# CALIBRATION OF THERMAL CONDUCTIVITY SENSORS FOR SUCTION MEASUREMENT

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ABSTRACT
Thermal conductivity sensors are gradually becoming a commonly used device for measuring soil suction. Application of thermal conductivity sensors includes *in situ* monitoring of soil suctions beneath highway pavements, building pads/slabs, embankments, waste piles, natural slopes and soil covers. Laboratory calibration is the first step leading towards the use of the sensors. This paper presents the laboratory calibration results of 16 commercially available thermal conductivity sensors. The calibration results reveal the systematic variations in responses amongst the sensors. In this way, the accuracy and possible errors can be estimated. A series of average calibration suction values and relationships were suggested for laboratory calibration and fitting of data for this type of sensor.

RÉSUMÉ
Les sondes de conductibilité thermiques deviennent graduellement un appareil ordinairement utilisé pour mesurer de succion de sol. L'application de sondes de conductibilité thermiques inclut l'interception de succions de sol en dessous des trottoirs de route, les dalles de bâtiment, les remblais, les tas de gaspillage, les pentes naturelles et couvertures de sol. Le calibrage dans le laboratoire est la première étape menant vers l'usage des sondes. Ce papier présente les résultats de calibrage dans le laboratoire de 16 sondes de conductibilité thermiques commercialement disponibles. Les résultats de calibrage révèlent les variations systématiques dans les réponses parmi les sondes pour que la précision et les erreurs possibles peuvent être estimées. Un feuilleton de valeurs de succion de calibrage a été recommandé pour le calibrage dans le laboratoire et ajustant de données pour ce type de sonde.

## 1 INTRODUCTION

Soil suction constitutes one of the stress state variables controlling the behavior of unsaturated soils. The measurement of suction is becoming increasingly routine for engineering works dealing with unsaturated soil. Various devices have been developed to measure the matric suction in the laboratory and in the field. Padilla *et al.* (2004) and Rahardjo and Leong (2006) summarized the most commonly used methods available for the measurement of soil suction. These methods include psychrometers, filter papers, null pressure plates, tensiometers, and thermal conductivity sensors. Each method has its application constraints. For example, psychrometers show a low sensitivity in the low suction ranges and their sensitivities deteriorate with time and as well, the results are meaningless when there are even small fluctuations in temperature. The "filter paper" technique cannot be automated and is therefore not practical for field use. Tensiometers require daily maintenance. On the other hand, thermal conductivity sensors are a promising device for laboratory measurement of soil suction and long-term *in situ* monitoring of soil suction (Fredlund 1992, Fredlund and Rahardjo 1993).

In a recent study on the failures of asbestos cement water mains in Regina, Saskatchewan, Canada, by Hu and Hubble (2006), unsaturated soil was identified as one of the critical factors that, combined with other factors such as temperature and precipitation, have contributed to the failure of the pipes. To understand the working environments and the corresponding responses of pipes in unsaturated soils, field instrumentation was installed to monitor the performance of a section of asbestos cement pipe in an expansive soil area of an older area of Regina where frequent pipe breakage has been observed in recent years. The instrumentation included thermal conductivity sensors to measure soil suctions in the soil backfill and native soil around the backfill.

Laboratory calibration is the first step leading towards the use of the thermal conductivity sensors for field measurements of soil suction. In this paper, commercially available thermal conductivity type sensors; namely the GCTS Fredlund Thermal Conductivity (FTC) sensors, were calibrated in the Golder Associates Ltd. laboratory, Saskatoon, SK, Canada. Calibration was performed using a pressure plate cell by applying a series of suction values and measuring the response of the sensors. The measured data were corrected using previously published temperature correction procedures, and compared. The

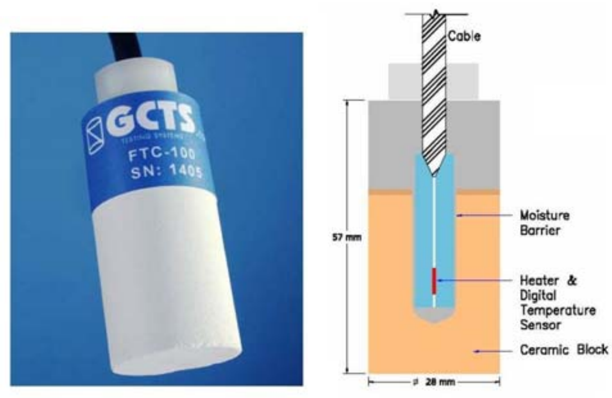


Figure 1. Photograph and cross-section of FTC sensor (from GCTS 2005)

temperature corrected data were best-fitted with a modified Feng and Fredlund (1999) equation. The fitted parameters were then statistically analyzed for their variations amongst the 16 sensors and their influence on the calibration curves. Finally, a series of average calibration suction values was suggested for laboratory calibration and fitting of data for this type of sensor.

## 2 FREDLUND THERMAL CONDUCTIVITY SENSORS

The FTC sensor used in this study is the commercial version of the previously tested prototype models developed at the University of Saskatchewan, Saskatoon, SK, Canada (Fredlund *et al*., 2000a,b; Marjerison *et al*., 2001; Feng *et al*., 2002; Shuai *et al*., 2002; Feng and Fredlund, 2003; Nichol *et al*., 2003; Shuai *et al*., 2003; Tan *et al*., 2003). Figure 1 shows a photo and the cross section of the FTC sensor.

The main part of the sensor is a ceramic block, which contains a small heating element and a digital temperature sensor embedded in the center of the block. The ceramic block is porous. Water from the surrounding soil can enter the block and equilibrate with the soil. A heat pulse can be applied to the block using the small heating element and the temperature rise within the ceramic is measured using a digital temperature sensor. The thermal conductivity of a porous media increases with increasing water content, therefore more heat will be dissipated during the time the heat pulse is applied if the block is wet. This will result in a lower temperature rise than if the block were dry. Therefore, the measurement of the temperature rise of the porous block that has come to water content equilibrium with a soil can be used to measure the water content of the ceramic block. The water content of the ceramic block is dependent on the matric suction of the soil surrounding the ceramic block. Hence, the temperature rise in the porous block can be calibrated against applied suction values in the laboratory.

The ceramic sensors are manufactured in batches. Generally, only one of the sensors from a batch of sensors is calibrated by the manufacturer and this is called “batch calibration”. However, depending on the accuracy required, the manufacturer can also provide individual standard sensor calibration. According to the manufacturer, the estimated differences between the three calibration procedures are shown in Table 1 (GCTS 2005). All calibrations correspond to the desorption curve and do not take hysteresis effect into consideration.

