Measurement of Soil Suction Using the MCS 6000 Sensor

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SUMMARY The MCS 6000 sensor was tested to evaluate its performance and reliability in measuring soil suction. The experimental results show good agreement with results obtained from other suction measurement techniques. It was concluded that the MCS 6000 sensor is suitable for use in geotechnical engineering applications.

1 INTRODUCTION

Soil suction is an important stress variable to measure when dealing with the shear strength and volume change behavior of unsaturated soils (Fredlund, Morgenstern and Widger, 1978 and Fredlund, Hasan and Filson, 1980). A reliable means of measuring soil suction is essential in order that quantitative analysis can be performed. The most common pieces of equipment for measuring soil suction are the tensiometer and psychrometer. The main disadvantage of the tensiometer is its low measuring range. The limitations of the psychrometer are that the soil must have a relatively high pore-water tension and must be in an equilibrium temperature environment (Krahn and Fredlund, 1972). Moreover, the thermocouple of the psychrometer is susceptible to corrosion. Picornell, Lytton and Steinberg (1983) used a commercial heat dissipation sensor, the MCS 6000 sensor, manufactured by Moisture Control System Corporation, Findlay, Ohio, U.S.A., to measure the matric suction in an expansive clay soil. They reported that the sensor was very sensitive and accurate at the low suction range (i.e., below 100 kPa) and could provide stable readings for a period of several years. Lee (1983) reported that the MCS sensor showed a good response to changing weather conditions when used under a field environment.

In this study, the MCS 6000 sensor was tested using both plastic and non-plastic soils to evaluate its performance and reliability in measuring the suction of unsaturated soils. Results were compared to those obtained by using the pressure plate (i.e., axis-translation technique) and the tensiometer.

2 THEORY OF THE MCS 6000 SENSOR

The theory of the sensor is based on the principle of heat dissipation in a porous material. Since the heat conductivity of a porous material is lower than that of the water, the heat dissipation in a porous material is sensitive to its water content. When a standard porous probe is inserted into a soil sample with a different pore-water tension, water will pass from the area of low tension to the area of high pore-water tension. The movement of water takes place through direct capillary flow or vapor diffusion until equilibrium is reached in terms of pore-water tension. The rate of heat dissipation of the standard porous material, therefore, can be measured by supplying a precisely controlled amount of heat at a fixed rate at the centre of the porous block and measuring the temperature rise at the same point after a fixed period of time. The temperature rise is inversely proportional to the moisture content in the standard porous block. The measured temperature is calibrated to read matric suction. The calibration is done by the manufacturer using a pressure plate technique.

3 EQUIPMENT

The equipment used in this study included the MCS 6000 sensor and a portable data display. A temperature control box was also used during the testing program.

3.1 MCS 6000 Sensor

The sensor consists of two temperature sensing semi-conductors (i.e., two diodes), a miniature heater and some electronic circuitry. The temperature sensing element and the heater are embedded in a cylindrical porous ceramic block contained in a Polyvinyl Chloride (PVC) module. Other circuitry is encapsuled in a remote in-line PVC module.

The sensor output signal is a time dependent voltage measurement. This voltage measurement has an approximately one to one linear relationship to the soil matric suction between 10 and 60 kPa (e.g., 60 kPa = 0.6 volt). For suction values above 60 kPa, the sensor must be calibrated. In this study, the calibration used was based on the extrapolation method suggested in the MCS user manual.

3.2 Portable Data Display

The MCS portable data display has a 3-digits read-out system. Measurements can be taken either manually or automatically.

3.3 Temperature Control Box

The temperature control box consisted of an insulated rectangular tank. Mounted in the lid of the box was a stirring motor for circulating the air, and a 100 watt light bulb for heating. The light bulb and the stirring motor were connected to a Fisher transistor relay which was controlled by a Jumo thermal regulator with a sensitivity of ±0.01°C.

4 TEST PROGRAM AND PROCEDURE

The testing program was conducted using a sandy clay till and a highly plastic lacustrine clay known as Regina clay. A silt sample from Cranbrook, Canada was also used to determine the response of the sensor for a non-plastic soil. The results of the classification tests for these soils are shown in Table 1.

