Suction Measurements on a Saskatchewan Soil Using a Direct-Measurement, High-Range Suction Sensor

DELWYN G. FREDLUND, JULIAN K-M. GAN, YUN GUAN, AND NEIL RICHARDSON

A tensiometric-type suction sensor capable of direct measurement of matric suctions greater than 100 kPa has recently been developed. The sensor has been used to measure matric suctions up to 1250 kPa. The sensor makes use of the tensile strength of water for the measurement of matric suction. The cavitation of water in conventional tensiometers occurs at a negative pressure approaching 1 atmosphere because of the presence of cavitation nuclei. In the absence of cavitation nuclei, the tensile strength of water can be on the order of several atmospheres. The direct-measurement, high-range suction sensor has been used for the measurement of matric suction on borehole samples obtained during a soils investigation at a bridge site near the town of Outlook, Saskatchewan, Canada. The method has proven to be fast and simple to use. Matric suction measurements of the samples from the Outlook bridge site are presented, along with an interpretation of the laboratory data.

Direct matric suction measurements using a tensiometer have generally been limited to a matric suction of about 90 kPa. Measurement of matric suctions greater than about 1 atm has had to rely on indirect means, such as the use of thermal conductivity sensors, the filter paper method, or the psychrometric method. The indirect methods usually require tedious calibration.

Research, particularly in the physical sciences, has shown that water under special conditions can have substantial tensile strength. Researchers at Imperial College (United Kingdom) found that a transducer used to measure the pore water pressure of a saturated clay during undrained-unloading tests in a triaxial cell recorded tensions of −365 kPa for a period of about 2 hr. The tension eventually bounced back to about −100 kPa. The observation was attributed to the tensile strength of water and led to the development of a tensiometer-type, high-range suction probe (*1*).

Further research into the tensile strength of water has been conducted at the University of Saskatchewan, Saskatoon, Canada. A direct-measurement, high-range suction sensor, making use of the tensile strength of water was developed at the university (2), the next step was to attempt to use the new sensor in a geotechnical application.

A bridge near Outlook, Saskatchewan, is being upgraded by Saskatchewan Highways and Transportation. Stability analyses of existing slopes near the site indicated that matric suction may be playing a significant role in the stability of the west bank of the river. Undisturbed samples were retrieved from three boreholes at the Outlook Bridge site for matric suction measurements at the University of Saskatchewan using the direct-measurement, high-range suction sensor.

DIRECT-MEASUREMENT, HIGH-RANGE SUCTION SENSOR

The cavitation of water in a conventional tensiometer occurs as gas or vapor bubbles begin to form in the water measuring system. The bubbles are triggered at gaseous or other hydrophobic surfaces, commonly called potential cavitation nuclei. In the absence of cavitation nuclei, water can sustain a high tension without cavitation. Tensile strengths of several atmospheres have been recorded (*3–7*) for water without cavitation nuclei.

Gaseous or other hydrophobic surfaces, which may be present in the water or on the surfaces of a water container, can be suppressed through the application of a high pressure. The potential cavitation nuclei in the system containing a small volume of water can be effectively eliminated by several cycles of high pressurization and depressurization (*2*).

A schematic diagram of the direct-measurement, high-range suction sensor developed at the University of Saskatchewan (*2*) is shown in Figure 1. The main components of the new sensor are the high-air-entry ceramic disk, stainless steel body, and high-pressure transducer. The surfaces of the stainless steel body were polished to a smooth finish to reduce potential cavitation nuclei sites.

A simple manual pressurization system was constructed for conditioning the water in the new sensor. The pressurization system can provide pressures ranging from −85 kPa to 15,000 kPa. The water in the sensor was conditioned by five to six cycles of pressurization and depressurization. Each cycle consisted of the application of a positive pressure of 12,000 kPa for 1 hr, followed by a negative pressure of 85 kPa for 1 hr. Studies have shown that the ability of the system to prevent cavitation does not significantly improve after more than six cycles of pressurization and depressurization (*2*).

The new suction sensor was tested for its response time and accuracy by comparing measured suctions to those induced in a soil by use of a pressure plate apparatus. The sensor was found to respond rapidly to pressure changes in the pressure plate. The measured pressure changes were essentially equal to the applied pressure changes. The time for the sensor to attain an equilibrium suction with the soil is a function of the soil type and the degree of saturation of the soil. The time for the sensor to attain equilibrium increased with the plasticity of the soil and with a decrease in degree of saturation.

D. G. Fredlund and J. K-M. Gan, Department of Civil Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, Saskatchewan, Canada S7N 5A9. Y. Guan, Department of Civil Engineering, University of Tennessee, 223 Perkins Hall, Knoxville, Tenn. 37996. N. Richardson, Saskatchewan Highways and Transportation, 3130 8th St. East, Saskatoon, Saskatchewan, Canada S7K 2H6.

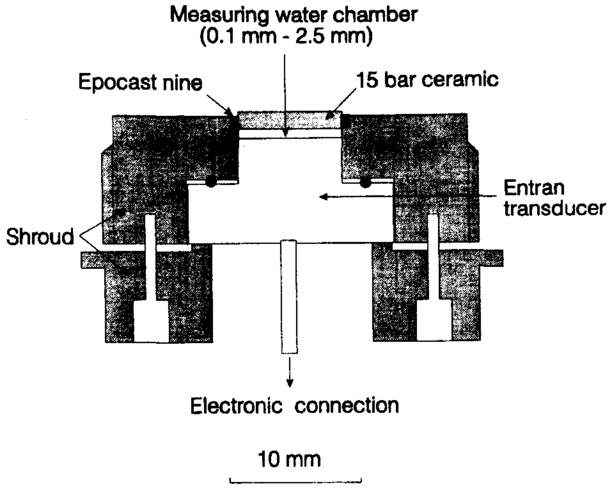

FIGURE 1 Direct-measurement, high-range suction sensor.

