Cyclic behavior of diatomaceous soils

Comportement cyclique des sols avec des diatomées micro fossiles

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ABSTRACT
There are several sites in the world where diatom microfossils have been detected in the soil, these natural deposits have singular physical and mechanical properties. However, the specialized literature on the topic is very scarce. To evaluate the influence of microfossils on the cyclic response of clayey soils, this paper presents the experimental results of two series of cyclic simple shear tests using an artificially prepared mixture of kaolin and diatom microfossils (K+D). Tests were carried out on normally consolidated and overconsolidated samples. Based on the available literature and the obtained results, an attempt was made to explain the influence of diatom microfossils on the cyclic behavior of fine-grained soils.

RÉSUMÉ
Il y a plusieurs sites au monde où des diatomées micro fossiles ont été détectées, ces dépôts naturels ont des propriétés mécaniques et physiques très particulières, néanmoins, il n'y a pas assez de bibliographie spécialisée du thème. Afin d'évaluer les effets des micro fossiles au comportement cyclique des sols argileux, cet article montre les résultants expérimentaux de deux ensembles d'essais de cisaillement simple cyclique, utilisant un mélange artificiel préparé avec du kaolin et des diatomées micro fossiles (K+D). Les essais sont été réalisés avec des échantillons normalement consolidés et surconsolidés. D'après la bibliographie et les résultants obtenus, une tentative pour expliquer l'effet des diatomées micro fossiles au comportement cyclique de sols fines a été faite.

Keywords: Diatoms, microfossils, kaolin, mixtures, cyclic behavior, Mexico City soil.

1 INTRODUCTION

There are several sites in the world where diatom microfossils have been detected in natural marine and lacustrine soil deposits (e.g. Mexico City, Mexico; Osaka Bay, Japan; California, USA; seabed sediments in Antarctic, Pacific and Indian oceans). The natural soil deposits that contain diatom microfossils have singular physical and mechanical properties that do not follow the well established geotechnical relationships; however, the specialized literature that evaluates the influence of the microfossils on engineering properties is very scarce, and is focused to reflect the impact on index properties, compressibility and pseudo-static shear strength of these soils (Pittenger *et al.,* 1989; Rack and Palmer, 1992; Day, 1995; Tanaka and Locat, 1999; Shiwakoti *et al.* 2002). To examine the influence of microfossils content in monotonic and cyclic behavior of soil, this paper present the experimental results of two series of simple shear tests using an artificially prepared mixture of kaolin and diatom microfossils (K+D) at different proportions. Tests were carried out on normally consolidated and overconsolidated samples.

Diatoms are unicellular algae. Their cell wall is silicified to form a frustule, comprising two valves, one overlapping the other like the lid of a box. There are a great variety of forms, usually rod-like, spherical, or circular disks with a typical length or diameter of about 30 to 110 µm. The diatoms skeletons are symmetric in shape and contain a large proportion of voids, both inside individual skeletons and between them. Diatoms typically have rough surface features, such as protrusions or indentations. Diatoms live in almost all kinds of aquatic and semi-aquatic environments that are exposed to light and volcanic or tectonic activity that contributes with the nutrients and the environmental conditions for their reproduction. Diatoms remains may accumulate producing sedimentary deposits that are also know as diatomite.

2 EXPERIMENTAL PROGRAM

The experimental program followed in this investigation consisted of the elaboration of five mixtures: kaolin (K) was mixed with diatomite (D) in proportions of 100% kaolin (100K:D0), 80% kaolin (K80:D20), 60% kaolin (K60:D40), 40% kaolin (K40:D60), and 100% diatomite (K0:D100). All mixtures were done based on dry weight proportions.

2.1 *Materials used*

The kaolin and the diatomite used in this investigation are products commercially available in Mexico.

2.2 *Preparation of sample mixtures*

The dosage of mixtures was based in weight and homogenized in dry. The mixture was placed in a blender and the necessary distilled water was added so that the mixture had the consistency of the liquid limit. The mixture was placed layered in a cylindrical mold of 13 cm in diameter and 16 cm in height, its internal surface was covered with a hard wax paper which facilitates the subsequent extraction of the material. The cylindrical mold served as consolidation mold, for which two porous stones were placed, one in the superior part and the other in the inferior one, both protected with filter paper to avoid occluding the porous stones. The cylindrical mold with the mixture was placed in a consolidation frame and a vertical stress of 125 kPa was applied during 28 days. After the time of consolidation had elapsed it proceeded to extract the soil

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sample, the wax paper facilitated this operation and diminished disturbance effects on the sample.

