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Comparisons of Correction Methods for Factors Influencing Thermal Conductivity Suction Sensors

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Abstract: Results from monitoring works have shown that thermal conductivity sensors have the capability to provide long-term, continuous, reliable matric suction and temperature readings for soils. Factors such as the hysteresis of the sensors and the effect of temperature on the thermal conductivity of the sensors have been found to influence the matric suction readings. Hysteresis of the ceramic tip allows matric suction readings to be obtained with reference to either the wetting curve or the drying curve. A method to accommodate the occurrence of capillary hysteresis is suggested and used in the presentation of data for soil suction. Comparisons between methods of correction proposed to eliminate the effect of ambient temperature on matric suction readings are illustrated to show the effect of each of these methods on the values of computed matric suctions.

Resumo: Resultados de um programa de monitoramento são apresentados demonstrando a capacidade de sensores de condutividade térmica na medição contínua e confiável de sucção mátrica durante longos períodos de tempo. Foi determinado que propriedades da cerâmica, tais como a histerese e o efeito da temperatura na condutividade térmica dos sensores influenciam as leituras de sucção mátrica. Um modelo de histerese para a cerâmica utilizada baseado nas curvas principais de secagem e de molhagem da cerâmica permite a leitura de sucção mátrica tanto em ciclos de molhagem quanto em ciclos de secagem. Um modelo capaz de acomodar a histerese da cerâmica foi modificado e utilizado nas leituras de sucção. Comparações entre dois métodos de correção propostos para eliminar o efeito da temperatura ambiente nas leituras de sucção mátrica são apresentados a discutidos.

1. INTRODUCTION

The development of thermal conductivity sensors for obtaining long term reliable matric suction measurements is important in understanding the behavior of unsaturated soils and bringing unsaturated soil mechanics into practice. The thermal conductivity matric suction sensors consist of a porous ceramic block with a heating device and an embedded temperature sensing circuit. The sensors are calibrated to determine the electric current output for a specific matric suction. Matric suction of the thermal conductivity sensors is in equilibrium with the surrounding soil. The correlation between the matric suction of the soil to the measured thermal conductivity of the sensors is an indirect method of measuring soil suction. Matric suction readings from these sensors can be subjected to environmental influences including temperature change and wetting-drying cycles (Shuai et al., 2002). The thermal conductivity sensors were initially calibrated in the laboratory at a constant temperature of 23^{0}C. Daily and seasonal temperature fluctuations in the field influence the thermal conductivity of water and subsequently decrease the accuracy of the matric suction readings by the sensors. The relationship between the water content of the porous block and the suction in the surrounding soil is not reversible due to capillary hysteresis (Feng, 1999). Capillary hysteresis results in different readings for matric suction being recorded depending on the wetting or drying state of the sensor.

In September 2000, two test installations were made in Saskatchewan, Canada; one located south of Torquay and the other north of Bethune (Marjerison et al., 2001). The two sites selected for the installation of the thermal conductivity sensors were thin membrane systems (TMS). The first site was located on Highway No. 345, approximately 3.5 km north of Bethune and the second site was located on Highway No. 350, approximately 8.6 km south of Torquay. Sixteen thermal conductivity sensors were installed beneath existing thin membrane system pavements at each site. Thin membrane system pavements consist of compacted native soil forming the subgrade material with a thin layer of asphalt to provide a dust free driving surface. Data from the thermal conductivity sensors installed at the test sites have been continuously recorded from September 2000 up to the present. For the purpose of this paper, only temperature and matric suction data from the thermal conductivity sensors recorded between the period of April 3rd, 2001 to July 12th 2001 are analyzed.

