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Some factors that influence soil suction measurements using a thermal conductivity sensor

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ABSTRACT: Thermal conductivity soil suction sensors have proven to hold great promise for the in situ measurement of soil suction. Thermal conductivity soil suction sensors can be subjected to the influences of environmental changes, such as temperature change, pH value change, freeze–thaw cycles and wetting–drying cycles once they are installed in the field. Some research has been done on each of these influences to show that thermal conductivity soil suction sensor can measure reasonable value of soil suction in a changing environment. The results from the research are provided in this paper. The results showed that pH value and freeze–thaw cycles have little influence on the accuracy of soil suction measurements. The soil temperature change and wetting–drying cycles have some influence, but it is possible to essentially eliminate these influences using the techniques described in this paper.

1 INTRODUCTION

The long-term performance of a geotechnical structure (i.e. dam, slope and cover, etc.) is closely related to the behavior of the soils with respect to shear strength, volume change and water flow. In order to evaluate the adverse influence of such factors on the structural adequacy, it is necessary to have an understanding of the soil suction (i.e. negative pore-pressure) profile with time in the soil. This is particularly true in arid or semi-arid areas where the soil moisture may be subjected to significant seasonal fluctuations.

One of the methods used for continuous in situ suction monitoring is the use of thermal conductivity soil suction sensors. This method uses a measurement of the thermal conductivity of a standard ceramic tip to indirectly determine soil suction. The thermal conductivity of the ceramic tip is correlated with the matric suction of the ceramic that is in equilibrium with the surrounding soil. This method has been proven to provide consistent and stable measurements of soil suction over a long period of time (Fredlund & Rahardjo 1993). However, the performance of thermal conductivity soil suction sensors in terms of strength, reliability and durability has been somewhat disappointing. The range of soil suction measurements has also been limited. A research program at the University of Saskatchewan has resulted in the development of a new thermal conductivity soil suction sensor (Fredlund et al. 1998) that overcomes many limitations and difficulties associated with previous commercially available thermal conductivity sensors.

Thermal conductivity soil suction sensors can be subjected to the influences of environmental changes when installed in the field. The environmental changes may be temperature change, pH change, freeze–thaw cycles and wetting–drying cycles. In order to further improve the performance of the new thermal conductivity soil suction sensors, a laboratory testing program was conducted to investigate the influences of various environmental factors on the performance of the new sensors. Some of the research results are presented in this paper.

2 FACTORS THAT INFLUENCE THE SOIL SUCTION MEASUREMENT

Subsequent to their installation, soil suction sensor is subjected to environmental changes. These environmental changes include ambient temperature, pH value, freeze–thaw cycle and wetting–drying cycles. The influences of these environmental factors on the performance of the new soil suction sensor are the focus of this study.

2.1 *Temperature change*

The soil suction sensors installed in the field experience daily and seasonal temperature fluctuation. Since the thermal conductivity of most materials changes with temperature, a change in temperature will influence the accuracy of the thermal conductivity matric suction sensor measurement. The influence of temperature change on the suction measurement, when using a thermal conductivity sensor, has been observed for more than a decade (Phene et al. 1971, Wong et al. 1988) and is shown in Figure 1. This influence is mainly attributed to the thermal conductivity change of water with ambient temperature. The thermal conductivity from 0°C to 100°C is shown in Figure 2 for air, ceramic and water.

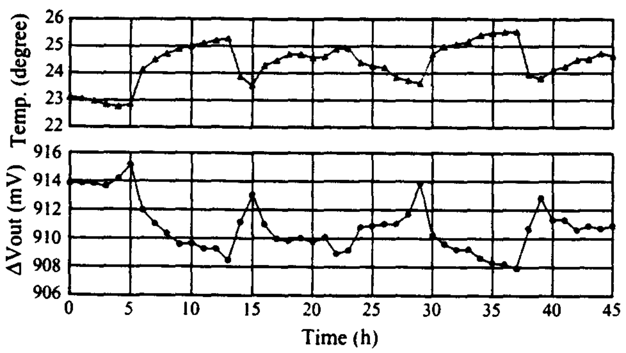

Figure 1. The influence of the ambient temperature on the measurement of soil suction.

