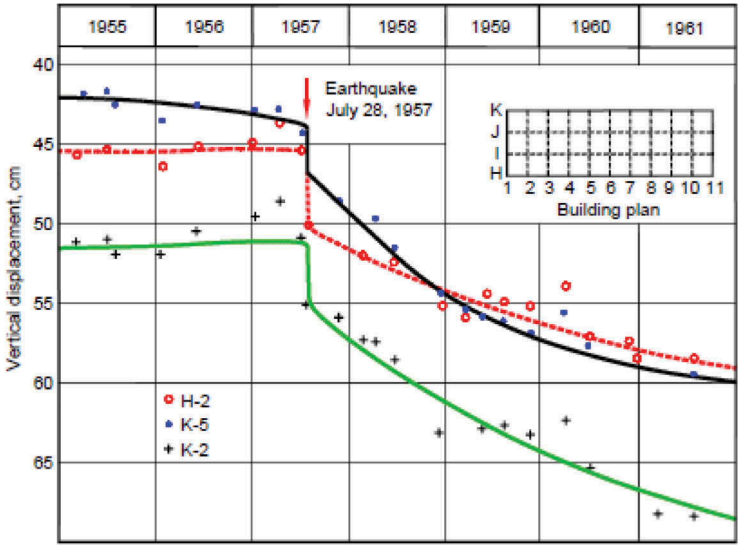

Figure 1. Effect of July 28, 1957 Guerrero earthquake on the settlement of a building (Zeevaert 1973).

Figure 2. Settlement of a building during September 19, 1985 Michoacan earthquake.

failure caused by reduction of the resistance of the soil. For example, Figure 2 shows an abnormal sudden settlement of approximately 95 cm between the sidewalk and a building founded on friction piles. Similar patterns of distress were observed in many other locations of MC in which the soil loss of shear strength did not necessarily lead to an overall foundation failure.

3.3 *The September 19, 2017 Puebla-Morelos earthquake* (M_w = 7.1)

The September 19, 2017 Puebla-Morelos earthquake of magnitude M_w = 7.1, occurred at 13:14:38 MC time. The epicentral parameters are 18.550°N, 98.489°W, 48 km depth (NEIC). According to U.S. Geological Survey, the location, depth, and normal-faulting mechanism of this earthquake indicate that it is an intraplate event, within the subducting Cocos slab, rather than on the shallower megathrust plate boundary interface.

Based on data collected by the satellite Sentinel 1A, from the European Central Agency, the Geospatial Information Research Center (CONACYT) reported that some areas of MC suffered relative subsidence of up 25 cm after the 19 September 2017 earthquake (López–Caloca et al. 2017).

4 EXPERIMENTAL INVESTIGATION OF MEXICO CITY SOIL UNDER CYCLIC LOADING

Taking into account the observations described in section 3, the Soil Dynamics Group at the Engineering School (UNAM), decided to conduct a broad experimental program dedicated to study the sudden subsidence phenomenon. The first stage of the program consists in

Figure 3. Photo of the apparatus developed.

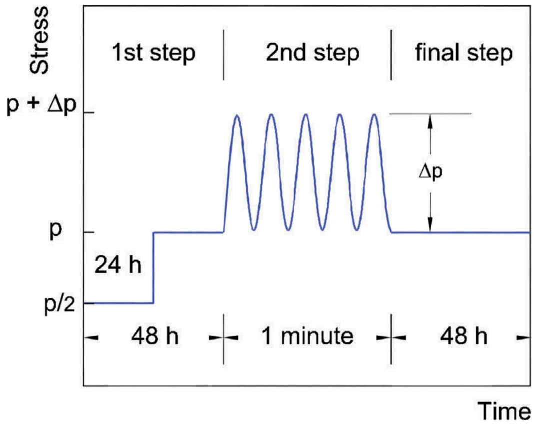

Figure 4. Testing loading sequence.

