Use of thermal conductivity sensors to measure matric suction in the laboratory

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The measurement of soil suction is pivotal to the application of soil mechanics principles in geotechnical engineering practice related to unsaturated soils. Volume change, shear strength, and seepage analyses all require an understanding of the matric suction in the soil. This note summarizes the use of thermal conductivity sensors to measure matric suction in the laboratory. The thermal conductivity sensor is described along with its mode of operation. A brief description is given of the procedure for calibrating thermal conductivity sensors using a pressure plate apparatus. The measurement of matric suction can be performed in the laboratory on Shelby tube samples. The laboratory measurements of matric suction can be adjusted for the effect of overburden pressure in the field. The required equilibration time for suction measurements is discussed along with details of the test procedure. The applications of the measured suction values to design are briefly discussed.

Key words: matric suction, negative pore-water pressure, thermal conductivity sensor, laboratory, undisturbed samples.

La mesure de la succion dans le sol constitue un jalon dans l'application des principes de la mécanique des sols non saturés dans la pratique de la géotechnique. Le changement de volume, la résistance au cisaillement et les analyses de l'infiltration requièrent tous la compréhension de la succion matricielle dans le sol. Cette note résume l'utilisation de détecteurs de conductivité thermique pour mesurer la succion matricielle en laboratoire. Le détecteur de conductivité thermique est décrit de même que son mode d'opération. L'on donne une brève description de la procédure pour calibrer les détecteurs de conductivité thermique au moyen d'un appareil comportant une plaque de pression. La mesure de la succion matricielle peut être réalisée sur des échantillons de tubes Shelby. Les mesures en laboratoire de la succion matricielle peuvent être ajustées en fonction de la pression des terres sus-jacentes sur le terrain. Le temps requis pour l'équilibration des mesures de succion est discuté de même que les détails de la procédure d'essai. Les applications dans le calcul des valeurs de succion mesurées sont discutées brièvement.

Mots clés : succion matricielle, pression interstitielle négative, détecteur de conductivité thermique, laboratoire, échantillons intacts.

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Introduction

A promising device for the measurement of matric suction in geotechnical engineering is the thermal conductivity sensor. Although the thermal conductivity sensor was developed for soil science applications some years ago (Phene *et al.* 1971*a*, *b*, 1987), it is only recently that the value of thermal conductivity sensors has been recognized in geotechnical engineering.

Previous publications (Krahn and Fredlund 1972; Fredlund and Rahardjo 1988) have examined various techniques for measuring total, osmotic, and matric suction. The thermal conductivity sensor is essentially unaffected by the salt content of the soil and has a relatively wide range for suction measurements (Lee and Fredlund 1984; Fredlund and Wong, 1988).

Lee and Fredlund (1984) evaluated the MCS sensor[1] (i.e., a thermal conductivity sensor) and used it to measure matric suction in several soils. In 1984, the MCS sensor became no longer commercially available. However, a similar thermal conductivity sensor, called the AGWA-II sensor,[2] manufactured by Agwatronics Incorporated, came on the market and has been used for further research (Fredlund and Wong, in press).

[1]MCS gauges were thermal conductivity sensors produced by Moisture Control Systems, Findlay, Ohio. The company no longer produces these sensors.

[2]AGWA-II sensors are manufactured by Agwatronics Incorporated of Merced, California.

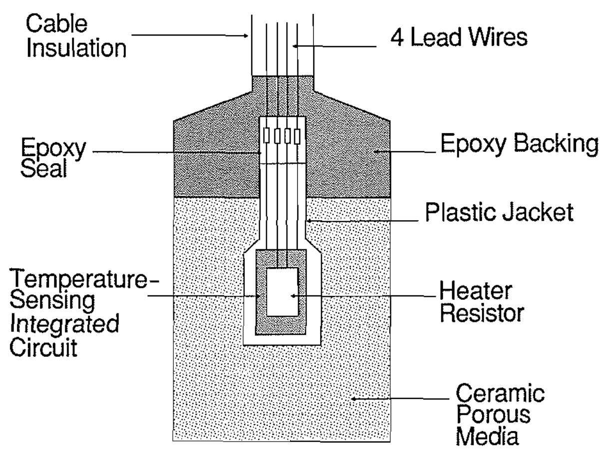

FIG. 1. A cross-sectional diagram of the thermal conductivity sensor.

