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Behavior of Mexico City soil under cyclic shear stresses

Comportement des sols de la ville de Mexico sous les contraintes de cisaillement cyclique

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ABSTRACT:. The behavior of the lacustrine subsoil of Mexico City (SMC) during three large magnitude earthquakes occurred on July 28, 1957 ($M_w = 7.6$), September 19, 1985 ($M_w = 8.0$) and recently on September 19, 2017 ($M_w = 7.1$), offered an exceptional opportunity for observing a singular phenomenon: the sudden settlements of buildings and ground. There is a strong correlation between the spatial distribution of damage associated with the mentioned seismic events and the lacustrine deposit location. Hence, the role of these deposits in the performance of superstructures is undisputed. The SMC's cyclic behavior was investigated by conducting two series of cyclic simple shear tests. These provide insight into the seismic behavior of high-plasticity clayey soils and analyze the degree to which cyclic behavior can explain the observed sudden settlement phenomena in Mexico City. The results indicate that significant degradation occurs once cyclic shear stress exceeds about 80% of the static undrained strength.

RÉSUMÉ: Le comportement du sous-sol de Mexico (SMC) lors de trois séismes de grande magnitude, le 28 juillet 1957 ($M_w = 7.6$), le 19 septembre 1985 ($M_w = 8.0$) et récemment le 19 septembre 2017 ($M_w = 7.1$), offre une occasion exceptionnelle d'observer un phénomène singulier: les tassements soudains des bâtiments et du sol. Il existe une forte corrélation entre la distribution spatiale des dommages associés aux événements sismiques antérieurs et l'emplacement du dépôt lacustre. Par conséquent, le rôle de ces dépôts dans la performance des superstructures est incontesté. Ensuite, le comportement cyclique de SMC a été étudié en effectuant deux séries d'essais de cisaillement cycliques simples. Un aperçu de la compression sismique des sols argileux à haute plasticité et analysent dans quelle mesure le comportement cyclique peut expliquer les phénomènes de tasseent soudain observés à la ville de Mexico. Les résultats indiquent qu'une dégradation significative se produit une fois que la contrainte de cisaillement cyclique dépasse environ 80% de la résistance statique non drainée.

KEYWORDS: Mexico City soil, simple shear testing, cyclic loading.

1 INTRODUCTION

Mexico City is one of the oldest metropolises in the Western Hemisphere, occupying an ancient plain (once a lake) surrounded by mountains and inhabited by at least 10 million people spread over 1,479 km^2. It is the fifth most populous city in the world. The behavior of the subsoil of Mexico City (SMC) during three large magnitude earthquakes occurred on July 28, 1957 ($M_w = 7.6$), September 19, 1985 ($M_w = 8.0$) and recently on September 19, 2017 ($M_w = 7.1$), have emphasized the need to understand the cyclic behavior of the SMC

During large magnitude earthquakes, natural soil deposits of lacustrine origin, like those in MC, are subjected to cyclic shear stresses with different amplitudes and frequencies that might induce transient and permanent deformations in soils. The structures located in these soil layers may have significant damage due to seismic loading. Thus, any saturated soil's seismic behavior, requires estimates of significant strains or strength loss that can contribute to ground deformations or instability during earthquakes.

It is generally recognized that the local soil characteristics influence the ground response when seismic waves propagate through a soil profile. The earthquake loading may lower the foundation´s undrained bearing capacity of clayey soils (Andersen 1988, 2009; Chu et al. 2008).

Most of the studies on seismic compression are limited in their applicability to clean sands (Silver and Seed 1971; Tokimatsu and Seed 1987), non-plastic silty sands (Polito and Martin 2001), and soils with large fines content and low plasticity (Stewart and Whang 2003; Stewart et al. 2004).

The principal objective of this research was to perform laboratory simple shear testing to provide insight into the cyclic behavior of high-plasticity clayey soils and investigate the degree to which cyclic behavior can explain the observed ground behavior during large magnitude earthquakes.

