Direct and Indirect Measurement of Soil Suction in the Laboratory

Hu Pan

Institute of Geotechnical Engineering, Faculty of Infrastructure Engineering Dalian University of Technology, Dalian, China e-mail: hupan0228@sina.com.

Yang Qing

Faculty of Infrastructure Engineering and The State Key Lab. of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, China
e-mail: qyang@dlut.edu.cn

Li Pei-yong

School of Civil and Safety Engineering, Dalian Jiaotong University, Dalian, China e-mail: dlutlpy@yahoo.com.cn

ABSTRACT

Soil suctions can be found in all ground that lies above the water table. It is one of the most important parameters describing the moisture stress condition of unsaturated soils and laboratory measurements of suction can be very useful for assessing the quality of the samples, estimating the in situ effective stress and realistic applications of unsaturated soil mechanics. This paper reports on direct and indirect soil suction measurement methods. Direct suction measurement techniques mainly include axis-transition technique, tensiometer and suction probe. Indirect suction measurement techniques are divided into three categories, namely, measurement techniques of matric suction, osmotic suction and total suction. Indirect matric suction measurement techniques include time domain reflectometry (TDR), electrical conductivity sensors , thermal conductivity sensor(TCS) and in-contact filter paper technique. Indirect osmotic suction measurement techniques chiefly include squeezing technique and saturation extract method. Indirect total suction measurement techniques include psychrometer technique, relative humidity sensor, chilled-mirror hygrometer technique and non-contact filter paper method. These techniques have been widely used in research laboratories and in engineering practice. However, each of these methods has its own limitations and disadvantages, and active research to improve these techniques need to be done in research laboratories and universities. This paper demonstrates working principles, measurement, and application of these methods based one recent literature and geotechnical engineering practice.

KEYWORDS: unsaturated soils, soil suction, suction measurement methods.

INTRODUCTION

General concept of suction was initially developed by soil physicist in the early 1900's . Total suction consists of two components: namely, matric and osmotic components. The matric component of total suction is defined as the component of free energy of the soil water, which is determined as the ratio of partial pressure of the water vapor in equilibrium with the soil water, relative to partial pressure of the water vapor in equilibrium with a solution identical in composition with a pool of soil water. The osmotic suction is the component of free energy of the soil water which is derived from the ratio of partial pressure of the water vapor in equilibrium with a pool of solution identical in composition with the soil water, relative to partial pressure of water vapor in equilibrium with a pool of pure water. This paper investigates and compares different techniques for suction measurements. Suction measurements are challenging for geotechnical engineers and no single piece of equipment covers the entire range of total suction that may be encountered. This is particularly true when measuring low values of total suction. Measurements of suction can be divided into two main categories; namely, direct method for measuring matric suction and indirect method for measuring matric, osmotic, and total suctions. Nowadays, significant contributions have been made by researchers and geotechnical engineers in the measurement of soil suction. However, almost all suction measurement methods have shortcomings including such aspects as reliability, cost, the range of application, and practicality. Therefore, there is still need for improving these soil suction measurement techniques. This paper reviews direct and indirect suction measurement techniques and summarizes basic working principles, measurement, and application of direct and indirect soil suction measurement methods based on the most recent literature and practice. Then, a critical evaluation of the applicability and limitations of the methods is also presented in the paper.

Direct Measurement of Soil Suction

Matrix suction can be obtained through direct measurement of the negative pore-water pressure. The pore-air pressure usually equal to on-site atmospheric pressure, and matric suction is the difference between air pressure and pore-water pressure. The direct measurement of matric suction requires a separation between water and air phase by means of a ceramic disk or a ceramic cup. The maximum value of matric suction that can be measured is limited by the air entry value of the ceramic disk or the ceramic cup used.

