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REGIONAL SOILS

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STATE-OF-DEVELOPMENT IN THE MEASUREMENT OF SOIL SUCTION

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SYNOPSIS

The measurement of soil suction is central to the application of unsaturated soil mechanics to geotechnical practice. Several devices for the measurement of soil suction are discussed in this paper. The working principles, typical results and state-of-development are presented for the most promising devices.

INTRODUCTION

Surficial soils in many parts of the world are classified as expansive, collapsible, and residual soils. These soils are generally unsaturated with pore-water pressures that are negative relative to atmospheric conditions. There has been a significant increase in our understanding of unsaturated soil mechanics' concepts, theories, and formulations during the past two decades. However, the knowledge can only be put into practice as devices for measuring the negative pore-water pressures are available. The measuring devices should be accurate and economical for use in engineering practice. There has been a great need for such devices in order to expand soil mechanics' practice to arid and semi-arid regions of the world.

This paper summarizes some recent experiences in measuring negative pore-water pressure and soil suction. The emphasis is on measuring insitu soil suction. The paper first outlines a brief theoretical context for soil suction and then discusses devices showing the greatest promise for use in geotechnical engineering.

THEORY AND DEFINITIONS OF SOIL SUCTION

The total suction of a soil can be related to the partial pressure of the pore-water vapor. From a thermodynamic standpoint, the total suction can be written,

$$\psi = -\frac{RT}{v_{vo}\,\omega_v} \ln \frac{\bar{u}_v}{\bar{u}_{vo}} \qquad [1]$$

where:

ψ = total suction (kPa)

R = universal (molar) gas constant (i.e., 8.31432 J/(mol K))

T = absolute temperature (i.e., $T = 273.16 + t^o$)(K)

t^o = temperature (^oC)

v_{vo} = specific volume of water or the inverse of water density (i.e., $1/\rho_w$) (m^3/kg)

ρ_w = water density (i.e., 998 kg/m^3 at $t^o = 20^oC$)

ω_v = molecular mass of water vapor (i.e., 18.016 kg/kmol)

$\bar{u}_v$ = partial pressure of pore-water vapor (kPa)

$\bar{u}_{vo}$ = saturation pressure of pore-water vapor over a flat surface at the same temperature (kPa)

The term $\bar{u}_v/\bar{u}_{vo}$ in Eq. 1 is also referred to as the relative humidity, RH(%). The relative humidity is commonly less than 100%, indicating a partial pressure lower then the saturation pure water vapor pressure over a flat surface at the same temperature (i.e., $\bar{u}_v < \bar{u}_{vo}$). The reduction in the water vapor pressure can be caused by a curved (i.e., concave) water surface such as is found in a capillary tube. The water vapor pressure or the relative humidity decreases as the radius of curvature of the water surface decreases. At the same time, the radius of curvature is inversely proportional to the difference between the air and water pressures across the surface (i.e., $(u_a - u_w)$). The $(u_a - u_w)$ term is called the matric suction; where: u_a is pore-air pressure and u_w is pore-water pressure. This means that one component of the total suction in Eq. 1 is matric suction which causes a reduction in the relative humidity.

The pore-water in a soil generally contains dissolved salts. The water vapor pressure over a flat surface of solvent is less than the vapor pressure over a flat surface of pure water. In other words, the relative humidity decreases with increasing dissolved salts in the pore-water in the soil. The decrease in relative humidity due to the presence of dissolved salts in the pore-water is referred to as the osmotic component of total suction. In summary, the total suction of a soil, ψ, can be considered as the sum of the matric suction, $(u_a - u_w)$, and the osmotic suction, π.

$$\psi = (u_a - u_w) + \pi \qquad [2]$$

The role of osmotic suction has commonly been associated more with unsaturated soils than with saturated soils. In reality, dissolved salts are present in both saturated and unsaturated soils. Therefore, the role of osmotic suction is equally important in both saturated and unsaturated soils. Changes in osmotic suction due to changes in salt content will affect the mechanical behavior of a soil. However, the osmotic suction change is not generally taken into account in an analysis if the change has been simulated during the laboratory measurement of soil properties.

