Use of a New Thermal Conductivity Sensor to Measure Soil Suction

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Abstract

Soil suction (i.e., negative pore-water pressure) measurements are essential to predicting and verifying the behavior of an unsaturated soil. Some difficulties were encountered with soil suction measurements made using earlier versions of thermal conductivity soil suction sensors. An improved thermal conductivity sensor has been developed at the University of Saskatchewan, Saskatoon, Canada. The durability and the accuracy of the new sensor has been significantly improved by using a specially designed ceramic and improved electronics.

Introduction

The measurement of negative pore-water pressure is essential to understanding the behavior of an unsaturated soil. The negative pore-water pressure (or soil suction) affects water flow, water storage, volume change and shear strength. As a result, there is need for a reliable technique to measure soil suction in an unsaturated soil. Various techniques are now available for measuring soil suction. Of these technique, the thermal conductivity sensor has been proven to be the most promising device for the in situ measurement of soil suction. 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.

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Thermal conductivity suction sensors consist of a temperature sensing element and a miniature heater embedded in a porous ceramic block (Fig. 1). The sensor is heated at a standard rate for a fixed heating period. During the heating period, part of the heat is dissipated and the undissipated heat results in a temperature increase at the center of the ceramic block. The amount of heat dissipation is controlled by the presence of water in the ceramic block since water is a better thermal conductor than air. The water content of the ceramic block is dependent upon the soil suction applied to the ceramic block by the surrounding soil. Thus, the change in the temperature at the center of the ceramic block is closely related to the change in matric suction of the surrounding soil. In other words, the temperature increase at the center of the sensor due to the heat pulse is a function of the soil suction of the surrounding soil being tested.

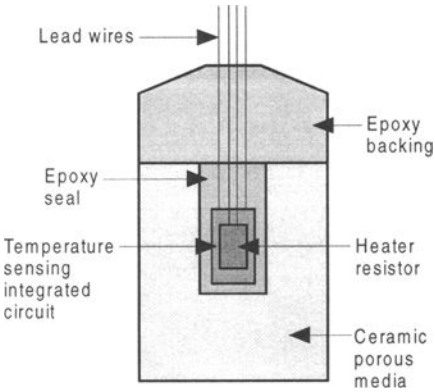


Figure 1 Cross-section diagram of a thermal conductivity soil suction sensor.

There have been numerous difficulties and shortcomings 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. In order to solve the difficulties associated with soil suction measurements, an improved thermal conductivity suction sensor has been developed at the University of Saskatchewan, Saskatoon, Canada.

In this paper, the special design considerations associated with the new thermal conductivity sensor, both in the ceramic and in the electronic aspects, are discussed. The calibration of the new thermal conductivity sensor is described. Some field and laboratory data obtained using the new thermal conductivity suction sensor are presented.

Special Design Considerations Associated with the New Thermal Conductivity Sensor

In order to ensure good performance of the new sensor, past problems needed to be addressed during the development of the new sensor. These considerations include the quality of the ceramic tip, the stability of the output signals and the sensitivity and accuracy of the new sensor.

Characteristic of the Ceramic Tip

The key component of the sensor is the ceramic tip. The ceramic used for soil suction sensors needs to have characteristics considerably different from regular ceramics. In general, regular ceramics possess a low porosity with a relatively uniform pore size distribution, while a high porosity with a wide distribution of pore sizes is required for the soil suction sensor tip in order to ensure a consistent accuracy that extends to the highly negative pore-water pressures. Due to the extremely wide range of possible soil suctions, the desired range of pore sizes for an acceptable ceramic tip should range from 0.1 to 0.0001 mm which corresponds to soil suctions ranging from 1 to 1500 kPa (Fredlund etc., 1994). A ceramic porosity higher than 50% is desired.

