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THERMAL CONDUCTIVITY SUCTION SENSORS - DESIGN CONSIDERATIONS

CAPTEURS A ASPIRATION POUR LA MESURE DE CONDUCTIVITE THERMIQUE - REFLECTIONS SUR LEUR CONCEPTION

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SYNOPSIS : Thermal conductivity type sensors have become quite common for the measurement of matric suction. Difficulties and shortcomings have become quite apparent with presently available thermal conductivity matric suction sensors. The ceramic tip is the single most crucial component of the thermal conductivity matric suction sensor. The requirements of the ceramic for reasonable accuracy over a wide range of matric suctions are examined and discussed from a theoretical standpoint, based on the capillary model. Other design aspects of importance in the construction of these sensors are also discussed in this paper.

INTRODUCTION

The role of matric suction in describing the behavior of unsaturated soil has now been firmly established. The techniques for measuring negative pore-water pressure (matric suction), however, lags far behind. It would be highly desirable to be able to directly measure negative pore-water pressure. There are, however, many difficulties associated with the direct measurement of the negative pore-water pressure, particularly in the range lower than -1 atmosphere. This has provided impetus to examining techniques which use an indirect method of measurement.

One of the more common methods used in recent years for the indirect measurement of matric suction is the use of thermal conductivity matric suction sensors (Fredlund, 1992). This method uses a measurement of the thermal conductivity of a standard ceramic stone. The ceramic stone is correlated with the matric suction of the ceramic which is in equilibrium with the surrounding soil. This method appears promising and this paper outlines some of the design aspects which should be given consideration.

There have been numerous difficulties and shortcomings experienced with the present commercially available thermal conductivity matric suction sensors. These difficulties and shortcomings can be broadly identified as: 1.) high cost of the sensors, 2.) high cost of calibrating the sensors, 3.) inaccuracies associated with portions of the suction range, and 4.) low strength and poor durability of the ceramic tip.

The cost of purchasing and calibrating the sensors is an important consideration since considerably more sensors are required when monitoring the movement of water above the ground water table. While a few piezometers can generally assess the positive groundwater conditions at site, the region above the groundwater is more dynamic since it interacts with the local microclimatic changes. Consequently, it may be necessary to have about three or more times as many sensors installed to fully characterize changes in the stress state. It is, therefore, essential that the cost of each thermal conductivity matric suction sensor be kept to a minimum while their reliability and accuracy be kept reasonably high.

GENERAL CHARACTERISTICS OF A THERMAL CONDUCTIVITY MATRIC SUCTION SENSOR

The primary components of thermal conductivity matric suction sensors are shown in Figure 1. Each component of this sensor requires in-depth research in order to produce a reliable and economical sensor. This paper will address but a few of these design considerations.

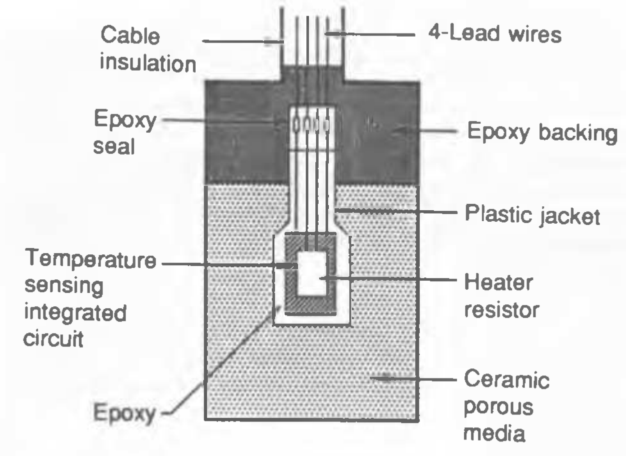

Fig. 1. A cross-sectional diagram of a thermal conductivity matric suction sensor showing its key components.