Axis-translation Technique

The working principle of this technique is artificially raising the atmospheric pressure experienced by a soil sample while maintaining the pore-water pressure to a positive reference pressure to avoid measuring negative pore-water pressure. Therefore, pressure difference u_a -u_w, otherwise known as the matric suction, also does not change. The measurement of matric suction using this technique is only limited by the air entry value of the ceramic disk used since cavitation can be avoided due to elevated pore-water pressure. Ceramic disks with a maximum air-entry value of 1500 kPa are available in the market (Soil moisture Equipment Corp, 2002). Since water pressure in the water compartment is maintained as close as possible at a zero value, the technique is called null-type axis-translation technique (Fredlund, 1989).The technique was adopted to determine unconfined wetting and drying curves in the low suction range (i.e., less than 1500 kPa). The range of axis translation technique to measure or control matric suction is limited by two factors, namely, the maximum air pressure which can be imposed on the experiment system and the air entry value of the ceramic disk. One challenge of the axis translation technique is it does not yield instantaneous results when used to impose matric suction, another drawback is the long equilibrium times associated with the axis translation technique make these experiments particularly susceptible to the process of air diffusion.

Tensiometer

Tensiometer is normally used for directly measuring the negative pore-water pressure of soil. The basic principle is that the pressure of water contained in a high air entry material will come to equilibrium with the soil water pressure making it possible to measure negative soil water pressures. Since a true semi-permeable membrane for soluble salts does not exist in tensiometer, the effect of osmotic component of suction is not measured. Thus, the measurement only provides the value of matric suction component in the soil. A small ceramic cup is attached to a tube filled with deaired water which is connected to a pressure measuring device. Saturate the ceramic cup and tube by filling with water and applying a vacuum to the tubing. Allow the ceramic tip to dry to reduce the water pressure in the sensor and remove any air bubbles that appear. Due to the cavitation problem, the use of a ceramic cup with a higher air entry value will not increase the measurement range of the tensiometer. However, improvements have been made to the tensiometer technique to enable measurements of matric suction greater than 100 kPa to be performed. The limitation is that air in the sensor will result in bad or less negative measurements of the pore water pressure for the following reasons: a) water vaporizes as the soil water pressure approaches the vapor pressure of water at the ambient temperature. b) air in soil can diffuse through the ceramic material; c) air comes out of solution as the water pressures decrease.

Suction Probe

The direct measurement of matric suction is preferred in unsaturated soil tests since measured pore-water pressures are more rapidly reflected. Ridley and Burland (1993) developed a suction probe for measuring matric suction of soil. The principle of making suction measurements using a suction probe is based on the equilibrium between the pore-water pressure in the soil and the pore-water pressure in the water compartment. Before equilibrium is attained, water flows from the water compartment into the soil, or vice versa. The suction probe measures the pore-water pressure(u_w). The matric suction can be computed since the applied air pressure (u_a) is known, and the matric suction is the difference between the pore-air pressure and the pore-water pressure ($u_a - u_w$).Basically, a suction probe consists of a pressure transducer with a high-air entry ceramic disk mounted at the tip of the transducer. The diaphragm of the pressure transducer responds to the pressure applied. In the suction probe, the volume of water reservoir beneath the ceramic disk or ceramic cup is minimized. Water in the water reservoir is pre-pressurized such that benefit of the high tensile strength of water can be utilized (Marinho and Chandler, 1995).Recently, Meilani *et al.* (2002) developed a mini suction probe for measuring matric suction along the specimen's height during triaxial test on an unsaturated soil. It is unique in its ability to make direct measurements over a wide range of soil suctions (i.e. up to 1500 kPa) and has been used extensively in both laboratory and field applications for a variety of clients and on a range of soil types. Measurements can be made in a borehole at depths between 0 and 5m or on samples after they have been recovered from the ground. Similar to the null-type axis-translation technique, the upper limit of matric suction that can be measured using this technique is governed by the air-entry value of the ceramic disk or ceramic cup used. The main problem is that there may be cavitation and air diffusion through the ceramic head during the suction measurement.

Indirect matric suction measurement

The indirect measurement of matric suction is commonly performed using a standard porous sensor made of a special material (e.g., filter paper, fiberglass, gypsum, nylon, sintered glass, clay ceramics, and metal). The measurement is performed by equilibrating the porous sensor with the matric suction in the soil. Therefore, the water content of the porous sensor represents the magnitude of matric suction of the soil.