2 THE SUBSOIL OF MEXICO CITY

The Subsoil of Mexico City (SMC) is unique in the context of most other natural soils (Díaz-Rodríguez, 2003). The grain size distribution of Mexico City soils corresponds to silty clays or clayey silts. The water content, void ratio, and plasticity are typically very high ($w \approx 220 - 430\%; e \approx 5 - 10;\ w_L \approx 140 - 380;\ w_P \approx 55 - 112\%$) . Mexico City soil is diatomaceous soil (Diaz-Rodriguez, 2003). The SMC's open structure created by diatoms is reinforced by the salty groundwater, which has a flocculating effect on the smectite-rich clay minerals. The normalized strength properties of the SMC vary with the yield stress σ'_Y and also with the diatom content (Díaz-Rodríguez and Santamarina, 2001). While the friction angle of soil decreases, as the plasticity index increases, the high plasticity of the SMC presents a friction angle ($\varphi = 43° - 47°$) comparable in magnitude to those of sands (Díaz-Rodríguez et al., 1992). Diatom content has a significant effect on the strength and stiffness of these soils (Díaz-Rodríguez 2011). Another feature of soils with high diatom content is the low excess pore pressures under undrained shearing, monotonic and cyclic. Furthermore, significant degradation of this diatomaceous soil only occurs once cyclic shear stresses exceed 80% of the static undrained strength (Díaz-Rodríguez, 1989)).

The shear wave velocity (V_s=70 - 90 m/s) is relatively constant with depth in the upper sequence (7 to 30 m depth) and the yield pressure σ'_y is higher than the in situ effective stress σ'_{v0}, in agreement with the stress-independent formation process (Díaz-Rodríguez et al., 1998). Diagenesis has led to apparent preconsolidation (thixotropic response and mechanisms are reviewed in Díaz-Rodríguez and Santamarina 1999).

The behavior of the SMC is nearly elastic even for shear strains as high as 0.3%. It has an unusually low hysteretic damping (i.e. little loss, energy during loading cycles), which leads to a high potential of amplification of seismic waves.

Hence, the SMC's role in the performance of buildings and ground during seismic events is undisputed.

3 MATERIALS AND TESTING METHOD

The two series of cyclic simple shear (CSS) tests described herein form part of an ongoing program of cyclic loading on Mexico City soil. The samples for the tests were obtained from the lake zone of Mexico City, from depths ranging from 15 to 18 m. The soil samples at these depths correspond to "Zone 4" according to Díaz-Rodríguez et al. (1998). This layer has a shear wave velocity, $V_{s.}$, nearly constant, with an average value of 81 m/s and yield stress, σ'_Y, also nearly constant, with a mean value of 85 kPa. In this uniform section of the deposit, the water content remained nearly constant, ranging from 240 to 280.-The soil samples were recovered using Shelby tubes (OD = 128 mm ID = 125 mm, area ratio 4.9%). Each tube was X-rayed, and no evidence of cracks or edge effects was found

A Norwegian Geotechnical Institute (NGI) type Simple Shear (SS) apparatus (Bjerrum and Landva, 1966) was used in this study. The cyclic SS setup provides a close simulation of vertically propagating horizontal shear waves while furnishing a simple configuration to apply Ko effective confining the soil element. The apparatus is fully automated and controlled by a computer unit. It consists of a pneumatic stress-controlled system capable of generating cyclic shear stresses. The test sample has a diameter of 71 mm and a height of 20 mm. It may be placed in a flexible membrane with lateral confinement provided by a stack of 31 circular Teflon-coated rigid aluminum rings, each 0.94 mm thick. A split mold surrounding the stacked rings, as well as the latex membrane, was used. Lubricant oil was applied between the stack rings to minimize friction. Vertical pressure is applied to the sample by the bottom platen, fixed in the horizontal direction but can move vertically. Both the upper and the lower platens have needles, 2 mm in height, to maintain good contact between the platens and the soil specimen.

Each series of tests is composed of a monotonic test and several cyclic tests. A monotonic constant volume simple shear (CVSS) test was carried out, following ASTM D 6528, to obtain τ_f, which was used to reference for the cyclic SS tests. The changes in σ_v are equivalent to the change in pore pressure that would be generated if the specimen was saturated while shearing in undrained conditions (Bjerrum and Landva, 1966; Dyvik et al., 1987). The shearing phase of the test was terminated at a maximum shear strain of 28%.

