Laboratory Measurement of Compression and Shear Wave Velocities of Mexico City Clay with Piezoelectric Crystals

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SUMMARY:
This paper presents the results of measurement of compression and shear wave velocities performed on Mexico City Clay samples consolidated isotropically in an instrumented triaxial cell. Experimental results include the testing of a sample retrieved from a site within the former lake bed in Mexico City and a specimen reconstituted from slurry. The paper describes an experimental set-up developed specifically to the testing of very soft clays that allows measuring both compression and shear wave velocities. It also discusses the effect of the magnitude of applied stresses and consolidation path on compression wave and in shear wave velocity values. The effects of bonding and ageing are also discussed by comparing the results of both natural and reconstituted samples. Finally, the relevance of the experimental results in connection to seismic response analyses in the Mexico Basin is also pondered and assessed.

Keywords: Laboratory measurement, P & S waves, very soft clay

1. INTRODUCTION

The subsoil in Mexico City consists mainly of lake bed materials arranged in a generally well ordered succession of extremely soft clays, which are the product of the hydration and degradation of volcanic effusions, i.e. clastic materials transported to the lowlands from the upper parts of the basin by water currents or glaciers and directly from the volcanoes, by eolic action. These soils are geologically very young and the clays are notorious for their extremely high water content and compressibility and, correspondignly, for their very low shear strengths. Layers of coarser materials such as ashes and pumices, are also present, the product of volcanic eruptions that occurred during the Upper Pleistocene, as well as various forms of organic matter and microfossils.

The lakes in the Basin of Mexico were desiccated gradually starting in the 16th century and nowadays the lacustrine system is practically non-existent. Clayey materials in the former lake zone are presently undergoing regional subsidence caused by water extracted from locally drilled wells. Regional subsidence is the origin of many complex problems of interest for geotechnical engineers. Another source of major concern for engineers, given that the city is also located in a very active seismic region, is the huge capacity of these soils to amplify seismic motions.

Researchers have recognized for more than sixty years the need for carrying out investigations into the basic engineering properties of Mexico City Clays. The accumulated knowledge gained throughout this time now allows engineers in the city to face projects with an improved understanding of the consequences of building foundations or tunnels, or performing excavations in these materials. Still, there are many aspects of the behaviour of the lacustrine clays of Mexico City, of their properties and characteristcs, that require further research especially in regard to the dynamic properties of these materials.

In this paper we present some of the results of an ongoing research project in which seismic wave propagation velocities were measured using piezoelectric crystals attached to Mexico City Clay samples mounted on an instrumented triaxial cell. Techniques and procedures for measuring compression and shear wave velocities, V_p and V_s, with piezoelectric crystals are presently being used in many laboratories around the world. These techniques are based on identifying seismic wave arrivals and travel times with receiving crystals that capture wave signals generated at the opposite end of a soil sampel by another piezoelectric crystal. Details of the technique, its principles, advantages and limitations have been discussed previously (Arulnathan et al, 1998; Santamarina and Fam, 1997; Brignoli, et al, 1996; Jovicic et al, 1996, 1998; Viggiani and Atkinson, 1995; Valle-Molina, 2006).

2. MEASURING SYSTEM

The measuring system in this research uses zirconate-titanate crystals placed inside a triaxial cell at the base and top caps of soil specimens, as illustrated in Figure 1. Excitation signals are sine waves produced with a function generator that works within the 75 Hz to 800 kHz range. Signals from the emitting and the receptor crystals are recorded with an oscilloscope and stored digitally in a computer. Travel times are measured with the oscilloscope. The photograph in Figure 2 provides an overall view of the experimental set up.

