Measurement of the soil water retention curve: practical considerations

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ABSTRACT: Recognising the importance of the soil water retention curve (SWRC) in establishing unsaturated soil properties, this paper aims to provide a review of various commonly used laboratory measurement techniques. Following a brief overview of various methods, the results of several SWRCs measured at the University of Pretoria using different techniques are discussed with an emphasis on practical aspects associated with each approach. The results indicate that SWRC measurement using the continuous tensiometer technique combined with either dewpoint hygrometer or filter paper measurements provide an efficient means to measure drying SWRCs over a wide suction range in a reasonable time frame.

1 INTRODUCTION

In geotechnical engineering practice it is common to approach analyses and designs based on the assumption that the soil in question is fully saturated. With the emergence of unsaturated soil mechanics, it has become increasingly recognised that the assumptions inherent in saturated soil mechanics are often not valid and as such, a considerable effort has been incurred globally to better understand the processes and mechanisms associated with the behaviour of unsaturated soils.

While the presence of the air-phase in the soil matrix is accompanied by many complexities, it is generally accepted that a wealth of useful information can be obtained from one test, namely the establishment of the soil water retention curve (SWRC). Fredlund (2018) stated how, together with saturated soil properties, use of the SWRC has provided a means of moving unsaturated soil mechanics into routine engineering practice. However, an issue with SWRC measurement is that it has historically been shown to be a time consuming and cumbersome process. This fact is highlighted by the information provided in Table 1 where the response time of various suction measurement devices are listed.

The aim of this paper is to illustrate advances over the past few decades regarding the measurement of SWRCs. Starting with older, more established procedures, an overview of methodologies that can be utilised to measure the SWRC are provided. Thereafter, the benefits and practical considerations of the more advanced state-of-the-art procedures are discussed.

Table 1. Response time of suction measurement techniques (Ridley & Burland 1993)

Measurement technique	Equilibrium time
Vacuum desiccator	Months
Psychrometer	Months
Filter paper (non-contact)	Weeks
Filter paper (contact)	1 week
Porous block	Weeks
Thermal block	Days

2 MEASUREMENT OF SOIL SUCTION AND SWRCs

The soil water retention curve describes the relationship between soil suction and moisture content. If a soil is dried out from a saturated state, suction within the soil will increase and the relationship between suction and moisture content will describe the primary drying curve. Conversely, if a soil close to its residual moisture content is progressively wetted up, suction will reduce and the primary wetting curve will be obtained. If a drying or wetting process is stopped part way and reversed, a scanning curve will be followed (Al-Haj & Standing 2016, Toll 2012). Since the value of suction at a specific moisture content will differ depending on the path taken to achieve that moisture content (primary drying, primary wetting or scanning) it is imperative to consider which branch of the SWRC is applicable to a given engineering problem. An example of a typical SWRC envelope, bound by the primary wetting and drying curves, are included in Figure 1.

An important aspect to consider when establishing SWRCs is the method used to measure suction. While the various methods used to measure suction can vary greatly in terms of their complexity, developments that have taken place over the past few decades have been primarily directed at extending measurement range and/or reducing measurement time. The following section provides a brief overview of four commonly used laboratory measurement techniques.