Readings obtained with the new suction sensor were also compared with readings obtained with the filter paper method, the null pressure plate method, and the thermal conductivity sensor (*2*). However, it is anticipated that the direct measurement of suction, using the new sensor, will be more accurate than any of the indirect methods used in the comparison. The filter paper method yielded results close to the new suction sensor readings for suction below 200 kPa. At suctions greater than 200 kPa, the filter paper method generally yielded lower and widely scattered values. The thermal conductivity sensor produced measurements that were close to the new suction sensor measurements for suction below 100 kPa. The thermal conductivity sensor produced lower values than the new suction sensor for suction values greater than 100 kPa. The null-pressure plate method produced readings higher than the new suction sensor for soils with a degree of saturation higher than 75 percent. The difference between the null-pressure plate value and the new suction sensor value decreases when the degree of saturation is less than 60 percent. The higher measurements obtained with the null-pressure plate method are believed to be a result of the presence of occluded air bubbles in soils nearing saturation.

The new suction sensor has been used to measure suctions up to 1250 kPa. Equilibrium negative pore water pressures of 1250 kPa have been maintained for as long as 72 hr. Studies of much longer duration would have to be conducted to determine the suitability of the new sensor for in-situ monitoring use. The accuracy of the matric suction measurements from the new sensor has been verified by the axis translation technique with use of a pressure plate apparatus. For matric suctions up to 500 kPa, an accuracy of ±20 kPa was obtained. The overall range of the pressure transducer is ±15,000 kPa. A high-capacity transducer was required to withstand the high pressure (12,000 kPa) applied during pressurization for conditioning of the water in the sensor system.

The sensor has been found to perform satisfactorily in clayey type soils and other types of soils that have a relatively high degree of saturation. Some difficulties have been encountered with the new suction sensor when measuring matric suctions in silty and sandy soils with degrees of saturation below 40 percent. The main difficulty is believed to be caused by minute evaporation from the sensor ceramic at low degrees of saturation of the soil. This difficulty can be largely circumvented by enclosing the soil specimen and the suction sensor in aluminium foil.

NEW OUTLOOK BRIDGE

Saskatchewan Highways and Transportation is preparing to replace the steel truss bridge that crosses Highway 15 near the town of Outlook, Saskatchewan, with a modern multispan, steel and concrete structure to accommodate current load dimensions. The proposed bridge alignment is adjacent to the existing structure but will require the grading of new bridge approaches on both the east and west sides of the South Saskatchewan River.

The total valley relief at the proposed crossing is approximately 30 m. The west river bank at the proposed site includes approximately 20 m of near vertical slopes of glacial and preglacial silt soils. Relict landslides exist on the west bank both immediately upstream and downstream of the proposed site.

Site investigation of the west bank (Figure 2) included the drilling of several stratigraphic boreholes for undisturbed sampling, geophysical logging, and installation of piezometers and inclinometers to document the hydrogeologic environment and stability of the river bank. After study of the geological and geotechnical conditions, researchers could not discover why the site of the proposed west bridge abutment and approach is stable whereas the adjacent areas are unstable. In other words, no obvious reason accounts for the apparent strength of the silt materials.

Stability analyses of landslides on the west bank led to unrealistically high strength parameters for the strata involved. Researchers theorized that a significant matric suction has made the silt strata of the west river bank cohesive. Core sampling and testing were undertaken to determine the in situ matric suction values of the silt strata. The values are to be used in the stability analyses of the site to refine the design of the bridge, the west bridge abutment, and west approach configurations.

Soil samples from three boreholes at the west bank of the Outlook Bridge site were retrieved for matric suction measurements using the new suction sensor. The samples were extruded at the Materials Laboratory of Saskatchewan Highways and Transportation in Regina. Each sample was wrapped with aluminium foil and waxed before delivery to the Geotechnical Laboratory at the University of Saskatchewan.

LABORATORY TEST PROCEDURE FOR MEASURING MATRIC SUCTION

Each soil sample was removed from storage in the humidity-controlled cold room before suction measurements were taken with the new suction sensor in the laboratory. The samples were kept in the laboratory over night to attain equilibration with the room temperature in the laboratory. It has been found that steep temperature gradients between soil and sensor affect the matric suction measurement.

The water system of the new suction sensor was preconditioned with five to six cycles of pressurization to about 12,000 kPa and depressurization to about –80 kPa. The conditioned sensor was then mounted onto the sensor stand (Figure 3). The ceramic face of the sensor was kept moist at all times.

