Alternative Method for Analysing Hydromechanical Behaviour of Unsaturated Soils

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Abstract. The suction-control techniques commonly used for laboratory studies of mechanical behaviour of unsaturated soils are much more time consuming than standard soil mechanics tests. In addition, few laboratories have the required apparatus for testing unsaturated soils. This paper proposes an alternative method of analysing hydromechanical behaviour of unsaturated soils with high-porosity. The method is divided in three tasks: 1) verification of the effect of void ratio changes on the water retention curve using filter paper; 2) determining water content changes by evaporation under the same test conditions; and 3) performing saturated and unsaturated consolidation tests. Unsaturated tests make use of samples that are less than 100% saturated and there is no suction control during the test. Therefore, only initial water content is known. Significant suction changes take place due to void closure and evaporation while testing. The results obtained using the proposed methodology showed the stress and suction path and enhance the understanding of the hydromechanical behaviour of unsaturated soils. The results also showed that analyses of water content alone cannot explain some unexpected results, such as: 20% initial water content samples present less deformation than 16% samples.
Keywords: unsaturated soil, hydromechanical behaviour, water content control test, filter paper method.

1. Introduction

The study of unsaturated soil mechanics has shown great progress in recent decades due to the need to solve practical engineering problems such as designing and maintaining foundations, pavements, dams, embankments, and canals subject to varying degrees of saturation during construction as well as during the design lifetime.

Paradigms have changed significantly. It was natural that first approaches considered mechanical and hydraulic behaviour uncoupled (Bishop, 1959; Matyas & Radhakrishna, 1968; and Fredlund *et al.*, 1978). Afterwards, several more recent papers have examined their interaction, *i.e.*, mechanical and hydraulic behaviour coupled (Vaunat *et al.*, 2000; Wheeler *et al.*, 2003; Sheng *et al.*, 2004, Della Vecchia, *et al.*, 2012).

Modern testing techniques for characterization of soil microstructure have led to studies of hydromechanical behaviour of unsaturated soils based on microstructural characterization and constitutive models coupling these three aspects (Gens & Alonso, 1992, Alonso *et al.*, 1999 and Alonso *et al.*, 2011, Alonso *et al.*, 2013).

Currently, characterizing and obtaining constitutive parameters of unsaturated soils is time-consuming and therefore testing and acquisition of equipment with suction control techniques, using advanced technology that is not available at most geotechnical laboratories, can be costly.

Accordingly, developing a methodology to evaluate the influence of suction on the mechanical behaviour of soils using basic tests in common use would be a significant contribution for the technical community since unsaturated soil concepts could then be used in geotechnical engineering practice.

In this context, this paper proposes an alternative method of measuring suction using the filter paper technique combined with gravimetric water-content control test.

2. Methodology

This section describes the soil used, sample preparation procedure and details of the gravimetric water content control test.

2.1. Material

The soil used in this study is a lateritic residual soil consisting of sandy red clay with over 50% porosity in its natural state extracted from the experimental field of the Post-graduation program of Geotechnics of the University of Brasília at 2 m depth. Kaolin is the predominant clay mineral however high levels of iron and aluminium oxide are also present (Cardoso, 1995; Araki, 1997).

Another particular feature of this soil is the high volumetric collapse produced by increasing the degree of saturation, even with loading held constant; hence the soil is sometimes referred to as a metastable soil.

Additionally, structural analysis showed that the soil consists of micro and macropores (Camapum de Carvalho *et al.*, 1994). The existence of micro and macropores results in a bimodal water retention curve with two air-entry values

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(AEV), one for the microstructure and the other for the macrostructure (Camapum de Carvalho & Leroueil, 2000). The soil continues to show bimodal structure and to maintain a high void ratio even when it is subjected to compaction (Otálvaro, 2013).

Table 1 shows specific gravity (G_s), consistency index (w_L and w_P), water content for compaction (w_{com}) and void ratio (e) of this soil.

Figure 1 shows two distinct particle size distribution curves of this very soil, where the solid line represents the curve when using a dispersing agent and the dashed line represents the curve when no dispersant agent is used. The soil is classified as a silt with low plasticity (ML) (Unified Classification System). However, it does not show hydraulic and mechanical behaviour consistent with this classification. Indeed, the hydraulic and mechanical behaviours are associated with the high content of clay, found in clusters which are strongly responsible for the hydromechanic responses, and may be observed when using dispersant agent.

The interpretation of results from mechanical tests, such as the direct shear test, requires particular care for this type of soil due to the fact that clay clusters control the soil mechanical response. The clay clusters are heavily affected when there is a change in the degree of saturation or stress state. Thus, samples of the same soil with different stress state and degree of saturation may behave as dense sand or normally consolidated clay.

2.2. Preparing samples

Semi-statically compacted samples were obtained to eliminate the natural heterogeneity found in soil samples. Camapum de Carvalho *et al.* (1987) asserted that the use of static compaction ensures more repeatability of soil properties and is also in agreement with the behaviour of compacted soils in the field.

The initial idea was to statically compact the sample with the void ratio and water content values found in the field, which were obtained by Silva (2007). However moulding in this state was not possible since the sample fragmented. Such behaviour is related to the fact that the natural soil contains bonding (iron and aluminium oxides) which allows the highly porous structure to exist. However, the process of preparing soil for the compaction test destroys the bonding, thus the same structure cannot be reproduced in laboratory.

For this study, the samples were compacted with the same water content as in the field (w = 20%). The compaction energy was below Standard Proctor resulting in samples with dry unit weight close to the soil in its natural state, as shown in Fig. 2.

Figure 3 shows the void ratio distribution for samples used by Silva (2009) for direct shear and consolidation tests. The methodology used proved to be efficient since void ratios of natural samples ranged from 1.08 to 1.23 with average of 1.16, which was the target void ratio. In addition, the coefficient of variation (COV) was 3.5%.

2.3. Tests performed

Water content control test, filter paper, and consolidation tests were performed for this study. Detailed descriptions of tests and conditions in which they were performed are found in this section.

