1994

Design and Data Acquisition for Thermal Conductivity Matric Suction Sensors

J. K.-M. GAN, D. G. FREDLUND, A. XING, AND W.-X. LI

The principles behind using the thermal conductivity sensor for an indirect measurement of matric suction are described. The factors controlling the thermal conductivity of the sensor are discussed. The requirements of the sensor for the measurement of matric suction in soils are examined from a theoretical standpoint by using the capillary model and a heat flow model. The current methods for the calibration of the sensors and the evaluation of the sensors' outputs are described. Alternative methods for the calibration of the sensors and the evaluation of the sensors' outputs are suggested in an attempt to determine a better way to evaluate the data. The data acquisition and the related electronics necessary for field monitoring of the matric suction sensors are discussed.

The role of matric suction in the behavior of unsaturated soil is now well understood (*1*). As a result, the need for reliable matric suction measurements is becoming increasingly important. To date there are no simple, accurate, and reliable methods of measuring matric suctions above 1 atm. In many of the applications in engineering, matric suctions above 1 atm are common. The filter paper method and the psychrometer method have been used in the past. Both are indirect methods that measure total suctions rather than matric suction. It is matric suction, however, that is most important in quantifying the mechanical behavior of the soils.

The concept of using the thermal conductivity of a standard ceramic as an indirect measurement of matric suction is attractive. The physics involved is readily comprehended; however, the performance of the sensor has thus far been disappointing. Various difficulties and shortcomings have become apparent as a result of increased usage in the field (*2,3*). The development of the thermal conductivity sensors for the measurement of matric suction has been presented elsewhere (*4*).

Details of the ceramic design are important when using thermal conductivity matric suction sensors. Strength, durability, and reasonable accuracy over a wide range of suctions are the basic requirements of the sensors. Presently available ceramics with high strengths have uniform pore size distributions. Theoretical design considerations based on the capillary model show that there is need for a continuously varying pore size distribution to measure matric suctions over a wide range. The challenge is to fabricate a high-strength ceramic with continuously varying pore sizes. The requirements of the thermal conductivity matric suction sensor are also examined from a heat flow perspective to investigate such issues as the optimum size of the ceramic tip, the duration of heating, and the rate of heating.

The attractiveness of the thermal conductivity matric suction sensors lies primarily in their field application. Data application possibilities provide for the continuous and remote monitoring of matric suction. Applications can be made in remote areas with a battery power supply. Data acquisition systems with automatic control and large storage memories are possible. The electronics associated with the sensors and the data acquisition system are important aspects in the proper usage of the thermal conductivity matric suction sensors for suction measurements.

PRINCIPLE OF OPERATION

The components of the thermal conductivity matric suction sensors are shown in Figure 1. The key component of the sensor is the ceramic. The ceramic has unique water retention characteristics that are a function of its pore size distribution. When the ceramic is placed in contact with soil, water will move between the soil and the ceramic until the matric suction in the ceramic equalizes with the matric suction in the soil. The matric suction in the soil will determine the water content of the ceramic at equilibrium, in accordance with the unique water retention characteristics of the ceramic.

The variables controlling the changes in the thermal conductivity of the sensor are its air and water contents. Air is a poor conductor of heat. Under atmospheric conditions and a temperature of 20°C, air has a thermal conductivity of 0.026 W/m K. Water, on the other hand, has a thermal conductivity of 0.6 W/m K, about 23 times greater than the thermal conductivity of air (*5*). Thus, the changes in the thermal conductivity of the sensor are a function of the changes in the water content of the ceramic. Through a calibration process, the matric suction of the ceramic can be correlated with the thermal conductivity of the ceramic. The thermal conductivity of the ceramic is reflected in the temperature rise of the ceramic when a precise heat pulse is applied.

The current practice when using thermal conductivity matric suction sensors consists of the following process. An initial reference temperature is taken. This is followed immediately by applying a precise heat pulse for 60 sec. The heat pulse is generated by applying a constant voltage of 10 V to the heating element inside the sensor. At the end of the 60-sec heating period the power supply is removed and a second temperature reading is taken.

The temperature rise at the end of the heating period is the net result of the heat supplied and the heat that is dissipated during the 60-sec heating period. The heat supplied is a constant quantity. It is controlled by the electrical power that is supplied and by the duration over which the electrical power is supplied. The heat

---

J. K.-M. Gan, D. G. Fredlund, and A. Xing, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 0W0. W.-X. Li, Department of Hydraulic Engineering, Tsinghua University, Beijing, People's Republic of China 100084.

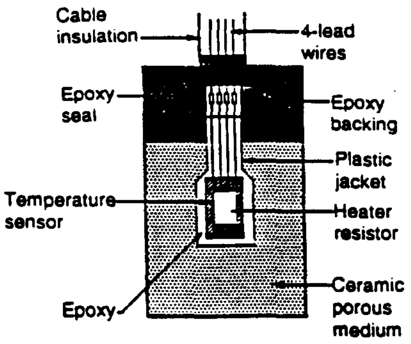

FIGURE 1 Components of a thermal conductivity matric suction sensor.

dissipated is dependent on the thermal conductivity of the ceramic. The thermal conductivity of the ceramic is a function of its water content. The water content of the ceramic is controlled by the matric suction of the soil in which the sensor is buried. Consequently, a relationship between the temperature rise in the sensor and the matric suction of the soil can be established.