TENSIOMETERS

A tensiometer measures the negative pore-water pressure in a soil. The tensiometer consists of a porous ceramic, high air-entry cup connected to a pressure measuring device through a small bore capillary tube. The tube and the cup are filled with deaired water. The cup can be inserted into a precored hole until there is good contact with the soil. After equilibrium has been achieved, the water in the tensiometer will have the same negative pressure as the pore-water in the soil. The water pressure that can be measured in a tensiometer is limited to approximately negative 90 kPa due to the possibility of cavitation of the water in the tensiometer. The measured negative pore-water pressure is numerically equal to the matric suction when the pore-air pressure is atmospheric (i.e., u_a equals to zero gauge). When the pore-air pressure is greater than atmospheric pressure, the tensiometer reading can be added to the pore-air pressure reading to give the matric suction of the soil. However, the matric suction must not exceed the air entry value of the ceramic cup. The osmotic component of soil suction will not be measured by tensiometers since soluble salts are free to flow through the porous cup.

There are several types of tensiometers available from Soilmoisture Equipment Corporation, Santa Barbara, California, U.S.A. Slow diffusion of air through the high air-entry cup is a problem common to all tensiometers. The Quick Draw tensiometer has proven to be a particularly useful portable tensiometer to rapidly measure negative pore-water pressures (Fig. 1). The water in the tensiometer is subjected to tension for only a short period of time during each measurement. Therefore, air diffusion through the ceramic cup with time is minimized. The Quick Draw tensiometer can repeatedly measure pore-water pressures approaching minus one atmosphere when it has been properly serviced. When it is not in use, the probe is maintained saturated in a carrying case which has water saturated cotton surrounding the ceramic cup. Figure 2 illustrates the distribution of matric suction along a trench excavated perpendicular to a railway embankment in British Columbia, Canada. The embankment soil consisted predominantly of unsaturated silt. The negative pore-water pressures were measured on the sidewalls of the trench using a Quick Draw tensiometer.

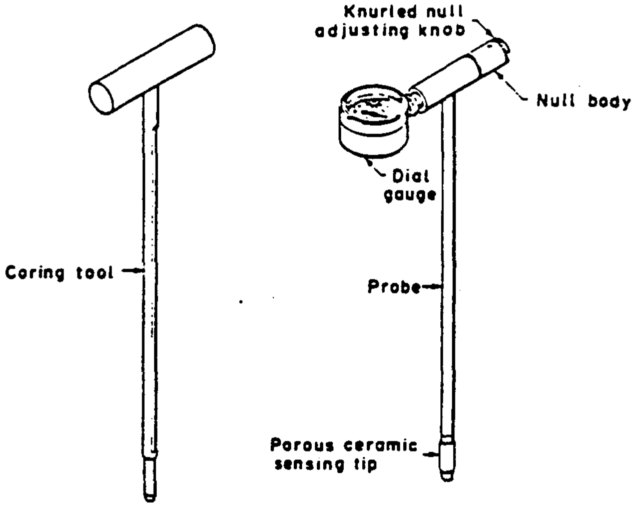


Fig. 1 "Quick Draw" tensiometer from Soilmoisture Equipment Corporation

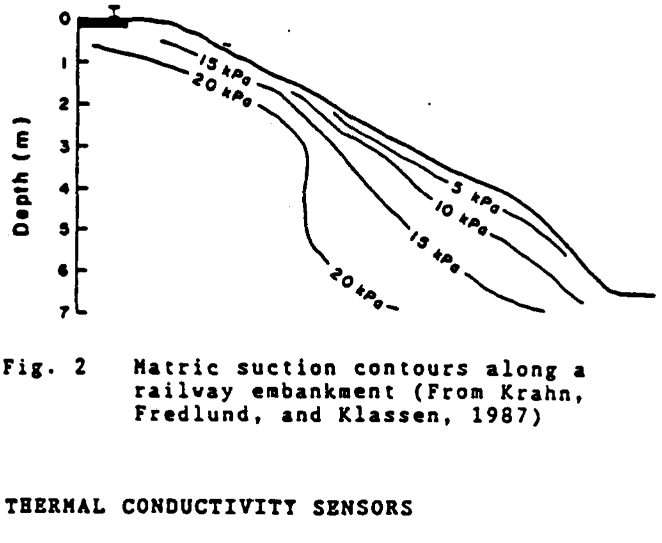


Fig. 2 Matric suction contours along a railway embankment (From Krahn, Fredlund, and Klassen, 1987)

