The Soil-Water Characteristic Curve and Determination Methods

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Abstract

The Soil-Water Characteristic Curve (SWCC) is a fundamental concept in soil mechanics and geotechnical engineering. It defines the relationship between soil suction and water content and provides valuable insight into the hydraulic behavior of soils. Accurate determination of the SWCC is crucial for various geotechnical applications, such as slope stability analysis, foundation design, and groundwater flow modeling. This paper highlights some different methods used to determine the SWCC, including laboratory tests like the axis translation, filter paper method, osmosic technique, tensiometer, vapor technique, and some estimating methods. Technological advancements have greatly enhanced the accuracy and efficiency of SWCC measurements, leading to improved decision-making in geotechnical projects.

Key words: soil-water characteristic curve (SWCC), hysteresis, axis translation ,filter paper ,vapor technique ,tensiometer , estimating methods

1. Introduction

The presence of matric suction in unsaturated soils is one of the major causes of variations in the behavior of saturated and unsaturated soils. Understanding the behavior of unsaturated soils requires investigating the matric suction present in these soils. On the other hand, the matric suction in these soils is dependent on the soil moisture content. Among them, the soil-water characteristic curve establishes a suitable relationship between the matric suction present in unsaturated soils and the moisture content, which provides a way to explain the variations in matric suction in these soils.

Most geotechnical engineering problems involve an unsaturated soil region. Conventional behavioral analyses do not consider this soil region due to a lack of understanding and the relative importance of geotechnical issues. Many structures, such as piles, tunnels, pavements, soil slopes, retaining walls, and landfill liners, are often constructed in contact with unsaturated soil and are influenced by moisture changes. Moisture variations can significantly affect the mechanical behavior of soil. A large number of soil collapse incidents have been reported in all over the world after rainfall. Therefore, considerable attention has been paid to the residual volume change of unsaturated soil due to suction changes (or moisture content). Changes in the water content of unsaturated soils are shown in a graph illustrating the relationship between soil water content and suction, known as the soil-water characteristic curve (SWCC). There is a significant difference between the curves in the drying phase (increasing matric suction) and wetting phase (decreasing matric suction). This difference is due to a phenomenon called hydraulic hysteresis, which plays a crucial role in controlling soil properties such as shear strength, volumetric changes, and settlement [1, 2 ,3, 4, 5, 6, 7].

In this article, initially, the effect of hysteresis is discussed, and then some laboratory methods for obtaining the soil-water characteristic curve (SWCC) are presented, along with some estimation methods proposed by researchers.

Table 1: summry of commn laboratory techniques for measuring and controling soil suction

technique		Suction component	Measure suction from/controlsuction with	Suction range(Mpa)
measure suction	tensiometer	Matric	Nagative pore-water pressure	0-0.1
	Filter paper	Matric/total	Water content of paper	0.1-30
control suction	Vapour equilibrium	total	Salt suction	3—100
	Axial translation	Matric	Air pressure	.01-1.5
	osmotic	Matric	Osmotic pressure	0-1

2. hysteresis

Soil suction is composed of two components, matric suction which includes capillary suction and osmotic suction (or salt suction). SWCC relates matric and/or total suction to volumetric water content or degree of saturation. A comprehensive description of the testing techniques commonly used for measuring or controlling soil suction can be found in many sources [8, 9, 10, 11, 12, 13, 14]. The best technique for determining SWCC depends on the intended application, available human and financial resources, and the magnitude of suctions that need to be induced. Table 1 summarizes the working principles and application ranges of these techniques.

