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Soil water retention curve of silty sand – experimental investigation using different laboratory methods

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Abstract. Most of the infrastructure investments and earthworks not requiring deep foundations are usually designed in the vadose zone to avoid excessive groundwater-structure interactions. The mechanical behaviour of soil material, under partially saturated conditions, is greatly influenced by pore-water tension, known as soil suction, and the characteristics of the Soil Water Retention Curve (SWRC). In the present paper, the SWRC of a silty sand was determined using two different experimental methods. In the first method, a modified pore water pressure transducer was used for suction monitoring, while the specimen was allowed to change its moisture content by natural evaporation. For the second method, a modified consolidation cell fitted with a high air entry value ceramic disc on the base pedestal was used. Suction was applied using the axis translation technique by utilising pore air and pore water pressure controllers, while moisture was monitored using a volumetric measurement system. Through the determination of the SWRC for the silty sand, this paper intends to compare the abovementioned testing methods based on the produced SWRCs and to reveal advantages and limitations.

1 Introduction

When designing earth structures like embankments, dams, dykes, and shallow foundations, unsaturated soil mechanics play an important role. Especially, nowadays when climatic events are changing very rapidly, understanding soil-water interactions, poses one of the challenges as it is affecting the durability and performance of geo-structures [1,2]. In this regard, unsaturated soil mechanics can play a key role in terms of proposing new approaches to designing geo-structures resilient to severe climatic events. As extreme events become more frequent and more devastating, there is a growing need to quantify the impacts on responses of earth structures over short- and long-term performances. A number of such challenges need to be tackled by interdisciplinary approaches, involving hydro-mechanical interactions in the soil profile.

The present paper mainly focuses on hydraulic soil behaviour, by analysing the relationship between water content and suction which, in the literature, is referred to as the soil–water characteristic curve (SWCC) or soil–water retention curve (SWRC) or less often soil–moisture curve (SMC). Such relationships have been used as a tool to predict the flow, shear strength and volume change behaviour of unsaturated soils [3]. Many authors refer to the soil-water "characteristic curve" as the relationship between water content and suction. Even though the term "characteristic" implies that a unique relationship can characterize the hydraulic and mechanical behaviour of unsaturated soil, this relationship is highly dependent on a number of factors, such as initial state, fabric, hydraulic pathway (wetting or drying), stress, temperature, etc. Due to that reason, the authors prefer to use SWRC.

Since a number of geotechnical structures are located in the vadose zone, presented in Figure 1, the measurement of negative pore-water pressure also expressed as soil suction, is of primary importance in the analysis and prediction of unsaturated soil behaviour.

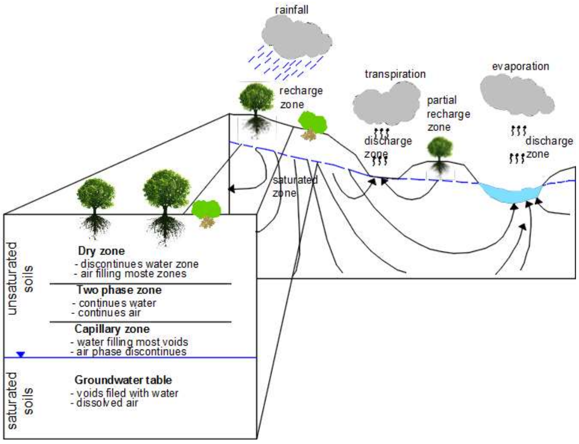


Fig. 1. Graphical presentation of unsaturated soil zone.

Nowadays science provides a number of instruments that allow precise measurement of soil suction by applying a number of techniques including tensiometers, pressure plates, filter paper, soil column and more [4]. There are however two major techniques used when measuring soil suction, i.e., tensiometric and axis translation. The first high-capacity tensiometers measuring negative pressure down to -1,500 kPa were developed by Ridley and Burland [5]. Several instruments have since been developed and successfully used in laboratory and field experiments [6]. Tensiometric technique shares with the axis translation technique a common working principle; that is, the measurement of a pressure differential across a high air entry porous ceramic. For this reason, these two suction measurement techniques are presented and discussed together to underline their similarities and their differences.

