Use of a new thermal conductivity sensor for laboratory suction measurement

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ABSTRACT: The thermal conductivity matric suction sensor has been proven to hold great promise for the *in situ* and laboratory measurement of soil suction. Some difficulties have been associated with the use of early versions of the thermal conductivity sensors. An improved thermal conductivity sensor has been developed at the University of Saskatchewan, Saskatoon, Canada to overcome these difficulties. The new sensor has some design aspects that are superior to that of previous sensors. These design aspects make the new sensor a more suitable device for both laboratory and *in situ* soil suction measurements.

1 INTRODUCTION

The measurement of soil suction is essential to the study of unsaturated soil behavior. Volume change, shear strength and seepage analyses all require an understanding of the matric suction in the soil. One of the more common methods used for continuous suction monitoring is the use of thermal conductivity matric suction sensors. This method uses a measurement of the thermal conductivity of a standard ceramic tip. The thermal conductivity of the ceramic tip is correlated with the matric suction of the ceramic which is in equilibrium with the surrounding soil. This method has been proven to be a promising device for the *in situ* and laboratory measurement of soil suction (Fredlund and Rahardjo, 1993).

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 over a long period of time. The measurements are essentially unaffected by the salt content of the soil (Lee and Fredlund, 1984 and Fredlund and Wong, 1989). The thermal conductivity sensors are also versatile and able to be connected to a data acquisition system for continuous and remote monitoring.

Some of the past difficulties associated with previous thermal conductivity sensors are the low strength of the ceramic, poor durability of the ceramic and electronics, and the low accuracy over portions of the suction range. The influences of factors, such as the soil temperature and the hysteresis properties of the ceramic on the suction measurement were not previously taken into account.

An improved thermal conductivity matric suction sensor was developed at the University of Saskatchewan, Canada, for the purpose of measuring soil suctions over a wide range of values. This paper describes the use of the new thermal conductivity sensors to measure matric suction in the laboratory.

2 GENERAL CHARACTERISTICS OF THE NEW THERMAL CONDUCTIVITY SOIL SUCTION SENSOR

The new thermal conductivity soil suction sensor (Fig. 1) has some characteristics that make it superior to previous sensors. Those characteristics make the new soil suction sensor more suitable for both laboratory and *in situ* soil suction measurement.

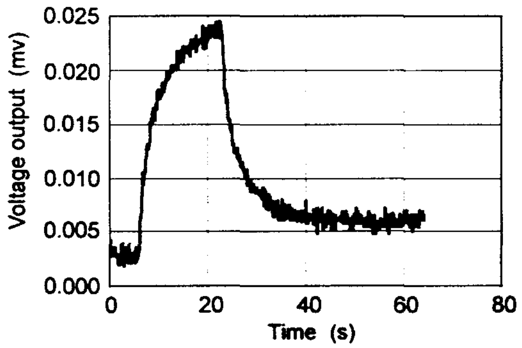
A new ceramic with a high porosity (i.e., more than 60%) and a wide range of pore sizes (i.e., ranging from 0.05 mm to less than 0.0001 mm) is used as the ceramic tip for the new sensor. This ceramic tip can be used to measure suctions from approximately 5 kPa to 1500 kPa. In addition, there is a near-linear relationship between water content and logarithm of soil suction between 5 kPa and 500 kPa.

The electronic properties of the new sensor have also been improved by using superior integrated circuitry for the temperature sensing device. Advanced signal conditioning (i.e., amplification, isolation and filtering) was used to further increase the resolution and accuracy of the new sensor. A comparison of heating curves measured before and after improvement is presented in Fig. 2 and the main technical specifications for the new sensor are listed in Table 1.