DESIGN CONSIDERATIONS OF THE CERAMIC

It is desirable that the ceramic of the thermal conductivity matric suction sensor be of high porosity to obtain large changes in the water content of the ceramic with varying matric suctions. The accuracy of the measurements increases with an increase in the porosity of the ceramic. Previous commercially available sensors had a porosity of about 70 percent. The calibrations obtained for some of these sensors are shown in Figure 2. The calibrations shown in Figure 2 show that the relationships between the rise in temperature due to the 60-sec heat pulse and the matric suction of the soil are nonlinear.

The maximum change in temperature over a matric suction range of 300 kPa was about 2°C to 2.5°C for some recent, commercially available sensors with 320-Ω heating elements operating with a 60-sec heat pulse supplied by a 10-V power source. Older model sensors have 1000-Ω heating elements. Tests have been conducted to investigate the maximum change in temperature obtainable by using different electrical power inputs. These tests were performed on sensors subjected to two extreme conditions: at saturation (i.e., matric suction equal to zero) and in the completely dry condition (i.e., corresponding to maximum suction in

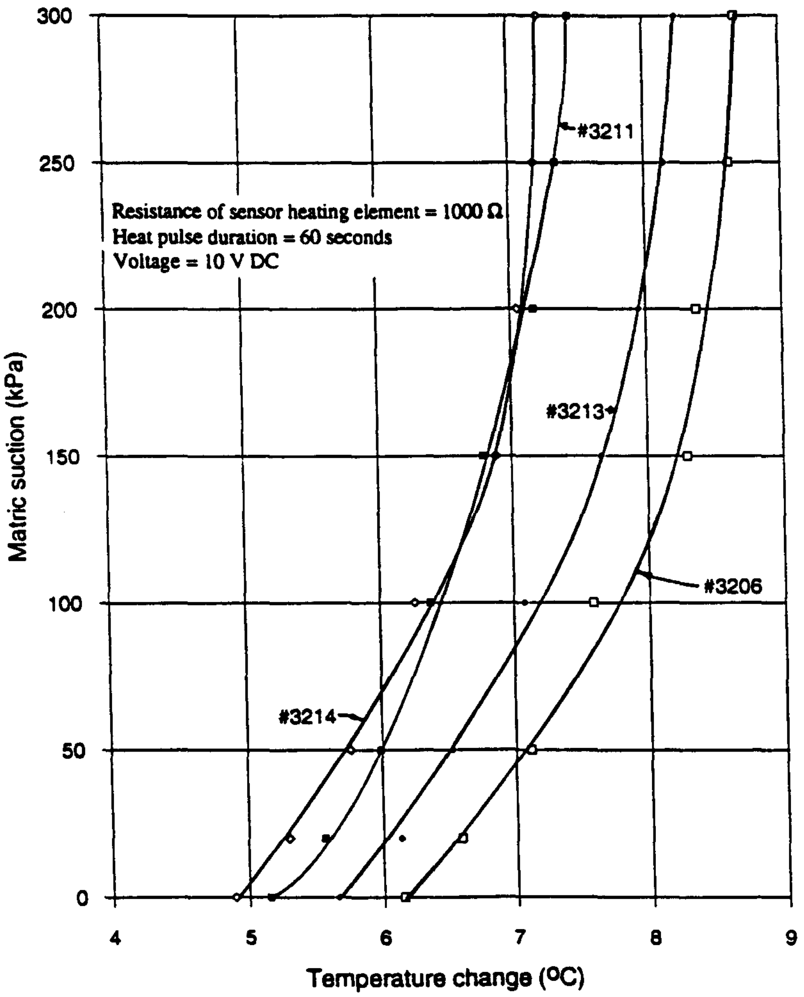

FIGURE 2 Calibration curves of some thermal conductivity matric suction sensors plotted as a function of matric suction versus change in temperature.

excess of 500 kPa). The results are presented in Figure 3. The results show that for an electrical power input of 10 V, the maximum difference in temperature between the two extreme conditions is about 2.75°C. This maximum difference in temperature is increased to 3.75°C if the electrical power input is increased to 12 V.

It is desirable that the ceramic have a continuously varying pore size distribution to cover a wide range of matric suctions. The maximum pore size that can be sustained without draining the ceramic at a specified matric suction is defined as follows.

$$u_a - u_w = 2 \frac{T_s}{r} \cos \alpha \tag{1}$$

where

u_a = pore air pressure,
u_w = pore water pressure,
T_s = surface tension of water (i.e., 72.75×10^{-3} N/m),
r = radius of pore (m), and
α = contact angle between the water and the pore material (usually assumed to be equal to zero).

