# 13

# Background, Theory, and Research Related to the Use of Thermal Conductivity Sensors for Matric Suction Measurement

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## ABSTRACT

This chapter describes the history and use of thermal conductivity sensors to measure matric suction. The technique uses an indirect measurement which is correlated to matric suction. The sensors were initially developed and used primarily with irrigation control systems. More recently, attempts have been made to apply the sensors to geotechnical engineering problems. This has resulted in the development of more refined calibration procedures. The thermal conductivity sensors have now been applied on several engineering projects, but more case histories are still required for their complete evaluation.

Various regions of the world are covered with soils which are often categorized as "problematic" soils from a geotechnical engineering standpoint. Soils in this category are (i) swelling soils, (ii) collapsing soils, and (iii) residual soils. Typically, their mechanical behavior does not adhere to classical soil mechanics behavior.

Common to all these problematic soils is the fact that their pore-water pressures are negative, relative to atmospheric conditions and most often, the soils are unsaturated. The negative pore-water pressures can be referenced to the pore-air pressure, [i.e., $(u_a - u_w)$] resulting in the definition of the term matric suction. Matric suction is now recognized as one of the stress state variables controlling the mechanical behavior of unsaturated soils (or soils with negative pore-water pressures). The development of techniques and devices for measuring matric suction is important to the advancement of soil mechanics for unsaturated soils. Of particular need is a device which will measure matric suction in situ.

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Direct measurements of negative pore-water pressures are limited to less than one atmosphere below zero gauge pressure because of cavitation of water in the measuring system. An indirect method for measuring matric suction involving thermal conductivity measurements is described in this chapter. This method makes use of the thermal properties of a standard porous medium, which is placed in contact with the soil. The resulting device is called a thermal conductivity sensor to measure matric suction. This chapter considers the potential of these sensors for use in geotechnical engineering.

## HISTORY AND DEVELOPMENT OF THERMAL CONDUCTIVITY SENSORS

The thermal properties of a soil have been found to be indicative of the soil water content. Water is a better thermal conductor than air. The thermal conductivity of soil increases with increasing water contents. This is particularly true where the change in water content is associated with a change in the degree of saturation of the soil.

Shaw and Baver (1939) developed a device consisting of a 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 correlate the thermal conductivity measurements to the water contents of the soil. Johnston (1942) suggested that the thermal conductivity sensor be enclosed in a porous medium that would result in a standard calibration curve. The porous material could then be brought into equilibrium with the soil under consideration. Johnston (1942) used plaster of paris to encase the heating element.

In 1955, Richards patented an electro-thermal element for measuring moisture in porous media. 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 proposed the use of a sandy silt material for the porous block. It was suggested that the porous cup should have an air entry value less than 10 kPa.

Bloodworth and Page (1957) studied three materials for use as a porous cup for the thermal conductivity sensors. Plaster of paris, fired clay, or ceramic and castone (i.e., 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 et al. (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. The sensing unit was embedded in a porous block. The optimum dimensions of the porous block were calculated based on a theoretical analysis. The block must be large enough to contain the heat pulse (particularly for the saturated sensor) without being interfered with by the thermal properties of the surrounding soil. As well, it was found that the higher the ratio of thermal conductivity and diffusivity, the higher the precision with which the water content can be measured. The distribution of the pore size was also important.

Gypsum, cereamics, and mixtures of ceramics and castone were examined as potential porous block materials by Phene et al. (1971). It was found that the ceramic block exhibited a linear response and provided a stable solid matrix.

In the mid-1970s, Moisture Control System Inc. (Findlay, OH) manufactured the MCS 6000 thermal conductivity sensors. The sensor was built using the same design and construction principles as developed by Phene et al. (1971). The manufactured sensors were subjected to a one point calibration. The suggested calibration curves were assumed to be linear from 0 to 300 kPa. Above 300 kPa the calibration curves were empirically extrapolated. In this region the calibration curves became highly nonlinear and less accurate.

The MCS 6000 sensors have been used for matric suction measurements in the laboratory and in the field (Picornell et al., 1983; Lee & 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 were obtained in the range below 300 kPa. 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. The results were in good agreement with piezometer and neutron probe data. However, Moisture Control System Inc. discontinued production in early 1980, and the MCS 6000 sensor is no longer commercially available.

In December 1981, Agwatronics Inc. (Merced, CA) commenced production of the AGWA thermal conductivity sensors as designed and developed by Phene et al. (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 et al., 1989; Fredlund & Wong, 1989). Several other difficulties have also been reported with the use of the AGWA-II sensors. These include the deterioration of the electronics and the porous block with time.