2.3 *Simple Shear Testing*

The simple shear apparatus utilized was the NGI type (Bjerrum and Landva, 1966), the artificial mixtures were performed on samples with 70 mm in diameter and 20 mm in height, placed on a flexible membrane with lateral confinement provided by a stack of circular thin aluminum rings covered with Teflon. Vertical loads were applied to reproduce the consolidation stresses (σ'_{vo}) while the aluminum rings enforces a K_o condition. During cyclic loading of the specimens, no effort is made to insure soil saturation (i.e., no backpressure is applied); instead, the testing is performed by keeping the specimen height constant and, thereby, maintaining a constant volume (Finn and Vaid, 1977; Hsu and Vucetic, 2006).

During the simple shear test, pore pressures are not measured directly during shearing. They are inferred from the changes in vertical stresses that are needed to maintain a constant specimen height. All tests were performed with two-way sinusoidal, load-controlled cycles at a frequency of 0.5 Hz applied until the sample reached 100 loading cycles or a cyclic shear strain $\gamma = \pm 10\%$. Monotonic tests were run immediately after cyclic tests. Monotonic strain-controlled pre-cyclic and post-cyclic tests were performed at a rate of 1.5%/h.

Two series of undrained tests were conducted. Each tests series consisted of 5 pre-cyclic, 15 cyclic and 15 post-cyclic tests. For test series "A", each sample was consolidated to an effective vertical stress of 260 kPa (OC R = 1). For test series "B", each sample was first consolidated to a maximum effective vertical stress of 260 kPa and then unloaded to the final effective vertical consolidation stress of 130 kPa, thus inducing an overconsolidation ratio (OCR) of 2.

3 RESULTS AND DISCUSSION

3.1 *Pre-cyclic monotonic behavior*

Simple shear tests were carried out on the mixtures after consolidation. The stress-strain plot and undrained stress paths for OCR=1, are presented in Fig. 1a and 1b respectively. It can be seen from these figures that the stress-strain curves show different characteristic that depend on the diatomite content:

- The peak undrained shear strength (S_u) increases with the increase in diatomite content.
- The increase in resistance is evident for a diatomite content bigger than 20%.
- Strain to reach S_u increases with increase in diatomite content

In addition:

- The pore pressure decreases with increase in diatomite content.
- The stress paths show enhancement of their dilation characteristics.
- The friction angle increases with increases in diatomite content.

The same behavior was observed in samples with OCR = 2, which presented an average decrease on their peak undrained shear strengths of 20%.

Similar results were obtained by Shiwakoti *et al.* (2002) in kaolin-diatomite mixtures tested with constant volume direct shear conditions. However, comparing these results with the proposed friction angle - plastic index correlation for several natural soils (Laad and Foott, 1974), the K60:D40 and K40:D60 mixtures deviate from this tendency and come closer to data from Mexico City soils (Díaz-Rodríguez and Santamarina, 2001) (Fig.2). Therefore, the presence of diatom microfossils in this natural soil is partly responsible for its unusual high shear strength and friction angle.

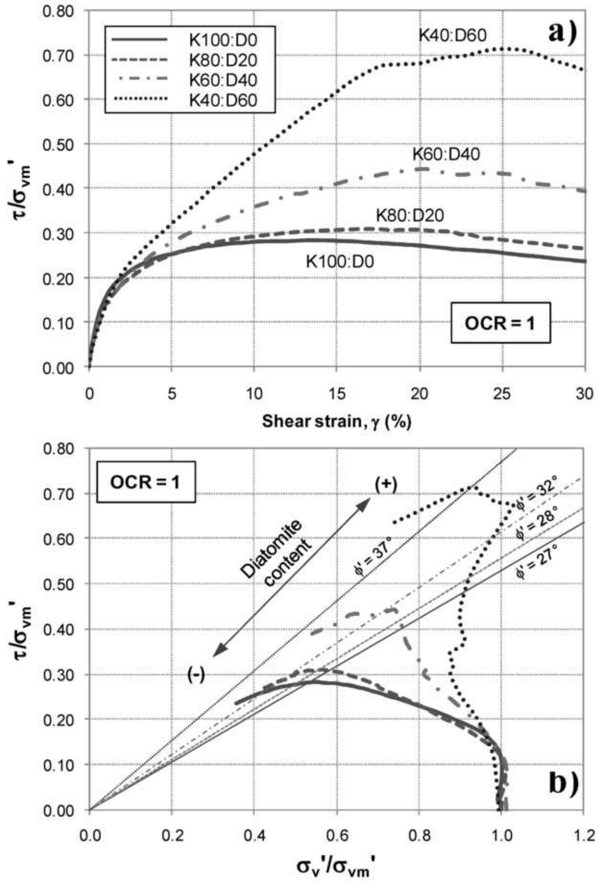

Fig. 1. Monotonic pre-cyclic behavior of samples with OCR = 1. **a)** Stress-strain curves **b)** Undrained stress paths.