The theoretical relationship between pore radius and the matric suction obtained from Equation 1, over the range of 0.1 to 10 000 kPa is shown in Figure 4. The corresponding pore radii vary from 1 mm down to 1×10^{-5} mm (i.e., both variables extend over a range of five orders of magnitude). The range of matric suctions of most common interest to geotechnical engineers is from 0 to 1000 kPa. The corresponding variation of pore size distribution would range from 1 mm down to 1×10^{-4} mm, a span of over four orders of magnitude.

The conditions of a high-porosity and a continuously varying pore size distribution are required to ensure accuracy and range. These aspects make it difficult to obtain a high-strength ceramic. A high-strength ceramic is typically of low porosity with uniform pore sizes. To avoid compromising on the strength of the ceramic, it is necessary to design a sensor for a specific matric suction range. For example, a sensor designed for a matric suction range of 100 to 400 kPa would have pore radii varying from 1.455×10^{-3} to 3.638×10^{-4} mm according to Equation 1.

It is desirable to have a linear relationship between matric suction and thermal conductivity to ensure accuracy in the measurement of suction. A linear relationship between matric suction and thermal conductivity is possible if the sensor has a continuously varying pore size distribution in which the volumes corresponding to every pore size are equal. Materials meeting this requirement will have a linear water retention characteristic relationship similar to Relationships A, B, and C shown in Figure 5. A typical water retention characteristic relationship for the ceramic from an AGWA-II sensor (*6*) is also shown in Figure 5 for comparison. The calibrations obtained so far have also shown that the matric suction versus temperature change relationship for the AGWA-II sensors is nonlinear (Figure 2).

THEORY OF HEAT FLOW

The thermal conductivity matric suction sensor should be as small as possible to expedite the moisture equilibration process between the sensor and the soil. However, the ceramic portion of the sensor must be sufficiently large to fully contain the applied heat pulse. Otherwise, the sensor reading will be influenced by the thermal

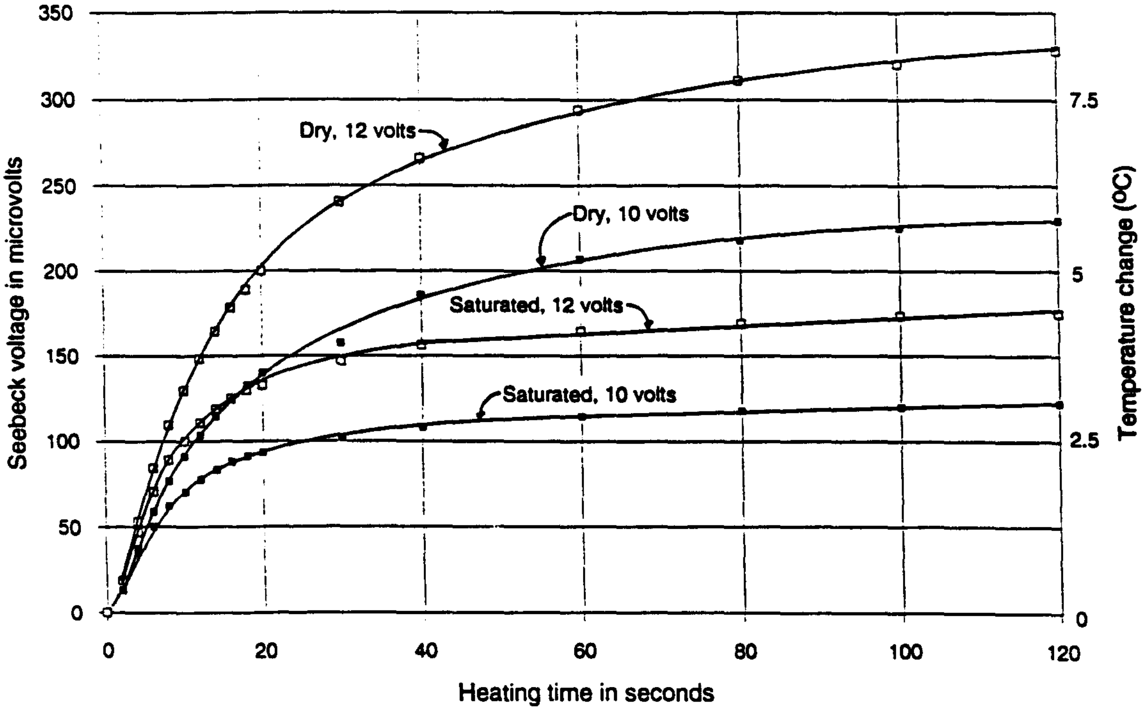

FIGURE 3 Seebeck voltage measured with time for a sensor in a saturated state and in a dry state heated at a 10- and a 12-V supply.