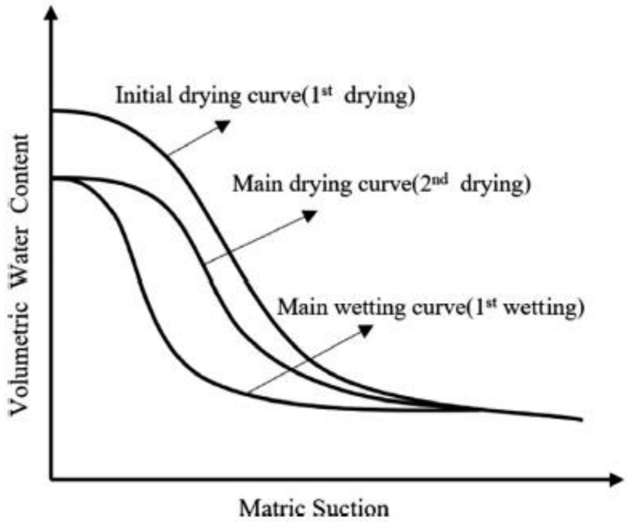

Figure 1 : Schematic of SWCC hysteresis

3.Tensiometer

3.1. Evolution of the Tensiometer

Sometimes in literature, users record pressures below -100 kpa using a tensiometer, but until the work of [15] was published, the geotechnical community was unaware of the possibility of creating a tensiometer that could reliably measure negative water pressures, up to -1500 kpa. This work created a new class of tensiometer called the High Capacity Tensiometer (HCT), which uses high-value ceramic entry pressures (0.3, 0.55, 1.5 Mpa) and is designed to allow access to the water reservoir of the device the actual tensile pressures.

The design of HCT [15] and subsequent designs were developed to delay cavitation inhomogeneity in the water present in these devices. This includes minimizing the volume and surface area of the internal water reservoir to reduce the potential number of nucleation sites, aiming to statistically decrease the probability of experiencing unpredicted tensile failures[15]. A second modification introduced by [16] involves the elimination of any materials that serve as good sources for nucleation sites, such as O-rings and elastomers, from the design of the tensiometer. The influence of elastomers on the behavior of HCTs has been demonstrated by [17]. In the initial version of the developed tensiometer at the University of Cambridge by [17], an elastomer was used in the design to isolate the pressure sensor from external stresses. Despite measuring stresses exceeding 100 kpa, these initial samples showed a wide range of maximum measurable suction pressures from 270 kpa to 480 kpa. When the elastomer was removed from the sensor design, nucleation only occurred at stresses higher than the nominal input air pressure. This change in maximum attainable suction pressure has also been reported in the observations of [18], where an O-ring was also used in the design.

3.2. Drawback of the Tensiometer

Unlike measuring positive pore water pressure, measuring negative water pressure has unique challenges, especially in interpreting suction data and in long-term measurement of soil suction. When measuring suctions using tensiometers, it is not always clear if the tensiometer has stopped registering the actual suction value. In fact, it has been argued that the biggest challenge associated with tensiometer measurements is discerning a good measurement from a bad measurement [19]. This challenge has been precisely demonstrated by [17, 20]. The second major challenge that current soil suction measurements face is their ability to obtain relevant long-term measurements. Although the pressurization process can reduce the amount of trapped gas in cracks, it can never completely eliminate it. It has been previously noted that the desorption process can slowly lead to bubble growth in the long term. Therefore, the stabilization resulting from the pressurization process must be considered temporary - the retained water in the reservoir is unstable and all tensiometers will eventually experience nucleation. However, there is currently no empirical data to predict how long a tensiometer can remain active in high suctions.

3. Axis translation

The axial translation technique is the most commonly used technique for suction control. Early developments of this technique began with the pressure plate outlet technique ([21],[22]). The axial translation technique is associated with a matrix suction component, in which the water potential is controlled using liquid phase transport through a saturated interface—typically a saturated high-entrainment value (HAEV) ceramic disc or a cellulose acetate membrane. Permeable to soluble salts This method involves transferring the reference pore air pressure through artificially increasing the atmospheric pressure in which the soil is immersed. Consequently, if the incompressibility of soil and water particles is assumed that is, if the curvature of the menisci is not strongly affected the negative pore water pressure increases by an equal amount. Converting the pore water pressure to the positive range allows its measurement [23] and thus its control if the water pressure is adjusted through a saturated interface in contact with the sample. This technique has been experimentally evaluated by [24] and by [25], with soils with continuous air phase and degree of saturation varying between 0.76 and 0.95.

3.1.Range of axis translation technique

The range of the axis translation technique for measuring or controlling matric suction is limited by two factors [23]: the maximum air pressure that can be applied to the system and the amount of air input into the ceramic filter. In practice, the maximum measurable suction using the axis translation technique is entirely dependent on the input value of ceramic air, as the highest air input value in currently available ceramics is approximately 1500 kpa.

