Use of the tensile strength of water for the direct measurement of high soil suction

Yun Guan and D.G. Fredlund

Abstract: A suction probe was developed to directly measure matric suction greater than 100 kPa. The suction probe contains a small volume of water, a nonthreaded, high-range pressure transducer, and a 15 bar (1 bar = 100 kPa) ceramic disk. Cyclic prepressurization up to 12 000 kPa was used to dissolve potential cavitation nuclei in the water in the suction probe to increase the sustainable tension of the water. Using a pressure-plate cell, the suction probe has been verified to be accurate and has a rapid response for pore-water pressures as low as –500 kPa. Measurements performed on various types of soils indicate that the suction probe is able to measure matric suction up to 1250 kPa with satisfactory accuracy. The filter-paper method and the thermal conductivity sensor generally gave lower values of matric suction than the suction probe, whereas the null-pressure plate gave higher values of matric suction than the suction probe. The suction probe appeared to be best suited for measuring suction in wet clayey-type soils. Some difficulties were encountered in measuring suction in soils with a low degree of saturation.

Key words: direct suction measurement, tensile strength of water, unsaturated soils, matric suction, cavitation, suction profile.

Résumé : Une sonde de succion a été développée pour mesurer directement des succions matricielles supérieures à 100 kPa. Cet appareil contient un petit volume d'eau, un capteur de pression non fileté à haute capacité et un disque en céramique 15 bar (1 bar = 100 kPa). Une pression cyclique préalable supérieure à 12 000 kPa a été utilisée pour dissoudre les germes de cavitation potentiels dans l'eau de la sonde, de façon à accroître la tension que l'eau peut supporter. Grâce à une cellule de type plaque de pression, on a pu vérifier la précision de la sonde, qui possède également une réponse rapide pour des pressions interstitielles aussi basses que –500 kPa. Les mesures faites sur différents types de sols indiquent que notre sonde peut mesurer des succions matricielles allant jusqu'à 1250 kPa sans perte de précision. La méthode du papier filtre et le capteur de conductivité thermique ont généralement donné des valeurs de succion matricielle inférieures à celles fournies par la sonde, alors que la plaque dite à pression nulle a donné des valeurs supérieures. Notre appareillage parait être meilleur pour la mesure des succions dans des sols de type argileux humides. On a rencontré quelques dificultés lors de la mesure de la succion dans des sols ayant un degré de saturation peu élevé.

Mots clés : mesure directe de la succion, résistance de l'eau en tension, sols non saturés, succion matricielle, cavitation, sonde de succion.
[Traduit par la rédaction]

Introduction

The engineering behavior of an unsaturated soil is significantly influenced by the suction in the soil. Soil suction consists of two components, namely, matric suction and osmotic suction. Matric suction is defined as the difference between the pore-air pressure and pore-water pressure and is a primary stress state variable required in analyzing the behavior of unsaturated soils.

Information on soil suction and soil suction changes is needed for the solution of various geotechnical problems involving unsaturated soils. For example, the analysis of so-called "problematic soils" (i.e., swelling soils, collapsing soils, and residual soils) is dependent upon the appropriate assessment of matric suction (Fredlund and Rahardjo 1993). The development in soil suction measurement has been relatively slow when compared with the rapid formulations of theories for unsaturated soil behavior. The direct measurement of matric suction has been limited to values below 100 kPa due to cavitation of water in the measuring system (Stannard 1992).

The limitations related to the direct measurement of suction are due to the fact that water usually was not able to retain its tension and would cavitate whenever the pressure drops below about –100 kPa. However, the tensile strength of water has been measured by many physicists to be greater than several atmospheres (Knapp et al. 1970; Trevena 1987). Recent studies have shown that water in a small chamber can sustain high tension. It should be noted that the term "tensile strength of water" found in the literature is a misnomer, since the tensile strength of water has never been directly measured. The measured tensile strength is only part of the true tensile strength of water and is significantly influenced by the surface condition of the container walls and the manner in which the tension is applied. The term tensile strength of water is used in this paper in the same sense as used in the literature (i.e., the measured tensile strength of water represents the overall ability of the water–container system to resist tension applied to the water).

Received June 18, 1996. Accepted March 15, 1997.

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This paper reports on the direct measurement of matric suctions greater than 100 kPa, using a suction probe which contains a small volume of water, a high-range pressure transducer, and a 15 bar (1 bar = 100 kPa) ceramic disk. High pressures were used to dissolve potential cavitation nuclei and increase the tensile strength of the water in the suction probe. The pressure-plate cell was used to test the accuracy and response time of the suction probe. Matric suction measurements using the suction probe were performed on various types of soils. Matric suction measurements using the suction probe were compared with measurements using the filter-paper method, the null-pressure plate method, and the thermal conductivity sensor.

Theory and historical background

The theoretical tensile strength of water has been estimated to be in the order of several hundred atmospheres (Vincent 1941; Temperley 1946, 1947; Harvey et al. 1947; Fisher 1948). The tensile strength of a liquid is the tensile stress at which the liquid ruptures or cavitates. Cavitation starts as gas or vapor bubbles begin to form in water. The vapor bubbles are triggered at gaseous or other hydrophobic surfaces which are commonly called potential cavitation nuclei. The net normal stress at the surface of a potential cavitation nucleus is equal to the difference between the vapor pressure and the hydrostatic pressure. The value of the net normal stress at the inception of bubble formation measures the tensile strength of water, S_{w}, which can be related to the surface tension, T_{s}, of a spherical gas bubble with a definite radius, r, by the equation

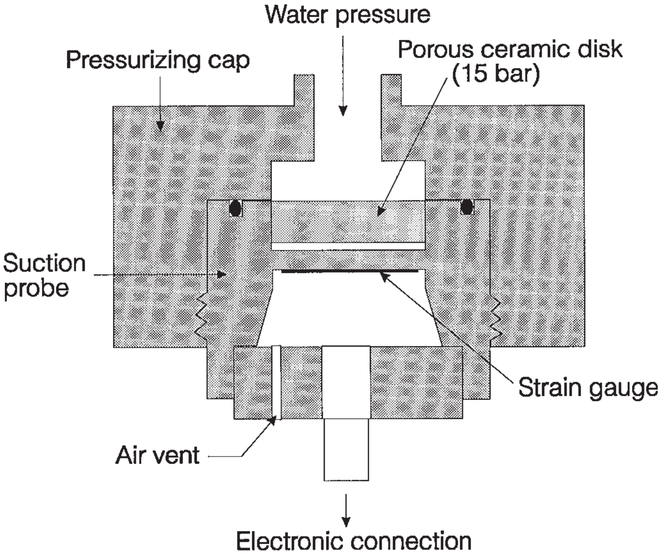
$$[1] \qquad S_{\mathrm{w}} = \frac{2T_{\mathrm{s}}}{r}$$

Water normally cavitates when the hydrostatic pressure is close to the vapor pressure. However, if the radii of cavitation nuclei are sufficiently reduced, water will have the ability to sustain a high tension without cavitation. For example, if the radius, r, is assumed to be the size of a water molecule (i.e., about 3×10^{-7} mm), at the inception of the formation of a gas bubble, S_{w} will be 480 000 kPa according to [1].