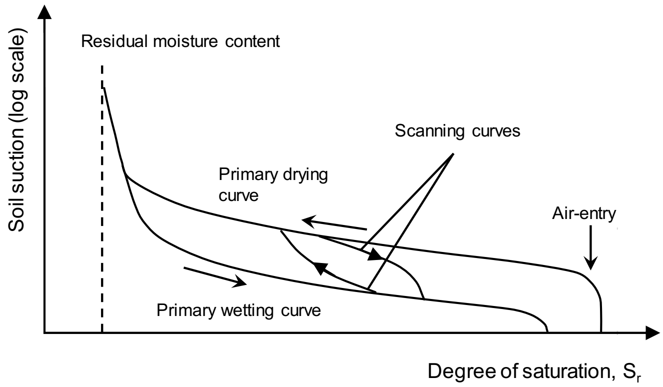

Figure 1. Typical soil water retention curves

3 SUCTION MEASUREMENT TECHNIQUES

3.1 *Pressure plate test*

A widely used method for measuring soil suction is through the use of the pressure plate apparatus depicted in Figure 2. In this test, a soil sample is placed on a saturated ceramic disc enclosed in a steel pressure vessel. The apparatus allows for soil air pressure to be controlled by varying air pressure within the cell. Pore water pressure can also be controlled through the water reservoir beneath the ceramic disc (Toll 2012). Suction is then controlled using the axis translation technique by imposing a known air pressure to the compartment containing the sample. This initiates the flow of water from the sample, through the ceramic disc to a water reservoir which is usually vented to the atmosphere. This process is continued until equilibrium is reached between the water content in the specimen and the applied matric suction (measured as the difference between the water pressure on the one side of the disc and the air-pressure on the other side of the disc) (Lu & Likos 2004). The measurement capacity of this apparatus is governed by the air-entry value of the ceramic disc which is typically limited to 1.5 MPa. While this method is reliable, it can be extremely time consuming.

A study conducted by Lourenço (2008) revealed how SWRCs measured by tensiometer using continuous drying (see Section 3.4) took two days whereas an SWRC on the same material measured with the pressure plate apparatus took 7 weeks.

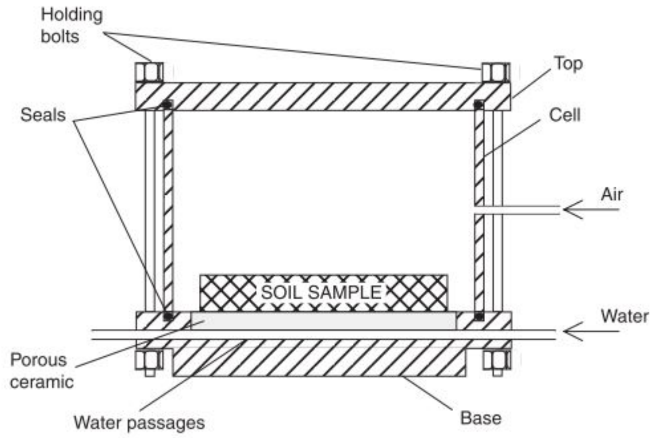

Figure 2. Pressure plate apparatus (Toll 2012)

3.2 *Filter paper method*

A useful approach to measuring soil suction which has existed for a considerable period of time, is the filter paper method. First proposed by Gardner (1937), it is a relatively simple method, capable of measuring both total and matric suction over a wide range up to 30 MPa (Al-Haj & Standing 2015, Ridley & Burland 1993). The principle on which the method is based is that hydraulic equilibrium between the soil water and an initially dry filter paper is established (a process for which ASTM D5298-16 recommends a period of seven days). Once equilibrium has been established, the water content of the filter paper is related to a value of soil suction through the use of a predefined calibration curve. Examples of calibration curves for Whatman No. 42 filter paper can be found in various publications (ASTM D5298-16, Chandler & Gutierrez 1986, Hamblin 1981). One benefit of the filter paper measurement technique is that it has the capability of measuring either total or matric suction depending on how hydraulic equilibrium between soil water and filter paper is achieved. If equilibrium is established by direct contact between the filter paper and soil sample, matric suction will be measured. Conversely, if filter papers are placed in a sealed container with a soil specimen and equilibrium is achieved through the vapour phase (non-contact measurement), total suction will be measured (Kim et al. 2016, Lu & Likos 2004).

3.3 *Dewpoint hygrometer*

The dewpoint hygrometer (also known as the chilled mirror hygrometer) is an instrument which allows total suction to be measured in the medium to high suction range (up to 300 MPa). This method of suction measurement is based on the thermodynamic relationship that exists between total suction and relative humidity. The procedure involves placing a small specimen (~10 cm^3) into a sealed chamber containing an exposed mirror. The temperature of the mirror is gradually reduced until condensation occurs on its surface. At this stage, the dewpoint and soil temperature are used to determine the relative humidity above the soil sample which, at temperature equilibrium, is a direct measurement of soil suction (Decagon Devices Inc 2015). In addition to its very high measurement capacity, an attractive characteristic of this measurement technique is that a single measurement can be obtained within approximately 15 minutes.

