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Typical Matric Suction Measurements in the Laboratory and in the Field Using Thermal Conductivity Sensors

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SYNOPSIS

The paper describes an indirect method of measuring matric suctions in the soil. Thermal conductivity measurements of a porous block in equilibrium with a soil mass are used to measure the soil suction. Typical results from matric suction measurements using this technique are presented in the paper.

1 INTRODUCTION

Many geotechnical problems in various regions of the world are associated with swelling soils, collapsing soils, and residual soils. Common to all these soils are the unsaturated nature of the soil and the negative pore-water pressures. Generally, the negative pore-water pressures are referred to the ambient or pore-air pressures and called "matric suction". Matric suction has been recognized as one of the stress state variables that control the mechanical behavior of unsaturated soils. Therefore, the development of techniques and devices for measuring matric suctions is important to the advancement of the unsaturated soil mechanics.

Direct measurements of negative pore-water pressures are limited to negative one atmosphere due to the cavitation of water in the measuring system. An indirect method of measuring matric suctions based on thermal properties of porous media is described in this paper. This method shows promise for future application in geotechnical engineering practice.

2 HISTORY AND DEVELOPMENT OF THERMAL CONDUCTIVITY SENSORS

Thermal properties of a soil have been found to be an indicative measurement of the soil water content. Water is a better thermal conductor than air. The thermal conductivity of soil increases with increasing water contents. Shaw and Baver (1939) developed a device of temperature sensor and heater which could be installed directly into the soil for thermal conductivity measurements. It was found that the presence of salts did not significantly affect the thermal conductivity of the soil. However, different soils would require different calibrations in order to translate the thermal conductivity measurements into the water contents of the soils. Johnston (1942) suggested that the thermal conductivity sensor be enclosed in a porous medium that had a standard calibration curve. This porous cover was then brought into equilibrium with the soil under measurements. Johnston (1942) used plaster of Paris to encase the heating element.

In 1955, L.A. Richards patented an electro-thermal element for measuring moisture in porous media (U.S. Patent # 2,718,141). The element consisted of a resistance thermometer which was wrapped with a small heating coil. The electro-thermal element was then mounted in a porous cup and sealed with ceramic cement. Richards suggested the use of a sandy silt material for the porous cup and that the cup should have an air entry value less than 10 kPa.

Bloodworth and Page (1957) studied three materials for use as a porous cup of thermal conductivity sensors. Plaster of Paris, fired clay or ceramic and castone, a commercially available dental stone powder were used in the study. The castone was found to be the best material for the porous cup.

Phene, Hoffman, and Rawlins (1971) developed a thermal conductivity sensor using a Germanium P-N Diode as a temperature sensor. The sensor was wrapped with 40-gauge Teflon coated copper wire that served as the heating coil. This sensing unit was then embedded in a porous block. The optimum dimension of the porous block was calculated from a theoretical model. The block must be large enough to contain the heat pulse without being interfered with by the thermal properties of the surrounding soil. Gypsum, ceramics, and mixtures of ceramics and castone were examined as a porous block material. It was found that the ceramic block exhibited a linear response and provided a stable solid matrix.

In the mid 1970's, Moisture Control System Incorporated of Findlay, Ohio, U.S.A., manufactured the MCS 6000 thermal conductivity sensors. The sensor was built using the same design and construction principles as developed by Phene, Hoffman, and Rawlins (1971). The MCS 6000 sensors have been used for matric suction measurements in the laboratory and in the field (Picornell, Lytton and Steinberg, 1983; and Lee and Fredlund, 1984). The sensors appeared to be quite suitable for field usage, being insensitive to temperature and salinity changes. Relatively accurate measurements of matric suctions below 300 kPa were obtained. Curtis and Johnston (1987) used the MCS 6000 sensors in a major groundwater recharge study. The sensors were found to be sufficiently responsive and sensitive; and the results were in good agreement with piezometer and neutron probe data. However, Moisture Control System Incorporated discontinued production in early 1980, and the MCS 6000 sensor is no longer available commercially.