Thermal conductivity sensor

A thermal conductivity sensor indirectly measures the matric suction in a soil. It consists of a porous ceramic block containing a temperature-sensing element and a miniature heater (Fig. 1). Measurements are made by drilling a hole in the soil, inserting the sensor, and allowing the water content of the sensor to come into equilibrium with the water content of the soil. Equilibrium occurs as water flows between the porous block and the soil. The amount of water in the porous block affects the rate of heat dissipation within the

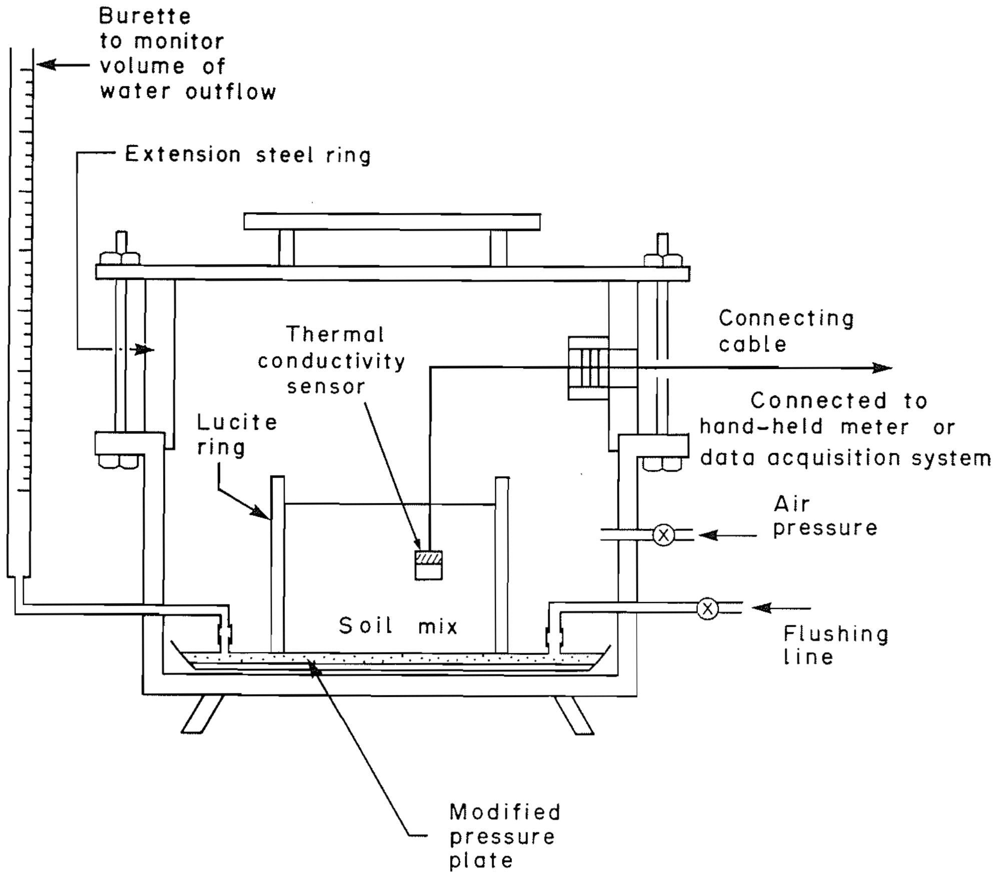

FIG. 2. Pressure plate calibration of thermal conductivity sensors.

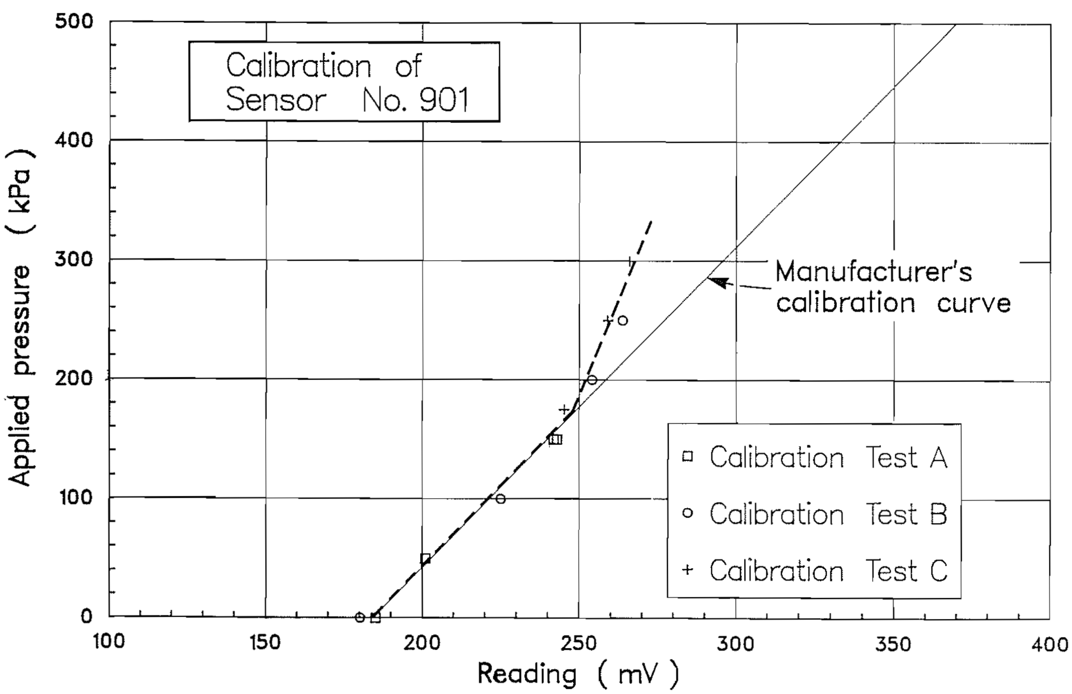

FIG. 3. Repeated calibration for sensor No. 901.

block, and can be measured indirectly by measuring the heat dissipation within the block. Since there exists a relationship between water content in the porous block and matric suction, the voltage reading from the sensor can be calibrated against matric suction.