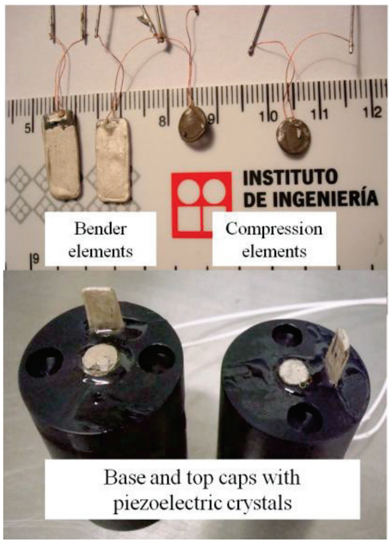

Figure1. Piezoelectric crystals for generating and recording seismic waves

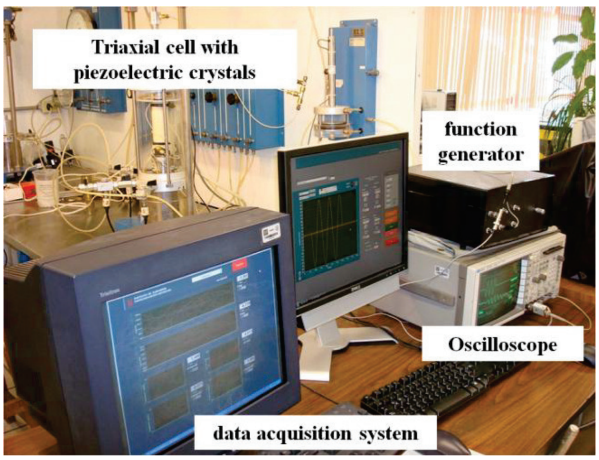

Figure2. General overview of the experimental set-up.

3. MATERIALS AND TESTING TECHNIQUES

Experimental results discussed in this paper were obtained from tests performed on two samples of Mexico City Clay. One of them (TX) was retrieved with a high quality thin wall sampler from a location in the northern part of Mexico City within the former Texcoco Lake and the other one (SCT) was reconstituted from slurry in the lab with materials sampled from a site in a densely urbanized zone. X-ray diffraction tests showed that both samples are very similar in terms of their mineralogical constituents (Valderrama, 2012). Index properties of both samples are also very similar as disclosed by the data shown in Table 1. Initial water contents indicated there refer to values of that parameter at the beginning of the isotropic loading tests discussed here.

The reconstituted sample was consolidated from slurry having water content of 450 %, equal to 1.5 times its liquid limit. The slurry was left to set in a 15 cm diameter oedometer and was later loaded up to 31.4 kPa. The sedimentation process took approximately 18 months after which the reconstituted soil was removed from the oedometer and stored under controlled temperature and humidity conditions. Cylindrical specimens could then be trimmed for testing in triaxial cells. Details of the reconstitution procedure and sample handling are given by Valderrama (2012).

Table1. Index properties of the samples tested

Sample	TX (natural)	SCT (reconstituted)
W_i, %	223	276
Liquid limit, %	310	301
Plastic limit, %	77	103
G_s	3.0	2.5

The samples were saturated before consolidation by increasing the total confining pressure and the applied back pressure in 50 kPa increments, keeping the applied effective isotropic stress at a value of 10kPa. V_p and V_s were measured with the piezoelectric crystals after each total stress increment, as well as Skempton's B parameter. Ordinates in the graphs of Figures 3 and 4 are values of V_p and V_s determined during the saturation stage, plotted in terms of the parameter B.

After achieving full saturation (B≥0.98), both samples were then consolidated isotropically; V_p and V_s were measured again after each effective stress increment.

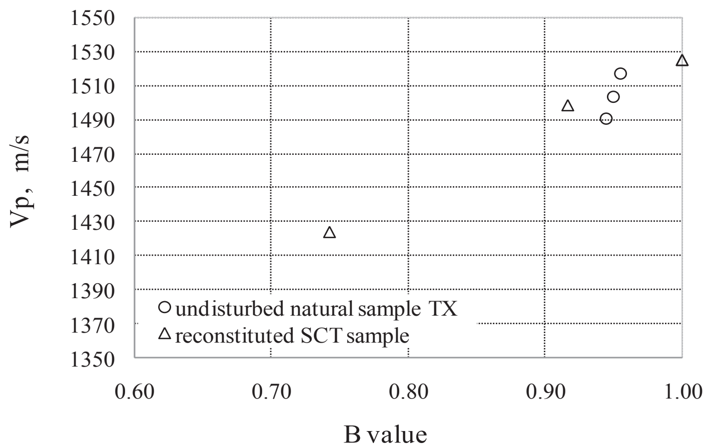

Figure 3. Values of compression wave velocities plotted against Skempton's B parameter during saturation.