2 Material and testing setup

2.1 Material

The material used in this study was silty sand with the Grain Size Distribution shown in Figure 2. This is a uniform sandy material with less than 10% of silty and clayey material. The main characteristics are presented in Table 1 [7].

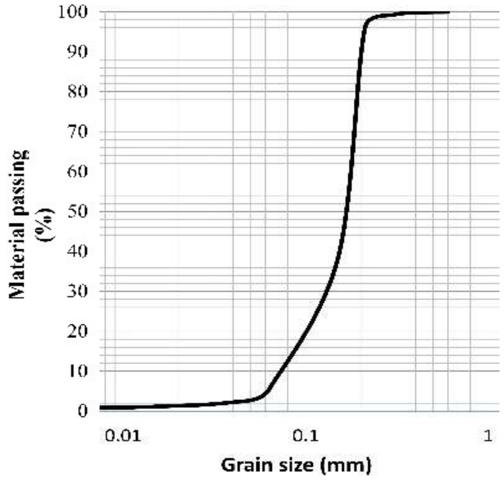


Fig. 2. Grain size distribution for the silty sand material.

Table 1. Characterisation of the silty sand material

D_{10}	D_{50}	ρ_s	e_{min}	e_{max}	w_{opt}
mm	mm	Mg/m^3	-	-	%
0.072	0.16	2.62	0.578	1.000	10.5

2.2 Evaporation method

The use of the tensiometer technique for the determination of the SWRC in the laboratory has been applied in the past by [8-14]. This technique involves the drying of the soil specimen naturally while the induced suction is measured by a Pore Pressure Transducer (PPT) fitted within the soil mass. The major advantage of this technique is that soil's drying can be imposed naturally, where negative pore water pressures are created [15]. In contrast with the axis translation technique, where desaturation occurs due to artificially elevated air pressure and air intrusion at the boundaries of the sample, in the tensiometer technique the internal pores desaturate by cavitation when the pore water pressure becomes highly negative. Therefore, the soil drying process and suction-induced replicate the processes occurring in nature. Moreover, the tensiometer technique provides a quick, reliable and inexpensive way to determine the SWRC of soil in the laboratory, compared to other methods.

Both drying and wetting SWRCs were determined in the laboratory using a specially designed pedestal (Figure 3). The experimental setup comprises an aluminium base, on which the soil sample was placed, with a fitted PPT for measuring pore suctions. The PPT, with a diameter of 6.4 mm, was kept in place using a cable gland which also provides insulation of the space occupied by the PPT cable. In order to ensure good contact between the soil sample and the aluminium base, rubber was placed at the margins of the soil sample. Also, an O-ring was fitted between the PPT and the aluminium base to prevent any exposure of the PPT head (ceramic porous stone) to the atmosphere.

Prior to testing, the PPT was fully saturated and calibrated [7]. The PPT was carefully fitted to the pedestal and its porous stone was always kept wet with a wet tissue to prevent cavitation. When the soil specimen was ready to be placed on the pedestal, the tissue was removed, and the soil specimen was pushed slightly on the PPT to ensure good contact. The insertion depth was selected to be between 3 and 5 mm to achieve good contact and prevent soil disturbance or cracking of the specimen.

