OBSERVATION AND USE OF SOIL SUCTION, 20 YEARS OF EXPERIENCE

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Abstract

Measurement of soil suction is one tool available for evaluation of unsaturated soils. It can be invaluable in estimating the depth of the active zone as well as correlating results from more expensive and time-consuming swell tests. Suction profiles can also be used to evaluate saturated lenses within the vadose zone as an aid to, or in some cases in lieu of, nested piezometers.

Many engineers attempt to assign too much "accuracy" to the results, and consequently get hung up on what the results actually mean. An example of this is the current use of suction values and theoretical, but incorrect, suction profiles by the Post Tensioning Institute's (PTI) slab-on-ground design procedure. The procedure correlates changes in total suction to volumetric movement. The vast majority of research indicates that it is a change in matric suction that drives soil movement.

Soil suction is also a stress state variable, not a stress variable. The difference is that a state variable can be used to evaluate the state of a material, not the actual stress. In unsaturated soils, this means that the suction value can be used to evaluate, for example, if the soil is dry and potentially expansive. However, the suction cannot be used as a stress variable, meaning that a change in the suction value is not the same as a change in stress.

This paper discusses the various methods and limitations of measurement of suction and its practical use in geotechnical engineering. Examples of both the effective use and misuse of suction are presented.

Introduction

Most of the basic research associated with the role played by the pore fluid in a soil was initiated by soil physicists and agronomists during the late 1800's and later transferred to engineering (Krahn and Fredlund, 1972). The concept of soil suction has been used in the geotechnical academic community for more than four decades; however, the rapid advancement in technology and information has resulted in strong interest by engineering consultants relative to the behavior of unsaturated soils. Critical review on the parameters influencing Soil-Water Characteristic Curve (SWCC) was presented by Malaya and Sreedep, 2012. The purpose of this paper is to present observations of a practicing engineer relative to the day-to-day measurement and use of suction data.

It is important to note that "suction" actually consists of two parts; matric suction, and osmotic suction, with the sum of the two being "total" suction. No mater what analysis procedure is proposed, distinction between which specific suction component is used, be it, matric, osmotic, or total, is critical to the application.

The paper is divided into a brief discussion of the definition of suction; how it is measured and limitations of the testing methods in a production laboratory. This is then followed by examples of applications of the data.

Definition of Suction

A discussion of the development of the theory of soil suction is provided by Fredlund and Rahardjo (1993). As a summary, "Soil Suction is commonly referred to as the free energy state of soil water" (Edlefsen & Anderson, 1943). The free energy state can be measured in terms of the partial vapor pressure of the soil water (Richards). The thermodynamic relationship between suction and partial pressure of the pore-water vapor can be written:

ψ = soil suction = $-(RT/v_{wo}w_v) \times \ln(u_v/u_{vo})$ ………………..…..………(1)

where:

R = Universal Gas Constant

T = Absolute Temperature

v_{wo} = Specific Volume of Water (inverse of the density of water)

w_v = Molecular Mass of Water Vapor

u_v = Partial Pressure of Pore Water Pressure

u_{vo} = Saturation Pressure of Water Vapor Over a Flat Surface of Pore Water

u_v/u_{vo} - Referred to as Relative Humidity (RH,%)

If a reference temperature of 20°C is selected, Equation 1 reduces to:

$\psi = -135022 \ln(u_v/u_{vo})$ ……………………………………………….(2)

Equation 2 illustrates that, at a given temperature, soil suction is a function of relative humidity. The term ψ is referred to as total suction since no distinction is made relative to pore water versus water containing soluble salts. The relationship between relative humidity and total suction is shown in Figure 1 (Fredlund and Rahardjo, 1993).