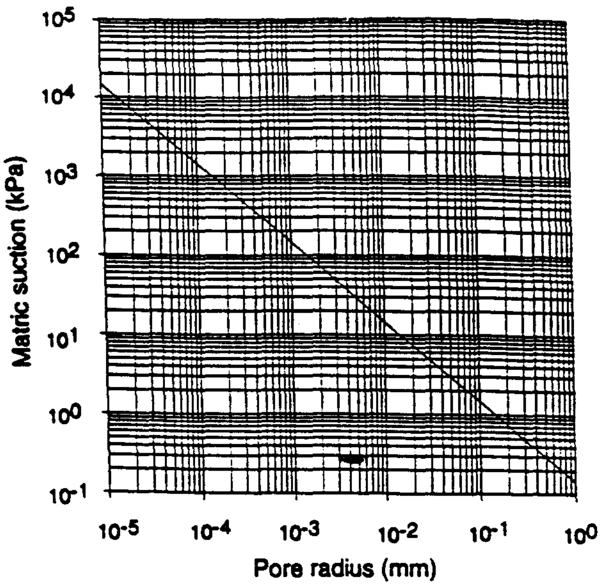

FIGURE 4 Relationship between pore radius and matric suction.

properties of both the soil and the sensor. If this is the case, the calibration obtained for the sensor will not be unique but will vary with the medium in which the sensor is buried. Calibration tests have been conducted using a commercially available sensor that has a diameter of 23 mm. The sensor was first calibrated with the 'or buried in a kaolin paste. The same sensor was then cali- .d with the sensor surrounded by air while only the end of the sensor was in contact with the high air entry disk via a thin layer of kaolin. The results from these calibrations are presented in Figure 6. The results indicate that the size of the sensor does not appear to be adequate. The calibrations obtained with the sensor surrounded by air consistently recorded a higher temperature rise than those obtained when the same sensor was buried in a kaolin paste.

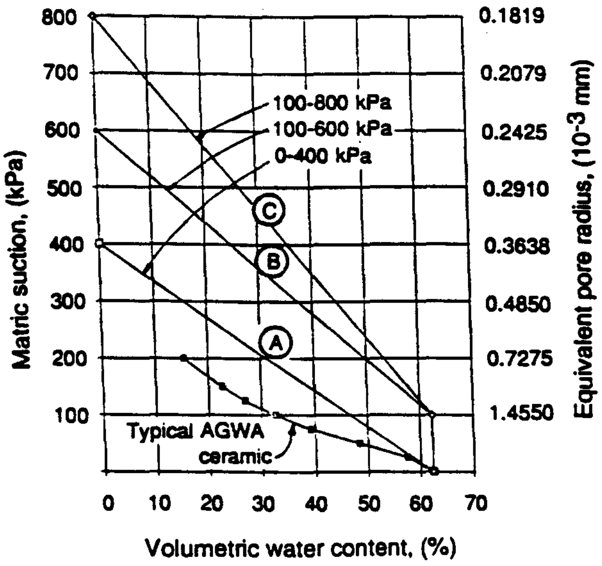

FIGURE 5 Ideal water content characteristic relationship of ceramics [actual water content characteristic relationship from an AGWA sensor (*6*) is shown for comparison].

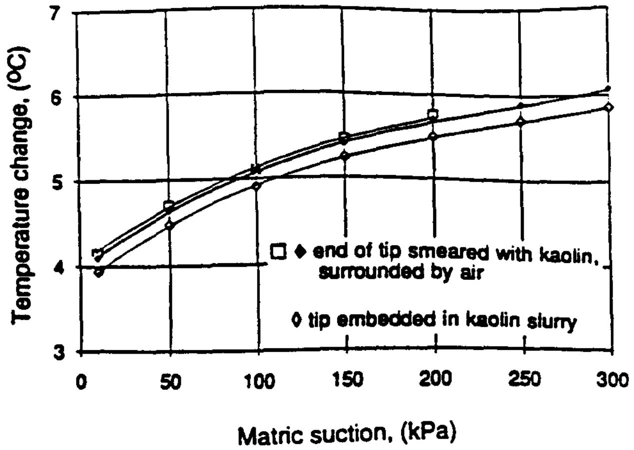

FIGURE 6 Calibration curves of a sensor when fully embedded in kaolin and when surrounded by air.

An infinite sphere (Figure 7) with a radius r ($0 < r < \infty$) can be used as a model to determine the optimal size of the sensor for a fixed heating rate and a fixed heating period. The heater has a radius r equal to a. The heater is assumed to be made of copper. The porous ceramic is assumed to be saturated with water. The thermal conductivity of the porous ceramic is at a maximum when the porous ceramic is saturated. This is the most critical case in the consideration of the optimal radius required to completely contain the applied heat pulse.