A thin layer of fine silt powder was applied to the ceramic face to help achieve good contact between the soil and the sensor. One

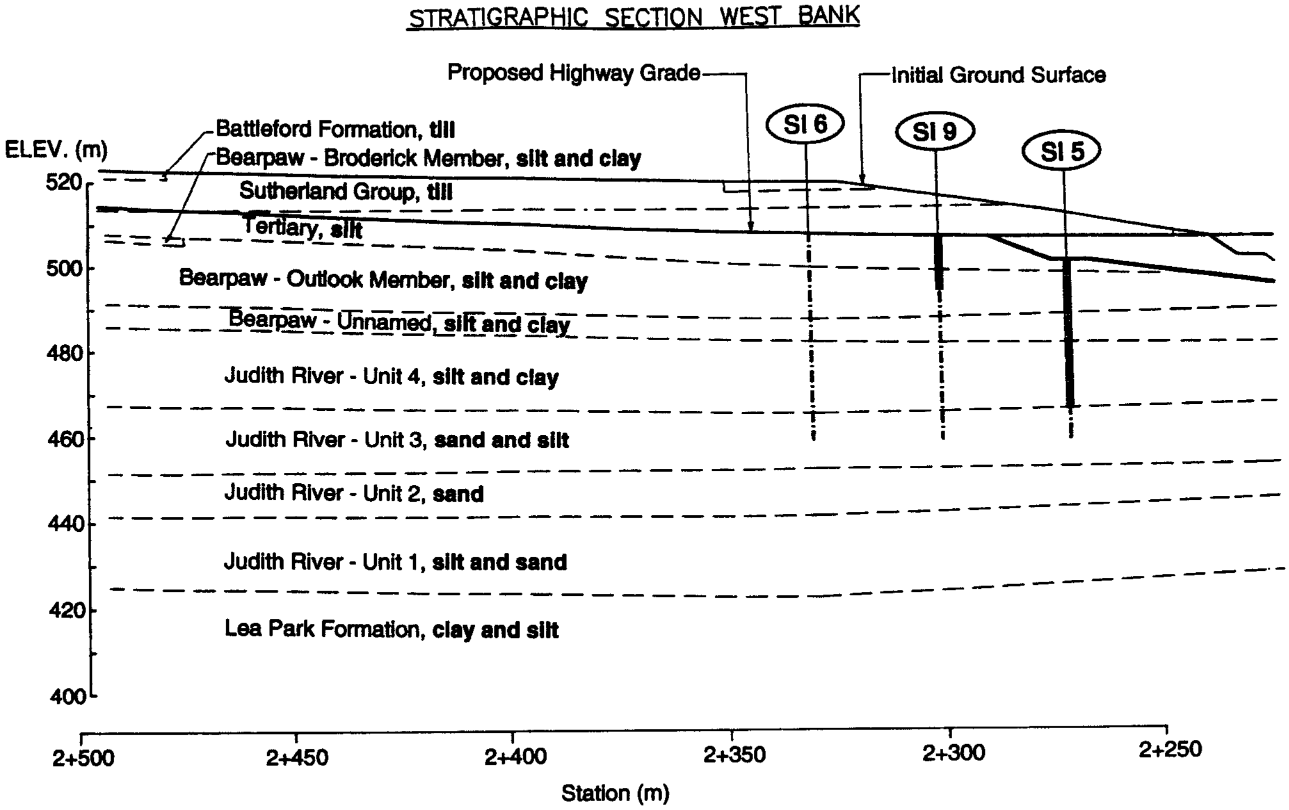

FIGURE 2 Cross-section of west bank, Outlook Bridge site, Saskatchewan, Canada.

face of the soil specimen was trimmed flat. The soil trimmings were used for an initial water content determination. The flat face of the specimen was placed directly onto the sensor (Figure 3). A token load was placed on the specimen to help maintain good contact between the soil and the ceramic sensor tip. The entire setup was then enclosed in a plastic bag to prevent any moisture loss during measurement.

Suction sensor readings with time were recorded using a data acquisition system. Readings were taken until equilibrium suction values were obtained. At the end of each suction test, some soil was taken from the face of the soil specimen in contact with the sensor and was used for a final water content determination.

LABORATORY TEST RESULTS

With the use of the new suction sensor, readings versus time were taken for 11 samples from borehole SI5, 9 samples from borehole SI6, and 10 samples from borehole SI9. The results are presented in Figures 4, 5, and 6, respectively. The matric suction values of the samples from boreholes SI5, SI6, and SI9 are summarized in Tables 1, 2, and 3, respectively. The water contents corresponding to each matric suction measurement along with degree of saturation measurements are shown in Tables 1, 2, and 3.

Measurements were made to determine the effect of temperature gradients between soil and sensor on the matric suction values measured with the new suction sensor. Two sets of matric suction read-

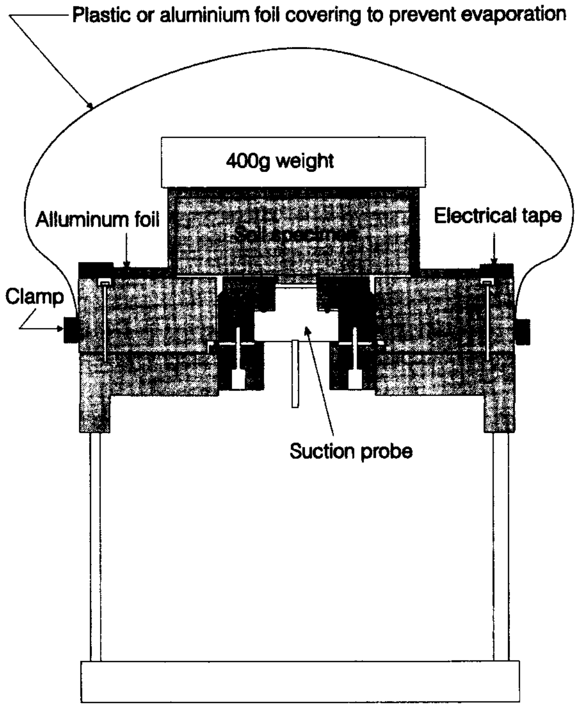

FIGURE 3 Setup of direct-measurement, high-range suction sensor for matric suction reading.

