D.G. FREDLUND, Professor of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, S7N 0W0
P.J. SATTLER, Research Engineer, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, S7N 0W0
J.K-M. GAN, Research Engineer, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, S7N 0W0

7TH INTERNATIONAL CONFERENCE ON EXPANSIVE SOILS

DALLAS, TEXAS (USA)
AUGUST 3 - 5, 1992

In situ suction measurements using thermal sensors

SUMMARY: Matric suction affects the mechanical behavior of unsaturated soils. Insitu measurements of matric suction may be obtained indirectly using a thermal conductivity sensor. The sensor consists of a small heater embedded in a porous ceramic block. At equilibrium, the heat dissipation characteristics of the block may be calibrated against soil matric suction. Proper procedures for calibration of the sensor have been developed at the University of Saskatchewan. Eighteen thermal conductivity sensors were installed in a railway embankment in Manitoba for insitu measurements of suction. About 25% of the sensors failed to function within the first year. Failure was attributed either to inadequate backfilling, or to the electronics in the sensor which discontinues functioning as a result of the sensor being subjected to positive pressures for a period of time. There appears to be reasonable correlation between insitu measurements of suction and local climatic conditions.

1. INTRODUCTION

Matric suction is well recognized as one of the stress state variables which controls the mechanical behavior of unsaturated soils. Appropriate theory is now available which takes into account the role of matric suction in the mechanical behavior of unsaturated soils (Fredlund, 1979). The measurement of matric suction, however, lags behind the theoretical development and proves to be a major hindrance to the acceptance of matric suction as a viable factor to be considered in routine engineering practice.

Various techniques are now available for measuring insitu matric suction (Fredlund and Rahardjo, 1988). These techniques are all continuously undergoing development and field verifications. In recent years, the thermal conductivity sensors have been found to produce reasonably reliable measurements. During this developmental stage, the documentation of case histories of field measurements of matric suction is essential in order to assess the reliability of measured values.

A short theory related to the thermal conductivity sensor will be presented. This will be followed by a description of the calibration procedure which has been developed at the University of Saskatchewan, Canada. Proper field installation is an important aspect for the proper working of any instrumentation system and a case history of a recent installation is described. Finally some insitu measurements are presented and discussed.

2. THEORY RELATED TO THERMAL CONDUCTIVITY SENSORS

A thermal conductivity sensor is comprised of a porous ceramic block with an embedded temperature sensing device and a miniature heater element [Figure 1]. Ideally, the porous ceramic block should have a 'well graded' distribution of pore sizes. The principle behind the method is that the porous block will attain a wide range of water contents over a range of matric suctions.

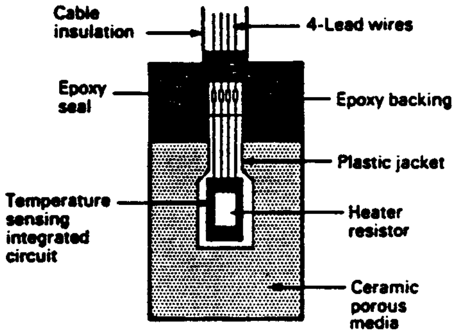

Figure 1 A Cross-sectional Diagram of the AGWA-II Thermal Conductivity Sensor

For any given sensor, the volume of the solid matrix and the volume of the void spaces are constant. The rate of heat dissipated within the solid matrix is, therefore, a constant. The voids in the porous ceramic are comprised of both air and water. The relative proportions of the air and the water will change with the degree of saturation of the ceramic. The thermal conductivity of air is small in comparison to the thermal conductivity of water. At atmospheric conditions and a temperature of 20° C air has a thermal conductivity of 0.026 W/m K and water has a thermal conductivity of 0.6 W/m K, a ratio of approximately 23. Hence, any changes in the thermal conductivity can be related solely to changes in the water content.