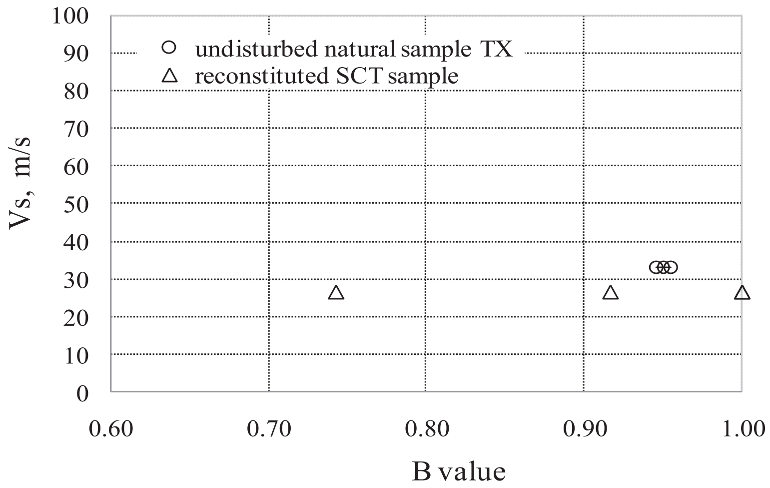

Figure 4. Values of shear wave velocities plotted against Skempton's B parameter during saturation.

4. ISOTROPIC COMPRESSIBILITY

The graph in Figure 5 shows the isotropic compressibility curve of the sample retrieved from the Texcoco site. As seen there, the sample was consolidated in 35 kPa steps up to 100 kPa; the sample was then unloaded down to 23 kPa and reloaded to 120 kPa. Two unloading-reloading cycles were applied (paths 2-3-2 and 4-5-6).

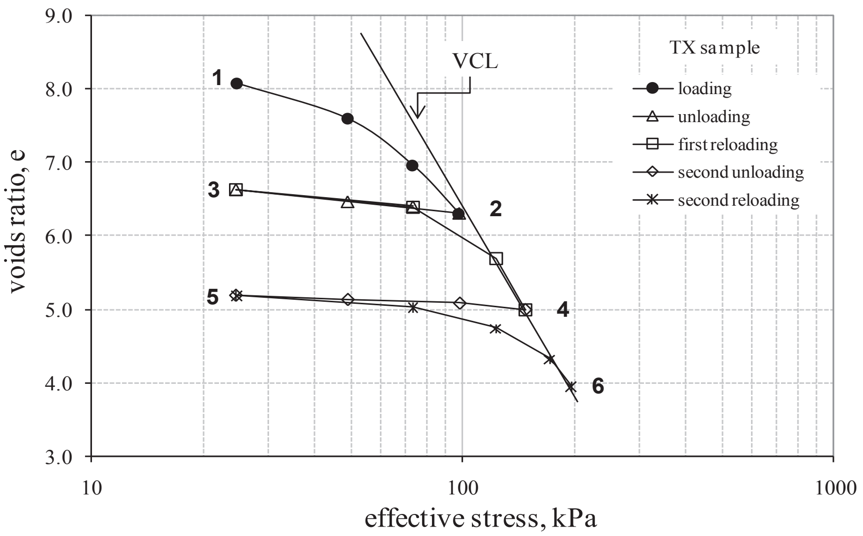

Figure 5. Isotropic compressibility curve for the TX natural sample.

The isotropic compressibility curve for the reconstituted SCT sample is shown in Figure 6. The specimen followed the reloading path indicated in the figure (under-consolidation stage, points 1 to 2) and yielded initially at about 25 kPa; the path defined by points 2 to 4 is called here the under consolidation line UCCL. The sample displayed another yield point upon reaching the virgin consolidation line (points 4 to 6). Two unloading-reloading cycles were applied (paths 2-3-2 and 4-5-6).

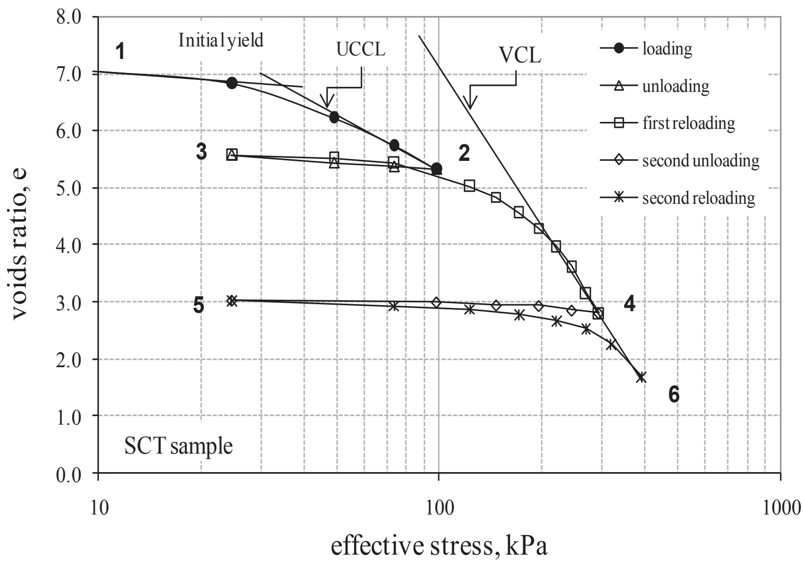

Figure 6. Isotropic compressibility curve for the reconstituted SCT sample.

