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Dynamic properties of Mexico City clay for wide strain range

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ABSTRACT: An experimental study has been carried out by using resonant column technique in torsion and cyclic simple shear apparatus on undisturbed specimens sampled from Mexico City lacustrine zone. The purpose of this study was to obtain a better understanding of the factors influencing the shear modulus and damping of soft clays. The test parameters studied were confining pressure, effective vertical stress, shear strain amplitude and time effect.

1 INTRODUCTION

Mexico City clay (MCC) is an exceptional material since its water content often exceeds 500% and its plasticity index commonly exceeds 300%. In spite of very high water content, MCC exhibits a remarkable elastic behavior (Díaz-Rodríguez, 1988 and 1989).

It is generally recognized that local soil characteristics influence the ground response when seismic waves propagate through a soil profile. Then, the basic data needed to evaluate the earthquake response of a particular site are soil dynamic properties. Furthermore, the importance of assessing the variation of the G and λ with γ for Mexico City soft clays is directly associated with the values of the maximum ground motions that could be observed at the surface of those soils. Chávez (1987) has shown the impact on the seismic hazard estimated for Mexico City soft clays, of the maximum ground motions expected for those soils when subjected to subduction or interplate earthquakes.

Field techniques permit evaluation of dynamic properties at low shearing strains, thus, field data are no directly usable for modeling earthquake response at higher strain levels. Laboratory tests by resonant column and cyclic simple shear permit evaluation of shear moduli and damping ratio over a wide range of shearing strains and permit easy control of other test variables. However, dynamic properties evaluated from laboratory tests may not be entirely representative of in situ soil behavior since the internal structure of clays is disturbed during sampling. The purpose of this study was to obtain the dynamic properties of Mexico City clay from laboratory tests for wide strain range.

2 MATERIALS AND METHODS

The site from where the specimens were sampled is located to the south-east of Mexico City. All soil samples were obtained using Shelby tube. The average properties of the soil were as follows: liquid limit, 390%; plastic limit 80%, natural water content, 230%; specific gravity, 2.40; void ratio, 5.5. The effective overburden pressure, σ'_o, was about 88 kPa and the critical stress, σ'_b, was estimated near 132 kPa.

The dynamic properties for low strain were determined by the resonant-column method using a Drnevich Long-Tor Resonant Column Apparatus. Filter paper strips were used to help drainage. All tests were carried out using a back pressure of 100 kPa. Specimens of 3.3 cm in diameter and approximately 6.8 cm long were used. The consolidation pressure was maintained on the sample for approximately 20 hrs beyond primary consolidation. Taylor square-root-of-time- method was used to determined the completion of 100% primary consolidation during all tests.

The NGI simple shear apparatus which is described in detail by Bjerrum and Landva (1966) was used for estimating high strain dynamic properties of clays. A cylindrical sample (71.3 mm in diameter and 24 mm in height) was confined by means of reinforced rubber membrane with a spiral winding wire having a diameter of 0.15 mm and being wound at 25 turns per cm, that allows vertical deformations and horizontal displacements with little or no changes in diameter. At the top and bottom of the sample there are porous stones equipped with approximately 2 mm long needles in order to prevent sliding between the sample and the porous stones. The cyclic shear load was applied to the specimen by a double acting compressed air piston. The cyclic tests were stress controlled, run at a frequency of 0.5 Hz. A pneumatic loading piston provided a vertical or normal load. Consolidated constant-volume shear tests were performed by clamping the loading head in a fixed position (to maintain a constant sample height) after the effective vertical pressure was applied. The constant-volume test is equivalent to undrained test. The changes of applied vertical stress on the specimens are equivalent to the changes in pore water pressure; these changes would have occurred in the specimen if it has been prevented from draining for a condition of constant applied vertical stress.