There were 16 sensors installed at each site and the spatial distribution of the sensors is shown in Figure 1. The individual sensors are connected to a multiplexer that in turn is connected to a data acquisition system. The multiplexer facilitates the acquisition of data from the sensors and communication with the system was accomplished through the use of a transceiver and a cellular antennae. Sensors were placed and labeled based on a vertical grid, starting from the centerline of the highway to the side slope. The majority of the sensors were placed under the inner and outer wheel path of the highway which had the highest traffic activity. Grid 1 with 5 sensors and Grid 2 with 4 sensors were located in the inner and outer wheel paths, respectively. Grids 3 and 4, each with 3 sensors were located on the shoulder and Grid 5 with only one sensor on the side slope.

Readings were taken daily at an interval of 4 hours with the exception of the winter months when readings were taken at an interval of 12 hours. This was due to the inability of the sensors to obtain readings once the sensors were frozen.

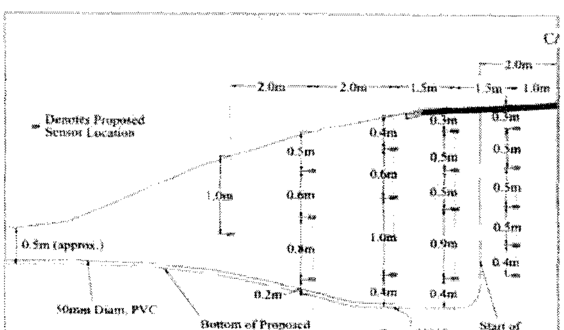

Figure 1: Spatial distribution of the thermal conductivity sensors in Torquay and Bethune (Marjerison, 2001)

2. THEORY

2.1 Correction for Hysteresis

Using limited calibration data, an empirical equation can be used to fit the measured calibration curves for the sensors with known hysteresis curves (Feng et al., 2002). The following equation has been proposed to fit to the main wetting and drying curves within the suction range of 0 kPa to 1000 kPa,

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

where ψ is the matric suction (kPa), ΔV is the measured rise in the temperature sensor output (mV) and a, b, c and d are the fitting parameters related to the main hysteresis loop. Equation 2 and Equation 3 proposed by Feng and Fredlund (2003) are used to fit the primary scanning curves,

$$V_d(\psi,\psi_1) = V_d + \left(\frac{\psi_1}{\psi}\right)^\alpha (V_w - V_d) \quad (2)$$

$$V_w(\psi,\psi_1) = V_w - \left(\frac{\psi}{\psi_1}\right)^\alpha (V_w - V_d) \quad (3)$$

where $V_d(\psi, \psi_1)$ 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 controlling the degree of curvature of the scanning curves. Feng and Fredlund (2003) proposed a best-fit value of 1.8 for the variable, α.

Equations 2 and 3 express the output voltage as a function of suction. Modification on Equations 2 and 3 are required in order to obtain the soil suction in the field as a function of the output voltage from the thermal conductivity sensor. The modification results in Equation 4 and 5,

$$\psi_d(V,V_1) = \psi_d - \left(\frac{V_1}{V}\right)^\alpha (\psi_d - \psi_w) \quad (4)$$

$$\psi_w(V,V_1) = \psi_w + \left(\frac{V}{V_1}\right)^\alpha (\psi_d - \psi_w) \quad (5)$$

where $\psi_d(V, V_1)$ is the soil suction at output voltage V on the drying scanning curve that starts at a voltage V_1; V_1 is the output voltage at which the scanning curve starts; ψ_w and ψ_d are the soil suctions at output voltage V on the main wetting and drying curves, respectively. In this study, Equation 1, 4 and 5 were used with an empirical parameter α, of 103. Values recommended for α are based on the investigation of hysteresis properties of the thermal conductivity sensors developed at the University of Saskatchewan (Feng and Fredlund, 2003). Other types of thermal conductivity sensors might require different values of α.

