Dynamic Behavior of Naturally Desiccated Clays via Resonant Column Testing at Constant Water Content Conditions

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Abstract

The surficial soil at a western region of Bogota (Colombia) is a sedimentary deposit of high compressibility lacustrine clays with lens of sand and peat and overconsolidation ratios (OCR) from 1 to 9 due to desiccation processes. This geomaterial is subjected to matric suctions up to 800 kPa that generate cracks above the groundwater level, in the vadose zone. Small-strain dynamic properties such as shear modulus, material damping, and shear wave velocity are key parameters for an adequate analysis and design of geotechnical structures like shallow foundations or pavements in this particularly condition. In order to characterize the dynamic behavior and its relationship with initial state and confinement level, fixed free resonant column tests at constant water content were performed in specimens of those desiccated, stiff, and overconsolidated materials. It was found that the influence of suction and confinement stress in shear modulus and damping ratio is more pronounced in lightly overconsolidated materials for similar water contents before the air entry value (AEV). Nonetheless, after the AEV, the stiffness response and the shear wave velocity take similar values in an independent way of the initial state. In highly overconsolidated conditions, the overall dynamic response is fairly similar before and after the AEV, despite the stress history.

1. INTRODUCTION

In the northwestern zone of Bogotá D.C. (Cundinamarca, Colombia, see Figure 1), sedimentary lacustrine clayey deposits of 400 m deep are subjected to drying-wetting cycles, originated by natural and anthropic processes in the last 100 years (Pineda & Colmenares, 2007). These deposits appear as overconsolidated stiff soils from the horizontal ground surface to depths between 6.0 m and 8.0 m. From this point, the soils become normally consolidated, then, soft and very soft. Near the surface, in the active zone of moisture variations, extremely volumetric changes take place, principally in drying paths, due to factors such as: foreign vegetation, deepening of the ground water table by well extraction and the prevalence of a microclimate with a negative water balance per year (Pineda & Colmenares, 2007; Rueda & Pineda, 2011). As a consequence of the loss of moisture and the decrease in volume, the soil mass loses its continuity. The formation of vertical drying cracks is caused by the complex relationships with the increase of matric suction The effects of the loss of continuity of the surficial clayey mass can be seen in the stability of pavement roads and other light structures such as one-store buildings with foundations supported on soil columns, which do not have the required capacity to support the service loads from the surface (Vesga, Caicedo, & Mesa, 2003)

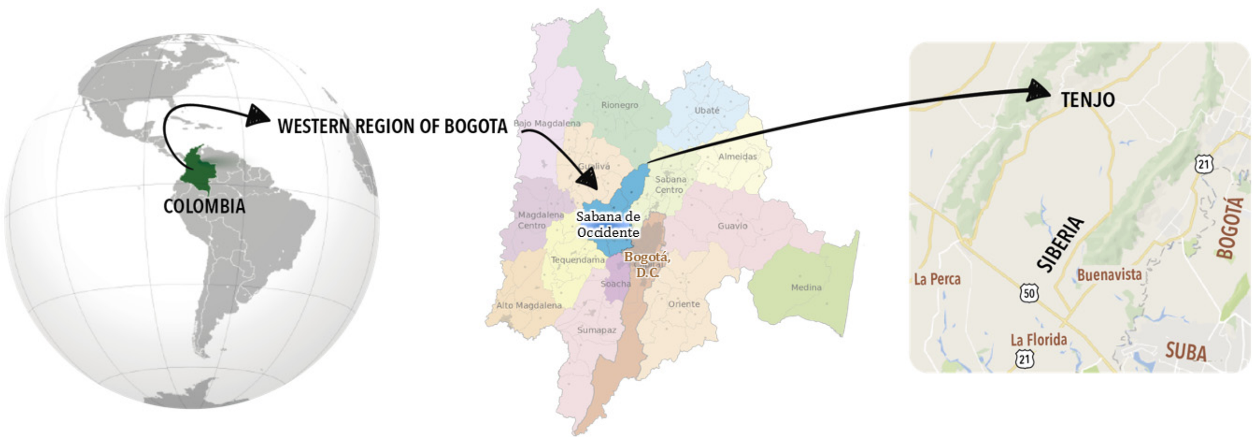

Figure 1. Location of study area (West *Sabana de Bogotá*, Siberia – Tenjo road).