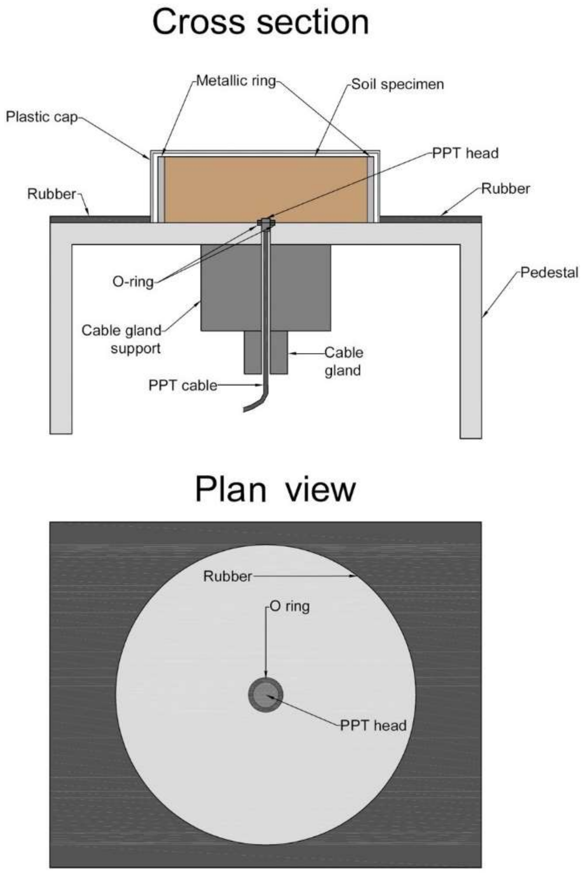


Fig. 3. Testing configuration for the tensiometer method.

The preparation of the soil specimens for testing consisted of the following steps: the soil was mixed with water in order to achieve the desired moisture content and then left sealed in a bag for 24 hours in order to equalise its moisture. The soil was then compacted in a mould using the standard Proctor test (applying 593.7 kJ/m^3) using initial specific water content of 20.5% and to reach the void ratio value of 0.64, which was then confirmed by oven drying and weighing the samples. A soil block was extruded from the mould, using a cutting ring, and cylindrical specimens of 75 mm in diameter and 18.5 mm in height were taken using a trimmer. Soil specimens and trimmers were kept in sealed vessels until the testing time in order to preserve their moisture. Just before the test, a small sample of the trimmings was dried in an oven (at 105◦) to determine the initial gravimetric water content.

The final specimen was weighed and placed on the base pedestal. The whole setup (pedestal, soil and PPT) was initially placed on a balance with a precision of 0.01 g and covered with a plastic case to protect it from drying. Once the test started, the plastic case was removed, and the soil was allowed to dry out naturally. By plotting the changes of the gravimetric water content (w) with suction (s), the SWRC of the soil was obtained. Volume changes of the specimen during drying and wetting cycles were not recorded, therefore the SWRC was plotted only in terms of w.

To evaluate the rate of desaturation caused by natural evaporation, three soil specimens were allowed to dry out while monitoring the change in their moisture content. Two of these (specimens 1 and 2) were exposed to atmospheric conditions, simulating the procedure followed during the SWRC test, while specimen 3 was covered by the plastic case. Figure 4 presents the change of the bulk gravimetric water content as determined by the balance readings. The two exposed specimens were prepared at different dry densities and at different initial moisture content. Results show that there are generally two branches on the desaturation curve. An initial linear part continues until the soil enters the residual state, followed by an asymptotic to the x-axis curve which indicates the deceleration of the desaturation process. As expected, the evaporation was occurring at a constant rate and became extremely small when the specimen was covered. For the two exposed specimens, the evaporation rate seems to be independent of the initial void ratio or moisture content.

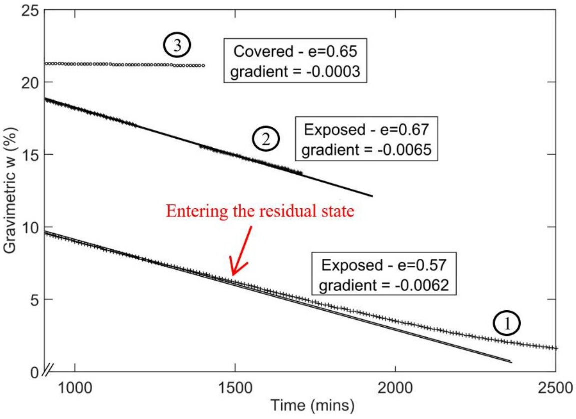


Fig. 4. Evolution of evaporation with time for three specimens. The gradient refers to the linear branch of each curve

Evaporation causes the reduction of the bulk water content of the soil specimen, however a question about the uniformity of moisture within the soil mass is raised. The top layer which is exposed to atmospheric conditions is evaporating faster than the bottom one and this might create a condition of non-uniform distribution of moisture. To investigate this, the moisture content of three specimens was determined by drying out in the oven samples taken from different locations, as shown in Figure 5. In this way, the moisture content profile was obtained. All specimens were prepared at the same initial void ratio (0.64) and similar initial moisture content (20.5%). Specimen A was left exposed to the atmosphere, at the same conditions as those during the SWRC test, for 24 hours. Specimen B was left exposed to the same conditions for 42 hours. Finally, in specimen C, entire test setup was covered by a plastic case which caused a reduced evaporation rate, compared to specimens A & B. The final water content of the three specimens, determined by the balance readings, were 10.1%, 1.6% and 18.0%, respectively.

