Soil Suction Measurements at Several Sites in Western Canada

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Much of the difficulty in understanding the behavior of unsaturated soils comes from the lack of reliable means to measure the in situ soil suction, particularly when the suction is in excess of one atmosphere. In 1984, an extensive study was undertaken to investigate the use of the latest technology available for the measurement of soil suction. Several systems of measurement or devices were used in the study. The main objective of the study was to demonstrate how to measure soil suction in situ. The primary system used for the in situ measurement of matric suction was a commercially available thermal conductivity sensor. These sensors were selected because of the wide range of soil suctions that were anticipated in the in situ clays. Also, the installed sensors required no servicing and were easily adapted to electronic data acquisition for remote measurement. Other independent methods used included thermocouple psychrometers and two filter paper techniques. Five sites, located in western Canada, were selected for this study. A detailed subsurface investigation was conducted at each location. Representative disturbed and undisturbed samples were obtained for material characterization and for laboratory determinations of soil suction. All sites were instrumented by installing a culvert, 915 mm in diameter and 6 m in length. The culvert was installed vertically, off the edge of the railway ties. Six holes were cut through the culvert wall at predetermined depths below the top of the subgrade. Plastic sleeves were installed into the side of the excavation through these openings. The thermal conductivity matric suction sensors were then installed in undisturbed soil at the end of the sleeve. The sensors were connected to a data-acquisition system suspended within the culvert. Laboratory determinations of soil suction, using the psychrometer method, were conducted on undisturbed samples in order to establish a basis for comparison with the in situ measurements. The results of the study indicate that the thermal conductivity matric suction sensors show good potential for the in situ measurement of soil suction. Reasonable agreement was demonstrated between the field measurements and the laboratory results for the clay and fine-grained soils tested.

The behavior of compacted and natural unsaturated soils is strongly influenced by the state of stress in the pore water. The pore-water pressure is negative (relative to atmospheric pressure) and varies in response to the surrounding microclimate. A change in the negative pore-water pressure in turn produces a change in the volume and shear strength of the soil. An understanding of the effect of changing negative pore-water pressures is important from an engineering standpoint *(1, 2)*.

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The negative pore-water pressure relative to the pore-air pressure (i.e., generally at atmospheric conditions) is referred to as matric suction. Another component of suction, called solute suction, is a function of the salt content of the pore fluid. The sum of the matric and solute suction is called total suction *(3–5)*.

The slowness in the development of a technology for understanding the behavior of unsaturated soils can be largely traced to the difficulties associated with measuring soil suction and in particular the negative pore-water pressure. Tensiometers have been used in soil science and other disciplines for several decades and have proven quite useful in measuring suctions less than approximately 0.9 atmosphere. The axis-translation technique has been used extensively in the laboratory. However, there has been a need for new devices and techniques that will provide reliable in situ measurements of soil suction, particularly in excess of one atmosphere of suction.

In 1984, a study was undertaken to investigate the latest technology available for the measurement of soil suction and an attempt to use this technology at several sites. The study was conducted by Clifton Associates Ltd., and was funded by Canadian Pacific Rail (CP), Canadian National Railways (CN), and the Transport Development Centre, Government of Canada (TDC). The main objectives of the study were

1. To measure soil suction in the field by using several methods;
2. To demonstrate the manner in which soil suction varies with the seasons in response to a changing microclimate; and
3. To assess the reliability of available devices for the measurement of soil suction. Particular attention was given to the use of the AGWA-II thermal conductivity sensor.

SYSTEMS TO MEASURE SOIL SUCTION

Three methods were used to measure suction in situ and in the laboratory. These were

1. The filter paper method,
2. The psychrometer, and
3. The AGWA-II thermal conductivity sensor.

Various types of tensiometers have been developed for measuring negative pore-water pressures. They have a limited range, require almost daily servicing, and are generally slow to equalize in highly plastic soils. It was decided not to use tensiometers in this study.

The Filter Paper Method

The filter paper method involves the placement of a filter paper either in direct contact with a soil specimen or in suspension above a soil suction specimen placed in a container *(6–8)*. Moisture equalization between the filter paper and the soil should take place in a relatively constant temperature environment. The filter papers are pretreated with a fungicide to inhibit bacterial growth.

The filter papers were allowed to equilibrate for at least 1 week before their water content was measured. The water content was then used along with the calibration curves to determine the suction of the soil. Considerable research has been done *(7, 9–12)* to establish calibration curves for the filter paper. Calibration curves established by McQueen and Miller *(7)* are shown in Figure 1.

Direct Contact Procedure

When dry filter paper is placed in contact with a soil sample, water will flow from the soil to the filter paper. Some water may enter the filter paper by vapor flow but equalization should be primarily through fluid flow as long as the soil is not extremely dry. Water movement should continue until the suction in the filter paper is equal to the suction of the soil. The filter paper is small in size when compared to the soil specimen and the amount of water movement from the soil is small. The filter paper is assumed to measure matric suction as there is a direct contact between the water in the soil and the filter paper.

Noncontact Procedure

When filter paper is suspended above a soil sample (i.e., no contact with the soil), the filter paper gains water from the soil through vapor movement. A potential difference exists between the soil pore water and the filter paper. The potential of the soil water is a function of matric suction and solute suction. Therefore, the equilibrium water content of the filter paper is a measure of the total suction of the soil.

Theoretically, it should be possible to measure both matric and total suction using slightly different filter paper procedures. A high degree of contact between the filter paper and the soil should result in the measurement of matric suction. No contact between the soil and the filter paper should result in the measurement of total suction.

Thermocouple Psychrometer Method

The thermocouple psychrometer measures total suction by using the Peltier effect to measure the relative humidity in the environment of a soil specimen placed in a sealed chamber *(13)*. The psychrometer is capable of measuring suctions ranging from approximately 100 to 8000 kPa. The accuracy of the suction measurement is a function of the constancy of the temperature environment in which the measurement is conducted *(14)*.

A psychrometer consists of a measuring junction of copper and constantan. A reference junction is also reused in measuring the sensor temperature. The construction of the 3-wire psychrometer and the chamber into which it is placed is shown in Figure 2.

