NOTE / NOTE

Calibration of thermal conductivity sensors with consideration of hysteresis

Man Feng and Delwyn G. Fredlund

Abstract: A thermal conductivity sensor monitors soil suction by measuring the changes in thermal conductivity of the porous tip. The thermal conductivity of the porous tip is a direct function of its water content. It has long been recognized that the suction versus water content relationship of a porous material exhibits hysteresis of various magnitudes between wetting and drying processes. The sensor output may correspond to various suction values of the sensor porous tip, depending on the wetting or drying state of the porous tip. The current calibration procedure, however, represents only one of the drying processes of the sensor porous tip. A laboratory testing program was carried out to better understand the hysteretic properties of the sensor output voltage versus the suction and to further improve the calibration procedure. The output of the sensor was monitored as the sensor porous tip was subjected to various drying and wetting processes. The test results indicate an error of 30%–70% for suctions higher than 100 kPa if the hysteretic effects of the porous tip are not considered in data interpretation. Based on the laboratory testing results, a revised calibration procedure was proposed that takes into consideration the capillary hysteretic effects.

Key words: thermal conductivity sensor, calibration, matric suction, capillary hysteresis.

Résumé : Un capteur de conductivité thermique mesure la succion du sol en mesurant les changements dans la conductivité thermique de la pointe poreuse. La conductivité thermique de la pointe poreuse est une fonction directe de sa teneur en eau. Il est connu depuis longtemps que la relation succion versus teneur en eau d'un matériau poreux présente une hystérèse de différentes grandeurs entre les processus de mouillage et de séchage. La sortie du capteur peut correspondre à diverses valeurs de succion de la pointe poreuse, dépendant de l'état de séchage ou de mouillage de la pointe poreuse. Cependant, la procédure de calibrage ne représente qu'un des processus de séchage de la pointe poreuse du capteur. On a réalisé un programme d'essais en laboratoire afin de mieux comprendre les propriétés d'hystérèse du voltage de sortie du capteur en fonction de la succion et d'améliorer encore plus la procédure de calibrage. Les données du capteur ont été mesurées alors que la pointe poreuse du capteur a été soumise à divers processus de séchage et mouillage. Les résultats d'essais indiquent une erreur de 30 % à 70 % pour des succions plus élevées que 100 kPa si les effets d'hystérèse de la pointe poreuse ne sont pas pris en considération dans l'interprétation des données. En partant des résultats des essais en laboratoire, on a proposé une procédure révisée de calibrage qui tient compte des effets de l'hystérèse de la capillarité.

Mots clés : capteur de conductivité thermique, calibrage, succion matricielle, hystérèse de capillarité.

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Introduction

Measurement of field soil suctions or suction changes is required when dealing with problems related to unsaturated soils in geotechnical engineering practice. Thermal conductivity soil suction sensors appear to be one of the promising devices for long-term in situ monitoring of soil suction (Fredlund and Rahardjo 1989; Fredlund 1992).

A thermal conductivity soil suction sensor consists of a cylindrical porous tip containing a miniature heater and a temperature-sensing element (Phene et al. 1971). Figure 1 shows the structure of a thermal conductivity sensor developed at the University of Saskatchewan (Shuai et al. 1998). The porous tip is a specially designed and manufactured ceramic with an appropriate pore-size distribution corresponding to the range of soil suctions to be measured. The heater at the centre of the ceramic tip converts electrical energy to thermal energy. A portion of the thermal energy will be dissipated within the ceramic tip. The undissipated thermal energy results in a temperature rise at the centre of the ceramic tip. The temperature sensor (i.e., IC in Fig. 1) measures the temperature rise with respect to time, in terms of output

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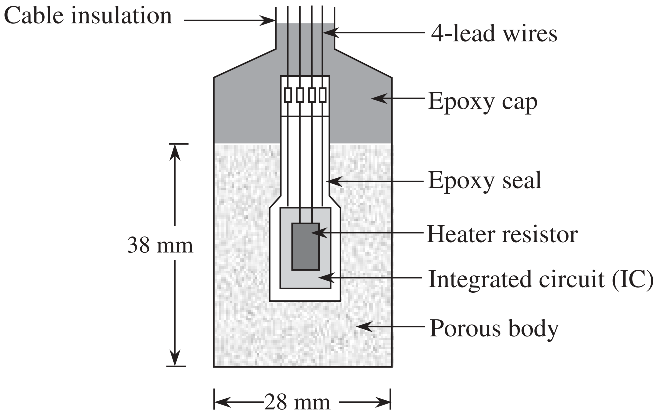
Fig. 1. A cross-sectional diagram of the newly developed thermal conductivity sensor (from Shuai et al. 1998).



voltage. Since water has a much higher thermal conductivity than air, the rate of dissipation of the thermal energy within the ceramic tip increases the water content of the ceramic. Higher water contents result in a lower temperature rise at the centre of the ceramic and, consequently, a lower output voltage from the temperature sensor. Since the suction in the sensor is equal to the suction in the surrounding soil, the voltage output of the temperature sensor (i.e., the output of the thermal conductivity suction sensor) can be calibrated against matric suction in the surrounding soil.