Typical calibration curves of the AGWA-II sensor are presented and discussed in this paper. The AGWA-II sensors have been used for laboratory and field measurements of matric suctions (van der Raadt et al., 1987; Sattler & Fredlund, 1989). Typical results are described in this paper together with techniques used in the measurements. The main consideration is given to the performance of the AGWA-II sensors which are the only sensors commercially available.

## THEORY OF OPERATION

A thermal conductivity sensor consists of a porous ceramic block containing a temperature sensing element and a miniature heater (Fig. 13-1). The thermal conductivity of the porous block varies in accordance with the

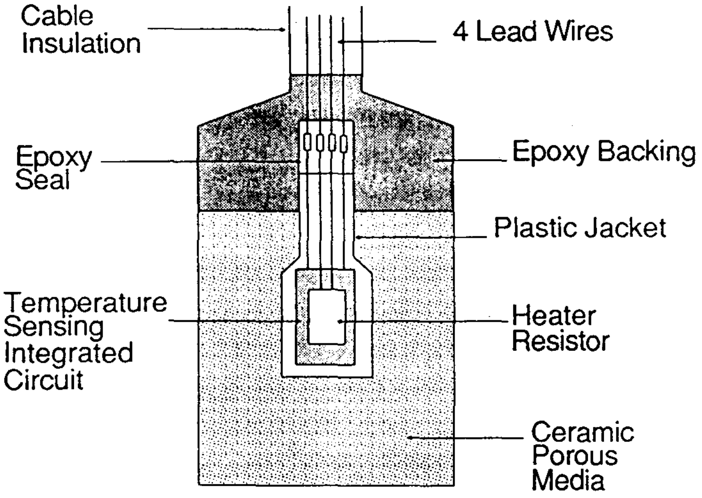

Fig. 13-1. A cross-sectional diagram of the AGWA-II thermal conductivity sensor.

water content in the block. The water content in the porous block is dependent on the matric suctions applied to the block by the surrounding soil. Therefore, the thermal conductivity of the porous block can be calibrated with respect to the applied matric suction.

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 state of stress in the soil (i.e., the matric suction of the soil). Thermal conductivity measurements at equilibrium are an indication of 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 presence of water within the porous block. The *change* in the thermal conductivity of the sensor is directly related to the *change* in water content of the block. Hence, 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 is inversely proportional to the water content of the porous block. The measured temperature rise is expressed in terms of a voltage output.

## CALIBRATION OF SENSORS

AGWA-II sensors are usually subjected to a two-point calibration prior to shipment from the factory. One calibration reading is taken with the sensors placed in water (i.e., zero matric suction). A second calibration reading is taken with the sensors subjected to a suction of approximately 100 kPa. This calibration procedure may be adequate for some applications.