In December 1981, Agwatronics Incorporated in Merced, California commenced production of the AGWA thermal conductivity sensors as designed and developed by Phene, Hoffman, and Rawlins (1971). There were several difficulties associated with the AGWA sensors that resulted in the replacement of the sensors by the AGWA-II sensors in 1984. A thorough calibration study on the AGWA-II sensors was completed at the University of Saskatchewan, Canada (Wong, Fredlund, Imre and Putz, 1989; and Fredlund and Wong 1989). Typical calibration curves of the sensor are presented and discussed in this paper. The AGWA-II sensors have also been used for laboratory and field measurements of matric suctions (van der Raadt, Fredlund, Clifton, Klassen and Jubien, 1987; and Sattler and Fredlund, 1989). Typical results are described in this paper together with techniques used in the measurements.

3 THEORY OF OPERATION

A thermal conductivity sensor consists of a porous ceramic block containing a temperature sensing element and a miniature heater (Fig. 1). The thermal conductivity of the porous block varies in accordance with the water content in the block. The water content in the porous block is dependent upon the matric suctions in the block. Therefore, the thermal conductivity of the porous block can be calibrated with respect to its applied matric suction.

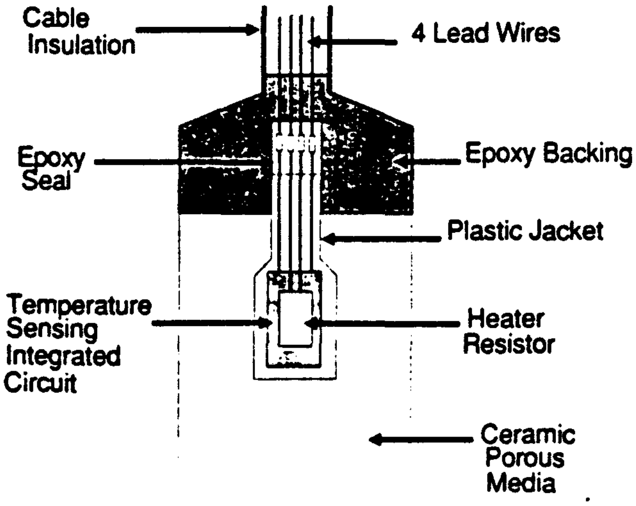

Figure 1 A cross-sectional diagram of the AGWA-II thermal conductivity sensor.

A calibrated sensor can then be used to measure the matric suction in a soil mass by placing the sensor in the soil and allowing it to come to equilibrium with the soil. Thermal conductivity measurements at equilibrium indicate the matric suction of the soil.

Thermal conductivity measurements are performed by measuring heat dissipation within the porous block. A controlled amount of heat is generated by the heater at the center of the block. A portion of the generated heat will be dissipated throughout the block. The amount of heat dissipation is controlled by the availability of water as the thermal conductor within the porous block. More heat will be dissipated as the water content in the block increases. The undissipated heat will result in a temperature rise at the center of the block. The temperature rise is measured by the sensing element after a specified time interval and its magnitude will be inversely proportional to the water content in the porous block. The measured temperature rise is expressed in terms of voltage output.

4 CALIBRATION OF SENSORS

The calibration of a thermal conductivity sensor is performed by applying a matric suction to the sensor which is mounted in a soil and reading the voltage output from the sensor. The voltage output is a measure of the thermal conductivity or the water content of the porous block under the applied matric suction. The matric suction can be applied to the sensor using a modified pressure plate apparatus (Wong, Fredlund, Imre and Putz, 1989; and Fredlund and Wong, 1989). The sensor is embedded in a soil that is placed on the pressure plate. The soil specimen provides continuity between the water phase in the porous block and in the high air entry disc. The matric suction is applied by increasing air pressures in the pressure plate, but maintaining the water phase at atmospheric pressures. The voltage output from the sensor can be monitored periodically until matric suction equilibrium is achieved. The above procedure is repeated for various applied matric suctions to provide a calibration curve. A number of thermal conductivity sensors can be calibrated simultaneously in one pressure plate. During calibration, the pressure plate setup is contained within a temperature controlled box.

At least forty AGWA-II sensors have been purchased and calibrated at the University of Saskatchewan, Canada. Typical non-linear calibration curves for the AGWA-II sensors are shown in Fig. 2. The non-linear response of the sensors is likely related to the pore size distribution of the ceramic porous block. Similar non-linearities were also observed on the calibration curves for the MCS 6000 sensor. The non-linear behavior of the AGWA-II sensors may be approximated by a bilinear curve as illustrated in Fig. 2. The breaking point on the calibration curve was found to generally be around 175 kPa. Relatively accurate measurements of matric suctions using the AGWA-II sensor can be expected, particularly within the range of 0 to 175 kPa which corresponds to the flatter portion of the calibration curve. Matric suction measurements above 175 kPa correspond to a steeper portion of the curve with a lower sensitivity.