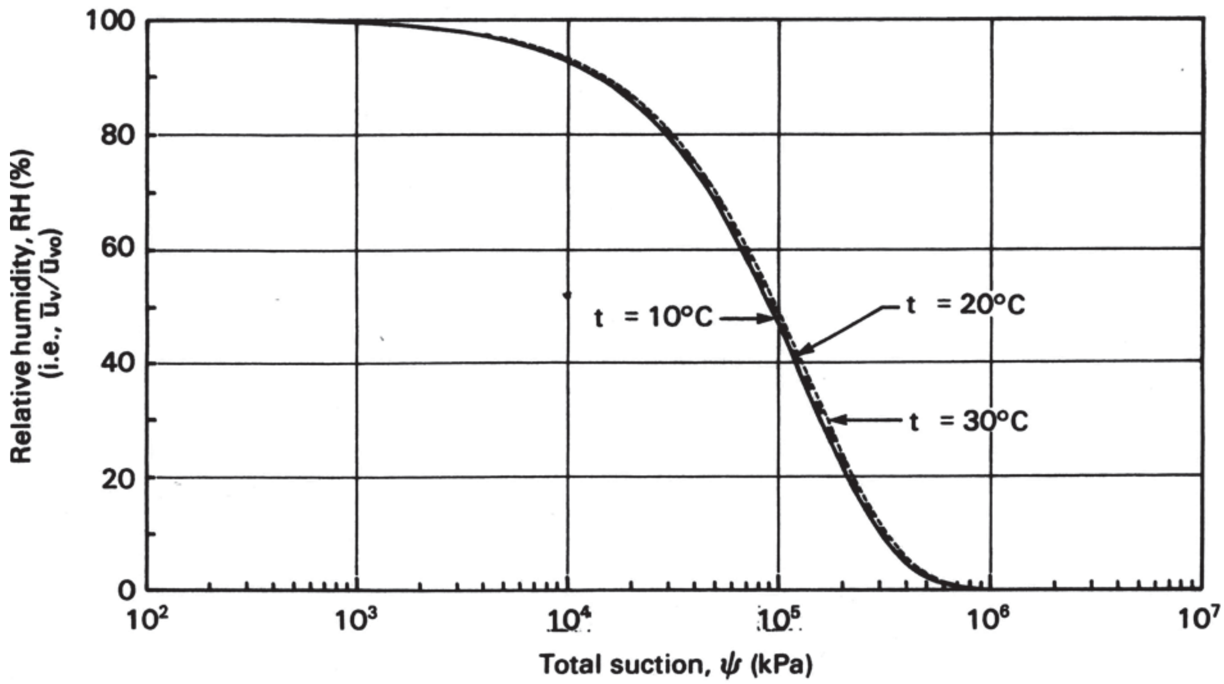

Figure 1. Relationship between relative humidity and total suction. (Fredlund and Rahardjo, 1993).

Total suction is the sum of matric suction and osmotic suction (Equation 3). Matric suction is considered to be the capillary component. Osmotic suction is considered to be the solute component.

$$\psi = (u_a - u_w) + \pi \quad \text{...}(3)$$

where:

$(u_a - u_w)$ = matric suction

u_a = pore-air pressure

u_w = pore-water pressure

π = osmotic suction

From the above discussion, measurement of total suction can be performed by measuring the relative humidity. Direct measurement of the capillary tension, i.e., the surface tension in the contractile skin can be used to measure the matric suction component. Fredlund and Rahardjo (1993), Lu and Likos (2003).

Measurement of Suction

Various methods have been developed to measure the total suction and the matric and osmotic component suctions. In general, if the procedure measures relative humidity, it is measuring total suction.

Common methods used to measure total suction include psychrometers and filter paper (non-contact). Psychrometers measure the relative humidity within a closed space after the space comes into equilibrium with the humidity of the sample. Correlations as shown in Figure 1 are then used to determine the suction.

Filter paper, non-contact method, is used by allowing the filter paper to equilibrate with the humidity of the air within a closed space containing the sample. The moisture content of the filter paper is then obtained and used with a developed correlation between moisture content in the filter paper versus humidity. The humidity is then used to determine the total suction.

The capillary component of suction, i.e., matric suction, can be measured directly by use of tensiometers, null-type pressure plates (axis translation) or filter paper (contact method) or indirectly by the use of thermal and electrical conductivity sensors.