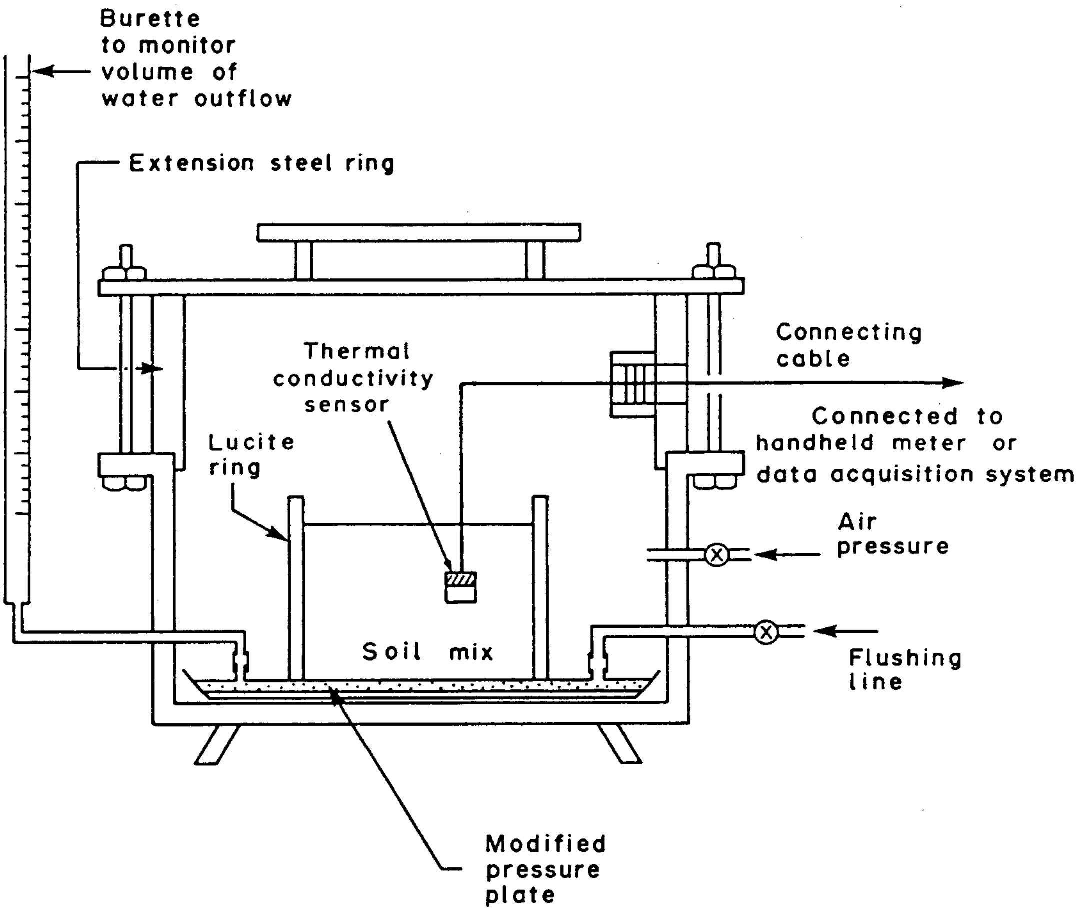

Fig. 13-2. Pressure plate calibration of thermal conductivity sensors.

However, it has been suggested that a more rigorous calibration procedure is necessary when the sensors are used for geotechnical engineering applications (Fredlund & Wong, 1989).

A more thorough calibration of thermal conductivity sensors can be performed by applying a range of matric suction values to the sensors while they are mounted in a soil. Readings of the change in voltage output from the sensor are taken at each applied suction. The change in 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 et al., 1989; Fredlund & Wong, 1989).

The sensor is embedded in a soil that is placed on the pressure plate (Fig. 13-2). The soil on the pressure plate provides continuity between the water phase in the porous block and in the high air entry disc. The matric suction is applied by increasing the air pressure within the pressure plate apparatus, but maintaining the water pressure below the pressure plate at atmospheric conditions.

The change in 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 in order to obtain a calibration curve. A number of thermal conductivity sensors can be calibrated simultaneously on the pressure plate. During calibration, the pressure plate setup should be contained within a temperature controlled box.

At least 40 AGWA-II sensors have been purchased and calibrated at the Univ. of Saskatchewan, Canada. Typical non-linear calibration curves for the AGWA-II sensors are shown in Fig. 13-3. 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. 13-3. The breaking point on the calibration curve was found to be generally around 175 kPa. Relatively accurate measurements of matric suctions with the sensor can be expected using the AGWA-II, particularly within the range of 0 to 175 kPa. Matric suction measurements above 175 kPa correspond to the steeper portion of the calibration curve which has a lower sensitivity.

Times for equilibrium during calibration have ranged from a few days to several months. The longer equilibrium times are required when the soils surrounding the sensors is relatively dry. However, in general, only a few days are required for equilibrium at each applied suction. The characteristic shape of the calibration curves remains the same as long as a reasonable calibration time is allowed. Equilibrium can best be assessed by observing the change in readings on the sensor over a period of several days.

A study on the AGWA-II sensors indicated consistent and stable output readings with time (Fredlund & Wong, 1989). The sensors were found to be responsive to wetting and drying processes. However, some failures

