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Monitoring Matric Suction in the Subgrade of Unpaved Roads

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Introduction

The performance and the capacity of thin pavements and gravel roads is controlled by the shear strength of the subgrade soil which in turn is a function of the matric suction. Matric suction is the negative pore water pressure within unsaturated soils. Most subgrades are constructed of moisture controlled compacted soils which are considered unsaturated.

The contribution of matric suction to the shear strength of a soil can be substantial as noticed in gravel roads in semi-arid regions where the road can be very 'soft' or incredibly 'hard' depending on the time of the year. The change in strength of the road is entirely due to an increase or decrease of matric suction in the subgrade. Changes in matric suction are a function of the local microclimate. When precipitation, or infiltration exceeds evapotranspiration (i.e. a flux of water into the subgrade) matric suction can be expected to decrease; lowering the strength of the subgrade. Conversely, when evapotranspiration is greater than infiltration the matric suction will increase and subsequently subgrade strength will also increase.

Many geotechnical problems use the Mohr-Coulomb failure criteria to define the shear strength of a saturated soil. The Mohr-Coulomb failure criteria has been extended to unsaturated soils by Fredlund (1979) by including the matric suction in the equation for shear strength. The shear strength can now be defined as:

$$\tau_f = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b$$

where:

c' = effective cohesion intercept

$(\sigma - u_a)$ = net normal stress state variable

ϕ' = effective angle of internal friction

$(u_a - u_w)$ = matric suction

ϕ^b = friction angle with respect to matric suction

Previously, the shear strength of a soil was considered a function of the net normal effective stress and the material properties. This suggests that the strength of the soil could only increase when the net normal stress changed, however, the subgrade soil strength does change usually without any change in net normal stress (i.e. overburden). To more closely represent unsaturated soils, addition of a second stress state variable (i.e. matric suction) permits changes in soil strength at a constant net normal stress.

All pavement design procedures and analyses are based on the shear strength of the subgrade soil either directly or indirectly. Broms (1965) developed a method to assess the bearing capacity of flexible pavements which included the effect of degree of saturation of the subgrade soil. The Broms method is the only pavement design method to attempt to directly include the stress state of the subgrade soil into the design. Unfortunately most pavement design procedures were developed before the principles of unsaturated soil mechanics were understood. As a result pavement design procedures tend to be empirical and the shear strength of the subgrade is given minimal consideration except for a single initial condition. Optimization of any pavement design strategy requires a good understanding of the factors which affect subgrade soil shear strength.

Matric suction measurement

An investigation was undertaken to measure the characteristics of the matric suction profile within a subgrade of a unpaved road including the influence of the local microclimate. Thermal conductivity sensors were considered the most appropriate method to measure in-situ matric suction for this investigation The thermal conductivity sensor indirectly measures the matric suction using the relationship between matric suction ant he thermal properties of a porous tip. Detailed evaluations and explanations of these types of sensors have been performed by Lee and Fredlund (1984) and Fredlund and Rahardjo (1988). A brief description of the sensors follows. The AGWA II thermal conductivity sensor is a commercially available sensor produced by Agwatronics of Merced, California. The AGWA II consists of five basic components:

- porous medium
- heater
- temperature sensing device
- epoxy jacket
- connecting wire

Figure 1 shows the basic components of a thermal conductivity sensor.

The sensors require calibration in the laboratory before field installation using a pressure plate extractor to determine the suction vs. output relationship or calibration curve of each sensor.

The thermal conductivity sensors were controlled by an automated data acquisition system called the HydroNet, manufactured by Design Analysis Associated Ltd. of Logan, Utah. Production of the HydroNet system has been discontinued. The HydroNet system is simple, compact and user friendly. The system consists of:

- Data logger (Model 16)
- Network interface (Model 10)
- Network battery (12V car)
- Laptop computer (setup only)

The HydroNet Model 16 is only capable of measuring two sensors on a single Model 16. If more sensors required measurement a number of Model 16 units could be connected in series, or a multiplexor could be used to switch between pairs of sensors. However, there was not one available for the Model 16. A multiplexor was developed with the assistance of the Electrical Engineering Department at the University of Saskatchewan for this system. The new multiplexor allowed the connection of sixteen sensors to a single HydroNet Model 16. The multiplexor is simply a number of switches which connect two sensors at a time. The voltage drop created by the sensor when a measurement is taken is used as an indicator to switch to the next two sensors. The unit does not switch to the next channel until the measurement is complete. The prototype multiplexor was tested in the laboratory during the calibration procedure before field installation to ensure reliability.