3.2. Drawback of axis translation technique

3.2.1. Equilibrium Time

The matric suction translation technique does not provide immediate results when used for applying matric suction. Even in the absence of soil, it takes a few minutes for a ceramic filter to reach equilibrium with changing air pressure, provided that the amount of free water above the ceramic disk is low [26]. When a soil specimen is added to the system, the equilibrium time increases due to the size and permeability of the soil sample. ASTM D-6836-02 standard specifies that the equilibrium time should be controlled based on the suction level and states that a system is considered in equilibrium if it does not discharge water for at least 24 hours for suctions less than 500 kpa. For suctions between 500 and 1000 kpa, this time should be 48 hours, and for suctions exceeding 1000 kpa, water should not be discharged for at least 96 hours. Many researchers have considered the behavior of equilibrium time, some reported that equilibrium was not achieved [27], while others reported that equilibrium was reached [28]. A closer look at the data in these articles shows that the conditions set by ASTM D-6836 were not fulfilled. Therefore, one of the challenges associated with the matric suction translation technique is the potentially long equilibrium time for each applied suction.

3.2.2. Moisture Loss Through system

The most visual way to apply high air pressure needed for the axial translation technique is to use compressed air. However, this can lead to hidden consequences of completely wrong measurements in low suctions. If a suction of 50 kpa is to be applied to a soil sample, the equivalent relative humidity should be 99.96%. In the case of output air from the compressor with a relative humidity of 99.7% (which is excessive and feasible), the equivalent suction should be about 400 kpa. This difference destabilizes the system because equilibrium is never achieved. In order to minimize this effect, a closed system may be adopted using nitrogen. The numerical analysis of the effect of moisture loss through compressed air lines was performed by [29].

3.2.3. Air Diffusion

Long-term equilibrium times are associated with the axis translation technique off-gassing experiments, particularly susceptible to air release processes [30] suggest that experiments lasting more than one day (without reaching equilibrium) experience air release. As mentioned earlier, if there is a bubble in the water tank, the measured volume changes become insignificant.

4.Osmotic technique

In the osmotic technique [31], a sample is placed in contact with a semipermeable membrane (permeable to water), while an aqueous solution containing large-sized polyethylene glycol (PEG) molecules circulates behind the membrane. PEG molecules cannot pass through the membrane, and as a result, osmotic suction is applied to the sample through the membrane. Due to the membrane's permeability to salt dissolved in water, the osmotic technique controls the suction of the matrix, similar to the translation technique. The amount of applied suction depends on the concentration of the solution; the higher the concentration, the greater the suction. The relationship between suction/concentration will be discussed in more detail later.

4.1. Advantage and drawbak of osmotic technique

In comparison to the axis translation approach, the osmotic technique offers the advantage of accurately reproducing the conditions of water uptake in real situations without the need for artificially applied air pressure. It is believed that this advantage is particularly significant in high saturation degrees, where the continuous flow of air is hindered by the presence of air bubbles, and potential artifacts created by the application of air pressure cannot be guaranteed.

The technological advantage of the osmotic method is that there is no need for the application of air pressure (thus no issue of air release). High suction pressures can easily be applied using high-concentration PEG solutions. It has been demonstrated that the upper limit of this technique can be increased to about 10 Mpa [32], and a controlled pressure gauge test with osmotic suction at 8.5 Mpa has been presented by [33]. This extension to high suction is apparently simpler than using the centrifugation technique [34].

The main problem with the osmotic method for sensitivity to attacks on cellulose acetate membranes is that it has been the most widely used method. When a semi-permeable membrane fails, PEG solution can infiltrate the sample and the suction is no longer controlled. It appears that this problem is more serious when applying higher suction along the wetting paths (reduced suction), as observed by [35].

5.Vapour control technique

The vapor equilibrium technique with relative humidity control is implemented in a closed system. The water potential of the soil is controlled by the migration of water molecules through the vapor phase from a reference system with a known potential to the soil pores until equilibrium is achieved. The thermodynamic relationship between the total suction of the soil moisture and the relative humidity of the reference system is provided by the psychrometric law [24]. The relative humidity of the reference system can be controlled by changing the chemical potential of different types of aqueous solutions ([36],[37]).

Hydrometric cells were installed inside a chamber with relative humidity control by[38], [39], [40]. The main issue with this experimental setup is the long time it takes to reach moisture equilibrium because vapor transfer is diffusion-dependent. In order to expedite the process, vapor transfer - either through the specimen or along specimen boundaries - can be facilitated by a convection circuit driven by an air pump ([41], [42], [43],[44], [45],[46].