Time domain reflectometry

Time domain reflectometry (TDR) was first suggested for measuring volumetric water content of soils by Topp *et al.* (1980). In the TDR technique, apparent dielectric constant of the soil (i.e., the bulk soil water) is measured, which is related to volumetric water content of the soil (Topp *et al.*, 1980).Since then, the method has been used by a number of researchers involving various disciplines (e.g., Dalton *et al.*, 1984; Kalinski and Kelly, 1993; Benson and Bosscher, 1999; Amente, *et al.*, 2000; and Yu and Drnevich, 2004). For a quite large range of water content and suction encountered in clay soils, water is held in the pores that are located within the clay clusters(i.e., intra-cluster pores). The pore-water held in the pores between the clay clusters is the bulk pore-water, which gives rise to the capillary phenomenon (i.e., matric suction)in the absence of a true semi permeable membrane. Therefore, time domain reflectometry practically measures matric suction instead of total suction. Time domain reflectometry requires soil-water characteristic curve of the soil tested to relate the measured volumetric water content to matric suction. Yu and Drnevich (2004) improved the technique such that gravimetric water content of the soil specimen can also be measured without separately testing the soil for determining its specific gravity and dry density. The advantage of the technique is mainly that reliable measurements of volumetric water content can be conducted within a short time duration (Benson and Bosscher, 1999). However, the limitation is that the technique requires a very sophisticated electronic device and the accuracy of TDR for measuring matric suction depends on the precise determination of SWCC of the soil tested.

Electrical conductivity sensors

Electrical conductivity sensors are commercially available (e.g. Soilmoisture Inc., Irrometer Company Inc., Measurement Engineering Australia and Environmental Sensors Inc.). The electrical conductivity sensor consists of a porous block and two concentric electrodes embedded inside the block. The electrical conductivity sensor measures the electrical conductivity of the porous block. As the moisture content of the porous block increases, the electrical resistance of the block decreases. The electrical resistance of the porous block can be related to the matric suction of the block. Usually the electrical conductivity sensor is read manually from a meter, limiting the number of readings when used in the field (Skinner *et al.*, 1997). Gypsum was found to be the most suitable porous block material as gypsum took the shortest time to saturate and responded fastest in matric suction measurements (Buoyoucos and Mick, 1940). This however has the unintended effect of degrading the electrical conductivity sensor as the gypsum eventually dissolves completely into the soil solution. Similar to the thermal conductivity sensor, the gypsum block of the electrical conductivity sensor also suffers from hysteresis. The electrical conductivity sensor has a long equilibration time (2–3 weeks) in a rapidly changing moisture environment (Aitchison and Richards, 1965). The equilibration times of the gypsum electrical conductivity sensors were found to vary with matric suction ranging from 6 h for a matric suction of 50 kPa to 50 h for a matric suction of 1,500 kPa. The sensitivity of the electrical conductivity sensor becomes very low when the matric suction exceeds 300 kPa. Besides, the electrical resistance of the porous block is also dependent on the salt concentration of the soil solution and may not be a direct indication of the moisture content of the porous block. These shortcomings had led to a diminished use of electrical conductivity sensor for matric suction measurement even in the agricultural industry (Skinner*et al.*, 1997). Currently, research on the electrical conductivity sensor is still ongoing to overcome its limitations.

Thermal conductivity sensor

Thermal conductivity sensor (TCS) is an equipment proposed by Shawand Baver (1939) to measurematricsuction.Sincethen,manyresearchershaveusedthetechniqueand examined other materials that can be used to enclose the TCS (Phene *et al.*, 1971; Lee and Fredlund, 1984; Fredlund and Wong, 1989). A thermal conductivity sensor employs a porous block, typically ceramic, as a medium to measure matric suction indirectly. The basic principle is if a matric suction gradient exists between the soil and porous block, water flux will occur until their suctions are equal. The thermal conductivity of the block consists of the thermal conductivity of the solid and the fluid (air or/and water) that fills the voids in the porous block. As the moisture content of the porous block increases, the thermal conductivity of the block increases. The moisture content of the block is measured by heating the porous block with a heater embedded in the centre of the porous block and measuring the temperature rise during heating. The temperature rise which is related to the thermal conductivity of the porous medium and the moisture content can then be used as an index of matric suction in the soil. The time to equilibrate depends on the temperature gradient and the hydraulic conductivity of the porous medium and surrounding soil. Thermal conductivity sensors have been used in the laboratory as well as in the field (Fredlund and Wong 1989; Oloo and Fredlund 1995; O'Kane *et al.* 1998; Marjerison *et al.* 2001; Nichol *et al.* 2003). Currently, thermal conductivity sensors are available commercially