3.4 *Tensiometer method*

With development of high-capacity tensiometers (HCTs) capable of measuring matric suction in excess of a megapascal (Ridley & Burland 1993, Lourenço et al. 2006) an increasingly common approach to SWRC measurement is to use HCTs in conjunction with electronic mass balances such that changes in moisture content can be recorded (Toker et al. 2004, Teixeira & Marinho 2006). This process can be carried out either continuously or in discrete stages (where drying or wetting is performed in stages) with either approach being significantly faster than other methods. Substantial developments in this approach to SWRC measurement have taken place at Durham University where the setup has been extended to accommodate continuous volumetric measurements throughout a drying or wetting cycle (Lourenço et al. 2007, Lourenço et al. 2011, Toll et al. 2015). This extended capability is crucial since it allows changes in matric suction to be plotted in terms of degree of saturation rather than gravimetric moisture content, the importance of which has been discussed by Toll et al. (2015). As a result of a collaborative PhD exchange program between the University of Pretoria (UP) and Durham University (DU) a similar experimental setup has been implemented at UP (see Fig. 3).

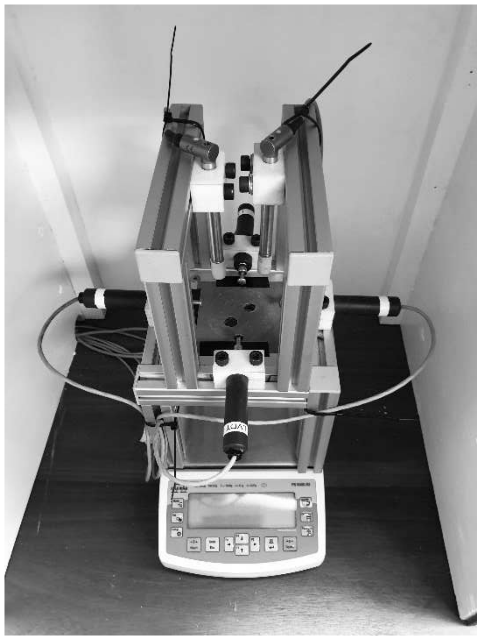

Figure 3. SWRC measurement setup at the University of Pretoria

4 PRACTICAL IMPLEMENTATION OF VARIOUS SUCTION MEASUREMENT TECHNIQUES

Since the measurement of the SWRC involves quantifying suction at moisture contents ranging from fully saturated to residual moisture content, it is not enough to only consider the characteristics of a given suction measurement method. An issue of practical importance are the implications that the chosen suction measurement method will have when attempting to establish a full SWRC. The following section discusses the results of several primary drying curves measured at the University of Pretoria using the various measurement techniques described in this paper. When presenting these results an effort is made to address practical concerns of each approach wherever necessary.

4.1 *Filter paper measurement*

Figure 4 illustrates the SWRC for a clayey material measured using the filter paper method with the best fit Fredlund-Xing Equation (Fredlund & Xing 1994) superimposed onto the data. From this result the benefit of having a wide measurement range becomes clear as the entire SWRC could be measured using a single method. Furthermore, since suction measurements are made at discrete points to target specific moisture contents, it is easy to obtain a corresponding volumetric reading at each point, thus allowing matric suction to be plotted as a function of degree of saturation.

The filter paper method has drawbacks related to the time required to measure the SWRC. For the data presented in Figure 2, the sample was prepared by saturating in a triaxial cell, followed by a consolidation process whereby the sample was consolidated to the desired initial void ratio. Upon removal from the triaxial cell, the sample was trimmed to its final dimensions before beginning the first suction measurement. Thereafter, a period of 7 days was required for each suction reading. Following each reading, volumetric measurements were taken, and the sample was allowed to dry out further to the next targeted moisture content. Since all readings were taken on one soil specimen, measurement of this SWRC took over 2 months. This period could have been significantly shortened to slightly over one week if separate specimens were prepared at each desired moisture content. However, doing so would increase the amount of time required for sample preparation and would necessitate meticulous preparation to ensure that each sample had exactly the same initial properties, thus following precisely the same primary drying curve, an aspect that is difficult to verify.