The variable $v(t, r)$ denotes the temperature in the sphere at time t and radius r. An initial temperature of zero is assumed for the theoretical study. That is, $v(0, r)$ is equal to 0 for $0 < r < \infty$. When heat is generated at the center of the sphere for a period of time t_p, there will be a temperature rise in the area near the center of the sphere [i.e., $v(t_p, r) > 0$ for small values of r] and the temperature, $v(t_p, r)$, eventually becomes 0 as r increases. Since radial heat flow is being considered, there exists a radius R beyond which the temperature rise is less than a given error tolerance. The radius R beyond which the temperature rise is less than the

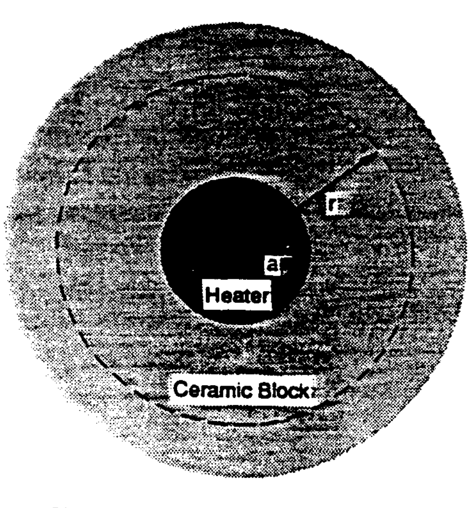

FIGURE 7 Spherical model used for the heat flow analysis.

given error tolerance can be called the optimal radius. Any point with $r > R$ is then considered not to be affected by the heat pulse.

The radial heat conduction equation in an infinite medium, when expressed in spherical coordinates, is (7)

$$\frac{\partial v}{\partial t} = k\left(\frac{\partial^2 v}{\partial r^2} + \frac{2}{r}\frac{\partial v}{\partial r}\right) \tag{2}$$

where $v = v(t, r)$ is the temperature in degrees celsius and k is the thermal diffusivity (cm²/sec) of the saturated porous medium. Since the thermal conductivity of copper is much higher than that of the ceramic medium, it is assumed that the inner sphere (i.e., $0 < r < a$) acts like a perfect conductor. It is also assumed that there is no contact resistance between the heater and the ceramic (i.e., at $r = a$). Some of the heat generated within the inner sphere is dissipated. The undissipated heat will result in a temperature rise in the inner sphere. Let Q denote the heating rate (cal/sec) generated in the inner sphere. The boundary condition at r equal to a is given as follows:

$$Q = \frac{4}{3}\pi a^3 \rho c \frac{\partial v}{\partial t} - 4\pi a^2 K \frac{\partial v}{\partial r} \tag{3}$$

where

K = thermal conductivity of the porous medium (cal/sec-cm-°C),
ρ = density of copper (g/cm³), and
c = specific heat of copper (cal/g-°C).

The first term on the right side of Equation 3 accounts for the contribution to the heat balance owing to the heater, which is also the inner sphere in the model. The second term of Equation 3 accounts for the heat that is dissipated in the porous medium.

Solving Equation 2 using an explicit finite difference method gives

$$v_{i+1,j} = v_{i,j} + \frac{k\Delta t}{\Delta r^2}\left[v_{i,j+1} - 2v_{i,j} + v_{i,j-1} + \frac{2}{a/\Delta r + j}(v_{i,j} - v_{i,j-1})\right]$$

$$i = 0, 1, 2, \ldots \qquad j = 1, 2, \ldots \tag{4}$$

where Δt is the length of the time step and Δr is the length of the radius step. From the boundary condition, Equation 3, it follows that

$$v_{i+1,0} = \frac{\Delta r \Delta t Q}{\lambda} + \frac{\frac{4}{3}\pi a^3 \rho c \Delta r}{\lambda} v_{i,0} + \frac{4\pi a^2 K \Delta t}{\lambda} v_{i+1,1}$$

$$i = 0, 1, 2, \ldots \tag{5}$$

where

$$\lambda = \frac{4}{3}\pi a^3 \rho c \Delta r + 4\pi a^2 K \Delta t$$

If the thermal conductivity K is not a function of temperature, the solution obtained is not affected by the initial boundary condition. If the thermal conductivity K is a function of the temperature, the solution will vary with the choice of the initial boundary condition. As a result, a thermal conductivity suction sensor would not have a unique calibration relationship. Rather, there would be a calibration curve for each initial temperature. Fortunately, the thermal conductivities of ceramic and water are fairly constant within a wide range of temperatures.

Using an initial boundary condition of $v = 0$ gives

$$v_{0,0} = v_{0,1} = v_{0,2} = v_{0,3} = \ldots = 0 \tag{6}$$

Numerical results based on Equations 4 and 6 are shown in Figures 8 and 9 for heating period t_p equal to 60 sec. Figure 8 shows the temperature distribution (i.e., in the infinite sphere) at the end of the heating period for different heating rates. The heating rate currently used in thermal conductivity matric suction sensor measurement is approximately 0.024 cal/sec for a fixed heating duration of 60 sec. According to Figure 8, a minimum sensor radius of 15 mm would be required to fully contain the heat within the sensor. Figure 9 shows the effect of the surrounding soil on the temperature distribution within the ceramic, where K_s is the ther-