When the sensor is embedded in a soil, a gradient is created in the water phase due to the difference in the water potential in the sensor and the soil. Flow will occur from the high potential to the lower potential until equilibrium is attained. In other words, at equilibrium the water phase of the sensor will always be at the same potential as the water phase of the surrounding soil. Since the mass of the soil is large compared to the mass of the sensor, and any neglecting hysteresis effects, the porous ceramic of the sensor will have a unique water content corresponding to a matric suction in the soil. These water contents can be related to the changes in the thermal conductivity of the sensor. Therefore, the thermal conductivities of the porous ceramic block can be calibrated with respect to the applied matric suctions.

For the AGWA-II thermal conductivity sensors, thermal conductivity measurements are performed by measuring the heat dissipated within the porous block. A controlled amount of heat is generated by the heater element at the center of the block with a controlled current supplied for a definite time period. Some heat dissipation will occur as heat is generated. The undissipated heat will result in a temperature rise at the center of the block. This temperature rise is measured by the sensing element after a specified time interval of heating. Two types of heat sensing devices are presently in use. One type of the AGWA-II uses an integrated circuit (IC) and the second type uses a thermocouple to measure temperature. In both cases, the heating time is 60 seconds. The temperature rise is related to the change in the thermal conductivity of the sensor which in turn is related to the change in the water content of the block.

3. CALIBRATION OF SENSORS

Calibration of the thermal conductivity sensors can be performed by applying a range of matric suctions to the sensors mounted in a layer of soil. This can be conducted within a pressure plate apparatus. At the University of Saskatchewan, Saskatoon, Canada, a pressure plate apparatus have been modified for calibration purposes (Fredlund and Wong, 1989). The modification consists of an extension ring with holes drilled through its side. These holes are required for the leads of the sensor to be directed outside the chamber to a monitoring device [Figure 2].

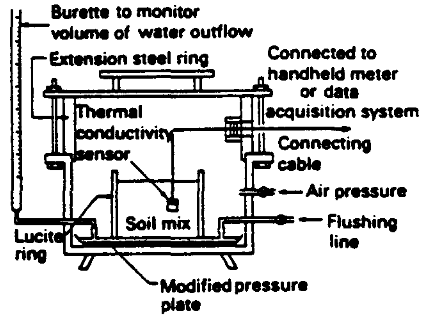

Figure 2 Pressure Plate Calibration of Thermal Conductivity Sensors

The setup consists of embedding the sensors in a soil that is placed on the pressure plate. The soil is used to provide continuity between the water phase in the porous block of the sensor and the high air entry disc. A fine silty soil was used as an interface soil. The matric suction is induced and controlled by maintaining an air pressure in the chamber while the water pressure below the pressure plate is usually maintained at atmospheric conditions. It was generally found that the equilibrium time is about two days. The pressure plate setup is contained within an insulated chamber to maintain a controlled temperature.

Calibration curves obtained for the AGWA-II sensors are typically non-linear. Typical calibration plots are shown in Figures 3 and 4. The non-linear calibration curves can be approximated by a bilinear curve as illustrated in the same figures. The breaking point on the bilinear calibration curve was found to be generally around 175 kPa. The AGWA-II sensor thus has superior accuracy in the range from 0 to 175 kPa than for matric suctions above 175 kPa which lie on the steeper portion of the calibration curve.

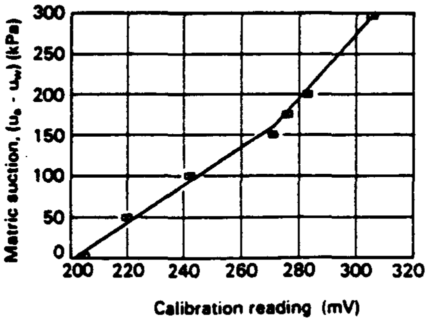

Figure 3 Calibration Curve for Sensor No. 16 (1376)