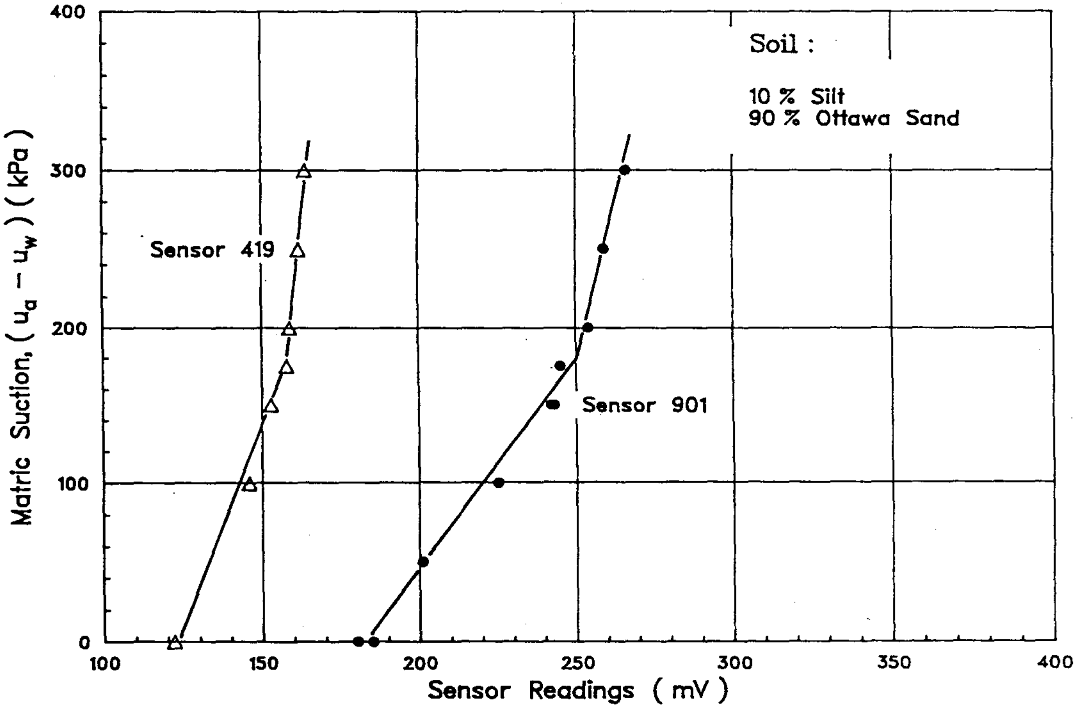

Fig. 13-3. Calibration curves for two AGWA-II thermal conductivity sensors.

have been experienced with sensors particularly when they are subjected to a positive water pressure. The failures are attributed to the possibility of moisture coming into contact with the electronics sealed within the porous block (Wong et al., 1989). As well, there have been continual problems with the porous blocks being too fragile. Therefore, the sensor must be handled with great care. Even so, there is a percentage of the sensors which crack or crumble during calibration or installation.

## TYPICAL RESULTS OF MATRIC SUCTION MEASUREMENTS

Laboratory and field measurements of matric suctions using the AGWA-II thermal conductivity sensors have been made in several types of soils (Rahardjo et al., 1989). The soils ranged from being highly plastic to essentially non-plastic and the sensors have been installed in either an initially wet or initially dry state.

Results of laboratory measurements on highly plastic clays from Sceptre and Regina, Saskatchewan are shown in Fig. 13-4, 13-5, and 13-6. The soils were sampled in the field using Shelby tubes. Matric suction measurements on compacted soils have also been performed on silts from Brazil (Fig. 13-7).

Laboratory measurements were conducted using two sensors in 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 2 d prior to being installed in the soil. The sensors were then inserted into predrilled holes in either end of the soil specimen. The specimen with

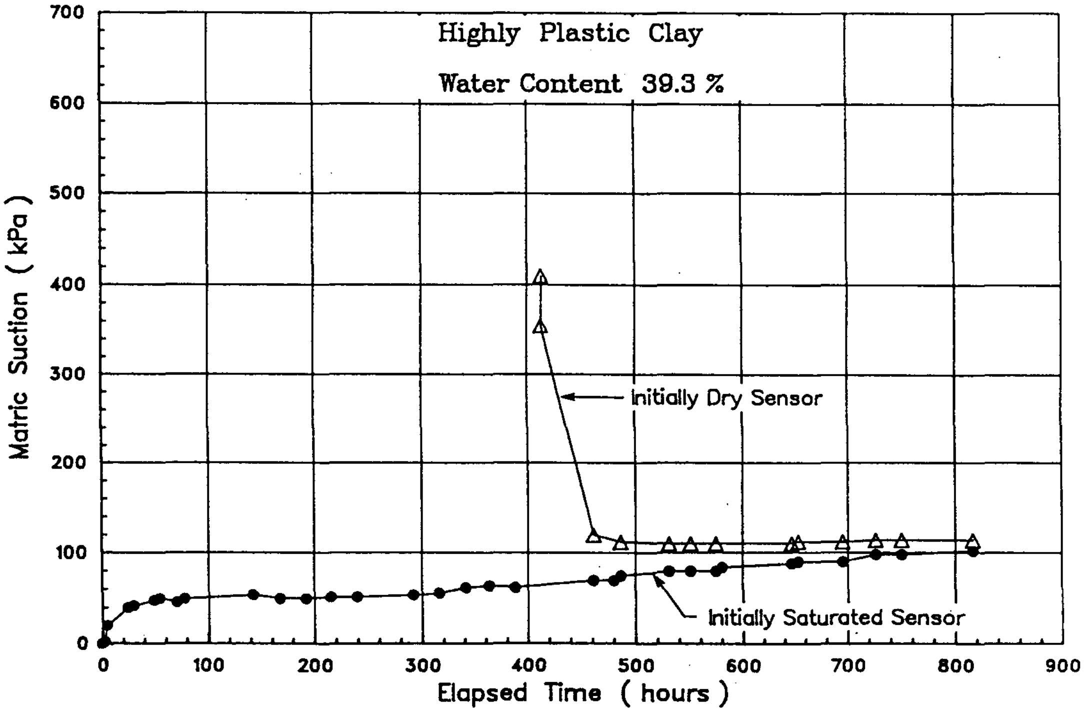

Fig. 13-4. Laboratory measurements of matric suction on highly plastic clay from Sceptre, Saskatchewan, Canada ($w$ = 39.3%).