3 TEST RESULTS AND DISCUSSIONS

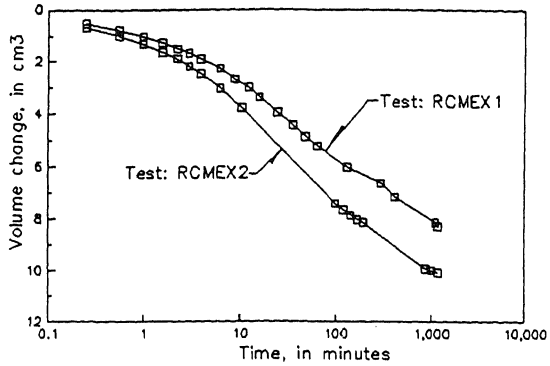
In the following sub-sections, results and discussions for the effects for various parameters on the shear modulus and the damping ratio will be dealt with.

3.1 The effect of consolidation time on the small strain modulus

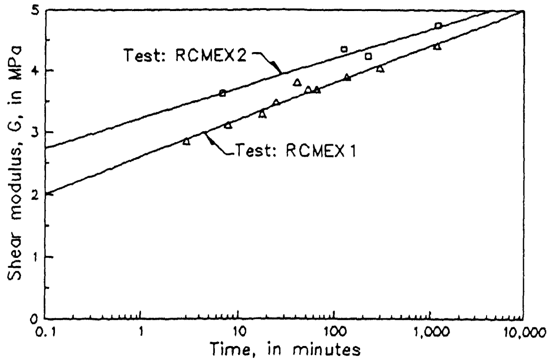
Several investigators (Hardin and Black, 1968; Marcuson and Wahls, 1972; Kokusho et al, 1982) have shown that time-dependency is a significant parameter affecting the dynamic properties of clays. The results of the investigations confirm that small strain dynamic shear moduli of clays increase with time of confinement under sustained pressures. Then, the small strain modulus defined as an average for the strain range of 8×10^{-5} to 2×10^{-4} was measured at appropriate time intervals during the consolidation stage. Graphs depicted in Fig. 1 show typical volume change and shear modulus against the logarithm of time t.

The volume change of the specimens indicated that the completions of the primary consolidation take place at about 80 minutes and after that the secondary consolidation follows. Those curves show the characteristics for low stress levels of recompression (overburden effective stress, σ'_o, less to the critical stress, σ'_b) which is referred to as type I (Zeevaert, 1986).

The variations of the small strain modulus are plotted against the logarithm of time. A consistent increase of shear modulus is evidently observed from Fig. 1. It can be approximated with a straight line on the semilogarithmic graph with no obvious kink at the completion of the primary consolidation. Results of this study suggest that, for low stress level of



a. Volume change vs duration of confinement

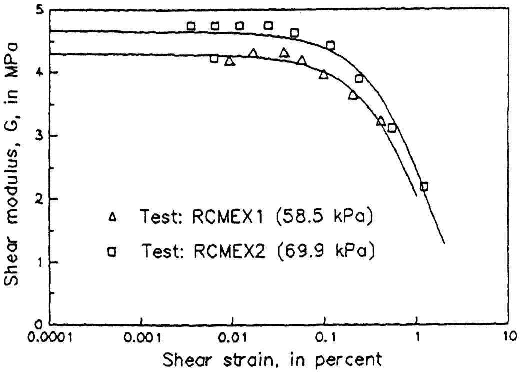


b. Shear modulus vs duration of confinement

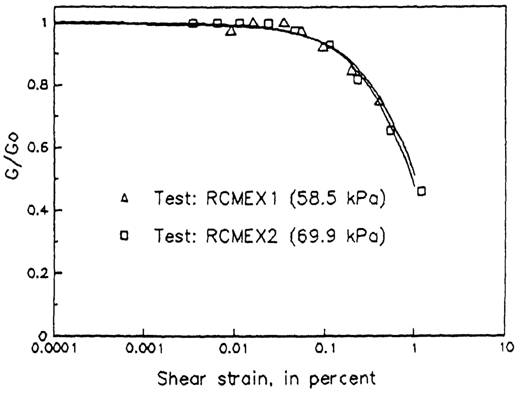
Figure 1. Typical volume change and shear modulus with consolidation time.

recompression, time-dependent change in shear modulus can not be separated into a period of primary behavior and a period of secondary behavior.