Site selection

The location of the gravel road chosen for this investigation is shown in Figure 2. The site is located on an east-west grid road directly north of the Saskatoon airport and approximately 15 km from the University of Saskatchewan campus. Traffic on the road consists of commuter traffic, grain trucks and heavy industrial traffic. The road is less than 10 years old, well maintained and open year round. Drainage in the area is good with sideslopes on the road at 4:1. The subgrade is a sandy clay till with numerous pebbles and coarse gravel sizes. The liquid limit of the till is 23.2% and the plastic limit is 10.9%. Thermal conductivity sensors were installed in the south half of the subgrade to maximize the influence of evapotranspiration. There is no evidence of bearing capacity failures of the subgrade at this time.

Installation procedure

The thermal conductivity sensors had to be placed directly into the subgrade. Access to the subgrade was obtained by digging a trench approximately 0.75m wide and approximately 1.75 m deep from the centerline of the road to the base of the side-slope with a backhoe. The trench permitted positioning of sensors at any point in the subgrade. Each sensor was inserted into the trench wall by augering a 25 mm diameter hole 75 mm to 125 mm deep at a slight upward angle. The sensors were then carefully inserted into the hole until the sensor tip was in contact with the back of the hole. The remainder of the hole was backfilled with cuttings from drilling.

It is most important to ensure there is good contact between the porous tip of the sensor and the surrounding soil. If good contact is not maintained the continuity of the water phase between sensor and soil is interrupted and the sensor will produce erroneous measurements. Careful backfill of the hole behind the sensor is required. Once all of the sensors are installed extension cables are connected to the lead wires. Each connection must be water tight, otherwise wires may corrode or the water may affect the measurement. Self sealing heat shrink was used around all connections to provide a water tight seal. Loops are placed in the lead wires near the sensor end to relieve any tension placed on the wire during backfill of the trench.

All lead wires run along the bottom of the trench and into a modified vertical section of culvert. Inside the culvert the sensor leads are connected to the data acquisition equipment . The purpose of the low profile culvert is to protect the data acquisition system from the environment and vandalism. The culverts was sealed around the bottom and access is provided through a locked lid at the top. The top of the culvert was sloped at 4:1 to ensure the top was flush with the sideslope of the road. The trench was backfilled with the excavated soil and compacted in lifts of six inches with no change in water content.

Field measurements of matric suction

Fourteen thermal conductivity sensors were installed in the subgrade immediately after the subgrade thawed in the spring of 1991. A typical calibration curve for a sensor is shown in Figure 5.1. The general shape of the curve is the same for all sensors, but the exact shape depends on the pore size distribution of the particles in the ceramic tip, as well as construction variations in the heating element and temperature sensing device. The analog to digital reading (A/D) on the vertical axis of the calibration curve has no units. It is a converted number used by the HydroNet to measure the difference in temperatures before and after heating. The matric suction measured by a sensor is determined from the A/D reading of the HydroNet through the calibration curve.

The facilitate the calculation of suction from the calibration curve, the relationship between A/D reading and suction was fitted to a second or third order polynomial equation. A single equation relating A/D reading or output from the sensor to suction simplify data management.

The output from three of the sensors is shown in Figure 4, Figure 5 and Figure 6.

Some sensors showed erratic behavior for short periods. These erratic measurements are few and the output of all sensors has since become stable. Equipment problems such as poor contact in the relays or poor soil-sensor contact could explain the irregular behavior. The periods of erratic behavior correspond to periods of heavy precipitation. The high humidity environment inside the data acquisition equipment housing could have caused poor contact between contacts in the relays. The data for sensor 315 in Figure 4 shows the suction to be slightly negative which means the pore-water pressure is positive rather than negative. Thermal conductivity sensors cannot measure positive pore-water pressures. The slightly negative measurements are attributed to estimation of the zero output from the sensor during the calibration procedure.

Figure 7 shows the distribution of sensors in the subgrade cross section. The data acquisition equipment was housed in the vertical culvert shown on the left and the centerlines of the southern wheel paths are shown on the right. The deepest sensor was 1.7 m and the shallowest was 0.3 m. Sensors were not installed in the subgrade within 0.6 m below the surface in the area of the wheel paths for three reasons. First, the soil was very hard and dry making it difficult to provide adequate soil-sensor contact. Second, this area is also where stresses from traffic are the highest creating the possibility for failure of the relatively weak porous tip of the sensor. Lastly, thermal conductivity sensors can only measure matric suctions up to approximately 400 kPa; suctions near the surface of the road are considerably greater than 400 kPa.