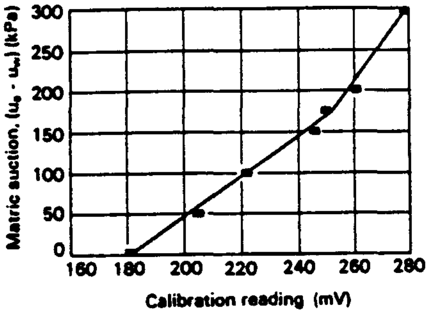

Figure 4 Calibration Curve for Sensor No. 13 (1472)

4. INSTALLATION OF THE SENSORS IN THE FIELD

Eighteen thermal conductivity sensors were installed along a section of railway embankment in the Emerson Subdivision Trackage in the Winnipeg area, Manitoba, Canada. These sensors were installed in connection with the remedial design of some unstable sections of the embankment. Analysis concluded that berming would alleviate some of the instability problems. Several miles of the embankment were bermed. A typical section of the berm is shown in Figure 5.

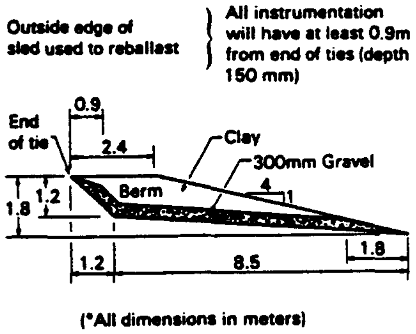

Figure 5 Schematic for a Typical Bermed Section

Four locations were selected for the instrumentation. These were located at Miles 43.07, 44.85, 47.2, and 51.2. Three of the locations were in the remedial work area (i.e., sections which were bermed). The control site was located at Mile 47.2, in an area which was not subjected to any remedial work.

Twenty sensors were earmarked for installation in the field. However, two sensors were broken, one during calibration and the other during installation. The porous material used for the sensor tips were fairly weak, requiring great care in handling, both during calibration and during installation.

Five thermal conductivity sensors were installed at each of Miles 43.07, 47.2, 51.2. Three thermal conductivity sensors were installed at Mile 44.85.

At each instrumentation site, a trench was cut into the side of the embankment using a backhoe. Each trench was about 700 mm wide. The bottom of each trench was cut to about 800 mm below the base of the ballast, or below the granular drain, whichever was lower. This resulted in the bottom of each trench being about 2 m below the top of the tie. The bottom of the trench was in the clayey soil. At the desired elevation for the thermal conductivity sensor, an auger hole was advanced at an upward angle into the side of the trench, using a small hand auger with a 25 mm diameter bit. The 25 mm hole was used to ensure a snug fit for the sensor. The sensor diameter is approximately 25 mm. Good contact between sensor and the soil is mandatory for the proper measurement of the insitu matric suction.

The 25 mm auger hole was approximately 150 mm deep. The upward slope of the hole was to prevent water from running along the lead wires and collecting at the sensor tip. The sensor was pushed into the 25 mm auger hole using a rod. The length corresponding to the exact depth of the hole was marked on the sensor cable. This helped ensure that the sensor was pushed all the way in to have good contact with the soil at the base of the hole. If the sensor was not installed properly, (e.g., if the sensor could not be pushed into the required depth due to the hole being too tight) the hole must be dug out and the sensor must be reinstalled in a new hole. The improperly installed sensor cannot be simply pulled out as this will break the weak porous tip.

The hole was then backfilled with the natural soft clay retrieved from the auger hole during augering. The backfill was carefully compacted into the hole. The bottom of the trench was then backfilled and compacted up to the elevation of the sensor. The sensor lead was then threaded through a plastic pipe and taken to the ground surface. The trench was then backfilled, with the pipe, buried in a near upright position. The top of the plastic pipe was capped to keep water from entering the pipe.