The effects of rate of time on modulus increase has been quantified by the ratio $N_G = \Delta G/G_{1000}$ (Anderson and Stokoe, 1978) in which ΔG is the increase in shear modulus per logarithmic cycle of time, and G_{1000} is the modulus measured 1000 minutes after the start of consolidation. The values of N_G for the tests shown in Fig. 1 range from about 11-13%. Clearly, time effects must be considered when conducting laboratory tests for shear modulus or when extrapolating for in-situ conditions.



a. Shear modulus vs shear strain



b. Normalized shear modulus

Figure 2. Shear modulus reduction curves.

3.2 Strain-dependent change of shear modulus

It is apparent that the modulus reduction curves for clays are highly variable and the rate of modulus reduction with shear strain, which is normally shown on a plot of G/G_o vs strain, where G_o is the low strain modulus for a shear strain of the order of 10^{-4} percent, seems to be related to mechanical properties of each particular clay.

Typical shear modulus reduction curves for MCC are shown in Fig. 2. The curves were obtained from a high amplitude test sequence in which the shear modulus was determined first at a low strain (about 0.008%) and then at progressively larger strains. The

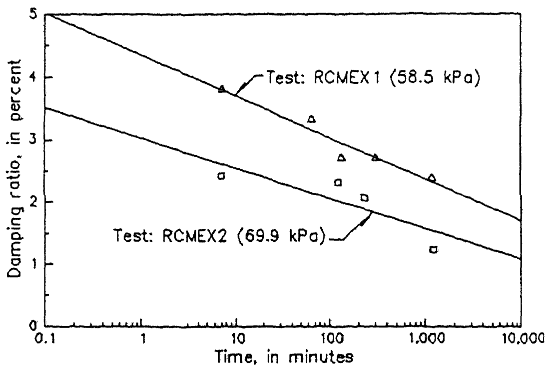


Figure 3. Damping ratio with consolidation time.

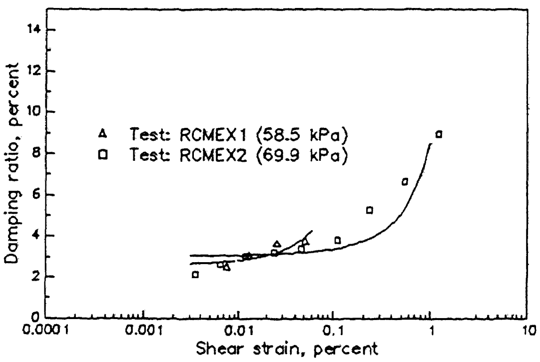


Figure 4. Strain dependent damping ratio.

shear modulus is approximately constant for strains less than 0.1%, suggesting linear elastic behavior in that range. For shear strains greater than 0.1%, the clay stiffness exhibits a large strain softening behavior.

If the limit between low and high strain behavior at which nonlinear behavior becomes important is arbitrarily defined as the value of γ_c for which $G/G_o = 0.80$, the Mexico City clay has the most linear stress-strain behavior among all clays, with $G/G_o = 0.8$ for strains up to $\gamma_c \approx 0.3\%$.

3.3 The effect of consolidation time and confining stress on the damping ratio

The variations of the damping ratio are plotted against the logarithm of time in Fig. 3. A consistent decrease of the damping ratio is evidently seen. It can be approximated with a straight line on the semilogarithmic graph with no obvious kink at the completion of primary consolidation. The decrease of the damping ratio with time indicates that the clay will exhibit much lower internal damping in situ than the value measured in laboratory. Apparently, the damping ratio shows a slight decrease as the confining stress increases.

3.4 The effect of confining pressure on high strain damping ratio

The variation of damping ratio for the wide strain range is shown in Fig. 4. In general, damping ratio of Mexico City clay increases continuously with increasing strain amplitude. A consistent dependency of the damping ratio on the confining stress could not be found. Mexico City clay has a low value of damping ratio $\lambda_{0.1\%} = 4$ to 5%. A comparison of curves for MCC obtained from this work and those reported for different clays was made. MCC curves were located slightly below the range of the other clays.