## 3 LABORATORY SENSOR CALIBRATION

Laboratory calibration curves form the key information required for the measurement of soil suction. The calibration curves provide the relationship between the temperature rise in the sensor and the applied matric suction. Once the temperature rise of the sensor is measured in the field, the suction in the soil can be determined from the calibration curve.

The calibration procedure involves equilibrating the thermal conductivity sensors to known applied matric suctions using a pressure plate cell. A specified heat pulse is applied to the ceramic block and the temperature rise after approximately one minute is recorded. The calibration curves are a best-fit of the matric suctions and the corresponding temperature rise.

Sixteen sensors were calibrated using pressure plate devices as shown in Figure 2, as part of this study. Although only one sensor was shown in this figure; the device was able to simultaneously accommodate 3 sensors. The sensors can also be calibrated using a Fredlund SWCC device, which is able to calibrate 5 sensors at a time. Six matric suction points (i.e., 0, 10, 40, 180, 450 and 1M kPa) were applied to the sensors and the corresponding temperature rise was measured. The calibration procedure was started first by checking the response of each sensor when the sensor was completely dry. This provides the temperature rise corresponding to 1M kPa, under the assumption that the dry condition represents a very high suction (approximately equal to 1M kPa). Then the sensors were saturated by submerging them in water for two days. The wet sensors were then installed in the pressure plate device for calibration, as shown in Figure 2. The sensors were set on a thin layer of kaolinite paste placed on the High Air Entry Value (HAEV) disk. Suction was applied by increasing the air pressure in the pressure plate cell while maintaining the water pressure in the water compartment at atmospheric conditions. A heat quantity of 60 mA was applied for 60 seconds to heat the sensors. The change in voltage output from the sensor was monitored periodically until suction equilibrium was achieved. The above procedure was repeated for the applied suctions of 0, 10, 40, 180 and 450 kPa. Table 2 lists the measured ambient temperature, T, inside the cell and temperature rise, $\Delta T$, data for the 16 sensors.

Table 1. Types of calibration procedures (GCTS 2005)

| Procedure | Applied suctions (kPa) | Expected accuracy (%) |
|---|---|---|
| Batch | 0, 10, 100, 500, 1M* | 10 |
| Individual “standard” | 0, 10, 100, 500, 1M | 5** |
| Individual full | 0, 10, 50, 100, 500, 1000, 1M | <5*** |

* 1 M kPa ($10^6$ kPa) is considered as the theoretical suction when the ceramic is completely dry.
** Accuracy can be better than 5%, but may vary depending on the range of the suction.
*** Accuracy is better than 5%, and can be considered relatively uniform through the measurement range.

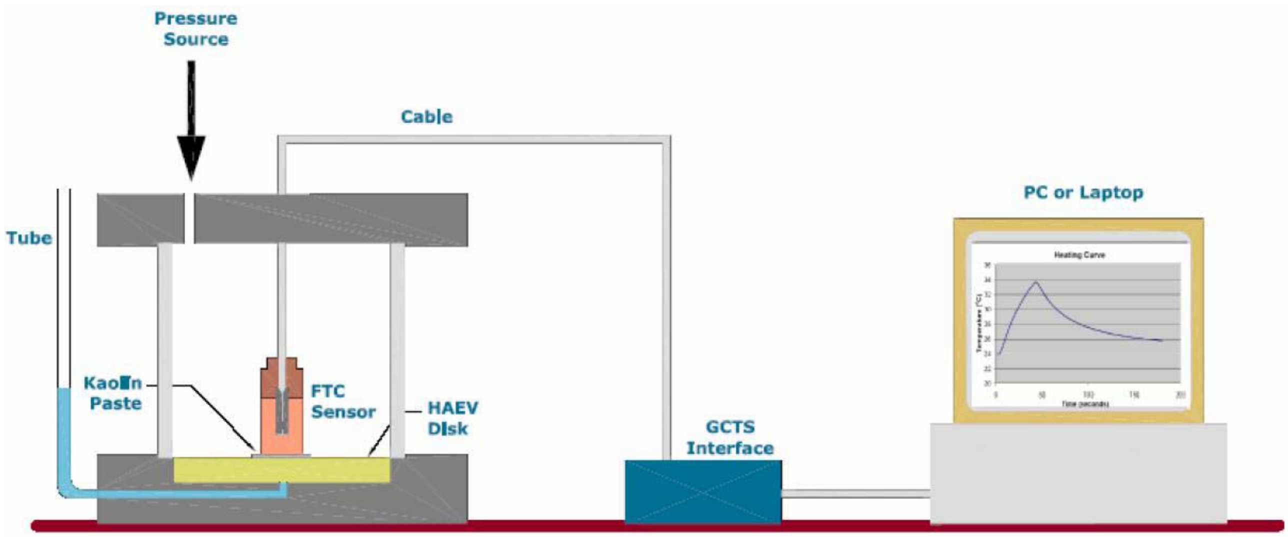


Figure 2. Calibration setup for the FTC sensors

## 4 TEST DATA ANALYSIS AND FITTING

### 4.1 Ambient temperature

Table 2 shows that the ambient temperatures fluctuated between 21 and 23 °C during the calibration process for the applied suctions of 0, 10, 40 180 and 450 kPa. The readings under dry conditions (1M kPa) were taken at a temperature close to 30 °C. Ambient temperature is known to influence the measured temperature rise of the sensors and has been observed by other researchers (e.g., Phene *et al*., 1971a, b; Shuai *et al*., 2002 and Nichol *et al*., 2003). It is necessary to make a correction from the actual calibration temperature to the desired reference calibration temperature. There are a couple of models available for the temperature correction. Shuai *et al*. (2002) proposed the following equation for the temperature correction:

$$\Delta T_{23^\circ C} = \frac{0.0014T + 0.5743}{0.6065} \Delta T_T \qquad [1]$$

where $\Delta T_{23^\circ C}$ and $\Delta T_T$ are the temperature rises at temperature 23 °C and the ambient temperature T, respectively. 23 °C has been assumed as the standard temperature for the purpose of temperature correction.

Nichol *et al*. (2003) proposed a more rigorous model to take into account the effect of ambient temperature on the changes in the thermal response of the FTC sensors:

$$\Delta T_{23^\circ C} = \Delta T\left(s_1 + s_2 T + s_3 T^2\right) \qquad [2]$$

where T is the ambient temperature and $s_1$, $s_2$ and $s_3$ are constants that depend on the range of measured suctions. The correction of temperature suggested by Nichol *et al.* (2003) is not only dependent on the ambient temperature, but also dependent on the magnitude of the soil suction. The proposed correction constants for ambient soil temperature are listed in Table 3. The measured FTC suction sensor core temperature rise is multiplied by the correction factor to obtain the core temperature rise that would have been measured at 23 °C. According to Nichol *et al*. (2003) method, the correction is largest near 0 kPa when the sensor has the highest water content. This is different from the Shuai *et al.* (2002) correction, which multiplies the measured suction data by a constant value across all soil suctions.