The sensor measures the thermal conductivity of a ceramic tip. The ceramic tip is in contact with the soil and has a water content dependent upon the suction in the soil. The thermal conductivity of the ceramic tip changes with the water content of the ceramic since the water has a much higher thermal conductivity than air. At a temperature of 20 °C at 1 atmospheric pressure, water has a thermal conductivity of 0.6 W/m K as compared to a value of 0.026 W/m K for air. Through a calibration process (Fredlund and Wong, 1989), the thermal conductivity of the ceramic can be correlated with the field matric suctions.

THEORETICAL DESIGN CONDISERATIONS OF THE CERAMIC

The maximum pore size which can be sustained at a specified matric suction is classically defined using Lord Kelvin's equation.

$$u_a - u_w = 2\frac{T_s}{r}\cos\alpha \qquad [1]$$

where T_s = surface tension (i.e., 72.75 x 10^{-3} N/m), r = radius of pore (m), α = contact angle (assume equal to zero).

For example, ceramic stone with nominal pore radius distribution of 2.9×10^{-3} mm would desaturate at a suction of 50 kPa.

Soil suctions can vary over a range of 7 orders of magnitude going from 0 kPa at its lowest value, and approaching 1 million kPa as zero water content is approached. Theoretically, the pore size distribution for a sensor should vary from having infinitely large pores to pores with a radius of 1.455 x 10^{-7} mm at 1 million kPa matric suction. The theoretical relationship between the pore radius and matric suction over a suction range of 0.1 kPa to 10000 kPa is shown in Figure 2. At the same time it must be recognised that the suctions commonly encountered in practice usually range from zero suction to about 1000 kPa.

As a result of the extremely wide range of possible soil suctions, it is necessary to design a sensor for a specific matric suction range. For example, for a sensor to be designed for the range of 10 kPa to 400 kPa the pore radius in the ceramic would have to vary from 1.455 x 10^{-2} mm to 3.638 x 10^{-4} mm according to Eq. 1. To ensure the best accuracy in the measurement, the sensor should have a linear relationship between matric suction and thermal conductivity. This is only possible if the sensor has a continously varying distribution of pore sizes, where the volumes corresponding to each and every pore size are the same. Materials with this characteristic will have a linear soil-water characteristic relationship similar to curves A, B, and C shown in Figure 3.

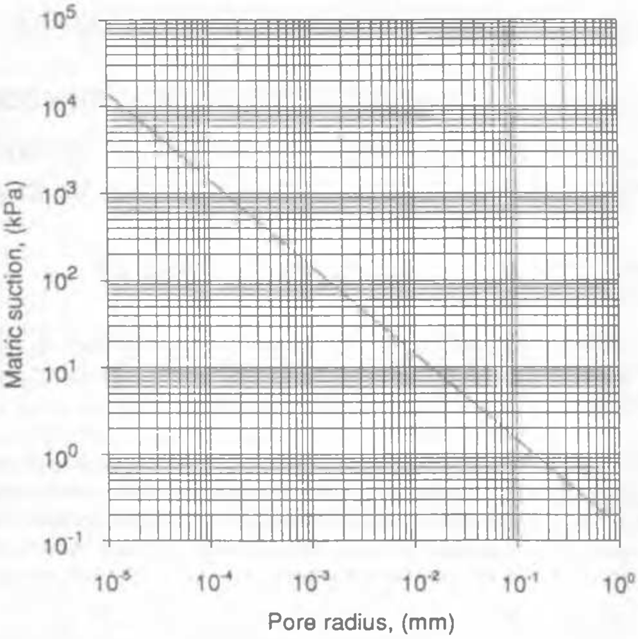

Fig. 2. Relationship between limiting pore radius and matric suction.