The measurement of heat dissipation within the block is accomplished by delivering a controlled amount of heat to the center of the porous block and measuring the temperature rise at the same point after a fixed period of time. More heat will be dissipated through the porous block with increas-

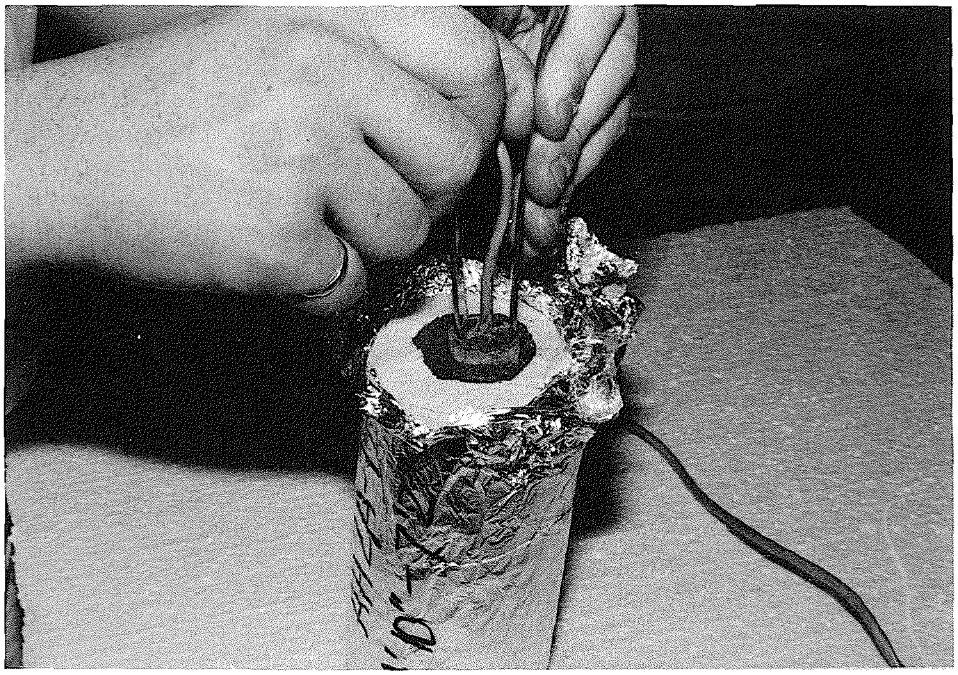

FIG. 4. Installation of a thermal conductivity sensor.

ing water content of the block. The heat not dissipated causes a temperature rise in the block. Consequently, the temperature rise in the porous block is inversely proportional to the water content of the block. As a result, the measured temperature rise is calibrated to measure the matric suction in the soil.

Calibration of the thermal conductivity sensor

The thermal conductivity sensors used were supplied with a calibration curve from the manufacturer. It is a two-point calibration and has been found to be inadequate for geotechnical engineering purposes (Wong *et al.* 1989).

The thermal conductivity sensors can be calibrated using a modified pressure plate apparatus (Fig. 2). The height of the pressure chamber was increased for the purpose of providing several circular ports along the chamber wall. The ports allow the lead wires from the sensor to be connected to the heat source and a readout device or data acquisition system.

Several sensors are first installed in a slurried soil placed inside a large lucite ring on the pressure plate apparatus. A matric suction is then applied to the soil by applying an air pressure to the chamber, and maintaining a zero water pressure below the high air entry ceramic disc. Water from the soil around the sensor will flow through the ceramic disc until equilibrium is attained.

The response of each sensor is monitored periodically to determine when equilibrium has been achieved. The reading at equilibrium is used for the calibration of the sensor. The procedure of applying a matric suction and waiting for equilibrium is repeated for various applied matric suctions to provide a complete calibration curve for each sensor.

A thorough calibration study has been completed on AGWA-II thermal conductivity sensors at the University of Saskatchewan (Wong and Ho 1987). Typical results indicate an essentially bilinear calibration curve (Fig. 3). The diagram shows consistent results for three separate calibration tests on the same sensor. The breaking point on the calibration curve was found to be around 175 kPa. Relatively accurate measurements of suction can be anticipated from the AGWA-II sensors in the 0–175 kPa range. Higher matric suction values correspond to a steeper calibration curve with a lower sensitivity.