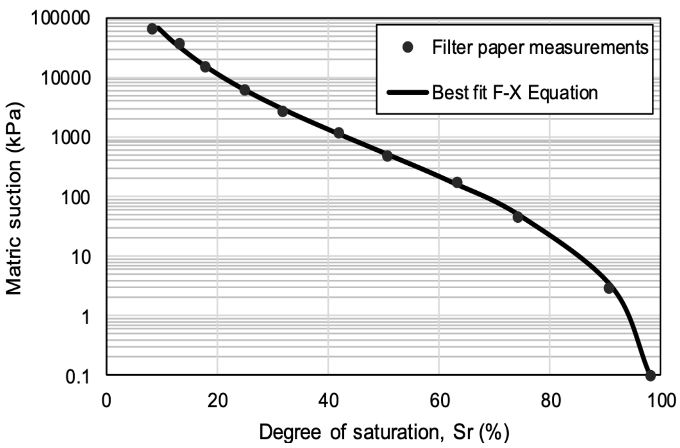

Figure 4. SWRC measured using the filter paper method

4.2 *Dewpoint hygrometer*

While the filter paper method allows for a measurement range which can account for most soils encountered in practice (up to 30 MPa), there are cases where this capacity is inadequate. The drying curves presented in Figure 5 are for two identical samples of a highly expansive bentonite clay sampled from the Limpopo province of South Africa.

Figure 5 illustrates the necessity to measure suction values in excess of 30 MPa when considering highly expansive clays. In Figure 5 it can be seen that magnitudes more than three times this value were measured using the dewpoint hygrometer. It should be noted that while the capacity of this instrument is 300 MPa, it was only possible to dry the sample out to a degree of saturation of approximately 65% under ambient laboratory conditions. While it would be possible to impose higher suctions on the sample through the use of precise humidity control, such procedures were not attempted, given the scope of this paper. Another notable trait of the results presented in Figure 5 is the considerable scatter observed at suctions less than 1 MPa. For applications where fluctuations of moisture close to saturation are of importance, this approach to SWRC measurement may be inadequate.

Similar to the filter paper approach, SWRC measurements using the dewpoint hygrometer involve individual measurements at various targeted moisture contents. It is therefore still possible to record sample volume after each suction measurement by removing the sample from its container and taking several height and diameter measurements. However, an issue with this approach is the danger of minute pieces of the sample breaking off. Since the sample used in this measurement technique has a volume of approximately 10 cm^3, the smallest material loss could result in significant errors when calculating sample moisture content.

When considering the measurement time required for each suction reading (an average of 15 mins), use of the dewpoint hygrometer presents an attractive approach to SWRC measurement. The time benefit gained is however significantly overstated for this method since the approach requires operator intervention for every point on the SWRC. To measure the drying curves presented in Figure 5, 28 hours of active operator intervention was required. When considering the cost of man hours required to complete the curve presented below, use of an automated system becomes more attractive.

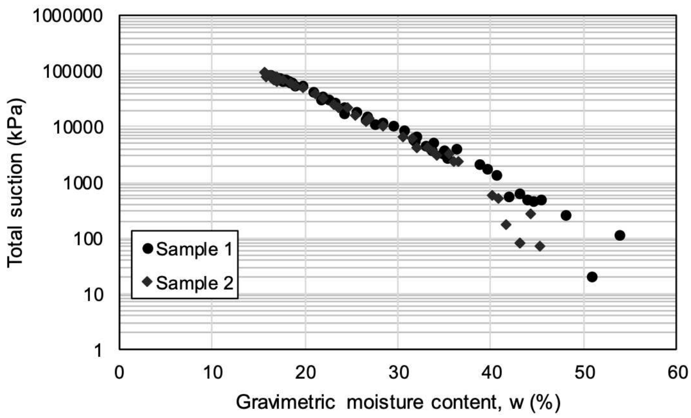

Figure 5. SWRC measured using the dewpoint hygrometer

4.3 *Continuous tensiometer measurement*

Use of high capacity tensiometers together with precision electronic balances allow for SWRC measurement to be a largely automated process. Following specimen preparation, the sample is placed on a frame (illustrated in Figure 3) and, once good contact between the soil sample and tensiometer ceramic have been established, no further intervention is required. The results presented in Figure 6 were measured with low-cost, high capacity tensiometers (Jacobsz 2018) on the setup illustrated in Figure 3.