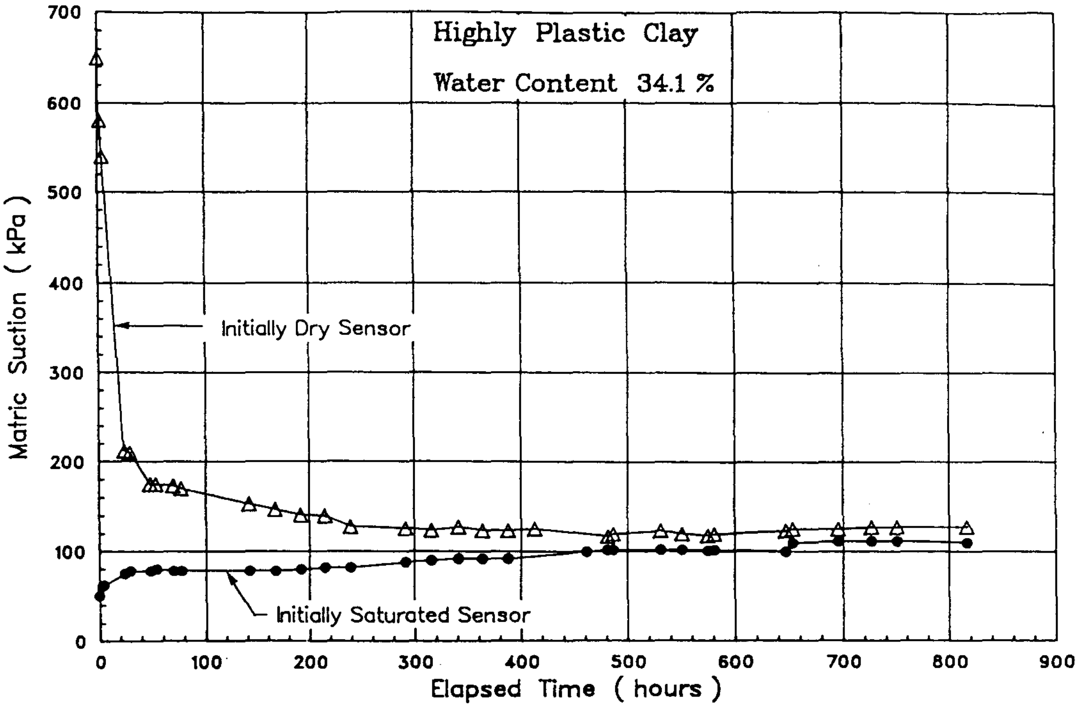

Fig. 13-5. Laboratory measurements of matric suctions on highly plastic clay from Sceptre, Saskatchewan, Canada ($w$ = 34.1%).