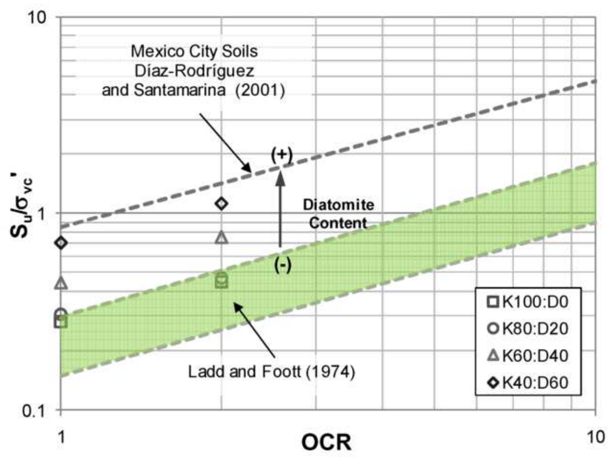

Fig. 2 Effect of OCR (σ_{vm}/σ_{vc}') in undrained shear strength normalized with respect to effective confining stress

3.2 *Behavior during simple shear cyclic loading*

3.2.1 *Samples with OCR = 1*

The development of maximum shear strain with loading cycles, under a stress ratio (τ_{cyc} /σ_{vm}') of 0.15 and diatomite content ranging from 0 to 100% is shown in Fig. 3a. The shear strain resistance first decreases with increasing diatomite content (i.e., K80:D20 mixture). As the diatomite content continues to increase, the shear strain resistance begins to increase (i.e., K40:D60 mixture). The K100:D0 and K0:D100 samples did not fail after 100 loading cycles and the shear strain was less than ± 2%.

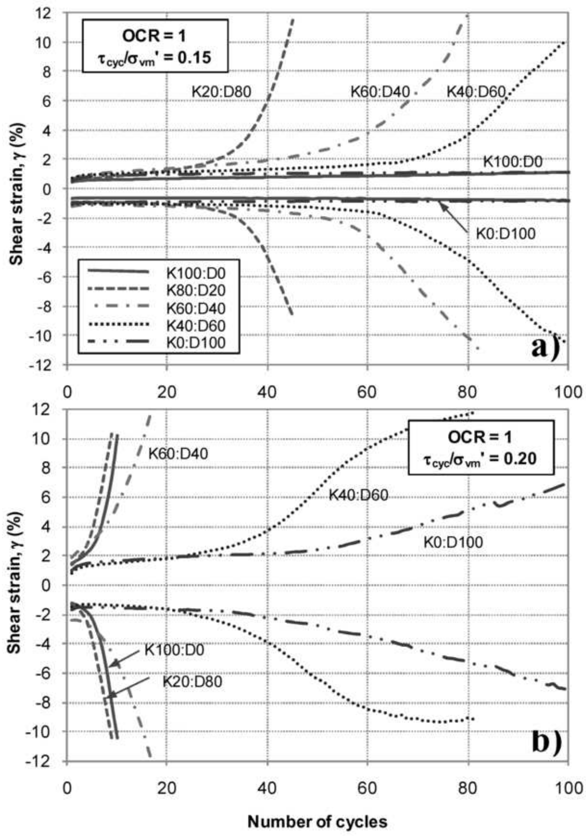

Fig. 3. Cyclic behavior of samples with OCR = 1 at different stress ratios **a)** τ_{cyc}/σ_{vm}' = 0.15 **b)** τ_{cyc}/σ_{vm}' = 0.15