The values of the tensile strength of water, as measured by physicists, were widely scattered, with most values greater than 500 kPa. A liquid under tension is in a metastable state (Temperley and Chambers 1946; Temperley 1947; Chapman et al. 1975; Green et al. 1990) due to the presence of potential cavitation nuclei in the liquid and on the container walls. Tiny crevices on the surfaces of dust particles and container walls are the most common cavitation nuclei. High positive pressures can suppress cavitation nuclei present in water and container walls and significantly increase the tensile strength of the water (Knapp 1958; Winterton 1977).

Previous research has been focused on measuring the maximum tensile strength of water. Little attention has been given to how long a tension can be sustained on the water phase. Chapman et al. (1975) and Winterton (1977) measured high tensions in water which were sustained for a few minutes. Henderson and Speedy (1980) reported a tension of 10 000 kPa that was sustained for over a week. Guan (1996) studied the behavior of a small volume of water subjected to high tensions using a high air entry ceramic disk and a high-range pressure transducer. It appears that there is a cavitation tension for a particular prepressurization procedure and a particular suction probe. A tension can be sustained for several hours if the applied tension does not exceed the cavitation tension.

Fig. 1. Schematic of the Imperial College suction probe (after Ridley 1993).



The methods used by physicists for measuring high tensions in water are not adaptable for the measurement of soil suction. Gilbert (1960) attempted to measure high tensions in sucrose solutions in a triaxial cell. Gilbert's work was largely ignored by other soil researchers. Ridley (1993) prepressurized a small volume of water in a tensiometer-type device (Fig. 1) and measured matric suctions up to 1500 kPa. Ridley and Burland (1994) found reasonable agreement between the matric suctions in a London clay measured using Ridley's tensiometer-type device and the filter-paper method. It was suggested that the microstructure of the soil, particularly the size of the voids, may affect the measurement of matric suction using the device. The device was later modified to measure the matric suction in osmotically controlled oedometer tests (Dineen and Burland 1995).

A suction probe was developed at the University of Saskatchewan for the direct measurement of high-range soil suction. Studies (Guan 1996) indicated that the suction probe could sustain pressures as low as –1250 kPa. The suction probe was used to measure matric suctions in various types of soils. The measurements using the suction probe were compared with those using the pressure-plate technique, the filter-paper method, and the thermal conductivity sensor.

Equipment description

The suction probe developed at the University of Saskatchewan consisted of a high-range pressure transducer (i.e., 150 bar) and a stainless steel shroud, which was precisely machined to embrace the transducer (Fig. 2). The sensing area of the transducer was a smooth, circular surface with a diameter of 7.0 mm. A 15 bar ceramic disk was fitted into the shroud. Shrouds of different sizes were manufactured. The transducer and shroud were assembled under water to leave a water-saturated chamber with a clearance between transducer and ceramic disk of 0.1–0.5 mm.

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Fig. 2. The construction of the Saskatchewan suction probe.

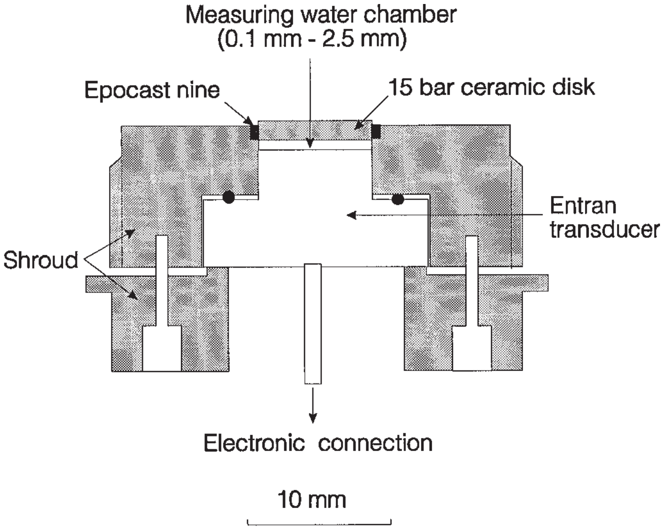


Table 1. Sustainable tensions for the ceramic disks used.

Ceramic disks	Sustainable tension (kPa)
No. 1	600–650
No. 2	1200–1250

A manual pressurization system was built to prepressurize the water in the suction probe. Figure 3 shows the components of the pressurization system. The suction probe was mounted onto the pressurizing cup. The piston could produce a pressure up to 15 000 kPa. A vacuum inlet was also constructed to provide the cup with a negative pressure of 85 kPa. A valve (i.e., B in Fig. 3) was used to switch between the positive and negative pressure lines. Experiments indicated that six cycles of pressurization produced the maximum sustainable tension in the suction probe. Each cycle includes the application of a positive pressure of 12 000 kPa for 1 h, followed by a negative pressure of –85 kPa for 1 h. The sustainable tension in the suction probe appeared to be related to the characteristics of the ceramic disk. The size of the water chamber did not appear to have an appreciable effect on the sustainable tension in the suction probe. The sustainable tensions in the suction probe for two ceramic disks selected for the measurement of soil suction are presented in Table 1.

Equipment verification

The accuracy and response time of the suction probe subjected to high tensions were tested using a modified pressure-plate cell fitted with a 5 bar ceramic plate. The experimental setup is illustrated in Fig. 4. A soil specimen was placed on the ceramic plate of the pressure-plate cell. The suction probe was placed on the soil. A grooved brass block was placed on the suction probe to ensure good contact between the suction probe and the soil. Water was added into the groove of the brass block to maintain a humid condition within the cell. Air pressure was applied to the cell to force the water in the soil to flow out through the 5 bar ceramic plate. When equilibrium was attained, a matric suction equal to the applied air pressure should exist in the soil. If the air pressure was released to zero (i.e., atmospheric pressure), a negative pore-water pressure, which is numerically equal to the preapplied air pressure, should be simultaneously established in the soil water and should be measured by the suction probe.