TABLE 1

SUMMARY OF THE PROPERTIES OF THE SOILS

	GLACIAL TILL		REGINA CLAY		SILT
	1	2	1	2	
Liquid Limit	37.9%	33.9%	71.3%	78.4%	22.7%
Plastic Limit	15.6%	17.0%	26.6%	30.6%	21.6%
Plasticity Index	22.3%	16.9%	44.7%	47.8%	1.1%
% Sand	37.0	31.8	11.0	5.6	5.0
% Silt	34.0	38.5	28.0	27.2	84.0
% Clay	29.0	29.7	61.0	67.2	11.0

1 -- test results obtained from this study
2 -- test results reported by Krahn et al (1972).

4.1 Matric Suction Measurements in Till, Clay and Silt

The sandy clay till and Regina clay samples were prepared at water contents ranging from 10 to 22 percent and 21 to 43 percent, respectively. Soils samples were compacted according to the ASTM D698-78 standard compaction specification and D1557-78 modified compaction specification. Following compaction, a hole was cored in the top of the sample using a special drill bit (Figure 1) into which the sensor was inserted. Different methods were used to install the sensor in the soil samples. These methods were:

1. placing a dry sensor directly into the sample,
2. placing a saturated sensor directly into the sample,
3. placing a saturated sensor into a wetted drill hole, and
4. placing a dry sensor into a wetted drill hole.

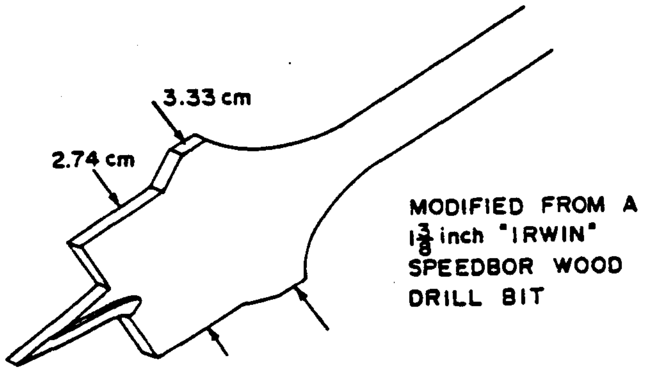

Figure 1 Special drill bit

For some of the Regina clay samples, a slurry (i.e., Regina clay slurry) was used as an interface material in an attempt to improve the contact between the sensor and the soil.

For samples with suction below 100 kPa, a tensiometer was also used to measure suction.

After installing the sensor in the soil, the samples were wrapped in a plastic film (i.e., saran wrap) and covered with masking tape. The sensor was connected to the portable data display unit. Several readings were recorded on the first day. Then one reading was taken per day until the results became stable. The samples were then cut into two halves to examine the contact between the sensor and the soil. The moisture content of the soil was then measured.

Silt sample was prepared at a water content of 21 percent. A saturated sensor was installed in the sample and the matric suction was measured as described previously. After the readings became stable, the sample was unwrapped and allowed to air-dry for a period of 2 to 3 hours. Afterward, the sample was wrapped again and matric suction was monitored until conditions became stable. The weight of the sample (with the sensor) was checked before and after the air-drying process to monitor the change in water content. The entire procedure was repeated until the water content of the sample was reduced to less than 8 percent. Another four samples were tested using the pressure plate extractor to control the suction in the silt. After equilibrium, a series of air-drying stages were performed on the silt samples.

4.2 Testing of the Ambient Temperature Effect

Two clay samples were prepared and compacted at a water content of 31 and 38 percent. After stable suction readings occurred, the samples were unwrapped and then covered again with only plastic film. The samples were then placed in a temperature control box. The temperature was initially set at 21°C (i.e., room temperature). Following the monitoring of equilibrium conditions, the temperature was increased by an increment of 2°C and the matric suction was monitored until equilibrium was reached. The procedure was repeated until reaching a temperature of 32°C.

5 PRESENTATION OF RESULTS

Plots of suction versus water content are used to evaluate the test results. Best-fit curves are presented in each case. In order to get an indication of the accuracy of the MCS sensor, results obtained by Krahn and Fredlund (1972) for a sandy clay till and Regina clay are included for comparison purposes.

Figures 2 and 3 show some examples of the suction versus time plots for the till and Regina clay samples. The method used to determine the initial time required for a stable reading is also included. The fluctuation in the data were severe for soil samples with a low water content. The suction plots using various installation methods are shown in Figures 4, 5 and 6. The time required to obtain a stable reading at various water contents for the till and clay are shown in Figure 7. Figure 8 summarized the test results for the silt samples. Results from null type pressure plate tests are also shown for comparison purposes. The suction versus temperature plots for two Regina clay samples are shown in Figure 9.