The measured temperature rises were corrected using the two formulae (Eqs. 2 and 3) and a statistical analysis of the corrected temperature rise data are listed in Table 4.

Table 2. Measured ambient temperature and temperature rise

| Sensor | Applied suction | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 kPa | | 10 kPa | | 40 kPa | | 180 kPa | | 450 kPa | | 1M kPa | |
| | T (°C) | ΔT | T | ΔT | T | ΔT | T | ΔT | T | ΔT | T | ΔT |
| 1 | 21.9 | 9.55 | 21.8 | 9.57 | 22.2 | 9.83 | 19.1 | 11.10 | 22.0 | 11.81 | 28.6 | 13.30 |
| 2 | 21.8 | 9.47 | 21.7 | 9.52 | 22.2 | 9.86 | 19.1 | 11.23 | 22.0 | 12.03 | 29.0 | 13.50 |
| 3 | 22.0 | 9.47 | 21.9 | 9.48 | 22.3 | 9.82 | 19.2 | 11.25 | 22.2 | 12.01 | 28.2 | 13.68 |
| 4 | 21.6 | 8.50 | 21.3 | 8.51 | 21.8 | 8.85 | 18.7 | 10.37 | 21.8 | 11.19 | 28.2 | 12.87 |
| 5 | 22.3 | 9.11 | 22.0 | 9.15 | 22.4 | 9.54 | 19.3 | 11.05 | 22.5 | 11.88 | 28.3 | 13.51 |
| 6 | 22.3 | 9.40 | 21.9 | 9.39 | 22.4 | 9.74 | 19.3 | 11.23 | 22.5 | 11.96 | 28.7 | 13.72 |
| 7 | 21.7 | 9.39 | 21.2 | 9.44 | 21.5 | 9.79 | 18.5 | 11.17 | 21.9 | 11.80 | 28.0 | 13.48 |
| 8 | 21.4 | 9.28 | 20.8 | 9.31 | 21.2 | 9.65 | 18.2 | 11.06 | 21.6 | 11.93 | 27.8 | 13.47 |
| 9 | 22.4 | 9.19 | 21.9 | 9.18 | 22.3 | 9.47 | 19.3 | 10.89 | 22.6 | 11.65 | 29.5 | 13.18 |
| 10 | 21.6 | 9.72 | 21.1 | 9.76 | 21.4 | 10.03 | 18.6 | 11.19 | 21.6 | 11.86 | 28.4 | 13.35 |
| 11 | 21.7 | 8.71 | 21.2 | 8.73 | 21.5 | 9.01 | 18.7 | 10.43 | 21.7 | 11.24 | 28.9 | 12.79 |
| 12 | 22.1 | 9.13 | 21.6 | 9.14 | 21.9 | 9.38 | 19.1 | 10.78 | 22.0 | 11.51 | 28.4 | 13.16 |
| 13 | 21.7 | 9.76 | 21.0 | 9.81 | 21.4 | 10.10 | 18.8 | 11.42 | 21.6 | 12.14 | 28.3 | 13.59 |
| 14 | 21.7 | 9.00 | 21.0 | 9.08 | 21.4 | 9.38 | 18.8 | 10.85 | 21.7 | 11.63 | 27.9 | 13.22 |
| 15 | 22.0 | 8.83 | 21.3 | 8.86 | 21.7 | 9.13 | 19.1 | 10.58 | 21.9 | 11.33 | 28.0 | 12.93 |
| 16 | 22.2 | 8.51 | 21.3 | 8.50 | 21.5 | 8.76 | 19.0 | 10.15 | | | 28.8 | 12.60 |

* Data for 450 kPa were not available due to a technical problem of the device.

Table 3. Temperature correction constants for Nichol *et al.* (2003) equation

| Suction (kPa) | $s_1$ - | $s_2$ $(°C)^{-1}$ | $s_3$ $(°C)^{-2}$ |
|---|---|---|---|
| 0-10 | 0.960 | $1.9 \times 10^{-3}$ | $-0.8 \times 10^{-6}$ |
| 10-30 | 0.962 | $1.8 \times 10^{-3}$ | $-0.7 \times 10^{-6}$ |
| 30-75 | 0.968 | $1.5 \times 10^{-3}$ | $-0.6 \times 10^{-6}$ |
| 75-300 | 0.973 | $1.3 \times 10^{-3}$ | $-0.5 \times 10^{-6}$ |
| 300-1M | 0.986 | $7.0 \times 10^{-4}$ | $-0.3 \times 10^{-6}$ |

The statistical analysis for the uncorrected suction data is also presented. The two temperature correction procedures only slightly change the measured suction data except for the case of 1M kPa. It can be seen from Table 1 that the test temperatures for all applied suctions (except for the 1M kPa) are close to the 23 °C standard temperature. However, a much larger effect related to the temperature correction will occur in the field as the temperature variations are generally wider than those experienced in the laboratory. Figure 3 combines the calibration test data corresponding to the Nichol *et al.* (2003) correction for all 16 sensors. While there are differences between the results of one sensor from the others, all sensors yield similar trends for the calibration data.

## 4.2 Calibration equations

Figure 3 shows that the relationship between the temperature rise (ΔT) in the sensors and the applied suction is quite nonlinear and follows a sigmoidal trend. There are various equations for fitting the data. The equation proposed by Feng and Fredlund (1999) had the following form:

$$\Psi = \left[\frac{b(\Delta T - a)}{c - \Delta T}\right]^d \quad [3]$$

where $\psi$ is the applied matric suction in kPa; ΔT is the temperature rise in °C, and a, b, c, and d are four parameters that define the shape of the calibration curve. Of the four parameters, a and c are equivalent to the temperature rise, ΔT, values obtained for the sensor under saturated and dry conditions, respectively. The parameter b defines the horizontal position of the curve while the parameter d defines the slope of the curve at point b. The physical meaning of the parameters b and d is not well defined in Eq. 3 and therefore an improved equation was proposed with the following form:

$$\Psi = \left(\frac{\Delta T - a_1}{c_1 - \Delta T}\right)^{d_1 \frac{c_1 - a_1}{4 b_1}} \quad [4]$$

In this equation, $a_1$ and $c_1$ have the same meanings at the a and c in Eq. 3. The $b_1$ parameter is the suction when ΔT has a middle value of temperature change (i.e., the inflection point on a semi-log plot, or $b_1 = (a_1 + c_1)/2$ ) and $d_1$ is the slope of the curve at point $b_1$ (i.e., $d\Psi / d\Delta T\big|_{\Delta T = (a_1 + c_1)/2}$ .