Soil samples obtained as above described in section 2.2 were subjected to consolidation tests in accordance with NBR 12007 (ABNT, 1990). There were two different testing objectives: one was to assess soil compressibility in different initial water content conditions; the other was to obtain the void ratios at which retention curves would be performed.

Table 1 - Basic soil characterization (Silva, 2009).

w_L (%)	w_P (%)	w_{com} (%)	G_s	e
36	26	24	2.74	1.16

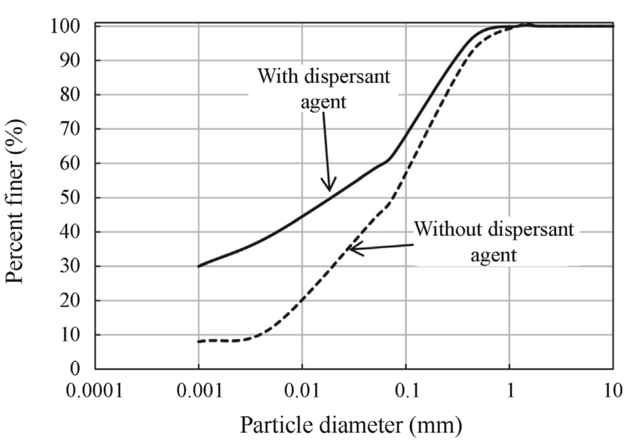

Figure 1 - Particle size distribution curves (Guimarães, 2002).

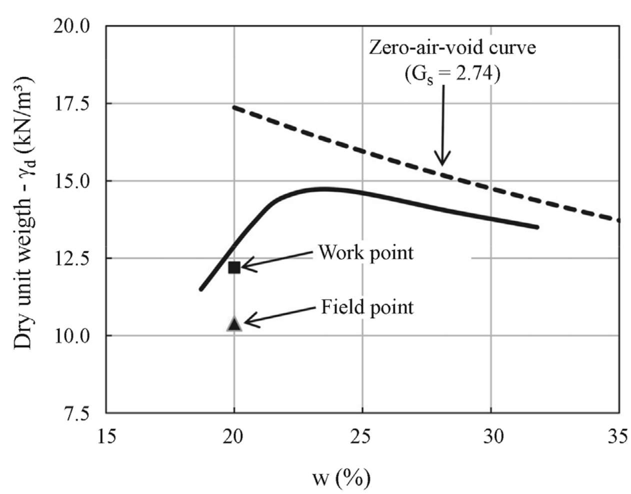

Figure 2 - Compaction Curve - Standard Proctor Energy (Silva, 2009).

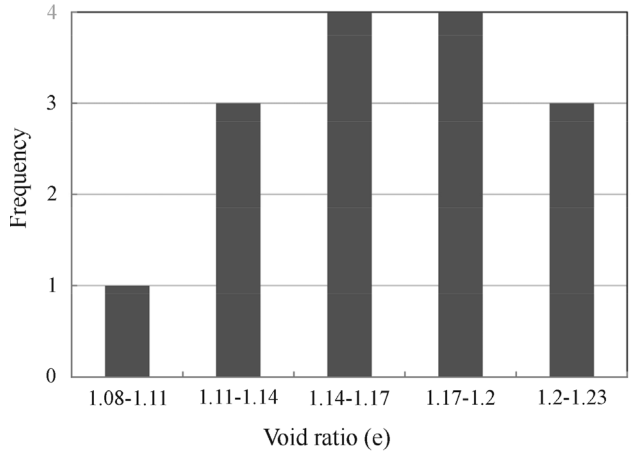

Figure 3 - Range of samples' void ratios.

In order to evaluate the effect of suction on soil compressibility, tests were carried out with different initial water contents (16%, 18%, 20%, 22%, and 24%) and in the saturated state. Samples at water content levels below the compaction water content (w = 20%) were air -dried to the required value. Samples at water content levels greater than the compaction water content were wetted, after the air-drying stage, by dripping water up to their required water content. The latter samples required 24 h to reach equilibrium. For the saturated state, the sample underwent saturation for 12 h before the test. To verify the collapse potential, the 22% and 24% water content samples were flooded, after stabilization of deformability readings were reached, at a vertical load of 1000 kPa.

When consolidation tests are performed under unsaturated conditions with no suction control, it is a general agreement to say that these tests were performed under constant water content. However, there is some natural loss of water content in the course of testing. Therefore, in order to determine water content values during testing, the followed methodology was proposed.

A soil sample was compacted in the conditions mentioned in the section 2.2. Specimens were then moulded from this sample in a similar way of those prepared for standard consolidation tests. Then, the soil specimens were held inside the oedometric cell within the moulding ring, with filter paper and porous stones at its upper and lower faces in order to simulate the conditions for the consolidation tests. Testing took place over a period of 24 h during which the weights of the soil specimen and temperature at the time of weighing were recorded simultaneously thus, the evolution of loss of water content to the environment could be determined.

Water evaporation rate is known to be related to soil water content; therefore ideally this test would ideally be conducted in samples with different initial water content values. However, as discussed in section 3.1, errors due to the use of a model obtained from a single water content value is irrelevant.

Moreover, in addition to the variation in water content, there is the effect of void ratio variation on suction values. Therefore, to determine suction values throughout the consolidation tests, not only the variations of water content (determined by water content loss tests) should be known, but the effects of the void ratios on the retention curve are also required. Thus, water retention curves for three different void ratios were determined.

In order to determine the void ratios at which retention curves would be performed, Silva (2009) carried out the previously mentioned consolidation tests for both saturated and unsaturated conditions and the results are shown in Fig. 4. Thus, water retention curves were determined for three different void ratios: compacted sample, (point A); unsaturated condition after loading and unloading cycle (point B) and saturated condition after loading and unloading cycle (point C).

The filter paper technique procedure proposed by Marinho (1994) was used to obtain the water retention curves. Whatman No. 42 filter paper,, which has the calibration curves previously determined, was used for the tests. Note that the tests were performed both in wetting and drying (mixed) paths.

3. Results and Discussion

This section presents and analyses the results used to obtain soil parameters for the unsaturated condition. Subsequently, from these parameters, the stress-strain curves of soil are analysed with different initial water contents emphasizing the effects of initial water content and variation of suction during the test.