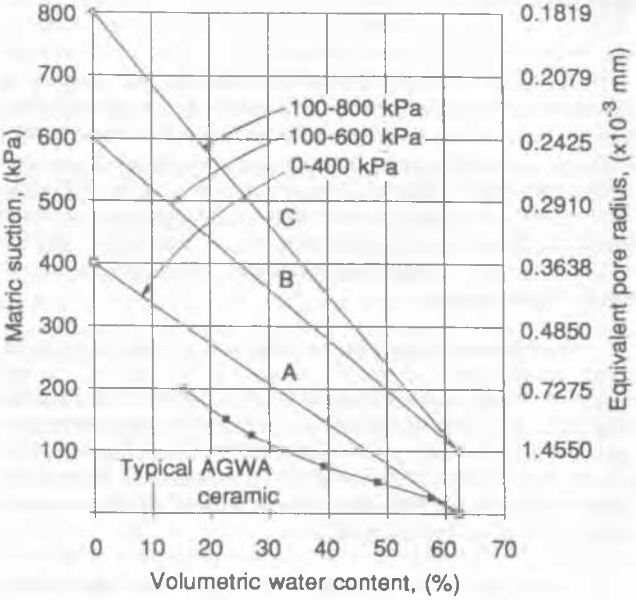

Fig. 3. Ideal water content characteristic curves of ceramic material with linear volumetric water content and matric suction relationship.

TYPICAL PORE SIZE DISTRTIBUTIONS

Ceramic engineers are commonly called upon to produce a ceramic with specific strength or hardness characteristics. The ceramic produced usually has a narrow range of pore size distribution. In other words, it is unusual to request that the ceramic should have a wide range of pore sizes.

One of the laboratory experiments which can be performed to assess the pore size distribution of a ceramic is the measurement of the water content of the ceramic versus the applied matric suction. In other words, it is the water content characteristic curve of the material. Ceramics manufactured for use as high air entry disks are often thought of as having one predominant pore size. For example, a 2 bar ceramic would be assumed to have relatively uniform pore radii of 7.275 x 10^{-4} mm, in agreement with Eq. 1. This is, however, not the case and experiments on high air entry disks show that there is a range of pore sizes. Figure 4 shows the water content versus matric suction relationships for several ceramics manufactured by Soilmoisture Equipment Corporation, U.S.A. It can be seen from this data that the 2 bar or the 3 bar SF (Standard flow) ceramic, for example, could be used in the indirect measurement of matric suction over the range from about 700 kPa to over 1000 kPa. In other words, this is the range over which the ceramic desaturates. This ceramic would not be good for matric suction measurement in the range from 0 kPa to about 700 kPa as there is little change in the water content with matric suction over this range. On the other hand, the 1 bar ceramic appear to commence desaturation at matric suctions greater than 100 kPa and continue to desaturate up to about 400 kPa and would be suitable for matric suction measurement in the range of 100 kPa to 400 kPa.

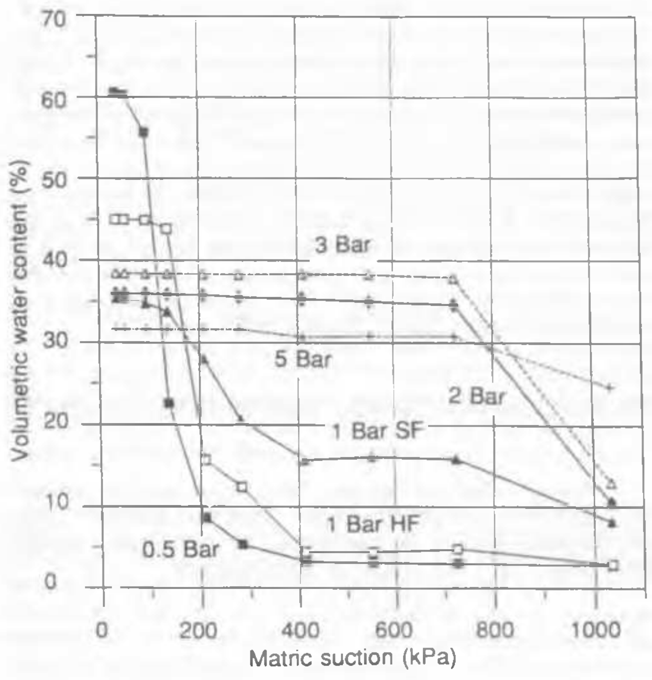

Fig. 4. Water content characteristic curves for several ceramics from Soilmoisture Equipment Corporation, USA.