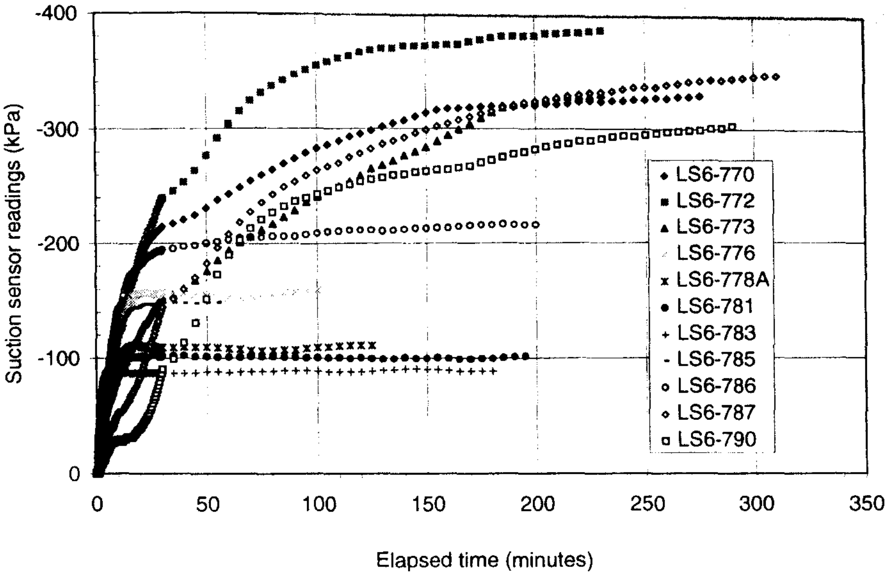

FIGURE 4 **Direct-measurement, high-range suction sensor reading versus time for samples from borehole SI5.**

ings for sample LS6-741 are presented in Figure 7. One set of readings was taken immediately after the sample was removed from the humidity-controlled cold room. The other set was taken 12 hr after the sample was removed from the room.

The matric suction, water content, and degree of saturation profiles of locations corresponding to boreholes SI5, SI6, and SI9 are presented in Figures 8, 9, and 10, respectively. Plastic limit and liquid limit data for samples obtained from approximately the same locations are also presented in these figures. These data were provided by Saskatchewan Highways and Transportation.

DISCUSSION OF RESULTS

Suction sensor readings versus time curves for the soil specimens from boreholes SI5, SI6, and SI9 (Figures 4, 5, and 6) show that the time needed to attain equilibrium increased with the matric suction of the soil. The time needed to attain suction equilibrium was short for matric suctions below 200 kPa. At higher matric suction values of about 300 to 400 kPa, equilibration came about gradually, and the time needed to attain suction equilibrium was rather long. The time needed to attain equilibrium was about 10 to 30 min for the soil

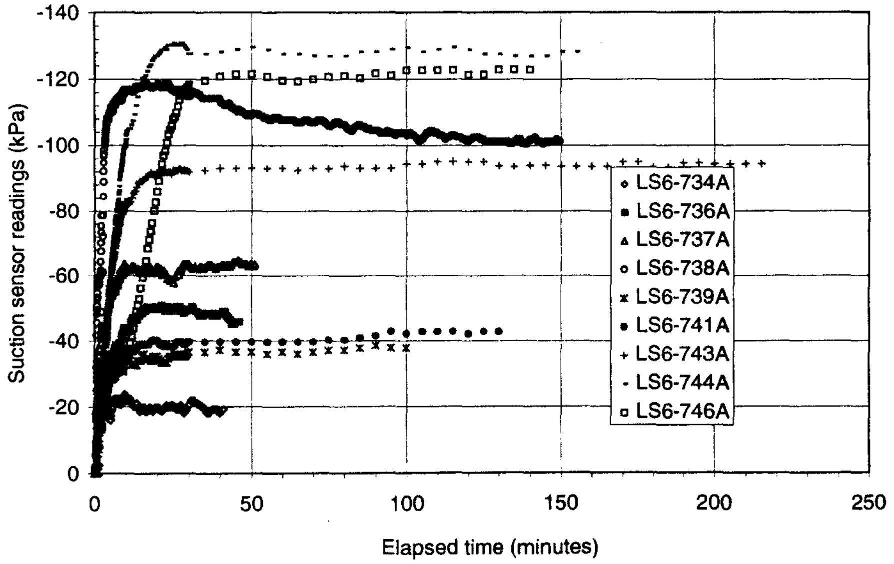

FIGURE 5 **Direct-measurement, high-range suction sensor reading versus time for samples from borehole SI6.**