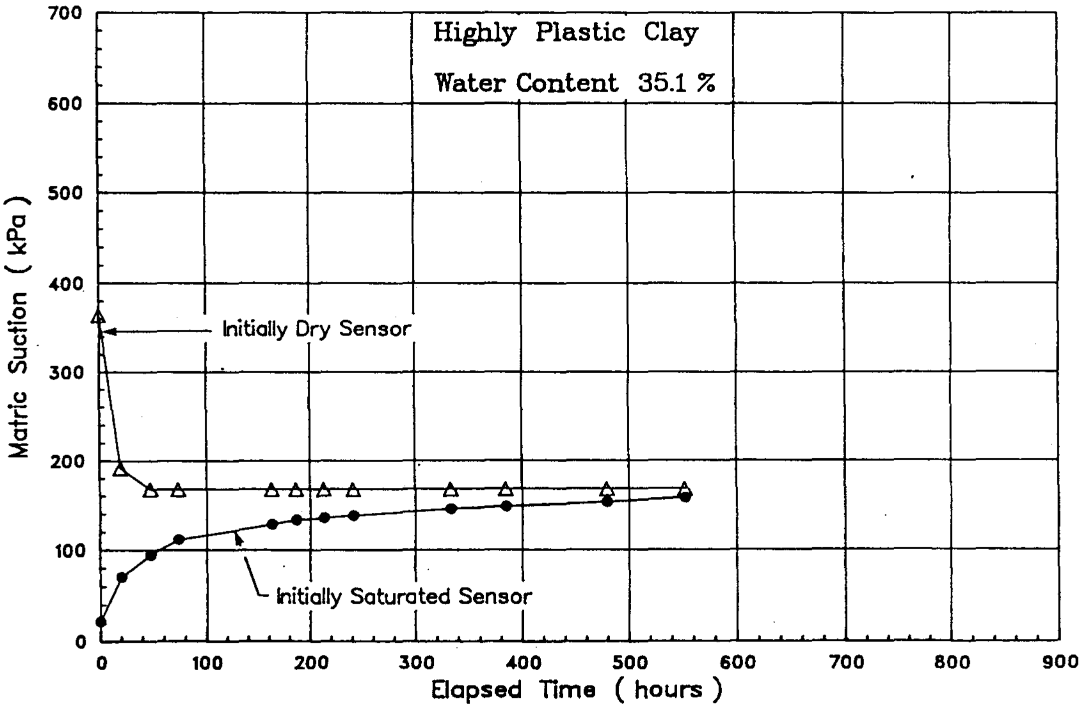

**Fig. 13-6. Laboratory measurements of matric suction on highly plastic clay from Darke Hall, Regina, Saskatchewan, Canada ($w$ = 35.1%).**

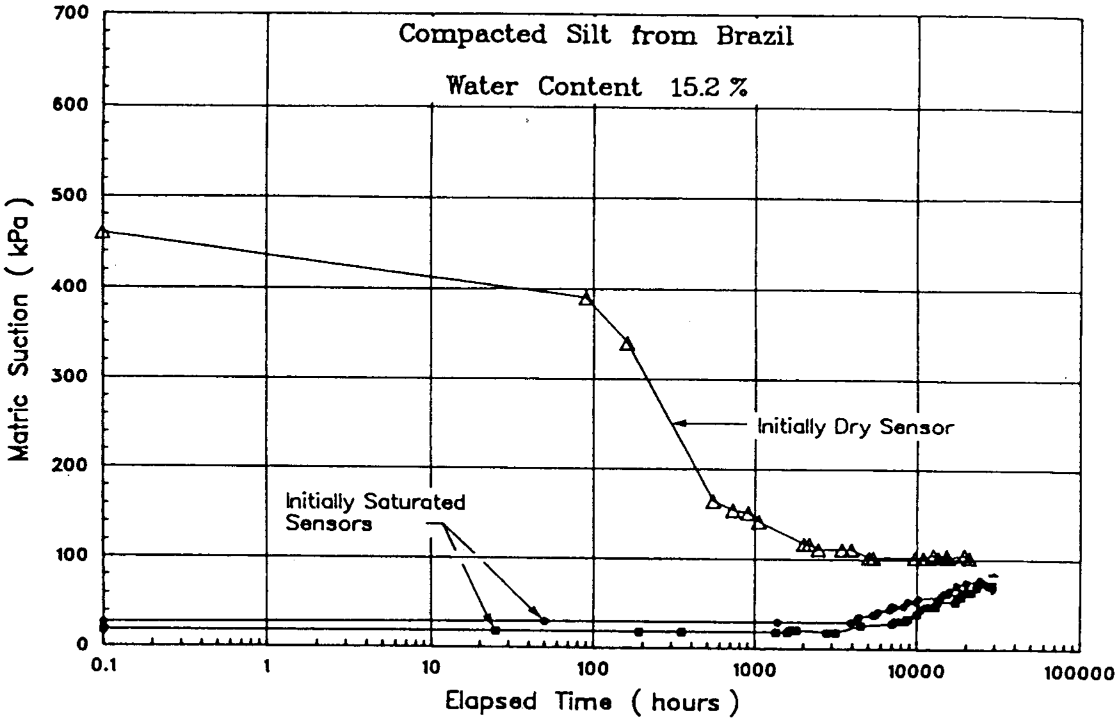

Fig. 13-7. Laboratory measurements of matric suctions on compacted silt from Brazil ($w$ = 15.2%).

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 required for the initially saturated sensor to come to equilibrium.

On the basis of many laboratory experiments, it would appear that the AGWA-II sensors, which were initially dry, yield a matric suction value which is closest to the correct value. In general, the initially dry sensor should yield a value which is slightly too high. On the other hand, the initially wet sensor yields a value which is too low. The following table (Table 13-1) gives the author's interpretation of the results presented in Fig. 13-4 to 13-7, inclusive. Part or all of the difference in matric suction values measured by the dry and wet sensors could be the result of hysteresis in both the sensor and in the soil. The differences are surprisingly small and not necessarily resulting from instrument error.

The sensors are calibrated along a drying mode, starting with a saturated sensor. However, it is recommended that the sensor be installed dry into the soil. The reason is that the amount of water entering the sensor is less when the sensor is dry than the amount of water that would be leaving the sensor if it were initially wet.