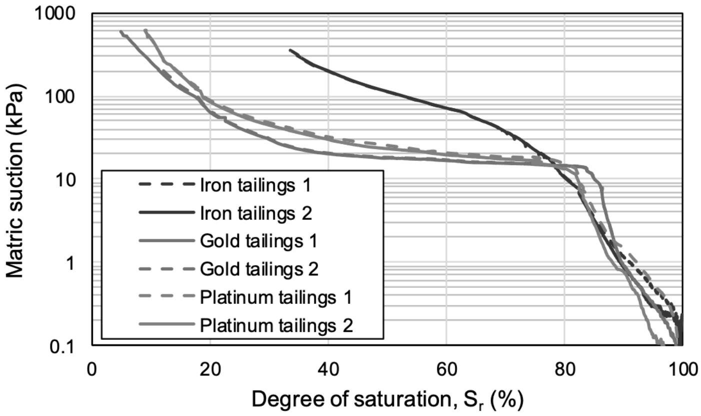

Figure 6. SWRC measured using continuous tensiometer and mass readings

4.4 *Combining measurement approaches*

Since the high capacity tensiometers commonly in use are limited to a capacity of approximately 2 MPa, efficient measurement of SWRCs over a wider suction range intuitively incorporates the rapid tensiometer method in combination with either filter paper or WP4 readings. While the dewpoint hygrometer measures total suction (as opposed to matric suction, as measured by tensiometers), the contribution of the osmotic component at lower moisture contents are said to be small and, as such, the results of the two procedures can be combined (ASTM D6836-16). The results of two SWRCs measured using the continuous tensiometer method in combination with the filter paper and dewpoint hygrometer technique respectively have been illustrated in Figure 7.

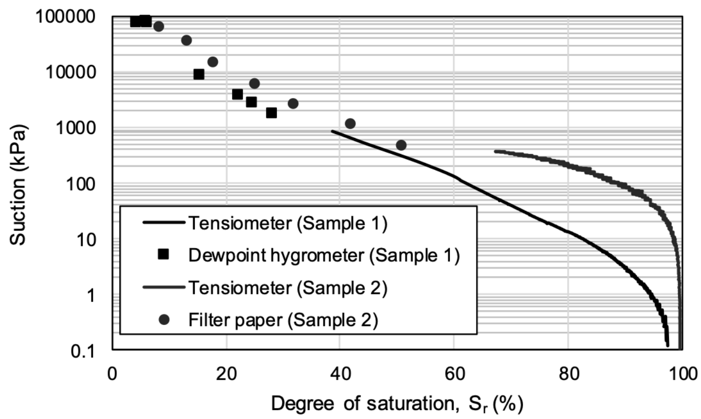

Figure 7. SWRC measurement using combined techniques

The techniques for measuring SWRCs described above quantify drying curves. It is important to realise that common problems associated with unsaturated soil behaviour are typically associated with wetting. Wetting results in suction loss, leading to a number of problems such as loss of strength and soil heave. It is therefore important to account for the wetting curve. This can be done by systematically increasing the moisture content in samples and then taking suction measurements using any of the methods discussed earlier. However, more work is involved as staged wetting, followed by a period to allow suction equilibration is required before a representative suction measurement can be taken. An alternative to explicit measurement of the wetting curve is estimation of the wetting curve by shifting of the primary drying curve as recommended by Fredlund et al. (2011).

5 CONCLUSIONS

The prevalence of unsaturated soils in arid regions as is the case for much of Africa has brought about the need to quantify unsaturated soil properties. Whereas the measurement of soil suction has historically been shown to be time consuming and cumbersome, technological advancements over the past few decades have made the measurement of the soil water retention curve (SWRC) far more accessible. The results presented in this paper illustrate how continuous tensiometer measurements together with comparatively older techniques can provide a quick and efficient means to accurately measure SWRCs over wide suction ranges.

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