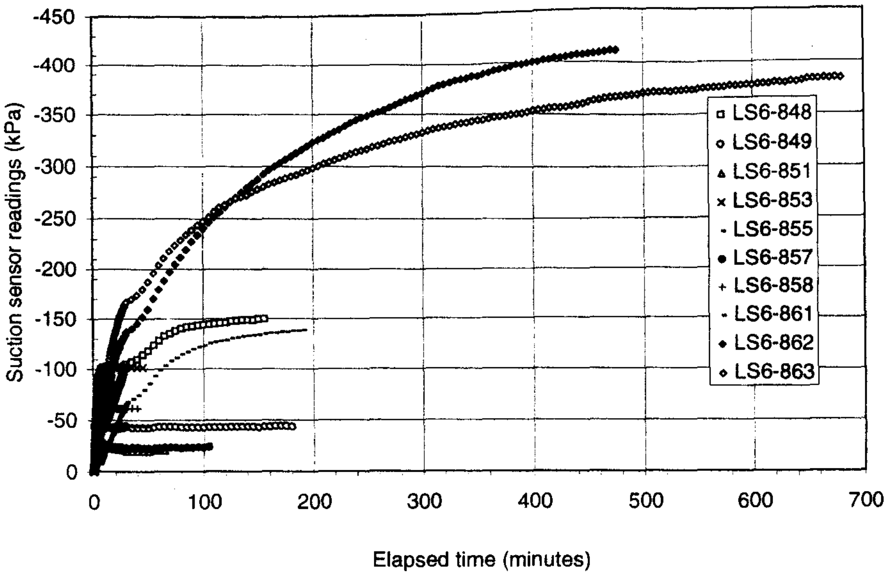

FIGURE 6 Direct-measurement, high-range suction sensor reading versus time for samples from borehole SI9.

TABLE 1 Matric Suction, Water Content, and Degree of Saturation Measurements for Samples from Borehole SI5

Specimen No.	Elevation (m)	Soil description	Initial water content (%)	Final water content (%)	Matric suction (kPa)	Degree of saturation (%)
LS6-770	510.31	uniform, brownish gray silt	11.70	11.41	328	61.0
LS6-772	508.76	uniform, light gray silt	15.42	15.00	385	
LS6-773	508.01	uniform, light gray silt	11.95	11.61	330	72.8
LS6-776	507.71	uniform, light gray silt	13.38	13.23	158	
LS6-778a	503.46	uniform, olive yellow silt	19.41	18.90	112	95.2
LS6-781A	499.96	olive yellow silt with iron stains	25.53	25.23	101	
LS6-783	496.91	yellowish gray silt with iron stains	25.37	24.15	88	86.0
LS6-785A	494.46	yellowish gray silt with iron stains	26.00	24.96	148	
LS6-786A	492.91	light gray silt, clay laminations with iron stains	22.60	22.33	216	95.6
LS6-787	491.41	dark gray clayey silt	25.16	24.49	348	
LS6-790	486.81	dark gray clayey silt	23.97	23.70	303	93.4

TABLE 2 Matric Suction, Water Content, and Degree of Saturation Measurements for Samples from Borehole SI6

Specimen No.	Elevation (m)	Soil description	Initial water content (%)	Final water content (%)	Matric suction (kPa)	Degree of saturation (%)
LS6-734A	513.34	uniform, brownish gray silt	14.57	14.69	20	92.6
LS6-736A	510.29	uniform, brownish gray silt	18.41	18.80	47	
LS6-737A	508.74	uniform, brownish gray silt	14.67	15.22	63	76.3
LS6-738A	507.24	uniform, light yellowish brown silt	15.09	15.44	101	
LS6-739A	505.74	uniform, light yellowish brown silt	18.54	18.69	37	84.6
LS6-741A	502.69	uniform, light yellowish brown silt	19.61	19.62	43	
LS6-743A	499.64	olive yellow silt with grayish brown zones	27.96	28.33	94	94.7
LS6-744A	498.09	silt, sand, clay laminations with iron stains	25.70	25.24	128	
LS6-746A	495.09	silt, sand, clay laminations with iron stains	24.41	25.15	123	94.4

TABLE 3 Matric Suction, Water Content, and Degree of Saturation Measurements for Samples from Borehole SI9

Specimen No.	Elevation (m)	Soil description	Initial water content (%)	Final water content (%)	Matric suction (kPa)	Degree of saturation (%)
LS6-848A	508.58	yellowish brown clayey silt	15.54	15.39	151	91.0
LS6-849A	505.83	yellowish brown uniform silt	15.60	15.80	44	
LS6-851A	502.83	yellowish brown uniform silt	19.71	19.48	20	94.3
LS6-853A	500.38	clayey silt with iron stains	26.84	26.52	102	
LS6-855A	497.33	silty sand with iron stains	28.27	28.03	44	93.9
LS6-857A	494.28	sand with iron stains	24.87	24.51	24	
LS6-858A	492.73	sand, silt, clay laminations with iron stains	23.98	23.33	61	93.7
LS6-861A	489.73	dark gray shale	25.76	25.81	138	
LS6-862A	486.68	dark gray shale	22.06	22.28	412	96.9
LS6-863A	485.13	dark gray shale	23.09	23.23	383	89.8

specimens with matric suctions below 200 kPa. For the soil specimens with matric suctions on the order of 300 to 400 kPa, the time needed to attain equilibrium was about 150 min (Figure 4), and could be as long as 500 to 600 min (Figure 6). It is suggested that the soil specimen and the suction sensor be enclosed in aluminium foil and plastic when high suctions are being measured.

Suction sensor reading versus time curves for sample LS6-741 (Figure 7) show the effect of temperature gradients between soil and sensor on the suction sensor reading. When sensor readings were taken immediately after the soil was removed from the humidity-controlled cold room, the sensor readings increased within about 5 minutes to a value of 156 kPa, which is several times higher than the matric suction of the soil.

On removal from the humidity-controlled cold room, soil sample LS6-741 was approximately 12°C (the temperature of the humidity-controlled cold room), which was approximately 10°C lower than the laboratory room temperature. The temperature gradients between the soil and the sensor resulted in high initial sensor readings. The readings eventually registered a lower equilibrium value as the temperature of the soil sample came to equilibrium with the room temperature. The results of the experiment showed that a temperature equilibration time of about 4 hr in the laboratory was adequate for the soil sample to come to equilibrium with the laboratory room temperature. The reason that temperature gradients between the soil and the suction sensor produce higher sensor readings is unknown.