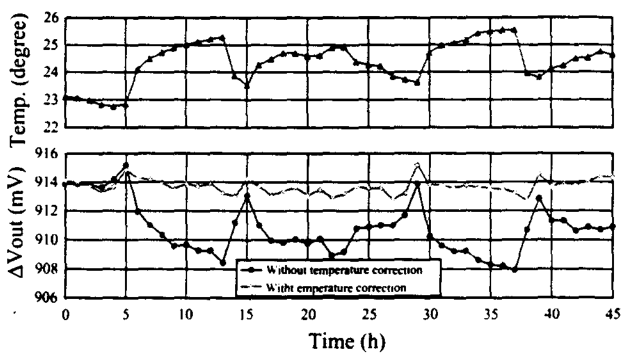

Figure 3. The output voltage from sensor no. with and without the temperature correction being applied.

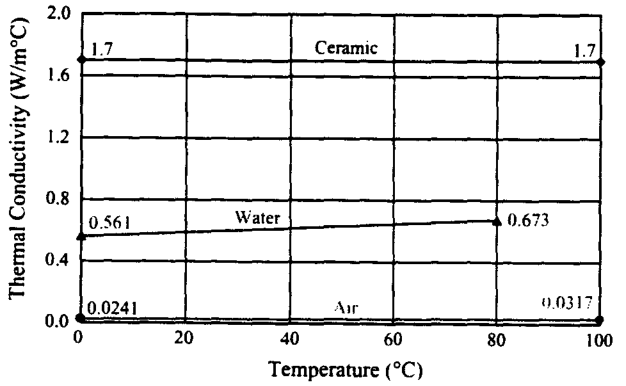

Figure 2. Thermal conductivity of the materials comprising a thermal conductivity soil suction sensor.

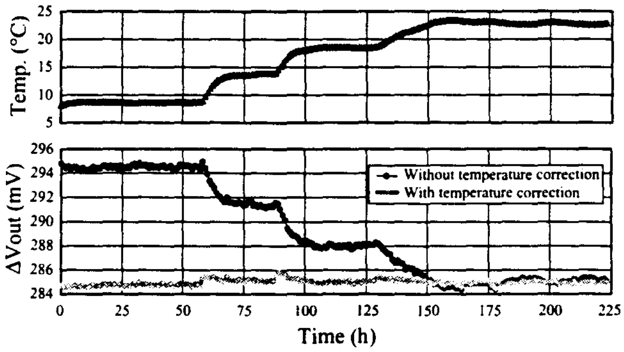

Figure 4. Test results for temperature correction technique verification for the case of an applied suction of 50 kPa.

It can be seen that the change of thermal conductivity with temperature is negligible for air and ceramic, compared to the change of thermal conductivity of water.

In order to eliminate the effect of thermal influences, a temperature correction technique was developed that can be expressed as follows:

$$\Delta V_{23^\circ\mathrm{C}} = \frac{0.0014t + 0.5743}{0.6065}\Delta V_t \qquad (1)$$

where t = the soil temperature; $\Delta V_{23^\circ\mathrm{C}}$ = the output voltage at 23°C; and ΔV_t = the output voltage at temperature, t.

Figure 3 shows the output voltage with or without temperature correction for one thermal conductivity sensor. The ambient temperatures during the measurements are also shown in the figure. It can be seen that the temperature influence is reduced by using the temperature correction technique.

Further research was conducted to verify the use of the temperature correction technique over a wide range of temperature. Three sensors were placed into a temperature-controlled chamber. The temperature inside the chamber was increased from 8°C to 23°C, step by step while the applied suction was maintaining a constant. The output voltages from the sensor were recorded and the temperature correction technique was used to modify the readings. A total of three tests were conducted. The constant suctions for each test are 10, 50 and 200 kPa, respectively. The test results at 50 kPa are shown in Figure 4 along with the temperature change. The test results indicate that the temperature correction technique is valid over a wide range of temperatures.

2.2 *Influence of freeze–thaw cycles*

Soil suction sensors installed in the cold region will be subjected to numerous freeze–thaw cycles. When the temperature drops below 0°C, the water inside the sensor freezes and expands. It is possible that the expanding ice may affect the performance of the sensor or even crack the sensor. The situation becomes even worse in regions with many cycles of freezing and thawing. Partial thawing may add new water to the ice inside the sensors and re-freezing adds further ice.