Ceramics manufactured by Agwatronics, Inc. U.S.A., specifically for use as thermal conductivity matric sensors, have a relatively wide range of pore size distribution. A typical water content characteristic curves for their ceramic was shown in Figure 2. It can be seen that there is an upper limit and a lower limit for the range over which matric suction can be measured.

Mercury injection tests have also been performed on the ceramics from Agwatronics Inc., U.S.A. The results show the relative amount of each pore size present (Figure 5). The differential pore volume distribution for the two ceramics are presented in Figure 6. Figure 6 shows that the pore size distribution is bimodal, with peaks occurring at 7 x 10^{-4} mm and 5 x 10^{-5} mm pore diameters. It is important to note that a considerable number of the pores must be in the smaller diameter range in order to ensure accuracy in the thermal conductivity measurement for higher matric suctions.

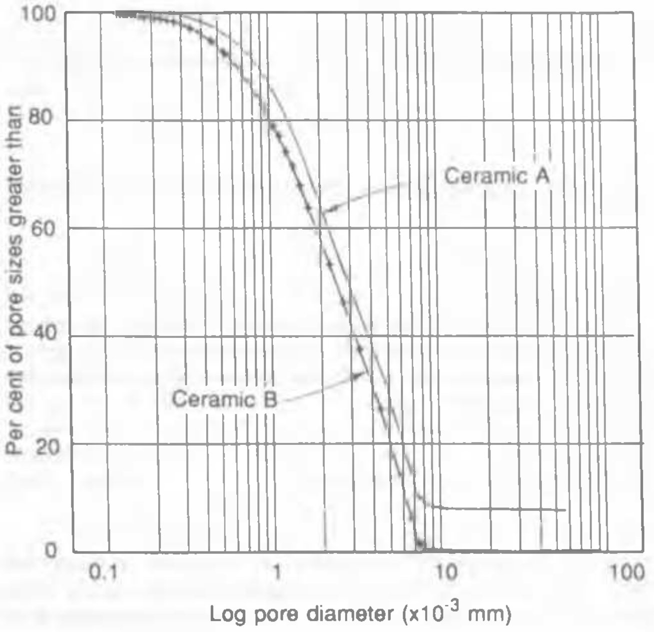

Fig. 5. Porosity distribution curves for two AGWA-II ceramic tips.

OTHER CHARACTERISTICS OF THE CERAMIC

The ceramic must have high strength characteristics for use in geotechnical applications. In general, ceramics manufactured with a narrow range in pore size distribution have high strength characteristics whereas those with a wide pore size distribution have been found to be soft, friable, and of insufficient strength. In addition, some materials have been found to soften with the time they are in the soil, reverting to a crumbly material. It is necessary to be able to force the sensor into the soil to ensure good contact, and at the same time not have to be concerned about breakage of the ceramic.