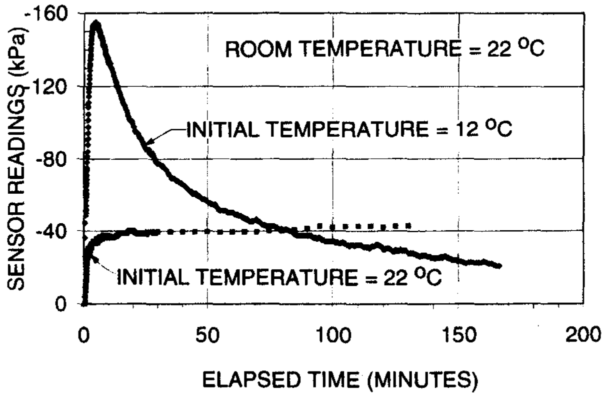

FIGURE 7 Effect of temperature on direct-measurement, high-range suction sensor readings for sample LS6-741.

The matric suction profiles presented in Figures 8, 9, and 10 show that matric suction was highest near the ground surface. The matric suction values decreased with depth from the ground surface and reached a low of between 20 and 100 kPa at an elevation of about 500 to 510 m. With increasing depth, the suctions measured in the laboratory again increased.

The measured negative pore water pressure for the borehole samples is affected by the release of the in-situ overburden pressure. The influence of unloading associated with the overburden pressure on the measured suction value of the soil is dependent on the degree of saturation and the stiffness of the soil. The B pore pressure coefficient for a saturated soil is 1.0. The B pore pressure coefficient

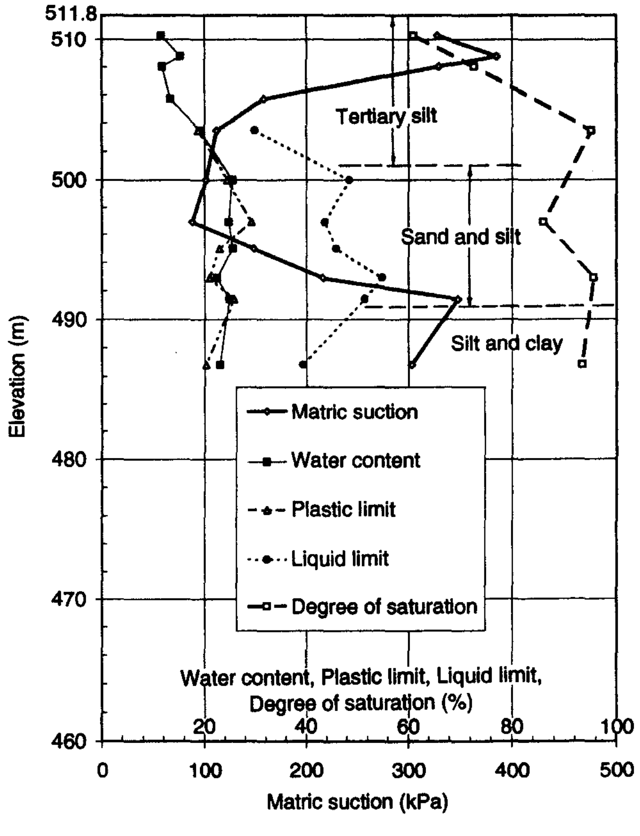

FIGURE 8 Matric suction, water content, degree of saturation, plastic limit, and liquid limit profiles of borehole SI5 location.

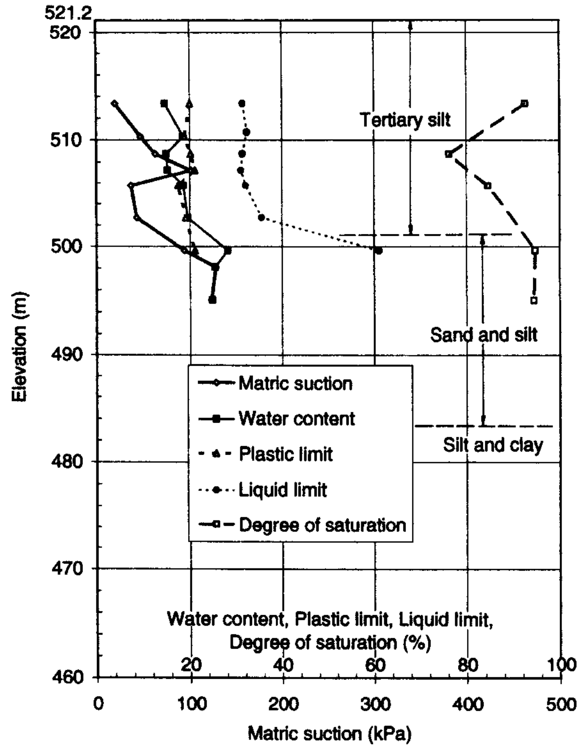

FIGURE 9 Matric suction, water content, degree of saturation, plastic limit, and liquid limit profiles of borehole SI6 location.