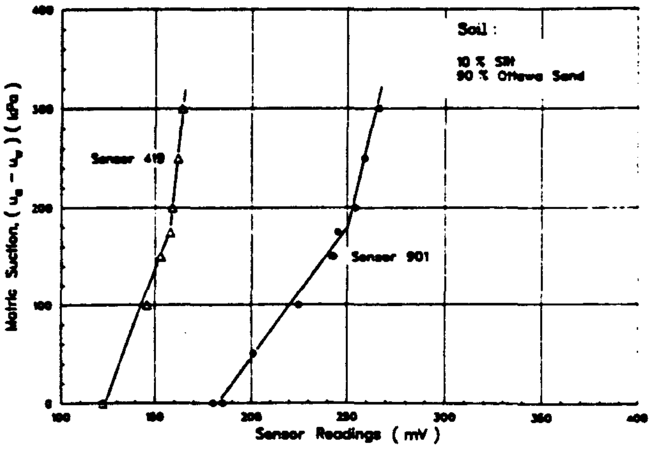

Figure 2 Calibration curves for two AGWA-II thermal conductivity sensors.

The study on the AGWA-II sensors indicated consistent and stable output readings with time. The sensors were found to be responsive to wetting and drying processes. However, some failures have been experienced with sensors that are subjected to a positive water pressure. The failures are attributed to the possibility of moisture coming into contact with the electronics sealed in the porous block (Wong, Fredlund, Imre and Putz, 1989).

5 TYPICAL RESULTS OF MATRIC SUCTION MEASUREMENTS

Laboratory and field measurements of matric suctions using the AGWA-II thermal conductivity sensors have been conducted using several types of soils. Results of laboratory measurements on highly plastic clays from Sceptre and Regina, Saskatchewan are shown in Figs. 3, 4 and 5. The soils were sampled from the field using shelby tubes. Matric suction measurements on compacted soils have also been performed on silts from Brazil (Fig. 6).

Laboratory measurements were carried out using two sensors on each soil specimen. One sensor was initially saturated while the other sensor was initially air-dried. The initially saturated sensor was submerged in water for about two days prior to measurements. The sensors were then inserted into predrilled holes on the specimen. The specimen with the installed sensors were wrapped in a plastic film to prevent moisture loss during measurements. The response of both sensors were monitored immediately and at various elapsed times after their installation. The results indicate that the time required for the initially dry sensor to come to equilibrium with the soil specimen is less than the equilibrium time for the initially saturated sensor.

Results from laboratory measurements of matric suction can be used to establish the negative pore-water pressures above a water table. Samples of Winnipeg clay from various depths of a railway embankment were brought to the laboratory for matric suction measurements using the AGWA-II sensors. The measured matric suctions can be plotted as a negative pore-water pressure profile (Fig. 7). The results indicate that the negative pore-water pressures increase to zero at depths approaching the water table.

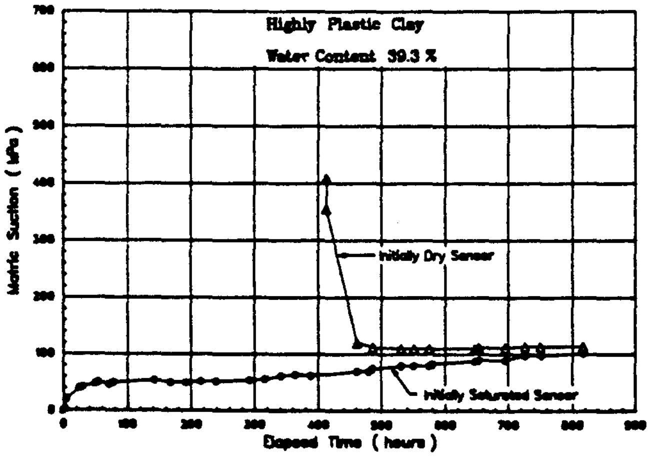

Figure 3 Laboratory measurements of matric suction on highly plastic clay from Sceptre, Saskatchewan, Canada.