Calibration is the first step leading towards the use of the thermal conductivity sensor for field measurements of soil suction. Presumably the calibration should reproduce the actual field conditions as closely as possible. The sensors are conventionally calibrated following a drying process. The calibration curve represents the relationship between the sensor output and the applied matric suction for the specific drying process. It is recognized, however, that the water content (and consequently the output voltage) versus matric suction relationships for a porous material exhibit hysteresis between the wetting and drying processes (Fredlund et al. 1994). Little research has been done to date on the hysteretic relationship between the output voltage of a thermal conductivity sensor and matric suction, associated with the drying and wetting of the ceramic tip. This paper discusses the calibration of the suction sensor when hysteresis is taken into consideration based on laboratory test data on the newly developed thermal conductivity sensors shown in Fig. 1.

Conventional procedure for calibrating the thermal conductivity sensors

Conventional calibration consists of first saturating the ceramic tip by submerging it in water and then gradually desaturating the ceramic tip by incrementally increasing the matric suction (Fredlund and Wong 1989). The output voltage of the suction sensor is monitored for each increment of matric suction. A modified pressure plate extractor, as shown in Fig. 2, is used to apply matric suctions (Fredlund and Wong 1989). The ceramic tip is embedded in a soil slurry placed on the pressure plate and contained inside a Lucite cylinder. The soil provides contact between the ceramic tip and the high air entry pressure plate to ensure the continuity of water flow between the ceramic tip and the pressure plate.

The ceramic tip of the suction sensor should be initially saturated. To saturate the ceramic tip, it is suggested that the ceramic tip be submerged in deaired water for about 2 days (Fredlund and Wong 1989). The suction sensor is directed through a hole in the extension steel ring and the tip is inserted into the soil mixture. The pressure chamber is closed and an air pressure is applied to the soil mixture while keeping the water pressure underneath the pressure plate at zero. The water within the soil mixture and the ceramic tip is allowed to drain through the saturated pressure plate in response to the applied pressure. The response of each suction sensor is monitored until equilibrium is achieved. This procedure is repeated for higher matric suctions and a calibration curve of sensor output voltage versus matric suction is obtained. Figure 3 shows two typical calibration curves of AGWA-II sensors using the procedure (Fredlund and Wong 1989).

Laboratory testing results associated with drying and wetting processes

The conventional calibration procedure follows only a drying process. To investigate the hysteresis of the suction sensor related to the drying and wetting cycles of the ceramic tip, a laboratory testing program was carried out at the University of Saskatchewan on the newly developed thermal conductivity suction sensors.

The experimental setup was similar to that for a conventional calibration test and is illustrated in Fig. 4. The use of a soil mixture to embed the ceramic tip was not desirable in this case. If the soil mixture surrounding the sensor is relatively fine in texture, the initially slurried mixture tends to shrink during the drying process and, consequently, cracks will develop and result in poor contact between the soil and the sensor. If a coarse-textured soil is used, the time required for equilibrium will be too long when the suction is relatively high due to the low coefficient of permeability of a coarse soil at high suctions. Therefore, in this testing program, a thin layer of kaolinite paste was placed between the ceramic plate and the sensor tip. The kaolinite paste was less than 0.5 mm thick and provided water flow continuity between the sensor tip and the ceramic plate and assisted in holding the sensor tip in place. There did not appear to be problems with significant volume change of the paste during the drying and wetting processes.

Six suction sensors were selected for testing. The ceramic tip of the sensor has a diameter of 28 mm and a height of 38 mm. The ceramic has a compressive strength of approximately 2100 kPa, a saturated coefficient of permeability of 2.0×10^{-6} m/s, a dry density of 0.81–0.84 Mg/m^3, and a porosity of 60%–61% (Shuai et al. 1998). The air-entry value of the ceramic is approximately 5–10 kPa (Feng 1999). A CR-10 Campbell Scientific data acquisition unit with a relay driver and a multiplexer was programmed to automatically provide electrical current to the heater and record the output voltage. Readings were taken at 1 h intervals.

The sensor ceramic tips were saturated using a vacuum method before being installed in the pressure plate extractor. A vacuum of 0.85–0.90 bar (1 bar = 100 kPa) was applied to

Fig. 2. Modified pressure plate extractor setup for calibrating thermal conductivity sensors using a conventional procedure (Fredlund and Wong 1989).