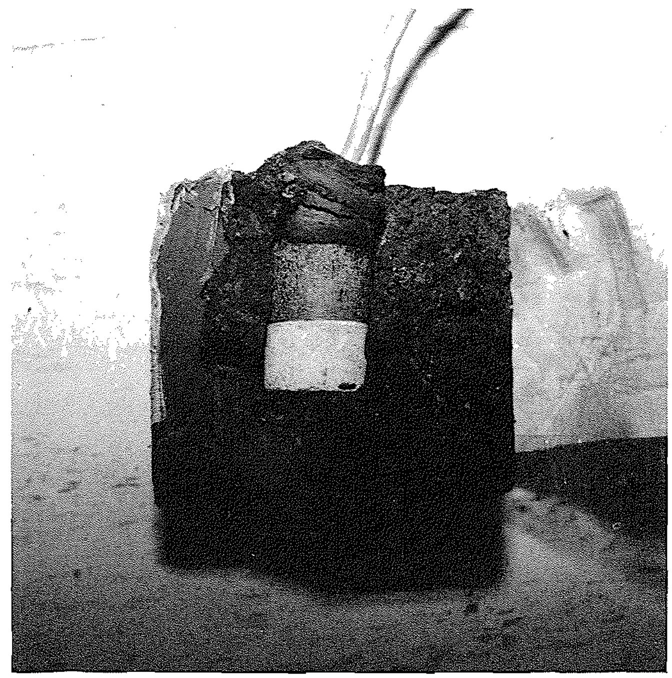

FIG. 5. Illustration of good soil-to-sensor contact.

Use of the thermal conductivity sensors to measure suction in the laboratory

An estimate of the *in situ* matric suction corresponding to a particular point in time can be obtained by measuring the matric suction on Shelby tube samples. Standard 64 mm

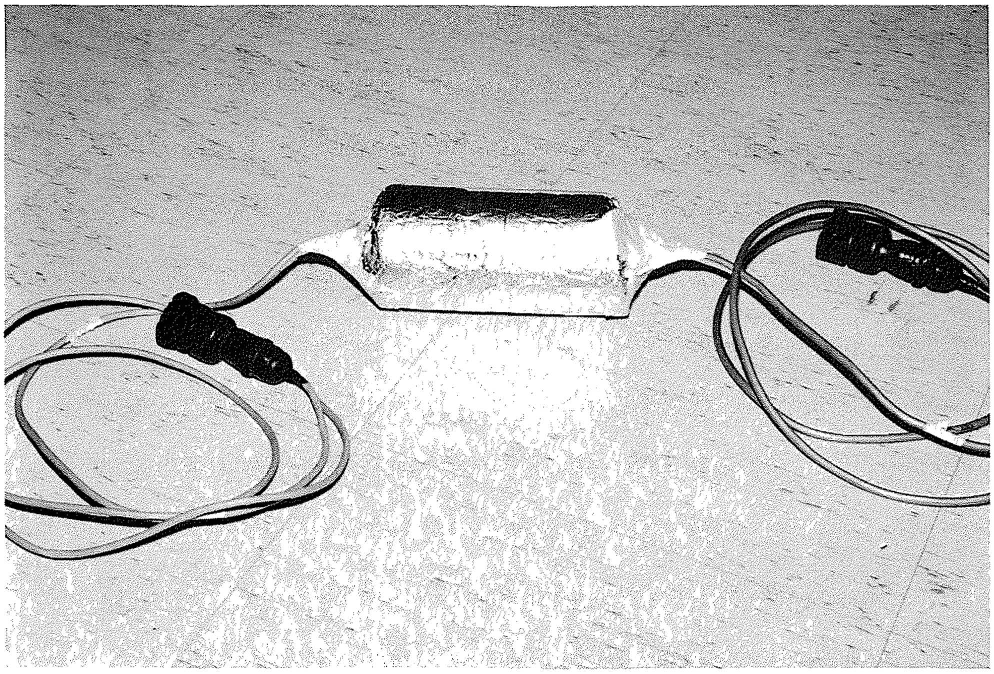

FIG. 6. A completely sealed sample with two thermal conductivity sensors installed.