The sensors were positioned to obtain a representative measure of the soil suction profile in the subgrade. The suction profile within the subgrade for July 26, 1991 is shown in Figure 8. The matric suction is generally lower beneath the shoulder and sideslope than beneath the travelled portion of the road, In addition, the sensors are closer to the surface in the sideslope which increases the effects of the infiltration of precipitation . Suction are higher in the travelled portion of the road for two reasons. First, infiltration in this area is low, especially if the surface is sealed by pavement. In the case of an unpaved surface the density of the subgrade in this area is higher than the shoulder of sideslope because of compaction due to traffic, The increase in density decreases the permeability of the subgrade soil and water cannot infiltrate into the subgrade as easily as it can on the shoulder and sideslope. Second, the path water has to travel is a greater distance if the surface is of very low permeability. For water to enter the subgrade under the travelled area it must move inward from the side slope or shoulder. The crown of the road will drain all precipitation away from the travelled portion to the shoulder and sideslope where the water can enter the subgrade. In many cases the water which enter in the sideslope or shoulder is consumed by evapotranspiration before it can reach the center of the road. However, infiltration of water into the subgrade occurs from the top down, thereby reducing the shear strength in the area where stresses are the highest, This explains the frequent occurrence of pavement failures near the edges of roads. Precipitation on the shoulder and sideslope has reduced matric suction and in turn lowered the shear strength causing a failure. A semi-arid climate which is found in most of Western Canada is ideal for maintaining reasonable matric suction in a pavement or railroad subgrade. Proper drainage and a precipitation deficit will provide matric suctions which will contribute noticeably to the shear strength of the subgrade.

The microclimate in the area of the site was not normal for the monitoring period. The precipitation and potential evapotranspiration data for April to July 1991 is shown in Figure 9. Potential evapotranspiration is usually at least double the amount of precipitation. However, in April and June precipitation exceeded potential evapotranspiration and was almost equal to potential evapotranspiration in May. By July precipitation and potential evapotranspiration were back to normal.

In general, the higher than normal precipitation would be expected to lower matric suction for April, May and June. Increasing matric suction would be expected in July. The matric suctions measured by the thermal conductivity sensors reflected this trend (Figure 4 and Figure 5). Sensors near the sideslope measured zero and low suctions for May and June. In July the suctions began to increase with lower precipitation and high evapotranspiration. The suctions at the location of sensor 410 never did decrease even throughout periods of high precipitation. The suction at this location would be expected to change only after extended periods of high evapotranspiration or precipitation. The sensors in the travelled portion of the road showed constant suction throughout the monitoring period demonstrating the effect of the low permeability of the materials above and the distance from the shoulder of the road.

Summary

An installation method for thermal conductivity sensors into the subgrade of an unpaved road has been described. Precipitation and potential evapotranspiration data have also been presented to assist interpretation of the suction data. The matric suction profile within the subgrade is not constant and is a function of the of the local microclimate. Suctions are generally lower beneath the shoulder and sideslope of the road and higher beneath the travelled portion. This would explain the frequent occurrence of failures near the edges of paved and unpaved roads.

Acknowledgments

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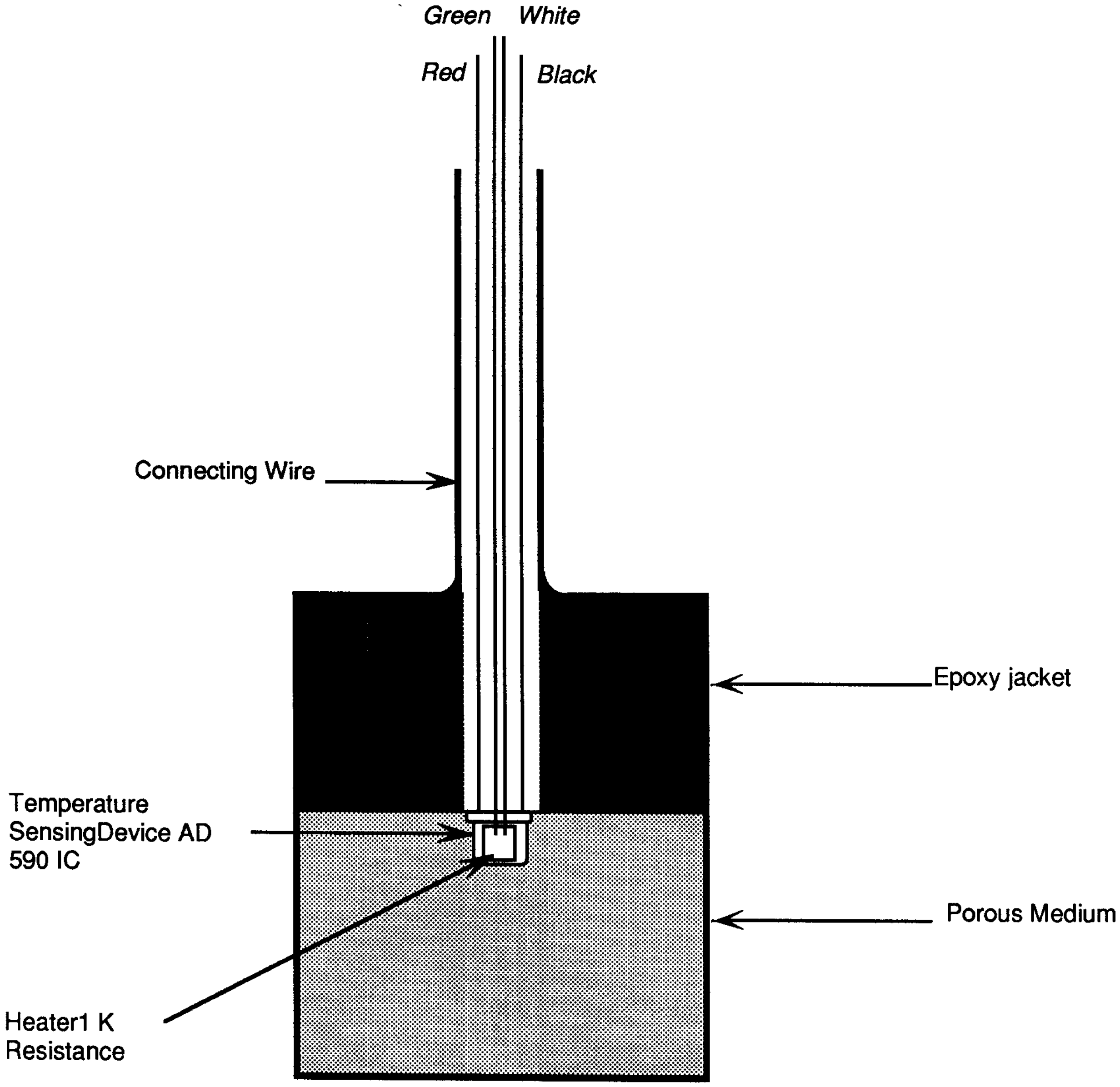