2.2 Temperature Correction

The influence of ambient temperature on the thermal conductivity of water affects the matric suction measurements of the thermal conductivity sensors. Shuai et al. (2002) took into account the effect of thermal properties of water and developed a correction for the ambient temperature as follows:

$$\Delta T(t, T_0) = \frac{0.0014t + 0.5743}{0.6065} \Delta T(t, T_1) \qquad (6)$$

where $\Delta T(t, T_0)$ is the rise in sensor core temperature that was measured at the ambient temperature during calibration (T_0) at time t and $\Delta T(t, T_1)$ is the field measured sensor core temperature rise at ambient temperature (T_1) at time t. The value of $\Delta T(t, T_0)$ is obtained from the field reading $\Delta T(t, T_1)$ and Equation 6. The value for matric suction is obtained based on the computed value of $\Delta T(t, T_0)$ and the laboratory calibration curve. Nichol et al. (2003) suggested that the thermal conductivity of the sensor should account for the thermal conductivity of the dry ceramic, the sensor water content and the interconnectedness of the water phase. By making several approximations, the estimated correction factor shown in Figure 2 was used to convert the field measured sensor core temperature rise to the measured sensor core temperature rise during calibration. The temperature rise correction factor is multiplied by the recorded temperature rise reading.

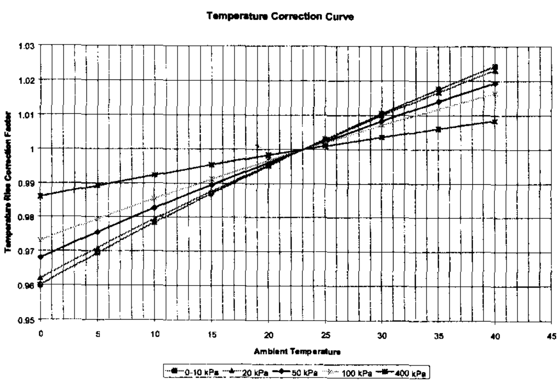

Figure 2: Correction factor for ambient soil temperature (Nichol et al., 2003)

The ambient temperature correction proposed by Nichol et al. (2003) takes into account matric suction. Since the equation proposed by Shuai et al. (2002) only considers the deviation in temperature from the calibration temperature and does not take into account the amount of water in the sensor, the correction is applicable for all matric suctions.

3. RESULTS AND DISCUSSION

In order to investigate the effect of environmental changes on the readings obtained by the thermal conductivity sensors, a comparison is made between suction readings obtained based on the main drying and wetting curve, suction readings when hysteresis is taken into account and soil temperature. The data analyzed in this study is from Sensor 1-1 in Torquay located at a depth of 0.3 meters beneath the inner wheel path of the road along Grid 1. The study focuses on a period of 100 days between April 3rd 2001 and July 12th 2001 when the sensor first thaws until the middle of summer. The soil temperature during this period ranges from above 0^{o}C to 34^{o}C.

Without making any temperature corrections, Figure 3 shows a comparison between soil temperature, suction values from the main drying and wetting curve and suction values obtained after taking hysteresis into consideration. The difference in suction readings obtained when hysteresis is not taken into account ranges from 32% to 36%. Suction readings obtained using correction for hysteresis show a high number of fluctuations with high magnitudes. Any relationship between the soil temperature and soil suction when hysteresis is taken into account is not clearly visible in this case.

Using the temperature correction method proposed by Nichol et al. (2003), Figure 4 makes the same comparison between soil temperature and soil suction when considering hysteresis and without. The difference in the range of suction values when hysteresis is not accounted for is slightly lower at 33% to 35%. The number of fluctuations in the suction values observed when hysteresis is considered appears to be lower with lower magnitudes when compared with the values presented in Figure 3. Generally, there appears to be an inverse relationship between soil temperature with soil suction. When hysteresis is taken into consideration, the decreasing number of fluctuations when compared to Figure 3 allows the relationship between soil temperature and soil suction to become more obvious. Increasing values of soil suction can be observed with decreasing temperature and vice versa.

The general relationship between temperature and soil suction is more obvious in Figure 5 where the temperature correction method proposed by Shuai et al. (2002) is used together with the correction for hysteresis.