The ceramics must have high strength characteristics for use in geotechnical applications. In other words, the ceramic must be sufficiently robust to withstand stresses associated with drilling or driving the sensor into position in the field. It must also be durable to resist the effects of freeze-thaw cycles and drying-wetting cycles in harsh environments. In general, ceramics manufactured with a low porosity and a narrow range in pore size distribution have high strength characteristics whereas those with a high porosity and a wide pore size distribution have been found to be soft, friable and of relatively low strength.

A series of laboratory tests was performed to make a suitable ceramic for a new thermal conductivity suction sensor. The new ceramic tip with a high porosity (i.e., more than 60%) and a wide range of pore sizes has been developed. The new ceramic tip has pore sizes that range from 0.05 mm to less than 0.0001 mm and 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. This ensures a reasonably accurate measurement of matric suction over a wide range of soil suction. Figure 2 shows a typical soil-water characteristic curve for the ceramic.

The strength of the new ceramic tip has also been significantly improved. The compressive strength of the ceramic has been increased to approximately 2100 kPa. The average splitting tensile strength is about 600 kPa. The greater strength helps prevent cracking and crumbling during installation and prolong operation in the field.

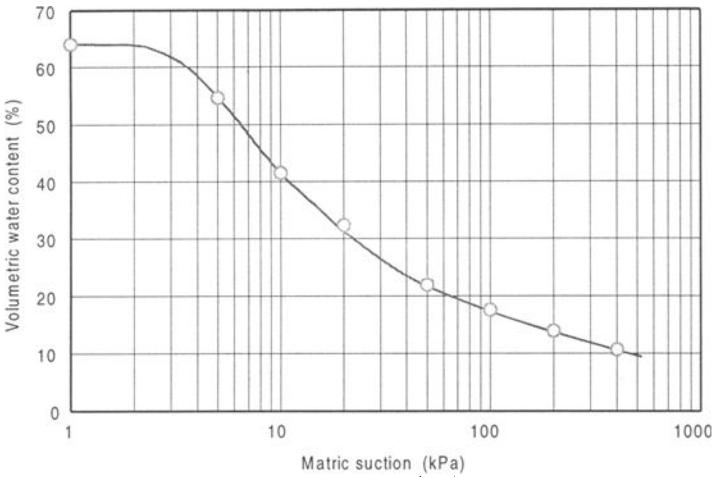


Figure 2. A typical soil-water characteristic curve for the new ceramic.

Characteristic of Electronic Design

The electronic design of the sensor mainly consists of three parts; namely, the temperature sensor selection, the signal conditioning design and the constant current sink design.

Temperature sensor

Two kinds of temperature sensors have been used to measure temperature changes inside the ceramic; namely, thermocouple and integrated circuit (i.e., IC).

A thermocouple consists of a junction of two different conductors (e.g., copper and constantan) when subjected to a temperature gradient generates a voltage. The device is sensitive to temperature gradient, but the voltage generated is very low, usually in the range of tens of microvolts, and is non-linear. This makes thermocouples less desirable for use in a thermal conductivity sensor.

An integrated circuit uses a silicon semi-conductor thermistor to measure temperature. Thermistors are resistors with a high rate of resistance change with temperature. The output voltage from the silicon semi-conductor thermistor can be amplified in the integrated circuit in order to provide improved resolution. The main advantages of the integrated circuit sensor is its higher resolution and its linear relationship between output and absolute temperature.

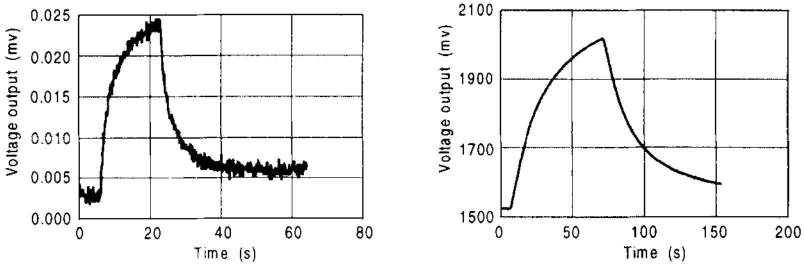
An integrated circuit, IC, was selected for the new sensor due to its higher accuracy. Another advantage with the integrated circuitry sensor is its ability to measure the soil temperature as well as the soil suction.