6. Filter paper method

The paper tension method has been used in soil science and engineering for a long time ([47], [48], [49], [50], [51], [52],[53]). Recently, due to its advantages compared to other suction measurement devices, such as affordability and coverage of a wide range of soil suctions, it has been accepted as a compatible test method for measuring soil suction. Essentially, the paper tension method reaches equilibrium with the soil either through vapor flow (total suction measurement) or liquid (matric suction measurement). At equilibrium, the amount of suction in the paper and soil will be equal. After achieving equilibrium between the paper and soil, the amount of water in the paper disc is measured. Then, using the moisture content of the filter paper against the calibration curve of suction, the corresponding suction value is obtained from the curve. This fundamental approach is proposed by the standard test method ASTM D 5298 [54] for measuring soil suction using filter paper. In other words, ASTM D 5298 [54] uses a single calibration curve that is used to deduce total and matric suction measurements. The ASTM D 5298 [54] calibration curve is a combination of wetting and drying curves. However, researchers have shown that the wetting and drying calibration curves do not correlate, observations that have also been made by [55].

6. Estimating methods

Estimating methods for determining the soil water characteristic curve can be classified into three categories. Each of these estimation methods has its advantages and limitations, and the choice of method depends on the available data, the desired level of accuracy, and the specific objectives of the study Below, we will discuss some of the models proposed by researchers so far.

Group 1:

In this group, the prediction of humidity percentage in the desired soil is carried out based on statistical methods. The basis of the work in this group is as follows: firstly, the relationship between the percentage of humidity in the sample and the percentage of the constituent particles (such as clay, silt, and sand) is established. Additionally, some soil properties such as apparent density are presented. Then, regression is utilized to determine the coefficients of this relationship in different soils, and the existing data is used for analysis. Some of these relationships are presented in table 2.

Table 2: summary of common estimating methods about group 1

researchers	Formula	guide
Gupta and Larson[56]	$\theta p = a^{*}Sand(\%) + b^{*}Silt(\%) + c^{*}Clay(\%) + d^{*}Om(\%) + e^{*}Dbd({}^{gr}/_{cm^3})$	*Om*= Mass percent of organic matter *Dbd= Dry bulk density of soil* *Θp* =The percentage of moisture in the suction *a b c d e*= Constant coefficients
Rawls et al[57]	$\theta p = a + b^{*}Sand(\%) + c^{*}Silt(\%) + d^{*}Clay(\%) + e^{*}Om(\%) + f^{*}({}^{Mg}/_{m^3})$	*Θp* =The percentage of moisture in the suction *a b c d f e*= Constant coefficients
Tomasella and Houdnet[58]	$\theta p = a^{*}Silt(\%) + b^{*}Clay(\%) + c$	*Θp* =The percentage of moisture in the suction *a b c* = Constant coefficients

Group 2:

In this group, in the first stage, the model suggested coefficients are determined by fitting the proposed model to the experimental data. In the second stage, for predicting the soil water characteristic curve, one of the regression methods is used to determine the model coefficients for the desired sample using the information from the previous stage. In the last stage, for the given suction, the volumetric moisture content of the sample is determined using the model coefficients determined in the second stage. Some of these relationships are presented in the table 3.

Table 3: summry of commn estimating methods about group 2

researchers	Formula	guide
Gardner [22]	$\theta = \frac{1}{1 + a\psi^{n}}$	Θ The percentage of moisture in the suction a n= Constant coefficients ψ amount of suction
Brooks and Corey[59]	$\theta = (\frac{\psi_b}{\psi})^{\lambda}$	Θ The percentage of moisture in the suction ψ amount of suction ψ_b= *Suction air entry*
van [60]Genuchten	$\theta = \frac{1}{1 + Aexp(a\psi - B)}$	Θ The percentage of moisture in the suction a A B= Constant coefficients ψ amount of suction

Group3:

This group, based on physical principles, focuses on establishing a relationship between the pore distribution mode and the suction existing in them, which ultimately leads to the relationship between the soil moisture content and the soil water suction. Some of the relationships in this category are presented in the table 4.