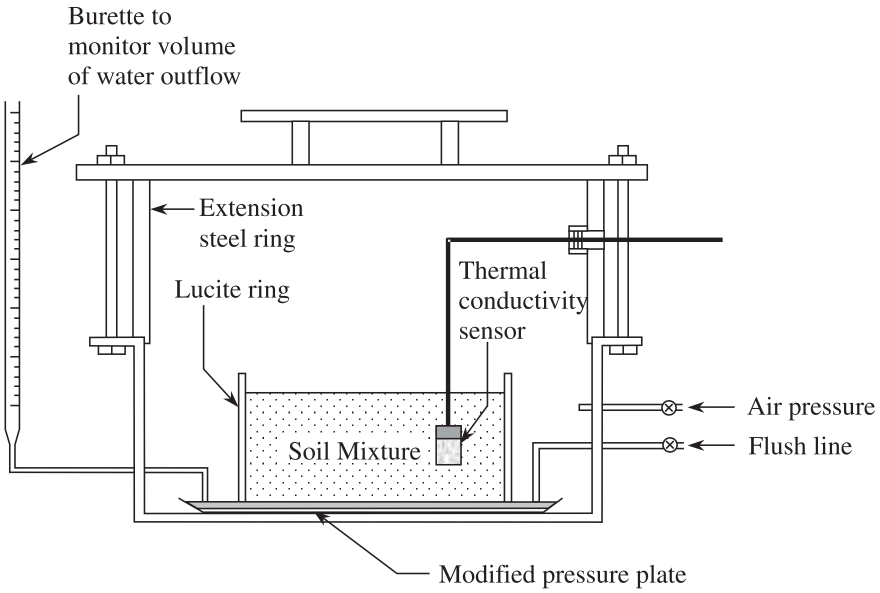
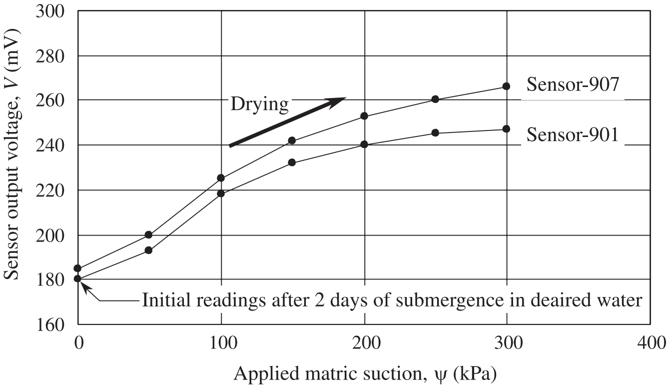


Fig. 3. Typical calibration curves for two AGRA-II sensors using the conventional calibration procedure (redrawn from Fredlund and Wong 1989).



the sensor ceramic for approximately half an hour to extract the air from the ceramic pore space. The ceramic tip was then submerged in deaired water for another half an hour and the vacuum was released. The sensor ceramic tip was left submerged in water for a few hours under atmospheric pressure. This procedure significantly shortens the time required for saturating the ceramic tips while effectively preventing air bubbles from being entrapped in the pores of the ceramic.

The saturated ceramic tips of the sensors were placed on the pressure plate extractor. Desorption and absorption tests were conducted following the capillary hysteresis curves illustrated in Fig. 5. The various branches of drying and wetting curves can be defined as follows: (1) initial drying curve — the sensor ceramic is dried from an initially saturated condition to residual water content by increasing the applied suction in increments; (2) main wetting curve — the applied suction is reduced incrementally from residual saturation to near-zero suction; (3) main drying curve — the ceramic is redried incrementally at the end of main wetting process to residual water content, and the loop formed by the main wetting curve and the main drying curve is referred to as the main hysteresis loop; (4) primary drying scanning curve — at a certain point on the main wetting curve, the suction is increased incrementally to residual saturation; (5) primary wetting scanning curve — at a certain point on the main drying curve, the suction is reduced incrementally to near-zero suction; (6) boundary-wetting curve — the ceramic tip is wetted from an air-dried condition in increments to near-zero suction.

Each suction increment was maintained until equilibrium was reached. For each suction increment, the sensor output was monitored automatically at an interval of 1 h. The equilibrium was considered to have been reached at the turning point where the sensor output versus logarithmic elapsed time curve flattened out. The equilibrium time ranged from 20 to 200 h and was generally longer for high suctions (above 200 kPa).

Similar hysteresis curves were obtained for the six suction sensors under study. The hysteresis curves associated with sensors 1, 2, and 3 are shown in Figs. 6, 7, and 8, respectively.

As shown in Figs. 6–8, the main hysteresis loop is always above the initial drying curve. The difference in the output voltage between the initial drying curve and the main drying curve varies with the applied matric suction. A relatively large gap was found to exist between the initial drying curve and the main hysteresis loop in the low-suction range between 0 and 15 kPa. This indicates that a relatively large amount of air was entrapped in the pores of the ceramic tip when it was first rewetted. Assume the sensor outputs to be V_{sat}, V_{dry}, and V_0 when the sensor tip is saturated, air-dried, and rewetted to zero suction, respectively. The difference between V_0 and V_{dry} is only 70%–85% of the difference between V_{sat} and V_{dry} for the six test sensors tested. The entrapped air cannot move freely and can only escape by diffusion, or some form of relaxation, which is an extremely slow process.

