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Increased accuracy in suction measurements using an improved thermal conductivity sensor

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ABSTRACT: Suction measurements play an important role in mine reclamation and environmental protection. The thermal conductivity matric suction sensor has been proven to hold the great promise for the *in situ* measurement of soil suction. There were some limitations associated with previously developed versions of these sensors. An improved thermal conductivity sensor has been developed at the University of Saskatchewan, Saskatoon, Canada. The accuracy of the new sensor has been increased through use of a specially designed ceramic, enhanced electronic and improved interpretation technique for the data.

INTRODUCTION

Suction measurements play an important role in mine reclamation and environmental protection. Frequently, the most economical and feasible reclamation option is to use a soil cover over the waste rock and tailings. Evaluation of the performance of cover systems can be ensured through *in situ* measurements of soil suction. The rate of water movement and degree of storage of the cover are related to the suction in the soil.

One of the more common methods used for continuous soil suction measurement involves the use of thermal conductivity matric suction sensors. Comparing with other suction measurement systems (e.g., filter paper, TDR and psychrometer), thermal conductivity sensors produce a reasonably reliable measurement of soil suction over a relatively wide range and are essentially unaffected by the salt content of the soil (Lee and Fredlund, 1984 and Fredlund and Wong, 1989). These sensors also have the advantage of versatility and ability to be connected to a data acquisition system for automated recording. However, some difficulties have been encountered with previously developed thermal conductivity sensors. These difficulties relate to poor durability, low accuracy and reliability for geotechnical and environment monitoring.

In order to obtain a relative inexpensive and reliable sensor to measure soil suction, an improved thermal conductivity soil suction sensor has been developed. In this paper, the special design considerations associated with the new thermal conductivity sensor are described. The factors that may influence the accuracy of the suction measurement, such as heating voltage variation, stability of the output signal, interpretation of the data and the hysteresis properties of ceramic, are discussed. The techniques developed to eliminate each of these negative influences are described. Some soil suctions measured using the new thermal conductivity sensor are also presented.

AN IMPROVED THERMAL CONDUCTIVITY SENSOR

Thermal conductivity sensors have been used to measure soil suction for long time (Shaw and Baver, 1939 and Johnston, 1942). However, the use of early versions of these sensors have been experienced numerous difficulties. The difficulties with the use of thermal conductivity sensors has ranged from problem associated with: i.) ceramic tips that were soft, friable and

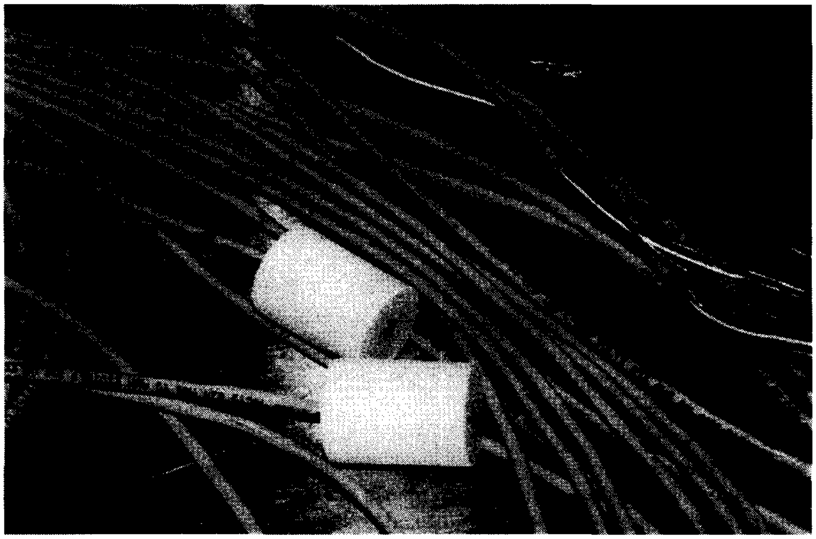


Figure 1 Thermal conductivity sensor developed at the University of Saskatchewan.

liable to crumble and crack during calibration or installation ii.) accuracy that was poor in the high suction range (i.e., greater than 200 kPa), and iii.) stability of the electronic signal from the sensor. In addition, the influence of factors such as heating voltage variation and the hysteresis upon wetting and drying of the ceramic, on the accuracy of the suction measurement needed to be studied. In order to resolve the difficulties associated with using thermal conductivity sensors, an improved thermal conductivity sensor was developed in the University of Saskatchewan, Saskatoon, Canada (Fig. 1).