Figure 1 Cross section of a thermal conductivity sensor

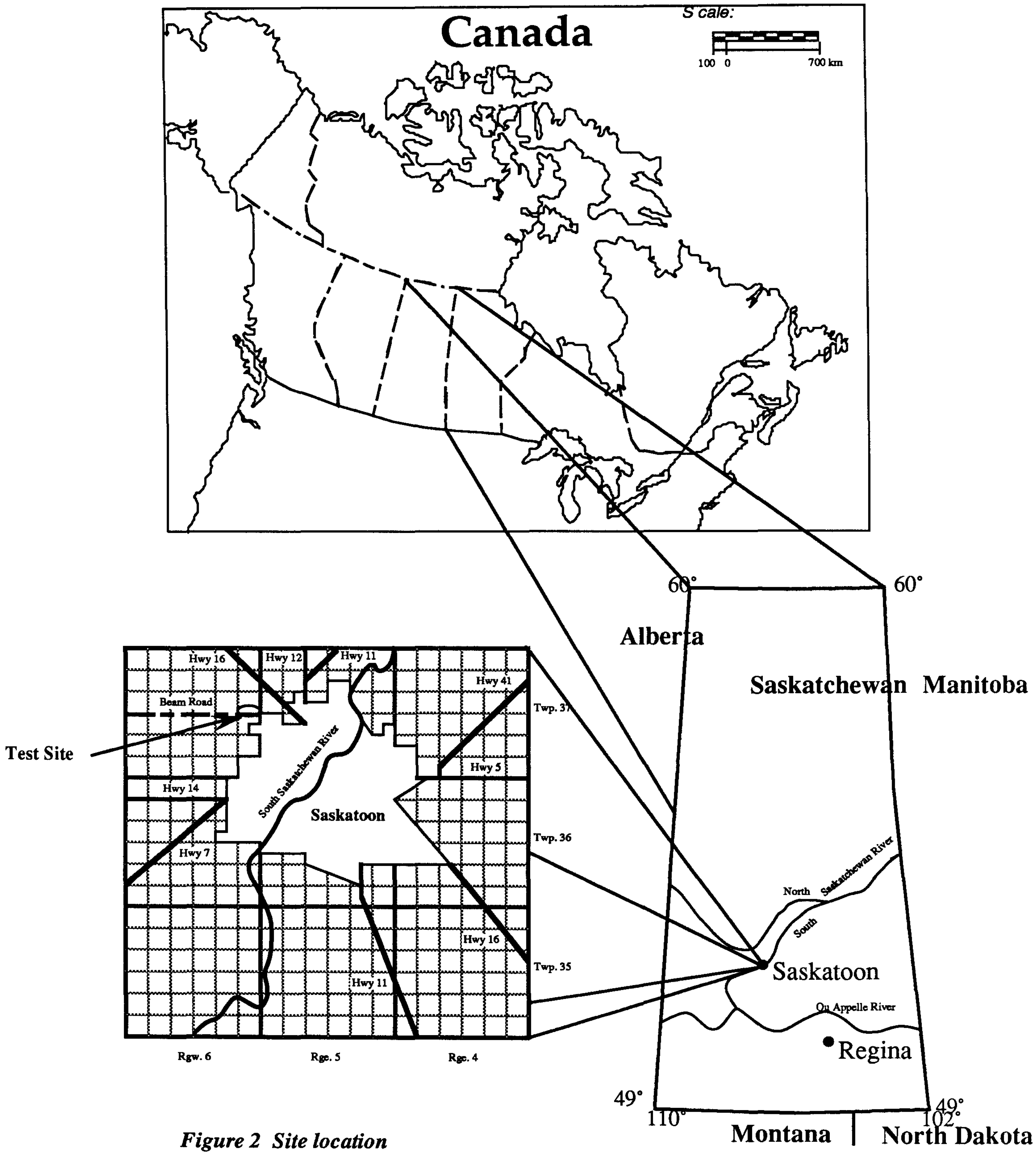

Figure 2 Site location