Tests have been conducted in a freezing environment at the University of Saskatchewan, to study the adverse influence of the freeze–thaw cycles on the performance of the new soil suction sensor. A pressure plate apparatus with three thermal conductivity soil suction sensors placed inside was insulated inside a temperature-controlled chamber. The suction inside the pressure plate apparatus remained constant while the temperature inside the chamber was dropped from 20°C

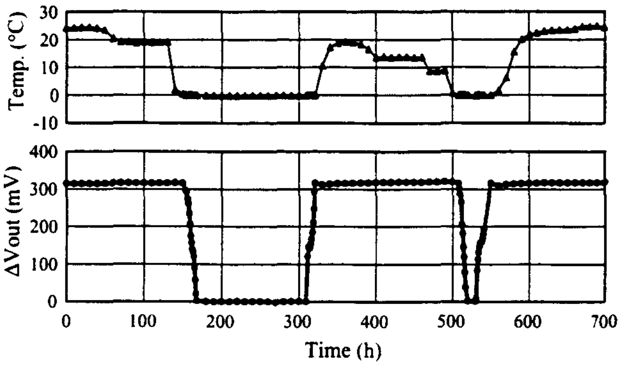

Figure 5. Influence of freeze–thaw cycles on the measurement of soil suction (applied suction = 50 kPa).

to below 0°C. When the sensors became totally frozen, the temperature inside the chamber was increased to above 20°C. The above procedure was repeated two times.

The voltage output from the sensor and temperature measurements with respect to time are shown in Figure 5. All three sensors appeared to respond in a similar manner. As the temperature decreased from above freezing to below freezing, the sensor readings drop rapidly to approximately zero. The sensor readings remain at zero as freezing continued. When the temperature was increased from below freezing to above freezing, the output voltage from the sensors increased rapidly from zero to the original reading before freezing. The same behavior was observed during the second freeze–thaw cycle. Similar observations were made by Fredlund et al. (1991) when using AGWA-II thermal conductivity soil suction for soil suction measurements in a freezing environment. The distinct drop in the output voltage during the freezing process can be attributed to the effect of the latent heat of fusion on thermal conductivity. During the freezing process, the latent heat of fusion is released at a constant temperature. Since the water in the sensor does not freeze simultaneously, but rather freezes in a gradual manner, the proportions of unfrozen and frozen water inside the sensor change with time. As a result, the temperature increase produced by the heat pulse will decrease with time and finally become zero. Since ice and water have different thermal conductivities, the output voltages are difficult to interpret and to convert to soil suctions during the freezing process. However, the test results shown in Figure 5 indicate that the freeze–thaw cycles do not appear to influence the soil suction measurements after thawing. In other words, the quality and the calibration properties of the new sensor do not appear to be affected by the freeze–thaw cycles. Also, there has been no observed damage to the sensor ceramic as a result of freeze–thaw cycles.

2.3 *The influence of pH value*

It is possible that in situ suction monitoring is required in an adverse acidity or alkalinity environment. In order to investigate the influence of the adverse environmental conditions on the performance of the new sensors, several tests were conducted.

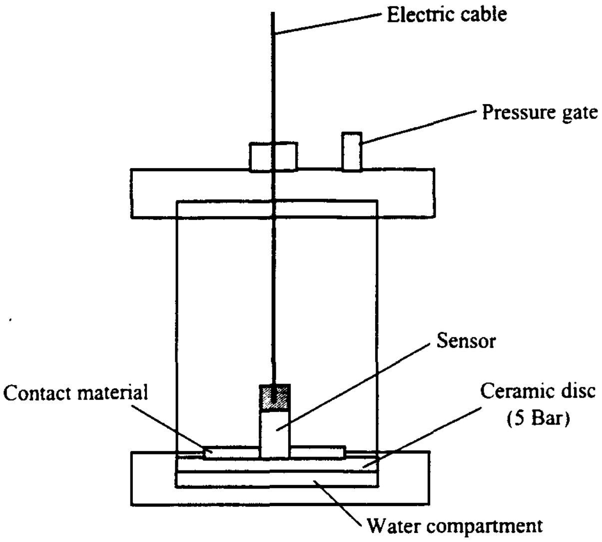

Figure 6. Physical layout of the test apparatus for the calibration of sensors.

Six sensors were used in the study. The six sensors were first submerged in distilled water. After saturation, the sensors were installed in a modified pressure plate apparatus for calibration, as shown in Figure 6. The sensors were set on a thin layer of contact material placed on the high air entry disk. The contact material ensured continuity between the water phase in the sensors and the water phase in the high air entry plate so that a continuous hydraulic flow between the sensors and the high air entry disk was maintained. Suction was applied by increasing the air pressure in the pressure plate apparatus while maintaining the water pressure in the water chamber at atmospheric conditions. The change in voltage output from the sensor was monitored periodically until suction equilibrium was achieved. The above procedure was repeated for various applied suctions ranging from 0 to 400 kPa so that a calibration curve was obtained. After calibration, the six sensors were divided into two groups. Three sensors were re-submerged in a hydrochloric acid solution (i.e. HCl) with a pH value of 4.25 and another three sensors were immersed in a solution of sodium hydroxide (NaOH) with a pH value of 10.9. The sensors remained submerged within the acid and base solution for 3 weeks. Then the sensors were moved to the pressure plate apparatus for re-calibration.