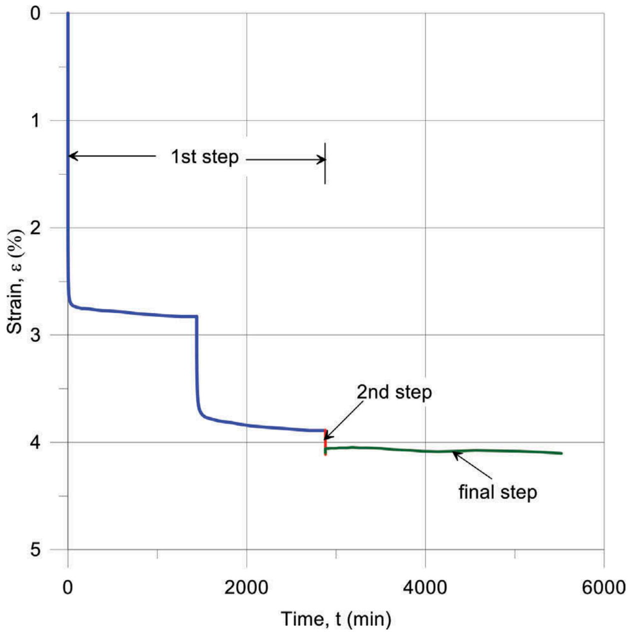

Figure 5. Time strain curve under static and cyclic loading.

subjecting each soil sample to a sustained vertical stress, allowing the samples to reach equilibrium, and then applying cyclic vertical stresses representative of an earthquake. It is recognized that such an approach is a first step to study the subsidence phenomenon. However, it is believed that such an approach is necessary to simplify this extremely complex problem to a form suitable for laboratory investigation.

Then, an apparatus to carry on one-dimensional consolidation tests under static and cyclic loads was developed (Figure 3). This apparatus is a modification of the conventionally used standard consolidation apparatus, adapted for use with static and cyclic loading applied either separately or simultaneously. The final trimmed size of the test specimens was 81 mm in diameter and 19 mm height. The ring used was made of Nylamid with a thin film of silicon grease.

The loading sequence employed in this investigation is schematically illustrated in Figure 4. In the first step, the sample is consolidated under a static stress p, reached in two increments with a duration of 24 h each one, in the second step, the sample is tested under both static

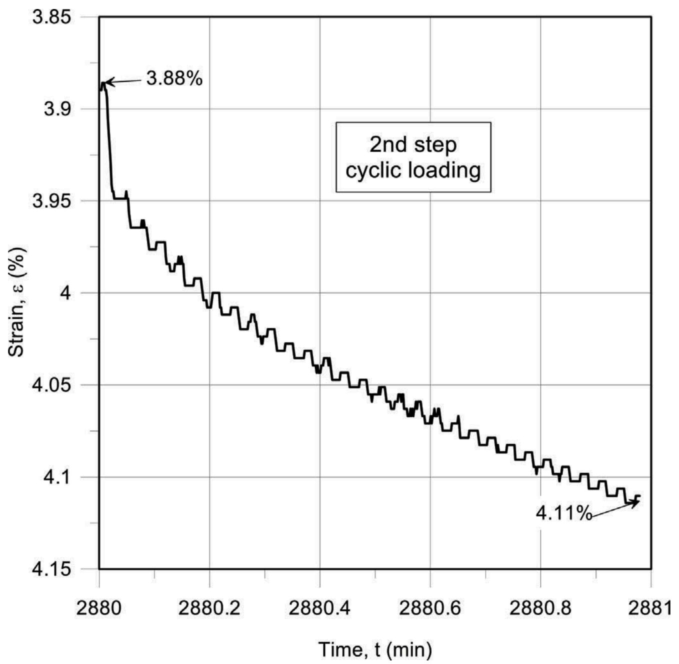

Figure 6. Time-strain curve under cyclic loading.

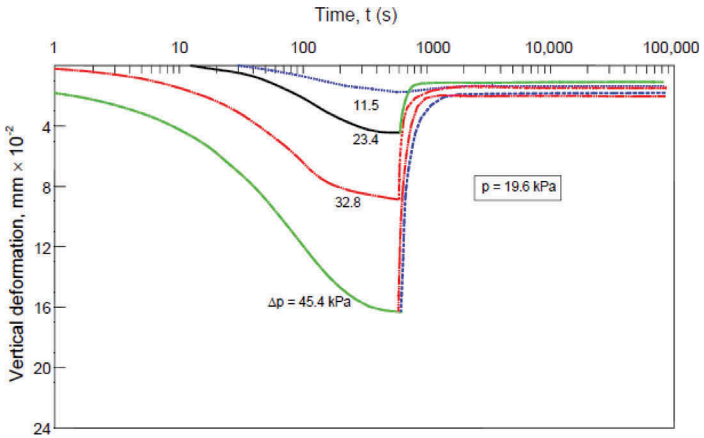

Figure 7. Vertical deformation induced in one-dimensional cyclic loading.

stress p and a cyclic stress Δp simultaneously for 1 minute of duration, and in the final step the static stress p was kept constant to observe the evolution of the settlement. The cyclic load was sinusoidal with 2 s period.