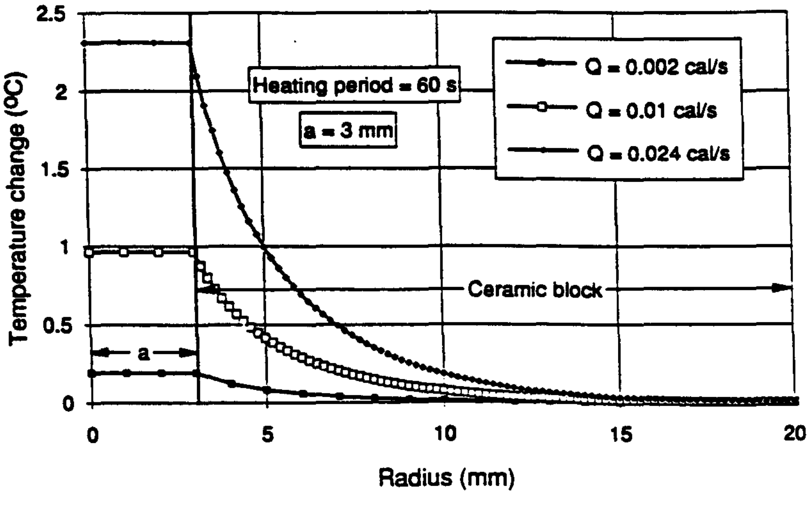

FIGURE 8 Temperature distribution at the end of heating for various heating rates.

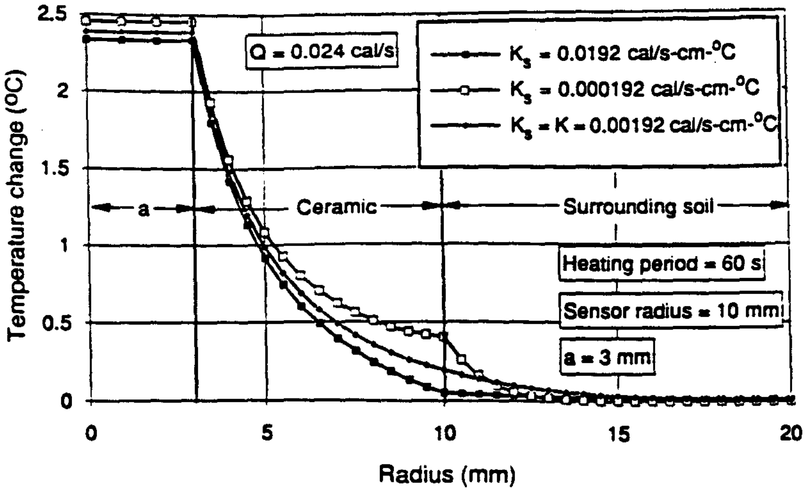

FIGURE 9 **Influence of the thermal conductivity of the surrounding soil on the temperature distribution within the ceramic.**

mal conductivity of the surrounding soil. Figure 9 was obtained for a sensor of 10-mm radius subjected to a heating rate of 0.024 cal/sec for 60 sec.

CALIBRATION AND ACTUAL READING

Calibration of the thermal conductivity matric suction sensors can be conducted by using a modified pressure plate apparatus. The modified pressure plate apparatus has special ports to accommodate the sensor leads. The sensors are buried in the soil inside the modified pressure plate apparatus. The matric suction of the sensors is controlled by maintaining a constant matric suction in the soil by the axis translation technique. Details of the procedure have been described elsewhere (*8*).

The current measuring procedure when using thermal conductivity matric suction sensors has been to take two temperature readings: one prior to applying heat and one at exactly 1 min after the application of a precise heat pulse. The difference between these two temperature readings is the temperature rise due to the heat pulse. The temperature rise due to the heat pulse is then calibrated against the matric suction.

There are other possibilities for handling the data output from the thermal conductivity matric suction sensor. One possibility is to use a continuous recording of the characteristic Seebeck voltage outputs of the sensor over the entire heating and cooling cycle. The area enclosed by the characteristic Seebeck voltage output curve over an entire heating and cooling cycle (Figure 10) can be correlated against the matric suction of the soil.

Another possibility may be to use the rate of change of voltage (or temperature) along some sections of both the heating and the cooling curves. The rate of change of voltage (or temperature) along the heating curve may prove to be more reliable. For instance, the rate of heat generated and dissipated early in the heating cycle will not be affected by the soil surrounding the sensor. Later in the heating cycle, as the influence zone from the applied heat expands, the effect of the surrounding soil will become increasingly important, particularly if the sensor is not sufficiently large for the specified heating rate and the specified heating period. Further studies into the rate of heat generation and the rate