Signal conditioning

In order to increase the resolution and accuracy of suction measurements, the quality of output signal from the temperature sensor should be improved and unwanted noise should be removed before the signal is sent to the data logger. This process is called signal conditioning.

Three approaches were used for signal conditioning; namely, amplification, isolation and filtering. The output signal from the integrated circuit was first amplified using an amplifier to the full range of the data logger. The amplified signal was isolated from outside noise sources and unwanted noises were filtered out using a filter prior to entering the data logger.

Signal conditioning significantly improves the quality of the output signal from the temperature sensor. A comparison of heating curves measured before and after improvement is presented in Fig. 3.



A. Measured heating curve before improvement B. Measured heating curve after improvement

Figure 3 The heating curves measured before and after improvement.

Constant current sink

A precisely controlled heating voltage across the heating element is necessary if reading are to be accurate and reproducible. There are many factors that influence the heating voltage across the heating element, such as cable length, environmental temperature and voltage vibration of power source, to name only a few. In order to eliminate these influences, a constant current sink was designed and manufactured at the University of Saskatchewan.

The constant current sink is able to maintain a constant current of 200 mA through the heater resistor. The constant current compensates for differences in resistance when different lengths of extension wires are used. It also compensates for small changes in the heating resistance caused by a change in environmental temperature. This constant current sink, along with the amplifier mentioned previously, were installed on the same PC board and called a constant current sink and amplifier. A picture of this device is shown in Fig. 4.

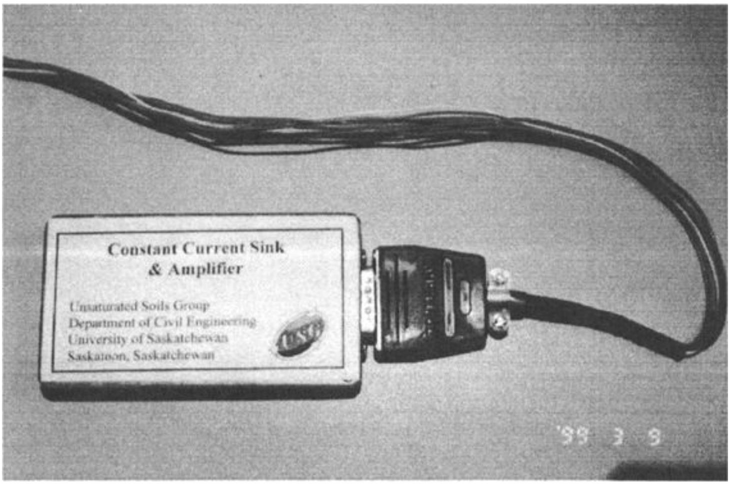


Figure 4 The Constant Current Sink & Amplifier device

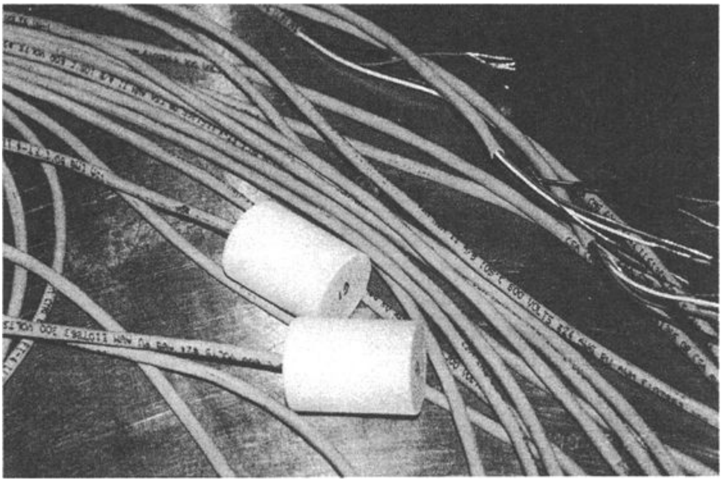


Figure 5 The thermal conductivity soil suction sensor developed at the University of Saskatchewan, Saskatoon, Canada.