3.1. Time dependence of water content

As previously mentioned, it is normally assumed that water content remains constant during consolidation tests

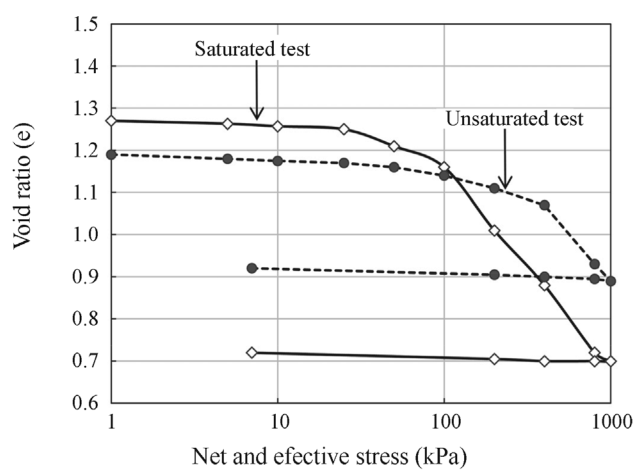

Figure 4 - Determination of points for retention curve tests (Silva, 2009).

with initial water content known, thus sample suction may thereafter be evaluated. However, samples tend to lose water to the environment during testing. In order to measure the amount of water lost, the water content control test described in the previous item was used.

The results for variation of water content over time are shown in Fig. 5. From this figure, empirical equations may be obtained to calculate sample water content for any given time *t* after start of testing. Two ratios are used - one for times of less than 240 min (6 h) and the other for over 240 min. Equations 1 and 2 below show these ratios.

$$w_c = w_i - 0.0035t \text{ for } t < 240 \text{ min} \quad (1)$$

$$w_c = w_k - 0.0017(t - 240) \text{ for } t > 240 \text{ min} \quad (2)$$

where w_c - corrected water content; w_i - initial water content; w_k - corrected water content for time 240 min and t - time elapsed from start of testing.

To demonstrate the potential of this technique, Table 2 shows that water content measurements for the samples subjected to consolidation tests are in good agreement with those predicted by Eqs. 1 and 2. Since the 22% and 24% initial water content samples were flooded at the end, it was not possible to check whether the values estimate for variation of water content over time were consistent with actual values. Due to the good results obtained for samples with less than 20% water content, the same is expected for samples at higher levels of water content.

Due to water content and void ratio variations, suction changes in the course of the consolidation test performed. A key requirement to obtain suction values during testing is to know how the water retention curve is affected by the void ratio, which is discussed in the next item.

Table 2 - Mean water content measured in tests and estimated from equations.

Sample	$w_{measure}$ (%)	$w_{estimated}$ (%)
16%	13.8	13.4
18%	15.8	15.4
20%	16.7	16.1

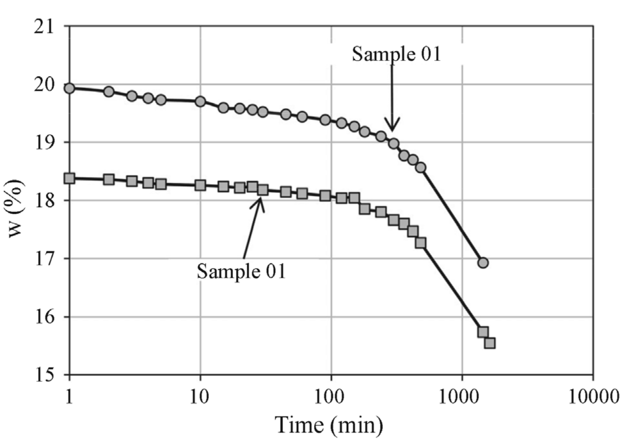

Figure 5 - Water content and time relationship.

3.2. Modelling the water retention curve

Figure 6 shows the retention curves obtained by Silva (2009) for different void ratios (0.77, 0.97 and 1.16) in relation to soil water content ($e_w = Se$). It is also shown the water retention curves data for void ratio of 1.6 obtained by Guimarães (2002) and Silva (2007) using undisturbed sample from a depth of 2 m.

According to Romero & Vaunat (2000), water present in the soil may be stored in two ways: in the macrostructure, in the form of free and meniscus water, in which active suction is related to capillarity; and in the microstructure, as adsorbed water; suction under these conditions is governed by physicochemical bonds. Thus, soil water content is the sum of two factors, namely macroscopic (w^M) and microscopic water content (w^m). This fact is clearly seen in soil water retention curves (Fig. 6).

In this way, Fig. 6 shows experimental data coinciding in terms of suction values for water content (e_w) below 0.44, which corresponds to the water found in the micropores. On the other hand, void ratio variations only affect the retention curve behaviour at values below 100 kPa (corresponding to e_w >0.44), in other words, significant on the macrostructural level.

The equation used for mathematical representation of the water retention curve of experimental data was proposed by Durner (1994), who modified the van Genuchten (1980) equation in order to extend its use to bimodal curves, typical of tropical soils as shown as following.

$$e_w = e_{wL}\left[\frac{1}{1+(\alpha_L(u_a-u_w))^{n_L}}\right]^{m_L} + e_{wS}\left[\frac{1}{1+(\alpha_S(u_a-u_w))^{n_S}}\right]^{m_S} \quad (3)$$

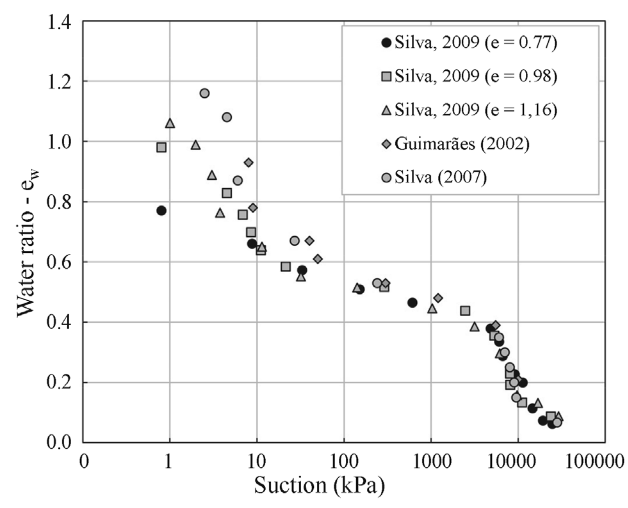

Figure 6 - Retention curves as a function of soil water content.