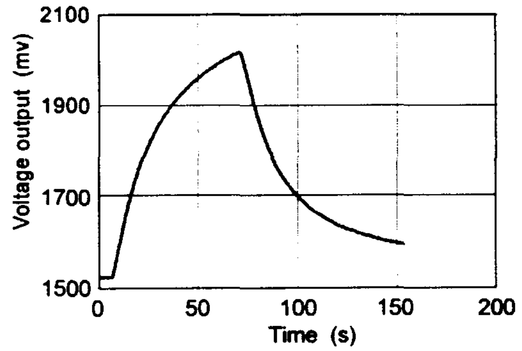
Figure 1 The thermal conductivity soil suction sensor developed at the University of Saskatchewan, Saskatoon, Canada.

Table 1. Technical specification.

Measurement parameters	Soil suction Soil temperature
Measurement range	Soil suction 5 to 1500 kPa Temperature -40 °C to 110 °C
Accuracy	± 5% for suction measurement ± 0.5 °C for temperature measurement
Resolution	0.33 mV
Soil types	Suitable for all soil types
Protection	Suitable for long-term burial
Temperature	0 to 40 °C for suction measurement (no damage when used in frozen soils, but suction readings do not represent soil suction)
Power supply	12V ~ 15V DC, 250 mA
Size	Diameter: 28 mm, Length: 38 mm
Cable length	Standard: 8m, Maximum: 100m



A. Measured heating curve before improvement



B. Measured heating curve after improvement

Figure 2 The heating curves measured before and after improvement.

4 CALIBRATION OF THE NEW SENSOR

The accuracy of the soil suction measurements obtained when using the thermal conductivity suction sensor is dependent upon their calibration. The calibration of the new sensor was performed by applying a range of matric suction values to the sensor. The sensor was embedded in a soil that was placed in a Tempe cell (Fig. 3). The soil in the Tempe cell provided continuity between the water phase in the porous ceramic tip and the water in the high air entry disk. A matric suction was applied by increasing the air pressure in the Tempe cell while maintaining the water pressure below the high air entry disk at atmospheric conditions. The change in voltage output from the sensor was monitored periodically until suction equilibrium was achieved. The above procedure was repeated for various applied suctions ranging from 0 to 400 kPa so that a calibration curve could be obtained.

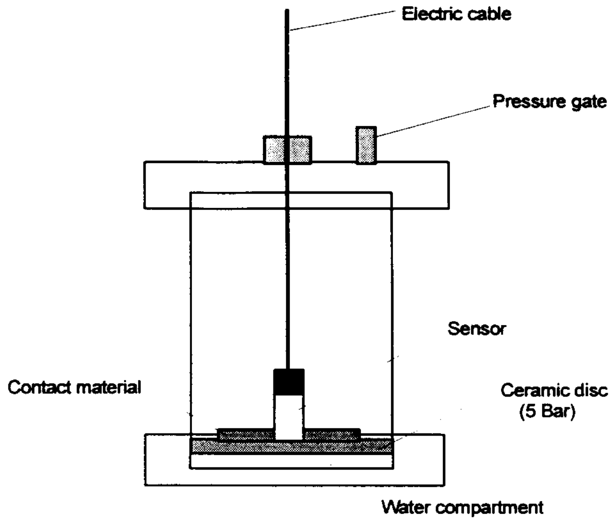


Figure 3 The physical layout of the test apparatus for calibration of sensors.

The calibration curve obtained from the calibration process is non-linear. In order to use the calibration curve to calculate the soil suction from the output voltage of the sensor, it is important to have a reasonably accurate characterization of the calibration curve. The following equation is proposed to fit the relationship between output voltage, ΔV, and soil suction, ψ.

$$\psi = \left[\frac{b \cdot (\Delta V - a)}{c - \Delta V}\right]^{d} \qquad (1)$$

where a = parameter designating the output voltage under saturated conditions; c = parameter designating the output voltage under dry conditions; d = parameter designating the slope of the calibration curve, and b = parameter related to the inflection point on the calibration curve.
A typical calibration curve for a sensor is shown in Fig 4 along with its parameters. Since there are four parameters in Eq. 1, only five calibration points are required to establish the calibration curve. As a result, the calibration process is simplified and the time required for calibration is significantly reduced. Equation 1 facilitates the calculation of the soil suction from the output voltage of the sensor and increases the accuracy of the suction measurement.