Characteristic of New Thermal Conductivity Sensor

With the above design considerations, an improved thermal conductivity soil suction sensor was developed at the University of Saskatchewan, Saskatoon, Canada (Fig. 5). The durability and accuracy of the new sensors have been significantly improved over that of earlier versions. The new thermal conductivity sensor has been found to be quite sensitive and accurate in measuring soil suction in the range from 5 to 1500 kPa. This is the range of greatest interest for geotechnical and geo-environmental engineering. The main technical specifications for the new sensor are listed in Table 1.

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	Less than ± 5% for suction measurement ± 0.5 °C for temperature measurement
Resolution (using CR10X)	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 reading will be incorrect)
Power supply	12V - 15V DC, 250 mA
Size	Diameter: 28 mm, Length: 38 mm
Cable length	Standard: 8m, Maximum: 100m

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 on a Tempe cell (Fig. 6). The soil in the Tempe cell provided continuity between the water phase in the porous ceramic tip and in the high air entry plate. The matric suction was applied by increasing the air pressure in the Tempe cell while maintaining the water pressure below the high air entry disk. 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.

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.

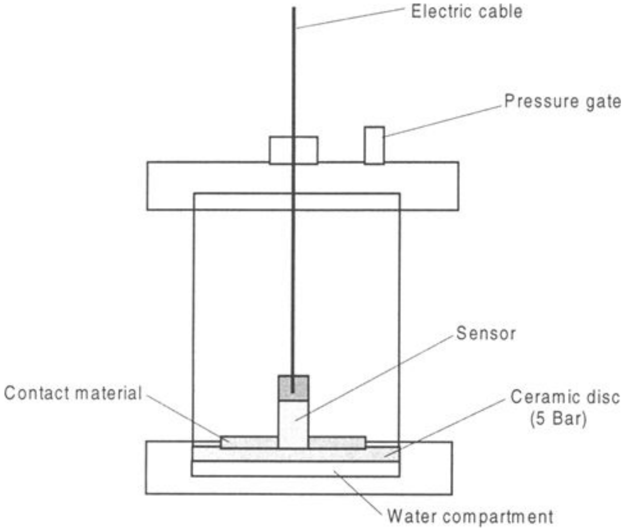


Figure 6 The physical layout of the test apparatus for calibration of sensors.

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

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 7 along with its parameter values. Since there are only 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.

Typical results of Soil Suction Measurements

Tests were undertaken to verify the performance of the new sensors. Those tests were divided into two parts, laboratory tests and field tests. Typical results are presented in this section.

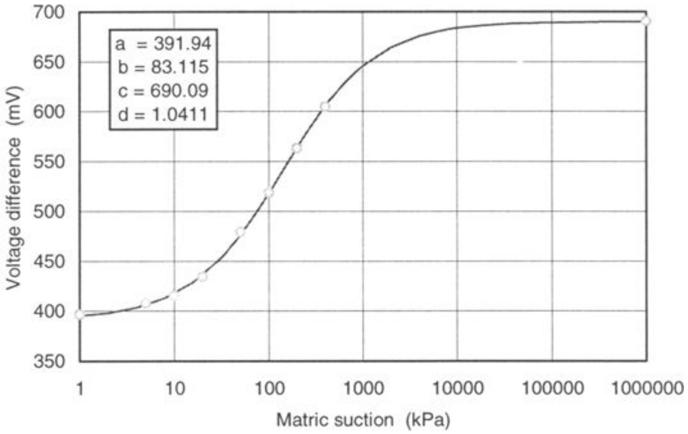


Figure 7 A typical calibration curve for a thermal conductivity sensor

Figure 8 presents soil suction results for laboratory measurements on an Indian Head till specimen. The soil specimen was compacted with a initial water content of 16%. Laboratory measurements were carried out using two sensors inserted from each end of a soil sample. One sensor was initially saturated while the other was initially air-dried. The sensors were inserted into predrilled holes in the sample. The sample with the installed sensors were wrapped in aluminum foil and sealed by duck tape to minimize moisture loss. The response of both sensors were monitored. The readings from both sensors were stable and showed that the same suction can be measured provided the effect of hysteresis of the ceramic is taken into account. The results indicate that the time required for the initially dry sensor to come to equilibrium with the soil specimen is less than the equilibrium time for the initially saturated sensor.