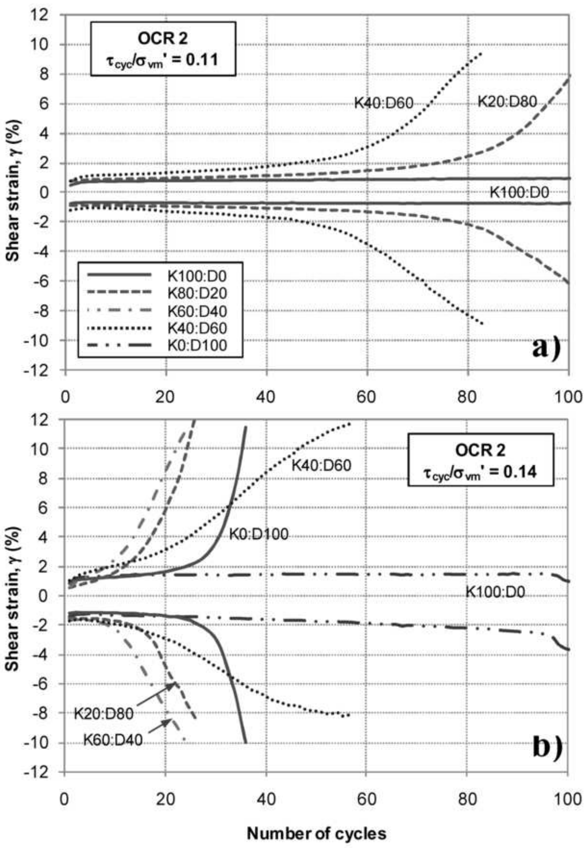

Fig. 4. Cyclic behavior of samples with OCR = 2 at different stress ratios **a)** τ_{cyc}/σ_{vm}' = 0.11 **b)** τ_{cyc}/σ_{vm}' = 0.14

Figure 3b shows the results for a higher stress ratio (τ_{cyc}/σ_{vm}') of 0.20 and diatomite content ranging from 0% to 100%. The general pattern is different. The K100:D0 sample is highly deformable and the K80:D20 sample presents less deformation resistance than the K100:D0. However, as the diatomite content increases the shear strain resistance increases considerably. The shape of the deformation pattern in K40:D60 sample, denote a change in the behavior for high levels of deformation ($\gamma > \pm 6\%$) where its cycle to cycle development tends to decay, however, the samples with smaller diatomite content shown in Fig. 4a (K80:D20 and K60:D40), exhibits a constant evolution of the last deformation cycles before reach $\gamma = \pm 10\%$.

3.2.2 Samples with OCR = 2

For OCR = 2 samples, the development of maximum shear strain with loading cycles is more sensitive to the stress ratio (τ_{cyc}/σ_{vm}) than samples with OCR = 1. Figure 4a shows the results for τ_{cyc}/σ_{vm} = 0.11 and diatomite content of 0%, 20% and 60%. It can be seen that the shear strain resistance decreases with increasing diatomite content.

For a little higher stress ratio (τ_{cyc}/σ_{vm}'= 0.14) the shear strain resistance is more complex, as is shown in Fig 4b. For the K80:D20 and K60:D40 samples the shear strain resistance decreases with increasing diatomite content. As the diatomite content continues to increase, the resistance is recovered and shows a maximum for the K0:D100 sample with shear strain around $\gamma = \pm 2\%$ after 100 loading cycles. The shape of the deformation pattern in the K40:D60 sample exhibits similar characteristics, in smaller proportion than the same mixture with an OCR =1 and stress ratio τ_{cyc}/σ_{vm}' = 0.20 (Fig 3b).

3.2.3 Contour diagrams

The development of shear strain versus number of cycles for any τ_{cyc}/σ_{vm}', can be plotted in contour diagrams of the type shown in Figs. 5 and 6. These contour diagrams are established from tests with constant cyclic shear stress and for a cyclic shear strain $\gamma = \pm 5\%$. Each test represents a horizontal section through the contours.

Samples with OCR = 1 (Fig. 5) exhibit that for any cyclic stress ratio, the strain resistance decreases for K80:D20 samples and the difference in resistance with K100:D0 samples increases as stress ratio decreases. As diatomite content and cyclic stress ratio increase the strain resistance increases considerably, nevertheless, for lower stress ratios this tendency is reverted and the resistance could be lower for higher diatomite contents.

For samples with OCR = 2 (Fig. 6) the strain resistance decrease as diatomite content increases for K80:D20 and K60:D40 samples along the whole scale of cyclic stress ratios applied, whereas in K40:D60 samples this decrement is exhibited only for the lower stress ratios applied. The increase in diatomite content produces an increase in the strain resistance especially for higher stress ratios.

3.3 *Post-cyclic monotonic behavior*

In case where failure does not occur it is often desirable to evaluate the effect of cyclic loading by determining the change in static strength of each specimen. According to Díaz-Rodriguez (1989) is possible to determine a degradation threshold defined as the cyclic stress ratio ($R = \tau_{cyc}/S_u$) that causes post-cyclic stress loss ($R_f = S_{uc}/S_u$) after 100 loading cycles. Figure 7 indicates with an arrow this stress threshold for each normally consolidated mixture. The stress threshold for K100:D0 samples is about 0.5 and as diatomite content increases the stress threshold decreases. The stress threshold for Mexico City soil is around 0.8.