Fig. 3. Components of the pressurization system.

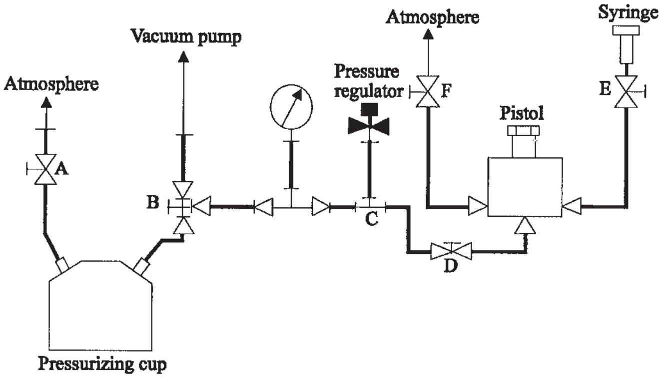
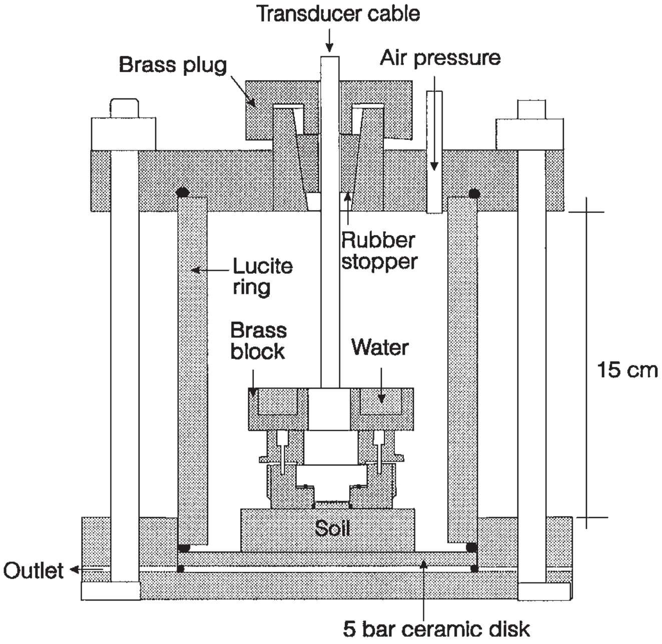


Fig. 4. The modified pressure plate for testing the Saskatchewan suction probe for negative pressures.



Soil suction measurement tests

Soil suction measurements were conducted in various types of soil using the suction probe. The soils are described in the next section. The setup for soil suction measurements using the suction probe is shown in Fig. 5. Soil suction measurements were also conducted using several other techniques for comparison.

Soil materials

A Regina clay and a fine silt were used to evaluate the performance of the suction probe for measuring soil suction. A compacted glacial till was used for a comparative study between

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Table 2. Properties of the glacial till.

Specific gravity	2.73
Liquid limit (%)	35.5
Plastic limit (%)	16.8
Sand size (%)	28
Silt size (%)	42
Clay size (%)	30
AASHTO Standard Proctor compacted dry density (Mg/m^3)	1.80
Optimum moisture content (%)	16.3

Table 3. Compaction densities and water contents for the glacial till.

Water content (%)	Dry density (Mg/m^3)	Degree of saturation (%)
16.3 (optimum)	1.80	86.5
15.0	1.78	77.2
13.0	1.73	61.3
11.5	1.66	48.7
11.0	1.61	43.1

Fig. 5. The schematic setup for soil suction measurement.

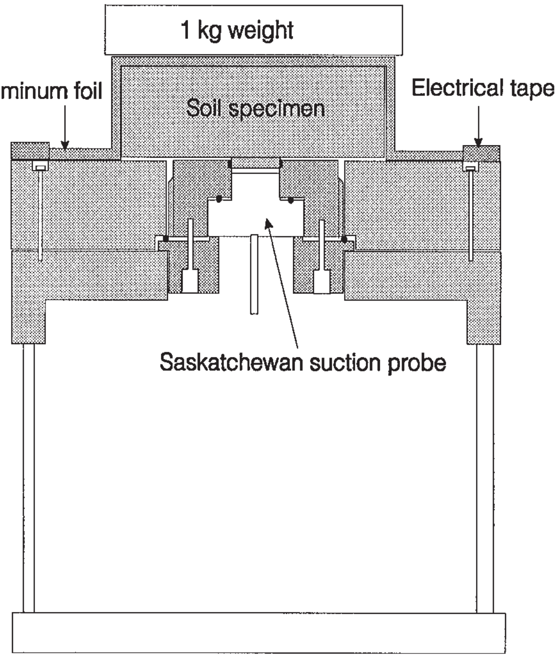
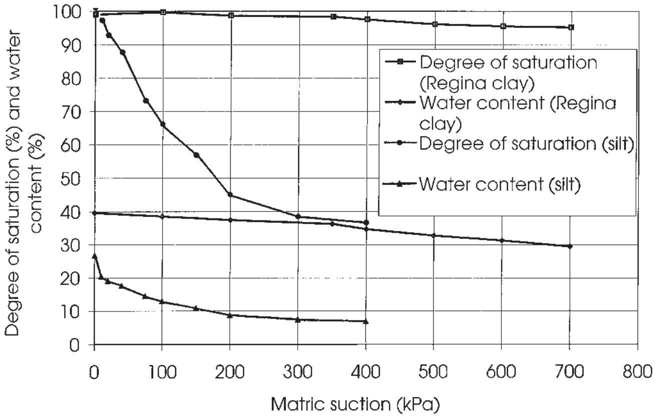


Fig. 6. Soil-water characteristic curves for Regina clay and the fine silt.



measurements made using the suction probe and those made using several other conventional techniques.

Air-dried Regina clay was machine ground to pass through a No. 200 sieve. The Regina clay was mixed into a slurry at a water content of about 100%. The slurry was placed in an oedometer and consolidated to a pressure of 500 kPa. The fine silt was also made into a slurry and consolidated to a pressure of 800 kPa. The soil-water characteristic curves for the Regina clay and the fine silt were established using a pressure plate. The results are presented in Fig. 6. The Regina clay specimen remained saturated at a suction of 700 kPa. The silt specimen started to desaturate at a matric suction of less than 10 kPa and reached the residual water content condition at a suction of about 300 kPa. The silt was used to determine if the suction probe was suitable for measuring matric suction in unsaturated soils.