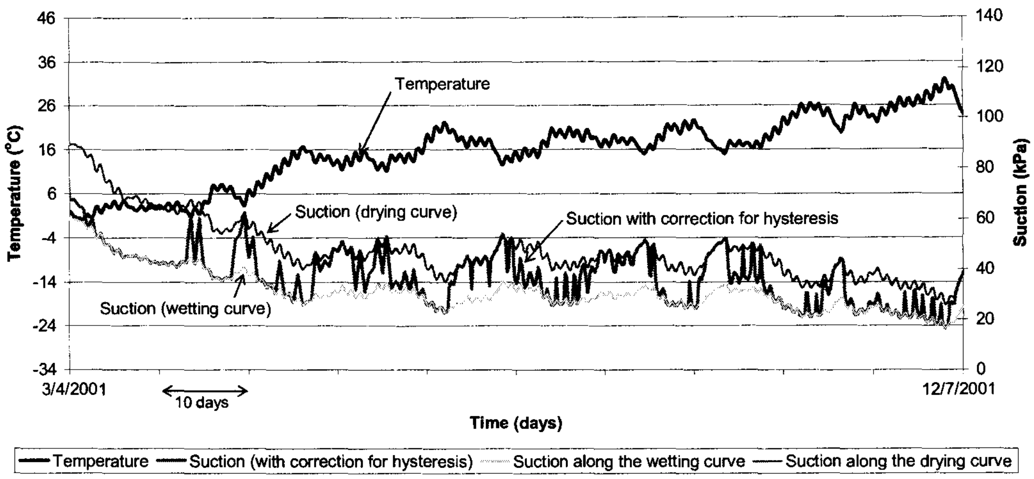

Figure 3: Comparison between Taking Hysteresis into Consideration and Without Using Either Temperature Correction Method

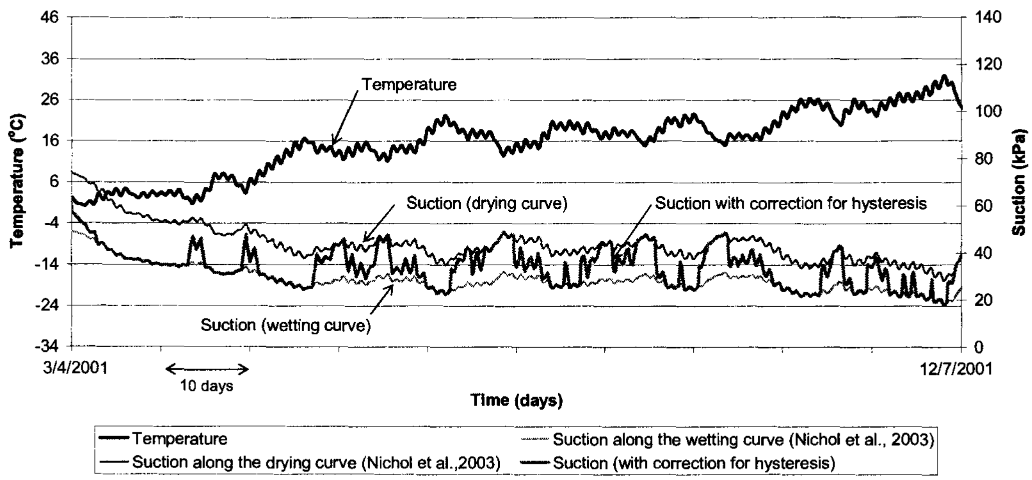

Figure 4: Comparison between Taking Hysteresis into Consideration and Without Using the Temperature Correction Method Proposed by Nichol et al.(2003)