The sensor developed at the University of Saskatchewan mainly consists of a specially designed ceramic tip, an integrated circuitry and a heating element (Fig. 2). The strength and durability for the new ceramic tip has been significantly improved over that of previous sensors. The compressive strength of the ceramic has been increased to approximately 2100 kPa. The tensile strength is about 600 kPa. The stronger sensor has a positive impact with respect to the prevention of cracking and crumbling during installation.

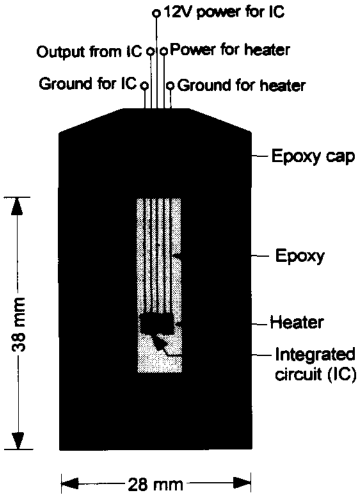
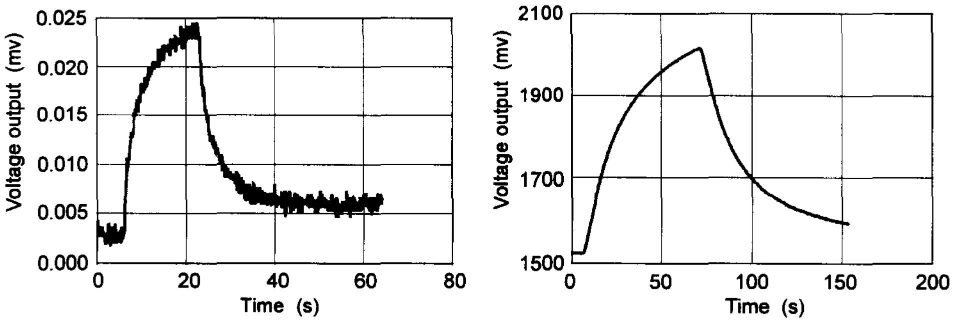


Figure 2 The physical layout of the thermal conductivity sensor developed at the University of Saskatchewan.

The new ceramic tip also has a high porosity and a wide range of pore sizes ranging from 0.05 mm to less than 0.005 mm. As a result, the soil-water characteristic curve for the new ceramic tip has been significantly improved ensuring a increased accuracy for suction measurements up to 1500 kPa.

With respect to the electronics, the quality of the output signal from the new sensor has been improved by using superior integrated circuitry for the temperature sensing device. Another advantage of using integrated circuitry for the temperature sensing device is that the



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

Figure 3 The heating curves measured before and after signal conditioning.

sensor can be used to measure the soil temperature as well as the soil suction. In the other words, the sensor is not only a soil suction sensor but also a soil temperature sensor. Soil suction can be measured as long as the temperature is above the freezing point of water while temperature can be measured over a wide range.

The advanced signal conditioning technique was also used to enhance the stability of the output signal from the sensor. The technique includes amplification, isolation and filtering. As a result, the stability of the output signal was significantly improved. Figure 3 shows the heating curves measured before and after signal conditioning.

With the above design considerations, 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 with a coefficient of variation less than ±5%. The main technical specifications for the new sensor are listed in Table 1.