## 4.3 Calibration parameters

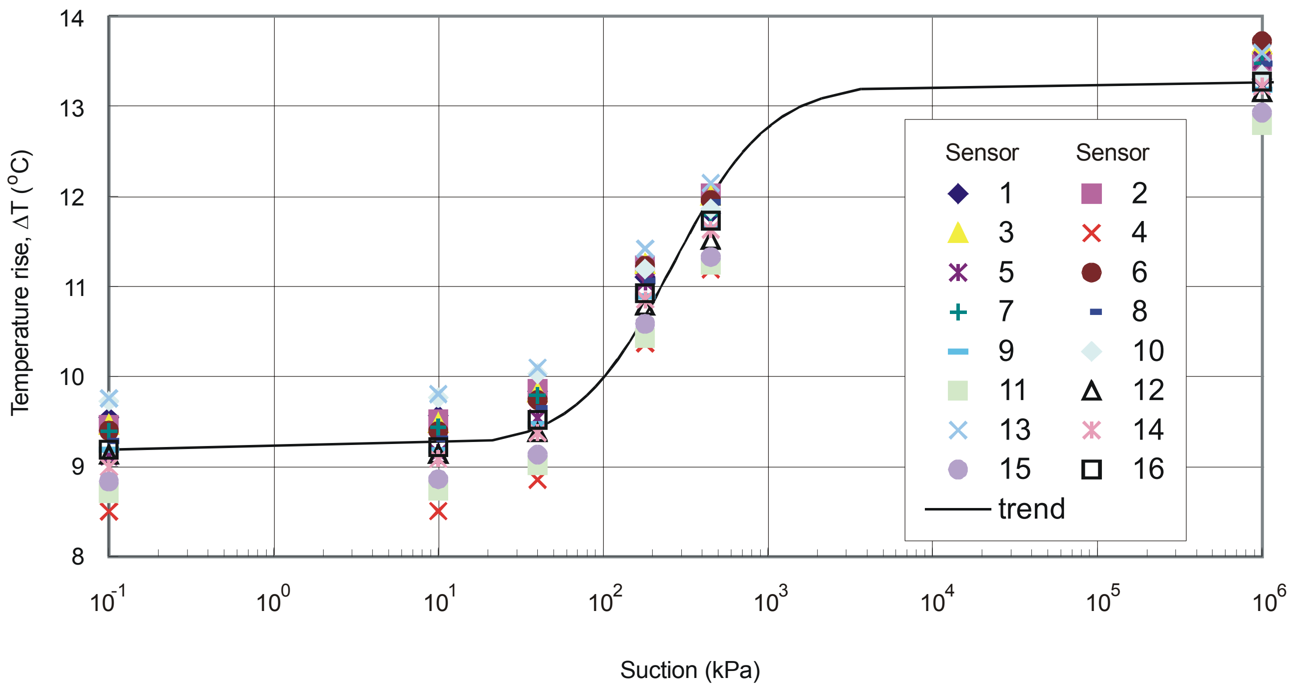


Figure 3. Corrected temperature rises using Nichol et al. (2003) equation versus applied suctions for FTC suction sensors

Table 4. Temperature correction of the measured suction data

| Applied Suction (kPa) | | No correction | Nichol *et al*. (2003)'s | | Shuai *et al*. (2002)'s | |
|---|---|---|---|---|---|---|
| | | Measured (°C) | Corrected (°C) | Change (%) | Corrected (°C) | Change (%) |
| 0 | Max | 9.788 | 9.763 | -0.26 | 9.758 | -0.31 |
| | Min | 8.526 | 8.507 | -0.22 | 8.502 | -0.28 |
| | Avg | 9.212 | 9.191 | -0.22 | 9.188 | -0.26 |
| 10 | Max | 9.852 | 9.817 | -0.36 | 9.807 | -0.46 |
| | Min | 8.538 | 8.511 | -0.31 | 8.505 | -0.39 |
| | Avg | 9.249 | 9.221 | -0.29 | 9.215 | -0.36 |
| 40 | Max | 10.136 | 10.108 | -0.27 | 10.098 | -0.38 |
| | Min | 8.786 | 8.761 | -0.28 | 8.756 | -0.34 |
| | Avg | 9.548 | 9.526 | -0.23 | 9.522 | -0.27 |
| 180 | Max | 11.530 | 11.453 | -0.67 | 11.417 | -0.98 |
| | Min | 10.248 | 10.184 | -0.63 | 10.154 | -0.91 |
| | Avg | 11.026 | 10.955 | -0.64 | 10.922 | -0.94 |
| 450 | Max | 12.183 | 12.155 | -0.23 | 12.145 | -0.31 |
| | Min | 11.218 | 11.195 | -0.21 | 11.187 | -0.28 |
| | Avg | 11.759 | 11.737 | -0.18 | 11.731 | -0.24 |
| 1M | Max | 13.542 | 13.649 | 0.79 | 13.720 | 1.31 |
| | Min | 12.432 | 12.532 | 0.80 | 12.599 | 1.34 |
| | Avg | 13.108 | 13.206 | 0.01 | 13.272 | 1.25 |

Table 5. Fitted parameters without temperature correction

| Sensor | Fitting parameters | | | | |
|---|---|---|---|---|---|
| | $a_1$ (°C) | $b_1$ (kPa) | $c_1$ (°C) | dΨ/dΔT (kPa/°C) | Power term |
| 1 | 9.571 | 243.098 | 13.133 | 181.008 | 0.663 |
| 2 | 9.491 | 223.263 | 13.317 | 178.408 | 0.764 |
| 3 | 9.487 | 250.700 | 13.522 | 199.751 | 0.804 |
| 4 | 8.530 | 246.132 | 12.720 | 182.547 | 0.777 |
| 5 | 9.127 | 228.292 | 13.349 | 156.794 | 0.725 |
| 6 | 9.415 | 255.881 | 13.542 | 195.411 | 0.788 |
| 7 | 9.419 | 242.008 | 13.325 | 194.955 | 0.787 |
| 8 | 9.319 | 230.556 | 13.325 | 159.262 | 0.692 |
| 9 | 9.199 | 242.306 | 12.989 | 189.478 | 0.741 |
| 10 | 9.756 | 252.453 | 13.181 | 231.642 | 0.786 |
| 11 | 8.734 | 238.538 | 12.616 | 171.028 | 0.696 |
| 12 | 9.151 | 262.644 | 12.997 | 198.670 | 0.727 |
| 13 | 9.788 | 231.555 | 13.429 | 200.062 | 0.786 |
| 14 | 9.022 | 234.387 | 13.069 | 197.494 | 0.852 |
| 15 | 8.854 | 245.751 | 12.780 | 178.446 | 0.713 |
| 16 | 8.526 | 208.871 | 12.432 | 133.880 | 0.626 |
| Max | 9.788 | 262.644 | 13.542 | 231.642 | 0.852 |
| Min | 8.526 | 208.871 | 12.432 | 133.880 | 0.626 |
| Avg | 9.212 | 239.777 | 13.108 | 184.302 | 0.745 |
| Stdv | 0.395 | 13.426 | 0.332 | 22.446 | 0.058 |
| CV | 4.292 | 5.599 | 2.530 | 12.179 | 7.843 |