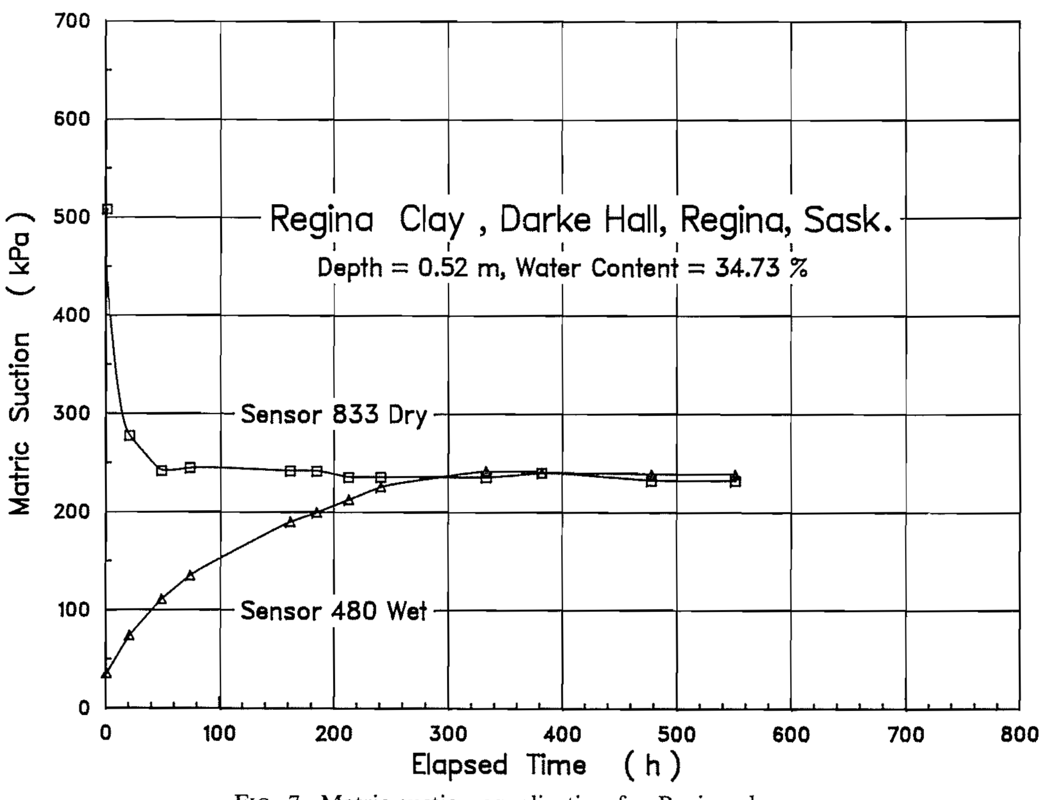

FIG. 7. Matric suction equalization for Regina clay.

diameter ($2\frac{1}{2}$ in.) by 915 mm long (3 ft) Shelby tubes can be used to obtain undisturbed soil samples at various depths within a soil profile. The ends of the Shelby tube should be sealed to prevent evaporation from the sample. The entire Shelby tube should be double bagged and stored in a moist environment until its extrusion in the laboratory.

A 125 mm (5 in.) long portion from the center of the extruded tube sample can be retained for the measurement of matric suction. It is important that the sample retained for the matric suction measurement be taken from the center portion of the Shelby tube to minimize sample disturbance. The sample should then be double wrapped in plastic film (such as Saran wrap), which is confined with a layer of masking tape. Next, the sample is double wrapped with aluminum foil to prevent moisture loss. Masking tape is wrapped around the aluminum foil. If necessary, the sample can then

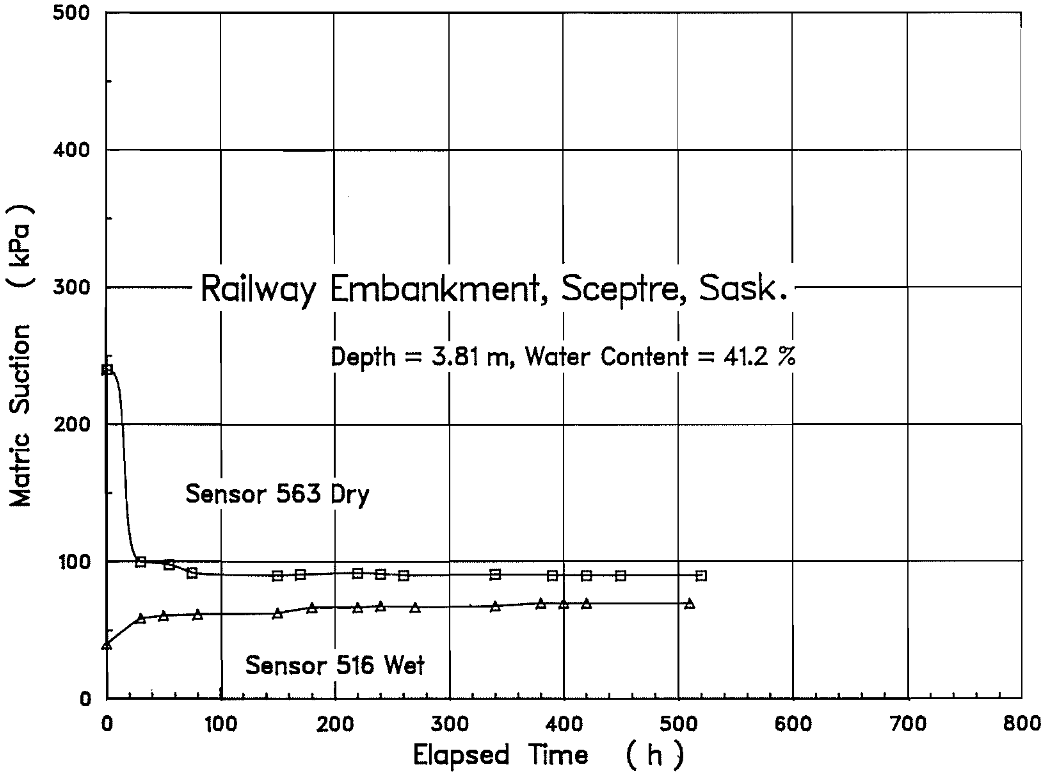

FIG. 8. Matric suction equalization for a sample obtained from a railway embankment near Sceptre, Saskatchewan.

be stored in a humidity-controlled environment room for up to several weeks awaiting the measurement of matric suction.

