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RECENT DEVELOPMENTS OF A SENSOR FOR THE INSITU MEASUREMENT OF MATRIC SUCTION

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ABSTRACT

A number of suction sensors have been proposed for the indirect measurement of matric suction in the field. The measurement that has been proven to show the great promise is that involving the use of the thermal conductivity matric suction sensor. However, there are some limitations associated with previously developed versions of these sensors. An industry-university research program of collaboration program leading towards the development of a new thermal conductivity sensor has been undertaken at the University of Saskatchewan, starting in September 1996. Significant progress have been made and the progress is described in this paper.

RÉSUMÉ

Plusieurs senseurs de succion ont été proposés pour le mesurage de matrice de succion dans le champs. La méthode de mesurage la plus prometteuse est celle impliquant I'utilisation du senseur de succion à conductivité thermique. Cependant, des limitations sont associées aux versions de senseurs antérieurement développées. En septembre 1996, un programme de recherche impliquant une collaboration industrie-université visant le développement d'un nouveau senseur à conductivité thermique a été entrepris à I'Université de Saskatchewan. Des progrès significatifs ont été faits et ces progrès sont décrits dans cet article.

INTRODUCTION

There are numerous geotechnical engineering applications when the measurement of negative pore-water pressure (i.e., soil suctions) could be of great assistance. The importance of negative pore-water pressure measurements almost bears a direct relation to the importance of positive pore-water pressure measurements in the classic areas of soil mechanics. Some examples are as follows.

Piezometers have been used to measure the positive pore-water pressure and thereby assess the degree of consolidation of a soft compressible clay. Likewise, negative pore-water pressure measurements are required to assess the potential heave in an expansive soil. Piezometer have been used to measure positive pore-water pressure in slopes in order to assess stability. Likewise, the water table is deep in some slope but there is the possibility of a slope failure as a result of decrease in soil suction. Piezometer have been used to measure positive pore-water pressures in order to better understand the hydrogeology of an area. Likewise, the near ground surface hydrogeology is often controlled by an interaction with the climatic environment and as such, negative pore-water pressure measurements can be used to establish the gradient pattern of flow in an unsaturated soil. The above examples illustrate the parallel that exists between the need for positive and negative pore-water pressure measurement.

There are also many other applications in geotechnical engineering regarding the measurement of negative pore-water pressure. The wide range of applications come about as a result of the fact that the infrastructure for societal development occurs near the ground surface when pore-water pressure are negative. Applications for the need to measure negative pore-water pressure may range from the study and design of subgrades for roads, airports and railways, to the study and design of covers and liners for waste containment. The particular study been reported or was initiated primarily as a result of the need to better understand the performance of covers.

The need for the measurement of negative pore-water pressure extends well beyond the geotechnical area. Probably the largest areas of application are related to signaling the onset and offset of irrigation for crops, golf courses, etc. One of the main requirements of those applications is the device has ability to be connected to data acquisition system for automatic measurement.

A promising device for the measurement of matric suction insitu is the thermal conductivity matric suction sensors (Fredlund, 1992). This method uses a measurement of the thermal conductivity of a specially designed ceramic. The ceramic is correlated with the matric suction of the ceramic that is in equilibrium with the surrounding soil. The primary components of thermal conductivity matric suction sensors are shown in Fig. 1.

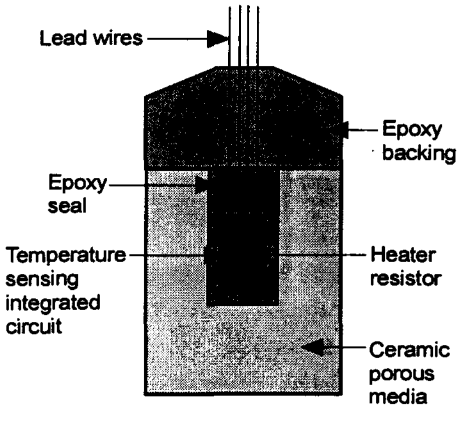


Figure 1 Cross-section diagram of a thermal conductivity, matric suction sensor.

Previous researches have indicated that the thermal conductivity sensors produce reasonable reliability measurement of suction over a relatively wide range and are essentially unaffected by the salt content of the soil. (Lee and Fredlund, 1984 and Fredlund and Wong, 1989). These sensors also have advantages of versatility and ability to be connected to data acquisition system for automatic measurement. However, the use of previously versions of these sensors have been plagued with numerous difficulties.