THERMAL CONDUCTIVITY SENSORS

A thermal conductivity sensor indirectly measures the matric suction in a soil. The sensor consists of a porous ceramic block containing a temperature sensing element and a miniature heater. Measurements are made by inserting the sensor into a pre-drilled hole in the soil and allowing the matric suction in the ceramic block to come to equilibrium with the matric suction in the soil. The equilibrium matric suction is related to the water content in the porous block. The amount of water in the porous block affects the rate of heat dissipation within the block. Therefore, the water content in the porous block can be measured indirectly by measuring the heat dissipation of the block. This is accomplished by generating a controlled amount of heat at the center of the porous block and measuring the temperature rise at the same point after a fixed period of time. More heat will be dissipated throughout the block with increasing water content in the block. The undissipated heat causes a temperature rise that is inversely proportional to the water content in the porous block. As a result, the measured temperature rise can be calibrated to measure the matric suction in the soil.

The thermal conductivity sensor calibration can be conducted using a pressure plate apparatus. A pressure plate set up for calibrating the sensor is shown in Fig. 3 together with a cross-section of a sensor. The height of the pressure chamber was increased in order to provide several circular holes along the chamber wall. The holes are used to connect several sensors to the read-out device or data acquisition system. Several sensors are first installed in a soil specimen which is placed in the pressure plate. A desired matric suction, $(u_a - u_w)$, is then applied to the soil specimen by applying an air pressure, u_a, and maintaining a zero water pressure below the ceramic disc. The pore-water will flow out from the soil specimen and collect in a volume change indicator. The water outflow will cease when equilibrium is attained. During calibration, the pressure plate setup is contained within a temperature controlled box. The response of each sensor is monitored periodically until equilibrium is achieved. The reading at equilibrium is used in the calibration of the sensor. The above procedure is repeated for various applied matric suctions to provide a calibration curve.

A thorough calibration study on AGWA-II thermal conductivity sensors has been completed recently at the University of Saskatchewan, Canada (Wong and Ho, 1987). The AGWA-II sensors used in the study were manufactured by Agwatronics Incorporation, Merced, California, U.S.A. Typical results indicate a non-linear calibration curve which may be approximated by a bilinear curve as illustrated in Fig. 4. The breaking point of the calibration curve was found to be around 175 kPa. It has been found that relatively accurate measurements of matric suctions can be expected from the AGWA-II sensor in the range of 0 to 175 kPa. Matric suction measurements above 175 kPa correspond to a steeper calibration curve with a lower sensitivity. The sensors also produced consistent and stable output with time.

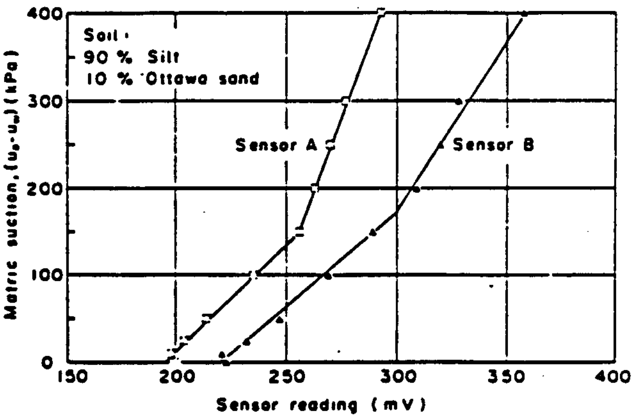


Fig. 4 Calibration curves for two AGWA-II thermal conductivity sensors form Agwatronics Incorporated (From Wong and Ho, 1987)