A soil specimen is placed in the chamber with the psychrometer. Water evaporates from the soil into the sealed chamber. Evaporation ceases when the relative humidity in the chamber is equal to that of the air in the soil. A soil with a high total suction will have a depressed relative humidity, and vice versa.

Measurements of relative humidity must be made in a controlled temperature environment. Therefore, it is essentially imperative that these measurements be made in the laboratory *(15, 16)*. The temperature environment was maintained within ±0.01°C during this study.

The output from the psychrometer is in microvolts, which can be related to soil suction through use of a calibration curve. A calibration curve for each psychrometer is established by placing the psychrometer above an aqueous solution of NaCl *(17, 18)*. This procedure is repeated several times using various molar strengths of NaCl. A typical calibration curve is shown in Figure 2.

AGWA-II Thermal Conductivity Sensors

The AGWA-II sensor consists of a thermister and a 20-ohm heater embedded in a porous ceramic block *(19)*. The sensor gives an indirect measure of matric suction by using the heat dissipation characteristics of the ceramic block and the fluid in the pores *(20)*. The thermal conductivity of the ceramic block is much lower than that of water. As such, the amount of water in the pores greatly influences its thermal conductivity. As the suction in the soil reduces the water content of the ceramic block, its thermal conductivity is reduced. These sensors are

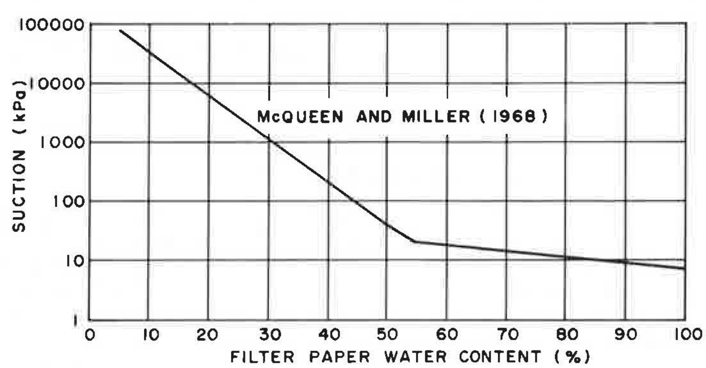
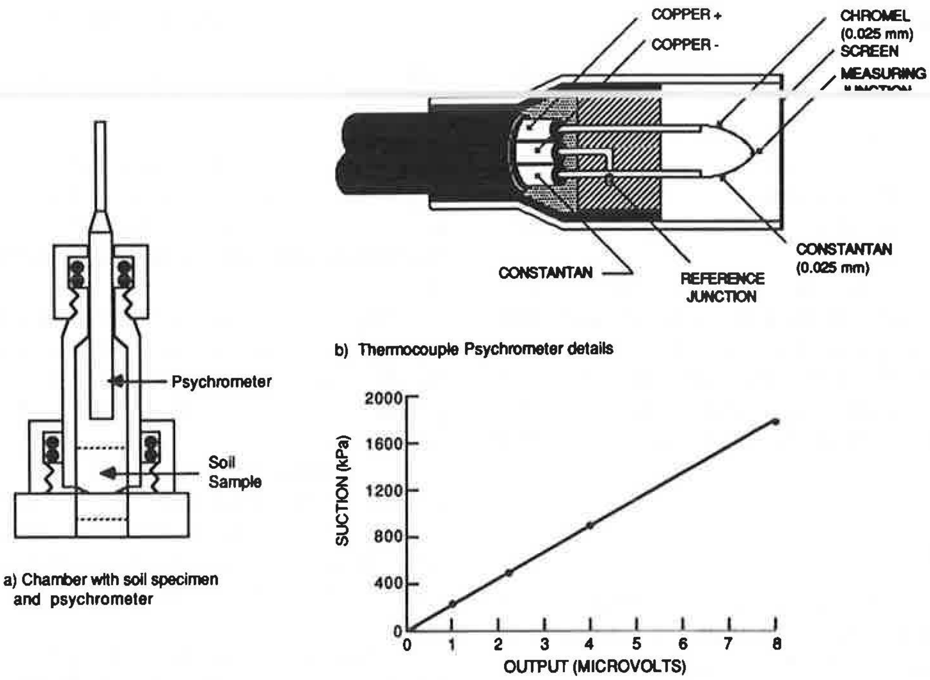


FIGURE 1 Calibration curve for filter paper versus suction.



c) Calibration Curve for Psychrometer

FIGURE 2 Details of the thermocouple psychrometer system to measure suction: (a) chamber with soil specimen and psychrometer, (b) thermocouple psychrometer details, and (c) calibration curves for psychrometer.

similar in principle to those manufactured previously by Moisture Control Systems of Findlay, Ohio *(21, 22)*.

The operation of the sensor can be described as follows. A controlled amount of heat (i.e., a constant current source for a specific time) is added to the center of the ceramic block. The temperature in the block is measured after a specified time interval. The rate at which heat dissipates is directly related to the water content of the ceramic block. The sensor is calibrated to give a fixed relationship between the rate of heat dissipation and the matric suction of the ceramic block.

Sensor calibrations were provided by the manufacturer. Their calibration procedure involved placing the sensors in a fine sand on a pressure plate apparatus. The sand and sensors were subjected to an applied suction until equilibration was established and their thermal conductivity was then measured. The sensors were read in the field using a hand-held meter. Some difficulties were encountered with the meter; these will be discussed later in this paper.

FIELD PROGRAM

Four sites located in western Canada were initially selected for the field program (see Table 1). A fifth site was subsequently added. The sites were selected on the basis of material type and proximity to major urban centers for ease of access. Sites Nos. 1, 2, and 3 are situated in highly plastic clay. Site No. 4 is situated in till and Site No. 5 is in a silty clay. Site No. 1 is located in an older subgrade that has not failed but is a continuing maintenance problem. Site No. 3 is located within a new subgrade, constructed within the last few years. Site No. 4 is located in a high-traffic section showing no distress. Site No. 5 is located in a large fill section that is currently performing well.

Sites Nos. 1, 2, 3, and 4 are all located within a 60-kilometer radius of Regina. Site No. 5 is located near Fort Saskatchewan, Alberta. The location of each site is indicated in Figure 3.