Table 6. Fitted parameters with Nichol et al. (2003)'s equation

| Sensor | Fitting parameters | | | | |
|---|---|---|---|---|---|
| | $a_1$ (°C) | $b_1$ (kPa) | $c_1$ (°C) | dΨ/dΔT (kPa/°C) | Power term |
| 1 | 9.549 | 256.924 | 13.234 | 185.240 | 0.664 |
| 2 | 9.469 | 239.841 | 13.428 | 187.509 | 0.774 |
| 3 | 9.468 | 267.877 | 13.618 | 212.788 | 0.824 |
| 4 | 8.507 | 262.106 | 12.812 | 193.467 | 0.794 |
| 5 | 9.112 | 240.120 | 13.447 | 160.060 | 0.722 |
| 6 | 9.399 | 273.478 | 13.649 | 207.341 | 0.805 |
| 7 | 9.395 | 256.929 | 13.417 | 197.769 | 0.774 |
| 8 | 9.291 | 241.968 | 13.414 | 156.509 | 0.667 |
| 9 | 9.186 | 260.763 | 13.106 | 201.078 | 0.756 |
| 10 | 9.730 | 270.870 | 13.280 | 235.538 | 0.772 |
| 11 | 8.712 | 251.991 | 12.719 | 170.199 | 0.677 |
| 12 | 9.133 | 280.262 | 13.094 | 209.252 | 0.739 |
| 13 | 9.763 | 249.056 | 13.528 | 204.840 | 0.774 |
| 14 | 8.999 | 251.630 | 13.157 | 205.344 | 0.848 |
| 15 | 8.835 | 257.397 | 12.868 | 175.658 | 0.688 |
| 16 | 8.510 | 223.151 | 12.532 | 140.830 | 0.634 |
| Max | 9.763 | 280.262 | 13.649 | 235.538 | 0.848 |
| Min | 8.507 | 223.151 | 12.532 | 140.830 | 0.634 |
| Avg | 9.191 | 255.273 | 13.206 | 190.214 | 0.745 |
| Stdv | 0.394 | 14.570 | 0.332 | 24.463 | 0.063 |
| CV | 4.286 | 5.707 | 2.516 | 12.861 | 8.474 |

Table 7. Fitted parameters with Shuai *et al.* (2002)'s equation

| Sensor | Fitting parameters | | | | |
|---|---|---|---|---|---|
| | $a_1$ (°C) | $b_1$ (kPa) | $c_1$ (°C) | dΨ/dΔT (kPa/°C) | Power term |
| 1 | 9.546 | 265.197 | 13.301 | 187.915 | 0.665 |
| 2 | 9.466 | 249.972 | 13.502 | 193.114 | 0.780 |
| 3 | 9.466 | 278.654 | 13.683 | 221.087 | 0.837 |
| 4 | 8.502 | 271.992 | 12.874 | 200.325 | 0.805 |
| 5 | 9.111 | 247.115 | 13.512 | 162.070 | 0.722 |
| 6 | 9.399 | 284.507 | 13.720 | 214.919 | 0.816 |
| 7 | 9.391 | 265.434 | 13.479 | 199.341 | 0.768 |
| 8 | 9.284 | 247.859 | 13.473 | 154.341 | 0.652 |
| 9 | 9.187 | 272.298 | 13.184 | 208.399 | 0.765 |
| 10 | 9.725 | 282.024 | 13.346 | 237.945 | 0.764 |
| 11 | 8.708 | 259.302 | 12.788 | 169.213 | 0.666 |
| 12 | 9.131 | 291.133 | 13.158 | 215.971 | 0.747 |
| 13 | 9.758 | 259.571 | 13.593 | 207.638 | 0.767 |
| 14 | 8.995 | 261.762 | 13.216 | 210.067 | 0.847 |
| 15 | 8.833 | 263.482 | 12.928 | 173.399 | 0.674 |
| 16 | 8.509 | 231.937 | 12.599 | 145.282 | 0.640 |
| Max | 9.758 | 291.133 | 13.720 | 237.945 | 0.847 |
| Min | 8.502 | 231.937 | 12.599 | 145.282 | 0.640 |
| Avg | 9.188 | 264.515 | 13.272 | 193.814 | 0.745 |
| Stdv | 0.394 | 15.590 | 0.333 | 26.264 | 0.067 |
| CV | 4.283 | 5.894 | 2.508 | 13.551 | 9.056 |

Equation 4 has been best fitted to the test data for each sensor for the measured data for the following cases; i) without temperature correction; ii) for the measured data corrected with Nichol *et al*. (2003) method; and iii) for the measured data corrected with the Shuai e*t al.* (2002) method. The resulting calibration parameters are listed in Tables 5, 6 and 7, respectively. Also included in the tables are statistical analysis results of the calibration parameters. The results presented in Tables 5, 6 and 7 indicate:

- The measured data with no temperature correction applied have the least scatter, while the corrected data with the Shuai *et al*. (2002) equation has the most scatter. This indicates that the correction procedure may bring in errors although it is necessary to correct the measured data when these measurements are performed at ambient temperatures other than the calibration temperature.
- For $a_1$ and $c_1$ parameters, the variation is the same for the uncorrected data and for data corrected with the two temperature correction procedures.
- The results indicate that the $b_1$ and slope, $d\psi/d\Delta T$, parameters are affected by the temperature correction procedures. The differences were quite significant with more consistent results obtained for the $b_1$ and $d\psi/d\Delta T$ parameters when using the Nichol *et*

*al*. (2003) correction procedure. Therefore, the Nichol *et al*. (2003) temperature correction is used for the remainder of the study.