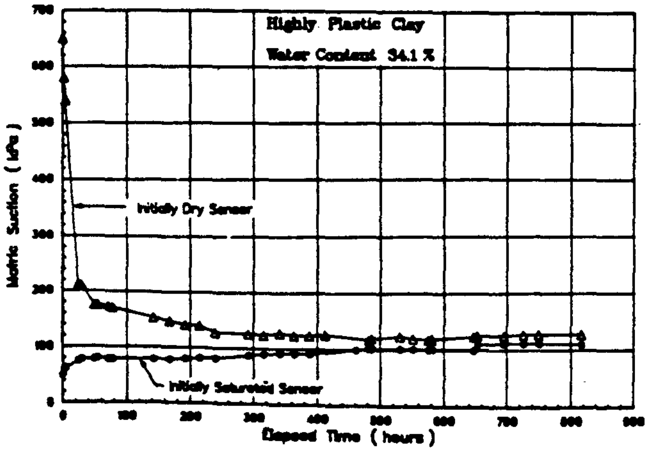

Figure 4 Laboratory measurements of matric suctions on highly plastic clay from Sceptre, Saskatchewan, Canada.

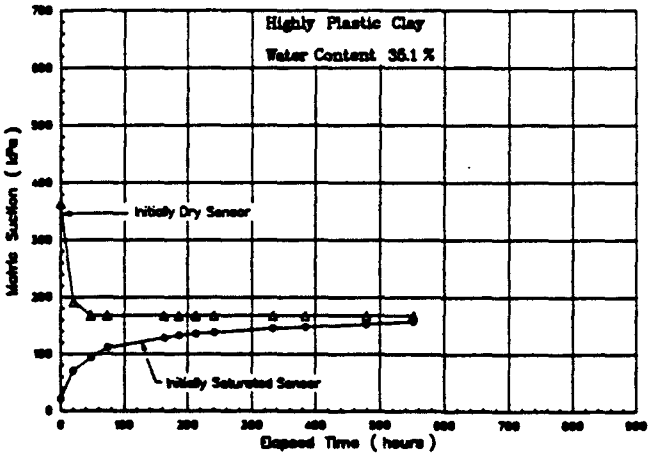

Figure 5 Laboratory measurements of matric suction on highly plastic clay from Darke Hall, Regina, Saskatchewan, Canada.

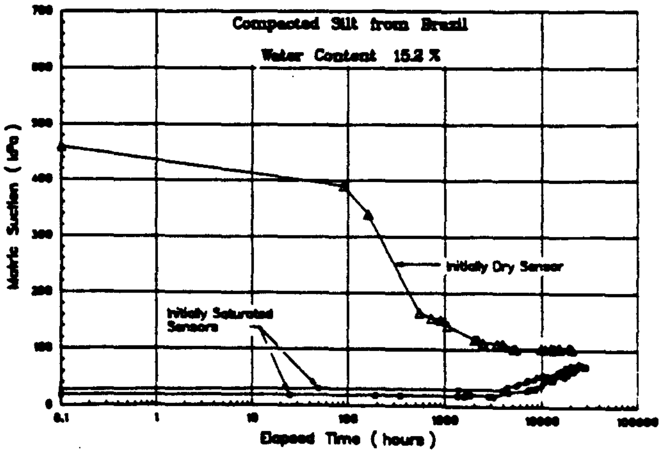

Figure 6 Laboratory measurements of matric suctions on compacted silt from Brazil.

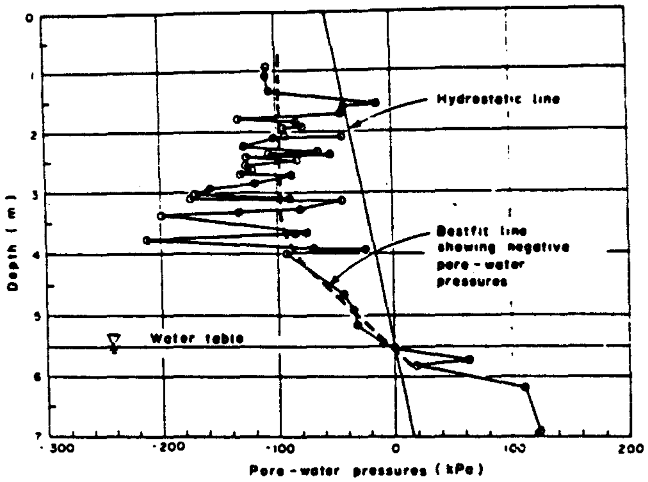

Figure 7 Negative pore-water pressure profiles obtained using the AGWA-II thermal conductivity sensors (From Sattler and Fredlund, 1989).