Table 4.1 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

FACTORS WHICH INFLUENCE THE ACCURACY OF THE SUCTION MEASUREMENT

Some factors that may influence the accuracy of the suction measurement using a thermal conductivity sensor were investigated. These factors are the heating voltage variation, the interpretation of the data and the hysteresis of the ceramic.

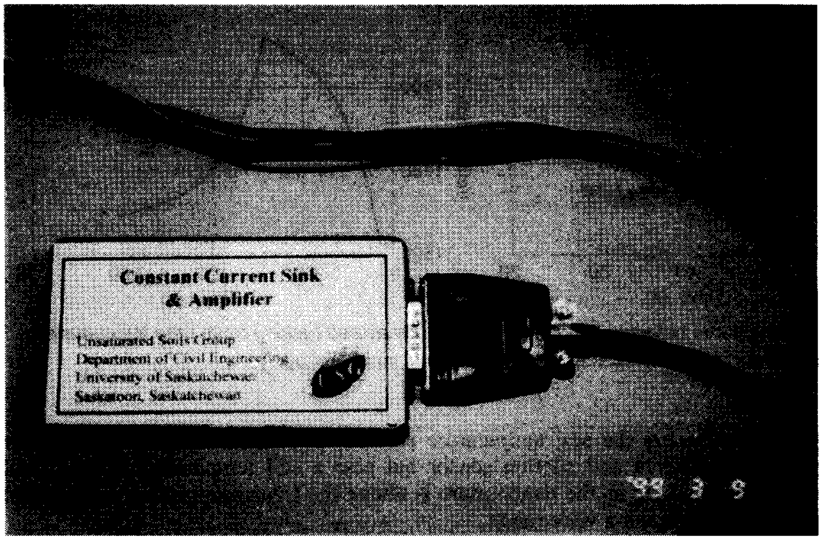


Figure 4 The Constant Current Sink & Amplifier device designed to be used with the data acquisition system.

The heating voltage variation

A precise controlled heating voltage across the heating element is mandatory if readings are to be reproducible. There are many factors that influence the heating voltage across the heating element, such as, cable length, environmental temperature and voltage vibration in the power source, to name only a few. In order to eliminate these influences, a constant current sink was designed and manufactured.

The device 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 the 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. According to the test results, the constant current sink and amplifier is able to function under freezing condition (i.e., -40°C). A picture of this device is shown in Fig. 4.

Interpretation of the data

The calibration curve obtained from the calibration process is non-linear (Fig. 5). 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 the soil suction, ψ.

$$\Delta V = \frac{ab + c\psi^{d}}{b + \psi^{d}} \qquad [1]$$

where:

a = parameter designating the output voltage at saturated condition
c = parameter designating the output voltage under a total dry condition
d = parameter designating the slope of the calibration curve
b = parameter related to the inflection point on the calibration curve

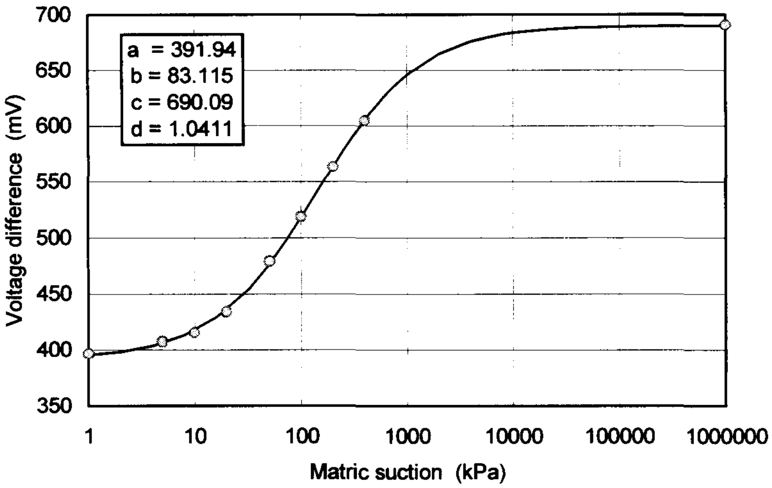


Figure 5 Typical calibration curve for a thermal conductivity sensor.