- The "power term" in the calibration equation contains three of the parameters; namely $a_1$, $c_1$ and $d_1$. The combination of these three terms was also analyzed to assess the statistical variation of the "power term". When the Shuai *et al*. (2002) temperature correction was applied, the average value for the "power term" was 0.745 with a standard deviation of 0.067 and a coefficient of variation of 9.06%, which is again larger than that of the Nichol *et al*. (2003) temperature correction.
- The statistical analysis indicates that the variables related to the inflection point (i.e., $b_1$ and $d\Psi/d\Delta T$) constitute the parameter that needs to be most accurately determined during the calibration process.

## 5 FITTING PARAMETER ANALYSIS

The best-fit calibration curve parameters are obtained for all three cases where the calibration data are corrected for slight temperature deviations in the laboratory. Figure 4 shows the comparison of the coefficient of variations for various fitting parameters. While all temperature corrections gave essentially the same results, the Nichol *et al*. (2003) temperature correction fitted parameters will be used for the remainder of this study because of its theoretical rigour. Variations in the fitting parameters for all 16 sensors are graphically illustrated in Figure 5.

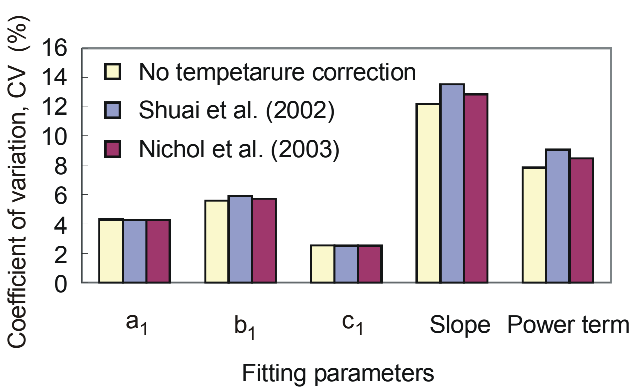


Figure 4. Comparison of the coefficient of variations for various fitting parameters

The $a_1$ curve fitting parameter is the temperature rise reading corresponding to the case of the completely saturated sensor (i.e., assumed to correspond to a suction = 0.1 kPa). The average value for the $a_1$ parameter is 9.19 °C and the standard deviation for all 16 suction sensors was 0.39 °C, giving rise to a coefficient of variation of 4.29%.

The $c_1$ curve fitting parameter is the temperature rise reading corresponding to the case of the completely dry sensor (i.e., an assumed suction = 1,000,000 kPa). The average value for the $c_1$ parameter is 13.21 °C and the standard deviation for all 16 suction sensors was 0.33 °C, giving a coefficient of variation of 2.52%.

The $b_1$ curve fitting parameter corresponds to the suction at the inflection point on the calibration curve. In other words, it is the suction when the sensor is approximately 50% saturated. The average value for the $b_1$ parameter is 255.3 kPa and the standard deviation for all 16 suction sensors was 14.6 kPa, giving a coefficient of variation of 5.71%.

The $d_1$ curve fitting parameter corresponds to the arithmetic slope of the calibration curve at the point of inflection on the calibration curve. This is also the point where the suction sensor is most responsive to changes in water content. The average value for the $d_1$ parameter is 190.2 kPa/°C and the standard deviation for all 16 suction sensors was 24.46 kPa/°C, giving a coefficient of variation of 12.86%.

The statistical analysis of the calibration parameters for the 16 suction sensors reveals the following information:

- Parameters $a_1$ and $c_1$ are the most consistent parameter measurements. The standard deviation is similar for both variables with values of approximately 0.3 to 0.4 °C.
- A typical value for the $a_1$ parameter is 9.2 °C. A typical value for the $c_1$ parameter is 13.2 °C. These typical values along with the computed standard deviations are useful guidelines for quality control and assessment for thermal conductivity suction sensors.
- The $b_1$ parameter can be used as an indication of the range where the sensor will perform most satisfactorily. The 16 suction sensors calibrated show the $b_1$ parameter to be around 260 kPa. The coefficient of variation on the $b_1$ parameter is slightly higher than for the $a_1$ and $c_1$ parameters. This would indicate that the calibration procedure should be designed such that accurate values can be obtained for the $b_1$ parameter.
- The $b_1$ and $d_1$ parameters are related to a common point along the calibration curve. The $d_1$ parameter showed the highest coefficient of variation of all 4 variables with a value of 12.9%. A typical value for the $d_1$ parameter is about 190. The calibration results indicate that attention needs to be given to the straight line portion (on a semi-log plot) of the calibration curve on each side of the $b_1$ suction value.

Figure 6 shows the calibration data points, and the corresponding fitting curves, for two typical sensors along with the average values for the 16 sensors. The calibration curves for the two sensors and the average calibration curve appears to be quite similar. It is possible to obtain a better understanding of the response of the