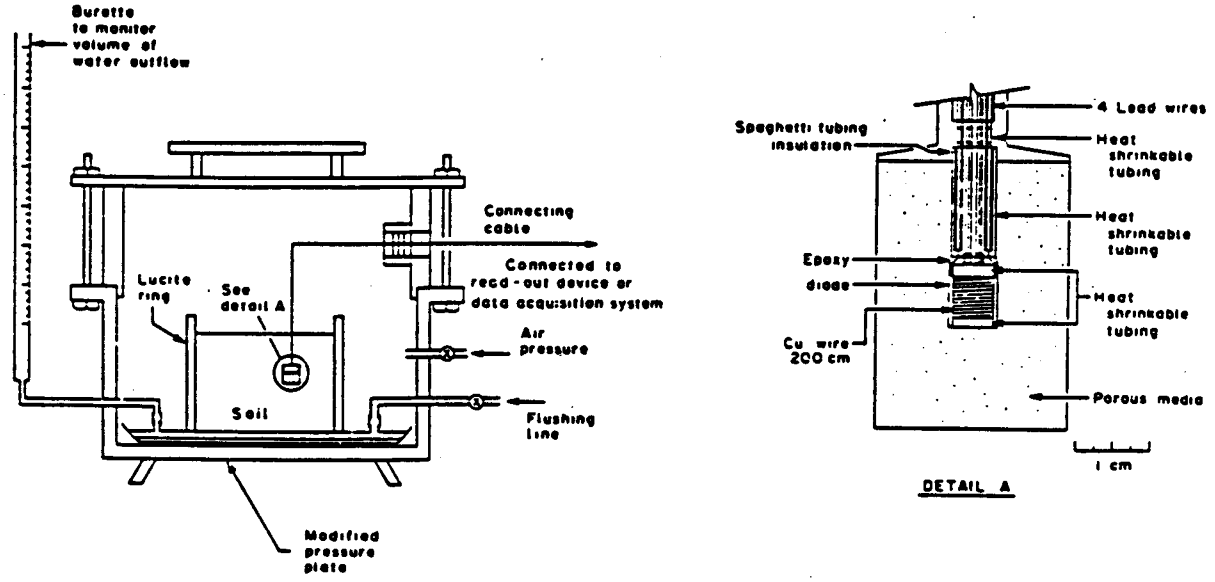


Fig. 3 Pressure plate setup for calibrating thermal conductivity sensors (From Wong and Ho, 1987)

The AGWA-II thermal conductivity sensors have been used for laboratory measurements of matric suction on a highly plastic clay from Sceptre, Saskatchevan, Canada (Fig. 5). The measurements were performed using two sensors. One sensor was initially saturated while the other sensor was initially dry. The responses of both sensors were monitored immediately and at various elapsed times after their installation. The results indicate that the equilibrium time required for the initially dry sensor is less than the equilibrium time for the initially saturated sensor. The AGWA-II sensors have also been used for measuring matric suction in a highway test track with a controlled environment (i.e., controlled temperature and humidity). Typical results on a glacial till subgrade are presented in Fig. 6. The measured matric suctions are constant with time and the water contents show a reasonable decrease in matric suction with respect to depth.

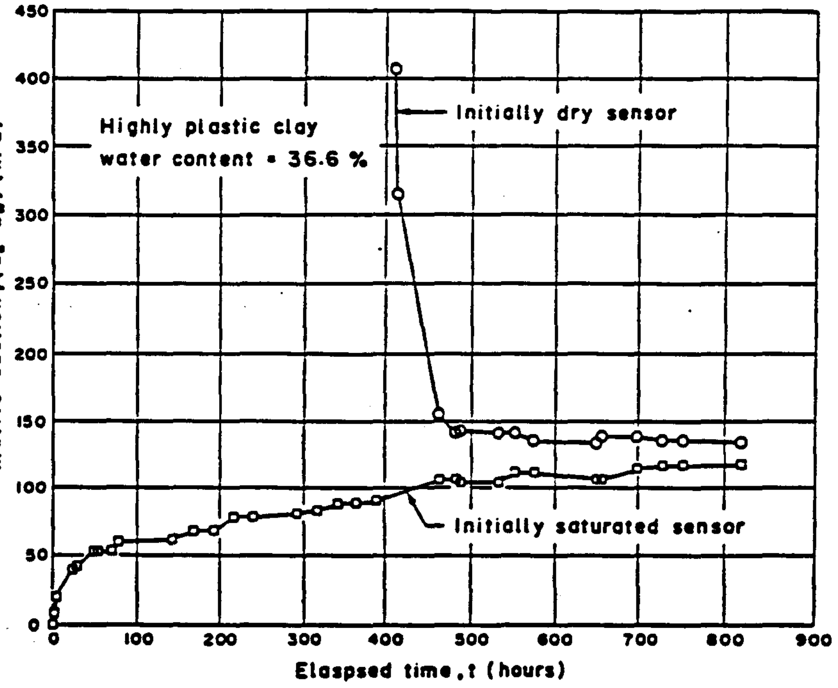


Fig. 5 Laboratory measurements of matric suction using the AGWA-II thermal conductivity sensors