5 FACTORS INFLUENCING THE SOIL SUCTION MEASUREMENT

Some factors may influence the suction measurement. This factors are soil temperature, freeze-thaw cycles and hysteresis of the ceramic.

5.1 *Soil Temperature*

The influence of soil temperature on the suction measurement is shown in Fig. 5. This influence is attributed to the change in thermal conductivity of the water with ambient temperature. In order to eliminate the influence of ambient temperature, a temperature correction was developed and can be expressed as follows,

$$\Delta V_{23\,^{\circ}C} = \frac{0.0014t + 0.561}{0.593}\Delta V_{t} \qquad (2)$$

where t = the soil temperature; $\Delta V_{23^{\circ}C}$ = the output voltage at 23°C; and ΔV_{t} = the output voltage at temperature, t.

Figure 5 shows the output voltage with or without temperature correction for one thermal conductivity sensor. The soil temperature during the measurements is also shown in the figure. It can be seen that

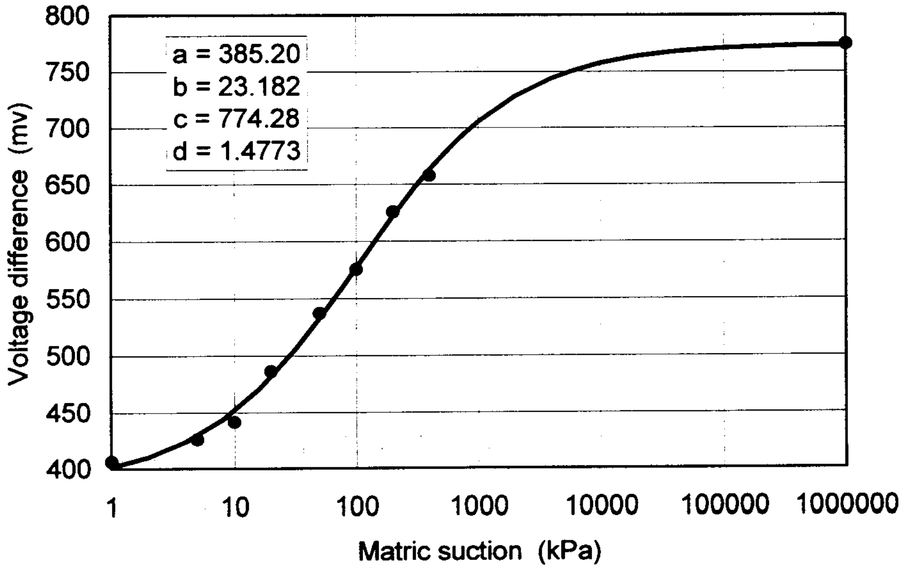


Figure 4 A typical calibration curve for a thermal conductivity sensor.