The gravimetric water content distribution of the three soil specimens is shown in Figure 5. Specimen C shows a more uniform distribution with depth compared to the exposed ones, which is attributed to the slow rate of evaporation. The exposed specimens show a gradual increment of w with depth which reveals that the upper layer evaporates first with the lower layers showing a delay. Even after 42 hours, when the top layer is almost dry, the bottom layer retains a small but significant amount of moisture, especially at the centre. There are, also, differences between the centre of the sample and the sides which are generally drier. It is worth noticing that the PPT is located at the centre of the specimen and at the bottom layer; therefore, suction readings correspond to the water content of the Bottom-Centre part which, in general, seems to be higher than the average moisture content determined by the balance readings.

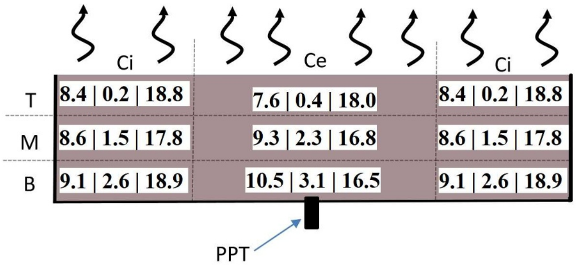


Fig. 5. Distribution of gravimetric water content within the soil mass for the three specimens. Abbreviations: T = Top, M = Middle, B = Bottom, Ce = Centre, Ci = Circumference. The values of *w* (in %) are referred as: Specimen A | Specimen B | Specimen C.

2.3 Axis translation method in consolidation cell

For the axis translation method, the consolidation cell shown in Figure 6 was used. The cell of maximum pressure capacity of 2,000 kPa.was manufactured by VJ Tech It consists of a sturdy cylindrical Perspex wall which exists between the base and the top ceiling, both made of anodized aluminium to minimise corrosion. On the base, an exchangeable ceramic disc with Air Entry Values (AEV) between 0.5 and 15 Bar is fitted to separate the water from the air phase of the soil pores. Below the ceramic disc, a spiral groove is connected to two water lines. The first line is linked to an automatic hydraulic pressure controller that applies the pore water pressure to the ceramic disc and, thus, to the specimen. The second water line is a flush line that is used to remove any trapped air bubbles from the water line and the spiral groove, including those dissolving into the pore water. The hydraulic pressure controller provides pressure control with a resolution of 0.1 kPa. Pore air pressure is applied through a pneumatic pressure controller, inside the consolidation cell, with a resolution of 0.1 kPa. Therefore, suction can be controlled using the axis-translation technique (i.e., by adjusting pore air and pore water pressures) very accurately. The consolidation cell can be equipped with an internal load cell and placed under a load frame if vertical stress is to be applied to the specimen. Sample volume changes can be monitored by recording the sample's height change with the use of a displacement transducer, mounted to the loading ram.

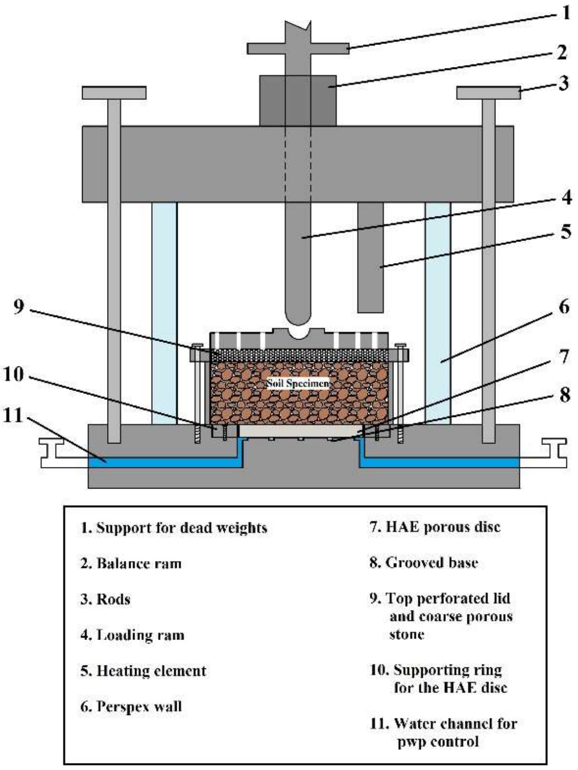


Fig. 6. Testing configuration for the axis translation method.