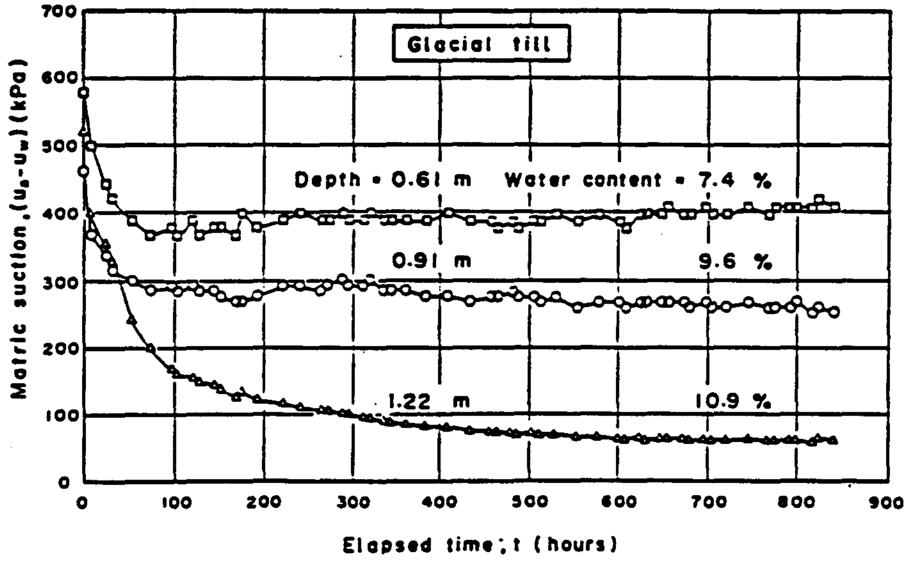


Fig. 6 Field measurements of matric suction using the AGWA-II thermal conductivity sensors under controlled environments

PSYCHROMETERS

Thermocouple psychrometers are used to measure the total suction in a soil by measuring the relative humidity, RH, in the soil. Total suction is related to relative humidity in accordance with Eq. 1 and is illustrated in Fig. 7. Details of the thermocouple psychrometer are shown in Fig. 8a. The measurements of total suction are carried out by placing a soil specimen in a small chamber together with the psychrometer (Fig. 8b). The relative humidity is then measured after equilibrium is attained between the air near the psychrometer and the pore-air in the soil. Equilibrium at relative humidities approaching 100 percent are difficult to obtain since the slightest lowering of temperature may cause condensation of water vapor. A controlled temperature environment of ±0.001°C is required in order to measure total suctions to an accuracy of 10 kPa (Krahn and Fredlund, 1972). The lower limit of total suction measurements using a psychrometer is approximately 100 kPa under a controlled temperature environment. The thermocouple psychrometer is capable of measuring total suctions up to 8000 kPa (Edil and Motan, 1984). Therefore, psychrometers are ideal for measuring high suctions in soils from arid regions. Insitu measurements of total suctions using psychrometers are not recommended because of significant temperature fluctuations which occur in the field. However, laboratory measurements can be conducted in a controlled temperature environment using undisturbed soil specimens from the field. The specimens should not be covered with hot wax following sampling, since temperature changes alter the relative humidity in the soil. Figure 9 illustrates measurements of total suctions on soil samples from various depths at a location near Regina, Saskatchevan, Canada.