Fig. 4. Apparatus for measuring the hysteresis properties of the relationships between sensor output voltage and matric suction.

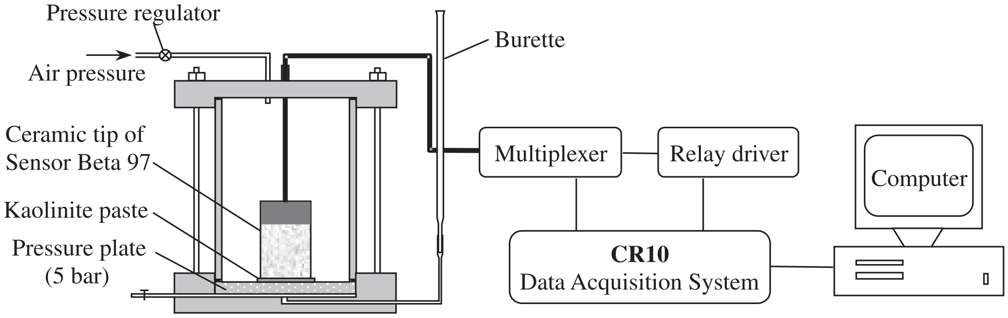


Fig. 5. Schematic illustration of drying and wetting procedures and definitions of each curve.

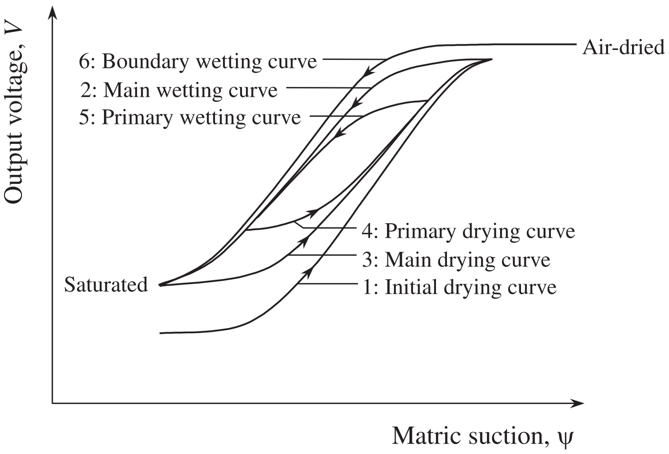
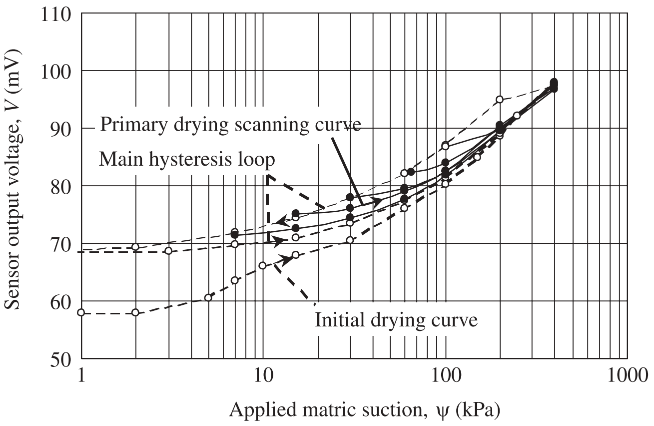
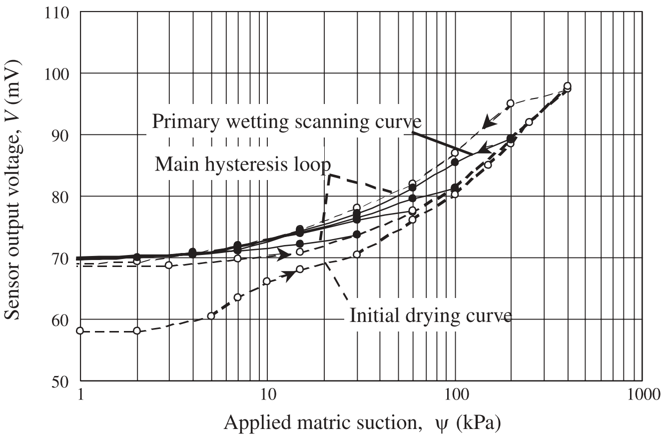


Fig. 6. The initial drying curve, main hysteresis loop, and primary scanning curves for sensor 1.



(*a*) Primary drying scanning curves



(*b*) Primary wetting scanning curves

The primary drying and wetting scanning curves were located within the main hysteresis loop. When a sensor is installed in the field, it will undergo wetting and drying cycles, and it is anticipated that the wetting and drying will be within the main hysteresis loop unless prolonged submergence has occurred. Tests were also carried out to evaluate the sensor ceramic capillary properties under prolonged submergence (Feng and Fredlund 1999; Feng 1999). Test results showed that for the newly developed sensor, the sensor output stays within the main hysteresis loop as long as the submergence is not over 15 days.