On the basis of many laboratory tests, the author would recommend that if only one sensor is installed in an undisturbed sample, the sensor should be initially dry. If the sensors have been calibrated using at least seven data

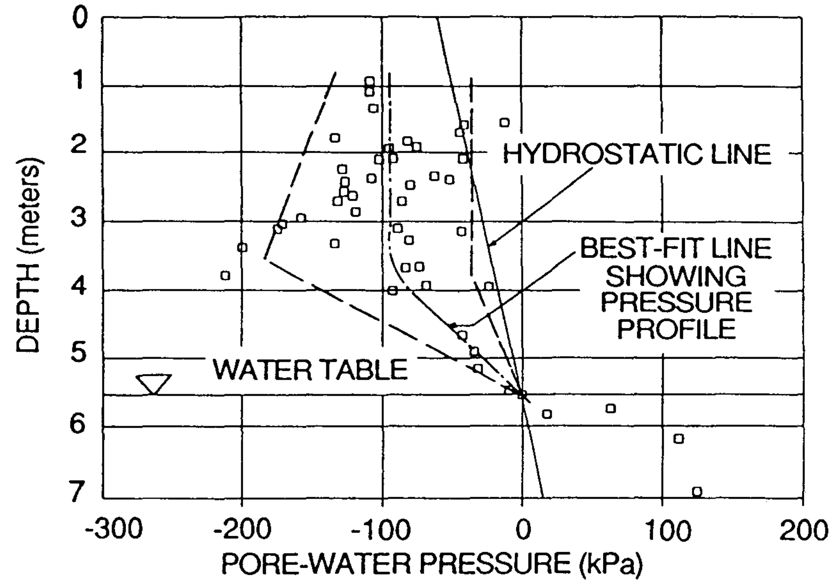

Fig. 13-8. Negative pore-water pressure profiles obtained using the AGWA-II thermal conductivity sensors (from Sattler & Fredlund, 1989).

points, the readings obtained in the laboratory should be accurate to within at least 15 kPa of the correct value provided the matric suction reading is in the range of 0 to 300 kPa. It may take 4 to 7 d before equilibrium has been achieved. If the sensors are left in situ for a long period of time, the measurements should be even more accurate.

Results from laboratory measurements of matric suction have been used to establish the negative pore-water pressures in undisturbed samples of Winnipeg clay taken from various depths within a railway embankment (Sattler et al., 1990). The samples were brought to the laboratory for matric suction measurements using the AGWA-II sensors. The measured matric suctions were corrected for the removal of the overburden stress and plotted as a negative pore-water pressure profile (Fig. 13-8). The results indicated that the negative pore-water pressures approached zero at the average water table and were, in general, more negative than the hydrostatic line above the water table.

Field measurements of matric suction under a controlled environment have been conducted in the subgrade soils of an indoor highway test track

**Table 13-1. Interpretation of laboratory matric suction measurements of four soils.**

| Soil type | Soil classification† | Water content | Figure no. | Initially dry sensor | Initially wet sensor | Best estimate |
|---|---|---|---|---|---|---|
| | | $g\ kg^{-1}$ | | kPa | | |
| Sceptre clay | CH | 393 | 13-4 | 120 | 100 | 114 |
| Sceptre clay | CH | 341 | 13-5 | 136 | 108 | 126 |
| Regina clay | CH | 351 | 13-6 | 160 | 150 | 157 |
| Brazil silt | MH | 152 | 13-7 | 100 | 68 | 90 |

† Unified classification system: CH—highly inorganic plastic clays; and MH—inorganic silts.