A scalpel blade is used to cut a 30 mm diameter ($1\frac{1}{4}$ in.) hole in the wrapping of one end of the plastic and aluminum foil encased sample. After the plastic and aluminum foil wrappings have been removed from the hole, a 22 mm ($\frac{7}{8}$ in.) diameter hole is drilled into the soil sample to a depth of about 40–50 mm ($1\frac{1}{2}$–2 in.) Care must be taken in drilling not to excessively smear the edges of the hole by drilling too fast and long. The hole should not be too large to ensure that the sensor makes a good contact with the soil. Some of the drill cuttings can be saved for sealing the sensor into the hole, whereas the remaining cuttings can be used for a water content determination.

Next, a dry ceramic sensor is pushed into the hole drilled in the sample. If the soil is extremely dry and the sensor resists being pushed into the sample, it may be necessary to ream or trim the hole drilled in the sample. Apply a firm and even all-around pressure when pushing the sensor tip into the soil. This can be achieved by using the ends of two ordinary tablespoons to push on the sensor at opposite sides of the lead wires (Fig. 4). Push the sensor into the sample until bottom resistance is realized. The objective is to obtain a good contact between the porous ceramic block of the sensor and the soil. Figure 5 illustrates a good soil-to-sensor contact. Use the drill cuttings to seal the top of the sensor into the drilled hole.

If desired, a second hole can be drilled into the other end of the sample for the installation of a second sensor. This would provide two suction measurements on a single sample. This may be of value in assessing the variability of the suction profile. Uniform soil samples will generally produce top and bottom matric suction measurements within 5–10 kPa. This is similar to the limits of accuracy of the thermal conductivity sensor.

To prevent loss of moisture from the sample, first wrap the sensor lead wires and sample opening with plastic film. Then double wrap the entire sample with the sensor in two layers of aluminum foil. Use masking tape to seal the ends of the sensor leads against the aluminum foil. Figure 6 shows a sealed sample with two sensors installed. The sample is then stored in a temperature-controlled box to prevent changes in matric suction that may arise from daily temperature fluctuations.

Equilibration time and sensor removal

An initial reading on the sensor should be taken once it has been installed in the sample. It is suggested that subsequent sensor readings be taken on a log time basis (i.e., 1 h, 2 h, 4 h, 8 h, 1 day, and then every day until equilibration). A dry sensor will show a decrease in matric suction with time (see Fig. 7); a wet sensor will show an increase in matric suction with time (see Fig. 7).

The dry sensor will result in a matric suction value that is slightly high, since water must flow from the soil into the sensor for equilibrium to be attained. An initially wet or saturated sensor will result in a matric suction value that is too low, since water must flow from the sensor into the soil for equilibrium to be attained.

The matric suction measurement obtained using an initially dry sensor generally provides a more accurate measure of suction because there is a smaller exchange of water between the soil and the sensor during the equalization process. The water content of a wet or saturated sensor is about 96%. An air-dried sensor has a water content of about 1%. Natural water contents of soils commonly range from 20 to 40%. The quantity of water flow from the soil to the