where e_w is the soil water content, and e_{wL} is the macropore void ratio; α_L is related to the air-entry value for macropores, n_L is the slope of the line that relates macropore water content and suction; m_L is the slope of the line that relates water content and suction in the transition region, and e_{wS} is the micropore void ratio; α_S is related to air entry value for micropores; n_S is the slope of the line that relates micropore water content and suction, and m_S is the slope of the line that relates water content and suction after hygroscopic soil water content value. Note that parameters m_L and m_S are obtained from n_L and n_S as follows:

$$m_L = 1 - \frac{1}{n_L} \tag{4}$$

$$m_S = 1 - \frac{1}{n_S} \tag{5}$$

Figure 7 show the relationship between Pore Size Density (PSD) and Water Retention Curve (WRC). It also shows the relationship between the Air Entry Value for the micropores (AEVs) and the dominant micro pore size α_S is determined. The PSD and WRC correlation helps to understand the modelling process of WRC for different void ratios.

Likewise, as previously mentioned, the parameters e_{wS} and n_S are related to the distribution of pores in the microstructure. Thus, as Romero & Vaunat (2000) showed, the microstructure is the part of the soil not affected by loading paths, these values are constant for all samples studied, even with different void ratios and moulding processes since compaction only alters the macrostructural level of soil structure. Findings showing microstructure pore distribution remaining unchanged with loading paths have been reported by Simms & Yanful (2002), Romero *et al.* (2005), Buenfil (2007), and Mascarenha (2008).

In the macrostructure, on the other hand, the reduction of void ratio causes the closure of the macropores, hence reduction of the values of e_{wL} and n_L. Moreover, this reduction leads to the increase of the macropore air-entry

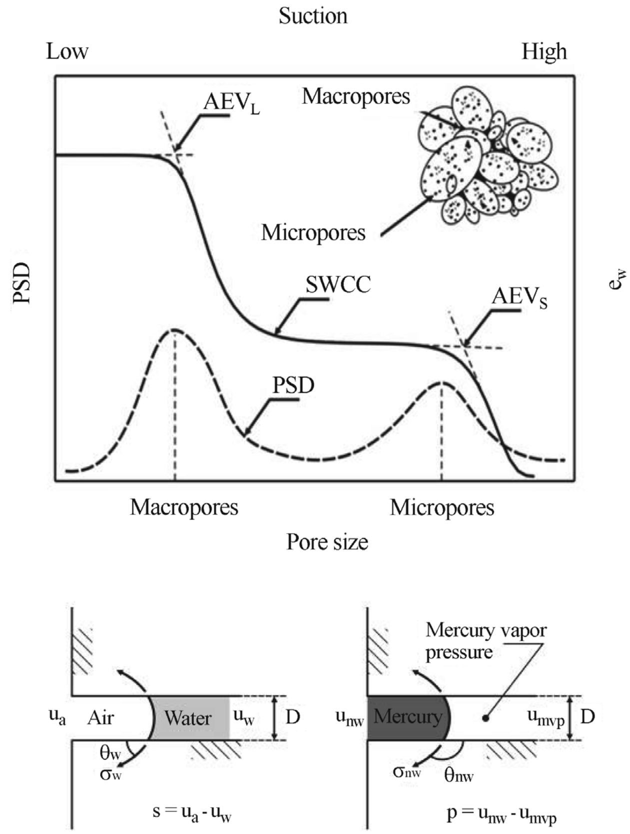

Figure 7 - Analogy between pore size density (PSD) and water retention curve (WRC) (modified from Otálvaro, 2013).

values (AEV_L) and reduction of the values of α_L. Based on these points, experimental data of water retention curves and respective fitting curves are shown in Fig. 8. The fitting parameters used are presented in Table 3.

Figure 9 shows the values of the parameters e_{wL}, α_L e n_L as functions of the void ratios from experimental data of Silva (2009). Note that for the void ratio interval shown, there is a clear correlation between the parameters associated with the macrostructure and the global void ratio. Fur-

Table 3 - Retention curve fitting parameters.

		Silva 2009			Silva 2007	Guimarães 2002
	Parameters	e = 1.16	e = 0.98	e = 0.77	e = 1.57	e = 1. 60
Macrostructure	e_{wL}	0.72	0.54	0.33	1.14	1.14
	α_L	0.55	0.35	0.19	0.35	0.35
	n_L	1.80	1.70	1.50	1.70	1.70
	m_L	0.44	0.41	0.33	0.41	0.41
Microstructure	e_{wS}	0.44	0.44	0.44	0.44	0.44
	α_S	1.5 x 10^{-4}	1.5 x 10^{-4}	1.5 x 10^{-4}	1.5 x 10^{-4}	1.5 x 10^{-4}
	n_S	2.5	2.5	2.5	2.5	2.5
	m_S	0.6	0.6	0.6	0.6	0.6

thermore, for this interval, the correlation is linear for all parameters, as seen in the Eqs. 6 to 8.

It is worth mentioning that no experimental data from Silva (2007) and Guimarães (2002) were used in the fittings, since these water retention curves were obtained from undisturbed soil samples in which bonding agents lead to a pore size distribution at microstructural level different from that of the compacted sample.

$$e_{wL} = 1.00e - 0.44 \tag{6}$$

$$a_L = 0.92e - 0.53 \tag{7}$$

$$n_L = 0.77e + 0.92 \tag{8}$$

Using Eqs. 6 to 8 combined with Eqs. 3 to 5, modelling of the retention curve may be completed. Table 3 shows the parameters associated with microstructure and the final equation is given by:

$$ew = (1.00e - 0.44)\left[\frac{1}{1+((0.92e-0.53)(u_a-u_w))^{0.77e+0.92}}\right]^{\frac{0.77e-0.08}{0.77e+0.92}} + 0.44\left[\frac{1}{1+(0.00015(u_a-u_w))^{2.5}}\right]^{0.6} \tag{9}$$

Once the relationships between suction, water content and void ratio are known they may be used to determine the suction path during the tests.