Table 4: summry of commn estimating methods about group 3

researchers	Formula	guide
Kovacs[61]	$\theta = n - \left[\left(\frac{h_{co}}{\psi}\right)^2 + 1\right] exp\left[-\left(\frac{h_{co}}{\psi}\right)^2\right] * \left[n - 1.4 * 10^{-2}\left(\frac{h_{co}}{\psi}\right)^{\frac{1}{6}}(n^2 - n^3)^{\frac{1}{3}}(h_{co})^{\frac{1}{2}}\right]$ $h_{co} = 7.5 * 10^{-2} * \left(\frac{1-n}{n}\right)\left(\frac{a_k}{D_h}\right) \quad 50 < \left(\frac{a_k}{D_h}\right) < 25 * 10^3$ $D_h = \left(\frac{10}{7 * logc_u} + 1\right) * D_{10}$	n = porosity a=shape factor D10=Diameter size of seeds Cu=uniformity coefficient ψ suction value
Aria and Paris[62]	$\theta_{v_i} = \rho_b \sum_{j=1}^{i}(w_j\rho_p)e \qquad i = 1\ 2\ 3 \ldots n$ $\psi = (2\gamma\cos\theta)/(\rho_w g * R_i\left[\frac{4en_i^{1-a}}{6}\right]^{.5}$ $n_i = 3\left(\frac{w_i}{\rho_b}\right)/(4\pi R_i^3)$	Θ=the amount of moisture in the case suction Ψ= suction value γ= surface tension of water Ri = average particle radius g = gravitational acceleration of particles pocky ratio a=experimental seed coefficient between 1.35 and 1.45 ψj=Corresponding mass percentage
[63] Fredland and Xing	$\theta = \theta_s\left[\frac{1}{ln\left[e + \left(\frac{\psi}{a}\right)^n\right]}\right]^m$ $c(\psi) = (1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)}$	Ψ= value suction ψr=residual suction e=2.71828 n=constant coefficients Θs= saturation humidity Θ=the amount of moisture in the case suction

Conclusion

The unsaturated part of the soil is very important in the water cycle of nature. One of the most important indicators that quantitatively describes the characteristics of this sector is the characteristic curve of soil water, which is used as basic information in many researches. Various methods have been presented by researchers to determine it. In this article, some of the most important and practical ones have been reviewed. The choice of the right method depends on the user according to the time and accuracy required and the cost.

References

[1] C. Gallage, Kodikara, J., & Uchimura, T. , Laboratory measurement of hydraulic conductivity functions of twounsaturated sandy soils during drying and wetting processes, Soils Foundation, 417–430 ((2013)).

[2] S.G. Goh, Rahardjo, H., & Leong, E. C. , Modification of triaxial apparatus for permeability measurement of unsaturated soils, Soils Foundation, 55(1), 63–73. (2015).

[3] W.B. Haines, Studies in the physical properties of soil. v. the hysteresis effect in capillary properties, and the modes of moisture distribution associated therewith, The Journal of Agricultural Science, 97–116. (1930).
[4] D. Hillel, ntroduction to environmental soil physics. , Soil Science, (2003).
[5] F. Masrouri, Bicalho, K. V., & Kawai, K, Laboratory hydraulic testing in unsaturated soils., Geological Engineering, , 691–704. (2008).
[6] H.Q. Pham, Fredlund, D. G., & Barbour, S. L. , A study of hysteresis models for soil–water characteristic curves, Canadian Geotechnical Journal,, 1548–1568. (2005).

[7] K. M, ffective stress and compressibility of unsaturatedclayey soil under drying and wetting cycles. , Periodica Polytechnica Civil Engineering 64(4):999-1006 (2020).
[8] R.H. Fredlund DG, Soil mechanics for unsaturated soils. , Wiley, New York (1993).
[9] B.J. Ridley AM, . A new instrument for the measurement of soil moisture suction, Ge´otechnique :321–32 (1993).

[10] Rajaee, Arash and Yousefi Kebria, Daryoush and Yousefi, MohammadSadra and Tarighati, Sara,1402,The effect of oil pollution on geotechnical and environmental properties of soils, 10th International Congress on Civil Engineering,Tehran
[11] T.W. Marinho FAM, Tarantino A ,. Measurement of matric suction using tensiometric and axis translation techniques, Geotech Geol Eng (2008).
[12] L.E. Bulut R, Indirect measurement of suction, Geotech Geol Eng (2008).
[13] C.Y. Blatz J, Oldecop LA ,, Vapour equilibrium and osmotic technique for suction control, Geotech Geol Eng (2008).
[14] N.M. Vanapalli SK, Sharma RS. , axis-translation and negative water column techniques for suction control, Geotech Geol Eng (2008).