The consolidation cell has the provision to accommodate a heating element and a temperature probe, thus allowing control of the internal temperature. This provides the ability to control the condensation that is otherwise formed on the cell walls. This is achieved by maintaining a temperature slightly higher than the ambient temperature in the laboratory [16].

Suction is applied to the specimen by adjusting the pore air and pore water pressures. Pore water pressure, which is applied through the ceramic disc, is kept constant throughout the test while air pressure is adjusted to the level needed to establish the required difference (i.e., suction). The volume of the water that is moving in and out of the specimen, through the ceramic disc, is measured using the hydraulic pressure controller. The resolution of this measurement is 0.001 cm^3, making volume change determination very accurate. The two pressure controllers are driven by a software package that allows the automatic adjustment of the pressures, while the readings of water and air pressure, water volume, sample height's change and temperature are logged into a PC. The volumetric and gravimetric water contents of the specimen, as well as the degree of saturation, are monitored during the test allowing the user to view them live and better control the stopping conditions for each step.

Prior to the test, the ceramic disc is saturated, using the method described by [17] to ensure the water phase continuity between the pore water and the hydraulic pressure controller. The procedure takes place inside the consolidation cell, without the need to transport the disc and risk of cavitation. After the saturation procedure is completed, water is removed from the consolidation cell and the ceramic disc is covered with a wet tissue for protection until the soil sample is put in place.

Figure 7 shows the desaturation process taken place in the modified consolidation cell under an applied suction of 5 kPa, using the ceramic disc with AEV of 5 Bar. The process continues until there is equilibrium and drainage ceases. This procedure can take considerable time and depends on the grain size distribution of the specimen, the applied suction level and the AEV of the ceramic disc. In this example, approximately 20 days are needed for equilibrium to be established.

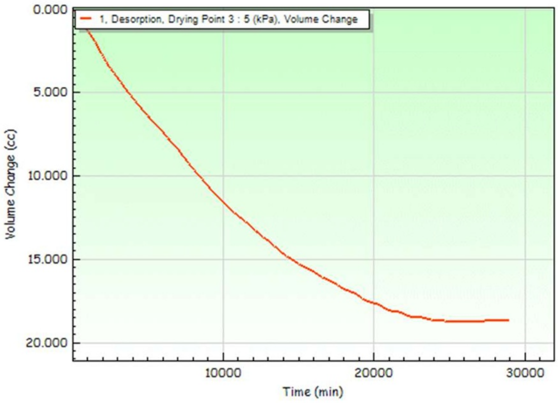
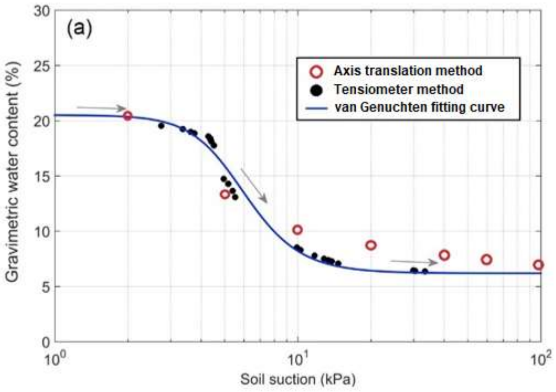


Fig. 7. De-saturation process at the axis translation test.

3 Results and Discussion

The experimental data derived for the drying and wetting SWRC for the silty sand are shown in Figure 8. The initial void ratio of the specimens was 0.64 and 0.66 for the tensiometer and axis translation methods, respectively. The initial gravimetric water content for both specimens was 20.5%. The laboratory temperature during the tests was maintained at 22 °C, with a variation of ± 1.5 °C. Furthermore, in the consolidation cell, the internal temperature was maintained at 24 °C (± 2 °C) to prevent condensation from forming at the cell wall. The ceramic disc that was used in the axis translation tests had an AEV of 3 Bar, while the ceramic stone of the tensiometer had an AEV of 1 Bar. Therefore, the applied suction in the axis translation method could reach 300 kPa without cavitation of the ceramic disc.