Table 2 gives some of the properties of the glacial till. Figure 7 shows the compaction curve for the glacial till. The compaction was conducted using the AASHTO Standard Proctor method.

Five compaction densities and water contents were selected for preparing glacial till specimens (Table 3). The water contents were near or on the dry side of optimum. The soil was statically compacted in three layers to form specimens of 101 mm in diameter and 20 mm in height. The matric suction of each specimen was determined using filter paper, null-pressure plate, and the suction probe in sequence. Matric suction measurements using the thermal conductivity sensor were conducted on a separate soil specimen, 40 mm in length.

Experimental procedures

Testing the suction probe for negative pressures

A specimen of reconstituted saturated Regina clay was used in the modified pressure plate (Fig. 4). An air pressure of 200 kPa was applied. The outflow of soil water through the 5 bar ceramic plate was collected. When the outflow ceased, the water underneath the 5 bar ceramic plate was removed using an air pump. The air pressure in the pressure chamber was quickly released to zero and the corresponding reduction in the water pressure in the suction probe was recorded. When the water pressure recorded by the suction probe ceased to change significantly, the water chamber of the pressure plate was filled with water. The air pressure was increased to 300 kPa and the above procedure was repeated. The test was repeated using pressures of 400 and 500 kPa. At the end of the test, the water content of the soil was measured.

The above procedures were also followed for the test on a reconstituted silt specimen.

Testing the suction probe against preapplied matric suctions

Matric suctions ranging from 150 up to 550 kPa were applied to reconsitituted Regina clay specimens in a pressure-plate cell. Matric suctions in the soil were measured using the suction

Fig. 7. Compaction curve of the glacial till.

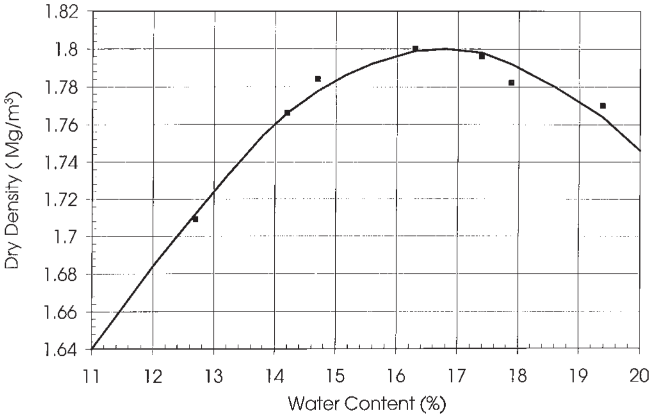
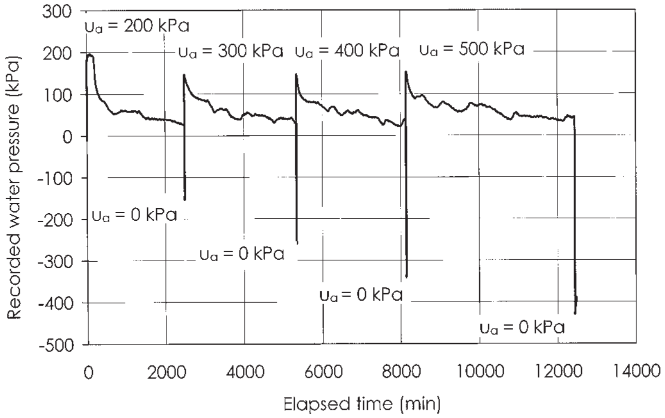


Fig. 8. Testing the Saskatchewan suction probe for negative pressure in Regina clay using the pressure-plate cell.



probe fitted with a No.1 ceramic disk (Table 1). Three different degrees of contact were deliberately created between the ceramic disk of the suction probe and the soil specimen: (1) noncontact—the surface of the 15 bar ceramic disk was made to recess below the surface of the suction probe, and the soil was not in contact with the ceramic disk; (2) contact through a clay slurry—a small amount of Regina clay paste (about 0.2 mm thick) was placed between the recessed ceramic disk and the soil; and (3) direct contact between soil and ceramic disk—the ceramic disk surface was made to protrude slightly from the surface of the suction probe such that the soil specimen was placed on the ceramic disk surface.

Similar tests were conducted using the reconstituted fine silt. The maximum matric suction applied to the reconstituted fine silt was 400 kPa.

Comparison with other conventional methods

A comparison study was made of suction measurements using the suction probe, filter-paper method, null-pressure plate method, and thermal conductivity sensor.

Schleicher & Schuell No. 589 White Ribbon filter paper was used, following the American Society for Testing and Materials procedure D5298-92 (ASTM 1992). A set of three filter papers was placed between two specimens of glacial till which were compacted at the same water content and the same dry density. The specimens were covered with two layers of aluminum foil and electric tape and placed in a sealed container. The container was placed in a polystyrene insulated chest and kept in a humidity-controlled room for 7 days. A balance with a capacity of 30 g and a sensitivity of 0.0001 g was used for weighing the filter paper.

Matric suction of the soil specimen was obtained from the water content of the middle filter paper. The calibration curve recommended by ASTM D5298-92 for Schleicher & Schuell No. 589 White Ribbon filter paper was used. Measurements were repeated on a number of soil specimens.

Following the filter-paper measurement, each soil specimen was placed on a saturated 5 bar ceramic plate in a pressure plate cell. A “null-flow” condition was obtained by adjusting the magnitude of the applied air pressure. At null-flow conditions, matric suction in the specimen was assumed to be equal to the applied air pressure.

The matric suction of each specimen was next measured using the suction probe fitted with a No. 2 ceramic disk (Table 1). A small amount of wet clay paste was applied between the soil and the suction probe to enhance the contact between the soil and the ceramic disk.

The thermal conductivity sensors used in this study were 28 mm long and 20 mm in diameter. The thermal conductivity sensors had a poor sensitivity for matric suctions above 150 kPa. The ceramic block of the thermal conductivity sensors had the tendency to crack after a usage of about 1 or 2 months.