5. FIELD MATRIC SUCTION MEASUREMENTS

Matric suction measurements at the Emerson Subdivision Trackage Site were commenced on September 28,. 1989. Data collected until November 7, 1990 is presented. At least 6 out of 18 sensors were found to malfunction. These malfunctions were attributed to broken or cracked sensor tips, and to the breakdown of the electronics due to water penetrating into the integrated circuit heat sensor device. Typical data from properly functioning sensors at each of the four instrumentation locations are shown in Figures 6 to 9. No readings were collected during the period form December to April when the sensors were frozen. The higher thermal conductivity of ice as shown in Figure 10, and the unknown proportions of frozen and unfrozen water makes the sensor readings difficult to interpret. Also, the latent heat of fusion associated with the transformation of water has a significant influence on the thermal conductivity of the sensor during freezing and thawing (Fredlund et al, 1991). This is shown in Figure 11.

Data from Sensors No. 3, 6, and 14 are presented in Figures 6, 7, and 8 respectively. These sensors were installed in the remedial work area, (i.e., within the bermed sections of the embankment).

Matric suction data obtained from thermal conductivity Sensor No. 3 indicates that matric suction decreased with a decrease in seasonal temperature. From September 1989 to December 1989, the matric suction readings obtained from Sensor No. 3 dropped from about 120 kPa to about 25 kPa. Readings taken over the next year also indicated that the matric suction reading decreased from a relatively high value in September to a lower value in November.