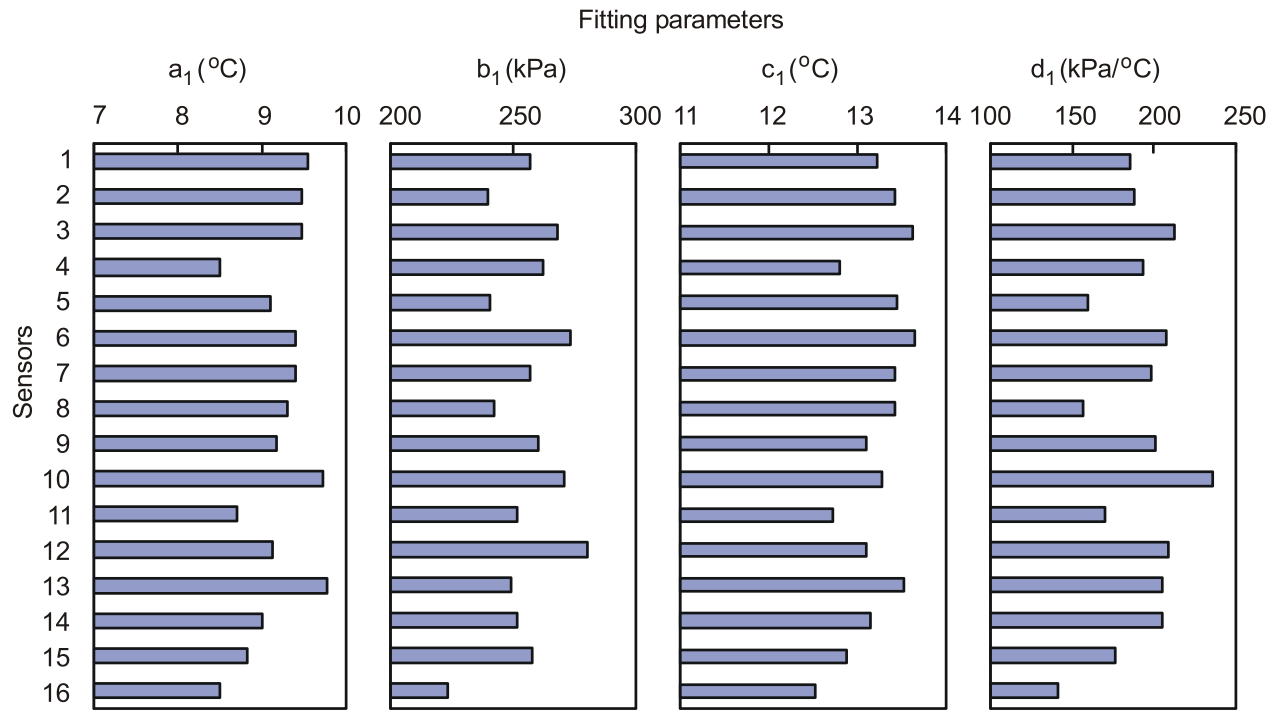


Figure 5. Variations in fitting parameters of Nichol et al. (2003) equation for all 16 calibrated FTC suction sensors

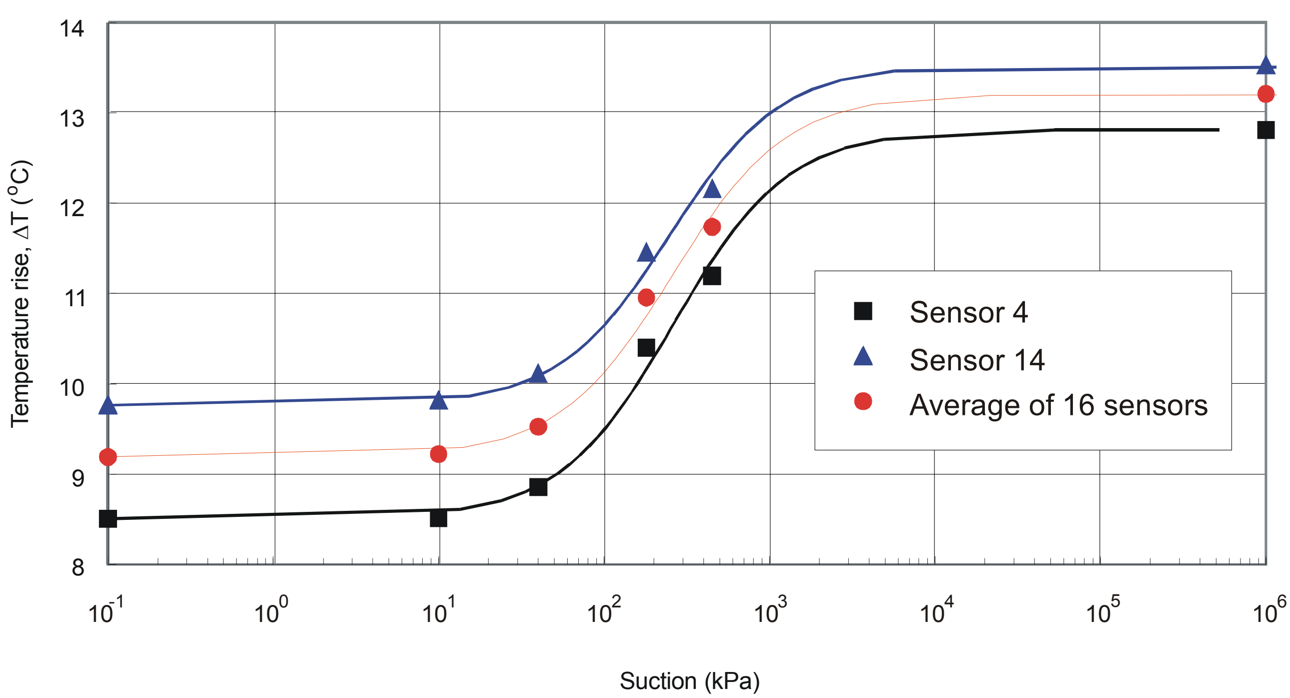


Figure 6. Calibration curves for sensors 4 and 14, and average of 16 sensors

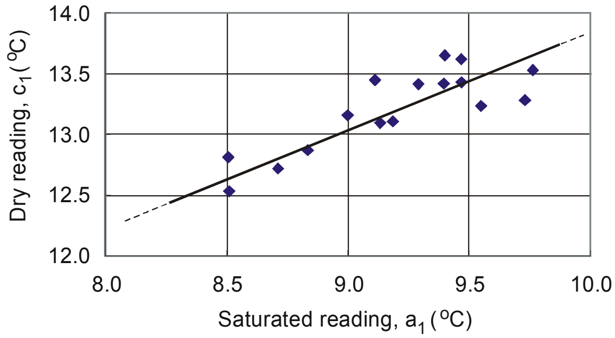


Figure 7. Comparison of the wet sensor reading and the dry sensor reading for the 16 FTC sensors

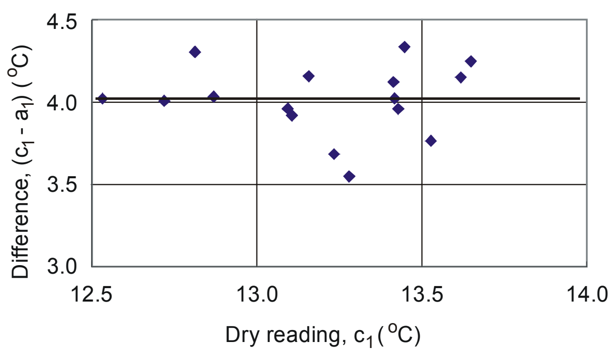


Figure 8. Comparison of the difference between the wet and dry sensor readings with the dry sensor reading

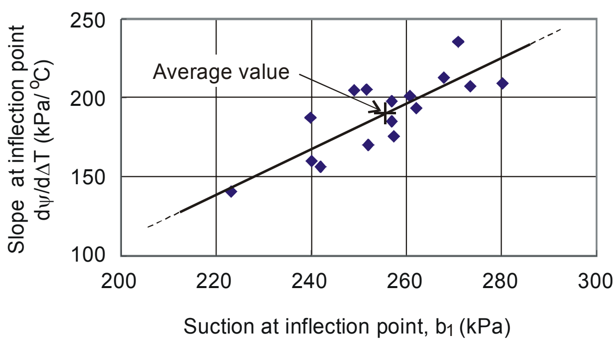


Figure 9. Comparison of the slope with the suction at the inflection point on the calibration curve

FTC sensors by comparing some of the calibration parameters. Figure 7 shows a plot of the response of the dry sensor to the response of the wet sensor. The results indicate that as the dry sensor response increases, so does the response of the wet sensor. Figure 8 compares the difference between the wet and dry response of the FTC sensors with the dry sensor reading. The difference between the wet and dry response remain quite similar for all sensors with an average value of 4.02 °C. The value of 4.02 °C indicates the temperature variation range of the sensors and it has been found to be a relatively constant value.