Difficulties with the use of thermal conductivity, matric suction sensors has ranged from problem associated with i.) the durability, strength and pore size distribution of the ceramic, ii.) the durability and accuracy of the electronics, and iii.) the influence of the hysteresis on the accuracy of the suction measurement. These problems have been the focus of an industry-university research program of collaboration (i.e., five companies participated in the program). The program was started in September 1996 and will extend over a three-year period.

The objective of the research study is to develop a relative inexpensive and reliable soil suction sensor for geotechnical and environment monitoring. Each of the above problems has been the focus of the research study. In each case, viable solutions to the above problems have been forthcoming and progress is discussed in this paper.

IMPROVEMENT OF CERAMIC TIP

The ceramic tip used for soil suction sensors requires some special characteristics. First, the ceramic tip should possess a wide distribution of pore size so that a linear logarithm variation in electrical response up to high suctions can be ensured. Secondly, the ceramic must be sufficiently durable to be handled in a fairly rough manner without cracking or crumbling when installed. Finally, the sensor must be sufficiently robust to withstand stresses associated with drilling or driving the sensor into position in the field.

There are many factors which influence above properties of the ceramic, such as, material component, additives, synthesis method and firing temperature, to name only a few. A laboratory test program was established to study the influence of each factors on the ceramic properties. On the base of the tests results, a recipe for a ceramic with a wide range of pore size distribution was determined. The ceramic has pore size in a range from 0.05 mm to less than 0.005 mm and can be used to measure matric suctions from approximately 5 kPa to 500 kPa. This is the range of greatest interest for geotechnical and geo-environmental engineering.

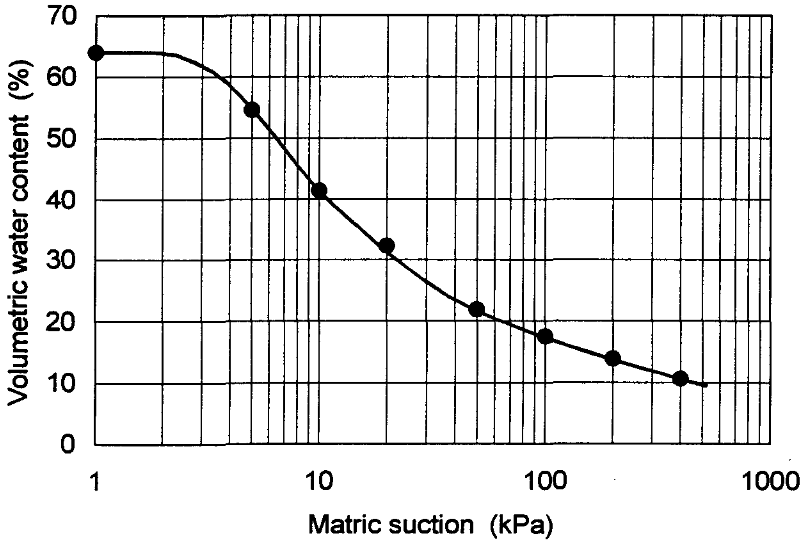


Figure 2 A typical soil-water characteristic curve of the newly developed ceramic.

In addition to the wide range of pore size distribution, the strength of the ceramic was also significantly improved. The compressive strength of the ceramic was increased to approximately 2100 kPa. The tensile strength is about 600 kPa. The stronger strength has a positive influence on the prevention of cracking and crumbling during installation. Table 1 lists some main properties of the ceramic. The typical soil-water characteristic curve of the ceramic is presented in Fig. 2.

Table 1 Some main properties of the new ceramic tip

Property	Magnitude
Average porosity	64%
Average compressive strength	2100 kPa
Average tensile strength	600 kPa
Saturated Permeability	2×10^{-6} m/s