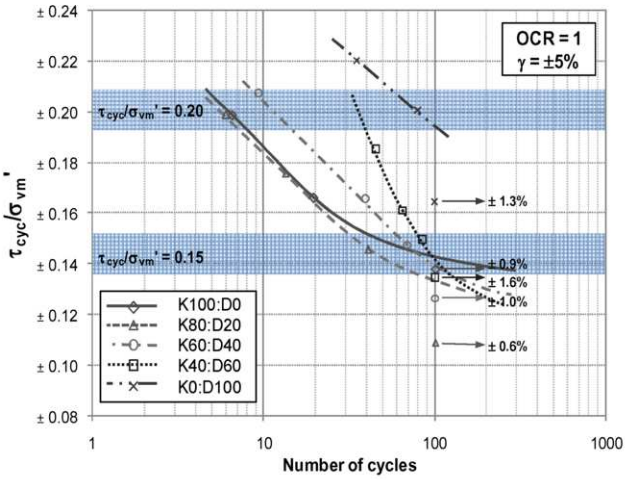

Fig. 5. Contour diagrams for samples with OCR = 2. Number of cycles to achieve $\gamma = \pm 5\%$ for any cyclic shear stress.

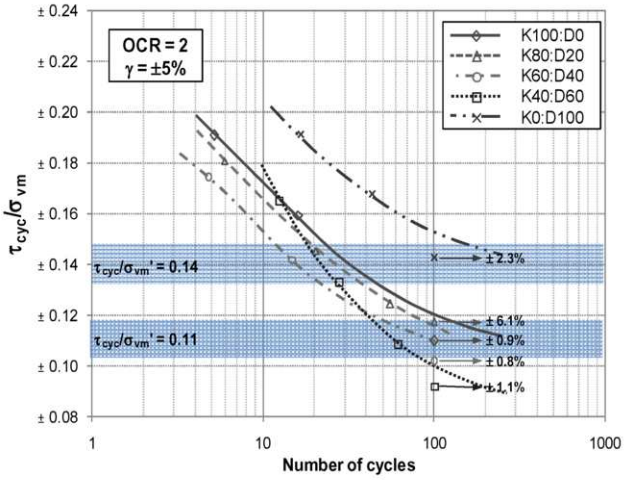

Fig. 6. Contour diagrams for samples with OCR = 2. Number of cycles to achieve $\gamma = \pm 5\%$ for any cyclic shear stress.

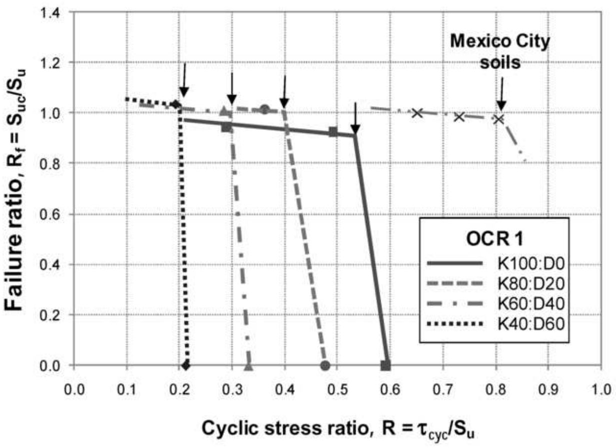

Fig. 7. Cyclic loading and residual undrained shear strength for samples with OCR = 1. Degradation threshold is indicated.

4 CONCLUSIONS

The cyclic behavior of artificial diatomaceous soils is complex and depends on several factors like diatomite content, shear stress ratio, shear strain of evaluation, and OCR.

- The strain resistance of normally consolidated samples decrease for lower diatomite contents, while increasing with diatomite contents larger than 20% and cyclic stress ratios higher than $\tau_{cyc}/\sigma_{vm}' > 0.14$.
- The strain resistance of overconsolidated samples decrease with increase in diatomite contents, while increasing with diatomite contents larger than 40% and cyclic stress ratios higher than $\tau_{cyc}/\sigma_{vm}' > 0.16$.

These results suggest that for high stress ratios, diatoms microfossils in the mixture control the cyclic behavior, whereas their rough surfaces and intricate geometry increase interlocking effects and consequently the strain resistance. On the other hand, at low stress ratios, the interaction between particles of kaolin and diatom microfossils may have a negative contribution, causing a decrease of the resistance. The contribution of diatoms is smaller for lower vertical effective stresses; with higher diatomite contents and stress ratios, the microfossils contribute to strain resistance. However this whole behavior may be affected if diatoms microfossils with different characteristics are used.

Finally, diatom content in Mexico City soils not explains their high degradation threshold.

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