The lower boundary of the hysteresis curve family (i.e., the boundary-wetting curve) was measured for sensors 4 and 5 by wetting the air-dried sensor tips to zero matric suction, as shown in Figs. 9 and 10. The lower boundary was not measured for the other sensors due to limited testing time.

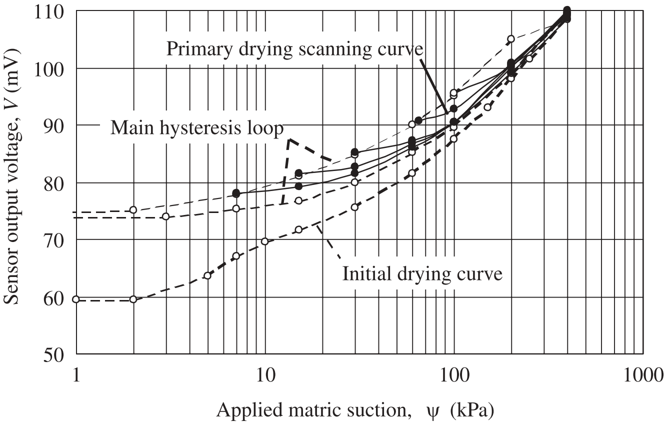
The hysteresis curves of the six test sensors were found to be stable and reproducible over a 2 year testing period. The thermal conductivity suction sensors appear to be suitable for long-term suction measurements.

Discussions of the test results with respect to the calibration

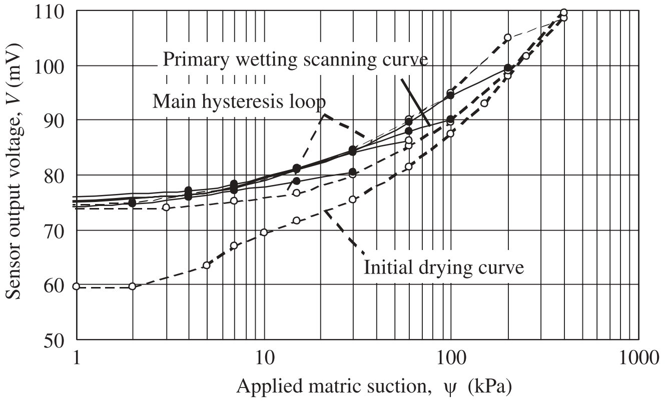
The results of this test program indicate that there are two problems associated with the conventional calibration procedure. First, the initial degree of saturation of the ceramic sensor tip is not known. It is assumed in the conventional calibration procedure that the sensor tip is saturated before being dried on a pressure plate extractor. The results of this test program show that a degree of saturation of only 75.1% was reached for a sensor ceramic after 2.5 months of submergence in water, and the degree of saturation was still increasing (Feng and Fredlund 1999). The degree of saturation of a sensor tip after 2 days of submergence in water depended on the ceramic ingredients and was approximately 60%–65% for the ceramic of the newly developed sensor.

The conventional calibration curve is likely close to the main drying curve and could be above the main drying curve if the sensor tip is submerged for a longer time, as illustrated by the shaded area in Fig. 11.

Fig. 7. The initial drying curve, main hysteresis loop, and primary scanning curves for sensor 2.