A typical re-calibration curve for a sensor after a 3-week immersion in HCl is shown in Figure 7. Also shown is the initial calibration curve. It was found that the new sensors performed successfully after the 3-week immersion in the solution of HCl and only negligible differences (i.e. less than a 5% difference) were observed. Similar results were found in the sensors immersed in a solution of NaOH and the results are shown in Figure 8.

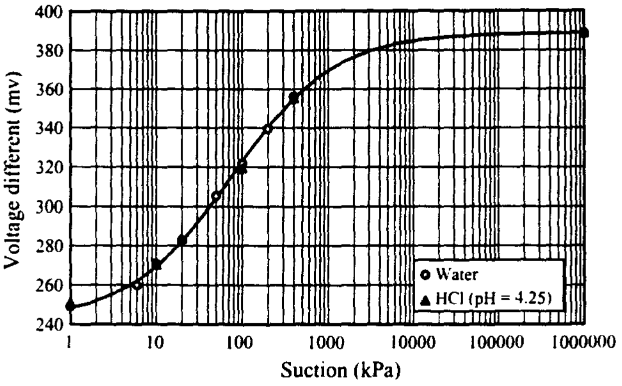

Figure 7. Initial and re-calibration curves for a sensor submerged in HCl (pH = 4.25) for 3 weeks.

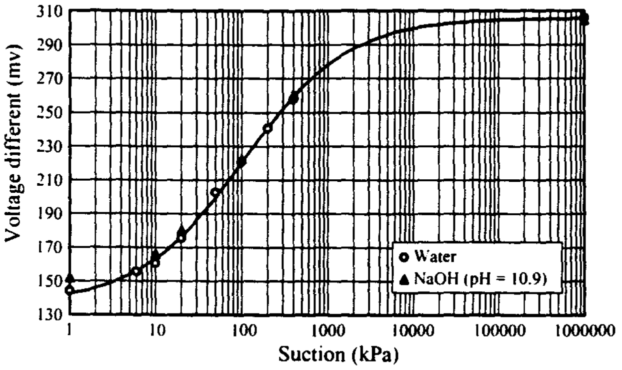

Figure 8. Initial and re-calibration curves for a sensor submerged in NaOH (pH = 10.9) for 3 weeks.

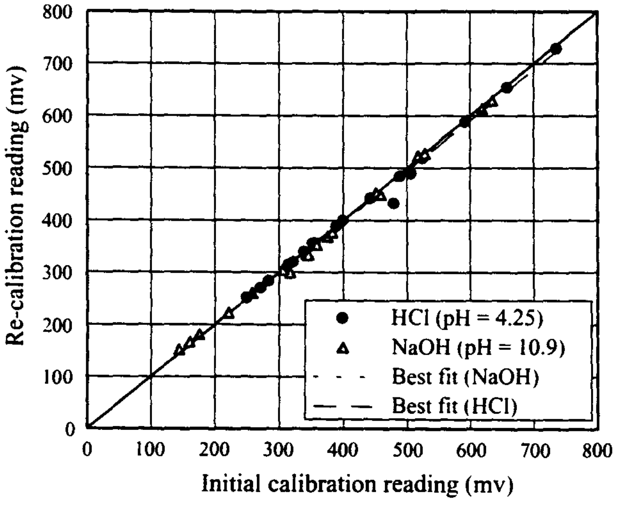

Figure 9. Regression curves for initial and re-calibration points for six sensors.

The results of a regression analysis performed on the six sensors are presented in Figure 9 by comparing the voltage outputs from the sensors during the initial calibration and re-calibration. Results show that there were negligible differences between the initial calibration and re-calibration values.

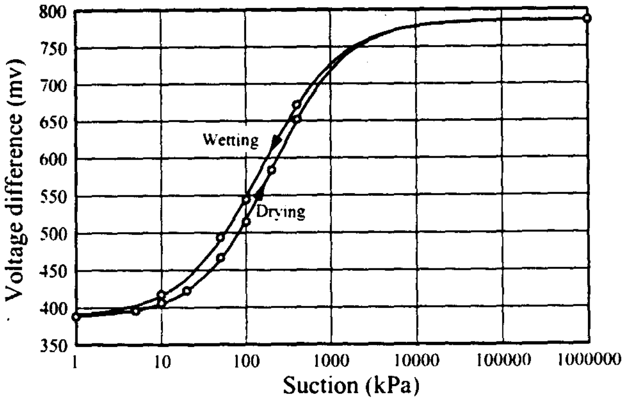

Figure 10. Hysteresis in the suction measurement using a thermal conductivity sensor.