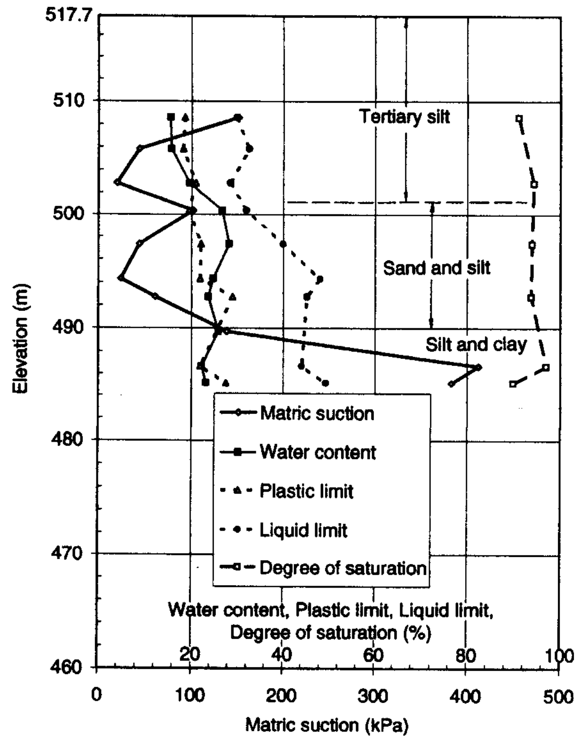

FIGURE 10 Matric suction, water content, degree of saturation, plastic limit, and liquid limit profiles of borehole SI9 location.

decreases when the degree of saturation decreases. For example, test results for a Peorian loess and a Champaign till showed that the B pore pressure coefficient dramatically decreased when the degree of saturation dropped below about 80 to 90 percent for both soils (*8*). Results for the Peorian loess are presented in Figure 11. Data are not available for the soil used in this test program.

Above the water table, the B pore pressure coefficient decreased with elevation as a result of a reduction in the degree of saturation of the soil. The coefficient was quite low (e.g., on the order of 0.1) near the ground surface and increased to a value of 1.0 in the capillary zone immediately above the water table.

The profiles in Figures 8, 9, and 10 show that the soils have degrees of saturation ranging between 80 and 90 percent. The B pore pressure coefficient is estimated to be on the order of 0.1 to 0.3, based on degree of saturation and the stiffness of the soils at the Outlook Bridge site. The measured suction values, along with the matric suction values corrected for B pore pressure coefficients of 0.1 and 0.3, are shown in Figures 12, 13, and 14. These results show that the soils at boreholes SI5, SI6, and SI9 have matric suction values ranging from 20 to about 400 kPa.

CONCLUSIONS

The direct-measurement, high-suction sensor has been used to obtain matric suction measurements of up to 400 kPa for a Saskatchewan soil. The time for the sensor reading to attain the soil suction value increased with an increasing matric suction in the soil.

The results show that the soils at the west bank of the Outlook Bridge site have matric suction values ranging from 20 kPa to about 400 kPa. The matric suction in the soil must be taken into account during a back-analysis of an existing landslide to obtain realistic in-situ shear strength parameters.

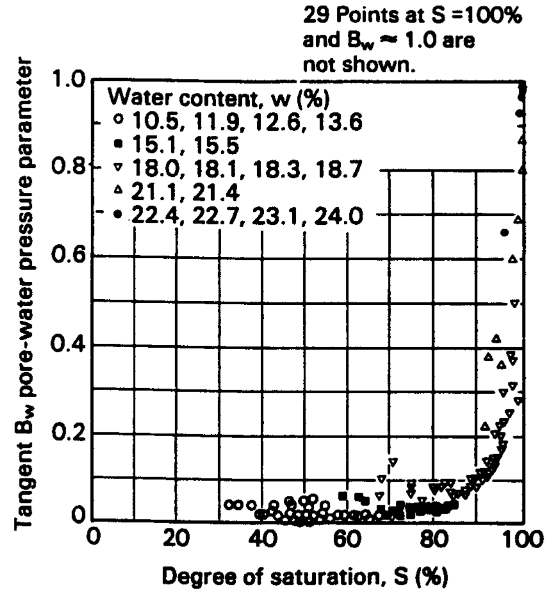

FIGURE 11 B pore pressure coefficient as function of degree of saturation of Peorian loess (*8*).

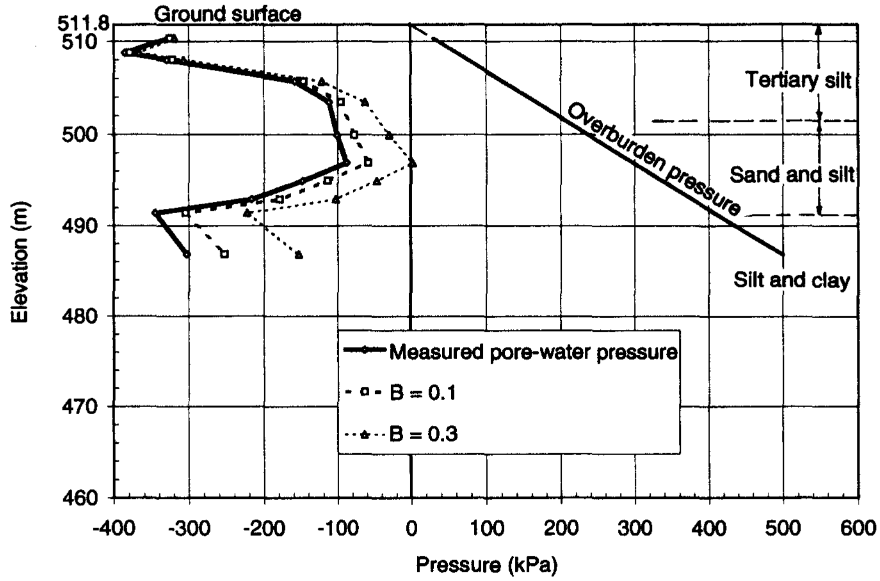

FIGURE 12 Pore water pressure profiles corresponding to various values of B pore pressure coefficient of borehole SI5 location.