A subsurface investigation was carried out at each of the above site locations. The investigation included the gathering

TABLE 1 SITE LOCATION FOR TEST INSTALLATIONS

Site No.	Location	Rail System	Mileage and Subdivision
1	Belle Plain, Saskatchewan	CN	Mile 24.3 CB01
2	Bechard, Saskatchewan	CN	Mile 78.3 Lewvan Sub.
3	Regina, Saskatchewan	CN	New Lewvan Bypass
4	McLean, Saskatchewan	CP	Mile 67.2 Broadview Sub.
5	Fort Saskatchewan, Alberta	CN	Mile 2.14 Beamer Sub.

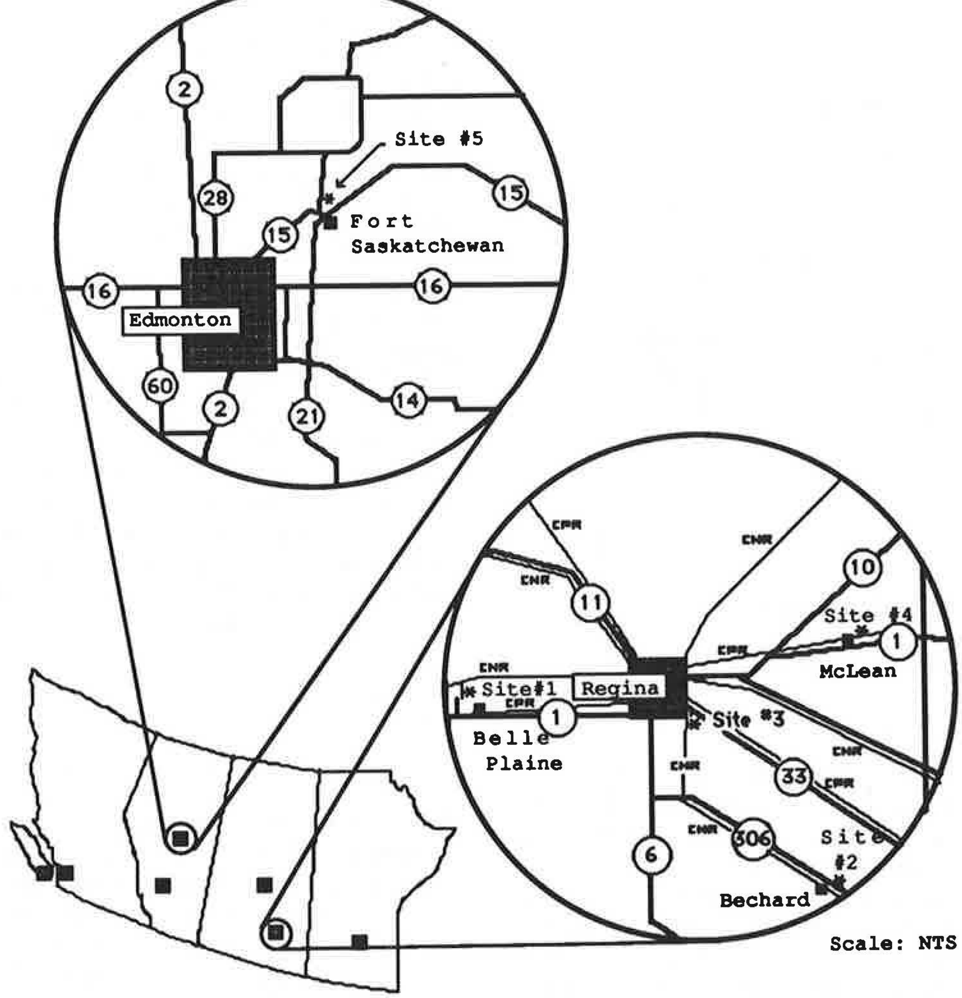


FIGURE 3 Plan showing location of sites in western Canada.

of representative disturbed and undisturbed samples for laboratory visual classification and index testing, followed by laboratory suction measurements. All sites were instrumented by installing a prefabricated 915-mm diameter culvert vertically, 6 m below the top of the tie elevation. The culvert was located directly off the end of the ties. AGWA-II sensors were installed at predetermined depths below the subgrade through the vertical wall of the culvert. A typical detail of this installation in illustrated in Figure 4. The location of the sensors for each site is indicated on the respective borehole logs. A standpipe piezometer was installed below the bottom of the culvert at each site to monitor the groundwater level.

The field monitoring of the AGWA-II sensors was initially performed with a hand-held readout device. In the early stages of the program, the sensors located within the Regina area were read every 1 to 3 days. The Edmonton site was read on a less frequent basis with the same readout device. Early in 1985, the frequency of readings was somewhat reduced. During the month of March an automated data acquisition system (i.e., data logger) was used. This method of data collection allowed the collection of data at an increased frequency. Initially, the data logger was used in a manual mode to read all of the sites in the Regina area. This was done to establish a correlation between the hand-held device and the data-acquisition system. The data-acquisition system was then installed at Site No. 1, where the performance of the system could be easily monitored. The data logger was initially set to read the sensors, on an hourly interval. The data presented in this paper cover only the results obtained using the hand-held readout device.

PRESENTATION OF DATA AND DISCUSSION OF RESULTS

Extensive data have been collected on suction measurements at the five sites. It is not possible to present and discuss all the data. Therefore, the data from Sites Nos. 1 and 3 have been selected for more detailed presentation and discussion. Only a brief summary of the findings from the other sites is included. Much of the interpretation of the data is based on previous research studies performed on similar materials *(4)*.