6 DISCUSSION

Depending upon the procedure used, the test results were found to agree reasonably well with the best-fit curve reported by Krahn et al (1972). Figures 4 and 5 show that soil samples with a low water contents result in severe fluctuations in the data. The test results show that the MCS 6000

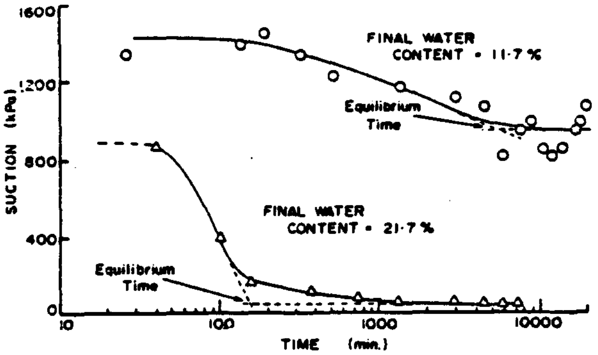

Figure 2 Time versus matric suction for glacial till

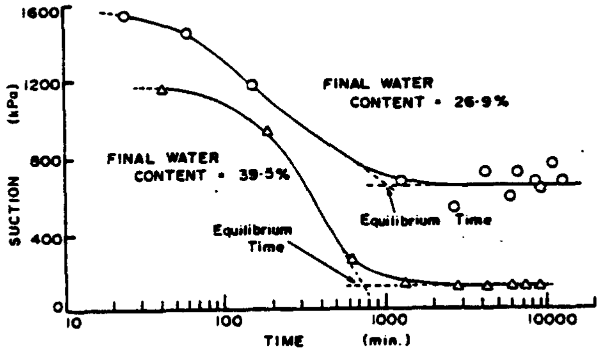

Figure 3 Time versus matric suction for Regina clay

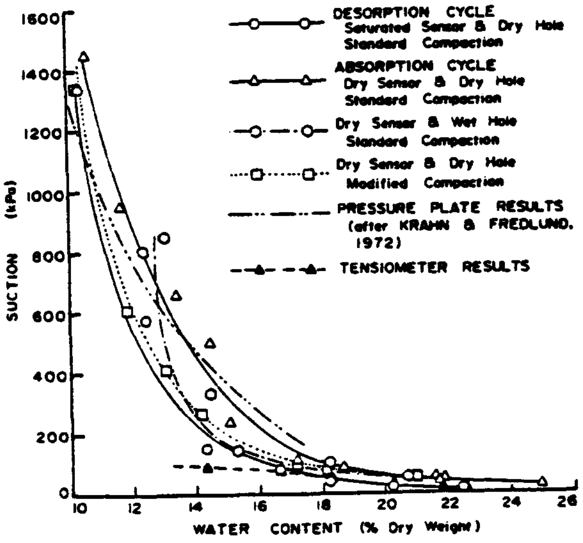

Figure 4 Matric suction versus water content for glacial till with various installation methods

sensor is relatively sensitive and accurate in measuring suctions below 100 kPa. The variation in the test result for the low suction range was ±6 kPa when compared to the tensiometer readings. It was also found that the MCS sensor gave a result very close to those of the tensiometer, when the saturated sensor was installed directly into the soil sample. The sensor commenced losing its sensitivity at higher suction values. At the suction values between 100 to 200 kPa, the fluctuation of the data was approximately ±10 percent from the best-fit curve for each series of tests. When the suctions were greater than 200 kPa the results showed considerable scatter.