In this context, the soil-water relationships of surficial clays were studied by several authors (Pineda, Arias, García, & Colmenares, 2015; Rueda & Pineda, 2011); who showed that most of the volumetric contraction/expansion in drying-wetting cycles occurs before the Air Entry Value (AEV), for saturation degrees between 85% and 100%. The change of volume after that limit state is less significant. Although the contraction phenomena in drying paths of these clays is a fairly well understood phenomena, the consequences of the increase in matric suction on the dynamic response (such us small-strain shear modulus – G; damping ratio – D, among others) of these naturally overconsolidated soils are not well studied. The dynamic properties and their relationships with matric suction-moisture equilibrium states have a significant importance in the analysis of many geotechnical problems in the particular conditions mentioned above, especially when the effect of transient loads on the stability of the cracked medium needs to be analyzed.

In previous works, Vardanega (2013) presented the results of the dynamic analysis of 21 clays, using the resonant column apparatus to date the stiffness at small strains and damping relationships with a mathematical formulation. A very good adjustment of the (G/G_{max}) curves was found, where 90% of the data was within a 30% margin, except for London Clay, since they determined that the influence of microcracks in these samples could lead to atypical values in the dynamic properties. All data were collected in saturated samples. Yang & Richard (2015) determined the dynamic response of cemented clays (kaolinite, bentonite and an equal mixture of kaolinite and bentonite - cemented with Portland cement type III and gypsum) using ultrasonic transducers, bender elements, and resonant column testing. A simple model useful for performing analysis of earthquake response, improved by cementation in partially saturated conditions, was proposed. They found that microstructure plays an important role in the dynamic response of naturally cemented clays, in congruence with other similar findings in structured soils (Pineda, Colmenares, & Hoyos, 2014). This article presents the initial results of an experimental investigation, in which the dynamic response of lacustrine clays was stablished using a “constant water content” condition in the tests, in order to date the effects of drying and matric suction development in the small-strain behavior.

2. MATERIALS AND METHODS

2.1. RESONANT COLUMN APPARATUS

The tests were performed on a resonant column GCTS - TSH-100 model (see Figure 2), which allows the evaluation of dynamic parameters such as shear modulus, resonant frequency, shear deformation and damping, in a measurement range from very small shear strains (10^{-4} %) to large strains (10^{-1} %).

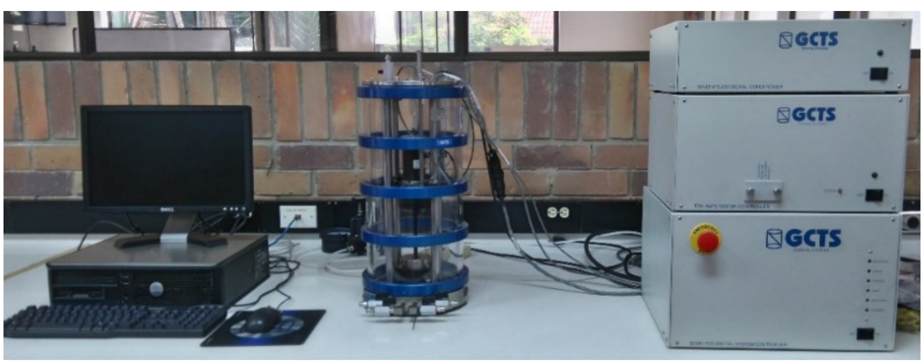

Figure 2. Resonant column apparatus (Universidad Santo Tomás, Bogotá - Colombia).

The equipment includes an LVDT - DC (Linear Variable Differential Transformer - Direct Current), shown in Figure 3. This element has a sensor with a measuring range of ± 6 mm, which allows to measure the vertical changes of the sample, and a laser proximitor, shown in Figure 4, that measures the angle of rotation of the upper part of the sample in contact with the motor applying the torque. During the test no pore pressure measurements were made.