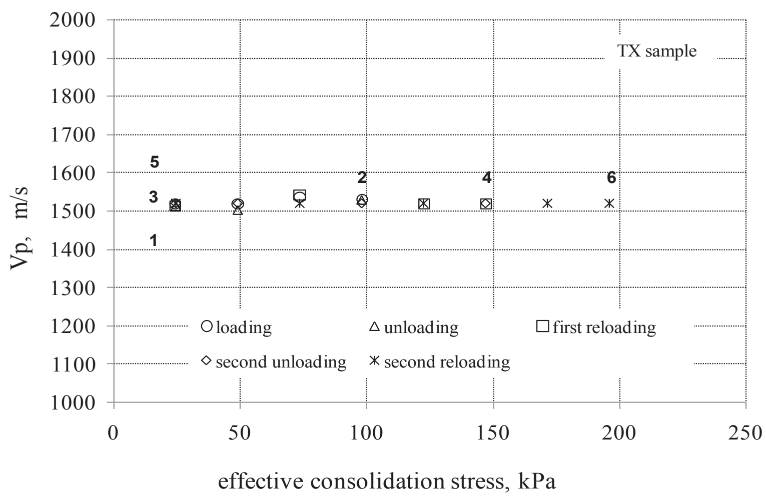

Figure 7. Compression wave velocities measured during isotropic loading of the natural TX sample.

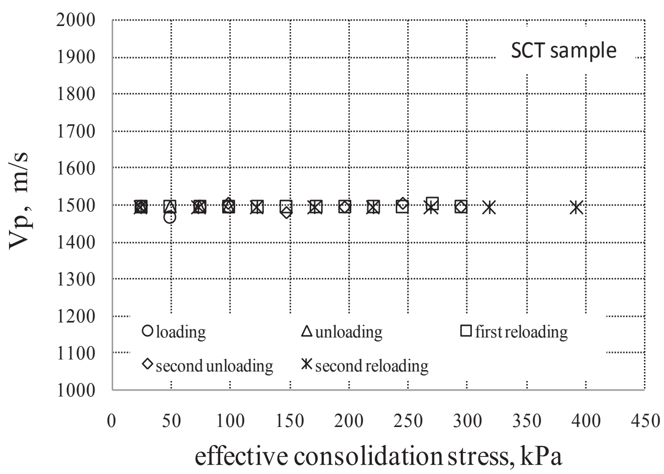

Figure 8. Compression wave velocities measured during isotropic loading of the reconstituted SCT sample.

5. SEISMIC WAVE VELOCITIES

As expected, compression wave velocities measured on both samples during subsequent isotropic loading, unloading and reloading are constant and equal to about 1550 m/s indicating that the two of them are fully saturated (Figures 7 and 8).

Shear wave velocities measured after each stress increment are shown in Figures 9 and 10 for the natural sample, TX, and the reconstituted SCT sample, respectively. Results in Figure 9 show that shear wave velocities measured in the natural TX sample are linearly related to effective stress. Velocities measured along reloading-unloading branches (points 2-3-2 or 4-5-4 to in Figure 9) align along two well-defined straight lines whereas the velocities measured along the VCL follow another linear trend (points 1-2-4-6).

The reconstituted SCT sample underwent two unloading-reloading cycles and the shear wave velocities measured along them were also related linearly to effective stress (points 2-3-2 and 4-5-4 in Figure 10). V_s values determined during initial loading along the UCCL (points 1-2, Figure 10) and afterwards, along the VCL (points 2-4-6) follow the same linear relationship with effective stress, notwithstanding the fact that the sample went past an initial yield.