Tensiometers and null-type pressure plates use high-entry ceramic tips or plates. The general concept is that the water in the ceramic will equilibrate with the water in the soil. The tensiometer measures the tension developed within a water reservoir as moisture flows from the ceramic into the soil, while maintaining the atmospheric air pressure. Null-type pressure plates maintain the water pressure at atmospheric while increasing the air pressure. Both procedures require intimate contact between the soil and ceramic tip or plate to assure continuity of the capillary regime.

The filter paper (contact method) and thermal/electrical conductivity sensors measure changes in moisture with the variation in moisture content calibrated to matric suction.

A technique for indirect measurement of osmotic suction consists of a pore fluid squeezer proposed by Manheim (1966) and discussed by Fredlund & Rahardjo (1993). This process consists of squeezing pore fluid from a sample of soil, measuring the electrical conductivity, then comparison with an electrical conductivity/osmotic pressure curve published in the U.S.D.A. Agricultural Handbook No. 60.

Various publications offer excellent discussions relative to each of these procedures. The reader is referred to either Fredlund and Rahardjo (1993) or Lu and Likos (2004). In addition, Pham and Fredlund, 2008, provided two new equations for SWCC. One equation has curve-fitting parameters that bear a meaningful relationship to conventional physical soil properties. The second equation is developed as a conventional curve-fitting equation.

The writer's firm has used numerous procedures and equipment to evaluate osmotic, matric and total suction in a production laboratory. These have included construction of a pore fluid extractor, tensiometers, filter paper (both contact and non-contact), null-type pressure plate extractors, dew point potentiameters, and the Fredlund SWCC device. Observations relative to each method are presented in the following discussion.

Observations

There appears to be two types of limitations relative to engineering use and measurement of soil suction; 1) those imposed by theory, and 2) those imposed by the physical limitations of the equipment and/or revised testing procedures. The following information is offered relative to the writer's observations. The list should be considered to be evolving.

Theoretical Impositions – Suction within any particular sample increases as the soil swells upon reduction of the overburden pressure during sample retrieval. Although this has been addressed from a theoretical perspective in the literature, there is no data published addressing the magnitude of change in suction associated with stress relief due to sampling. Clearly this is an important factor if the value of suction (either total or matric) is used to evaluate the behavior of any particular soil, and especially if a quantifiable correlation between suction and heave is desired.

Another limiting imposition is associated with hysteresis. SWCC typically have hysteresis relative to the drying and wetting portions of the curve as shown in Figure 2 (Lu and Likos, 2003). Analysis of Figure 2 illustrates that it is possible to have two different matric suction pressures for the same volumetric water content. The left side of Figure 2 (the wetting curve) would have a lower moisture content relative to the suction pressure. The right side of Figure 2, the drying curve, has equal suction, but a higher moisture content.

Similarly, the hysteresis in SWCC for soil decreases significantly (Blight, 2013) as soils are not virgin in nature after been subjected to multiple drying and wetting cycle.

Any attempt to analyze shrink or swell movement as a result of changes in the suction pressure would theoretically have to account for whether the entire profile is on the drying or wetting curve. It is entirely feasible that at different locations on a site, different conditions could control.

Similar hysteresis has been identified relative to hydraulic conductivity and matric suction (Lu and Likos 2003).