After the consolidation step, the specimens were subjected to stress-controlled, constant volume, undrained cyclic loading in the form of a sinusoidal wave at a frequency of 0.5 Hz. The tests were terminated at the end of 100 cycles of loading.

4 TEST RESULTS

In Series 1 and 2 of this investigation, the cyclic stress-strain-excess pore pressure behavior was studied for different cyclic shear stress amplitudes and two OCR values.

Figure 1 presents two typical normalized shear stress versus shear strain curves (tests MC1 and MC6) on samples of the SMC not subjected to cyclic loading with consolidation stress σ'_{vc} equal to 150 and 70 kPa, respectively. The horizontal shear stress τ_h shows a gradual rise to the peak. There is relatively slight decrease in τ_h until the shear strains become very large, exceeding about 28%.

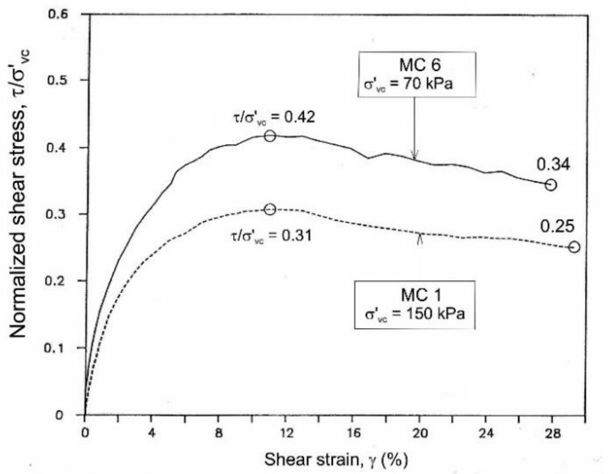


Figure 1 Normalized shear stress vs shear strain on Mexico City soil samples.

The soil specimen MC1 ($Series\ 1; OCR = 1$) was reconsolidated to an average effective consolidation stress $\sigma'_{vc} = 150\ kPa$ reaching a peak τ_f = 46.3 kPa $\left(\frac{\tau_f}{\sigma'_{vc}} = 0.31\right)$ at a shear strain γ of 10.9%. The soil specimen MC6 ($Series\ 2; OCR \cong 2$) was reconsolidated to an average effective consolidation stress $\sigma'_{vc} = 70\ kPa$ reaching a peak τ_f = 29.3 kPa $(\frac{\tau_f}{\sigma'_{vc}} = 0.42)$ at a shear strain γ of 10.8%.

4.1 *Cyclic behavior of Series 1*

A typical set of results obtained from tests on NC samples of the SMC with $\sigma'_{vc} = 150\ kPa$ and cyclic stress ratio $R_{cyc}(=\frac{\tau_{cyc}}{\tau_f})$ values ranging between 65% and 100% are shown in Table 1 and Figure 2.

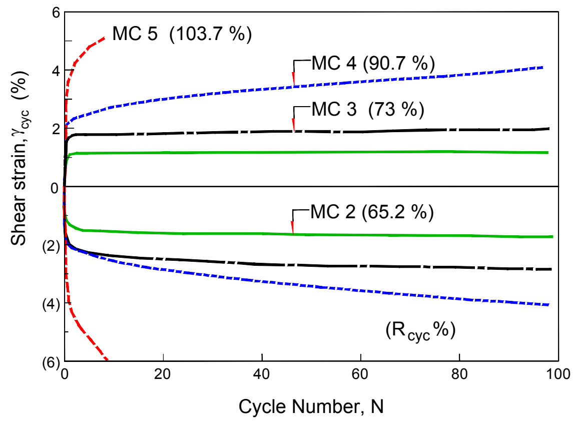
Figure 2 shows two plots: (a) envelopes of cyclic shear strain γ_{cyc} versus the number of cycles N; (b) envelops of normalized induced pore pressures $\Delta u/\sigma'_{vc}$ versus the number of cycles N, in which Δu is equal to the change in total vertical stress required to maintain a constant sample height (i.e. undrained conditions) during shearing. Results in Figure 2 show the following

1 Symmetric cyclic shear strains γ_{cyc} are developed as a result of the symmetric two-way cyclic loading (Figure 2a). For simplicity, only the envelopes of maximum and minimum shear strain versus N are shown. If R_{cyc} is smaller than 80%, the cyclic strains develop rapidly in the first two or three cycles and then reach stable shear strains with N (Tests MC2 and MC3), indicating a null degradation of stiffness.