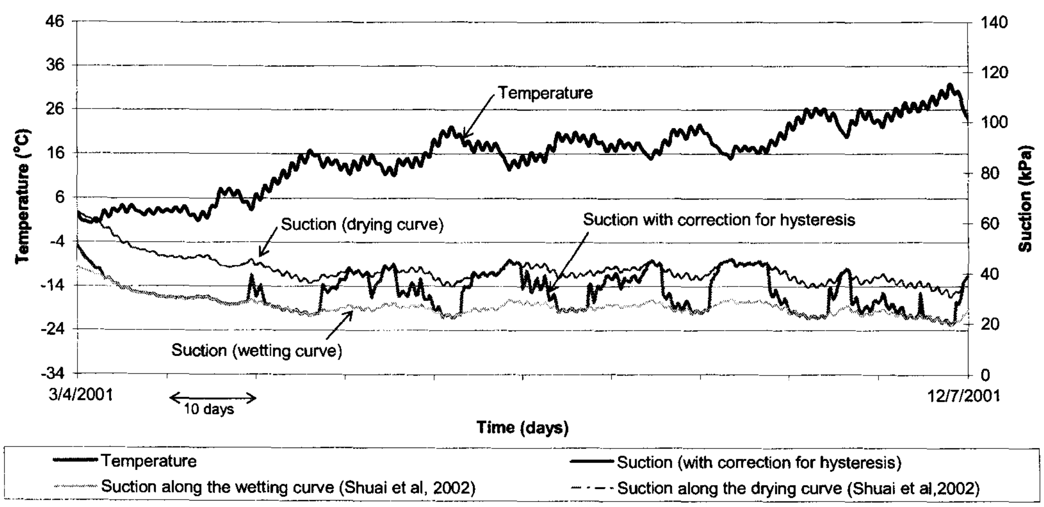

Figure 5: Comparison between Taking Hysteresis into Consideration and Without Using the Temperature Correction Method Proposed by Shuai et al. (2003)

The presence of a thermal gradient is a driving force for moisture movement in the soil and since the hydraulic gradient also affects heat transfer, temperature would also be related to soil suction. When hysteresis is not taken into account, the difference in soil suction readings obtained from the drying and wetting curve ranges from 33% to 35%. The soil suction curve obtained using the temperature correction proposed by Shuai et al. (2002) while taking hysteresis into account yields the lowest number of fluctuations with the lowest magnitudes. The lack of noise in this computed curve allows a clearer observation of the inverse relationship between soil temperature and soil suction.

Figure 6 compares the matric suction values obtained from the drying and wetting curves without taking hysteresis into account to isolate the effect of various temperature correction methods on the resultant suction readings. A comparison is made on the suction values obtained when no temperature correction method was used and using the temperature correction methods proposed by Nichol et al. (2003) and Shuai et al. (2002).