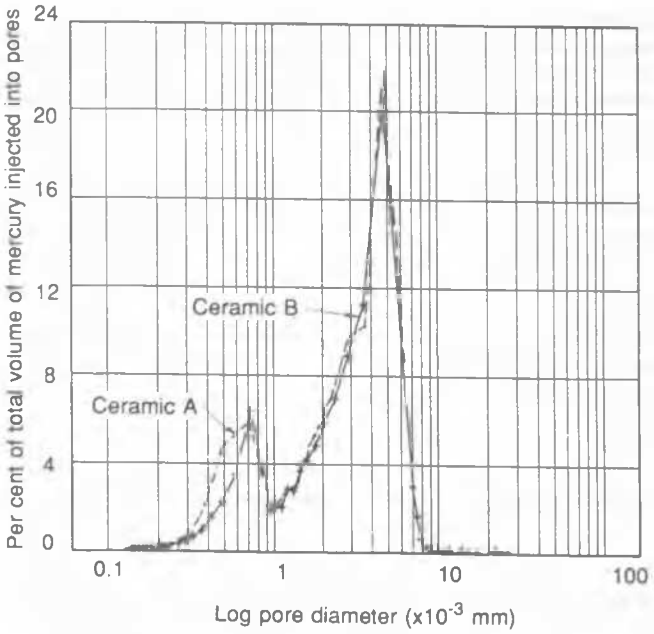

Fig. 6. Differential pore volume distribution curves for two AGWA-II ceramic tips.

The ceramic must be durable in order to withstand the freeze-thaw cycles in harsh environments. Experience to date has shown that at least 30% of the low strength ceramic sensors malfunction after one season of freeze-thaw cycles.

HYSTERESIS OF THE CERAMIC

The water content versus matric suction curves for a porous material, during wetting and drying, are generally not the same. Little research has been done to-date on the hysteresis associated with ceramics. There is, however, indirect evidence that hysteresis may not be a serious problem. For example, thermal conductivity matric suction sensors with differing initial water contents, have been inserted in a soil sample and been found to produce essentially the same matric suction reading (Figure 7). The initially dry sensor has been found to produce slightly higher matric suction values than the initially wet sensor (Sattler and Fredlund, 1989). This is as would be anticipated. However, the difference between the two readings has been found to be quite small and this would infer that there is limited hysteresis in the ceramic. Further research on ceramics should involve the direct measurement of the wetting and drying curves.

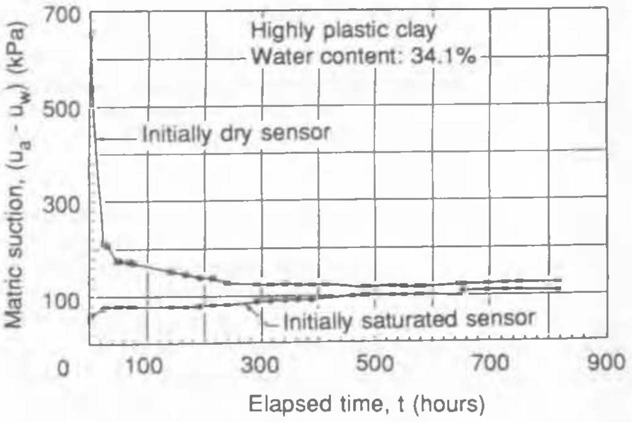

Fig. 7. Laboratory measurements of matric suctions on a highly plastic clay from Sceptre, Saskatchewan, Canada, using an initially saturated sensor and an initially dry sensor.

CHARACTERISTICS OF THE HEATING SOURCE

Generally a 1 kΩ resistor has been used as a heating element. It is possible to have one or more of these heating elements in a sensor. However, the zone of thermal influence changes with the size of heating source. The influence of the heating source must be kept within the ceramic, for the period of temperature change measurement.

When the zone of heating influence goes beyond the ceramic, the surrounding material will influence the thermal conductivity measurement. This, in turn, will influence the measured matric suction value. Figure 8 shows changes in the calibration curves for a sensor surrounded first by soil and secondly, by air. The second sensor made contact with the ceramic disk only at the end of the tip of the sensor. The end of the tip of this sensor was smeared with a layer of soil to ensure good contact with the ceramic disk. The results show that for this sensor the ceramic tip is not sufficiently large to fully contain the heat pulse. The solution is to either increase the size of the tip or to reduce the heat pulse, or to do a combination of both. The variables related to the heater design involve i) the thermal output of heater, ii) the duration of heating, and iii) the size of the ceramic.

CHARACTERISTICS OF THE TEMPERATURE SENSORS

Several electronic devices have been used to measure temperature changes inside the ceramic. These have involved IC chips (i.e., integrated circuits), thermocouples, and thermistors. Each of these systems has its advantages and disadvantages.