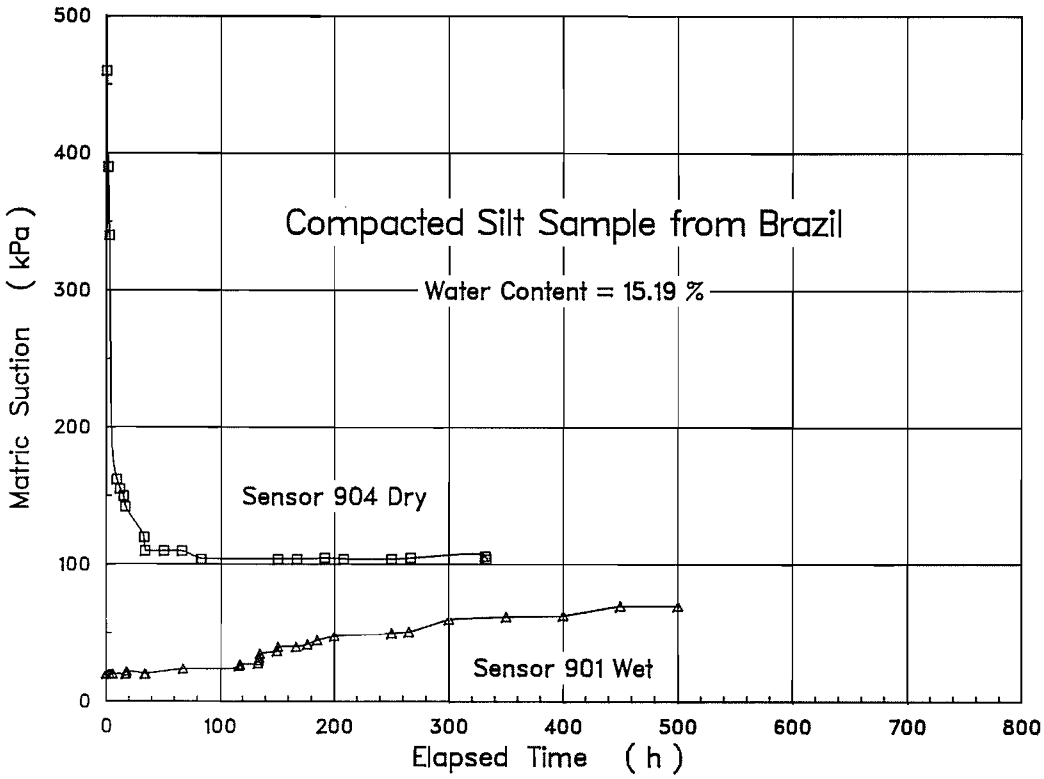

FIG. 9. Matric suction equalization for a compacted silt from Brazil.

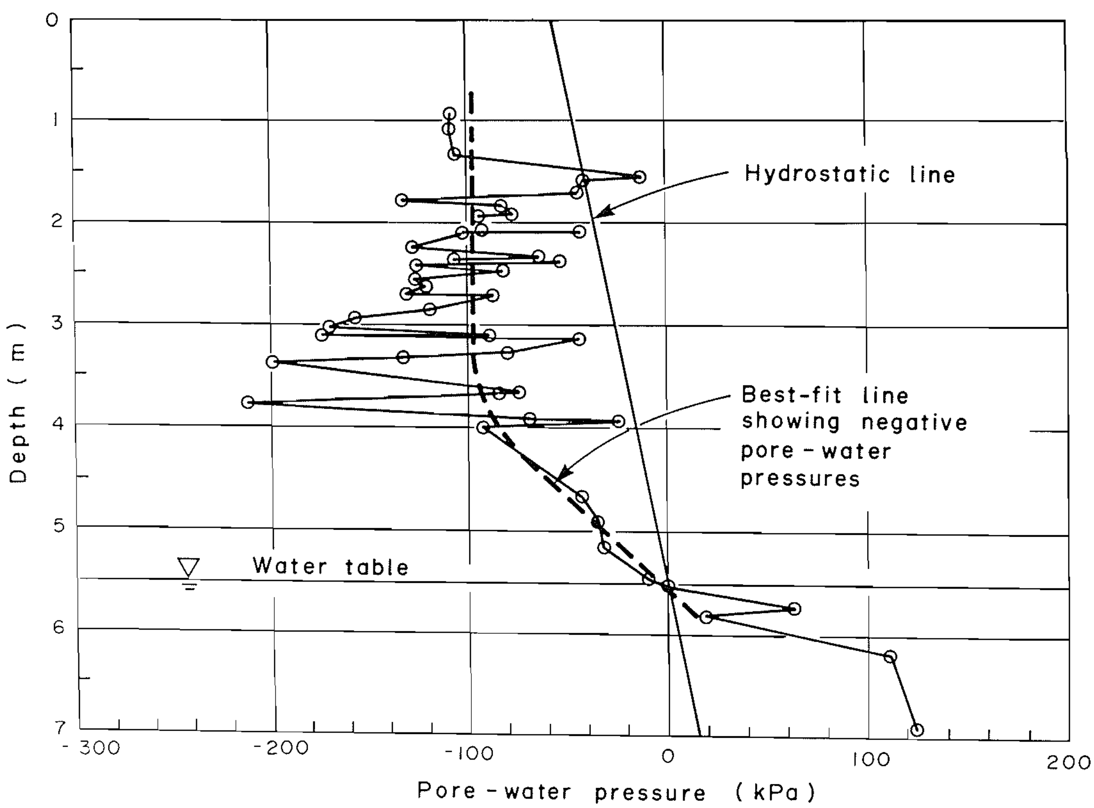

FIG. 10. Adjusted pore-water pressure data showing the water table and hydrostatic line.

sensor, or vice versa, will generally be least when the sensor is initially dry.

Utilization of an initially dry sensor generally requires less time for equilibrium to be attained. For this reason, the authors suggest that the sensor tip be installed dry. However, for soils with relatively high water contents there may be some justification for using a somewhat wet sensor. Generally, a dry sensor installed in an undisturbed sample will take about 3–4 days to reach equilibrium.

The equilibrium matric suction after about 3–4 days represents the matric suction for the undisturbed soil with the overburden stress removed. In many cases it is necessary that these measured matric suction values be adjusted for the overburden pressure. A suggested procedure for adjustment is described in the next section.