(*a*) Primary drying scanning curves

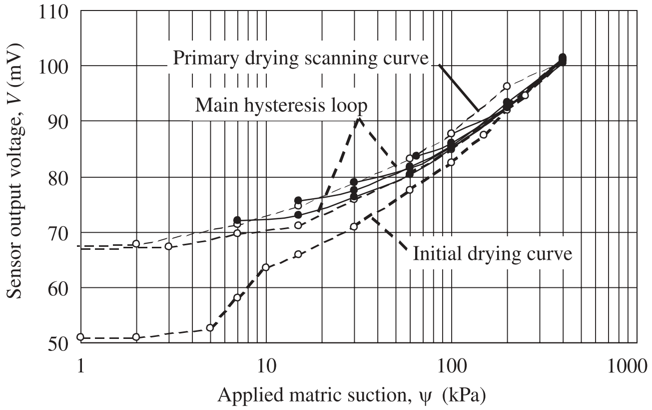


(*b*) Primary wetting scanning curves

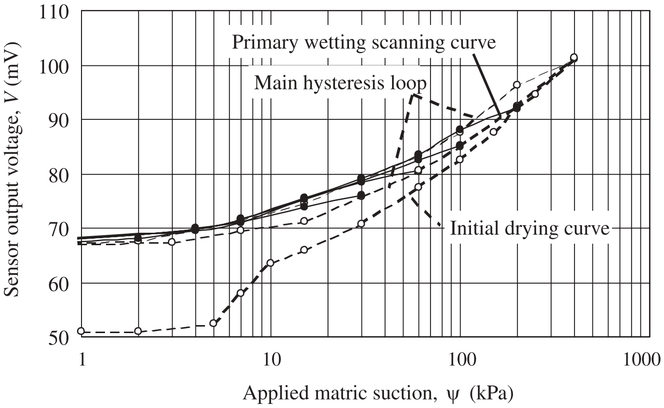
The second problem is that the conventional calibration curve is only a drying curve. It does not take into consideration the effects of capillary hysteresis in the ceramic tip. When a suction sensor is installed in the field, the ceramic tip of the sensor will experience numerous drying and wetting cycles depending on the moisture movement in the surrounding soil. For a certain output voltage from the sensor, the corresponding matric suction could be anywhere between the main drying curve and the main wetting curve or even between the initial drying curve and the main wetting curve, depending on the drying and wetting history. Therefore, if only a drying curve is used as the calibration curve, an error in the measurement will occur as a result of hysteresis.

If the conventional calibration curve is assumed to be the main drying curve, the maximum error will occur when the sensor tip is undergoing a wetting process along the boundary-wetting curve at the time the output voltage reading is taken. Test results of this study show that the average maximum possible error in the suction measurement varies from sensor to sensor and can be up to 70% for suctions higher than 100 kPa (Feng and Fredlund 1999; Feng 1999). The effects of capillary hysteresis on the measurement of matric suction when using thermal conductivity suction sensors can be significant.

Fig. 8. The initial drying curve, main hysteresis loop, and primary scanning curves for sensor 3.

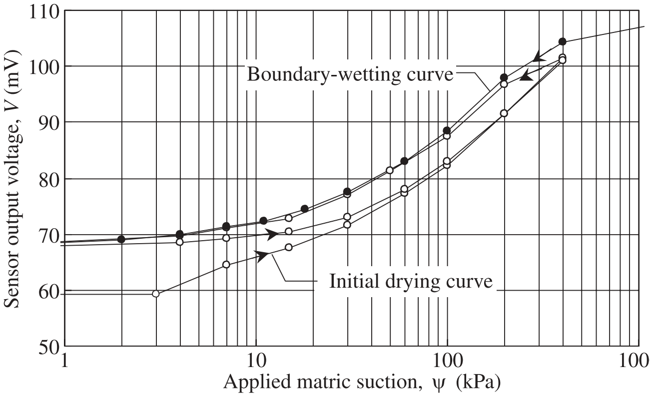


(*a*) Primary drying scanning curves



(*b*) Primary wetting scanning curves

Fig. 9. The boundary-wetting curve for sensor 4.



Prediction of hysteresis curves

The test results indicated that hysteresis should be taken into consideration when calibrating the thermal conductivity soil suction sensors. It is impractical, however, to measure all possible hysteresis curves. It is desirable to develop an appropriate mathematical model that can be used to estimate the hysteresis curves based on a limited amount of calibration data.

Fig. 10. The boundary-wetting curve for sensor 5.

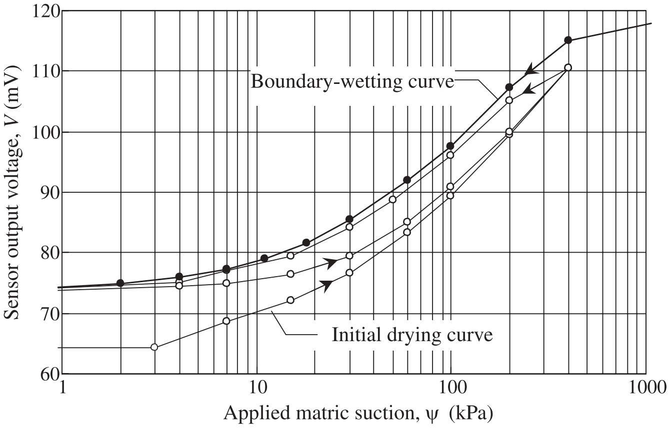
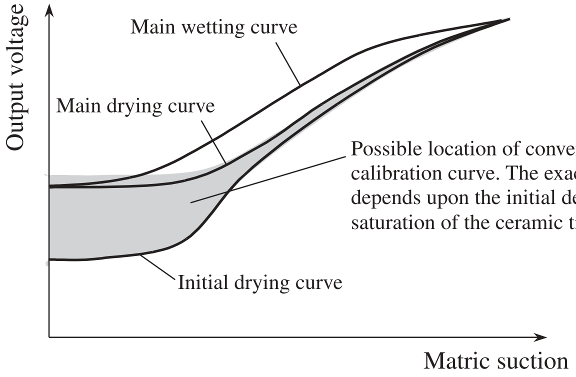


Fig. 11. Schematic illustration of the possible location of the calibration curve using the conventional calibration procedure.