A preliminary result (obtained with the apparatus of Figure 3) on a kaolinite soil sample is shown in Figure 5. This figure shows the time-strain curve obtained by applying the loading sequence of Figure 4. It can be observe that the strain at the end of the first step, after 48 h (2880 min), was 3.88%, and at the end of second step, during the application of the cyclic load was 4.11%, this means that the cyclic loading produced a deformation of 0.22 % in a very short period of time (a sudden strain), After that, the soil sample presented a recovery of 0.032 %. Figure 6 highlights the evolution of the strain during the second step.

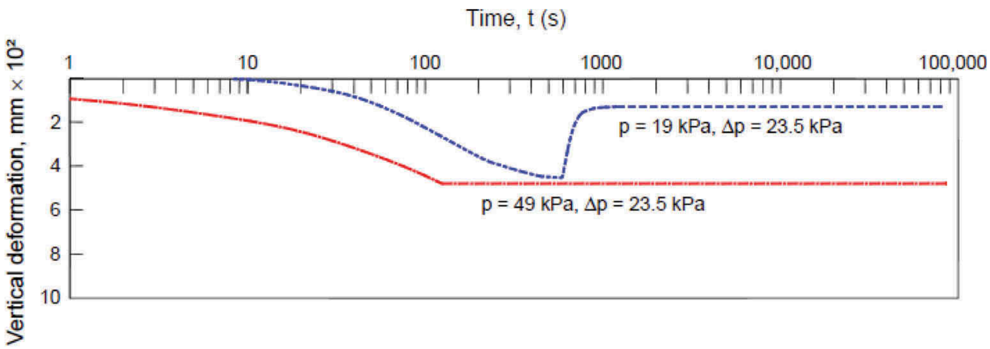

Figure 8. Comparison between two soil samples with different consolidation stress.

The current study allowed reassessing experimental tests on the behavior of Mexico City soils previously carried out by Díaz-Rodríguez & Leyte-Guerrero (1989). However, In this case, the response is reinterpreted in terms of the stress ratio $\alpha = \sigma'_Y/(p + \Delta p)$.

Among other results, it was found that the yielding stress, σ'_Y, (Diaz-Rodríguez et al. 1992a) is a key parameter in the behavior of the soil samples tested. Specifically, it was found that specimens preserve the nature structure when $\alpha > 1$, the strains produced are according to current knowledge, but when α falls below 1.0, the soil sample becomes gradually destructured, the sequence of cyclic stresses generate considerably larger strains, which may occur suddenly. Additionally, due to the cyclic loading the yield stress may suffer a reduction, possibly caused by the remolding of the soil samples during cyclic loading and damage to soil structure.

Figure 7 shows the evolution of the vertical strains with time, both during and after the application of a short sequence of cyclic stresses. The amplitude of the static stress remained constant and equal to 19.6 kPa (lower than the yielding stress). It can be seen that although the amplitudes of the cyclic stresses were large, from 11.5 to 45.4 kPa (α from 2.27 to 1.07), the soil sample presented a very important elastic recoverability. Figure 8 shows a comparison between two soil samples with different consolidation stress, 19.6 and 49 kPa with cyclic stress amplitudes of 23.5 and 18.6 kPa respectively (α equal to 1.63 and 1.04). It can be seen that for the condition of lower consolidation stress, the soil sample presented a great recovery, but for the condition of higher consolidation stress, the soil sample did not have elastic recovery, this result suggests an effect of strain history.

5 CONCLUSIONS

Evidence was presented that Mexico City soils suffered sudden subsidence during the occurrence of three large magnitude earthquakes. Sudden subsidence is a phenomenon that is far from being understood and whose transcendence is not fully appreciated. Hence, the Soil Dynamics Group at the Engineering School (UNAM) has an ongoing experimental program dedicated to study such important phenomenon.

The laboratory results presented support the following conclusions concerning the behavior of the subsoil of Mexico City tested under one-dimensional cyclic loading conditions. It is realized that the observations apply strictly to the soil and test conditions employed in the experiments.

1) Vertical strains caused by cyclic loading are larger than that caused by static loading.
2) The Mexico City soil exhibits elastic behavior in spite of its very high water content, if the cyclic load is superimposed on a constant static stress lower than the yield stress σ'_Y ($\alpha > 1$).
3) If the cyclic stress is superimposed on a static stress larger than the yielding stress σ'_Y ($\alpha < 1$), the soil sample become gradually destructured, the sequence of cyclic stress generates considerably larger strains, which may occur suddenly.

4) The results suggest an effect of strain history.
5) Findings of this experimental research requires further validation

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