Field measurements of matric suction under a controlled environment have been conducted on the subgrade soils of an indoor highway test track. The temperature and the relative humidity within the test track facility are controlled. Twenty-two AGWA-II sensors were installed in the subgrade of the test track. The sensors were initially air-dried and installed into pre-drilled holes at various depths in the subgrade. The sensor outputs were recorded twice a day. Typical matric suction measurements in the compacted Regina clay subgrade are presented in Fig. 8. Consistent readings of matric suction around 460 kPa were monitored for a period of 2.6 months prior to flooding the test track. The sensor responded quickly upon flooding as indicated by the rapid drop in matric suction readings to zero. The results demonstrated that the AGWA-II sensors provide stable measurements of matric suction over a relatively long period of time.

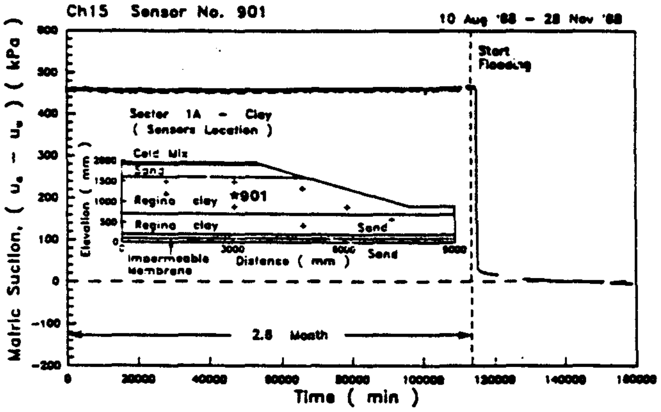

Figure 8 Field measurements of matric suction using the AGWA-II thermal conductivity sensors under controlled environments.

Matric suction variations in the field can be related to environmental changes. Several AGWA-II sensors were installed in the field at various depths of Regina clay that exhibit high swelling potentials. Matric suctions in the soil were monitored at different times of the year. The results clearly indicate seasonal variations of matric suctions in the field with the greatest variation occurring near ground surface (Fig. 9). It appears that the AGWA-II sensors are reasonably sensitive for matric suction changes in the field.

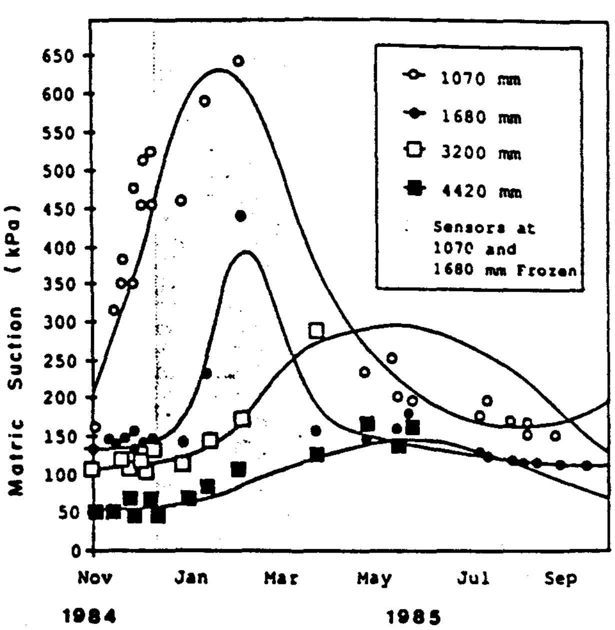

Figure 9 Idealized plot of matric suction versus time of year for various depths of Regina clay in Saskatchewan (From van der Raadt, 1988).

6 CONCLUSIONS

The thermal conductivity sensors appear to be promising devices for matric suction measurements either in the laboratory or in the field. However, proper calibration should be performed on each sensor prior to its use. The calibration study on the AGWA-II sensors reveals that the sensors are reasonably sensitive for matric suction measurements up to 175 kPa.

It is possible that future improvements on the AGWA-II sensors will enhance the sensor's performance. A better seal for the electronics within the sensor could reduce the contact of water with electronics in the sensor when it is subjected to prolonged submergence. This improvement would reduce the mortality rate of the sensor. In addition, pre-treatment of the ceramic block during fabrication can be improved to produce a stronger porous matrix that does not easily break.

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