The comparison of the drying SWRC for both methods showed a good agreement. The tensiometer method seems to produce lower values of gravimetric water content compared to the axis translation method, especially at high suction. This could be attributed to the difficulty to achieve equilibrium with the tensiometer method, as the sample is continuously drying out due to evaporation. In contrast, the samples in the axis translation are allowed enough time to equilibrate under an applied level of suction. Furthermore, as shown in Figure 5, at high levels of suction (i.e., specimen 2) *w* around the PPT seems to be higher than the measured average moisture content using the balance readings. Since suction is measured locally, at the bottom and central section of the specimen, it could be stated that the real moisture content, corresponding to the measured suction, is underestimated.



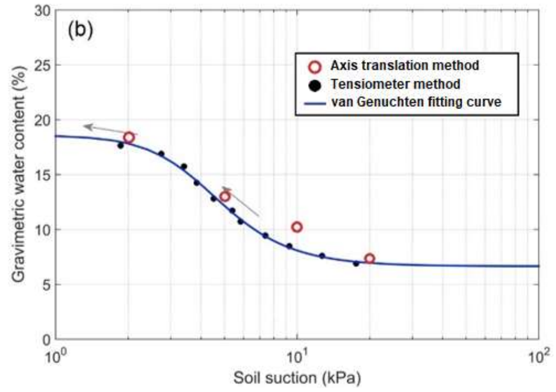


Fig. 8. Soil Water Retention Curves derived with the two methods. (a) drying curve, (b) wetting curve. A van Genuchten curve has been fitted to the experimental results of the tensiometer and axis translation methods .

For the wetting curve, the equalisation points showed again a good match as both methods produce similar results. The wetting curves show hysteretic behaviour against the drying curves, with *w* becoming 18 % and 18.5 % when suction dropped to 2 kPa.

On the results obtained with the tensiometer method, the van Genuchten fitting curve [18] has been drawn. The fitting parameters for the drying and wetting curves are shown in Table 2. The AEV of the silty sand was found to be 4 kPa by using the results from the tensiometer method. The same value was determined by the axis translation method. The residual *w* with the tensiometer method was determined at 5.9 % and was found slightly higher by the axis translation method (i.e., 7.1 %).

Even though the tensiometer method is a continuous procedure of measuring suction and moisture content changes to the specimen, in the axis translation method the equalisation of moisture content within the soil sample is achieved in a more controlled way.

Table 2. van Genuchten fitting parameters of the drying and wetting curves for the tensiometer method. e: initial void ratio - α, n, m: fitting constants - w_r: residual water content - α_{ev}: air entry value – R^2: coefficient of determination.

Parameter	Drying curve	Wetting curve
e (-)	0.64	0.64
α (kPa)	0.182	0.248
n (-)	4.192	3.294
m (-)	0.761	0.696
w_r (%)	6.2	-
α_{ev} (kPa)	3.53	2.51
R^2 (-)	0.9763	0.996

4 Conclusions

The present study describes techniques allowing precise and reliable suction measurements. Two methods were compared and discussed. The axis translation method used in consolidation cell can be successfully used, however, it was revealed that differences to the tensiometer method occur.

Based on the derivation of the SWRC for silty sand, using the tensiometer and the axis translation methods, it is shown that the consolidation cell offers a more controlled procedure to apply suction to the soil specimen, using the axis-translation technique, while accurately monitoring water volume changes. Sample volume changes can, also, be monitored by recording the height changes occurring to the specimen during the drying and wetting processes.

The axis translation method is more time-consuming, compared to the tensiometer method. In the tensiometer method, the derivation of the SWRC is continues, while in the axis translation method, there should be an equalisation period which can vary due to the sample's properties and ceramic stone's characteristics.

Tensiometers allowed recording negative pore water pressure, while in a axis translation suction is applied through the application of positive pore water pressure. This difference may produce different results. This is due to the stress state and history that have a significant impact on the hydraulic behaviour of tested material.

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