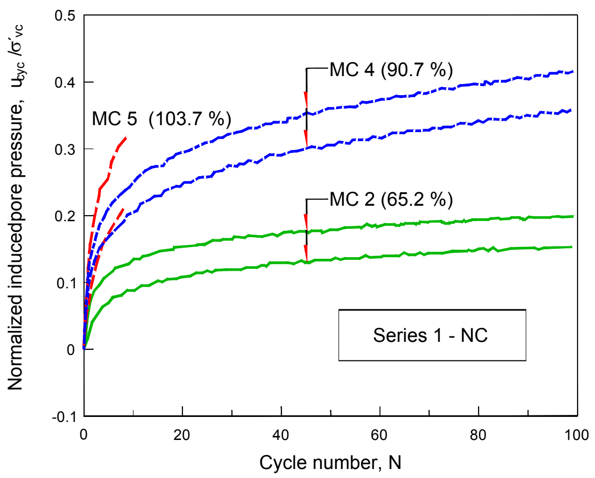
2 In tests with R_{cyc} values greater than about 80%, the cyclic shear strains increase with N (Test MC4). If $R_{cyc} > 1$, the strain accelerates and the sample fails in cyclic loading (Test MC5).

Table 1. Summary of undrained cyclic simple shear tests on Mexico City soil samples

Test	σ'$_v$	τ_{cyc}/τ_f	γ_{cyc}	u_{cyc}	u_{cyc}/σ'_v
No	kPa	%	%	kPa	
SERIES 1 (N C= 1)					
MC1	150	Monotonic test			
MC2	150	65	1.13	28.2	0.19
MC3	150	73	1.95	31.8	0.21
MC4	150	90	4	55	0.37
MC5	150	103	Failure		
SERIES 2 (OC≈ 2)					
MC6	70	Monotonic test			
MC7	70	64	1.81	13.3	0.19
MC8	70	77	2.48	17.42	0.25
MC9	70	80	3.41	17.5	0.25
MC10	70	84	4.84	18.9	0.27
MC11	70	95	6.88	26.3	0.37



a) Shear strain vs cycle number



b) Normalized excess pore pressure vs cycle number

Figure 2. Results from the undrained cyclic simple shear test on NC Mexico City soil samples

3 Positive excess pore pressure Δu develops rapidly in the first cycles (Figure 2b), with a nonzero average. For simplicity, only the envelopes of normalized maximum and minimum pore water pressure versus N are shown. It is interesting to note that the values of pore water pressure have been consistently positive even though the horizontal stress varies from positive to negative values.

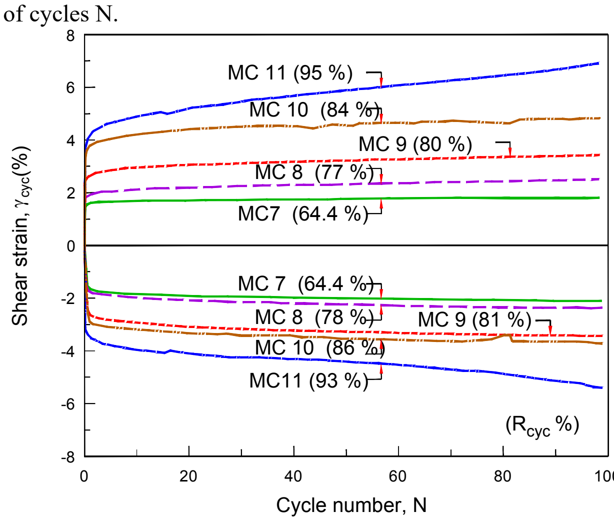
4 There is a cyclic component of excess pore pressure but remain constant with N.