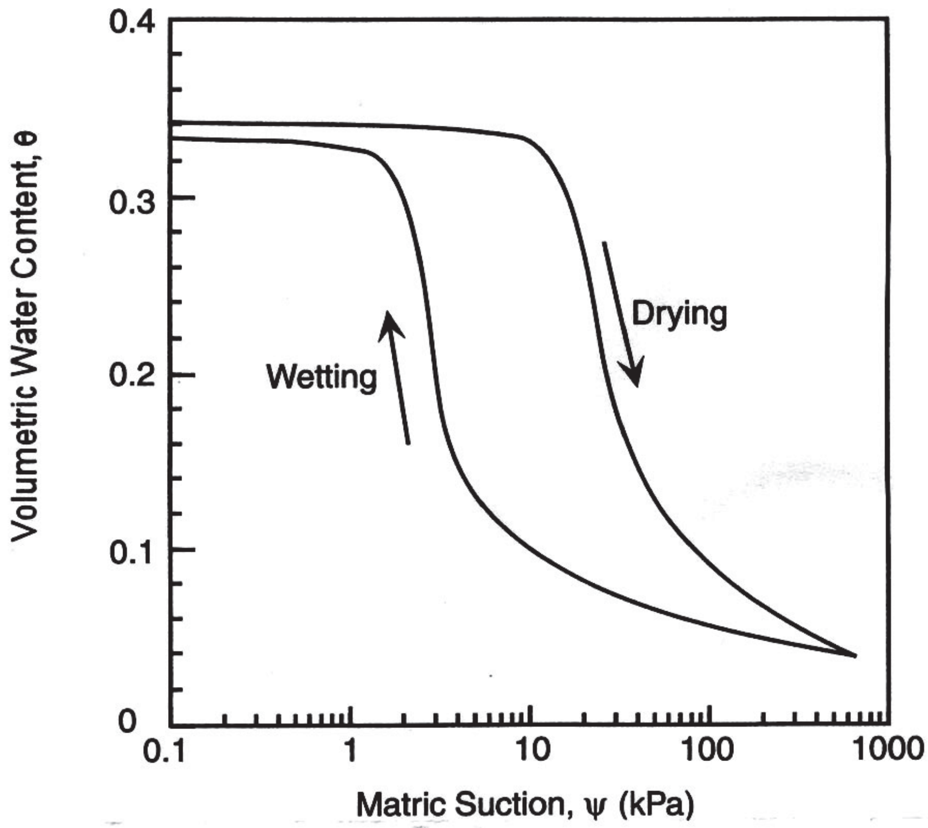

Figure 2. Hysteresis in the suction, volumetric moisture content curve (Lu and Likos, 2003).

Hysteresis creates a significant challenge for the practicing engineer in that it is frequently difficult to determine if the soil is in the drying or wetting phase. An example of the type of conflict that arises is shown by analysis of Figure 2.

As pointed out by Lu (2008), it is also important to understand that soil suction is a stress state variable, not a stress variable. A stress state variable can be used to evaluate the relative state of any particular soil. For example, for two samples of clay with similar material properties, the difference in the degree of expansion can be evaluated by comparing suction values. The sample with the higher suction would be expected to expand to a greater degree than the one with the lower suction. The state of these two samples could also be evaluated by use of the liquidity index, or relative moisture. However, because of the sensitivity of suction to even minor changes in moisture, the suction value can readily distinguish the differing state of the material.

It is incorrect, however, to apply the suction value as a stress variable. This means that application of a change in suction directly to any particular property, be it permeability, strength, or deformation, is incorrect.

<u>Physical Limitations</u> – Review of general literature from academia indicates that a vast majority of research relative to suction is conducted on soils of low to moderate plasticity, i.e., materials with a Plasticity Index (PI) of less than 25. Various complicating factors relative to the actual measurement of suction have been encountered in highly plastic soils. General observations in highly plastic soils are discussed below.

<u>Pore Fluid Extractor</u> – A pore fluid extractor meeting the exact dimensions identified by Fredlund and Rahardjo (1993) was constructed to evaluate the conductivity of the pore fluid and subsequently the osmotic suction. A sample of highly plastic weathered shale was used for the initial test. The sample had a PI of approximately 45, with a moisture content 3 percent points below the plastic limit (PL). Despite high pressure, no fluid was extracted. The pressure warped the steel plunger to the point that it could not be re-inserted into the steel vessel. It is recommended that, if this technique is attempted, a low PI silty clay or clayey silt be used initially to evaluate the effectiveness of the procedure.

<u>Pressure Plate</u> – A Soilmoisture Equipment Corp. pressure plate extractor equipped with a 15-bar ceramic plate has been routinely used to develop the drying portion of SWCC. Good success has been reported on materials with a low to moderate PI (generally less than 25), and on recompacted samples of CH clay.