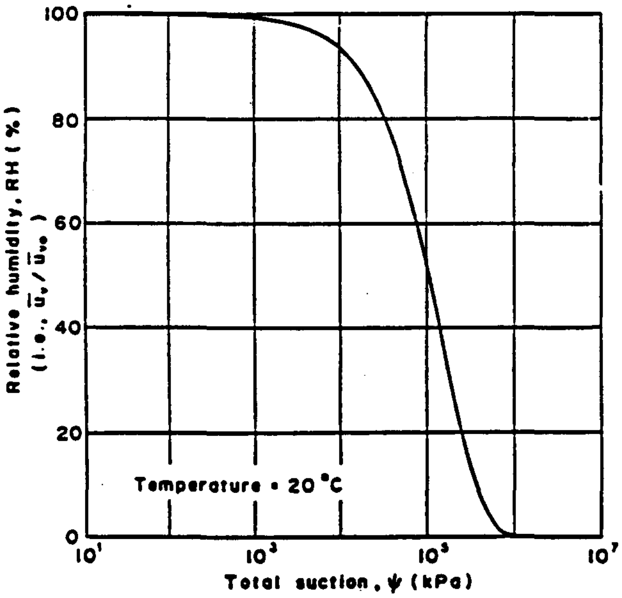
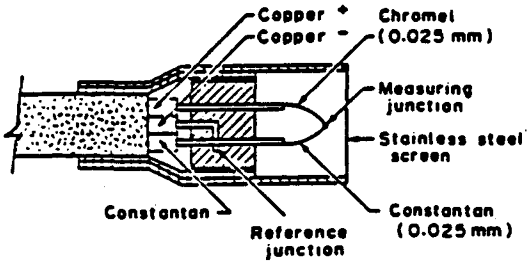
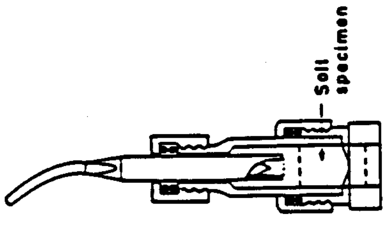


Fig. 7 Relative humidity versus total suction relationship



a) Thermocouple psychrometer details



b) Chamber with soils specimen and psychrometer

Fig. 8 Details of thermocouple psychrometer manufactured by J.R.D. Merrill Specialty Equipment, Logan, Utah, U.S.A.

FILTER PAPER

Theoretically, the filter paper method can be used to measure the total or matric suction of a soil. The method is based on the assumption that a filter paper can come to equilibrium (i.e., with respect to water flow) with a soil having a specific suction. The equilibrium can be reached by water exchange between the soil and the filter paper in a liquid or vapor form. When a dry filter paper is placed in contact with a soil specimen, moisture flow takes place from the soil to the paper until equilibrium is achieved (Fig. 10). When a dry filter is suspended above a soil specimen (i.e., no contact with the soil) the vapor flow of water should occur from the soil to the paper until equilibrium is obtained (Fig. 10). Having established equilibrium conditions, the water content in the filter paper can be measured. The filter paper water content is related to a suction value through use of the filter paper calibration curve as illustrated in Fig. 11. Theoretically, the equilibrium water content of the filter paper corresponds to the soil matric suction when the paper is placed in contact with the soil and liquid flow occurs. On the other hand, the equilibrium water content of the filter paper corresponds to the total suction of the soil if the paper is not in contact with the soil and only vapor flow occurs. The filter paper method can be used to measure almost the entire range of suctions.

A comparison between the results of suction measurements using filter papers and psychrometers is shown in Fig. 9. The results from the non-contact filter paper agreed closely with the psychrometer results indicating that total suction was measured.