3.3. Stress-strain relation in unsaturated soil

Figure 10 shows compression curves for the samples tested with different initial water content values. Generally, the results are as expected with deformability rising as initial soil water content rises. The only exception to this is seen in the results from the sample at 16% initial water content, which will be analysed in detail in this section.

All samples have two loading components related to the increase of vertical stress and suction changes. In this case, suction changes arise from both the sample water content and void ratio decreasing in the course of testing. Fig-

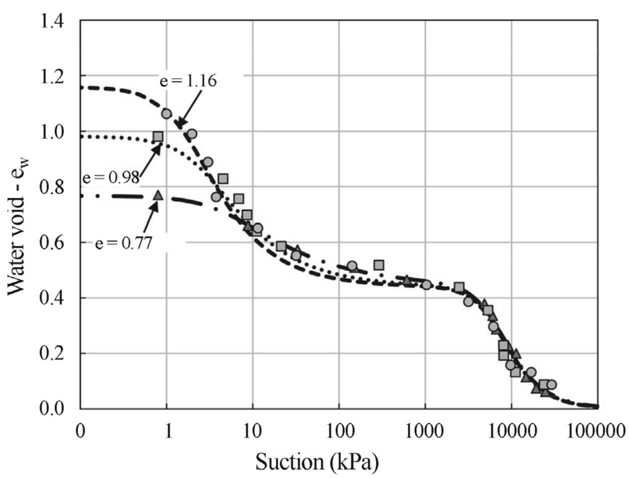

Figure 8 - Retention curve fittings as a function of soil water content.

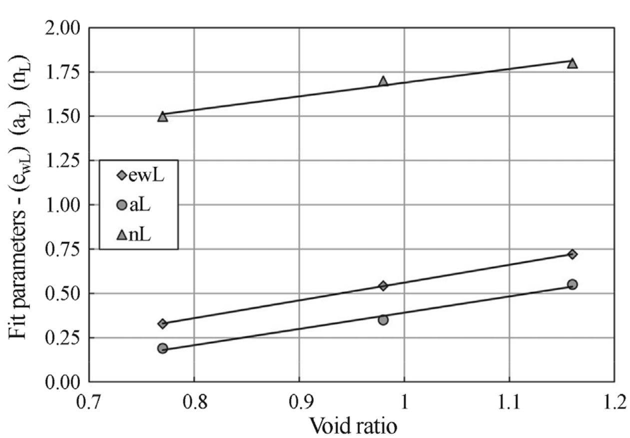

Figure 9 - Retention curve fitting parameters as a function of void ratio.

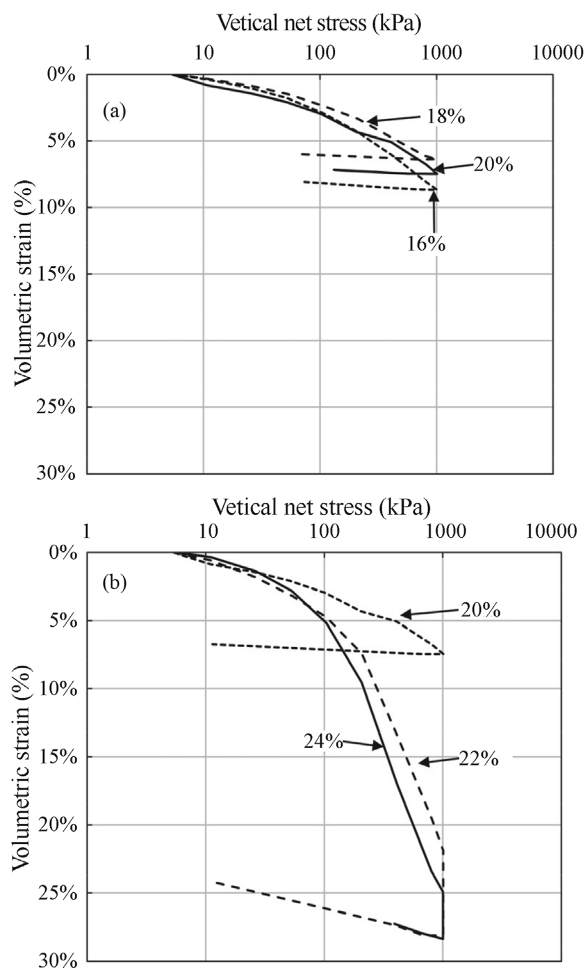

Figure 10 - Volumetric deformations of the consolidation test (a) 16, 18 and 20% initial water content samples (b) 20, 22, and 24% initial water content samples.

ure 11 shows water content and suction variation for each sample during the test. Furthermore, these paths are compared with the water retention curves, which allow understanding particular aspects to be discussed along this section. The paths shown in Fig. 11 were obtained using Eqs. 1, 2 and 9.

An analysis of Fig. 11 shows that although the samples have the same structure, the effect of water content variation is different in each case. For example, in the higher (22% and 24%) water content samples there is outflow of water from soil macrostructure, while in the lower water content (16%) sample, water flows out of the microstructure.

This factor helps to explain two aspects observed in the soil behaviour shown in Fig. 10: different behaviour for samples with different water content and the fact that the 16% water content sample showed larger volumetric deformations than the 18% and 20% water content samples.

On the other hand, the higher water content samples (24% and 22%) show low suction values throughout the test: for the 24% water content sample suction ranges from 7 to 30 kPa and for 22% from 11 to 78 kPa. Despite the short range of suction values, the samples experiences accentuated collapse due to saturation, as seen in Fig. 10, which is associated with the pore-size distribution, as explained in the following.

When suction is reduced to zero by saturating the 22 and 24% initial water content samples, its effect are experienced by the macropores range as shown in Fig. 11. Thus suction plays a key role in the soil structural stability, since its reduction leads to closing macropores and therefore volumetric collapse.