The writer's firm has had limited success developing the SWCC on undisturbed samples of high PI clay. The samples tend to warp at higher pressure resulting in loss of contact between the plate and sample. Equivalent surcharge pressures equal to 287.282 kilopascal (kPa) have been applied to the sample with limited success to control warping associated with drying of the sample. In addition, the in-situ samples of higher PI clay in the North Texas area have suction values exceeding the 15-bar limiting pressure of the device.

<u>Dew Point PotentiaMeter (WP4-T)</u> – This device is manufactured by Decagon Devices Inc., USA and can be used to evaluate the total suction (the device is basically an enclosed psychrometer). Excellent results have been obtained on all types of materials; however, the time for the device to come to equilibrium can be several hours for CH clay. In addition, for samples of low plasticity and high moisture (conditions of low suction), the mirror within the device appears to remain moist after approximately 10 samples, and thus the device will continuously read "0". It has been found that in these conditions the device needs to "rest" for a period of 30 minutes to 1 hour before additional readings are performed. This delay can significantly affect production. This condition has been overcome by utilizing two devices.

Shah et al., 2006 have shown that WP4 has been less effective considering higher water content for repeatability and total suction below 1000 kPa.

<u>Fredlund SWCC Device</u> – The device is relatively new to the market and is manufactured by GCTS Testing Systems for measurement of the matric suction. It is designed based on a Tempe pressure cell and is intended to be used to develop both the drying and wetting portion of the SWCC curve. The SWCC results obtained to date for the drying portion of the curve have been consistent with available literature.

To use at high pressure (up to 15 bars) with nitrogen gas, the manufacturer recommended non-relieving valves within the control board. These valves have prevented the release of pressure, negating the ability to obtain the wetting portion of the SWCC. Alternative methods to relieve the pressure provided by the manufacturer have not been effective.

Filter Paper – The filter paper method has proven to be a very cost-effective method for obtaining both matric (contact method) and total (non-contact) suction. Whatman #42 paper (currently manufactured by Schliecher & Schuell) has been used exclusively by the writer's firm for over 20 years.

Significant questions have arisen since publication of the procedure in ASTM regarding filter paper calibration curves. ASTM has a single calibration curve. Rahardjo and Leong (2006) recommend one curve for total suction versus various curves for matric suction. An extensive discussion of the filter paper method, to include development of a single calibration curve, is presented by Marinho and Oliveira (2006). Clearly there is some debate as to the appropriate procedure to use to obtain the correct suction value.

Marinho and Oliveira (2006) also reported that the distance between the filter paper and the sample affects the rate of moisture absorption when evaluating total suction. Marinho recommended a distance of 8 mm between the filter paper and sample. This distance is not discussed in the ASTM procedure.

Observations Relative to Use

Despite the forgoing discussion, the use of suction data in day-to-day engineering practice has been beneficial in understanding the behavior of unsaturated soils. Specific examples illustrating use of suction profiles for definition of seasonal drying, variation in site conditions and calculating values for the PTI design procedure for Ground-Supported, Slab-on-Grade Foundations are provided below.

Seasonal Drying – Identification of the zone of seasonal drying of an expansive soil profile is important because of the relationship between the lateral to vertical swell. Laboratory swell tests are routinely performed in an odometer with only vertical swell possible. Engineering judgement is therefore required to assess the potential lateral strain or swell if the laboratory test is to be used to predict surface heave.

One of the common empirical methods used to predict surface movement in the North Texas region was developed by McDowell (1959). This method includes a lateral to vertical strain of 3 to 1. In other words, McDowell divided the measured vertical swell from laboratory samples by 3 to account for horizontal swell. The reduced value was then used to calculate surface movement.

This is a reasonable approach in the seasonally active zone. However, if, for example, site grading results in excavation of the seasonal zone, with potentially expansive soils below the seasonal zone, the horizontal to vertical strain or swell ratio of 3 to 1 would be incorrect since limited shrinkage cracks may be present below seasonal drying.

Data collected from soil samples from Irving, Texas is shown in Table 1. Boring A was obtained in September 2013 following seasonal drying weather. Boring B was obtained in June 2014 following normal seasonal rainfall.

Table 1. Soil Samples from Irving, Texas.