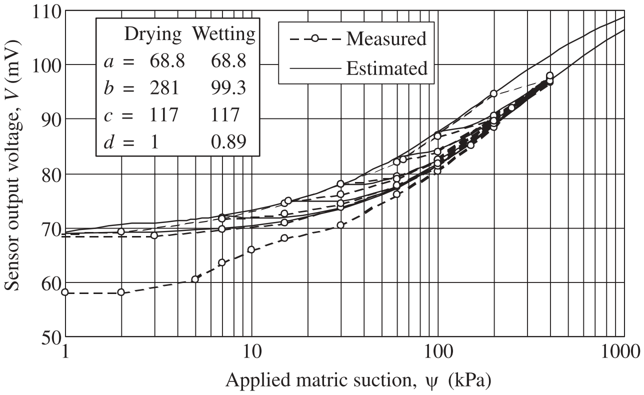
Several hypothetical hysteresis models have been proposed in the literature (Feng 1999). An examination of some of the hysteresis models using the measured hysteresis data from the ceramic sensors showed that the models either require too much calibration data or cannot provide a reasonable prediction of hysteresis (Feng 1999).

The experimental results showed that the hysteresis curves were consistent from one suction sensor to another. If a prediction model can be developed that fits the measured calibration curves of the sensors with known hysteresis characteristics, the model can be used to predict hysteresis curves of other sensors of the same type. The following equation is proposed to fit the main drying and main wetting curves:

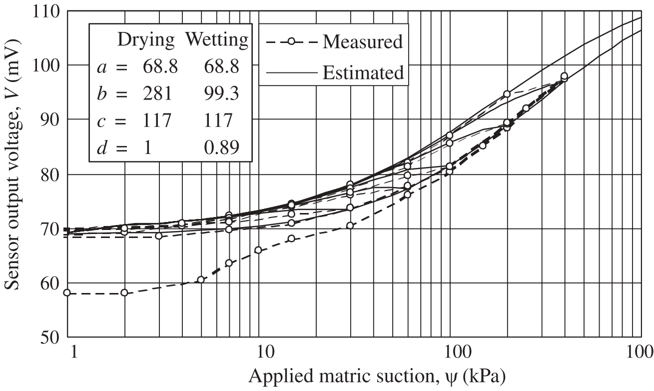
$$[1] \qquad V(\psi) = \frac{ab + c\psi^d}{b + \psi^d}$$

where a is the sensor reading at suction equal to zero on the main hysteresis loop, c is the sensor reading when the ceramic tip is in a dry condition. Parameters a and c are easy to measure and remain the same for the main wetting and main drying curves, respectively. With one branch of the main hysteresis loop measured, only two parameters, b and d, remain unknown for the other branch. If two points on the unknown branch are measured, this branch can be estimated using eq. [1].

Fig. 12. Measured and predicted primary scanning curves for sensor 1.



(a) Primary drying scanning curves



(b) Primary wetting scanning curves

With one branch of the main hysteresis loop measured and the other branch estimated, the following equations are used to fit to the scanning curves:

$$[2] \qquad V_\mathrm{d}(\psi, \psi_1) = V_\mathrm{d} + \left(\frac{\psi_1}{\psi}\right)^\alpha (V_\mathrm{w} - V_\mathrm{d})$$

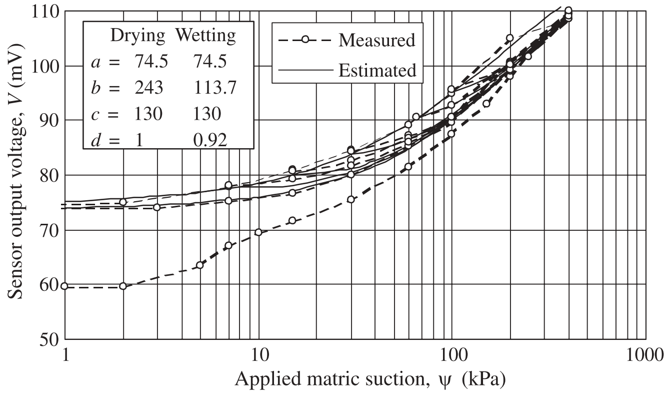
$$[3] \qquad V_\mathrm{w}(\psi, \psi_1) = V_\mathrm{w} + \left(\frac{\psi}{\psi_1}\right)(V_\mathrm{w} - V_\mathrm{d})$$

where $V_\mathrm{d}(\psi, \psi_1)$ is the output voltage at suction ψ on the drying scanning curve that starts at a suction value ψ_1; ψ_1 is the soil suction at which the scanning curve starts; V_w and V_d are the output voltages at suction ψ on the main wetting and drying curves, respectively; and α is an empirical parameter that controls the degree of curvature of the scanning curves and is the only unknown parameter in the eqs. [2] and [3].