The new sensors have also been installed in the test cover site in the Key Lake area, Saskatchewan, Canada. The cover consisted of 0.7 m sandy till underlain by 0.6 m outwash sand.

A total of 22 new sensors were installed at the site. Twelve sensors were installed in a trench and another 10 sensors were installed in a observation shaft. The layout of sensor installation in the cover is shown in Fig. 9.

Data from sensors located at 14 cm, 35 cm, 58 cm and 115 cm from September 12 to September 18, 1997, are presented in Fig. 10 along with precipitation data. Soil suction data obtained from the sensors indicates that soil suction usually decreased after a heavy rain and then increased until the next rain event. The increase in soil suction was caused by evaporation from the cover surface. Therefore, the fluctuations in soil suction were most significant at the top of the cover and became less significant with depth (Fig. 10).

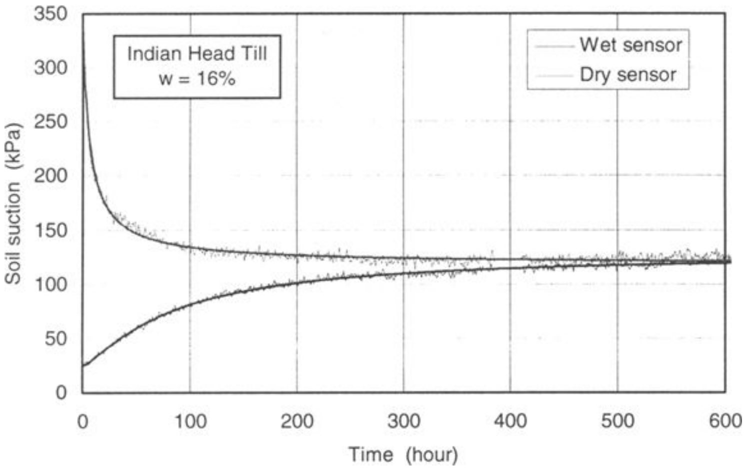


Figure 8 Laboratory measurements of soil suction on Indian Head till

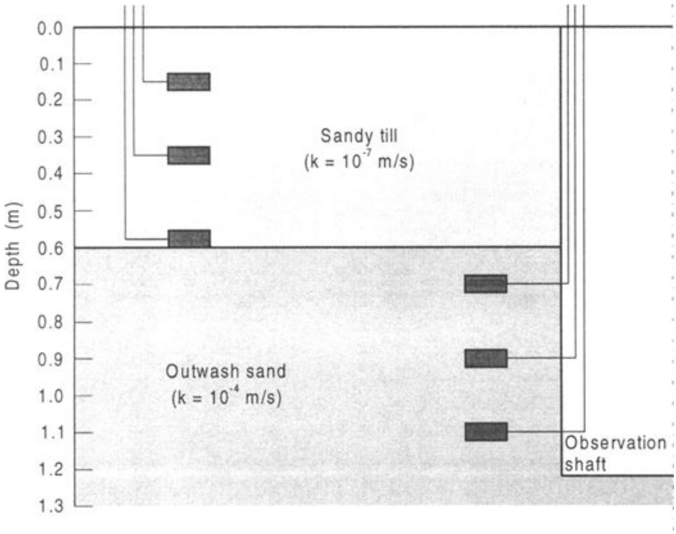


Figure 9 The layout of sensor installation in the test cover site in the Key Lake.