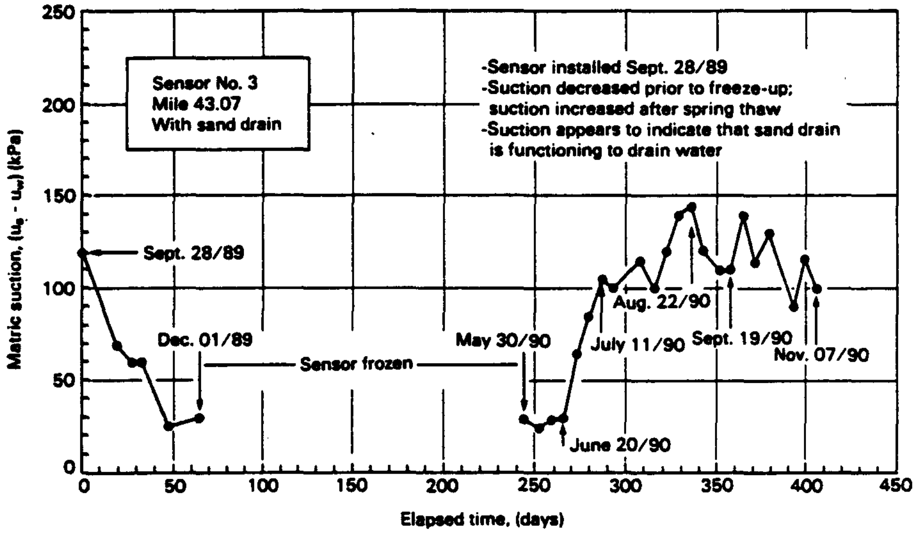

Figure 6 Matric Suction vs. Elapsed Time for Sensor No. 3

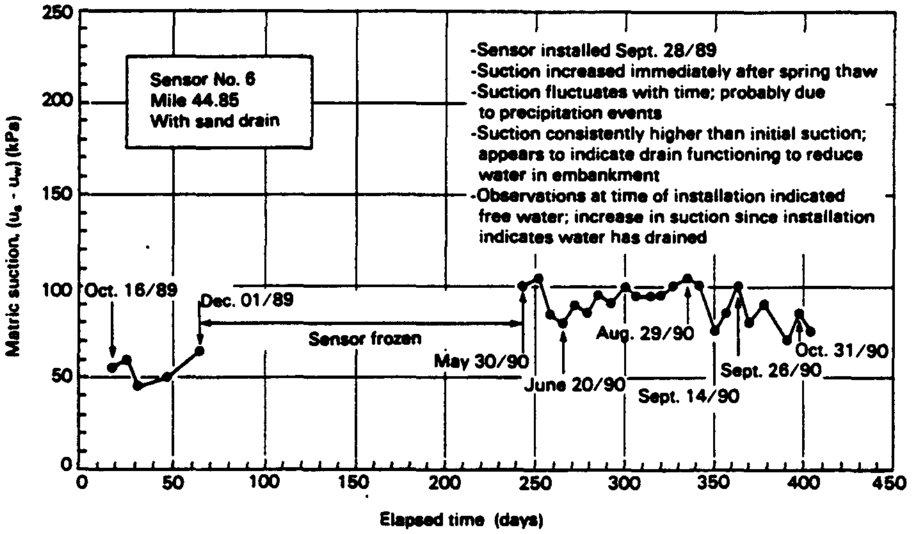

Figure 7 Matric Suction vs. Elapsed Time for Sensor No. 6

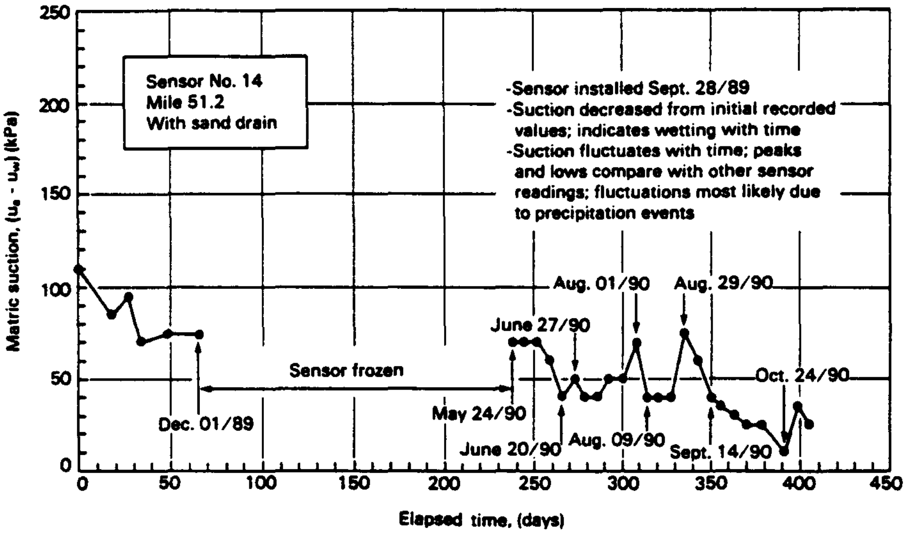

Figure 8 Matric Suction vs. Elapsed Time for Sensor No. 14.

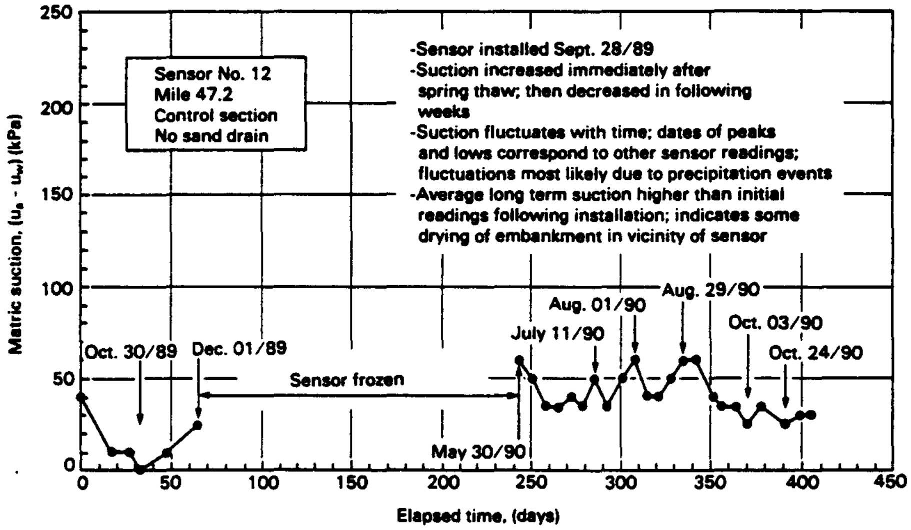

Figure 9 Matric Suction vs. Elapsed Time for Sensor No. 12

During the spring period, Sensor No. 3 registered a low matric suction of about 25 kPa. The matric suction reading began to increase after June 20, 1990, which corresponds to the beginning of our hot Prairie summer. This indicates a drying out of the embankment with time over the hot season. The matric suction readings reach a high of about 150 kPa in late August. From late August onwards to November, the matric suction readings decreased, probably due to the lower evaporation rate over the precipitation rate in the fall season.