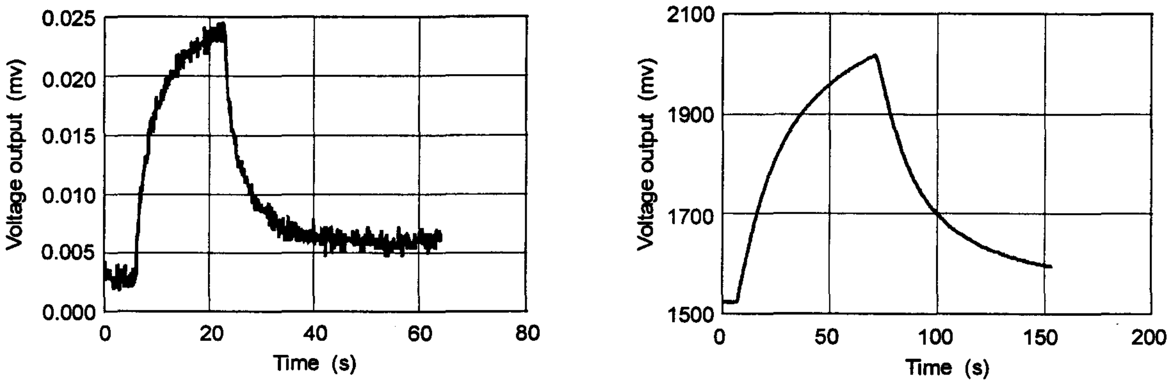
IMPROVEMENT OF THE ELECTRONICS

The ceramic tip includes a temperature sensor and a heating unit cast within the ceramics. The temperature change after heating is measured by the temperature sensor and the information is sent to the data logging system. The accuracy of the measurement depends primarily on the resolution of the data logging system and the quality of the output of the temperature sensor. The later, in turn, depends on the type of temperature sensing device. Other factors, such as the variation in heating voltage, variations in the resistance of heating element and noise, also influence the quality of the output.

Two kinds of temperature sensing devices are widely used for temperature measurement, namely, thermocouple and integrated circuit (i.e., IC). Thermocouple were widely used in previously developed thermal conductivity sensors. However, use of a thermocouple as a temperature sensing device is not as satisfactory as an IC due to its low voltage generation. On the other hand, an IC produces consistent and accurate measurements of temperature over a wide range of temperature. Therefore, an IC system was used as the temperature sensing device for the new sensor.

Other measures have also been taken to improve the accuracy of the temperature measurement. A voltage regulator was used to decrease the variation in power voltage. The signal from the IC was amplified, filtered and isolated to eliminate noise, before being sent to data logging system. A data logging with high resolution was used. By taking these measures, the quality of the output has been significantly improved. A comparison of heating curves measured before and after improvement is presented in Fig. 3.

In order to further increase the accuracy of suction measurement, each sensor is designed to read independently over a period of a few minutes. The entire heating curve (i.e., a series of about 100 readings) were recorded for each measurement instead of just taking one reading (i.e., at end of the heat pulse) as with previous sensors. An equation has been developed to best-fit the heating curve. The parameters obtained from curve fitting procedure are used to calibrate the sensors. By using this procedure, the influence of the fluctuation of the output voltage is eliminated and the accuracy of suction measurement is further increased.



A. Measured heating curve before improvement

B. Measured heating curve after improvement

Figure 3 The heating curves measured before and after improvement.

NEW THERMAL CONDUCTIVITY SENSOR - BETA-97

A new thermal conductivity sensor, called Beta-97, has been developed and is shown in Fig. 4. The sensor consists of a ceramic tip containing a temperature sensor and a heating unit. The ceramic tip was made according to new recipe and has a diameter of 28 mm and a height of 38 mm. An integrated circuit was used as a temperature sensor and a resistor was used as a heating unit. Suitable epoxies have been tested and used as a seal material to ensure suitable thermal conductivity properties and low volume change upon water adsorption.

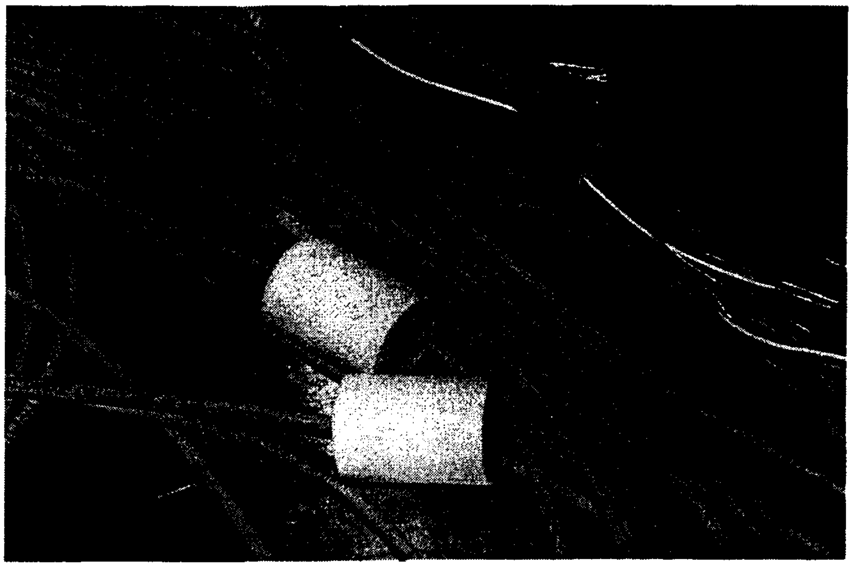


Figure 4 Beta-97 thermal conductivity, matric suction sensor.