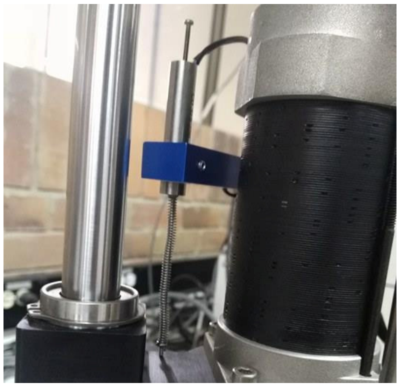

Figure 3. LVDT.

Figure 4. Laser proximitor.

2.2. SAMPLE DESCRIPTION

The studied material is a clay extracted from the quaternary “Sabana Formation”, which consists mainly of lacustrine sediments with thicknesses from 200 meters to 400 meters (González, Forero, & Rangel, 2002) and even there are places where thicknesses can reach more than 400 meters. At different depths, there are layers of peat and sand lens.

The clays used in the tests were extracted using a thin-walled sampler, in order to obtain high quality samples. The first sample, named M1, was extracted from 5.85 meters depth and corresponds to a high compressibility clay (CH), according to USCS, with a void ratio of 2.82 and an initial gravimetric water content of 104.41%. However, the tests were performed with different moisture states w (%) and saturation degrees S (%), as shown in Table 1, according to the soil water relationships mentioned later in numeral 3. These states were reached by subjecting the cylindrical samples to an unconfined drying path, in a controlled environment with a relative humidity of 82% and a temperature of 18°C. The samples had an average diameter of 38 mm and 76 mm in height. Figure 5 shows a typical configuration of a sample and the detail of the base pedestal of the RC apparatus.

Table 1. Description of samples.

Nomenclature	*w* (%)	*S* (%)	Description	Sample	%<75 µm	Depth (m)	LL (%)	PL (%)	PI (%)	USCS
M1-1	104,41	100,00	Natural water content	Gray Clay	95	5,85	176,23	51,80	124,43	CH
M1-2	95,56	96,91	Point before the AEV							
M1-3	67,25	80,53	Point after the AEV							
M2-1	114,23	99,60	Natural water content	Brown Clay	96	9,85	174,50	51,14	123,36	CH
M2-2	83,21	98,08	Point before the AEV							
M2-3	56,21	96,66	Point after the AEV							

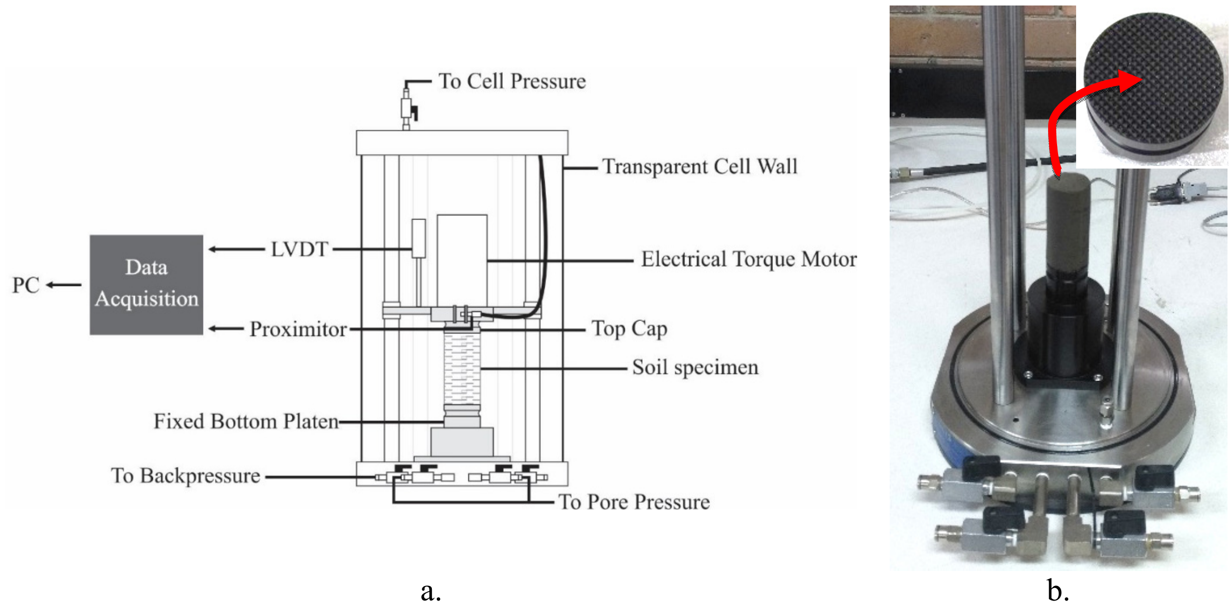

Figure 5. Resonant column system a) General layout of the resonant column and b) sample on the pedestal of the RC, and a detail of the top cap.