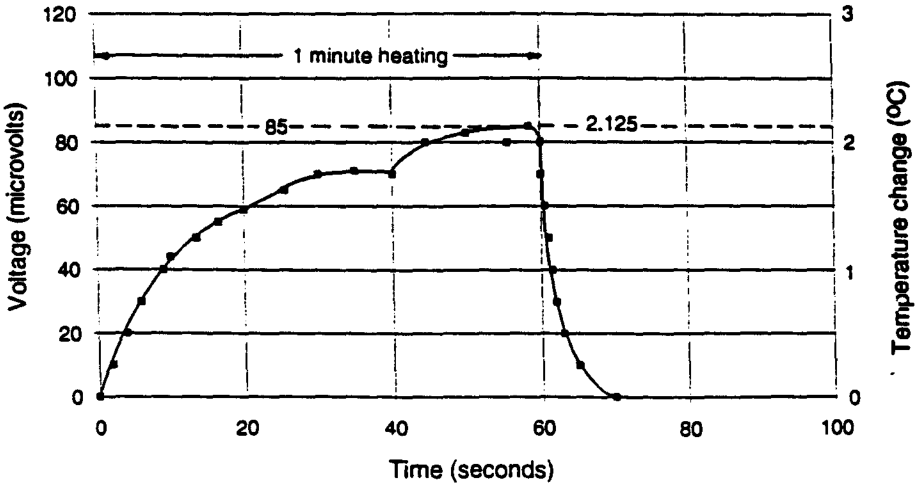

FIGURE 10 **Seebeck voltage output measured over an entire heating and cooling cycle.**

of heat dissipation are needed to find the most satisfactory method for the indirect measurement of matric suction.

The Seebeck voltage outputs measured with time for a ceramic saturated state and in an air-dry state were presented earlier ure 3). It is possible to generate a series of curves between these two curves for any range of matric suction values (Figure 11). That is, rather than using only the maximum change in temperature to correlate with matric suction, another possibility would be to numerically best-fit the Seebeck voltage response curves. It may be possible to obtain greater accuracy in the measurement of suction by this approach.

FIELD MONITORING

The thermal conductivity sensors constitute an attractive option for the field monitoring of matric suction because of their suitability to data acquisition systems. The data acquisition possibilities provide for almost continuous and remote monitoring. These are of value when attempting to obtain information related to environmental changes. The pore water pressure conditions in the unsaturated zone are quite variable because of the influence of the microclimate and the variability of the soil properties. Multiple sensors are usually required at each instrumentation site to properly characterize the matric suction profile changes.

A typical monitoring site is usually remote and usually has no power supply. The layout of one such typical monitoring scheme used in a railway embankment is shown in Figure 12. Typically, multiple sensors involving leads of various lengths are used. The electrical connections to link the sensors to the data acquisition system become complex. Having sensors with leads of various lengths is undesirable from a fabrication and calibration standpoint. Multiple sensors will require a multiplexing system to control and monitor the sensor readings.

Depending on the distance of the site from the control office, visits to the site to retrieve data may occur infrequently. The power source to the system must be able to last for long durations. Other means of providing power such as the use of solar power panels are options. The system should also be able to store large amounts of data between site visits. A modem may be required for communicating with the data logger.

The data acquisition system must be able to take an initial temperature reading and then supply a constant heat pulse to the sensor for a specific duration (e.g., for 60 sec) and then take another temperature reading. The system must be able to carry out this execution automatically and sequentially for all of the sensors.

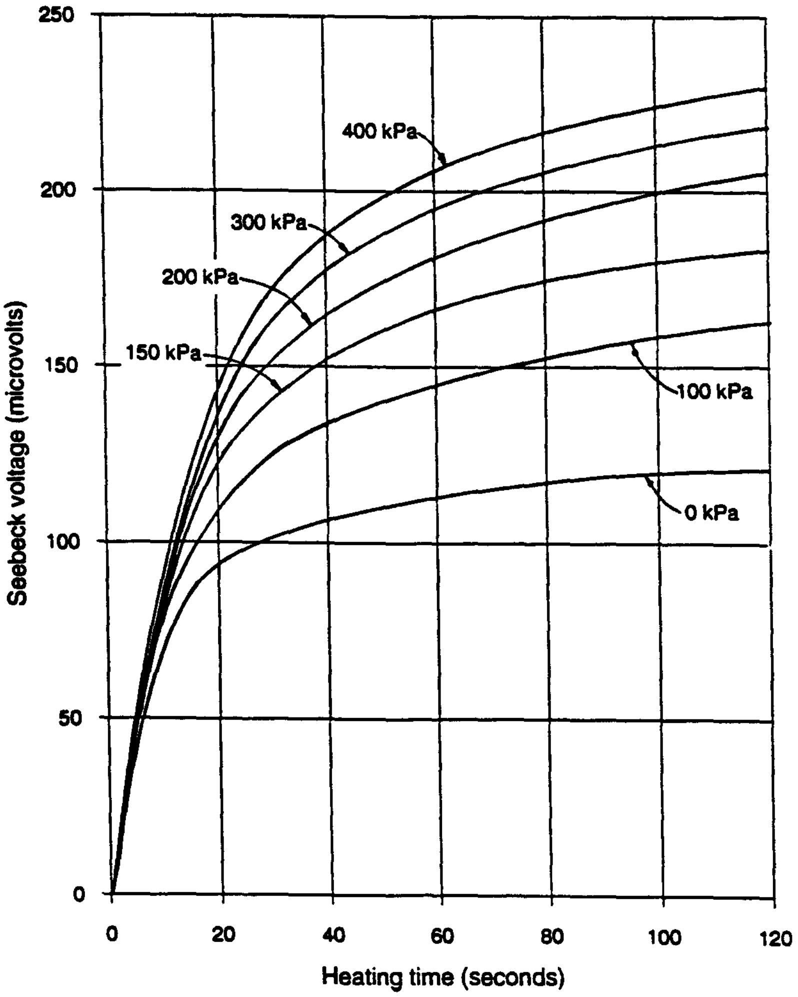

FIGURE 11 Idealized Seebeck voltage characteristic curves of a sensor at various matric suction values.