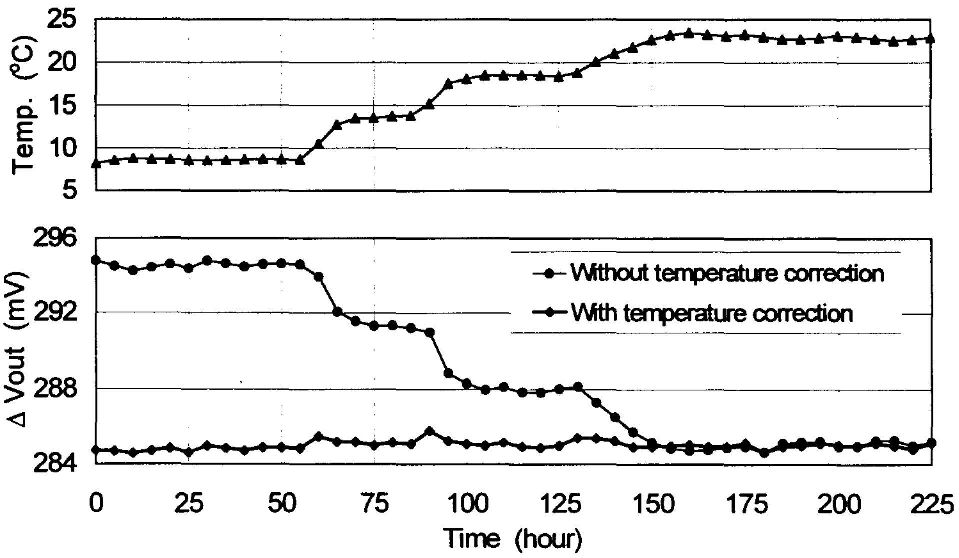


Figure 5. The influence of the ambient temperature and temperature correction technique verification (suction = 10 kPa).

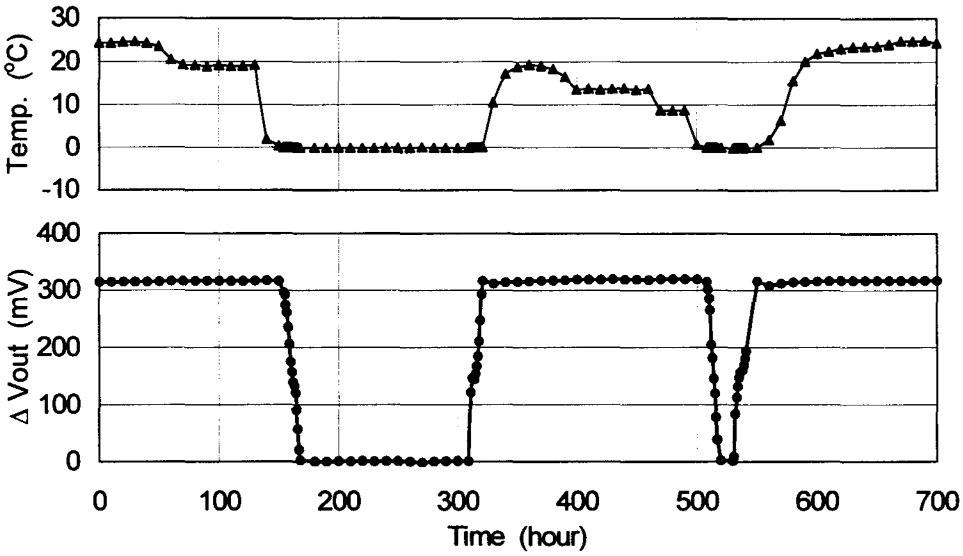


Figure 6 Influence of freeze-thaw cycles (suction = 50 kPa).

the temperature influence is significantly accounted for by using the proposed temperature correction technique.

5.2 *Freeze-Thaw Cycles*

Experiments in the laboratory have shown that there are difficulties associated with measuring negative pore-water pressures in freezing soils when using thermal conductivity soil suction sensors (Fredlund etc., 1991). Distinct drops in the output voltage have been observed during the freezing and thawing processes (Fig. 6). These drops are attributed to the effect of the latent heat of fusion on thermal conductivity. As soil freezes, the proportions of unfrozen and frozen water changed and since ice and water have different thermal conductivities, the output voltages are difficult to interpret and to convert to soil suctions. However, the freeze-thaw cycles do not appear to influence the soil suction measurements after thawing. In the other words, the quality and the calibration properties do not appear to be affected by the freeze-thaw cycles (Fig. 6).

5.3 *The Hysteresis of the Ceramic*

The water content versus matric suction curves for any porous material during wetting and drying are generally not the same. The hysteresis in the soil-water characteristics of the ceramic may cause hysteresis in the sensor response upon wetting and drying (Fig. 7) The research conducted by Feng (1999)