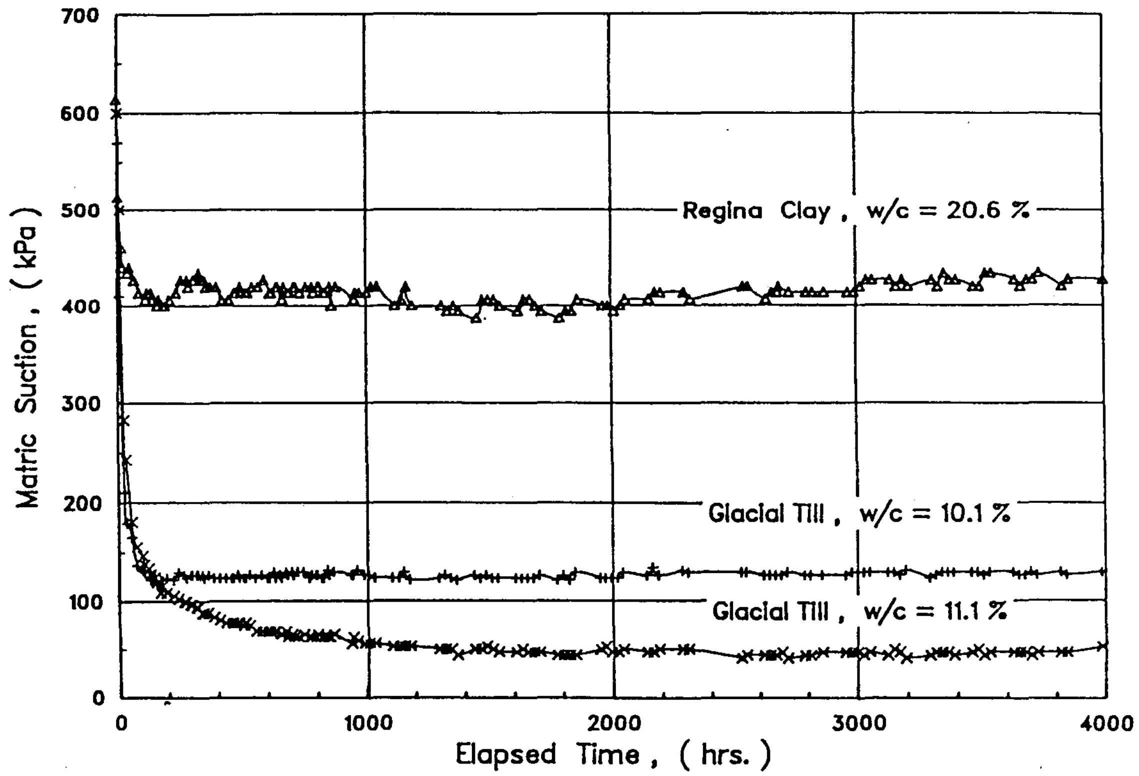

Fig. 13-9. Field measurements of matric suction using the AGWA-II thermal conductivity sensors under controlled environments.

(Loi et al., 1989). 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 subgrade consisted of a highly plastic clay and glacial till. 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 on the compacted Regina clay and glacial till subgrade are presented in Fig. 13-9. Consistent readings of matric suction ranging from 50 to 400 kPa were monitored over a period of more than 5 mo prior to flooding the test track. The sensors responded quickly upon flooding (data not shown on Fig. 13-9). The results demonstrated that the AGWA-II sensors provide stable measurements of matric suction over a relatively long period of time.

Matric suction variations in the field can be related to environmental changes. Several AGWA-II sensors have been installed at various depths in the subgrade below a railroad. The soil was a highly plastic Regina clay that exhibits high swelling potentials. Matric suctions in the soil were monitored at various 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. 13-10).

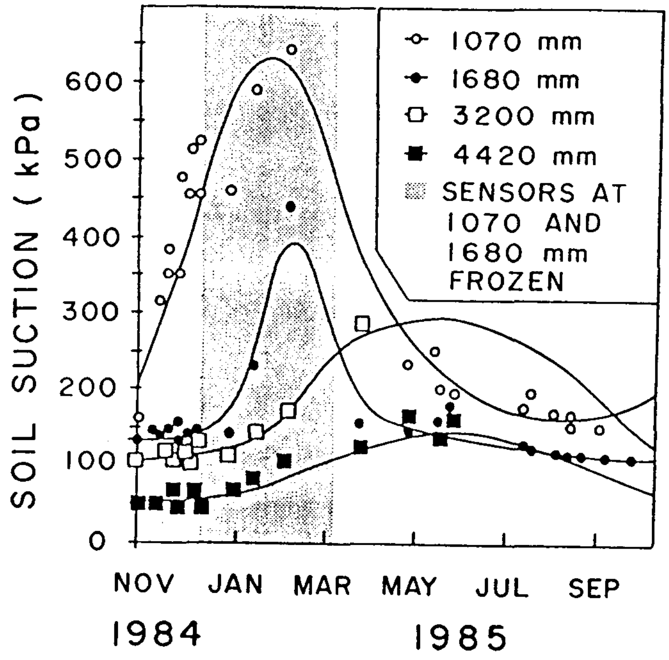

Fig. 13-10. Idealized plot of matric suction versus time of year for various depths of Regina clay in Saskatchewan (from van der Raadt, 1988).

## CONCLUSIONS

Thermal conductivity sensors appear to be a promising device for measuring matric suction 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 revealed that the sensors are quite sensitive for measuring matric suctions up to 175 kPa.

It is possible that future improvements on the AGWA-II sensors will further enhance their performance. For example, a better seal around the electronics within the sensor could reduce the effect of soil water. As well, a stronger, more durable porous block would produce a better sensor for geotechnical engineering applications. These improvements would reduce the mortality rate of the sensor.

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