5 A very sharp increase in cyclic pore water pressure followed by a modest build-up of pore pressure with N, indicating a gradual degradation of stiffness.

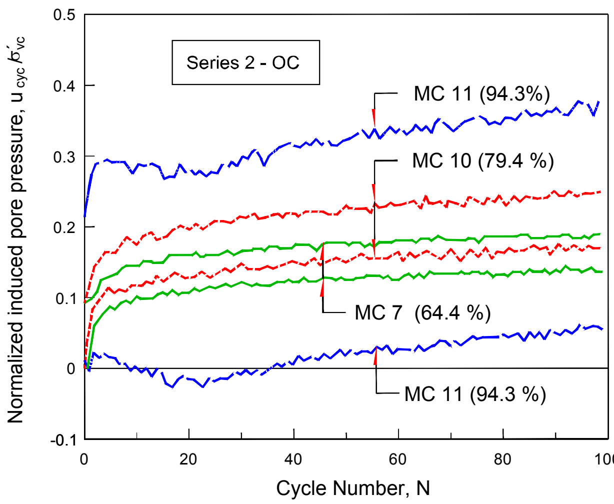
4.2 *Cyclic behavior of Series 2*

A typical set of results obtained from tests on OC samples ($OCR \cong 2$) of the SMC with $\sigma'_{vc} = 70\,kPa$ and R_{cyc} values ranging between 64 and 94% are shown in Table 1 and Figure 3.

Figure 3 shows two plots: (a) Envelopes of cyclic shear strainγ_{cyc} versus the number of cycles N; (b) Envelops of normalized excess pore pressures $\Delta u/\sigma'_{vc}$ versus the number of cycles N.



a) Shear strain vs cycle number



b) Normalized pore pressure vs cycle number

Figure 3. Results from the undrained cyclic simple shear test on OC Mexico City soil samples

Results in Figure 3 shows the following:

1. Symmetric cyclic shear strains γ_{cyc} are developed as a result of the symmetric two-way cyclic loading (Figure.

3a). For simplicity, only the envelopes of maximum and minimum shear strain versus N are shown. If R_{cyc} is smaller than 80%, the cyclic strains seem to become constant with N (Tests MC7, MC8, and MC9).

2. In tests with R_{cyc} values greater than about 80%, the cyclic shear strains increase with N (Test MC9 and MC10).
3. Positive excess pore pressure Δu develops rapidly in the first cycles (Figure 3b). For simplicity, only the envelopes of maximum and minimum pore water pressure versus N are shown. It is interesting to note that the values of pore water pressure were positive if R_{cyc} is smaller than 80%. For R_{cyc} values greater than about 80%, the pore water pressure increase out of proportion and reach negative values. The relationship between R_{cyc} and the development of pore water pressure appears to be quite complex. It is believed that during cyclic shearing, the breakage of particle bonds disturbs the equilibrium of clay structure, with the repulsive forces tending to increase the distances between particles and hence the volume of clay under constant volume conditions; this results in negative pore water pressure.

5 CONCLUDING REMARKS

The research's principal objective was to perform laboratory simple shear testing to provide insight into the seismic behavior of high-plasticity clayey soils and to analyze the degree to which cyclic behavior can explain the observed ground displacement in Mexico City. The results of this research confirmed some previously mentioned features.

Based on the data presented in this paper, the following conclusions may be drawn:

1. Under monotonic undrained shear stresses, the shear strain at peak is nearly constant for OCR = 1 and 2.
2. Results indicate low excess pore pressures under undrained shearing, both monotonic and cyclic.
3. The potential for strength loss and Mexico City soils' failure under cyclic loading depends on the applied cyclic stress ratio.
4. A stress threshold was confirmed: significant degradation of this diatomaceous soil only occurs once cyclic shear stresses exceed 80% of the static undrained strength.
5. There is a limited degradation in stiffness with the number of cycles if the applied cyclic stress ratio is lower than 80%.
6. The cyclic loading conditions may lower the foundation's undrained bearing capacity of clayey soils and produce sudden settlement phenomena observed in the field.