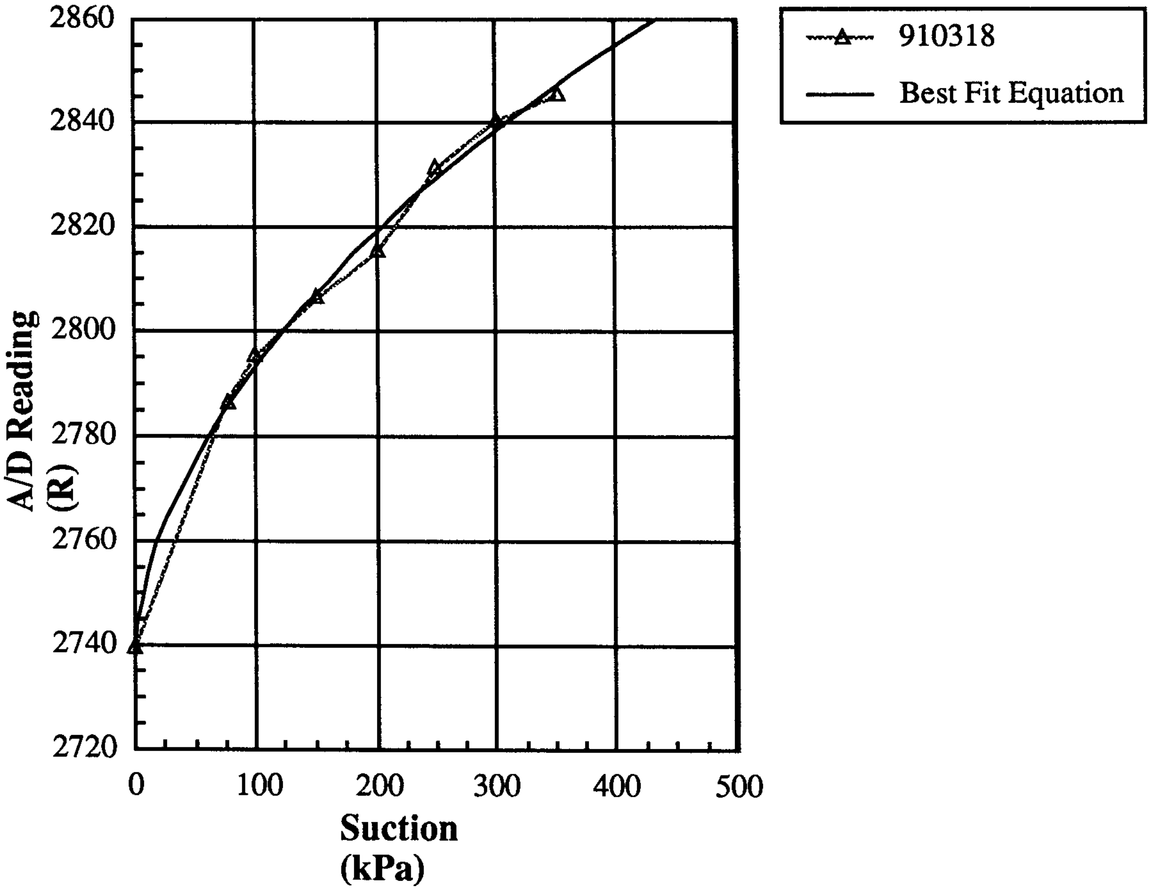

Figure 3 Typical calibration curve output for a sensor