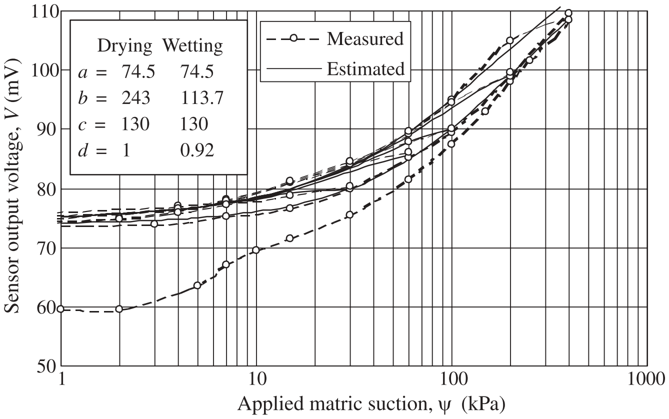
The measured hysteresis curves of the six sensors were fitted using eqs. [1], [2], and [3]. Similar prediction results were obtained for the six sensors. The predicted curves of the main hysteresis loop and primary scanning curves for sensors 1, 2, and 3 are shown in Figs. 12, 13, and 14, respectively.

A best-fit value of α equal to 1.8 was used for both the primary drying scanning curves and the primary wetting scanning curves of all six sensors. Figures 12–14 show that the predicted curves are close to the measured curves. The errors between the predicted and measured values are under

Fig. 13. Measured and predicted primary scanning curves for sensor 2.

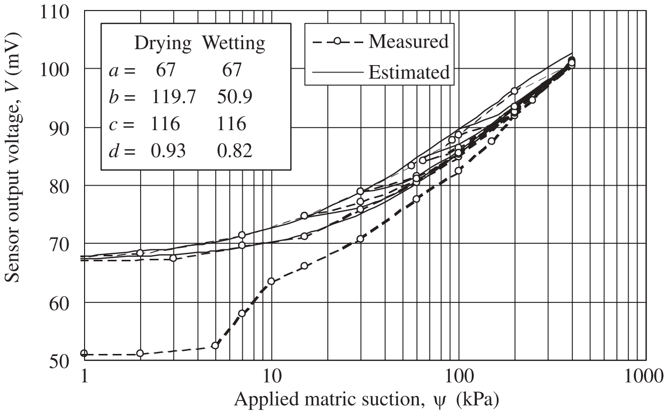


(*a*) Primary drying scanning curves

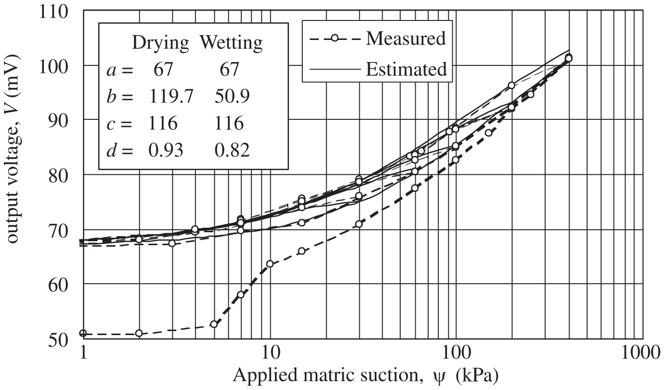


(*b*) Primary wetting scanning curves

Fig. 14. Measured and predicted primary scanning curves for sensor 3.



(*a*) Primary drying scanning curves



(*b*) Primary wetting scanning curves

5%. The α value of 1.8 appears to be reasonable for predicting the primary scanning curves for the newly developed suction sensors. It should be noted that the α value could be different for sensors other than the newly developed suction sensor. It is necessary to investigate the hysteresis properties using typical sensors to estimate the α value when calibrating other types of thermal conductivity sensors.

Summary and recommendations on the calibration procedure

The results of the laboratory testing program showed that the hysteresis curves of a newly developed suction sensor were stable and reproducible over a 2 year experimental period. The thermal conductivity suction sensors appear to be a reliable means for long-term measurement of laboratory and in situ matric suction.

This study shows that the conventional calibration procedure used to obtain the calibration curve can result in errors related to the capillary hysteresis of the ceramic. The magnitude of these errors may be unacceptable for some engineering applications.

The following procedure is recommended for calibrating the newly developed suction sensors: (1) saturate the ceramic sensor tip by submerging it in water for 2 days or more; (2) place the sensor ceramic tip in the pressure plate cell and apply a suction of 50–100 kPa; (3) when equilibrium has been reached, reduce the applied suction to zero; (4) after equilibrium at zero suction, increase the applied suction in increments following the conventional calibration procedure to measure the *main drying curve*; and (5) rewet the ceramic sensor to obtain two points on the main wetting curve.

The *main wetting curve* is estimated using eq. [1]. The *primary scanning curves* are estimated using eqs. [2] and [3], assuming an α value of 1.8.

A similar procedure can be used to calibrate other types of thermal conductivity suction sensors. However, a study of the hysteretic properties of the ceramic sensor output voltage versus matric suction should be carried out to establish the value of the α parameter for eqs. [2] and [3].

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