Presentation of results

Testing the suction probe for measuring negative water pressures

Figure 8 shows the changes in water pressure with time from tests on reconstituted Regina clay using the suction probe. Table 4 provides a summary of the water pressure, u_w, before and after the application and release of each air pressure, u_a. When an air pressure of 200 kPa was applied to the pressure chamber, the suction probe recorded an instantaneous increase in water pressure from 0 to 195 kPa. The water pressure gradually reduced to about 25 kPa after 42 h. The pressure measured by the suction probe did not return to zero. This was probably due to the slow rate of soil water flow under the small pressure gradient. The resolution of the high-range pressure transducer, which is about ±20 kPa, might also be a contributing factor to the pressure in the suction probe not returning to zero.

Reducing the air pressure from 200 to 0 kPa caused the water pressure to immediately fall from 25 kPa to a reading of –158 kPa. The change in air pressure (i.e., –200 kPa) was close to the change in water pressure (i.e., –(25 + 158) = –183 kPa). The water pressure measured by the suction probe gradually increased because water slowly flowed into the soil. When the water pressure reached –151 kPa, an increase in air pressure to 300 kPa produced an instantaneous jump of water pressure to about 145 kPa, an increase of 296 kPa.

Further tests also showed that a change in air pressure in the pressure chamber instantaneously produced an approximately equal change in water pressure in the suction probe. The difference between the change in the air pressure inside the pressure chamber and the change in water pressure in the suction probe was generally less than 5%. The Regina clay remained saturated throughout the test.

Table 4. Results of a test of the suction probe for negative pressures on Regina clay.

u_{a1} (kPa)	u_{w1} (kPa)	u_{a2} (kPa)	u_{w2} (kPa)	$\Delta(u_{a2}-u_{a1})$ (kPa)	$\Delta(u_{w2}-u_{w1})$ (kPa)	$\frac{\Delta(u_{w2}-u_{w1})}{\Delta(u_{a2}-u_{a1})}$(%)
0	0	200	195	200	195	2.5
200	25	0	–158	–200	–183	8.5
0	–151	300	145	300	296	1.3
300	30	0	–262	–300	–292	2.7
0	–256	400	146	400	402	0.5
400	40	0	–341	–400	–381	4.7
0	–341	500	–148	500	489	1.5
500	44	0	–443	–500	–487	2.6

Note: u_{a1} and u_{w1} are the measured air and water pressures before the change in air pressure, and u_{a2} and u_{w2} are the measured air and water pressures after the change in air pressure.

Table 5. Results of a test of the suction probe for negative pressures on silt.

u_{a1} (kPa)	u_{w1} (kPa)	u_{a2} (kPa)	u_{w2} (kPa)	$\Delta(u_{a2}-u_{a1})$ (kPa)	$\Delta(u_{w2}-u_{w1})$ (kPa)	$\frac{\Delta(u_{w2}-u_{w1})}{\Delta(u_{a2}-u_{a1})}$(%)
0	0	200	189	200	189	6.1
200	11	0	–176	–200	–187	7.1
0	–151	300	153	300	304	1.1
300	7	0	–283	–300	–290	3.1
0	–262	400	142	400	404	1.1
400	24	0	–364	–400	–388	3.1
0	–358	500	168	500	526	5.1
500	7	0	–473	–500	480	4.1

Figure 9 and Table 5 give the results of a calibration test on a reconstituted silt specimen. Again, a change in the air pressure inside the pressure chamber instantaneously produced an approximately equal change in the measured water pressure. The difference between the change in air pressure inside the pressure chamber and the change in water pressure in the suction probe was again generally less than 5%.

Measurement of preapplied matric suctions

Figure 10 gives the suction measurements on a reconstituted specimen of Regina clay, using a suction probe with a recessed No. 1 ceramic disk. The gap between the ceramic disk and the transducer was 0.3 mm. Preapplied matric suctions of 200, 300, and 400 kPa were used. In the first test, water from the ceramic disk of the suction probe evaporated into the air space between the soil and the ceramic disk, causing the tension in the water in the suction probe to continuously increase. The water in the suction probe cavitated at a tension of about 650 kPa.

In the next set of tests, a small amount of Regina clay paste (about 0.2 mm thick) was placed onto the recessed ceramic disk to ensure good contact between the ceramic disk and the soil. Equilibrium was reached in about 5 h. While measuring suction in the specimen with a preapplied matric suction of 400 kPa, the system cavitated at a tension of about 400 kPa. This value was considerably lower than the maximum sustainable tension determined for the No.1 ceramic disk (Table 1). It was found that the inner face of the ceramic disk of the suction probe had become relatively soft. The surface of the ceramic disk could be peeled with a slight fingernail scratch. The suction probe had been subjected to repeated cavitations over a long period of time. The previous cavitation history appears to have weakened the ceramic disk. The ceramic disk was then replaced.

Fig. 9. Testing the Saskatchewan suction probe for negative pressure in silt using the pressure-plate cell.

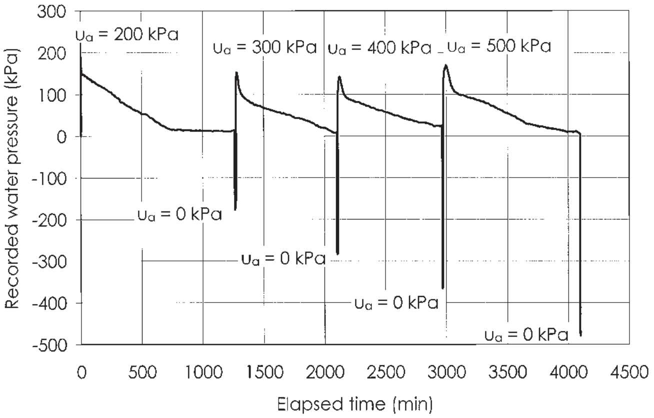


Figure 11 shows the results of matric suction measurements in a Regina clay placed in direct contact with the ceramic disk of the suction probe. The preapplied matric suctions varied

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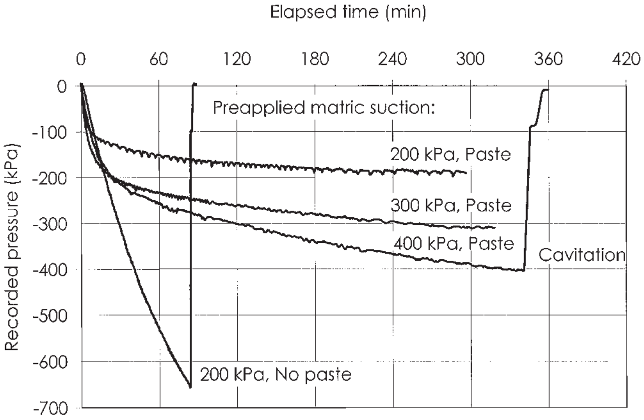


Fig. 10. Matric suction measurements on reconstituted Regina clay using a recessed ceramic disk.