2.4 *The influence of the hysteresis of the ceramic*

The water content versus matric suction curves for any porous material during wetting and drying are not the same. The hysteresis in the characteristics curve for the ceramic may cause hysteresis in the sensor response upon wetting and drying. Attempts have been made to better understand the characteristics of capillary hysteresis in the porous ceramic tip and its influence on the measurement of soil suction (Feng 1999).

Six new soil suction sensors were used to investigate the hysteresis associated with the relationship between the output voltage of the sensor and the applied soil suction. The sensors were installed in the pressure plate apparatus shown in Figure 6. Matric suctions below 10 kPa were applied by keeping the air pressure in the pressure plate cell at one atmosphere, while decreasing the water pressure in the water chamber by lowering the water level in the attached burette. Matric suctions higher than 10 kPa were applied by increasing the air pressure in the cell while keeping the water pressure in the water chamber constant. Both desorption and absorption tests were conducted to measure the drying and wetting paths. A typical test set of results is shown in Figure 10.

It was found that there was hysteresis in the soil suction measurement when using the thermal conductivity sensors. In other words, there is a difference between the drying curve and wetting curve. The maximum possible relative error in the suction measurement can be as high as 30% if the conventional calibration curve is used without considering the effects of the hysteresis. However, test results did indicate that the hysteresis curves were stable and reproducible over a 2-year experimental period (Feng 1999). In other words, the wetting and drying curves for a ceramic tip will not change with time, meaning the thermal conductivity soil suction sensors are a reliable tool for long-term laboratory and in situ suction measurements.

In order to eliminate the influence of hysteresis in the ceramic, a hysteresis model was proposed on the basis of the test results (Feng 1999). This model can

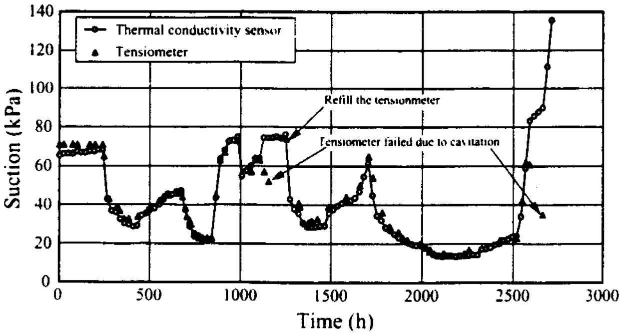

Figure 11. A comparison between the suction measured using a tensiometer and the suction measured using a thermal conductivity soil suction sensor.

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 soil suction. A comparison between the suction measured using a tensiometer and the suction measured using a thermal conductivity sensor when considering hysteresis is shown in Figure 11. Both sensors were installed in an Indian Head till soil specimen. Good agreement was noticed between the soil suction measured using a tensiometer and the suction measured using a thermal conductivity soil suction sensor. Cavitation of the water in the tensiometer caused a difference in the results.

3 CONCLUSIONS

Thermal conductivity soil suction sensors have proven to hold promise for the in situ measurement of soil suction. Thermal conductivity soil suction sensor can be subjected to the influences of environmental changes, such as temperature fluctuation, pH value change, freeze–thaw cycles and wetting–drying cycles. Research has been reported on each of these influences to show that the new sensors can measure reasonable values of suction in a changing environment.

The influences of pH value and freeze–thaw cycles on the performance of the thermal conductivity soil suction sensor are negligible. However, a distinct drop in the suction measurement is observed during the freezing process. The drop is attributed to the effect of the latent heat of fusion associated with water. As a result, the sensor readings are meaningless when the soil becomes frozen.

Soil temperature change has an influence on soil suction measurements due to a change in the thermal conductivity of water with temperature. A temperature correction technique was proposed to eliminate the temperature influences and increase the accuracy of soil suction measurements.

Hysteresis exists when using a thermal conductivity sensor for the measurement of soil suction. However, the hysteresis curves are stable and reproducible over a 2-year experimental period. A hysteresis model was proposed to account for hysteresis. This model can be used to modify data obtained according to the wetting or drying history of the sensor. This model has been successfully used for analyzing laboratory suction measurements.

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