Boring No.	**Depth (m)**	**Moisture Content (%)**	**Plasticity Index (PI)**	**Total Suction (kPa)**	**Swell Test (%)**
Boring A	0.457	12.9		7415.22	
	0.914	17.0		4719.08	
	1.372	24.0	59	3364.07	
	2.743	24.9		2642.03	
	4.267	25.9		1911.38	
	5.791	26.9	39	1288.94	6.7
	7.315	27.9		1254.94	
	8.839	26.8	43	1057.67	5.6
Boring B	0.457	18.0		2249.41	
	0.914	19.2		2103.38	
	1.372	16.5		2052.15	
	2.743	25.5		1714.11	
	4.267	23.8		1405.29	
	5.791	19.2	47	1826.15	10.9
	7.315	20.8		1171.63	
	8.839	23.0		1251.11	
	10.363	19.3		979.63	

Suction profiles illustrating seasonal drying on a site in Irving, Texas is shown in Figure 3. Comparison of the two curves shows a seasonal depth of approximately five meters. For swell tests performed on samples from the upper five meters, a lateral to vertical modification of 3 to 1 may be applicable. For potential swell below the seasonal zone (for example, if site grades required excavation of five meters), there may not be any reduction in swell associated with lateral strain because of the lack of shrinkage cracks. By understanding the suction profile, a more educated estimate of the potential for surface movement can be made.