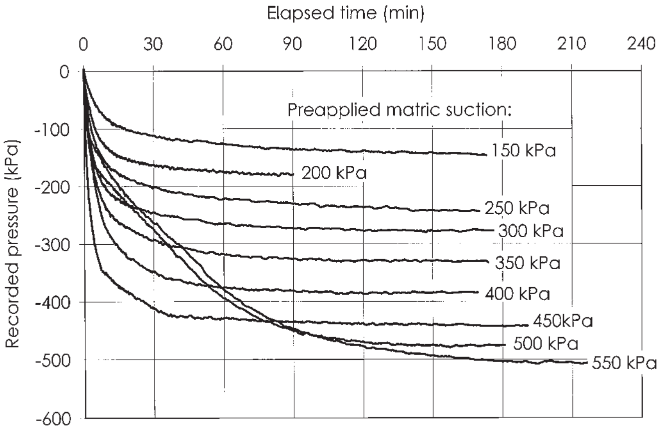


Fig. 11. Matric suction measurements on reconstituted Regina clay in direct contact with the ceramic disk.

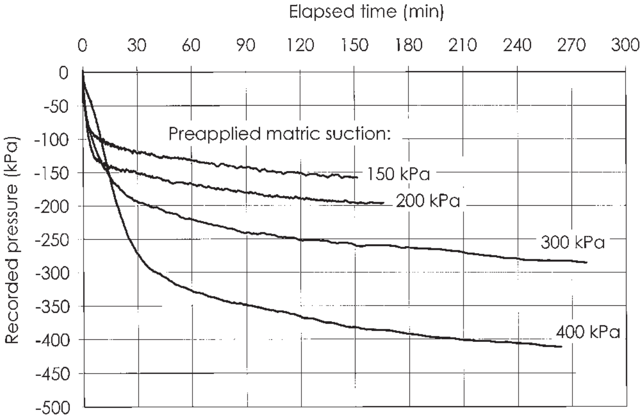


Fig. 12. Matric suction measurements on reconstituted silt.

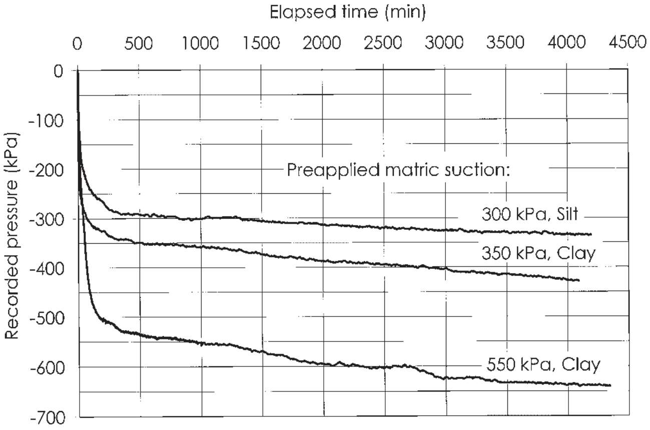


Fig. 13. Matric suction measurements on reconstituted silt and Regina clay.

from 150 to 550 kPa in increments of 50 kPa. The recorded curves were in good agreement with the preapplied matric suctions up to 450 kPa. The recorded negative pressures for preapplied matric suctions of 500 and 550 kPa developed more slowly than in the previous tests. This could be due to the occurrence of a tension crack in the central part of the soil specimen when the preapplied matric suction exceeded 450 kPa. The presence of a crack increased the time required for equalization. However, the presence of the crack did not appear to influence the matric suction reading at equilibrium.

For all the above tests in which the specimen had good contact with the ceramic disk, the measured tensions were approximately equal to the preapplied matric suctions. The equalization was also faster for soils in direct contact with the ceramic disk of the suction probe.

Figure 12 gives the results of measurements of matric suction on the silt specimens. There was a slight drift in the recorded suctions, particularly when the preapplied matric suction exceeded 300 kPa. A matric suction of 300 kPa corresponds to a degree of saturation of about 38% for the silt specimen.

Figure 13 shows three measurements of matric suction on reconstituted silt and Regina clay specimens, using the suction probe with a fresh No.1 ceramic disk. Preapplied suctions of 300, 350, and 550 kPa were used. The results show that water tensions in the suction probe can be sustained for at least 72 h.

Comparison with other methods of suction measurement

Measurements of matric suction on the glacial till, using different methods, are summarized in Table 6. The change in the degree of saturation during each measurement is also given in Table 6. The results presented in Table 6 suggest that the measurements were reproducible except for those from the filter-paper method. Figure 14 shows measurements obtained using the suction probe and filter-paper methods. When doing this comparison, it should be noted that the filter-paper method is anticipated to be the less accurate of the two methods. Figure 15 shows the measurements obtained using the suction probe, null-pressure plate, and thermal conductivity sensor. The measurements obtained by Vanapalli (1994) using a null-pressure plate are also presented in Fig. 15.

Figure 16 shows the water tensions recorded by the suction probe for selected degrees of saturation of 86.6, 77.4, and 61.3%, respectively. Suction measurements on two specimens prepared at the same degree of saturation gave close results. Equilibrium was reached in about 4 h. The values of matric suction at equilibrium were about 68, 173, 320 kPa, respectively. Reductions in the degree of saturation of the soil during

Table 6. Summary of matric suction measurements on the glacial till at different compaction densities and water contents.