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7 REFERENCES

Andersen, K. H. (2009). Bearing capacity under cyclic loading – offshore, along the coast, and on land. The 21st Bjerrum Lecture presented in Oslo, 23 November 2007. *Canadian Geotechnical Journal*, 46 (5): 513-535.

Andersen, K. H. and Lauritzsen, R. (1988). Bearing capacity for foundations with cyclic loads. *Journal of Geotechnical Engineering*, ASCE Vol. 114 (5): 540-555.

Ansal, A. M. and Erken, A. (1989). Undrained behavior of clay under cyclic shear stresses. *Journal of Geotechnical Engineering*, ASCE Vol. 115 (7): 968-983.

Bjerrum, L. and Landva, A. (1966). Direct simple-shear test on Norwegian quick clay, *Géotechnique* 16 (1): 1-20.

Chu, D. B., Stewart, J. P., Boulanger, R. W. and Lin, P. S. (2008). Cyclic softening of low-plasticity clay and its effect on seis mic foundation performance. *Journal of Geotechnical and Geo environmental Engineering*, ASCE 134 (11): 1595-1608.

Díaz-Rodríguez, J. A. (1989). Behavior of Mexico City Clay subjected to undrained repeated loading, *Canadian Geotechnical Journal* 26 (1): 159-162.

Díaz-Rodríguez, J. A. (2003). Characterization and engineering properties of Mexico City lacustrine soils, in *Characterization and Engineering Properties of Natural Soils*, Balkema Publishers, Vol. 1, 725-755.

Diaz-Rodríguez, J. A. (2011). Diatomaceous soils: monotonic behavior. *International Symposium on Deformation Characteristics of Geomaterials*, Seoul, Korea.

Diaz-Rodríguez, J. A. (2019). Sudden soil subsidence in Mexico City due to strong ground motions. *Proceedings of the 7th Int ernational Conference on Earthquake Geotechnical Engineering* , Rome, Italy: 1903-1910.

Díaz-Rodríguez, J. A. and Santamarina, C. (2001). Mexico City soil behavior at different strains – Observations and physical interpretation. *Journal of Geotechnical and Geoenvironmental Engineering,* ASCE 127(9): 783-789.

Díaz-Rodríguez, J. A., and Santamarina, J. C. (1999). Thixotropy: The case of México City soils. *XI Panamerican Conference on Soil Mechanics and Geotechnical Engineering*, Brazil, Vol. 1, 441-448.

Díaz-Rodríguez, J. A., Leroueil, S. and Alemán, J. D. (1992). Yielding of Mexico City clay and other natural clays. *Journal of Geotechnical Engineering* ASCE 118 (7): 981-995.

Díaz-Rodríguez, J. A., Lozano-Santa Cruz, R., Dávila-Alcocer, V.M., Vallejo, E. and Girón, P. (1998). Physical, chemical and mineralogical properties of Mexico City sediments: a geotechnical perspective. *Canadian Geotechnical Journal*, 35 (4): 600-610.

Dyvik, R., Berre, T., Lacasse, S. ad Raadim, B. (1987). Comparison of truly undrained and constant volume direct simple shear tests, *Géotechnique* 37 (1): 3-10.

Polito, C. P. and Martin II, J. R. (2001). Effects of nonplastic fines on the liquefaction resistance of sands. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE 127 (5):408-415.

Silver, M. L. and Seed, H. B. (1971). Volume changes in sand during cyclic loading. *Journal of Soil Mechanics and Foundations Division,* ASCE 97 (9): 1171-1180.

Stewart, J. P. and Whang, D. H. (2003). Simplified procedure to estimate ground settlement from seismic compression in compacted soils. *2003 Pacific Conference on Earthquake Engineering*, Paper 046, 8 p.

Stewart, J. P., Smith, P. M., Whang, D. H. and Bray, J. D. (2004). Seismic compression of two compacted earth fills shaken by the 1994 Northridge earthquake. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE 130 (5):461-476.

Tokimatsu, K. and Seed, H. B. (1987). Evaluation of settlements in sands due to earthquake shaking. *Journal of Geotechnical Engineering*, ASCE 113 (8): 861-878