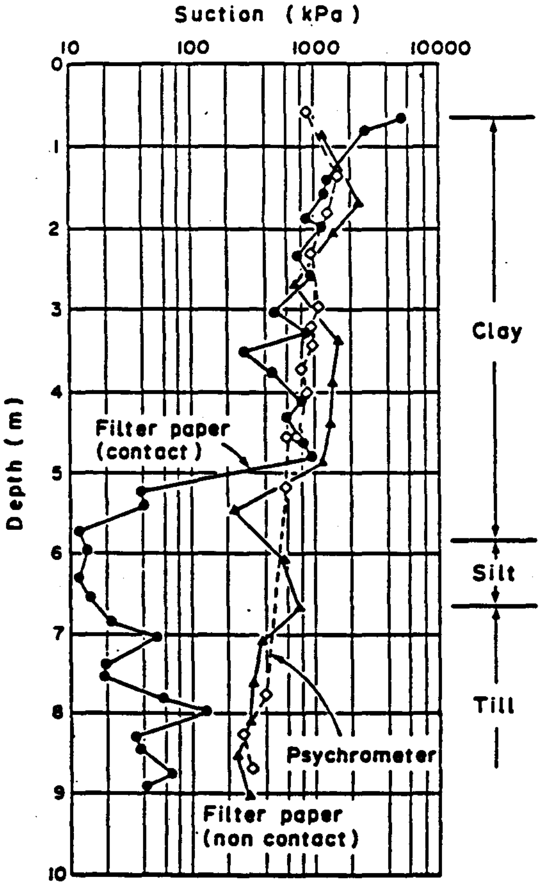


Fig. 9 Suction profile versus depth obtained using thermocouple psychrometers and the filter paper method (From van der Raadt, Fredlund, Clifton, Klassen and Jubien, 1987)

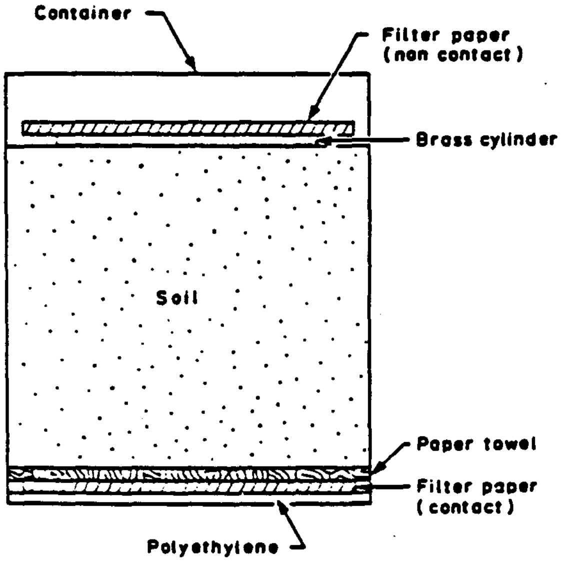


Fig. 10 Contact and non-contact filter paper method for measuring matric and total suctions, respectively (From Al-Khafaf and Hanks, 1974)

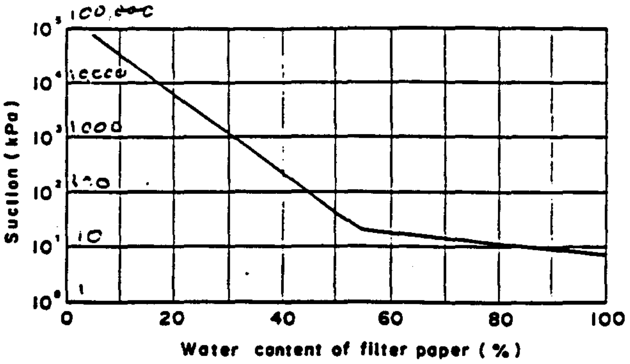


Fig. 11 A typical calibration curve for filter paper (From McQueen and Miller, 1968)

However, the contact filter paper did not exhibit consistent results with respect to depth. This is believed to be due to poor contact between the filter paper and the soil specimen that resulted in the total suction being measured instead of the matric suction (i.e., in the depth range of 0 to 5 m in Fig. 9).

PORE FLUID SQUEEZER

The osmotic suction of a soil can be determined by measuring the electrical conductivity of pore-water from the soil. Pure water has a low electrical conductivity in comparison to the pore-water that contains dissolved salts. Therefore, the electrical conductivity of the pore-water from the soil can be used to indicate the total concentration of dissolved salts which is related to the osmotic suction of the soil. The pore-water in the soil can be extracted using a pore fluid squeezer which consists of a heavy-walled cylinder and piston squeezer (Fig. 12). The electrical resistivity (or electrical conductivity) of the pore-water is then measured. A calibration curve (Fig. 13) can be used to relate the electrical conductivity to the osmotic pressure of the soil.

SUMMARY

Several devices for measuring total, matric, and osmotic suctions have been described in this paper. Techniques and limitations associated with each device are outlined. More research is required on the measurement of suction. However, it is now possible to measure the components of soil suction for engineering projects. The best procedures and devices vary, depending primarily upon the range of suction being measured.