The new sensor was found to be relatively sensitive and accurate in measuring matric suctions in the range from 2 to 500 kPa. Its performance has proven to be satisfying to-date. A typical calibration curve of the Beta-97 sensor is shown in Fig. 5. The strength, durability and accuracy of the new thermal conductivity sensor have also been significantly improved over that of previous sensors.

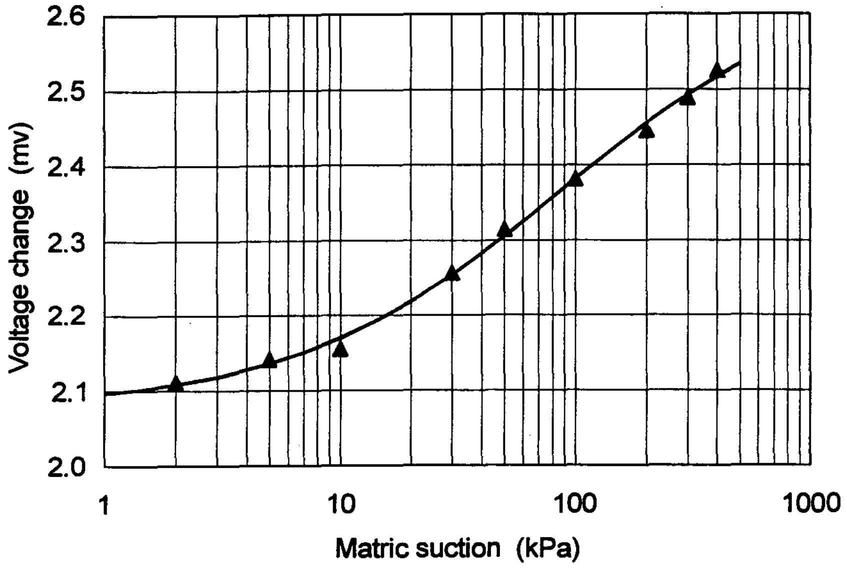


Figure 5 The typical calibration curve for the new sensor.

HYSTERESIS OF THE CERAMIC

The water content versus matric suction curves for a porous material during wetting and drying are generally not the same. The hysteresis in the soil-water characteristics of the ceramic may cause hysteresis in the sensor response on wetting and drying. To-date, little research has been done on the hysteresis associated with the ceramic. As a part of the research program, the study on the ceramic involving the direct measurement of the wetting and drying curves was conducted. Some results are presented in Fig. 6.

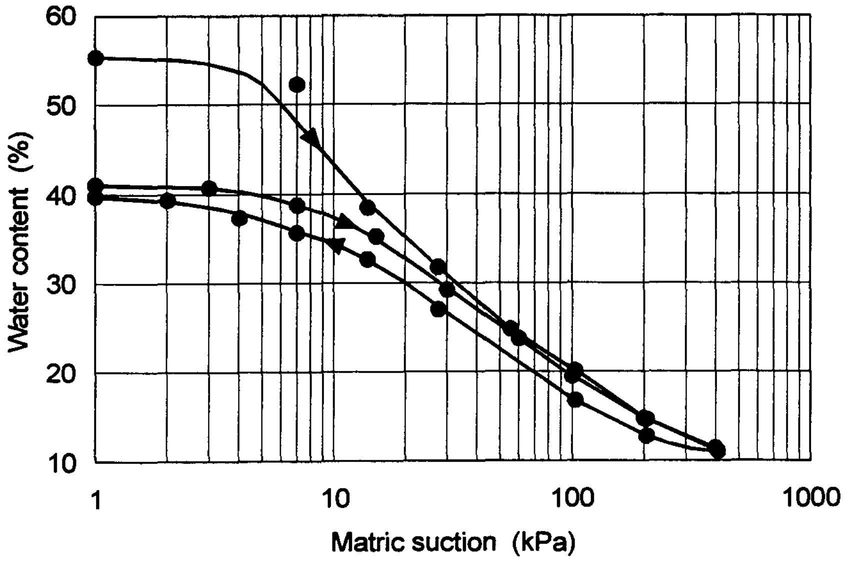


Figure 6 Hysteresis loop in the soil-water characteristic curve of the ceramic.