[15] A. Ridley, The measurement of soil moisture suction, Ph.D. Thesis, University of London, 1993.
[16] B.J. Ridley AM, . Measurement of suction in materials which swell, Appl Mech Rev:727–732 (1995).

[17] B.M. Take WA, Tensiometer saturation and the reliable measurement of matric suction, Geotechnique :159–172 (2003).

[18] F.D. Guan Y, ,, Use of tensile strength of water for the direct measurement of high soil suction, Can Geotech J 34:604–614 (1997).
[19] M.L. Tarantino A, ,, Design and construction of a tensiometer for direct measurement of matric suction., Proceedings of 3rd international conference on unsaturated soils (2002).

[20] B.M. Take WA, Tensiometer saturation and the reliable measurement of matric suction, Geotechnique :159–172 (2003).

[21] L.A. Richards, A pressure membrane extraction apparatus for soil suction, Soil Science 51(5):377-386 (1941).
[22] W.R. Gardner, Calculation of capillary conductivity from pressure plate outflow data, Soil Sci. Soc. Am.Proc., 20: 317-320. (1956).

[23] J.W. Hilf, An investigation of pore-water pressure in compacted cohesive soils, Thesis. Technical Memo No.654, United States Bureau of Reclamation, Denver., 1956.
[24] D.G.a.M. Fredlund, N.R., Stress state variables for unsaturated soils, Geotech. Engrg. Div., ASCE, 103(5):447-466. (1977).

[25] A.a.M. Tarantino, L. , A study of the efficiency of semi permeable membranes in controlling soil matric suction using the osmotic technique, Unsaturated Soils for Asia, 303-308, Toll and Leong eds, Balkema (2000).
[26] H. Schreiner, Volume change of compacted highly plastic African clays, PhD thesis, Imperial College, 313 pp (1988).

[27] W.A. Gee GW, Zhang ZF, Campbell GS, Mathison J, The influence of hydraulic nonequilibrium on pressure plate data, Vadose Zone J1:172–178 (2002).
[28] T.S. Leong EC, Rahardjo H, Modified Pressure Plate Apparatus, Geotech Test J 27(3):322–331 (2004).
[29] R. E, Controlled-suction techniques. 4 Simpo´sio Brasileiro de Solos Naˆo Saturados N˜ SAT, Gehling WYY, Schnaid F (eds) PortoAlegre, Brasil,pp 535–542 (2001).
[30] R.H. Fredlund DG, Soil mechanics for unsaturated soils, Wiley-Interscience Publications (1993).
[31] D.P.a.C. Y.J., An evaluation of the osmotic method of controlling suction, Geomechanics and Geoengineering: An International Journal, vol. 3 (1),1-11. (2008).
[32] P. Delage, Howat, M.D. and Cui, Y.J.. . The relationship between suction and swelling properties in a heavily compacted unsaturated clay, Engineering Geology, 50: 31-48. (1998).

[33] O.a.M. Cuisinier, F, Influence de sollicitations hydriques et mécaniques complexes sur le comportement d'un sol gonflant compacté, Can. Geotech. J., 42(3): 731–741. (2005).

[34] E.V.a.J. F., Strength and deformation of partly saturated soils. , Conf. Soil Mech. and Found. Eng. 1, 43-46. Rio de Janeiro, Balkema., 1998.
[35] R.A.D.K.a.Z.L. Monroy R., The suitability of osmotic technique for the long term testing of partly saturated soils, Geotech. Testing J. (30)3, 220-226. (2007).

[36] P. Delage, Howat,M.D. and Cui, Y.J. ,. The relationship between suction and swelling properties in a heavily compacted unsaturated clay, Engineering Geology, 50: 31-48 (1998).

[37] A.M. Tang, and Cui,Y.J., Controlling suction by the vapour equilibrium technique at different temperatures and its application in determining the water retention properties of MX80 clay, Can. Geot. J., 42:287-296. (2005).
[38] F. Esteban, Caracterización experimental de la expansividad de una roca evaporítica, Ph. D. Thesis, Universidad de Cantabria. Spain (in Spanish). 1998.