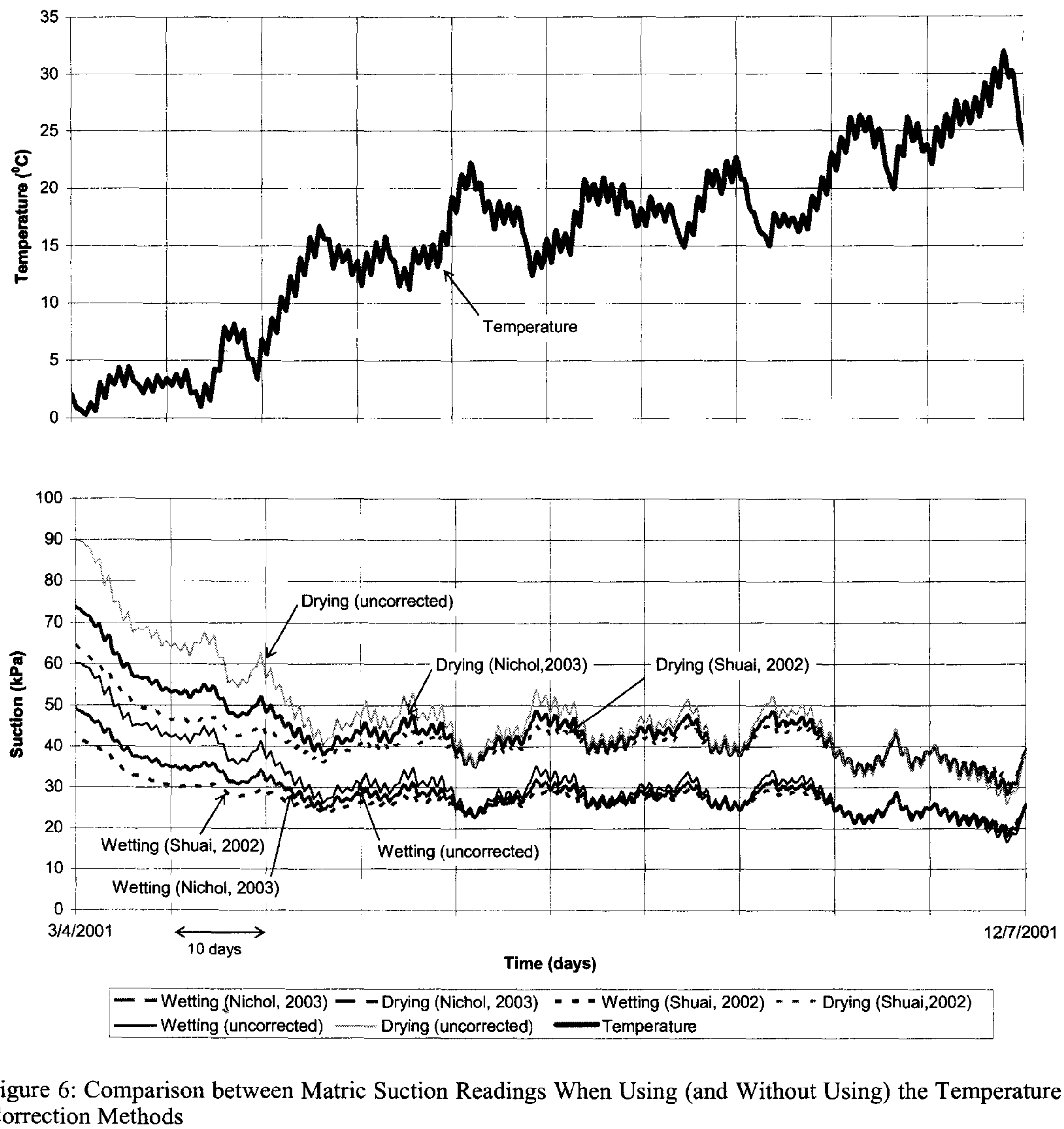

Figure 6: Comparison between Matric Suction Readings When Using (and Without Using) the Temperature Correction Methods

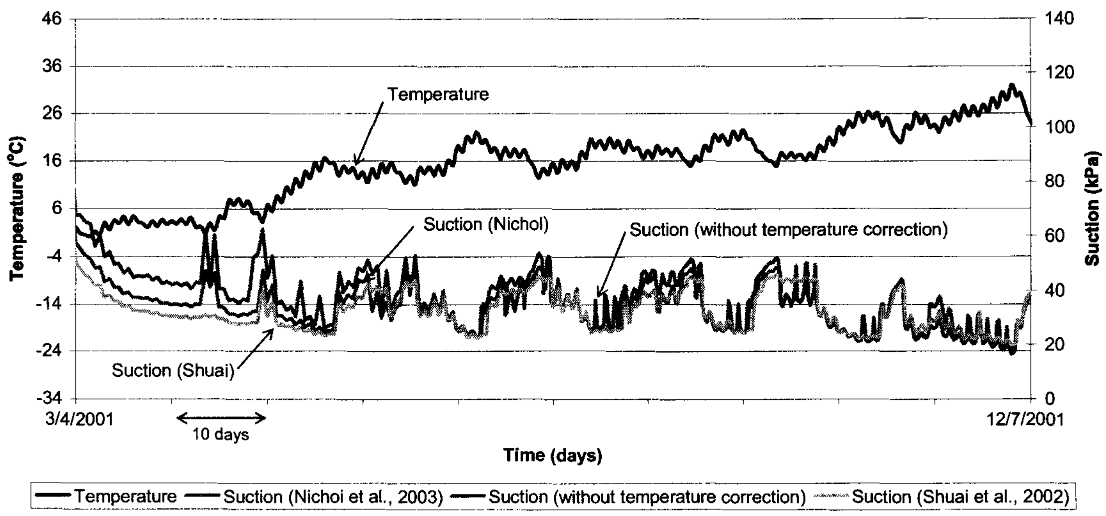

Figure 7: Comparison between Suction Values Obtained With and Without Temperature Correction Methods While Taking Hysteresis into Consideration