(e.g. Campell Scientific, Inc. and GCTS). The attractiveness of the thermal conductivity soil suction sensor lies primarily in its ability to produce a reasonably reliable measurement of soil suction over a relatively wide range of suctions and the measurements are essentially unaffected by the salt content of the soil (Lee and Fredlund, 1984 and Fredlund and Wong, 1989). Another advantage of thermal conductivity sensors is their versatility and ability to be connected to a data acquisition system for continuous and remote monitoring. There have been numerous shortcomings and difficulties experienced with previously developed versions of thermal conductivity suction sensors. These difficulties and shortcomings can be identified as: 1.) low strength and poor durability of the ceramic tip, 2.) insensitivity and inaccuracy particularly in the higher range of suctions, and 3.) poor stability of the electronic signal. Nowadays, the thermal conductivity sensor shows hysteretic behavior on drying and wetting. In addition, the main problem with the thermal conductivity sensor is the variable uniformity of the porous block from sensor to sensor. This means that a separate calibration curve is required for each thermal conductivity sensor.

In-contact filter paper technique

Filter paper technique was established for measuring soil suction by soil scientists and agronomists (e.g., Gardner, 1937; Fawcett and Collis-George, 1967; Al-Khafaf and Hanks, 1974; Hamblin, 1981; Greacen *et al.*, 1987; and Deka *et al.*, 1995). In geotechnical engineering fields, many researchers have also used the technique as a routine method for suction measurement (e.g., McKeen, 1980; Chandler and Gutierez, 1986; Chandler *et al.*, 1992; Houston *et al.*, 1994; Fredlund *et al.*, 1995; Ridley, 1995; and Leong *et al.*, 2002). The in-contact filter paper technique is used for measuring matric suction of soils . Direct contact between the filter paper and the soil allows water in the liquid phase and solutes to exchange freely. In the in-contact filter paper technique, water content of an initially dry filter paper increases due to a flow of water in liquid form from the soil to the filter paper until both come into equilibrium. Therefore, a good contact between the filter paper and the soil has to be established. After equilibrium is established between the filter paper and soil, the water content of the filter paper is measured. Then, by using the appropriate filter paper calibration curve, the suction of the soil is estimated. The in-contact filter paper method becomes inaccurate in high matric suction range since water transport is dominated by vapor transport (Fredlund *et al.*, 1995). The water content of filter paper is converted to matric suction using an in-contact filter paper calibration curve. The calibration curve for the filter paper matric suction measurement is commonly established using a pressure plate apparatus (e.g., Al-Khafaf and Hanks, 1974; Hamblin, 1981; Greacen *et al.*, 1987; Deka *et al.* 1995; and Leong *et al.*, 2002) or against known suction pressures of solutions. Leong *et al.* (2002) found that the filter paper technique exhibits hysteresis. It is also important to note that only ash-less filter papers should be used in the filter paper technique and only Whatman 42 and Sleicher and Schuell 59 (or SS 59) filter papers are commonly used (Leong et al, 2002).The filter paper method is a simple technique and can be reliable if the basic principles of the method are understood and a strictly practiced laboratory protocol is carefully followed. Filter papers should be allowed to equilibrate for a sufficient time and 1 week of equilibration period is usually considered satisfactory for most soil suction measurements. Therefore, the limitations are response times (7-14 days) may be too long and filter may not make good contact with soil.