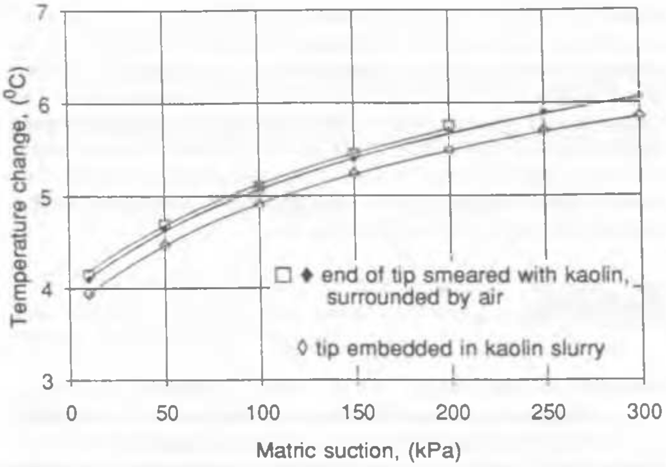

Fig. 8. Sensor response curves when fully embedded in kaolin and when surrounded by air.

Integrated circuit temperature sensors (IC) are available both in voltage and current output configurations. The output from the IC sensor is linearly proportional to absolute temperature. Typical sensitivities are 1 μA/K and 10 mV/K for the current and voltage sensor, respectively. This sensitivity is relatively high and as such makes them preferable for use in sensor design. On the other hand, their functionality is dependent upon the electronics being maintained completely dry. If moisture vapor slowly diffuses into the electronics, the temperature sensor malfunctions. This has been found to be the main cause of sensor malfunction while making suction measurements insitu. If the pore-water pressure in the soil approaches zero or becomes positive, the life expectancy of the sensor has been found to be greatly decreased (Wong et al, 1989). The use of the IC system for temperature measurement should also involve the design of a protective system to ensure that moisture does not reach the electronics.

T-type thermocouples have a sensitivity of 40 μV/°C. This sensitivity is considerably lower than that of the IC sensors. The advantage of using thermocouple sensors is their ruggedness and stability with time.

Thermistors are also compact in size and can be used for temperature measurement in the sensor. Thermistors, unlike the other systems of temperature measurement, are nonlinear in their response and as such require greater complexity in the readout or data acquisition system. To-date, little use has been made of thermistors as a temperature sensor in thermal conductivity, matric suction devices.

In order to obtain the greatest accuracy in measuring thermal conductivity, it is important to consider the entire temperature response curve during the heating and cooling periods. The continuous response from an IC sensor is shown in Figure 9. The heater was activated for one minute. During this time the temperature increases in a nonlinear manner. The temperature decreases quite rapidly subsequent to the heater being switched off. Generally, the voltage reading (or the temperature change reading) at the end of the 1 minute heat pulse is used, (i.e., 85 μV or 2.125 °C, respectively), as an indication of thermal conductivity. However, it is the study of the entire heating and cooling responses which could provide a more accurate understanding of the thermal conductivity of the sensor.

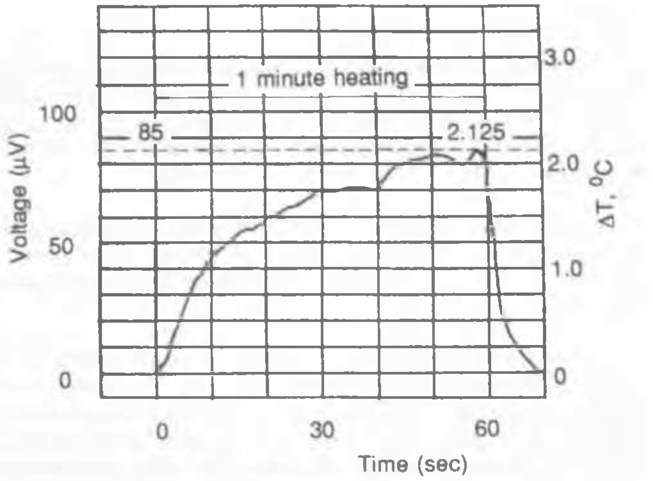

Fig. 9. Typical voltage output from an AGWA sensor which uses an IC type temperature sensing device.