3. WATER RETENTION PROPERTIES

To obtain the Soil Water Retention Curve (SWRC) in drying, matric suction measurements were carried out on samples, using the filter paper technique (Whatman # 42), in which the sensor remains in contact with the specimen.

The adjustment of the experimental data of M1 and M2 in the SWRC was made with the model proposed by Fredlund & Xing (1994). For the adjustment, it was necessary to take into account the Air Entry Value (AEV) of the specimens. Figure 6(C) shows that the AEV of M1 is 1600 kPa, and its desaturation degree is 95%, and in M2 the AEV is 3200 kPa, and the saturation value at this point is 98%. Additionally, the data related with the stress history of the profile obtained by Pineda *et al*. (2015) is shown in Figure 6 (a), (b). The clays from the surface up to 6 m depth appear as overconsolidated, with OCR between 2 and 9, while samples varying from 6 to 8 m and greater depths have values of OCR from 1 to 2. In Figure 6 (c), the AEV increases in depth, while the initial void ratio has an opposite trend. Then, the depth does not turn out to be a factor that determines the reduction of the voids due to the effect of the drying.

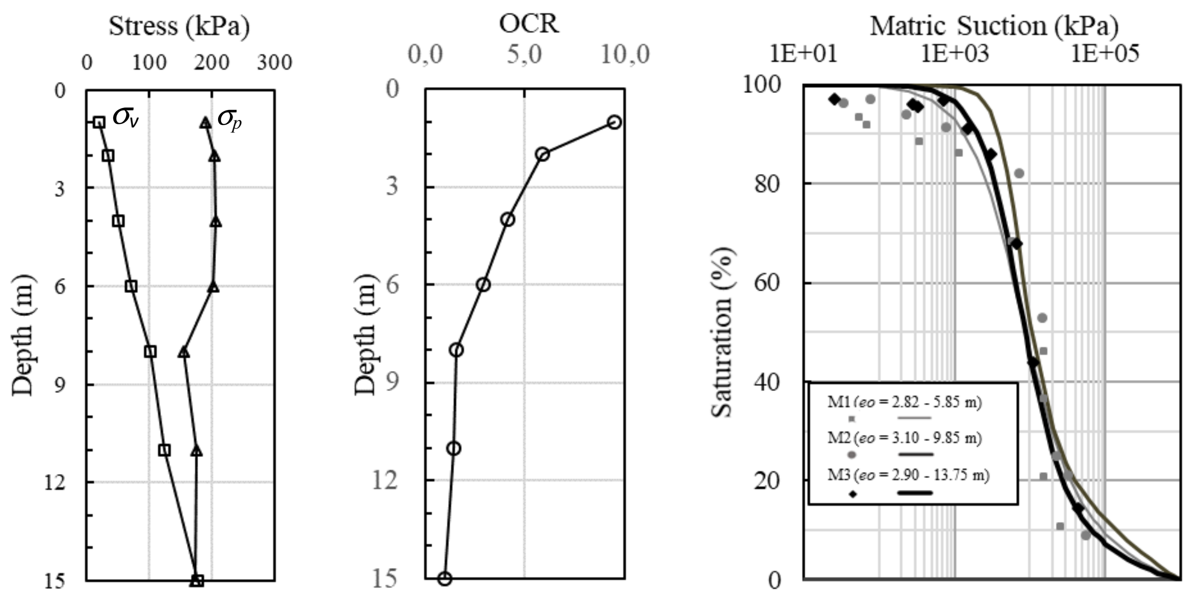

Figure 6. (a.) Vertical effective and preconsolidation stress with depth, (b.) over consolidation ratio with depth and (c.) soil water retention curve SWRC.