3.5 Comparison of resonant column and simple shear results

The stress-strain relationship during cyclic loading by using simple shear apparatus was established from a number of readings taken during some of the loading cycles.

The dynamic properties were calculated from the stress vs strain hysteresis loop for the first loading cycle based on the assumption that no volume change occurred during each cyclic loading. The first cycle was of special interest, as it provides information on the soil properties at the outset of cyclic loading before any cyclically-induced degradation has taken place.

The shear modulus and the damping ratio were calculated from the hysteresis loop. The dynamic shear modulus, G, is defined as a secant modulus between the end of the hystersis loop, i.e.

$$G = \frac{\sigma_{c,max} - \sigma_{c,min}}{\gamma_{c,max} - \gamma_{c,min}}$$

The equivalent damping ratio, λ, was calculated using the well-known expression

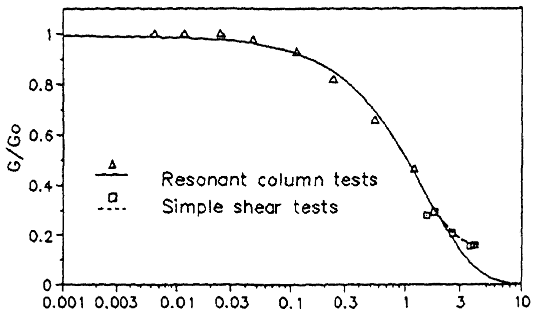
$$\lambda = \frac{1}{4\pi} \frac{\textit{Area of hysteresis loop}}{\textit{Area of triangle}}$$

Figs. 5a and 5b show the results of simple shear apparatus together with the results of resonant column for the normalized shear modulus and the damping ratio, respectively. An essentially good agreement of the modulus and damping ratio can be recognized in quantitative manner between the simple shear and resonant column test results. This means that the different stress and confining conditions inherent to the individual testing devices have no significant effect on the measurement of the dynamic properties of MCC.

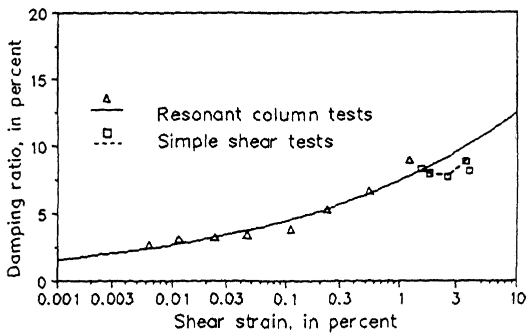
4 CONCLUSIONS

The results presented above support the following conclusions concerning the behavior of Mexico City clay tested under dynamic conditions. It is recognized that such conclusions are limited to the type of soil and particular conditions of this experimental work.

1. Mexico City clay exhibits atypical properties due to the complexity of its volcanic-lacustrine origin.
2. The threshold level for strain effect is near 0.1%. When the amplitude of motion is less than this level, shear modulus is independent of strain amplitude. A rapid decrease in shear modulus occurs when strain exceeds 0.1%.



a. Strain dependent normalized modulus



b. Strain dependent damping ratio

Figure 5. Strain dependent shear modulus and damping ratio

3. The shear modulus increases about linearly with the logarithm of time when the duration of confinement ranges between 5 and 1,000 minutes.
4. The damping ratio of clay decreases with the consolidation time, implying that the in situ clay will exhibit a smaller damping ratio compared to that measured in the laboratory.
5. Hence, time must always be considered when reporting and interpreting shear moduli and damping ratio for Mexico City clay data from laboratory tests.
6. The strain-dependent change of the modulus ratio, G/G_o is not sensitive to changes in the confining pressure.
7. An essentially good agreement of the shear modulus and damping ratio can be recognized in

quantitative manner between the simple shear and resonant column results. This means that the different stress and confining conditions inherent to the individual testing devices have no significant effect on the measurement of both parameters.

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