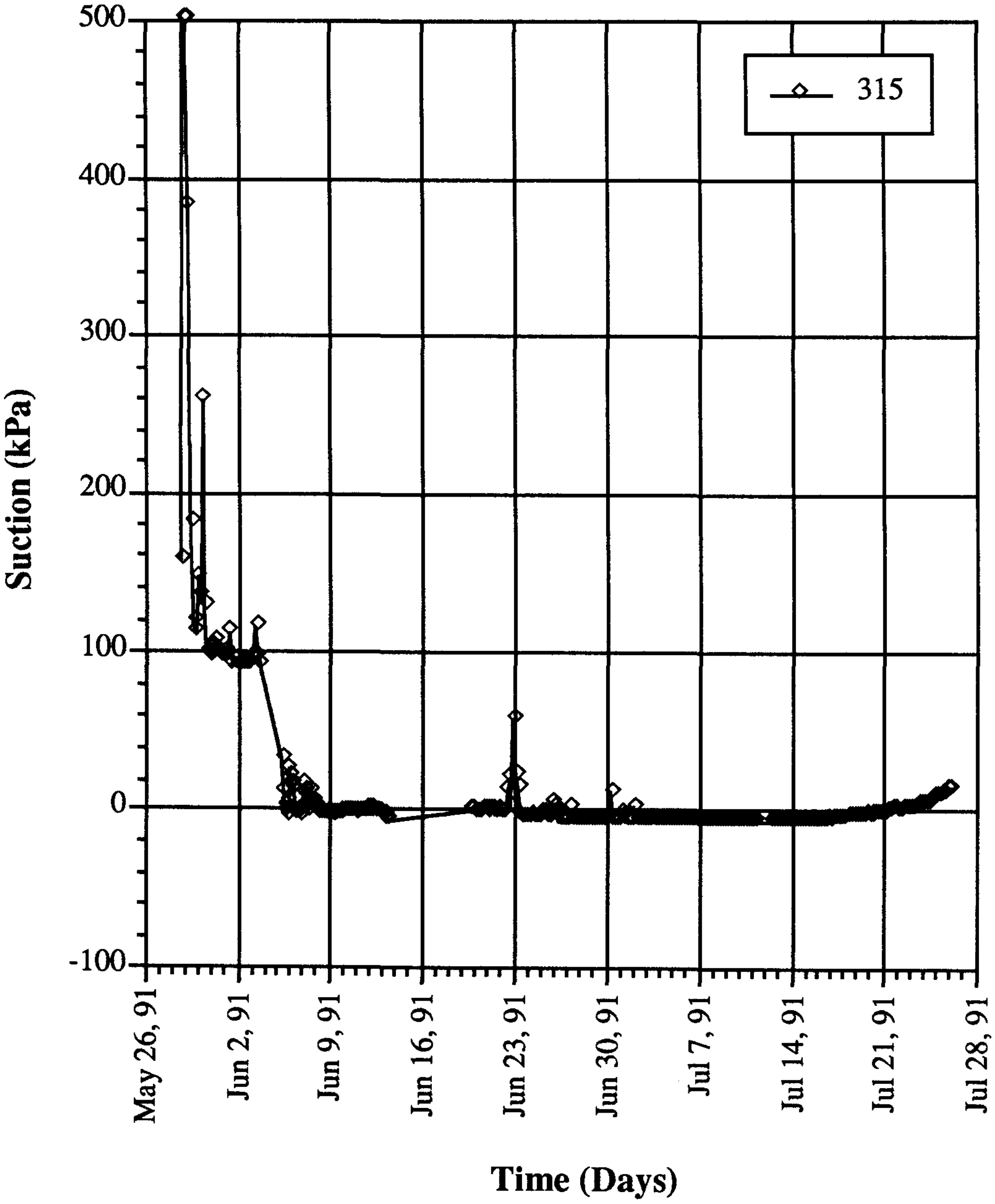

Figure 4 Matric suction data from sensor 315

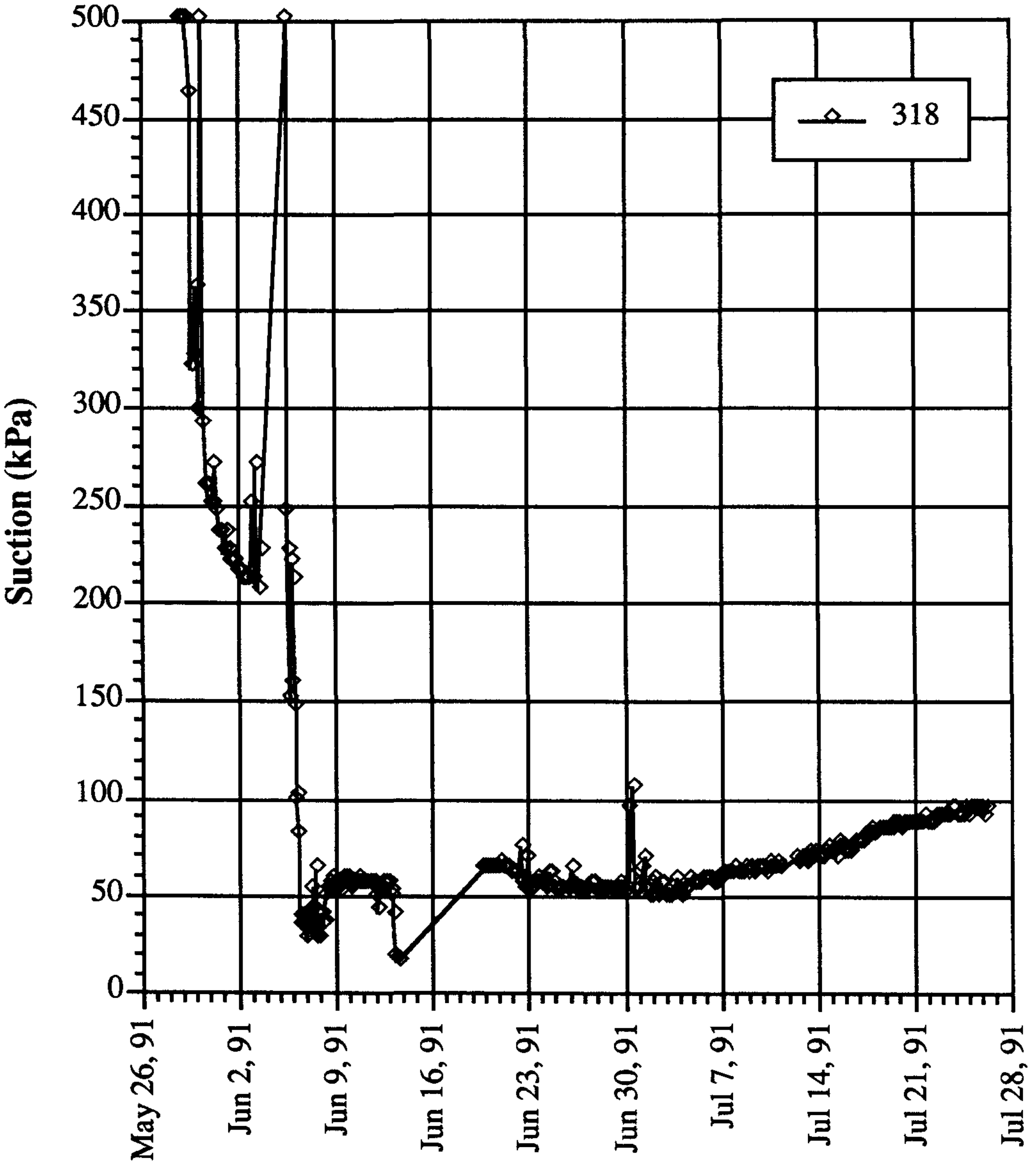