Site No. 1

Site No. 1 is located on CN trackage near Belle Plaine, Saskatchewan. The track condition at this location is poor and

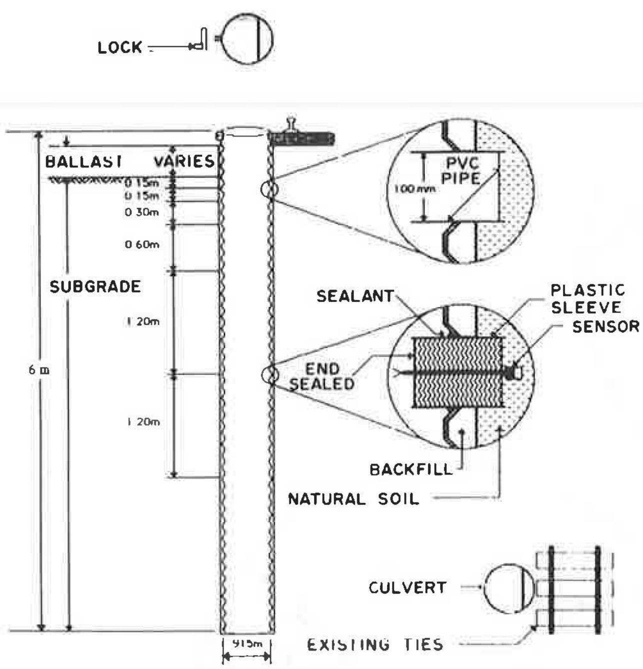


FIGURE 4 Typical culvert and sensor installation details.

much effort has been devoted annually to lifting and aligning the tracks. This is a spur line into a large potash mine and as such is subjected to heavy loading. The track has bearing capacity failures for most of its length.

The stratigraphy consists of 460 mm of gravel ballast and subballast overlying 5.6 m of stiff, highly plastic clay. The clay is underlain by a stiff-to-hard glacial till at the 6.1 m depth (Figure 5). A standpipe piezometer was installed with its tip at 9 m below grade. The piezometer remained dry for the duration of the project but a small amount of seepage entered the culvert during the spring breakup period.

AGWA-II sensors were installed on November 7, 1984. The sensors were saturated before installation. It is estimated that as much as 30 days were required to produce equilibration between the sensor and the soil (Figure 6). Most of the sensors appeared to have reached an equilibrium condition early in 1985. In late February 1985, the sensors began to freeze. During the equilibration time, the suction measurements climbed as the excess water within the sensor was drawn out by the suction of the soil. After some time, the sensors appeared to have stabilized with only a few departures from this trend. It is not known whether these periodic fluctuations are indeed variations in soil suction or whether they are related to the temperature influences on the hand-held readout device or possibly due to the temperature variations in the soil.

Based on the data collected to date, the AGWA-II sensors indicate matric suctions ranging from 75 to 250 kPa for the surficial clays. The suction profile was S shaped with respect to depth. Higher suctions were noted near the top of the subgrade just underlying the ballast. The suctions then varied slightly and finally decreased with depth (Figure 7). The suctions measuring using the AGWA-II sensors are in the range anticipated for Regina clay at the observed field water contents.

Both contact and noncontact filter paper measurements were made on undisturbed samples taken on November 7, 1984. The tests were performed in the laboratory. The filter paper was placed against the soil sample and double wrapped with Saran Wrap and tinfoil and taped for the contact measurements. The samples were stored in a moist room at 22°C. The measured matric suctions ranged from 20 to 3000 kPa (Figure 8). The large scatter would indicate that possibly some of the filter papers did not have satisfactory contact with the soil and as a result measured total suction.

The results of two sets of data (i.e., two testholes) from filter papers not in contact with the soil are also shown in Figure 8. The total suctions ranged from 50 to 1800 kPa with a typical average of 545 kPa.

Total suction measurements using the psychrometer are shown in Figure 9. The results are relatively constant, ranging from 260 to 600 kPa. These values are also in the range of anticipated values for Regina clay at the observed water contents. Although the filter paper and psychrometer measurements are in the same order of magnitude, the filter paper results show considerable scatter. It appears that at low water contents it may be difficult to obtain a good contact between the soil and the filter paper.

Site No. 2

Site No. 2 is located on CN trackage south of Bechard, Saskatchewan. The track condition at this site is poor and requires periodic maintenance. This is a branch line with the principal commodity transported being grain.

The stratigraphy consists of 760 mm of gravel ballast and sand subballast overlying 1200 mm of stiff, highly plastic clay. This clay was strongly organic in nature. Underlying this clay is a stiff-to-hard, highly plastic clay that becomes less plastic just above the glacial till contact at the 7.9 m depth. The till was stiff to hard. A standpipe piezometer was initially dry but later indicated a water level 5.4 m below grade.

The AGWA-II sensors were installed on November 8, 1984. The measured matric suctions ranged from 130 to 225 kPa, with an average of 160 kPa. The contact filter paper measurements gave an average suction of 1075 kPa. This would indicate poor contact between the soil and the filter paper. The noncontact filter papers gave total suction ranging from 150 to 400 kPa, with an average of 240 kPa. These results could possibly be too low due to condensation droplets as a result of slight fluctuation in temperature. The psychrometer data gave total suctions ranging from 280 to 650 kPa, with an average of 490 kPa. The psychrometric data appear to be in the anticipated range for total suction.

Site No. 3

Site No. 3 is located on CN trackage near Regina, Saskatchewan. This line was recently moved to make way for the construction of the new Lewvan expressway in the city of Regina. The track condition is excellent. Recent construction and compaction were primary reasons for the selection of this site.