For the drying curves, the difference between the soil suction values obtained using the temperature correction method proposed by Nichol et al. (2003) with the uncorrected value ranges between 0% and 17.5%. The temperature correction method proposed by Shuai et al. (2002) varies from 0% to 28% with the uncorrected suction values. For the wetting curves, a difference of 0% to 18.1% is observed when comparing the suction values obtained using the correction method proposed by Nichol et al. (2003) with the uncorrected values. Differences ranging from 0% to 28.8% are observed when comparing the suction values obtained using the method proposed by Shuai et al. (2002) with the uncorrected values. For both the drying and wetting curves, the correction method proposed by Shuai et al (2002) yields suction values that are between 0% to 10% different from the suction values obtained using the method proposed by Nichol et al. (2003). The sensors were calibrated in the laboratory at a room temperature of 23^0C. At soil temperatures approaching 23^0C, lower differences are observed between the corrected values with the uncorrected values. Higher differences in soil suction readings can be observed when the soil temperature fluctuates away from 23^0C.

Below the ambient temperature during calibration (i.e., 23^0C), matric suction values without any temperature correction are above both the corrected values. At temperatures above 23^0C, the opposite is observed with uncorrected matric suction readings lower than both the corrected values. Corrected matric suction values using the method proposed by Nichol et al. (2003) are consistently between the uncorrected matric suction values and the matric suction obtained using the method proposed by Shuai et al. (2002). This trend is noticed in both the drying and wetting curves.

The corrected values for the drying curves are still lower than the uncorrected matric suction on the wetting curve. This is an indication that the hysteresis of the sensors has a more significant influence on the matric suction readings then the effect of the soil temperature. The overall trend observed for both the drying and wetting regardless of the temperature correction methods used show an inverse relationship between soil temperature and soil suction. Comparison between soil suction values obtained when hysteresis is taken into account using the various temperature correction methods can be seen in Figure 7. Soil suction values using the temperature correction methods are compared with the suction values obtained without using any temperature corrections. The suction values obtained using the method proposed by Nichol et al. (2003) yield differences between 0% and 24%. Using the correction method by Shuai et al. (2002) gives differences ranging from 0% to 50%. The maximum difference in readings obtained using the method by Shuai et al. is two times larger than Nichol et al.

The same method is used in all three cases when considering the effect of hysteresis. The difference between the suction readings obtained is due to the different temperature correction methods used. When the cases are presented without taking hysteresis into account, the maximum difference between both the correction methods is 10%. The maximum difference between both the temperature correction methods increases to 26% when hysteresis is taken into account. The occurrence of this maximum difference in this study is minimal when compared to the large amount of suction data.

4. CONCLUSIONS

Modifications made to the equation proposed by Feng and Fredlund (2003) to accommodate the effect of hysteresis resulted in reasonable suction readings. The relationship between soil temperature and soil suction is more obvious when using the temperature correction method proposed by Shuai et al. (2002). The temperature correction method proposed by Nichol et al (2003) yielded intermediate suction values, fluctuations and magnitudes. This temperature correction method is theoretically more accurate but is more difficult to implement. Large amount of data requires a temperature correction method that is easier to handle. The method proposed by Shuai et al. (2002) has a maximum difference of 26% when compared to the results from the method by Nichol et al. (2003). Consideration can be given to the method proposed by Shuai et al. when dealing with extensive suction data that does not require a high degree of accuracy.

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6. ACKNOWLEDGEMENTS

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