A typical calibration curve for a sensor is shown in Fig 5 along with its parameter values. Eq. 1 accurately fits the calibration data over the entire suction range. 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. As well, using calibration Eq. 1 facilitates the calculation of the soil suction from the output voltage of the sensor and increases the accuracy of the suction measurement.

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. To-date, little research has been done on the hysteresis associated with the ceramic.

Figure 6 shows measured wetting and drying curves for the new ceramic. Some hysteresis is observed in the soil-water characteristic curve of the ceramic, along with some initial saturation condition. When the suction is lower than 20 kPa, there can be a significant hysteresis during the first drying and wetting cycle. The hysteresis becomes less significant during the second wetting and drying cycle. The reason for this may be that the saturation condition was not the same during the first and second drying and wetting cycle.

At beginning of the test, the sensor was saturated under a vacuum of 80 kPa to ensure 100% degree of saturation. However, at the end of the first drying and wetting cycle, the sensor was saturated under zero matric suction. Since no vacuum or back pressure was applied to the sensor, it is impossible to remove all of the small air bubble isolated inside the ceramic. Therefore, the water content of the ceramic at beginning of the second drying and wetting cycle is less than the water content at beginning of the first drying and wetting cycle. Further test results indicate that, using the sensor saturated under 0 kPa matric suction gives a hysteresis at the first drying and wetting cycle that is almost the same as that of the second drying and wetting cycle. This result indicates that, in order to accurately measure soil suction, the sensor should be saturated under 0 kPa matric suction instead of being saturated under a vacuum.

The hysteresis of the ceramic became less significant and quite reproducible when the measured matric suction is greater than 20 kPa. The research conducted by Feng (1999) indicated that the maximum possible relative error in the suction measurement caused by the hysteresis is about 30%. In the other words, the hysteresis of the ceramic should be considered during the measurement of soil suction. The suctions measured with or without consideration of

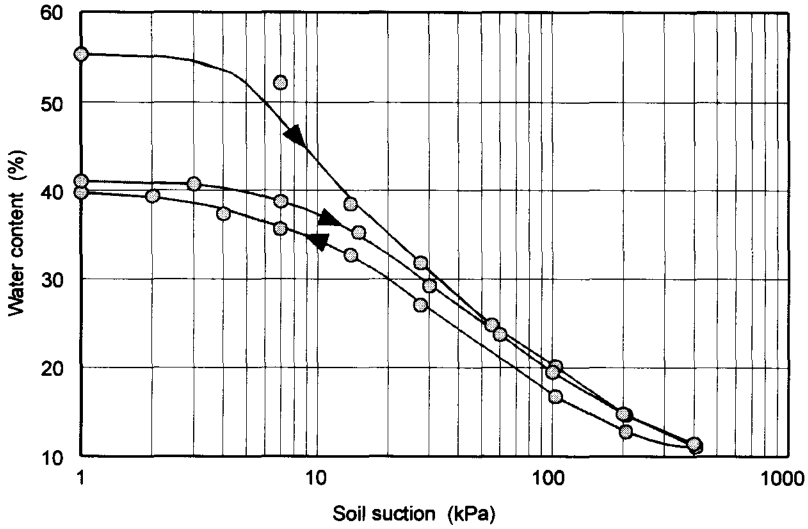


Figure 6 Hysteresis loop in the soil-water characteristic curve of the ceramic.