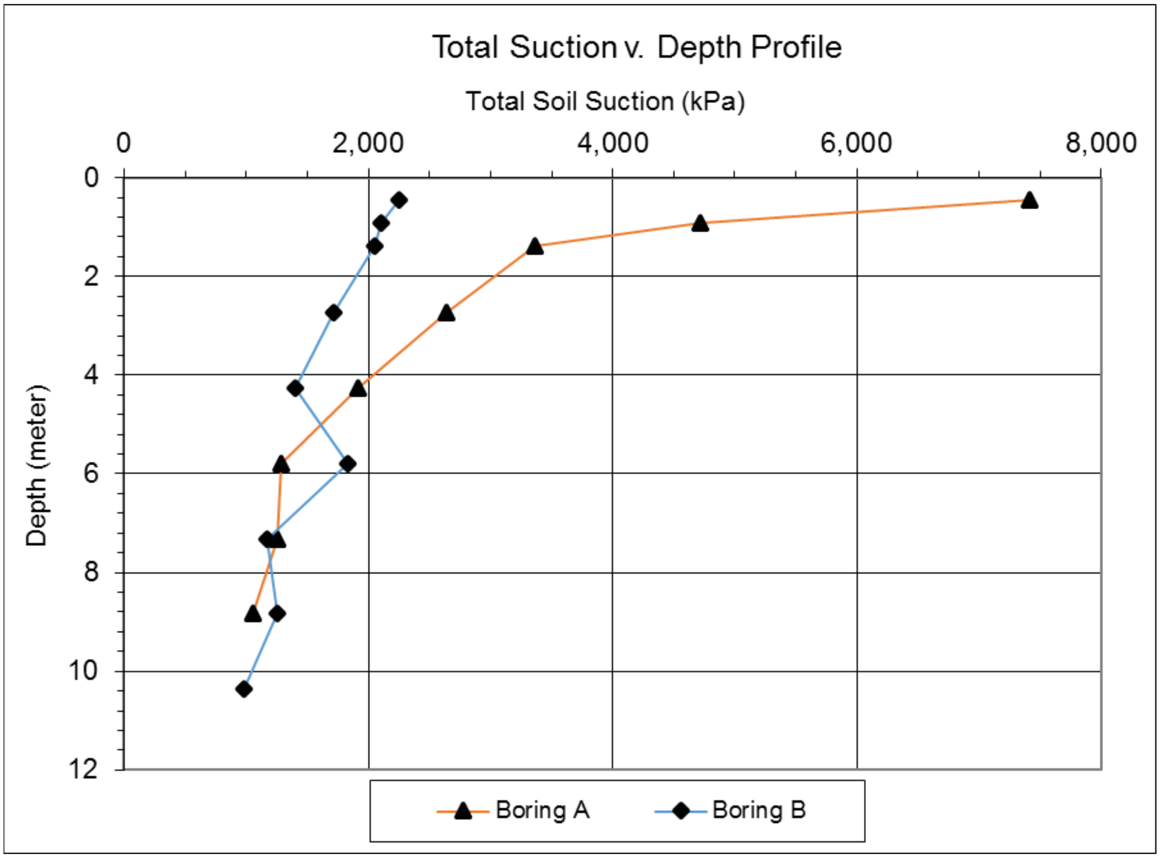

Figure 3. Suction profiles illustrating seasonal drying.

Variation In Conditions Between Borings - This example is illustrated in Figure 4. Analysis of the relative moisture profile, between the two borings indicates that Boring C has a relatively "drier" profile; however, this could also be associated with a change in material type. However, the total suction profiles clearly indicate that the soils in Boring C are drier because of the higher suction.

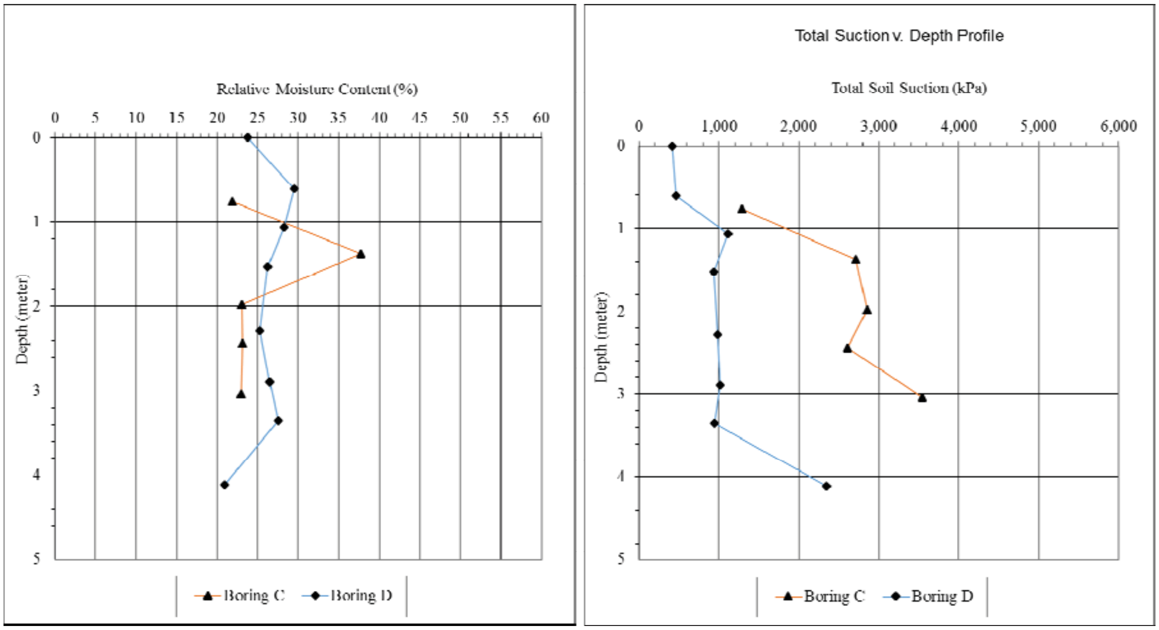

Figure 4. Illustration of variation in moisture and total suction between borings.

Although this may seem to be a relatively simple example, the relevance of understanding suction profiles becomes apparent when using the VolFlo program as recommended by the Post Tensioning Institute (PTI) (2004) for design of ground-supported slabs. This analysis is performed in the example below.

The other feature to note about Figure 4 is the relative magnitude of the suction values. Because the measured suction is total, it includes both the matric and osmotic components. The particular material shown in Figure 4 is a residual soil weathered from clayey shale and as such, the osmotic component is a significant part of the total suction. The higher values in Boring C exceed the 4.5 pF value discussed in the PTI literature.