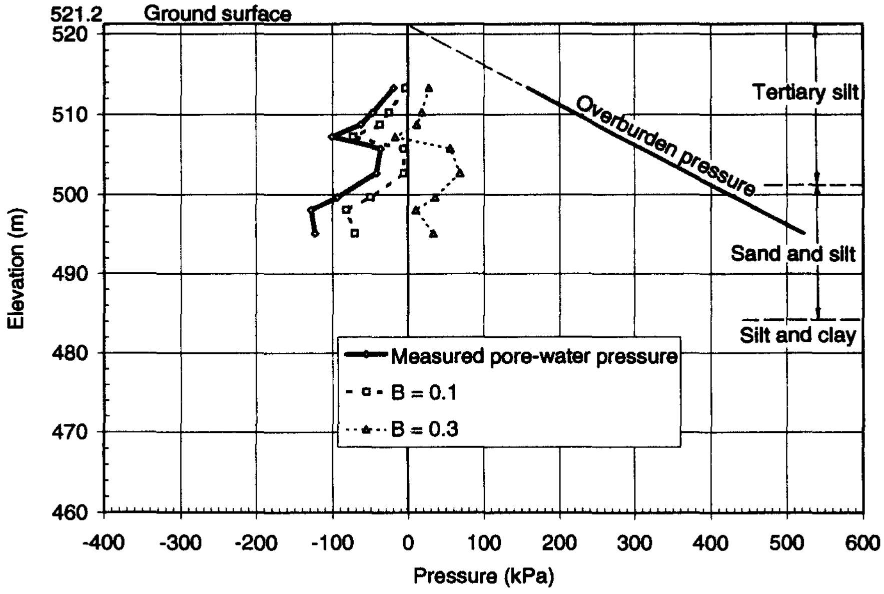

FIGURE 13 Pore water pressure profiles corresponding to various values of B pore pressure coefficient of borehole SI6 location.

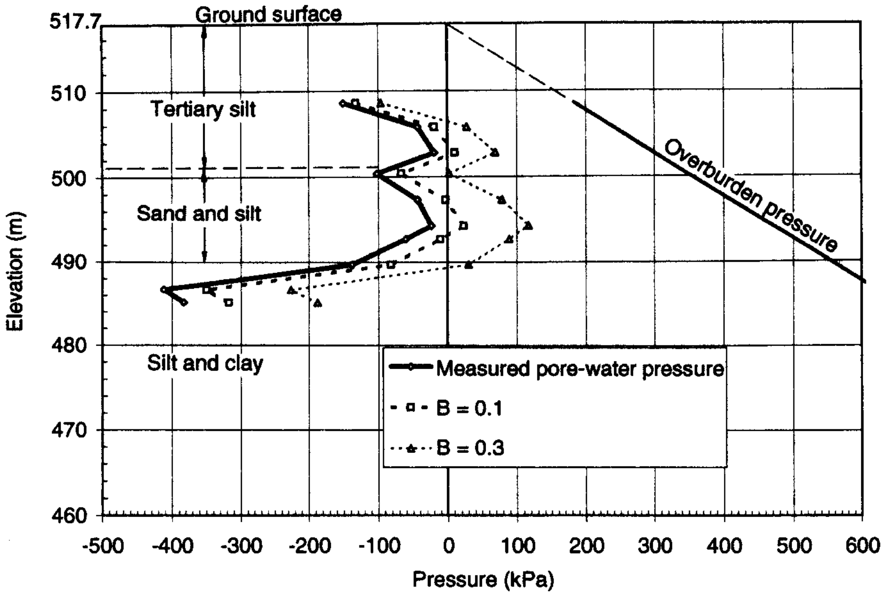

FIGURE 14 **Pore water pressure profiles corresponding to various values of B pore pressure coefficient of borehole SI9 location.**

REFERENCES

1. Ridley, A. M. *The Measurement of Soil Moisture Suction.* Ph.D. dissertation. Imperial College, London, United Kingdom, 1993.
2. Guan, Y. *The Measurement of Soil Suction.* Ph.D. dissertation. University of Saskatchewan, Saskatoon, Saskatchewan, Canada, 1996.
3. Vincent, R. S. Measurement of Tensions in Liquids by Means of a Metal Bellows. *Proceedings of Physics Society,* Vol. 53, 1941, pp. 126–140.
4. Temperley, H. N. V. The Behavior of Water under Hydrostatic Tension H. *Proceedings of Physics Society,* Vol. 58, 1946, pp. 436–443.
5. Temperley, H. N. V. The Behavior of Water Under Hydrostatic Tension In. *Proceedings of Physics Society,* Vol. 59, 1947, pp. 199–208.
6. Harvey, E. N., W. D. McLeroy, and A. H. Whiteley. On Cavity Formation in Water. *Journal of Applied Physics,* Vol. 8, No. 2, 1947, pp. 162–172.
7. Fisher, J. C. The Fracture of Liquids. *Journal of Applied Physics,* Vol. 19, 1948, pp. 1062–1067.
8. Campbell, J. D. *Pore Pressures and Volume Changes in Unsaturated Soils.* Ph.D. dissertation. University of Illinois at Urbana–Champaign, 1973.

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