Data from Sensor No. 6 as presented in Figure 7 did not show as much variation in matric suction with seasonal temperature as did Sensor No. 3. It did show, however, that the matric suctions recorded from May 1990 to October 1990 were consistently higher than the matric suctions recorded just after the sensor was installed. This would appear to indicate that the gravel layer within the berm was effective as a drain.

The data presented in Figure 8 for Sensor No. 8 indicates that the gravel layer within the berm was not functioning as effectively as a drain. The lower matric suction readings during the second year indicates that the embankment is becoming wetter with time.

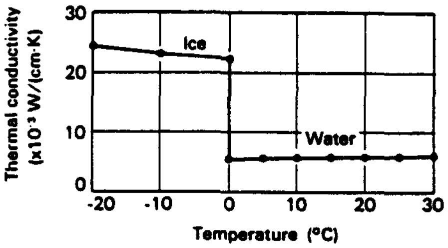

Figure 10 Thermal Conductivity of Ice and Water at Various Temperatures

The data recorded for a sensor installed in the control section which was not subjected to any remedial work, (i.e., not bermed) are presented in Figure 9. The trend in the measured matric suctions show that the average long term suction was higher than the initial reading taken shortly after installation. This was probably due to some drying of the embankment. The average matric suctions recorded were generally much lower than those for the sensors within the berm sections. This suggests that the gravel layer within the berm did, in general, improve the drainage of the embankment.

All sensor readings show considerable fluctuations. These fluctuations were found to correspond approximately, to periods of precipitation.

6. CONCLUSIONS

Analysis of the data collected from the four sites indicates satisfactory performance of the sensors in the field. The range of measured matric suctions was reasonable and remained relatively constant with time.

The ceramic material for the sensor tips and the electronic for the sensor require considerable improvements. A stronger ceramic with a wide range of pore sizes is needed. The problem associated with the integrated circuit of the heat sensing element can be circumvented by using a thermocouple. However, an improvement to the integrated device would be preferable as there are advantages in using the integrated circuit sensor.

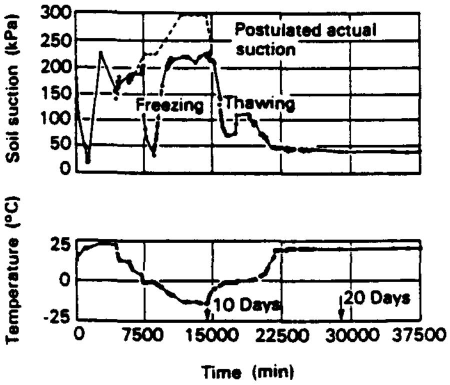

Figure 11 Suction Measurements of a Glacial Till Specimen Subjected to Freezing and Thawing

7. REFERENCES

Fredlund, D.G., 1979. Appropriate Concepts and Technology for Unsaturated Soils, Second Canadian Geotechnical Colloquium, Canadian Geotechnical Journal, Vol. 16, No. 1, pp. 121-139.

Fredlund, D.G. and Rahardjo, H., 1988. State-of-Development in the Measurement of Soil Suction, Proceedings of the International Conference on Engineering Problems of Regional Soils, Beijing, China, pp. 582-588.

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

Fredlund, D.G., Gan, J.K. and Rahardjo, H., 1991. Measuring Negative Pore-Water Pressures in a Freezing Environment, Session on "Moisture Migration in Freezing and Thawing Soils", 70th Annual Meeting, Transportation Research Board, Washington, D.C.