Indirect osmotic suction measurement

Nowadays, most researchers have focused on the relationship between water content and matric suction. Nonetheless, the osmotic suction may also play an important role in the hydro-mechanical behaviour of clayey soils. Osmotic suction presents in both saturated and unsaturated soils and depends on the concentration of ions dissolved in the pore water. However, osmotic suction remains nearly constant in saturated soils (unless the soil is exposed to chemical contamination) whereas it can change significantly in unsaturated soils. As the soil losses water by evaporation, the concentration of the dissolved ions increases, and the osmotic component of suction also increases. Osmotic suction can be measured using several indirect methods. The first method for measuring osmotic suction is called saturation extract method. In the technique, distilled water is added to slurry up a soil. The soil water is subsequently drained out to measure its electrical conductivity. The electrical conductivity of the soil water is converted to suction using an osmotic suction-electrical conductivity conversion curve such as that provided by USDA (1950). Krahn and Fredlund (1972) found that despite its simplicity, the saturation extract method had a poor accuracy for determining in situ osmotic suction. In the second method, the soil pore-water can be extracted using a pore-fluid squeezer, namely, squeezing technique. The determination of osmotic suction by measuring the electrical conductivity is generally applicable for the entire range of osmotic suction. This technique consists in squeezing a soil specimen to extract the macro pore water and then measuring its electrical conductivity. This can be related to the total concentration of dissolved salts, which can in turn be related to the osmotic suction of the soil. Romero (1999) has validated two empirical relationships to correlate the electrical conductivity to the osmotic suction and made significant contribution to the measurement of osmotic component of suction. The pore fluid squeezer technique has shown to give the most reasonable measurement of osmotic suction (Krahn & Fredlund, 1972; Wan, 1996). In general, the results of the squeezing technique measurements appear to be affected by the magnitude of the extraction pressure applied (Engelhardt & Gaida,1963; Iyer, 1990) and this influence is found to depend on the type of soil.

Indirect total suction measurement

Various techniques have been used to indirectly measure total suction of soils. Among the indirect total suction measurement techniques are psychrometer, relative humidity sensor, chilled mirror hygrometer technique and non-contact filter paper method. The indirect measurements of total suction require determination of other parameters such as dew point (i.e., in the psychrometer), relative humidity and temperature (i.e., in the relative humidity sensor and the chilled-mirror hygrometer technique) and water content (i.e., in the non-contact filter paper technique).

Psychrometer technique

There are two main types of psychrometers; namely, thermocouple psychrometer and thermistor or transistor psychrometer. The thermocouple psychrometer was first introduced by Spanner (1951). The device makes use of Peltier and Seebeck effects. The Peltier effect is a temperature drop induced by an electrical current passing across a junction made of two different metal wires, which is a function of relative humidity of vapor space where measurement is conducted. The thermistor or transistor psychrometer was developed by Richards (1965). Transistor psychrometer consists of a thermally insulated container that holds the psychrometer probes and a data logger for measurement and recording of output. The transistor psychrometer is an electronic wet and dry bulb thermometer in which a wet and dry transistor probe is used instead of wet and dry thermometer bulbs as in thermistor psychrometers. Evaporation takes place as both bulbs are exposed to vapor space in the soil, which results in an electromotive force being generated. The temperature depression of the wet transistor, which holds a standard-size water drop, is measured with the sensors in the probe. The wet and dry transistors are employed as heat sensors and the voltage output from the probe is used to infer total suction. Improvements in performance have been made that allow the device to measure a much wider range of total suction, from about 100 kPa to about 10,000 kPa. Much of the improvement is due to calibration procedure and advances in micro-chip technology (Woodburn *et al.* 1993). The range and accuracy in measurements are also attributed to sensitivity of the transistors to changes in temperature. It has practically replaced thermocouple psychrometers in many laboratory soil suction measurements. Recent studies by Bulut *et al.* (2000, 2002) showed that transistor psychrometer has a better capability of measuring total suction at lower levels when compared with other psychrometric methods. The psychrometer technique has been widely used by many researchers (e.g., Rawlins and Dalton, 1967; Krahn and Fredlund, 1972; Campbell *et al.*, 1973; Hamilton *et al.*, 1981; Brown and Bartos, 1982; Lee and Wray, 1995; Zerhouni, 1995; Ridley and Wray, 1996; Harrison and Blight, 2000 and Tang *et al.*, 2002). There are many positive aspects, but few negative aspects associated with the accuracy of psychrometers for measuring total suction. Firstly, variability in the electromotive force generated induces error in high suction range. Besides, Ridley and Wray (1996) noted that inaccuracies of the psychrometer technique may be caused by the insensitivity of psychrometer due to temperature effects. Refinements to minimize the temperature sensitivity of the psychrometer techniques may be possible through careful analysis of heat and vapor flow through and around the measuring sensors. Furthermore, there may exist a possibility of deterioration in the sensitivity of psychrometer due to corrosion problem (Hamilton, 1981 and Zerhouni, 1995). Unlike the filter paper method, no reports of hysteresis of the psychrometer technique for total suction measurement have been found recently.