[39] F. Bernier, Volckaert, G., Alonso, E.E. and Villar, M.V. , . Suction controlled experiments on Boom clay, Engineering Geology, 47: 325-338. (1997).
[40] M.V. Villar, Investigation of the behaviour of the bentonite by means of suction-controlled oedometer tests, Engineering Geology, :67-73. (1999).
[41] M. Yahia-Aissa, Comportement hydromécanique d'une argile gonflante fortement compactée, Ph. D. Thesis, Ecole Nationale des Ponts et Chaussées, France., 1999.
[42] J.G. Blatz, J., A system for controlled suction in triaxial tests, Géotechnique, 50(4):465-469. (2000).
[43] X. Pintado, Caracterización del comportamiento termohidro mecánico de arcillas expansivas, Ph. D. Thesis, Universitat Politècnica de Catalunya, Spain (in Spanish). 2002.
[44] E.C. Leong, Tripathy, S. and Rahardjo, H., Total suction measurement of unsaturated soils with a device using the chilled-mirror dew point technique, Géotechnique, 53(2): 173–182. (2003).

[45] L.a. Oldecop, E.E.. , Testing rockfill under relative humidity control., Geotechnical Testing Journal,27(3): 1-10. (2004).
[46] A. Dueck, Hydro-mechanical properties of a water unsaturated sodium bentonite. Laboratory study and theoretical interpretation, Ph. D. Thesis, Lund University,Sweden., 2004.
[47] R.G.a.C.-G. Fawcett, N. , A Filter-Paper Method for Determining the Moisture Characteristics of Soil, Australian Journal of Experimental Agriculture and Animal Husbandry, Vol. 7, pp. 162-167 (1967).
[48] R.G. McKeen, Field Studies of Airport Pavement on Expansive Clay, Proceedings 41h International Conference on Expansive Soils, Vol. 1, pp.242-261, ASCE, Denver, Colorado, 1980.
[49] S.a.H. Al-Khafaf, R. J. , Evaluation of the Filter Paper Method for Estimating Soil Water Potential, Soil Science, Vol. 117,No. 4, 194-199. (1974).
[50] I.S.a.M. McQueen, R. F., Calibration and Evaluation of a Wide-Range Gravimetric Method for Measuring Moisture Stress,, Soil Science, Vol. 117,No. 4, 194-199. (1968).
[51] A.P. Hamblin, Filter Paper Method for Routine Measurement of Field Water Potential, Journal of Hydrology, Vol. 53, No. 3/4,pp.355-360. (1981).

[52] R.J.a.G. Chandler, C. I.. The Filter Paper Method of Suction Measurements, Australian Journal of ExperimentalAgriculture and Animal Husbandry, Vol. 7, pp. 162-167 (1986).

[53] G.E. Swarbrick, Measurement of Soil Suction Using the Filter Paper Method, First International Conference on Unsaturated Soils, Eds.: E. E. (1995).
[54] ASTM Standard D5298-03, "Standard Test Method for Measurement, A. of Soil Potential (Suction) Using Filter Paper, S.a.R.I. Book of ASTM Standards, Vol. 4, No. 8,, W.C. ASTM International, PA.
[55] S.L. Houston, Houston, W. N., and Wagner, A. M., , Laboratory Filter Paper Suction Measurements, Geotech. Test. J.,Vol. 17, No. 2, pp. 185–194. (1997).
[56] S.C. Gupta, andLarson, W. E. , Estimating soil-water retention characteristics from particle size distribution, organic matter percent, and bulk density, Water Resour. Res., 15:1633–1635. (1979).

[57] W.J. Rawls, and Brakensiek, D.L., Estimating soil water retention from soil properties, the Irrigation and Design Division, ASCE, 108(IR2), PP.166-171. (1982).
[58] J. Tomasella, and Hudent, M.G, Estimating soil water retention characteristics from limited data in Brazilian Amazonia, Soil Sci., 163:190-202 (1998).

[59] R.H. Brooks, and Corey, A. T. (1964). "Hydraulic properties, C.S. of porous media." Hydrology Paper No. 3, F.C. Univ., Colo.
[60] C.R. Mckee, and Bumb, A.C. (1987). "Flow testing coalbed, m.p.w.i.t.p.o.w.a.g. In, P.-. SPE Formation Evaluation.
[61] G.S.h.E.S. Kovacs, A. Publishaers, The Netherland.
[62] L.M. 12. Arya, Paris, J.F. (1981). "A physico-empirical model to, p.t.s.m.-c.f.p. size, d.a.b.d.d.S.S.S. of, America Journal.
[63] D.G. Fredlund, and Xing, A. (1994). "Equations for the soilwater, characteristic curve." Can. Geotech. J.