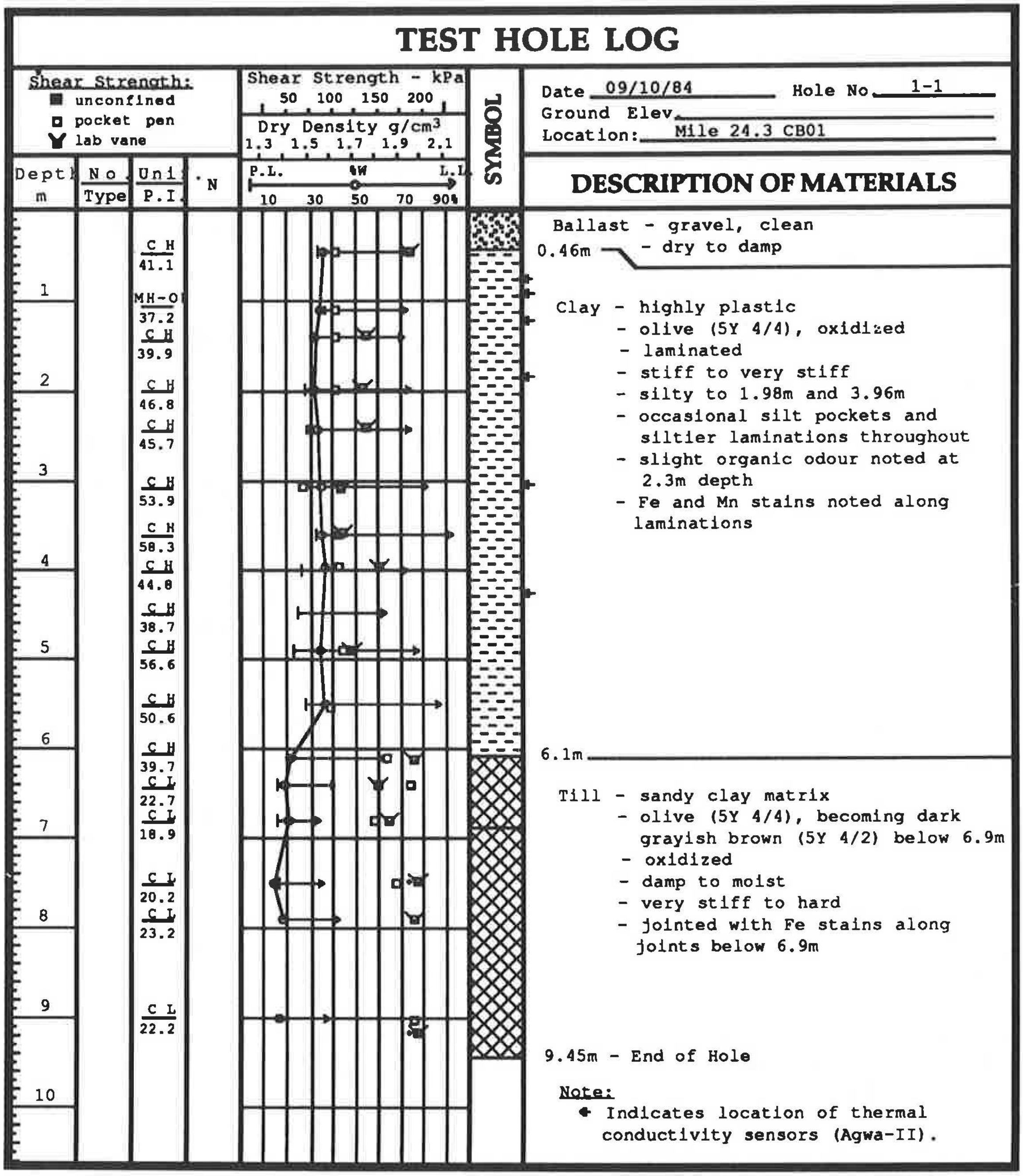


FIGURE 5 Test hole information from Site No. 1, Belle Plaine.

The stratigraphy consists of 460 mm of gravel ballast and subballast. Underlying the ballast is stiff-to-hard, highly plastic clay, which becomes less plastic just above the clayey silt contact at 5.8 m. The underlying silt has a thickness of 800 mm. Till was encountered below the silt and had a medium-to-stiff consistency (Figure 10). A piezometer was installed with its tip 9.1 m below the top of the tie. After the water levels stabilized in the standpipe piezometer, a water level of 4.7 m below grade was measured.

AGWA-II sensors were installed in the surficial clay at this site on November 8, 1984. By February 14, 1985, all sensors were responding well (Figure 11). The AGWA-II sensors were installed only within the surficial clays. The matric suction measured by the AGWA-II sensors indicated a range of from 60 to 275 kPa, with an average value of 160 kPa (Figure 12). The data show a typical S-shaped distribution of suction versus depth, rapidly decreasing to the water table.

The contact filter paper method indicated an average suction for the clay of 800 kPa with a range of from 400 to 5000 kPa (Figure 13). The noncontact filter paper method showed suctions ranging from 675 to 1500 kPa, with an average value of 1360 kPa. The above results would indicate that when an attempt is made to measure matric suction using filter paper, total suction is often inadvertently measured.

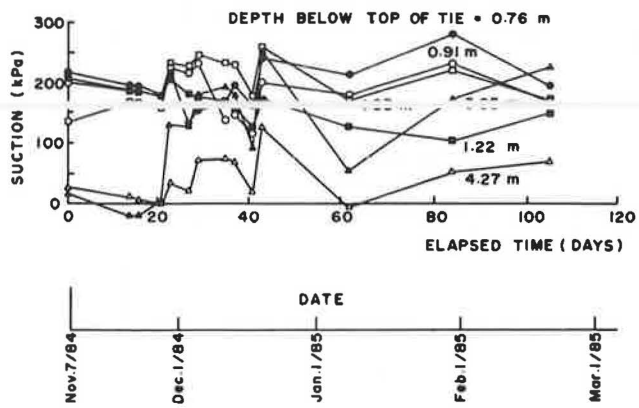


FIGURE 6 Plot of suction versus elapsed time for AGWA-II sensors at Site No. 1.

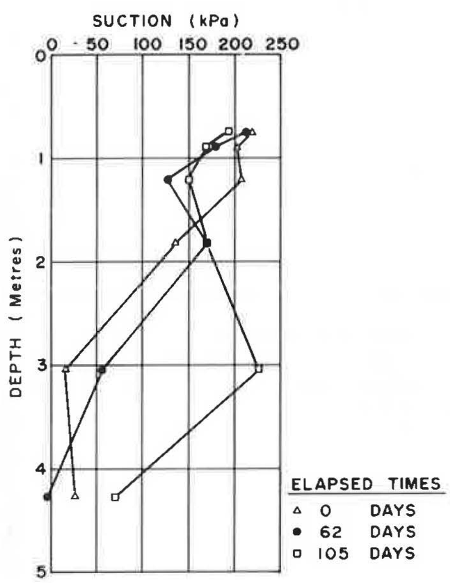


FIGURE 7 Plot of matric suction versus depth measured using AGWA-II sensors at Site No. 1.

The results from the psychrometer measurements are also shown in Figure 13. The psychrometer measurements indicate total suctions ranging from 575 to 1575 kPa, with an average of 920 kPa.