Relative humidity sensor

The relative humidity (RH) sensor is usually used in meteorological fields for measuringthe dew point of air. Many types of RH sensor are available commercially. Examples of the RH sensors are products of Vaisala Oyj (Vaisala, 2002). The relative humidity (RH) and temperature of vapour spaceof the soil are measured and total suction (s_t) can be computed using Kelvin's law (Fredlund and Rahardjo, 1993). Albrecht *et al.* (2003) used a polymer capacitance sensor for measuring relative humidity of a number of soils ranging from sand to clay. The polymer capacitance sensor consists of two electrodes that are separated by a thermoset polymer film. Depending on the RH value being measured, the film adsorbs or release water. The RH value is determined by measuring changing capacitance of the polymer film. Polymer capacitance technology is recently used in this type of sensors as the technology provides high reliability to the relative humidity measurement, insignificant hysteresis, and insensitivity to temperature fluctuation where measurement is conducted (Wiederhold,1997 and Benson and Bosscher, 1999).

With this technology, a rapid response of the sensor in measuring relative humidity is obtained.

Chilled-mirror hygrometer technique

Chilled-mirror hygrometer technique was first introduced to measure relative humidity of food products (e.g., Hand, 1994 and Zhang, *et al.*, 1996) and pharmaceuticals (e.g., Ahlneck and Zografi, 1990 and Friedel and Cundall, 1998). It has been used in soil science to quantify water potential of soils (Gee *et al.*, 1992 and Brye, 2003). In geotechnical engineering applications, the technique has been used for measuring total suction of soils (Leong *et al.*, 2003; Albrecht *et al.*, 2003; and Schanz *et al.*, 2004). A chilled-mirror hygrometer uses the chilled mirror dew point technique to infer total suction under isothermal conditions in a sealed container. Measurement of total suction with the chilled-mirror hygrometer is based on equilibrating the liquid phase of the water in a soil sample with the vapor phase of the water in the air space above the sample in a sealed chamber. The chilled-mirror hygrometer measures dew point and temperature of the headspace above the specimen. The specimen is contained in a special closed chamber to minimize drying of the specimen. Water vapor from the soil specimen is allowed to condense on the mirror and a photoelectric cell is used to detect the exact point at which condensation first appears on the mirror. The temperature of specimen which is considered to be equal to the temperature of vapor space is measured via an infrared thermocouple. The relative humidity or the water activity of the specimen is computed from the measured dew point and temperature. A small fan is also employed to circulate the air in the sensing chamber and speed up vapor equilibrium. The soil samples and device were kept at the same location for at least several hours for temperature equilibrium prior to the testing. The chilled mirror technique offers a fundamental characterization of humidity in terms of the temperature at which vapor condenses. Temperature control is very important. The measured difference between dew point and sample temperatures must be kept small. It is important to avoid contamination of the instrument. Leong *et al.* (2003) reported that the technique could be used to quantify total suction as low as about 150 kPa. The value is considered small in the case of low total suction measurement where much larger error can be expected. By considering the error of total suction measurement and the way of how the isothermal equilibrium between the specimen and the vapour space is maintained, the technique is considered to be the most accurate means for measuring total suction. Another promising hygrometer that has been used for measurement of total suction is the polymer capacitance sensor which consists of two electrodes separated by a film of thermoset polymer that absorbs or releases water as the relative density of the surrounding air changes (Albrechtetal, 2003).