4. RC CONSTANT WATER CONTENT TESTS.

As previously mentioned, samples were subjected to a controlled drying process, in order to reach a known degree of saturation and matric suction values, starting from the previous development of the SWRC of each material. After obtaining the desired value of the degree of saturation, the samples were stored for seven days in order to stabilize their water content to finally perform the resonant column test. To quantify the loss of moisture during the dynamic test, loading and unloading isotropic cell pressure probes were performed on a sample of clay with similar characteristics to the specimens tested. The sample was subjected to increments in confinement of 100 kPa from 0 kPa to 400 kPa, measuring in each increment the mass change of the sample. An average of mass loss was 0.13 g in each interval, implying a decrease in water content of the order of 0.19%. According to the described procedure, the tests can be considered at constant water content.

5. RESULTS AND DISCUSSION

Figure 7, shows the variation of the maximum shear modulus *(G_{max})* against the normal mean confining pressure *p* (in kPa). It is possible to observe that the module in all cases increases as the confinement increases, which is due to the stiffening of the specimens.

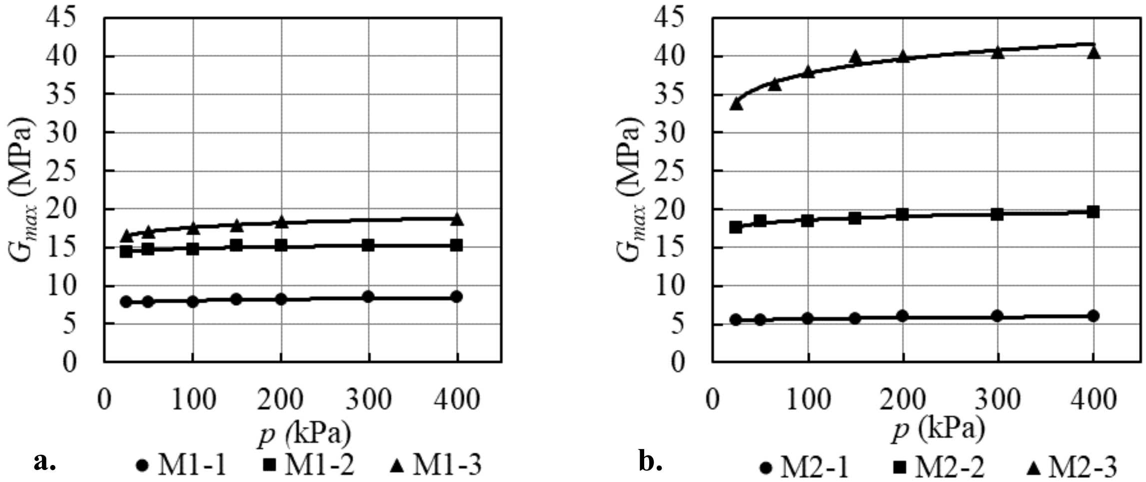

Figure 7. Variation of shear modulus G_{max} (MPa) with confining pressure p (kPa) for (a.) M1, (b.) M2 and (c.) M1 and M2 to natural water content.

Now, the function of the G_{max} curves (MPa) against p (kPa) is given below in which the parameters A and B are the best-fit power regression constants (Pineda, Colmenares, & Hoyos, 2014). In Table 2, the A and B coefficients are related for each specimen at different moisture condition. It was found that the coefficient A increases with decreases in the water content and increases in the matrix suction in the specimens independently of the depth, however the rate of variation of this parameter is higher for the deeper sample. The coefficient B presents small values, although without a defined trend that allows to infer dependence of stress history in relation to the changes of the initial water content.

$$G_{max} = A\ (p)^{B}$$

Table 2. Adjustment parameters A and B.

Sample	Depth (m)	A	B	R2
M1-1		70.551	0.0290	0.8012
M1-2	5.85	135.829	0.0198	0.8605
M1-3		141.586	0.0474	0.9925
M2-1		48.318	0.0355	0.8944
M2-2	9.85	157.627	0.0361	0.9402
M2-3		273.403	0.0701	0.9363

Figure 8 shows the variation of the normalized shear modulus (G/G_{max}) with respect to the shear strain (γ), it is observed that for both M1 and M2 as the shear deformation increases, the G modulus decreases, due to the loss of soil stiffness, it is also possible to observe in each graph that the samples containing the highest water content (M1-1 and M2-1) show higher deformations, because the presence of water inside the sample makes the sample softer and less rigid.