Description						
Dry density, ρ_d (Mg/m^3)	Water content, w (%)	Degree of saturation, S (%)	Method	Range of ΔS during test (%)	Approximate equalization time	Matric suction (kPa)
1.80	16.3	86.6	Suction probe	0.4	1 h	73, 64
			Filter paper	0.9	7 days	61–65
			Thermal conductivity[a]	0.8	30 h, 5 h	37, 67
			Null-pressure plate	0.5	8 h	138, 143
1.78	15.0	77.4	Suction probe	1.1	4 h	172, 175
			Filter paper	0.4	7 days	154–197
			Thermal conductivity[a]	0.8	40 h, 18 h	84, 123
			Null-pressure plate	0.6	12 h	205, 213
1.73	13.0	61.3	Suction probe	0.8	4.5 h	320, 321
			Filter paper	0.6	7 days	209–342
			Thermal conductivity[a]	0.4	60 h, 10 h	252, 253
			Null-pressure plate	1.0	16 h	369, 350
1.66	11.5	48.7	Suction probe	0.5	16 h, 24 h	813, 781
			Filter paper	0.4	7 days	524–752
			Thermal conductivity[a]	0.6	55 h, 20 h	386, 379
			Null-pressure plate	—	—	>700
1.61	11.0	43.7	Suction probe	0.3	18 h, 15 h	950, 907
			Filter paper	0.4	7 days	587–792

Fig. 14. Results of matric suction measurements on glacial till using the Saskatchewan suction probe and filter paper.

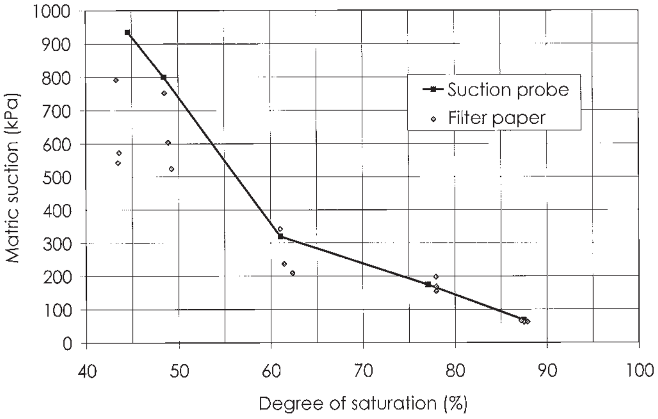
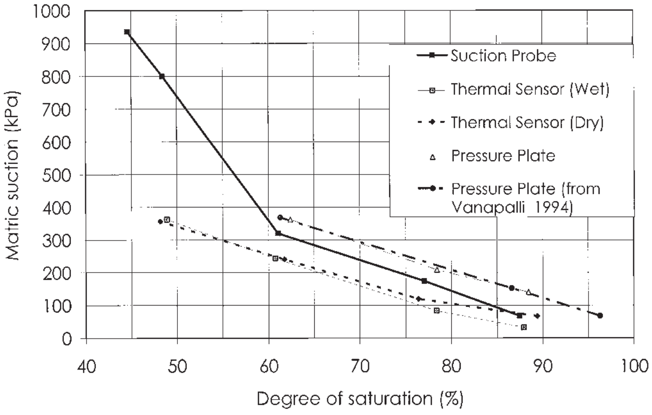


Fig. 15. Results of matric suction measurements on glacial till using the Saskatchewan suction probe, the pressure plate, and the thermal conductivity sensor.



the time the measurements were being made appear to be less than 1%.

Figures 17 and 18 show the suction measurements for selected degrees of saturation of 48.7 and 43.7%, respectively. Again, suction measurements on two specimens prepared at the same degree of saturation gave similar results. The matric suctions measured by the suction probe were 800 and 950 kPa, respectively.

Interpretation of data

Accuracy and response time of suction probe

The accuracy and response time of the suction probe were established using the modified pressure-plate cell. Differences between applied tensions and measured negative pressures were less than 5%. The accuracy of the tension measurement appears to be limited by the accuracy of the transducer used in the suction probe.

The response time of the suction probe to a change in the applied tension is a few seconds. The fast response of the suction probe is attributed to the rigidity of the chamber of the suction probe and the high degree of saturation of the soil being measured.

Mass transfer during suction measurement

The moisture transfer between suction probe and soil takes place in both the liquid and vapor phases. Moisture from the suction probe continuously evaporates into the soil and the vicinity surrounding the ceramic disk. Liquid water transfer occurs through the contact between the soil and the ceramic disk of the suction probe. The development of tension in the suction probe during matric suction measurement is a combination of evaporation

Fig. 16. Matric suction measurements on glacial till specimens prepared at degrees of saturation of 86.6, 77.4, and 61.3%, respectively.

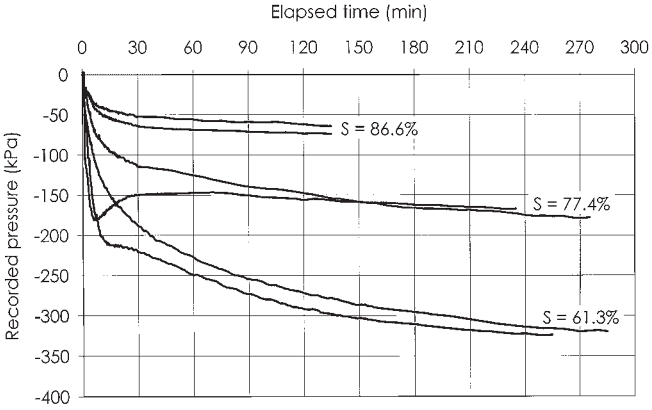


Fig. 17. Matric suction measurements on glacial till specimens prepared at a degree of saturation of 48.7%.

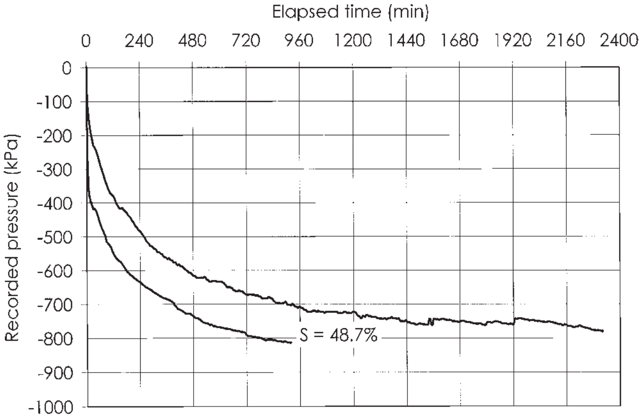


Fig. 18. Matric suction measurements on glacial till specimens prepared at a degree of saturation of 43.7%.