Table 1: Summary of suction measurement methods

		Technique (Method)	Suction range (kPa)	Equilibrium time
Direct suction measurement	Matric suction	axis-transition technique	0-1500	hours
		tensiometer		hours
		suction probe		minutes
Indirect suction measurement	Matric suction	time domain reflectometry	0-1500	hours
		electrical conductivity sensor	50-1500	6-50hours
		thermal conductivity sensor	0-1500	hours-days
		in-contact filter paper	all	7-14 days
	Osmotic suction	squeezing technique	0-1500	days
	Total suction	psychrometer technique	100-10000	1 h
		relative humidity sensor	100-8000	hours-days
		chilled-mirror hygrometer	150-30000	10 minutes
		non-contact filter paper	all	7-14 days

Non-contact filter paper method

The filter paper covers a wide range of suction measurements. For the non-contact technique, a dry filter paper was suspended above a soil specimen in a sealed container for water vapor equilibrium between the filter paper and the soil specimen at a constant temperature. The vapour space above the soil specimen acts as a true semi-permeable membrane which is only permeable to water vapour but not to ions from the pore-water. The separation between the filter paper and the soil by a vapor barrier limits water exchange to the vapor phase only and prevents solute movement. Therefore, in this technique, total suction is measured. Having achieved equilibrium condition, the filter paper is removed and water content of the filter paper determined as quickly as possible. Then, by using the appropriate filter paper calibration curve, the suction of the soil is estimated. Prior to total suction measurements, filter papers are calibrated to determine the relationship between equilibrium water content and relative humidity.The calibrationcurveforthenon-contactfilterpapertechniqueisestablishedusingvapourequilibrium technique (e.g., Gardner, 1937; Fawcett and Collis-George, 1967; Chandler and Gutierez, 1986; Houston *et al.*, 1994; and Leong *et al.*, 2002). There are still many concerns about the reliability of the filter paper method.

The filter paper method is a simple and economical technique and can be reliable if the basic principles of the method are understood and a strictly practiced laboratory protocol is carefully followed. As accuracy of the filter paper technique is dependent on the accuracy of the filter paper water content versus suction calibration curve, the calibration technique of the filter paper method has been investigated by numerous researchers (e.g. Houston *et al.* 1994; Bulut *et al.* 2001; Leong *et al.* 2002). Calibration equations should be developed specifically for the specific filter paper being used. The most commonly used filter papers are Whatman No. 42 and Schleicher & Schuell No. 589-WH. The Schleicher & Schnell No. 589-WH filter paper is now called grade 989-WH in the US. Both the in-contact and non-contact filter paper techniques have been standardized in ASTM D 5298-94 (ASTM, 1997). While the in-contact filter paper method is inaccurate in the high matric suction range, sensitivity of the non-contact filter paper technique diminishes at low total suction. Ridley and Wray (1996) found that the non-contact filter paper technique is insensitive when used for measuring low total suctions due to possible vapor and temperature non-equilibrium during measurement. Generally, similar filter papers as used in the in-contact filter paper technique can be used in the non-contact filter paper technique. The limitations is its long equilibrium time and strict protocol is needed during the experiment.

CONCLUSION

This paper has summarized basic working principles, calibration, measurement, and application of direct and indirect soil suction measurement methods based on the most recent literature and practice. Direct suction measurement techniques mainly include axis-transition technique, tensiometer and suction probe. Indirect suction measurement techniques have been grouped into three categories,namely, measurement techniques of matric suction, osmotic suction and total suction. Each piece of soil suction measurement equipment have its own advantages and limitations. Table 1 summarizes key characteristics of direct and indirect suction measurement methods.

To conclude, apart from its advantages, almost all suction measurement methods have limitations and shortcomings such as the cost, reliability, practicality and range of application. Correct matric suction is obtained only if the appropriate calibration curve is used. It has been proceed by the practice that squeezing technique is the best method to measure osmotic suction. Accurate total suction measurement is still difficult with current technology, especially for total suction levels below about 100 kPa. Another drawback of the indirect total suction measurement method is it usually takes long times to reach equilibrium. The filter paper method is simple and is the most economical indirect suction measurement method. However, unless a correct and strictly practiced laboratory protocol is followed, the filter paper method may give inaccurate and questionable results. Therefore, more research is needed in research laboratories and universities to improve primary methods of suction measurement.

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