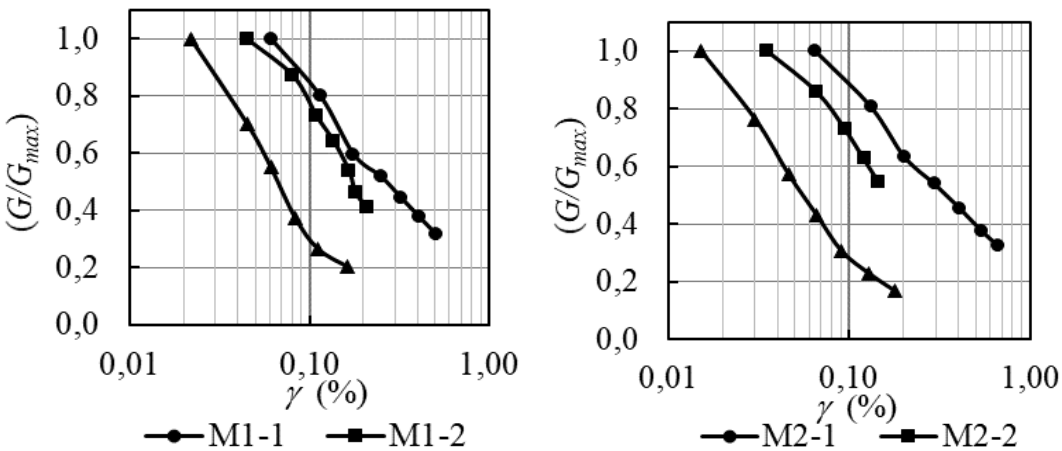

Figure 8. Normalized shear modulus G/G_{max} with shear strain response γ(%).

In Figure 9, we find the resonance curves obtained when testing the sample at a confinement of 400 kPa, it is evident in dynamic response that the influence of water content is significant in the energy dissipation. M2 is a sample that has a lower OCR than M1, therefore in this specimens there are greater shear strains are developed at resonance.

In Figure 10, it can be observed that damping decreases as sample confinement increases, this dynamic property refers to the energy dissipation rate after cyclic torsional loads are applied. In M1 the damping increases as the water content decreases, but in M2, it was found a different tendency because the less damping occurs in M2-2, this could be associated to a micro-fissuring phenomena of the desiccated specimen.