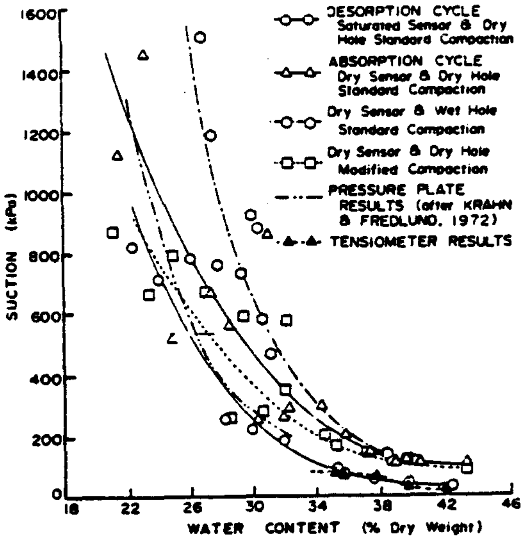

Figure 5 Matric suction versus water content for Regina clay with various installation methods

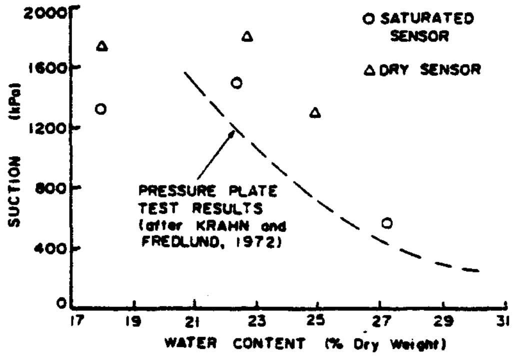

Figure 6 Matric suction versus water content for Regina clay using slurry as an interface between MCS sensor and soil with standard compaction samples

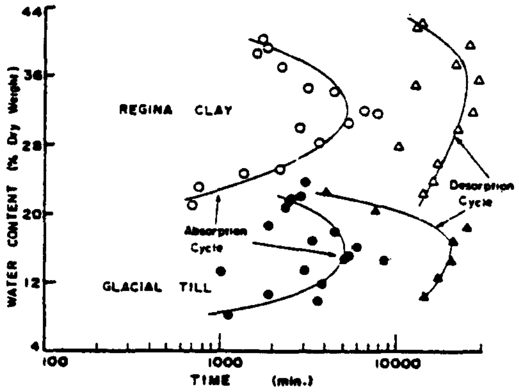

Figure 7 Water content versus response time for glacial till and Regina clay

6.1 Cause for the Variation in the Results

The variation in the test results are believed due to the following factors:

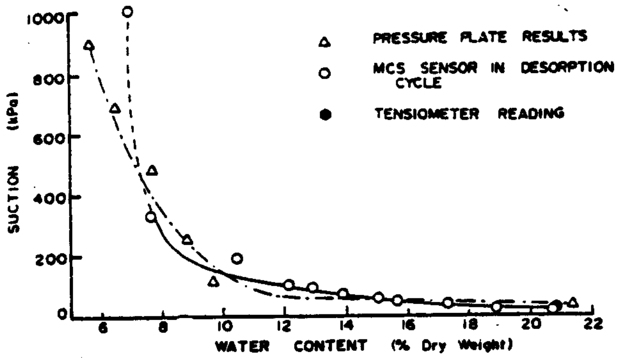

Figure 8 Matric suction versus water content for silt

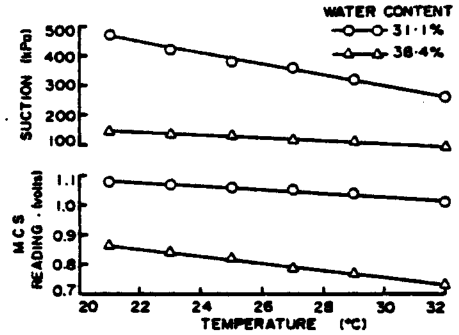

Figure 9 Temperature effect on MCS sensor reading for Regina clay

6.1.1 Limitation of the sensor

The MCS 6000 sensor is believed to have a linear output of voltage in the range from 10 to 60 kPa. However, the voltage output is no longer linear for suction readings higher than 60 kPa. A typical response curve for the suction versus sensor output voltage is shown in Figure 10. As can be noted, the curve drops off rapidly after exceeding a suction of 300 kPa. For example, 1.1 and 1.2 volts have respective suction values of 700 and 1240 kPa. A change of 0.1 volt corresponds to a change of 540 kPa in suction. Therefore, the highly non-linear nature of the calibration curve for the sensor is one of the factors which contributes to scatter in the data.