Figure 12 shows the distribution of pores in the soil obtained by indirect measurements using the methodology reported by Mascarenha (2008) and Otálvaro (2013) for different void ratios. Note that the PSD also helps to explain why the suction value associated with macropore air-entry (AEV_L) for this soil is so low.

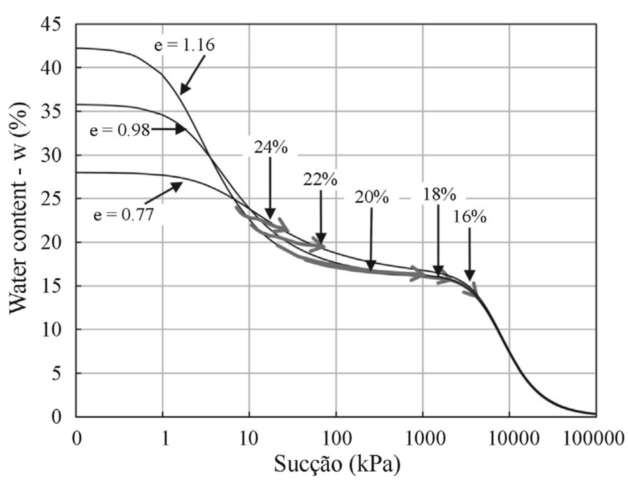

Figure 11 - Water retention curve - water content agains suction.

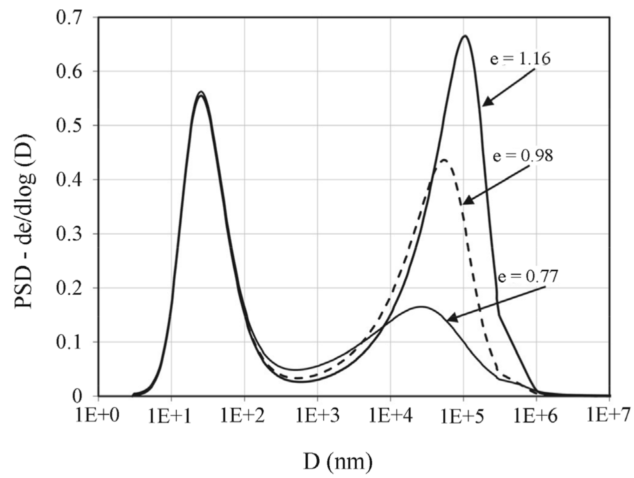

Figure 12 - Changes in pore size density functions of a collapsible soil.

It is worth noting that Figs. 11 and 12 justify what was said previously about the effect of loading being significant only for the macropores range while the microstructure remains constant after different types of loading.

The other aspect to be considered is that the process of water outlet for the 16% water content sample starts at the micropores level. Suction values for this sample ranged from 1480 to 4445 kPa. The high suction value associated to this sample should increase soil stiffness, as described in several studies such as Alonso *et al.* (1990). However, since these suction values led to outflow of water from the micropores, another phenomenon should be considered - the contraction of the clay clusters that form the microstructure.

Alonso *et al.* (1999) mentioned that soil macrostructural response is strongly influenced by microstructural behaviour. A simpler way of evaluating the influence of the macrostructural response caused by microstructure variation will be presented, through a formulation, and subsequently discussed.

Other aspects for interpretation of the results in Fig. 10 are seen in Fig. 13, which shows net vertical stress and suction paths for all samples. The data shows that although all the samples have similar variations in water content (about 0.05), the effect on suction values depends on whether this variation takes place in the soil microstructure or macrostructure as mentioned previously.

An uncertain point in relation to obtaining suction values from the methodology presented is that the water retention curves were carried out on mixed (wetting and drying) paths. The water retention curves obtained by Otálvaro (2013) for a soil from Brasilia with similar physical and mineralogical characteristics of the soil studied in this paper showed hysteresis. The present study ignored hysteresis effect and therefore if this behaviour is present in the soil studied it was not taken into account when determining its compressibility parameters.

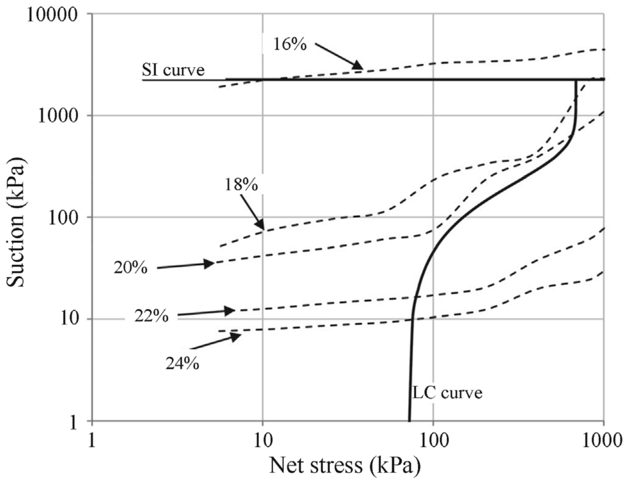

Figure 13 - Variation of suction values during consolidation tests for samples with different water contents.

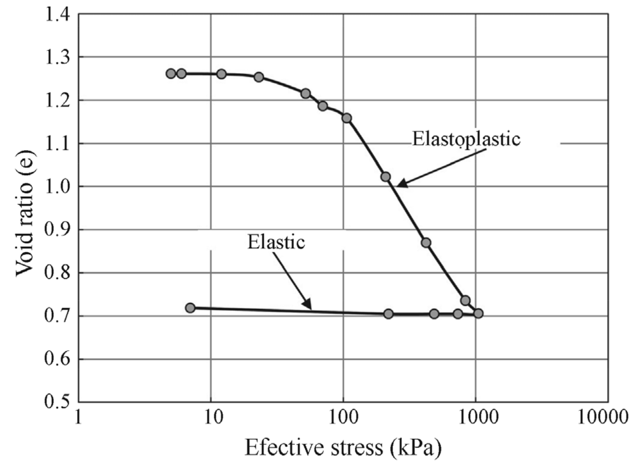

Figure 14 - Consolidation curve for a saturated sample.