Figure 9 compares the slope of the calibration curve at the inflection point with the suction reading at the inflection point. The relationship indicates that as the suction increases at the inflection point, so does the slope of the calibration curve. The number of data points along the calibration curve is somewhat limited. It is anticipated that if more data points had been obtained, the relationship would likely have shown less scatter. In fact, it is anticipated that the scatter between the slope and the suction at the inflection point might tend to a single value if more data point were available since there appears to be an auto correlation effect between these two parameters.

The observations related to the relationship between the calibration parameters provide useful information for future calibration of FTC suction sensors. The following are some of the observations that were obtained from the present calibration study:

- If the sensors are manufactured using the same procedure, it can be anticipated that the response of the sensors should be similar to the responses observed on the 16 sensors.
- The calibration curve shape can be used to optimize the suction values that should be applied to the sensors when undertaking the calibration process.
- The relationships observed between the calibration parameters can provide an indication as to when the sensors might not be functioning satisfactorily.
- The manufacturer should consider using this calibration data, along with future calibration studies, to establish a "quality assurance, QA", related to the manufacturing of the FTC sensors.

## 6 CONCLUSIONS

There are a number of conclusions that can be arrived at concerning the use of the FTC suction sensors. The conclusions are preliminary because only 16 sensors were calibrated.

- The calibration equation previously published for the thermal conductivity suction sensors can be slightly modified to render best-fit parameters that have greater physical meaning, as shown by Eq. 4.
- Typical values for the 4 best-fit parameters are as follows: $a_1$ = 9.2 °C, $b_1$ = 255.3 kPa, $c_1$ = 13.2 °C and $d_1$ = 190.2 kPa/°C
- The Nichol *et al.* (2003) temperature correction appears to be the most suitable temperature correction equation to account for suction readings at temperatures other than the calibration temperature. However, it is suggested that a further study related to larger temperature variations would be of value.

- Based on the 16 sensors that were calibrated, the following calibration suctions are recommended in addition to the dry and saturated sensors conditions; namely, $\Psi_1$ = 50 kPa, $\Psi_2$ = 100 kPa, $\Psi_3$ = 250 kPa and $\Psi_4$ = 400 kPa.

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REFERENCES

Feng, M. and Fredlund, D.G. 1999. Hysteretic influence associated with thermal conductivity sensor measurements. Proceedings of the 52nd *Canadian Geotechnical Conference*, Regina, October 25-27, 651-657.

Feng, M., Fredlund, D.G. and Shuai. F. 2002. A laboratory study of the hysteresis of a thermal conductivity soil suction sensor. *Geotechnical Testing Journal*, 25: 303-314.

Feng, M. and Fredlund, D.G. 2003. Calibration of thermal conductivity sensors with consideration of hysteresis. *Canadian Geotechnical Journal*, vol. 40, pp. 1048-1055.

Fredlund, D.G. 1992. Background theory and research related to the use of thermal conductivity sensors for Matric Suction Measurements. Advances in measurement of soil physical properties: bringing theory into practice. *Proceedings of a symposium sponsored by Division S-1 of the Soil Science Society of America*, editors, G.C. Topp, W. D. Reynolds and R.E. Green, San Antonio, Texas, Oct. 21-26: 249-262.

Fredlund, D.G. and Rahardjo H. 1993. *Soil mechanics for unsaturated soil*. Wiley, New York.

Fredlund, D.G., Shuai, F. and Feng, M. 2000a. Use of a new thermal conductivity sensor for laboratory suction measurement. *Unsaturated Soils for Asia*, eds H. Rahardjo, D.G. Toll and E.C. Leong, Balkema, Rotterdam, 275-280.

Fredlund, D.G., Shuai, F. and Feng, M. 2000b. Increased accuracy in suction measurements using an improved thermal conductivity sensor. *Tailing and Mine Waste '00*, Fort Collins, Colorado, Jan 23-26: 443-450.

GCTS. 2005. SuctionData 1.12: *User's guide and reference*. GCTS, Tempe, Arizona.

Marjerison, B., Richardson, N., Widger, A., Fredlund, D.G. and Berthelot, C. 2001. Installation of sensors and measurement of soil suction below thin membrane pavements in Saskatchewan. *54th Canadian Geotechnical Conference*, Calgary, Alberta, Canada. Sep 16-19: 1328-1334.

Nichol, C., Smith L. and Beckie, R. 2003. Long-term measurement of matric suction using thermal conductivity sensors. *Canadian Geotechnical Journal*, 40:587-597.

Padilla, J.M., Perera, Y.Y. and Fredlund, D.G. 2004. Performance of Fredlund thermal conductivity sensor, *Proceedings of the Eleventh Tailings and Mine Waste Conference*, Vail, Colorado, October 10-13: 125-133.

Phene, C.J., Rawlins, S.L. and Hoffman, G.J. 1971a. Measuring soil matric potential *in situ* by sensing heat dissipation within a porous body: I. Theory and sensor construction. *Soil Science Scoiety of American Proceedings*, 35: 27-33.

Phene, C.J., Rawlins, S.L. and Hoffman, G.J. 1971b. Measuring soil matric potential *in situ* by sensing heat dissipation within a porous body: II. Experimental results. *Soil Science Society of American Proceedings*, 35: 225-229.

Rahardjo, H. and Leong, E.C. 2006. Suction measurement. Keynote, Unsat2006, ASCE *Geotechnical Special Publication*, No. 147, Vol.1, pp. 81-104.

Shuai, F., Clements, C., Ryland, L. and Fredlund, D.G. 2002. Some factors that influence soil suction measurements using a thermal conductivity sensor. *Unsaturated Soils*, Juca, de Campo and Marinho (eds), 325-329.

Shuai, F., Fredlund, D.G. and Samarasekera, L. 2003. Numerical simulation of water movement in the suction equalisation of a thermal conductivity sensor. *Geotechnical Testing Journal*, 26: 142-151.

Tan, E., Marjerison, B. and Fredlund, D.G. 2003. Measurement and analysis of temperature and soil suction below thin membrane surfaces (TMS) in Saskatchewan. *56th Canadian Geotechnical Conference*, Winnipeg, Manitoba. Sept 29 - Oct 1: 107-114.