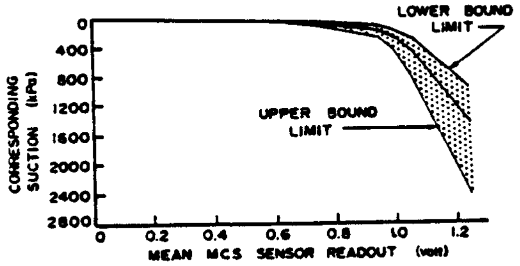

Figure 10 Mean voltage readout of the MCS sensor versus the corresponding matric suction with accuracy (from MCS 6000 system user manual)

6.1.2 The contact between soil and sensor

In the initial stages of the laboratory testing program, sensors were installed in a hand trimmed hole. The contact between the soil and the sensor was found to be inadequate in the case of relatively dry sandy clay till. Later in the program, a clay slurry was used as an interface material between the Regina clay samples and the sensor in order to obtain a better contact. When the samples were dissected after completion of the test, cracks larger than 2 mm in width were found throughout the interface slurry. The presence of cracks created an inadequate contact between the soil and the sensor.

The use of a special drill bit (Figure 1) for the installation of the sensor did not significantly reduce the scatter in the data at high suction level (i.e., higher than 200 kPa). However, it did appear to provide a relatively good contact between the sensor and the soil. The problem of inadequate contact between the sensor and the soil requires further research.

6.1.3 The entrapped air effect

Nagpal and Boersma (1973) reported that air entrapped during the installation of porous probe into the soil will cause a lower thermal conductivity of the porous probe. This in turn results in a higher suction measurement.

6.2 Silt Soil Data

The pressure plate technique used to control the suction in the silt was considered to be unsuccessful due to the following reasons:

1. Due to the shrinkage of the silt, the contact between the MCS sensor and the soil became inadequate at suctions above approximately 200 kPa.
2. The 1500 kPa high air entry porous plate may not be precise enough at low suctions (i.e., below 100 kPa).

Referring to Figure 8, the MCS sensor, however, did show a good response below 100 kPa. The data fluctuated slightly in the range between 100 and 200 kPa. It was concluded that the sensor was capable of measuring suctions up to approximately 200 kPa in a non-plastic silt.

6.3 The Hysteretic Effect

In the testing program, both saturated and dry MCS sensors were used to measure the matric suction of the soil. When the porous sensor comes into contact with an unsaturated soil, two possible situations can arise. First, the soil could draw water from the porous block. As the water passes into the soil, the suction in the soil decreases. Secondly, the porous block could draw water from the surrounding soil into the block. As water passes into the porous block, the suction in the soil increases.

Referring to Figures 4 and 5, the desorption cycle (i.e., saturated sensor installed into a dry drilled hole) of the sensor gives a lower suction than the absorption cycle (i.e., dry sensor installed into a dry drilled hole) at a same water content. Therefore, there is some hysteresis associated with the method used to measure suction.

6.4 Temperature Effect

The matric suction was found to decrease with an increase in temperature (Figure 10). Previous studies (Richards and Weaver, 1944; Gardner, 1955; Wilkinson and Klute, 1962) have demonstrated a similar phenomenon. When the temperature in the control box was increased, heat was transferred to the soil. It is believed that moisture then migrated from the warmer to the cooler portion of the soil sample. Consequently, a higher water content was measured near the central portion of the soil surrounding the MCS sensor. This resulted in a lower suction readings. This phenomenon is similar to that reported by Gardner (1955).

7 CONCLUSION

The following conclusions can be drawn on the basis of the test results and the procedures used.

1. The MCS 6000 sensor is relatively sensitive and accurate in measuring suctions below 100 kPa. The variation in the suction measurement should be in the order of ±6 kPa. The sensor commences losing its sensitivity at higher suction values. At suctions between 100 to 200 kPa, the fluctuation of the data was approximately ±10 percent from the best-fit curve for each series of tests. For suction value higher than 200 kPa, the results show considerable scatter.

2. The procedure of placing a saturated sensor into the soil sample is recommended for measurements at the low suction level.

3. The suction values measured during the absorption of the sensor were higher than those measured during a desorption of the sensor.

4. The maximum time required for the sensor to reach equilibrium occurred at water contents near optimum. The equilibrium times for the absorption cycle were in the order of 3 days. The equilibrium time for the desorption cycle was considerably longer.

5. An increase in the ambient temperature in a close system lead to a decrease in the suction readings for the soil tested.

6. The results indicate that the MCS 6000 sensor can be used in geotechnical engineering to measure soil suction.

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