The subgrade at Site No. 3 was just recently constructed. The plot of shear strength versus depth, as illustrated on the testhole log (Figure 10), shows a correlation with the suction profile measured on February 14, 1985. The plot of shear strength by both the vane shear and pocket penetrometer methods indicates an undrained strength of 200 kPa near the top of the subgrade, dropping off rapidly to 100 kPa at the 3 m depth. The shear strength is maintained at this value and only slightly increases when the siltier material is encountered at the 5.8 m depth. The strength then increases slightly within the till. The reason for the increase in shear strength near the surface can be attributed to both the increased suction and possibly the compactive effort applied during construction.

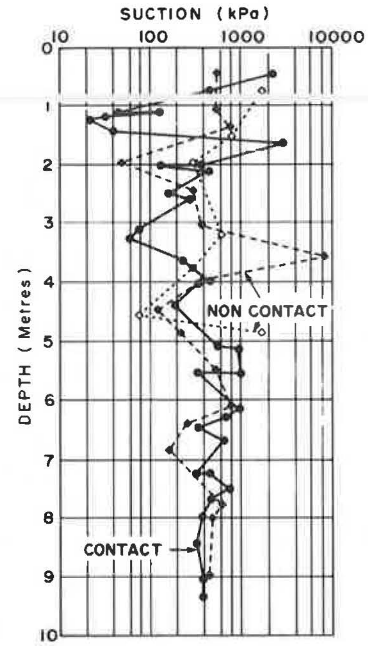


FIGURE 8 Suction versus depth for test hole No. 1 using the McQueen and Miller filter paper method.

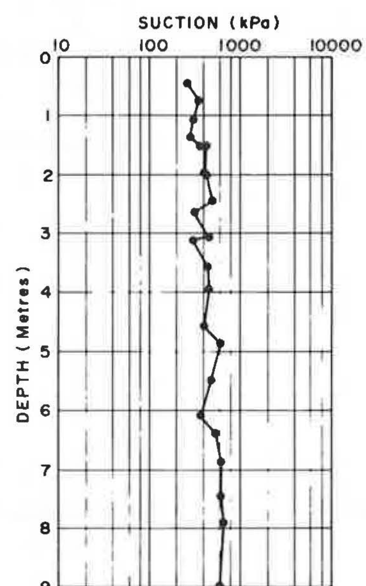


FIGURE 9 Plot of total suction versus depth for Site No. 1 using the psychrometric method.

Site No. 4

Site No. 4 is located on the CP main line 3.5-km east of McLean, Saskatchewan. The site, founded almost entirely on till, is subjected to large traffic volumes of various loadings and is performing well.

The stratigraphy at this site is relatively uniform. The surficial strata consist of 760 mm of gravel ballast and subballast.

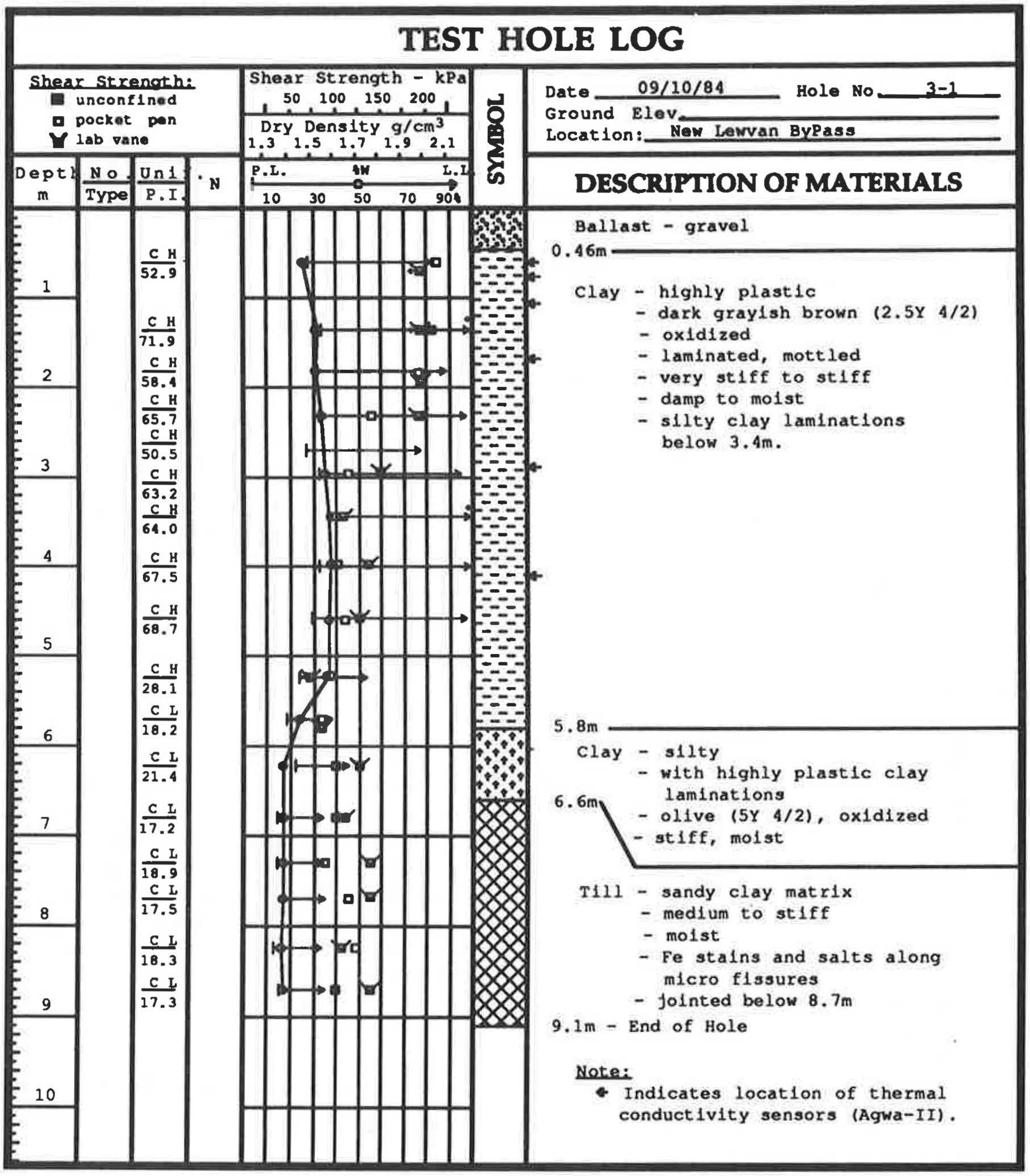


FIGURE 10 Test hole information from Site No. 3, Lewvan Expressway, Regina.