3.4. Obtaining constitutive parameters

Figure 14 shows the void ratio-effective stress curve for the saturated condition. In this case, all volumetric change is associated with vertical loading. Therefore the following parameters associated with constitutive models such as Cam-clay or Barcelona Basic Model (Alonso *et al.*, 1990) may be obtained: pre-consolidation stress for saturated conditions (p_0^*), elastic stiffness parameter (k), and plastic stiffness parameter for saturated condition (λ_0).

However, the results shown in Fig. 10, in which there is no direct suction control, in principle, cannot be used to define constitutive model parameters, but may be used to enhance interpretation of soil behaviour.

The volumetric strain found for consolidation testing of the 16% initial water content sample was larger than that of samples with 18 and 20% initial water content. The reason for this is associated with suction changes leading to contraction of microstructure, as discussed previously.

In order to separate strain due to loading from that due to contraction of the 16% water content sample microstructure, it will be assumed there is no plastic deformation due to loading, only elastic deformations, whereas suction changes produces elastic and plastic deformations (Fig. 15).

Although the hypothesis cannot be proven from the results presented in this paper, it will reveal helpful in understanding soil behaviour and obtaining a set of parameters to simulate the paths used.

Figure 15a shows the variation of the sample void ratio due to suction change alone, in accordance with the above assumption. Based on this curve, the Barcelona Basic Model constitutive parameters for suction changes may be obtained (Alonso *et al.*, 1990): hardening parameter (s_0),

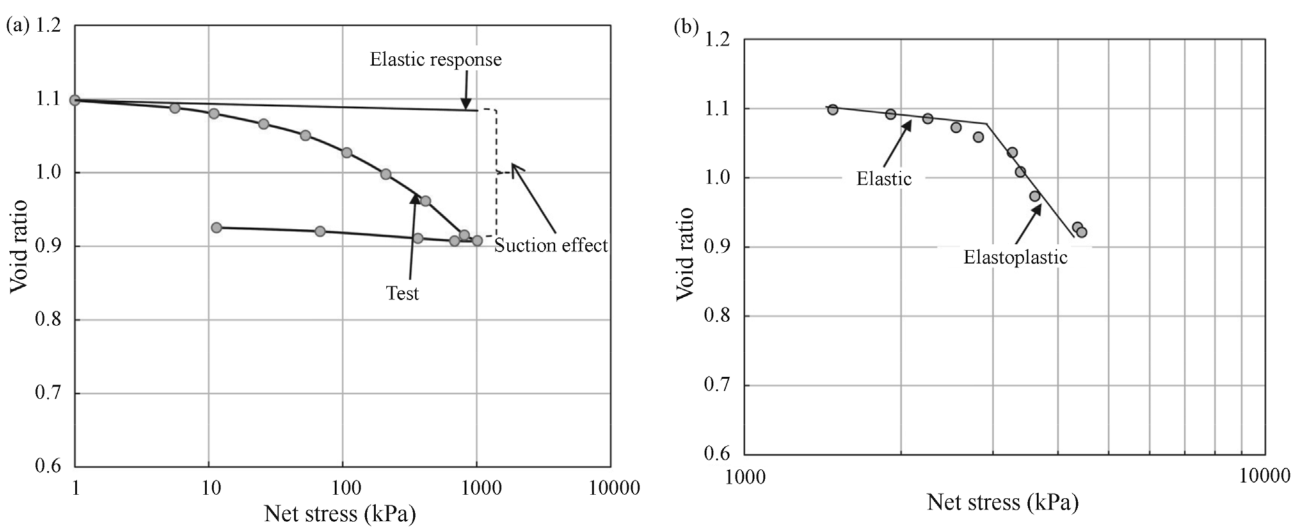

Figure 15 - Consolidation tests -sample at 16% water content: a) Variation of void ratio with net stress; b) Variation of void ratio with suction.

Table 4 - Barcelona Basic Model (BBM) parameters.

Author	Stress			Elastic		Plastic volumetric compressibility			
	p_c (kPa)	p_0* (kPa)	s_0 (kPa)	κ	κ_s	λ_0	λ_s	r	β (kPa^{-1})
Present study	7.5	70	2250	0.002	0.02	0.20	0.20	0.50	0.007
Peixoto (1999)	20	50	-	0.02	-	0.32	-	0.50	0.01

elastic stiffness parameter for change in suction (k_s) and plastic stiffness parameter for change in suction (λ_s).

All parameters required by the Barcelona Basic Model to reproduce the paths shown in Fig. 10 are presented in Table 4. The parameters obtained by Peixoto (1999) for the same soil in its natural (or undisturbed) state are also shown. The values match quite well, particularly given the fact that the samples used were in different conditions.

Figure 13 shows hypothetical LC (loading-collapse) and SI (suction increase) yield surfaces obtained using parameters from Table 4. This figure clearly shows that 16% initial water content sample would be yielding by reaching the SI. In contrast, 22% and 24% initial water content samples would quickly reach LC and be deformed by vertical stress alone. The 18% initial water content sample only reaches LC and SI for high stress levels and the 20% initial water content sample does not touch SI and is always tangential to LC, although it does reach LC at high levels of loading, with strain occurring due to vertical stress.

In order to validate the model parameters shown in Table 4, test simulations were performed to obtain the results shown in Figs. 16 to 18. In general, the results obtained with the parameters match experimental results quite well. Furthermore, in the 16% and 18% initial water content samples there are two inflection points in the fittings of the consolidation curve. This is due to a fact that loading stabilization times were not constant, thus causing different variations of suction in the course of the test.