Figure 5 Matric suction data from sensor 318

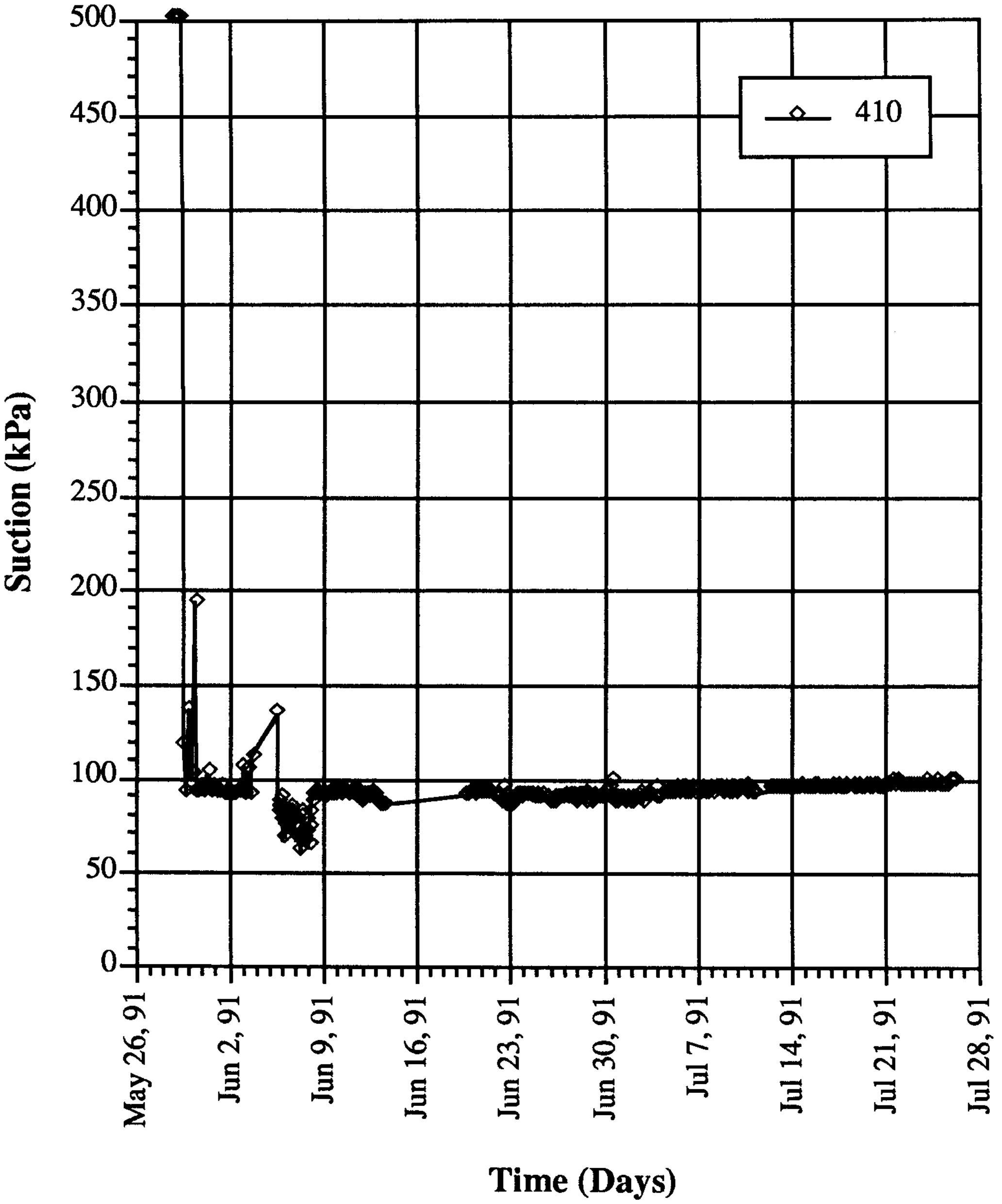