Underlying these strata are 740 mm of stiff-to-very-stiff silty clay. This material is believed to be fill. Stiff-to-hard till was encountered below the fill at the 1.5 m depth. A piezometer was installed with its tip 1.9 m below the top of the tie. The piezometer was initially dry but subsequently indicated a water level at 6.6 m below grade.

AGWA-II sensors were installed at this site on November 8, 1984. By February 15, 1985, all sensors were responding well. The first three sensors were installed within the fill. The bottom three sensors were installed in undisturbed till. The sensors measured suctions ranging from 60 to 160 kPa, with an average of 100 kPa.

The contact filter paper technique indicates suctions ranging from 225 to 575 kPa with an average of 370 kPa. The noncontact filter paper tests showed total suctions ranging from 650 to 1050 kPa, with an average of 900 kPa. These results are higher than would be anticipated. Possibly the air space around the specimens was too large relative to the size of the container.

The psychrometer measurements show total suctions ranging from 260 to 620 kPa, with an average of 425 kPa.

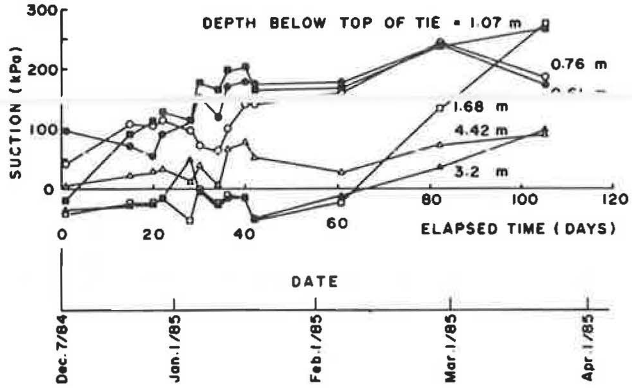


FIGURE 11 Plot of suction versus elapsed time for AGWA-II sensors at Site No. 3.

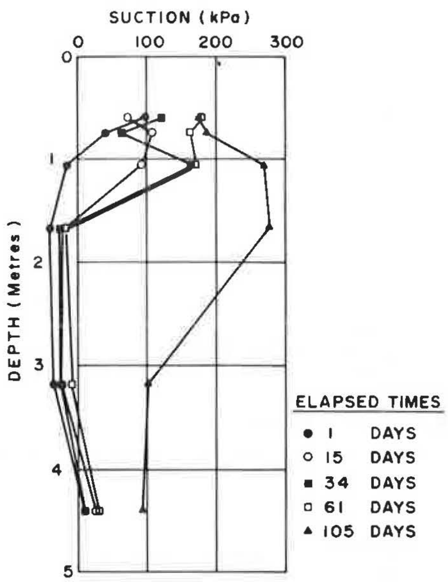


FIGURE 12 Plot of matric suction versus depth measured using AGWA-II sensors at Site No. 3.

Site No. 5

Site No. 5 is located on CN trackage near Fort Saskatchewan, Alberta. The site was selected because it was a large fill section and because the foundation materials were silty in nature.

The stratigraphy at this site was not uniform. It consisted of 1100 mm of gravel ballast and subballast. This stratum was frozen to 500 mm at the time of the investigation. Underlying this was 4.7 m of stiff-to-very-stiff silty clay fill material. A 300-mm-thick layer of organic topsoil and rubble was encountered at the 5.8 m depth. Stiff, silty clay was encountered below the organic layer at the 6.1 m depth. Fine- to medium-grained, water-bearing sand was encountered at 7.9 m. A piezometer indicated a water level at 6.1 m.

AGWA-II sensors were installed on October 30, 1984. All of the sensors were installed within the silty clay fill material. The matric suctions observed ranged from 0 to 200 kPa, with an average of 175 kPa. Possibly the sensor showing the lowest reading had not yet responded.

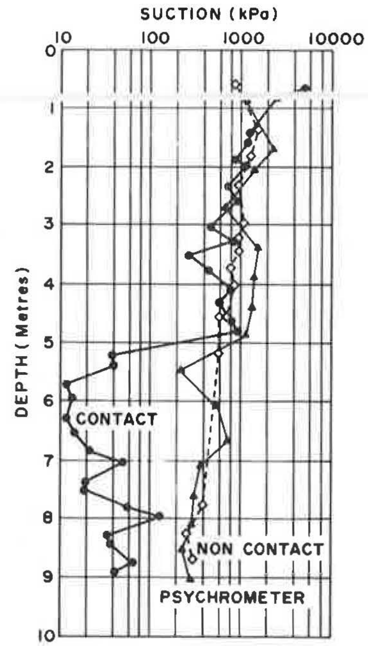


FIGURE 13 Filter paper and psychrometer results versus depth at Site No. 3.

The contact filter paper technique showed suctions ranging from 75 to 400 kPa, with an average of 175 kPa. The noncontact filter paper results showed suctions ranging from 325 to 450 kPa. The psychrometer results showed total suctions ranging from 125 to 365 kPa, with an average of 280 kPa.

The above results appear to be reasonable. The matric suction was 100 kPa near the surface, dropping off to zero at the 5 m depth. The total suction varies from a high of 300 kPa to a low of 200 kPa. The contact filter paper data appear to jump from a total suction measurement to a matric suction measurement as more water becomes available in the soil.

COMPARISON OF SUCTION MEASUREMENTS SYSTEMS

Filter Paper Method

The plots indicate varying trends of suction versus depth. Site No. 3 has high suctions near the surface, dropping off toward zero near the water table. On many of the plots from contact filter paper tests, there is an occasional spike showing a high suction. It appears that these spikes are not high matric suctions but are actually total suction measurements obtained while attempting to measure matric suction. This would indicate that when using the contact filter paper method, a given test may measure either matric or total suction. In almost all cases, the matric suctions measured were either close to the expected value or substantially greater. When greater, there was typically reasonable agreement with other measurements of total suction.