CHARACTERISTICS OF DATA ACQUISITION SYSTEMS

Numerous data acquisition systems can be purchased as "off-the-shelf" items and used to read the thermal conductivity matric suction sensors. Generally these systems can simultaneously read 8 to 32 sensors. The procedure has been to first scan all the sensors and obtain initial temperature readings. The heating pulse is then applied for all the sensors. At a specified elapsed time, a second set of temperature readings is taken and referenced back to the first readings. This gives an indication of the thermal conductivity and thereby, the matric suctions.

Each of the sensors draws a significant current during the heating process and as such it may be better to change the manner in which data is acquired from the sensors. Since readings do not have to be obtained at small intervals of time, it may be superior to read each sensor individually. In this way, the current applied to the sensor during the heating process can be controlled more accurately. If this procedure is used it may be necessary to design and build specialized, but greatly simplified, data acquisition equipment for reading the sensors.

CHARACTERISTICS OF THE SEALANT

The heater and temperature sensing device along with the associated wires must be sealed inside the ceramic using a suitable epoxy. The epoxy should have as high a thermal conductivity as possible. This is usually accomplished using an epoxy with a metallic base.

The sealant must also have a low diffusivity with respect to moisture movement. It may also be necessary to encapsulate the electronics in a special material in order to minimize moisture movement into the electronics.

SUMMARY

Currently available thermal conductivity matric suction sensors show promise for application in the area of unsaturated soil mechanics. At the same time they presently have numerous limitations. The ceramic tip is weak, with poor durability and reasonable accuracy can be obtained only over a narrow matric suction range.

Theoretical considerations would show that a continous pore size distribution with increasingly higher proportions of the smaller pore sizes are required to obtain a linear relationship between water content and matric suction.

The ceramic required for the thermal conductivity sensor is the single most problematic aspect related to the design of the sensor. High strength is essential for handling and installation. High porosity ceramics with a wide range of pore sizes are necessary to obtain a substantial matric suction range and accuracy. However, at the present time high strength ceramics are only available with fairly uniform (or a narrow range) pore sizes.

Research to-date has shown that there is good potential for the development of a reliable and accurate thermal conductivity matric suction sensor. At the present time, it is obvious that further research and development is necessary in order to produce the best possible sensor.

In the region above the groundwater table it may be necessary to have a considerable number of sensors to fully characterize changes in pore-water pressure. The pore-water pressure conditions in the unsaturated zone are more variable due to the variability in the properties of the soil and due to the effects of the microclimate. The implications of this rationale are that the cost of each suction sensor must be kept to a minimum. At present, both the cost of manufacturing the sensors and the cost of calibrating the sensors are too high. Further research should address both the production and calibration with the aim that the unit sensor costs be reduced.

REFERENCES

Fredlund D.G. and Wong, D.K.H. (1989). Calibration of Thermal Conductivity Sensors for Measuring Soil Suction. *Geotechnical Testing Journal*, GTJODJ, Vol. 12, No. 3, pp. 188-194.

Fredlund, D.G. (1992). Background, Theory, and Research Related to the Use of Thermal Conductivity Sensors for Matric Suction Measurement. *Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice*. SSSA Special Publication No. 30, pp. 249-261.

Wong, D.K.H., Fredlund, D.G., Imre, E. and Putz, G. (1989). Evaluation of AGWA-II Thermal Conductivity Sensors for Soil Suction Measurement. *Transportation Research Board*, National Research Council, Washington, D.C., pp. 131-143.

Sattler, P. and Fredlund, D.G. (1989). Use of Thermal Conductivity Sensors to Measure Matric Suction in the Laboratory. *Canadian Geotechnical Journal*, Vol. 26, No. 3, pp. 491-498.