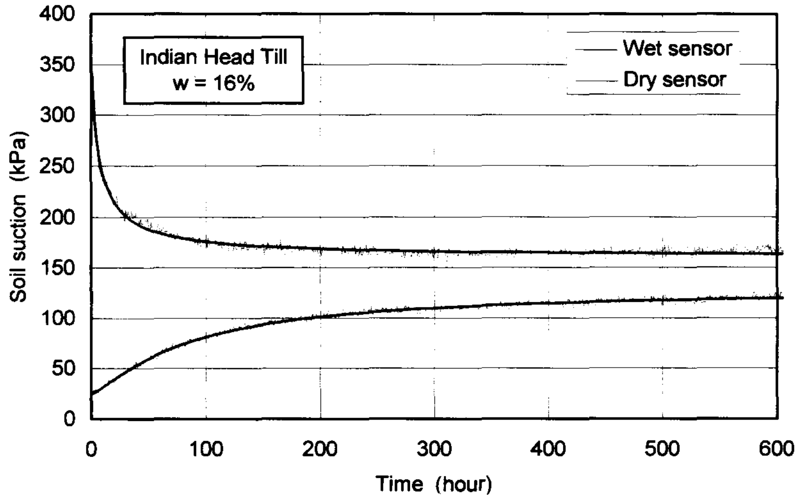


Figure 7 Soil suctions measured without taking into consideration the hysteresis of the ceramic

hysteresis in the ceramic are shown in Figs. 7 and 8. The suctions were measured by placing sensors with differing initial water contents into a soil specimen. A gap of 40 kPa was observed between the suctions measured with an initially dry sensor and with an initially wet sensor. The gap was eliminated by taking the hysteresis in the ceramic into consideration (Fig. 8).

The scanning curves between the drying and wetting curves were also investigated and are shown in Fig. 9. In order to improve the interpretation of the sensor data, a hysteresis model was proposed (Feng, 1999). This model can be used to modify data obtained in engineering practice according to the wetting or drying history of the sensor. As a result, it is possible to obtain greater accuracy in the assessment of suction. A comparison between the actual suction change and the predicted suction change using the hysteresis model is shown in Fig. 10. Good agreement was noticed between the predicted suction changes and actual suction changes.

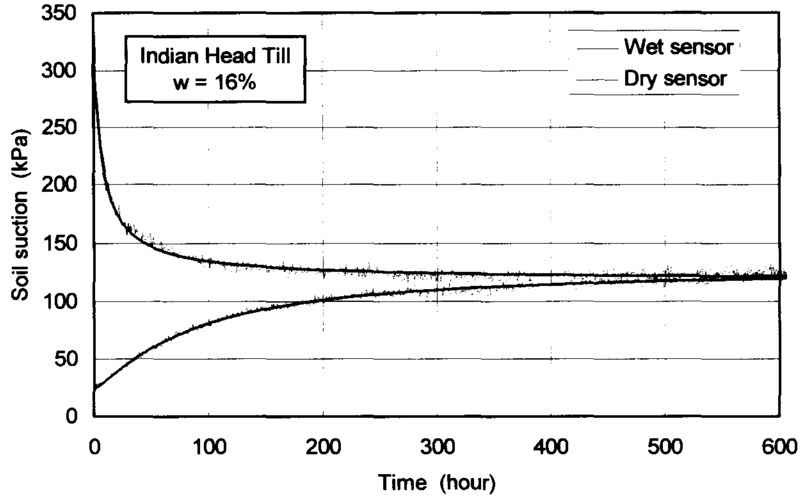


Figure 8 Soil suctions measured taking into consideration the hysteresis of the ceramic