To remove the sensor from the sample, the outer layers of aluminum foil and masking tape are removed from the sensor lead wires and sample. Then the sample is cut in half with a knife. Next, the sensor is removed by cutting along the vertical direction of the sample to within a few millimetres of the location of the sensor. Vertical cuts are made all around the sensor to loosen the soil adjacent to the sensor tip. As the soil is loosened from the sensor the ceramic tip should be eased out of the soil with care so as not to damage the sensor. The sensor should be allowed to dry for about half a day before being installed into the next sample.

Presentation of laboratory measurements

Figures 7–9 present matric suction results for laboratory measurements on several undisturbed samples. (One set of results are for samples compacted in the laboratory using static compaction.) The results indicate a similar type of equalization curve for each of the matric suction measurements. Both an initially dry and an initially wet sensor are used in several cases.

Figure 7 presents some of the results of laboratory measurements performed on samples retrieved from beneath the floor slab at Darke Hall, Regina, Saskatchewan. The results portrayed in Fig. 7 are for a Shelby tube sample retrieved from 0.52 m beneath the floor slab where the *in situ* water content was 34.7%. Both the wet and dry sensor measurements came to equilibrium at a matric suction equal to about 240 kPa. Generally, the wet and dry sensor measurements converge to slightly different values. The reason for the difference in measurement is related to whether the flow of water is into a dry sensor or out of a wet sensor. This aspect is discussed in detail by Wong *et al.* (1989).

Matric suction measurements were performed on undisturbed Shelby samples from a railway embankment near Sceptre, Saskatchewan. Figure 8 shows the matric suction measurements on a sample obtained at a depth of 3.81 m with an *in situ* water content of 41.2%. The dry sensor equalized to a matric suction value of 95 kPa, whereas the wet sensor came to equilibrium at a matric suction value of 65 kPa.

Figure 9 shows one set of results on a soil obtained for testing from Brazil. The soil specimen was prepared using standard American Association of State Highway Officials (AASHO) compaction at a water content of 15.19%. The sensor that was installed dry came to equilibrium at a matric suction of 105 kPa. The sensor that was installed wet came to equilibrium at a matric suction value of 65 kPa. The difference between these values is quite large and the value of 105 kPa is felt to be most meaningful.

Figure 10 shows results obtained from the Emerson Subdivision railway embankment near Winnipeg, Manitoba (Clifton *et al.* 1988). The samples were from a number of boreholes along a section of the railway and do not necessarily depict the variation that may be found in a single borehole. Time and equipment constraints did not permit sensor measurements using both wet and dry sensors. A total of 52 undisturbed samples were tested on this project. The sensors were installed dry and allowed to come to equilibrium.

Interpretation of suction measurements

The matric suction data from the Emerson Subdivision railway embankment were plotted as negative pore-water pressures with depth as shown in Fig. 10. When the soil is sampled, the confining total pressure is reduced to zero. Therefore, the sample has a tendency to expand. Expansion of the sample results in an increase in matric suction. Consequently, the matric suction measured in the laboratory may need to be adjusted to reflect the *in situ* matric suction corresponding to the field confining pressures. For the data shown in Fig. 10, the overburden pressure was subtracted from the matric suction measurements to give adjusted matric suction data. The above-described adjustment assumes that the B pore pressure parameter was 1.0 and the at-rest earth pressure coefficient was 1.0. Any value from 0 to 1 can be used for the B parameter, but a value of 1.0 results in the largest adjustment to the matric suction measurements.

The measurements confirm that the embankment is composed of extremely variable soil with suctions varying with respect to depth. The existence of softer clay layers is indicated by the presence of the lower matric suction values. The matric suction results show a value of zero at the location of the water table. The suction measurements can also be compared with the hydrostatic line. Values from below the water table are not meaningful. The best-fit line indicates a possible pore-water pressure profile.

The considerable scatter in the data makes it difficult to select values for either design or back-analysis purpose. In the particular case in hand, the design matric suction values were selected as the mean of the measurements minus one standard deviation (i.e., $\bar{x} - \sigma_d$) for the upper 4 m. The suction was then assumed to decrease linearly to zero at the water table. These values are lower than about 75% of the suction values.

When analyzing volume change problems related to expansive soils, a design analysis may need to be based on the mean and possibly the mean plus one standard deviation. In many cases, there may be insufficient data for a statistical-type approach and reliance must be placed on engineering judgement.

Summary

The techniques involved in the use of thermal conductivity sensors have been described and illustrated. The paper presents data showing the measurement of matric suction in the laboratory and to some degree the interpretation of data. The results indicate that measurements of matric suction can be performed on undisturbed Shelby tube samples taken to the laboratory. Care must be taken to ensure that the samples are not permitted to dry under laboratory conditions prior to and during the matric suction measurements. It is necessary to calibrate the thermal conductivity sensors prior to their use for suction measurements.

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samples upon which the laboratory measurements of matric suction were made.

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