The measurements of total suction using the noncontact filter paper method seem to work reasonably well. However, there

were some difficulties relating the results of this method to the results obtained by the psychrometer method. It should be noted that when there was disagreement, the results of the filter paper method were usually higher than those from the psychrometer method.

The Psychrometer Method

The psychrometer method showed reasonably good correlation with the noncontact filter paper method for the measurement of total suction.

The AGWA-II Method

The results obtained using the AGWA-II sensors illustrate the variation of suction with depth and time. The variation of suction for a particular sensor with respect to time is attributed partly to the equilibration period for the sensor. Most of the profiles of suction versus depth indicate a high suction near the surface and then decrease with depth.

Some problems have been identified with the hand-held readout device. This was particularly true during the early stages of the study.

PROBLEMS IDENTIFIED AND RESOLVED TO DATE

Filter Paper Methods

There were several problems identified with this method during the study. One of the major problems associated with the contact filter paper method arises out of an inability to consistently measure matric suction. This problem became evident when attempts to measure matric suction resulted in the measurement of high suctions. It is speculated that this phenomenon occurs when matric suction determinations are attempted on samples with insufficient pore fluid to ensure fluid flow into the filter paper. The net result is that when matric suction measurements are attempted using the contact procedure, total suctions are frequently obtained.

There are numerous procedural problems experienced with the filter paper methods. These problems arise out of the extremely small measurements required for water content determinations. A filter paper will weigh approximately 0.25 g. Typical water contents will range from 30 to 60 percent. This requires the measurement of an extremely small quantity of water. After the filter paper has equilibrated it must be removed from the sample and its initial wet weight measured. The instant the filter paper is removed from the soil, evaporation begins. This results in the wet weight of the filter paper's changing constantly. This problem also occurs to a lesser extent after the filter paper is oven dried and the dry weight is being measured. The problem is directly related to the relative humidity of the ambient atmosphere. The humidity in the laboratory is virtually always different from that required for equilibrium in the filter paper. Therefore, a weight change in the filter paper always occurs. It was also noted that the tare containers used in water content determinations gained and lost water from the filter papers. The net effect of these difficulties is that this method is technique sensitive.

Various procedural techniques were employed in an attempt to minimize the effects of some of the difficulties discussed. Efforts were made to reduce the time of handling the wet filter papers before weighing to a matter of seconds. This reduced the total magnitude of loss. Similar procedures were invoked for the dry weight determinations.

The measurement of total suction worked well in almost all cases and it is possible that this method is better suited to this type of measurement.

Psychrometer Method

The procedures are somewhat involved and the equipment costs are significantly greater with this method compared with the filter paper method. There were no major difficulties associated with calibration or testing. The main difficulty is the high sensitivity of the psychrometer and the readout device to thermal gradients. To overcome this difficulty, the sample and the psychrometer were enclosed within a chamber. The chamber itself was then submerged in a multibuffered water bath. The bath temperature was maintained to within ±0.01°C.

After the psychrometers were calibrated, the time required for each suction measurement was approximately 2 to 3 days. For all sites except Site No. 4, the data collected agreed with expected values and with the values of total suction determined by the filter paper method.

The psychrometer equipment has been in use for several years, has proven reliability, and is readily obtainable. This, combined with the high repeatability of calibration and test results, would indicate that it is more reliable than the filter paper method.

AGWA-II Sensors

AGWA-II sensors have only recently been designed and built. The company is a small, specialized firm that must also do considerable development research. The hand-held readout device was designed and built by a third-party developer. The hand-held readout device, sensor interface, and power supply are new products but the sensors have been in use for several years. The sensors have been used primarily in irrigation to control automated irrigation systems *(23)*. The sensors appear to be proven devices with few difficulties.

The system was plagued with minor technical difficulties and setbacks throughout the project. The problems included electronic incompatibility of the hand-held readout device with the data logger as well as power supply difficulties. The electronic incompatibility of the hand-held device and the data-acquisition system resulted in a shift in the calibration of the original sensors. The net result was that a negative suction was measured for some of the sensors. This became less noticeable with time as the suctions increased. The offset difficulty was found to exist with the hand-held readout device and not with the data-acquisition system. The calibration equations for the sensors were also found to be incorrect for the hand-held readout device. The incorrect calibrations resulted in the entire calibration curve's being offset approximately 50 kPa. The sensors read by the hand-held device would indicate a suction of 50 kPa lower than the actual value. Some of the sensors were

recalibrated by the manufacturer and it was established that this was indeed the case. This difficulty was resolved in three ways. First, when the data-acquisition system was purchased, this problem no longer existed. Second, the supplier exchanged the hand-held device for an updated model with this problem rectified. Finally, the offset was established by running the original hand-held device and the new data logger in parallel to establish the correction for the data already collected. It should be noted that the data presented in this paper are not corrected for the calibration offset.

PRELIMINARY CONCLUSIONS

The results of this study would indicate that suction can be measured in the field. Reasonable agreement was demonstrated among the field measurements, laboratory results, and anticipated results. The major discrepancies were explainable. The manner in which soil suction in the subgrade varies throughout the season has only been partially addressed.

Our comments and conclusions regarding the measurement systems tested are as follows:

1. The filter paper method theoretically measures matric suction when there is sufficient contact between the filter paper and soil sample. However, it is difficult to ensure that there is sufficiently good contact between the filter paper and the soil. The filter paper method should not be used to determine matric suction.
2. The noncontact method appears to measure total suction, reasonably well. It is important to ensure reasonable temperature control during the equilibration period. The method agrees quite well with the psychrometer method but the results generally exhibit more scatter.
3. The psychrometer method, which measures total suction, is sensitive to the thermal environment in which the test is performed. The test is also operator sensitive. The measurement should only be performed in a laboratory.
4. The AGWA-II sensors and equipment had several difficulties related to supply of equipment and some minor technical difficulties. Most of the difficulties experienced with this equipment have been resolved. The AGWA-II method is the preferred method for measuring suction for several reasons. First, the method demonstrates relatively consistent and reasonable results. Second, this method measures matric suction. Third, the system lends itself to data acquisition and battery operation, which is essential for field measurement at remote locations.

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