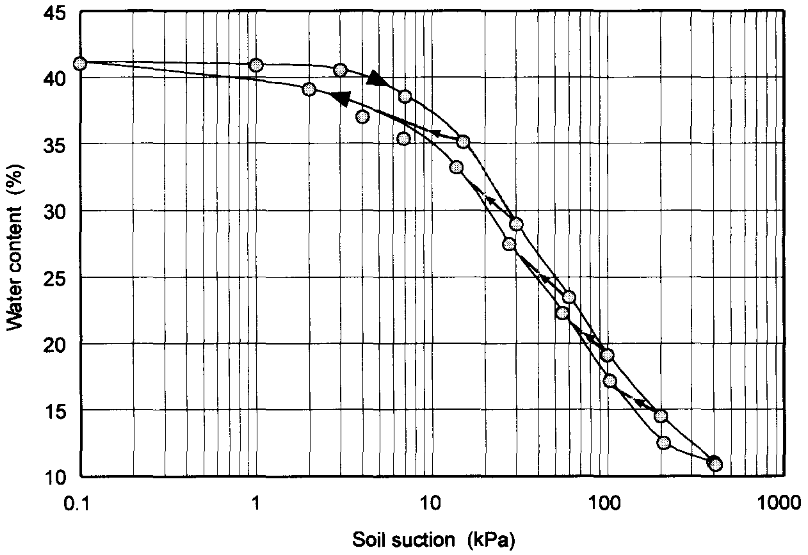


Figure 9 Wetting scanning curves measured for the new ceramic.

CONCLUSIONS

Currently available thermal conductivity matric suction sensors show promise for the *in situ* measurement of soil suction. An improved thermal conductivity soil suction sensor was developed to eliminate limitations associated with earlier sensors.

The durability and accuracy for the new thermal conductivity sensors have been significantly improved. 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 with a coefficient of variation less than ±5% over the range.

A constant current sink was developed to ensure a constant heating voltage. The influence of the cable length on soil suction measurements was eliminated through the use of this constant current device.

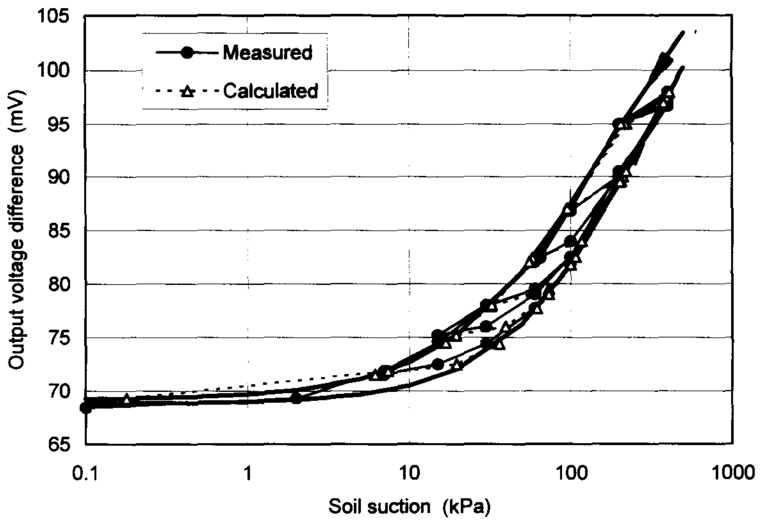


Figure 10 A comparison between the applied suction and the predicted suction using the hysteresis model.

A calibration equation was proposed to facilitate in the calculation of soil suction versus output voltage. There is an increase in the accuracy of soil suction measurements. It was found that the equation accurately fits calibration data over the entire suction range.

The hysteresis of the ceramic has an influence on soil suction measurement. A hysteresis model was proposed and can be used to interpret sensor data collected according to the drying or wetting history of the sensor.

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REFERENTS

Feng, M. 1999. The effects of capillary hysteresis on the measurement of matric suction using thermal conductivity sensors, *M.Sc. thesis*, University of Saskatchewan, Saskatoon, Saskatchewan, Canada. 168p.

Fredlund, D.G. and Wong, D.K.H. 1989. Calibration of thermal conductivity sensors for measuring soil suction, *ASTM Geotechnical Testing Journal*, vol. 12, no. 3, pp. 188-194.

Johnston, L.N. 1942. Water permeable thermal radiators as indicators of field capacity and permanent wilting percentage in soils, Soil Sci., vol. 54, pp. 123-126.

Lee, R.K.C. and Fredlund, D.G. 1984. Measurement of soil suction using the MCS 6000 gauge, *in* Proc. 5th Int. Conf. Expansive Soils, Inst. of Eng., Adelaide, Australia, pp. 50-54.

Shaw, B. and Baver, L.D. 1939. An electrothermal method for following moisture changes of the soil insitu, Proc. Soil Sci. Soc. Amer., vol. 4, pp. 78-83.