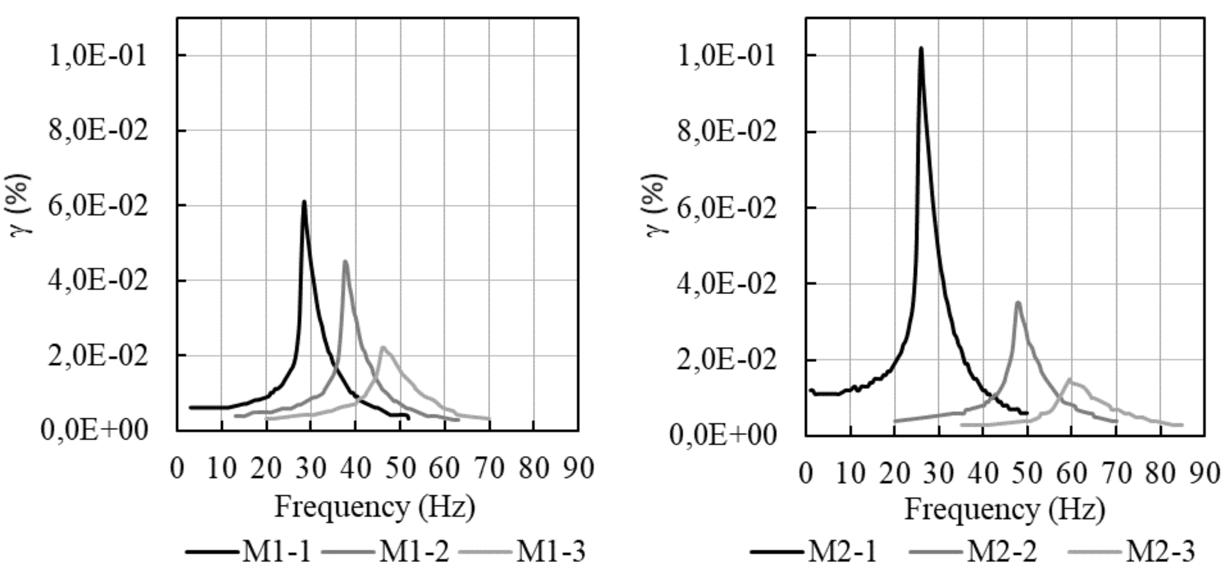

Figure 9. Resonance frequency response for different water contents at *p*=400 kPa

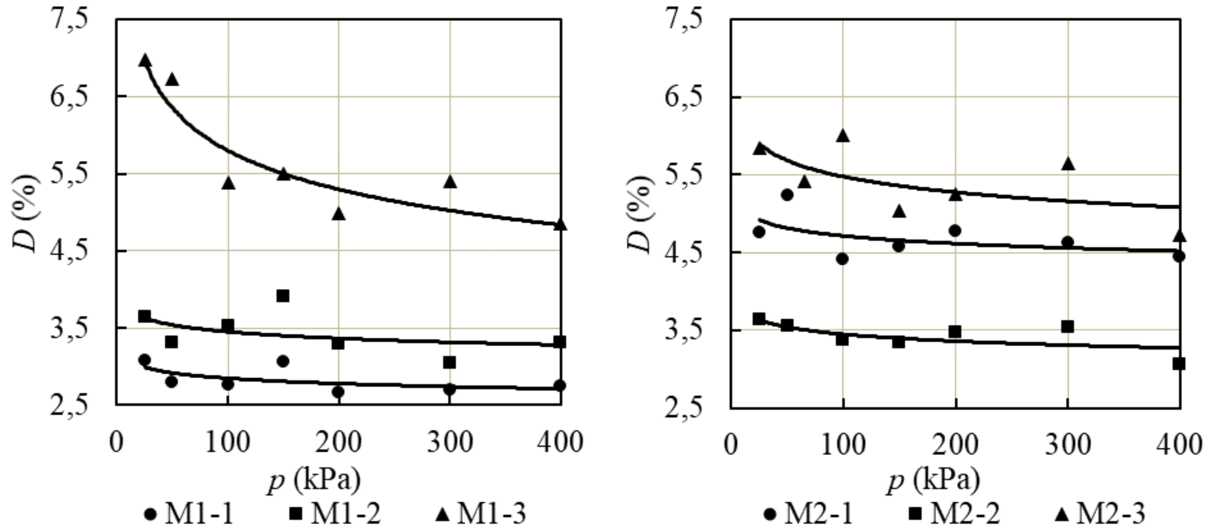

Figure 10. Damping ratio with confining pressure *p* (kPa).

6. CONCLUSIONS

In this research, tests were carried out on the resonant column equipment, establishing the variation of the dynamic properties of a lacustrine clayey material with different water content-matric suction states, after drying processes. The tests were carried out on samples with different degree of saturation states, in order to understand the influence of desiccation or drying in dynamic response of the clays.

Mainly, it was found that after inducing a loss of moisture in the samples, the small-strain stiffness increases, therefore the shear modulus increases also. The sample M2, at natural water content have a G_{max} smaller than M1, principally by OCR dependency. This means that due to the stress history of the materials, the influence of confinement level is more significant in deeper samples. It was observed also, that for confinement levels above 100 kPa, the there is little variations of shear modulus independent of OCR values.

From the SWRC, it was observed that AEV is inversely proportional to OCR, but M1 presented a lower value of this matric suction limit, which may be associated to the micro-cracking of the sample. Additionally, during both matric suction and resonant column testing, it was verified that the specimens to be subjected to water contents after the AEV begin cracking processes. The dynamic properties are profoundly affected by water content – matric suction conditions.

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