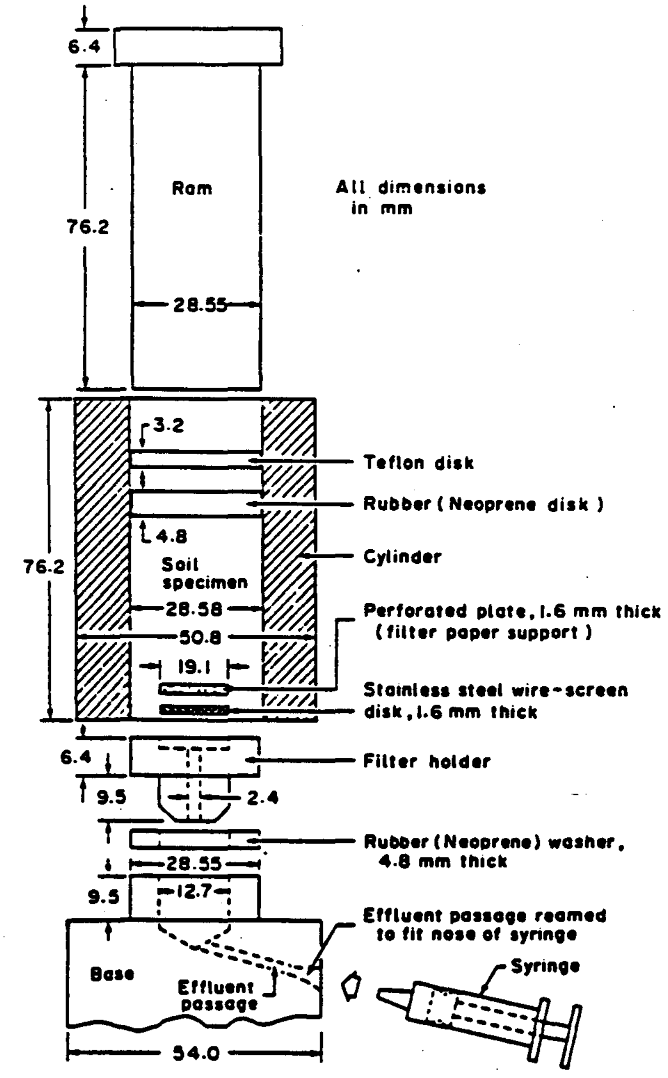


Fig. 12 Pore fluid squeezer (From Manheim, 1966)

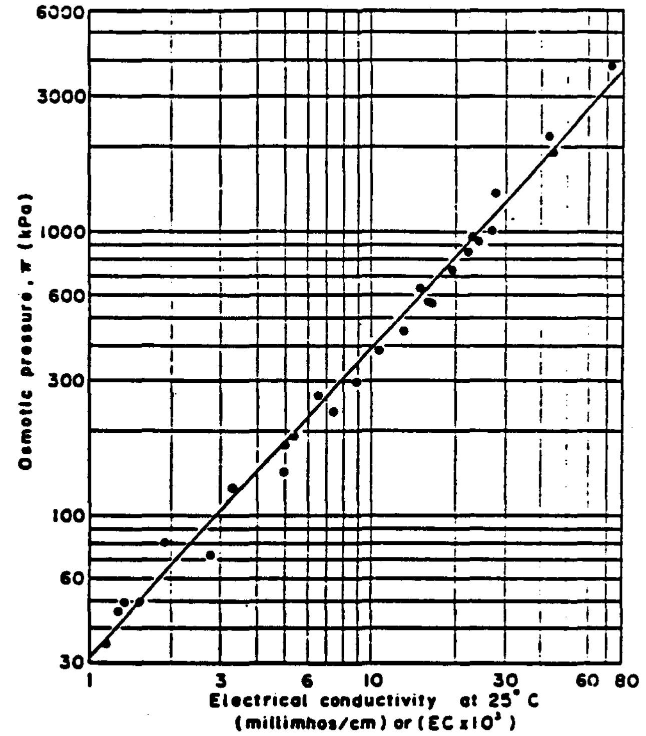


Fig. 13 Osmotic pressure versus electrical conductivity relationship for pore-water containing mixtures of dissolved salts (From USDA Agricultural Handbook No. 60, 1950)

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