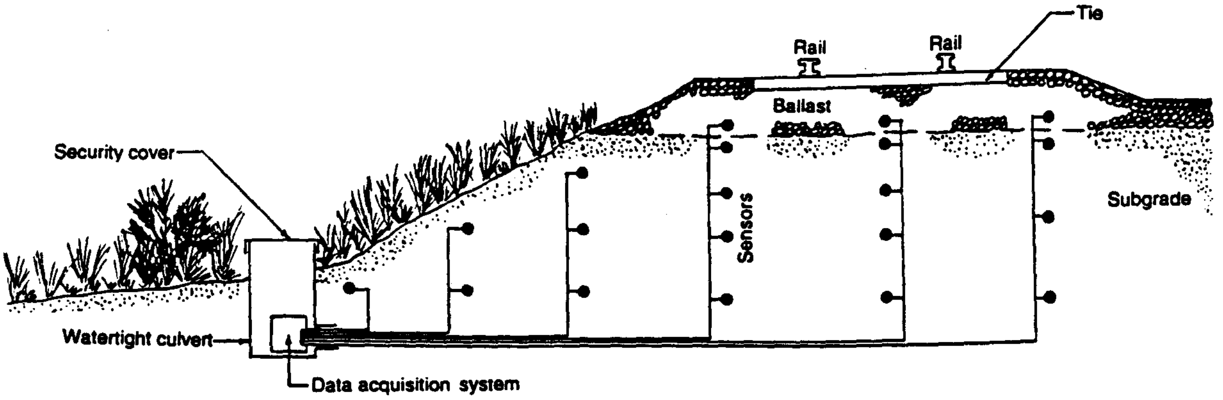

FIGURE 12 Layout of thermal conductivity matric suction sensors installation in a railway embankment.

The data acquisition system presently used in the field monitoring of matric suction with thermal conductivity matric suction sensors is fairly complex. A simpler data acquisition system dedicated specifically to the thermal conductivity matric suction sensors would be desirable.

CONCLUSION

There is need for an indirect method of measuring matric suction. One such possibility is the use of thermal conductivity matric suction sensors. Fabrication of a durable ceramic for an accurate matric suction sensor is difficult. Theoretical considerations show that it is necessary to fabricate sensors for specific ranges of matric suction. The theory of heat flow in a porous medium shows that the calibration of a thermal conductivity sensor is unique since the thermal conductivity of the ceramic, water, and air are not a function of the temperature within the normal working range of temperatures.

The present method of measuring matric suction by using the maximum temperature change does not necessarily result in the most accurate measurements possible. As a result consideration should be given to other possible procedures for analyzing the outputs from the thermal conductivity matric suction sensors.

The data acquisition system presently used with the thermal conductivity matric suction sensors is complex. A simpler dedicated data acquisition system is needed.

REFERENCES

1. Fredlund, D. G., and H. Rahardjo. *Soil Mechanics for Unsaturated Soils.* John Wiley and Sons, Inc., New York, 1993.
2. Loi, J., D. G. Fredlund, J. K. Gan, and R. A. Widger. Monitoring of Soil Suction in an Indoor Test Track Facility. In *Transportation Research Record 1362,* TRB, National Research Council, Washington, D.C., 1992, pp. 101–110.
3. Fredlund, D. G., P. J. Sattler, and J. K. Gan. Insitu Suction Measurement using Thermal Sensors. *Proc., 7th International Conference on Expansive Soils,* Dallas, Tex., 1992, pp. 325–330.
4. Fredlund, D. G. 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, Soil Science Society of America, Madison, Wis., 1992, pp. 249–261.
5. van Wijk, W. R., ed. *Physics of Plant Environment,* 2nd ed. North-Holland, Amsterdam, The Netherlands, 1963.
6. Mandziak, T. *Development of a Matric Suction Sensor.* M.S. thesis. University of Saskatchewan, Saskatoon, Saskatchewan, Canada, 1991.
7. Carslaw, H. S., and J. C. Jaeger. *Conduction of Heat in Solids,* 2nd ed. Oxford University Press, New York, 1959.
8. Fredlund, D. G., and D. K. H. Wong. Calibration of Thermal Conductivity Sensors for Measuring Soil Suction. *Geotechnical Testing Journal,* Vol. 12, No. 3, 1989, pp. 188–194.