Figure 6 Matric suction data from sensor 410

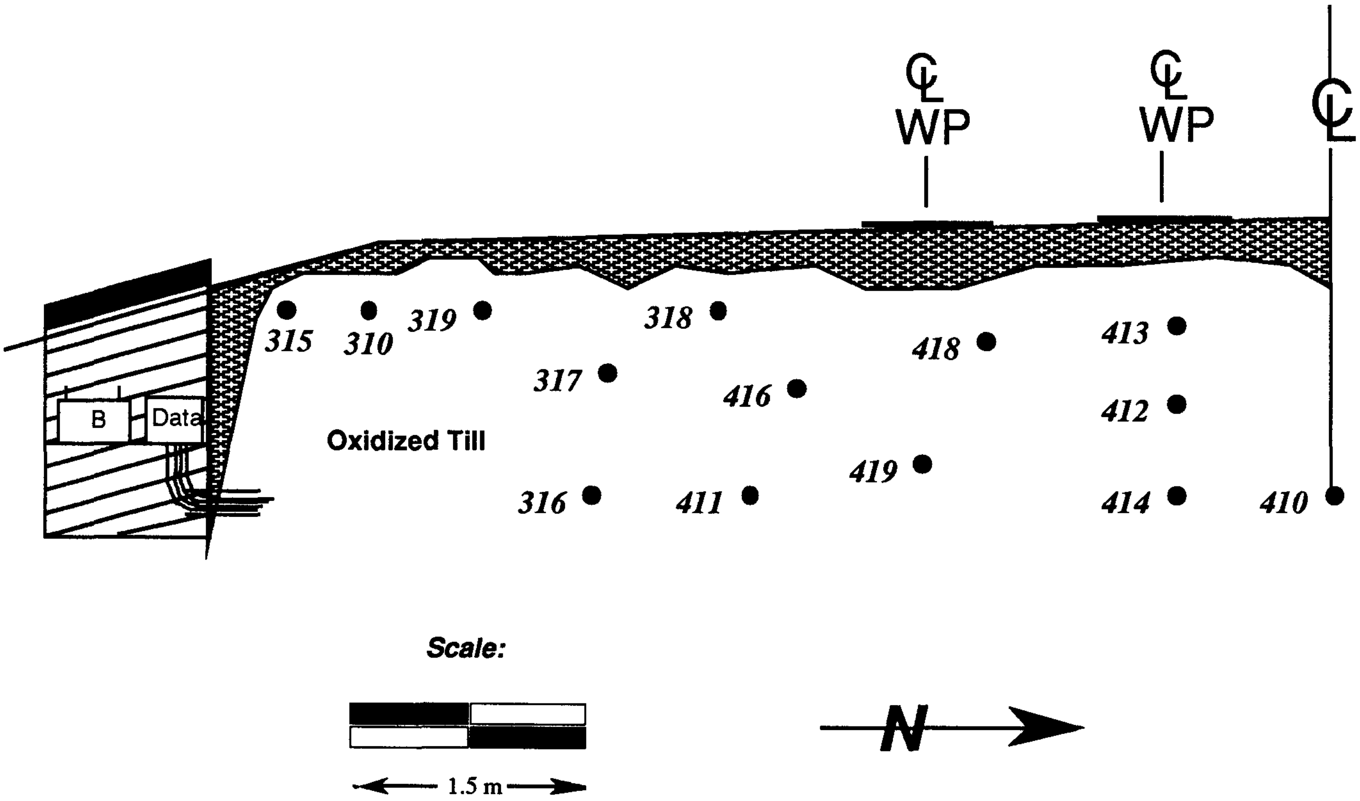

Figure 7 Sensor location in subgrade