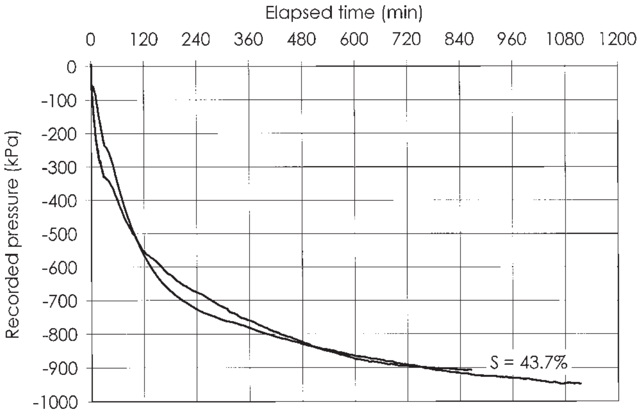
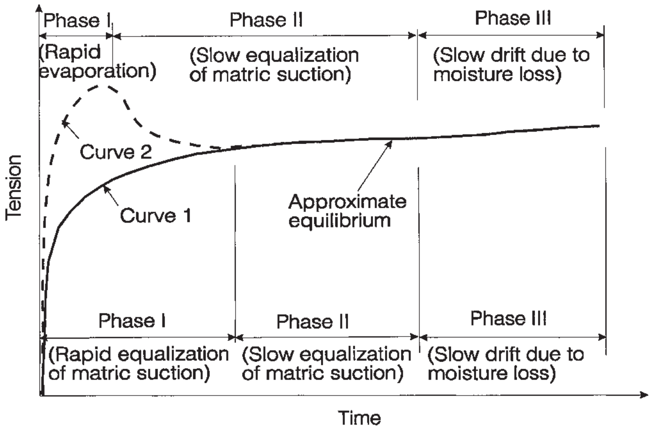


Fig. 19. Water tension in the suction probe response curves during the measurement of matric suction.



and liquid flow between the soil and the ceramic disk of the suction probe. If moisture is continuously lost from the system through evaporation during measurement, a continuous increase in tension would be observed. The amount of moisture lost through evaporation may be minuscule; however, this loss can have a significant effect on the suction measurements.

The development of tension in the suction probe during matric suction measurement may be divided into three phases as follows (Fig. 19):

Phase I: This is the initial phase of tension development. A significant amount of tension is rapidly produced during this relatively short period of time (e.g., 5–10 min). In this phase, liquid water transfer is more dominant than the evaporation process (curve 1). Curve 2 (also see Fig. 16) occurs when the tension in the suction probe has already developed due to evaporation before the suction probe is put into contact with the soil. However, the process of matric suction equalization due to liquid water transfer will soon become dominant as long as there is a good contact between the soil and the suction probe. The tension developed due to evaporation will decrease and the tension will reach equilibrium with the matric suction in the soil.

Phase II: Following phase I is a process during which matric suction equalization due to liquid water transfer is dominant but slow. At the end of this phase, equilibrium between the tension in the suction probe and the matric suction in the soil is reached. The liquid water transfer from the soil into the suction probe is able to offset the loss of moisture from the suction probe due to evaporation.

Phase III: After a relatively horizontal portion occurs on the tension-response curve, a slow increase in tension was always observed for the matric suction measurement of both saturated and unsaturated soils in this testing program. This is mainly attributed to the moisture loss due to evaporation from both the soil and the suction probe during the measurement. For the soil specimens used in the program, the water content generally decreased by up to 0.1% after the measurement of matric suction. Figure 14 also shows the approximate relationship between the matric suction and water content for the glacial till. A decrease in water content by 0.1% could account for an increase in the measured matric suctions from about 7 to 31 kPa for the glacial till, depending upon the degree of saturation of the till.

Comparisons with other suction measurement methods

The filter-paper method gave measurements close to the values obtained using the suction probe for matric suctions less than 200 kPa. As the soil became drier, the filter paper generally gave lower values. The scatter in the results obtained by the filter-paper method is more pronounced for soils with a low degree of saturation. Similar conclusions were also obtained by Ridley (1993). The scatter in the results is probably because equilibrium is not achieved in 7 days; particularly for soils at low degrees of saturation. Deka et al. (1995) suggested that equalization periods longer than 7 days are required for dry soils when using the filter-paper method.

The thermal conductivity sensors produced measurements which are relatively close to the suction probe measurements for matric suctions less than 100 kPa. The thermal conductivity sensors, either initially dry or wet, appeared to underestimate the matric suction at values exceeding 100 kPa. The thermal conductivity sensor has a low sensitivity for suctions above 150 kPa.

The null-pressure plate gave higher values of matric suction than the suction probe, particularly for soils with a degree of saturation higher than 75%. The difference, however, became less significant when the degree of saturation was less than 60%. The higher matric suctions measured using the pressure-plate method, particularly for soils with a high degree of saturation, were also found by Madsen et al. (1986) and Campbell (1988). The primary reason for the higher matric suction measurements using the null-pressure plate may be due to occluded air bubbles in the soil water. A theoretical study undertaken by Bocking and Fredlund (1980) indicated that occluded air bubbles in a soil can result in an overestimation of matric suction when using the null-pressure plate technique.

Conclusions

The tensile strength of water can be used to directly measure high soil suctions. The suction probe developed as part of this research program can be used to measure matric suctions up to 1250 kPa in both saturated and unsaturated soils. The accuracy of the suction probe appears to be mainly limited by the resolution of the pressure transducer used in the suction probe.

The suction probe is most suited to soils for which evaporation from the suction probe is less pronounced during the measurement process. These soils include wet clayey-type soils and other soils with a relatively high degree of saturation. Reasonable agreement was observed between measurements using the suction probe and those using the filter-paper method and the thermal conductivity sensor for soils with relatively high degrees of saturation. The discrepancies in the measurements using the suction probe, filter paper, and thermal conductivity sensor became more pronounced with decreasing degree of saturation in the soil. The null-pressure plate gave higher values of matric suction than the suction probe for soils near or above the optimum water content. The discrepancies in the measurement using the suction probe and the null-pressure plate became relatively small as the degree of saturation of the soil was reduced.

A soil–water system provides a satisfactory system for studying the behavior of water subjected to high tensions. It appears that a tension can be sustained for a relatively long period of time as long as it does not exceed the maximum sustainable tension for a particular suction probe.

The slow drift in measured negative pressure should be further investigated and minimized. Complete elimination of the drift may be difficult, since the suction probe is extremely sensitive to minute losses of water during the measurement. It is suggested that measurements of matric suction should be made in a constant, high-humidity environment in which evaporation from the suction probe is reduced to a minimum.

Acknowledgement

The authors acknowledge the assistance of Julian K-M. Gan in writing this paper.

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