Example - Development of the design values for a ground-supported post-tensioned slab was performed considering the two suction profiles illustrated in Figure 4, and the "trumpet" shaped profile recommended in the PTI manual. To simplify the study, one soil type was used in the profile.

Three analyses were performed from soil samples in Borings C and D for the edge lift condition (dry to wet suction profile). The results are shown in Table 2. For Condition 1, the starting profile used was the one measured in Boring C. For Condition 2, the starting profile was the one measured in Boring D. For Condition 3, the starting profile was the default profile recommended in the PTI literature. For each case, the end profile was the default profile from the VolFlo program.

Table 2 illustrates, the magnitude of the edge lift variable, y_m, varies significantly between the "default" trumpet shape and the suction profile measure in Boring C. Part of the reason for the large variation in the edge lift value is associated with the use of total suction, which because of the inclusion of the osmotic component, results in suction values exceeding those recommended in the PTI procedure.

Table 2. Calculated PTI design values for Suction Profiles Shown in Figure 4.

Condition	Edge Lift Distance, e_m, meter	Edge Lift, y_m, centimeter
1 (Profile Boring C)	1.067	23.876
2 (Profile Boring D)	1.067	14.478
3 (Default Profile)	1.067	9.652

Conclusions

Available technology allows for the rapid and relatively easy determination of soil suction. A review of various publications indicates that the methods used to arrive at the "true" value of suction is still evolving and will be subject to continued debate in academic circles.

It should be remembered that suction is a stress state variable, not a stress variable. As a stress state variable, the specific value of suction is not relevant; rather what is relevant, is the relationship between suction values. In other words, the relationship between values is important, not the specific value.

References

Fredlund, D.G. and Rahardjo, H. (1993), *Soil Mechanics for Unsaturated Soils*, John Wiley & Sons, Inc.

Lu, Ning and Likos, William J. (2004), *Unsaturated Soil Mechanics*, John Wiley & Sons, Inc.

Rahardjo, H. and Leong, E.C. (2006), "Suction Measurements", *Unsaturated Soils, 2006*, Proceedings of the Fourth International Conference on Unsaturated Soils, ASCE Publication No. 147, pp. 81-104.

Marinho, F. and Oliveira, O.M. (2006), "The Filter Paper Method Revisited", *Geotechnical testing Journal*, Volume 26, Number 3, pp. 250-258.

Post-Tensioning Institute. (2004). "*Design of Post-Tensioned Slabs-on-Ground, Third Edition*. Phoenix, Arizona.

Lu, Ning. (2008), "Is Matric Suction a Stress Variable". *Journal of Geotechnical and Geoenvironmental Engineering*. Volume 134, Number 7, pp. 899 - 905.

McDowell, C., (1959), "The Relationship of Laboratory testing to Design for Pavements and Structures on Expansive Soils". Quarterly of the Colorado School of Mines, Vol. 54, No. 4, pp. 127 - 153.

Krahn, J., and Fredlund, D.G., (1972) "On Total, Matric and Osmotic Suction." Soil Science, Vol. 114, No. 5, pp. 339 – 348.

Malaya, C., and Sreedeep, S., (2012) "Critical Review on the Parameters Influencing Soil-Water Characteristic Curve." Journal of Irrigation and Drainage Engineering, Vol. 138, No. 1, pp. 55 – 62.

Pham, H.Q. and Fredlund, D.G, (2008) "Equations for the Entire Soil-Water Characteristic Curve of a Volume Change Soil" Canadian Geotechnical Journal, Vol 45, No. 4, pp. 443 – 453.

Blight, G.E. (2013) "Unsaturated Soil Mechanics in Geotechnical Practices" Leiden, the Netherlands, CRC Press.

Arifin, Y.F., and Schanz, T. (2009) "Osmotic Suction of Highly Plastic Clays." Acta Geotechnica, Vol 4, No 3, pp. 177 - 191.

Shah, P.H., Sreedeep, S., and Singh, D.N., (2006) "Evaluation of Methodologies Used for Establishing Soil-Water Characteristic Curve." Journal of ASTM International, Vol. 3, No. 6, paper ID JAI14084.