It was found that there is hysteresis in the soil-water characteristic curve of the ceramic. The hysteresis appears to be most significant when the suction is less than 20 kPa. In some cases, the hysteresis of the ceramic may not be a serious problem when the measured matric suction is greater than 20 kPa. By placing sensors with differing initial water contents into the same soil sample, Fredlund et al (1994) found that the initial dry sensor gave higher matric suction values than initially wet sensor. However, the difference between the two readings was quite small and this inferred that there was limited hysteresis in the ceramic.

When the suction is lower than 20 kPa, there is a significant hysteresis during the first drying and wetting circle. The hysteresis becomes less significant during the second wetting and drying circle. The reason for this may be that the saturation condition was not the same during the first and second drying and wetting circle. At beginning of the test, the sensor was saturated under a vacuum of 80 kPa to ensure 100% degree of saturation. However, at the end of the first drying and wetting circle, the sensor was saturated under 0 kPa matric suction. Since no vacuum or back pressure was applied to the sensor, it is impossible to remove all of the small air bubble isolated inside the ceramic. Therefore, the water content of the ceramic at beginning of the second drying and wetting circle is less than the water content at beginning of the first drying and wetting circle. Further test results indicated that, using the sensor saturated under 0 kPa matric suction, the hysteresis at the first drying and wetting circle was almost the same as the second drying and wetting circle.

The scanning curves between the drying and wetting curve were also measured during the research and is shown in Fig. 7. It is anticipated that a scanning curve model can be used to further improve the interpretation of the sensor data. This model would be used to modify data obtained in practice according to the wetting or drying history of the sensor in order to obtain the greatest accuracy of the suction measurement.

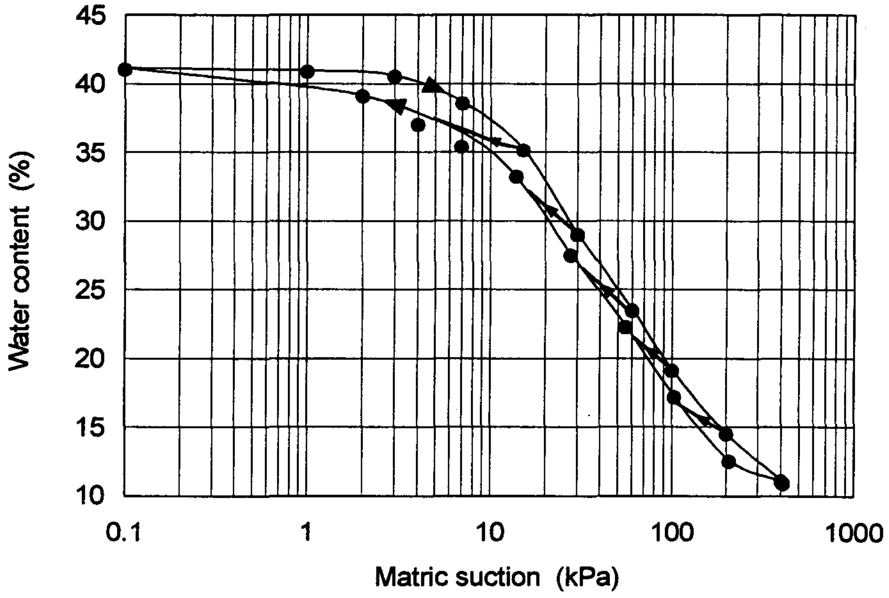


Figure 7 Wetting scanning curves of the ceramic.

CONCLUSION

Currently available thermal conductivity matric suction sensors show promise for application in the dry cover monitoring. At the same time they presently have numerous limitations. In order to develop an inexpensive and reliable soil suction sensor for environmental monitoring, a research program was undertaken. Significant progress has been achieved.

A recipe for a new ceramic tip with a wide range of pore sizes has been determined. The strength, durability and soil-water characteristic of the new ceramic tip have been significantly improved over the previously developed.

The accuracy of new data acquisition system has been increased by using an improved integrated circuit as a temperature sensing device and by taking other electrical measures.

A new thermal conductivity sensor, called Beta-97, has been developed. The new sensor was found to be relatively sensitive and accurate in measuring matric suction in the range from 2 to 500 kPa. Its performance appears to be satisfied and it is expected that this new sensor will perform satisfactorily for environmental monitoring.

The hysteresis of the ceramic was also studied in this program. It was found that hysteresis may not be a problem in interpreting suction data. However, in order to obtain the greatest accuracy, a model for describing the scanning curves between the drying and wetting curves should be used to modify the readings according to the drying or wetting history of the sensor.

The program is still in progress and it is anticipated that further improvements will be achieved in the near future.

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