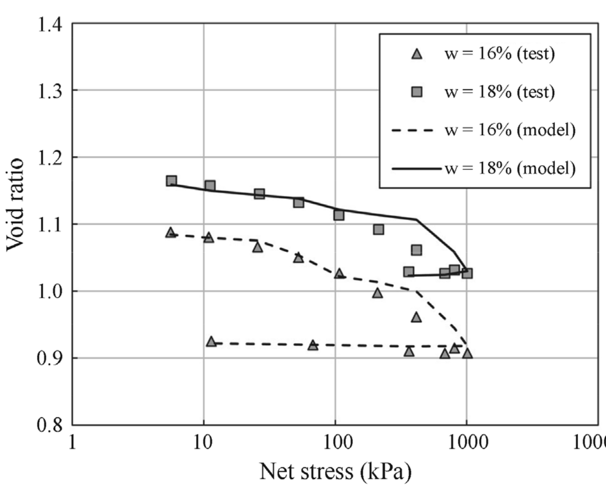

Figure 16 - Experimental results from consolidation tests and model simulations 16% and 18% initial water content samples.

Another problem observed in the fittings was that the 22% initial water content sample showed less collapse than the simulation.

A point to note is that if the variation of suction values in the course of the consolidation test were not taken into account, a consistent fitting could not be obtained for two reasons. One is that, although the 16% initial water content sample has a higher initial suction value, it shows more strain than the 18% and 20% initial water content samples,

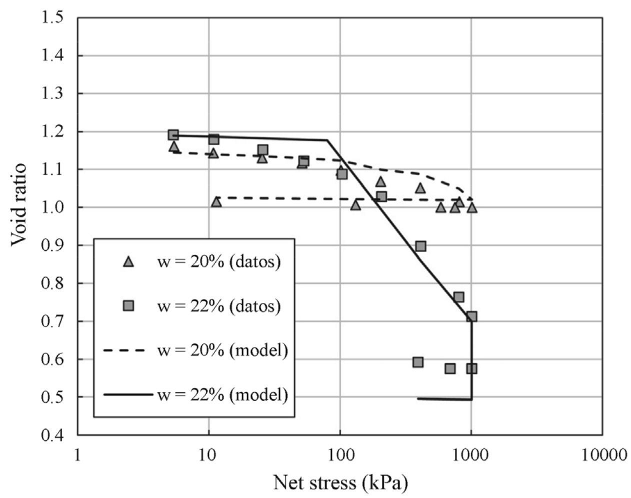

Figure 17 - Experimental results from consolidation tests and model simulations -20% and 22% initial water content samples.

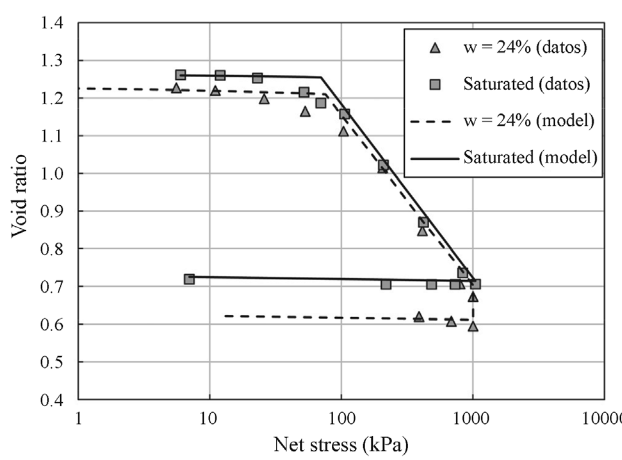

Figure 18 - Experimental results from consolidation tests and model simulations - 24% and saturated initial water content samples.

which was due to the large variation in suction during testing and these strain occurring in the microstructure, resulting in permanent deformations.

The second reason is that, the collapse due to flooding under 1000 kPa stress in the 22% and 24% initial water content samples would be underestimated, since both samples present initial suction of around 10 kPa, but reached 78 and 30 kPa of suction respectively before flooding, due to decrease of water content. Note that the underestimation of collapse due to assuming constant water content is greater than from the use of retention curve in mixed (wetting and drying) paths to estimate suction values in the course of consolidation tests.

4. Conclusions

In the consolidation tests performed assuming constant water content, suction change due to evaporation of water and reduction of voids is not considered. Thus, soil shrinking due to increased suction is associated with the increase of vertical stress. In some cases, this may be wrongly reflected in the value of the compressibility coefficient.

The water content control test described in this paper proved to be efficient at obtaining water content values over the test period, and values estimated by the method proposed were similar to those measured at the end of the test.

Additionally, a water retention curve could be obtained for different void ratios showing that the variation of void ratio affecting soil suction values is only significant in the soil macrostructure.

Suction changes due to water evaporation rate and reduced voids was incorporated in the estimation of constitutive parameters and proved quite adequate, which was confirmed by simulations of the experimental data.

The evaporation rate for the 22% and 24% initial water content samples must be higher than for a 20% sample, which means that soil water content before flooding the sample was smaller than the estimated value. Additionally, the water retention curve used to estimate suction was obtained from a wetting path, whereas in the consolidation tests they were estimated from a drying path. Both factors combined result in estimated suction lower than actual suction, which would lead to underestimating collapse.

Finally, it is important to note that these parameters were obtained by means of simple testing: filter paper, water content control test and consolidation tests.

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List of Symbols

AEV: air entry values
COV: coefficient of variation
e: void ratio
e_w: soil water content
e_{wL}: macropore void ratio
e_{wS}: micropore void ratio
G_s: specific gravity
k: elastic stiffness parameter
k_s: elastic stiffness parameter for change in suction
m_L: slope of the line that relates transition water content and suction
m_S: slope of the line that relates water content and suction after hygroscopic soil water content value
n_L: slope of the line that relates macropore water content and suction
n_S: slope of the line that relates macropore water content and suction
p_c: reference stress
p_0^*: pre-consolidation stress for saturated conditions
PSD: Pore Size Density
r: parameter defining the maximum soil stiffness
s_0: hardening parameter
t: time elapsed from start of testing
w: water content
w_c: corrected water content
w_{com}: compaction water content
w_i: initial water content
w_k: corrected water content for time 240 min
w_L: liquid limit index
w^M: macroscopic water content
w^m: microscopic water content
w_P: plastic limit index
α_L: parameter related to air-entry value for macropores
α_S: parameter related to air-entry value for micropores
β: parameter controlling the rate of increase of soil stiffness with suction
λ_0: plastic stiffness parameter for saturated condition
λ_s: plastic stiffness parameter for change in suction