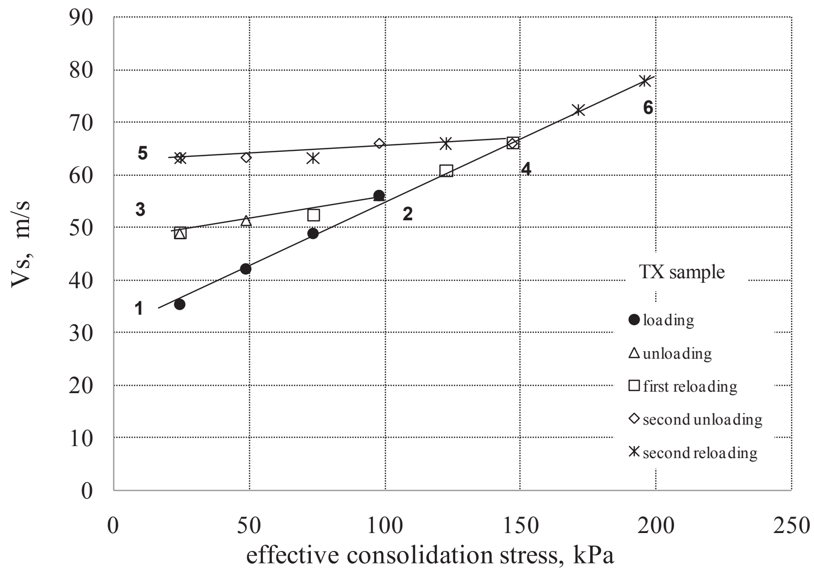

Figure 9. Shear wave velocities in the TX sample as a function of effective consolidation stress

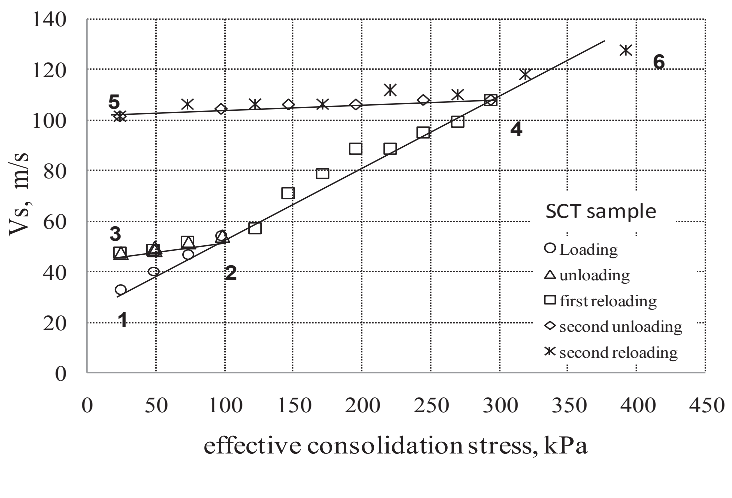

Figure 10. Shear wave velocities in the SCTsample as a function of effective consolidation stress

It is a well known fact that, having measured V_p and V_s, Poisson's ratio can be obtained from

$$\frac{V_p}{V_s} = \sqrt{\frac{2(1-\upsilon)}{(1-2\upsilon)}} \tag{1}$$

Values of υ obtained from the measurements discussed here are very close to 0.5, which confirms the fact that the saturation ratios are high and/or very close to 100% and that the process is occurring under constant volume (Bishop and Hight, 1977).

7. SHEAR MODULI

Stiffness moduli were derived from the well known elastic relationship:

$$G=\rho V_s^2 \tag{2}$$

where G is the stiffness modulus and ρ is mass density. Stiffness moduli were normalized by an equivalent pressure, p'_e defined as the effective stress corresponding to a given voids ratio along the VCL. Normalizing soil parameters and soil behaviour with this parameter has been used extensively in the past (e.g., Wood, 1990).

Normalized stiffness moduli, G/p'_e plotted against $p'/p'e$ are shown in Figure 9 for both samples. For normally consolidated states, p'/p'_e =1.0 and , p'/p'_e >1 corresponds to overconsolidated states. For overconsolidated states, the relationship between G/p'_e and p'/p'_e is not unique:

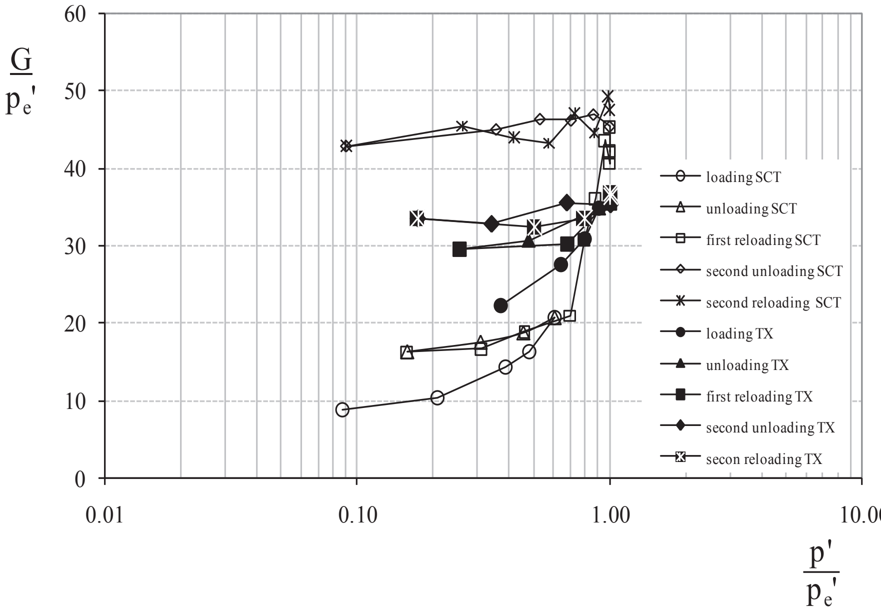

Figure 11. Normalized shear moduli plotted against $p'/p'e$ for samples TX and SCT

On the other hand, results presented in that figure show that G/p'_e is approximately the same for the two samples in normally consolidated states and equal to 55 on average which is the slope of the linear trend, G versus p', shown in Figure 10. The graph was produced using data from tests on both the natural TX and the reconstituted SCT samples.

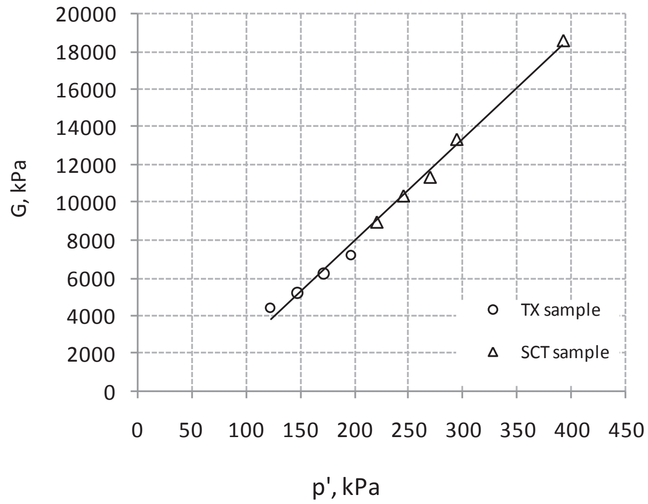

Figure 12. Shear moduli as a function of p' for normally consolidated states, both samples.

8. CONCLUSIONS

This paper described an experimental set up with which both compression and shear wave velocities can be measured with piezoelectric crystals in soil samples inside a triaxial cell.

Reference was made to experimental results obtained from tests performed on an undisturbed sample retrieved with a high quality sampler from a site within the former lake bed in Mexico City and on a specimen reconstituted from slurry, with material obtained from another site within the same basin.

In terms of index properties, both samples were very similar but were obviously very different in regard to stress history, ageing, time-dependent bonding effects, etc. The isotropic compressibility curve obtained when testing the reconstituted sample displayed an initial yield point and, upon the application of additional stresses, it yielded again and it eventually reached its virgin consolidation line. These features were not present in the clay sample retrieved with good quality samplers.

Shear wave velocities measured after each isotropic load increment were found to be related linearly to effective stress. It was found that the linear relationship between V_s and p' is not unique: a different linear relationship was found for each isotropic unloading-reloading cycle. Differences apparently become smaller after the first cycle, a condition that will be looked at in more detail in future studies.

On the contrary, a unique linear relationship between shear wave velocity and effective stress was found for the natural and the reconstituted samples. This is a finding that needs further investigation.

The same conclusions can be drawn when looking at the results in terms of normalized stiffness moduli and normalized stress. The relationship between G/p'_e and p'/p'_e is not for overconsolidated states, it varies in each unloading-reloading cycle in each of the two samples tested. For both the natural and the reconstituted sample, at normally consolidated states it was found that $G \approx 55p'$.

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