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Direct Measurement of High Soil Suction

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ABSTRACT: A tensiometer-type suction probe was developed to directly measure soil suctions greater than 100 kPa. Cavitation was prohibited by cyclically pre-pressurizing the water in the suction probe to high pressures of 12,000 kPa. Tests using the axis-translation technique showed that the suction probe was accurate and rapid in response to changes in negative pore-water pressures as low as -500 kPa. Measurements performed on various types of soils indicated that the suction probe was able to measure matric suction up to 1000 kPa with satisfactory accuracy. Variations were observed between the measurements of matric suction on a compacted glacial till, using the suction probe, filter paper method, null-pressure plate, and thermal conductivity sensor. The suction probe appeared to be the most accurate of all these techniques. However, difficulties were encountered in measuring soils with a degree of saturation less than 40%.

1. INTRODUCTION

Measurements of soil suction is necessary for the solution of various geotechnical problems involving unsaturated soils. Typical engineering problems are those associated with slope stability, soil swelling and shrinking, soil collapsing, seepage, lateral earth pressures, and soil compaction. Analyses of these so called "problematic" soils (i.e., swelling soils, collapsing soils, residual soils, and soft clays) are dependent upon the appropriate assessment of soil suction.

Water is normally thought to have little tensile strength and will cavitate at a negative pressure of about -100 kPa. Consequently conventional tensiometers are limited to a direct measurement of soil suction less than 100 kPa. However, under some conditions, the tensile strength of water has been measured by physicists to be greater than several atmospheres (Knapp et al., 1970; Trevena, 1987). The application of the tensile strength of water has been quite scarce. This paper reports direct measurement of high soil suction, using the tensile strength of the water in a tensiometer-type suction probe. The suction probe was used to measure matric suctions in various types of soils. The measurements using the suction probe were compared with the measurements using filter paper method, null-pressure plate technique, and thermal conductivity sensor.

2. BACKGROUND

The tensile strength of water is the tensile stress at which the liquid water cavitates or ruptures. The tensile stress in ordinary liquid water is generally thought of as being equal to the vapor pressure minus hydrostatic pressure. Historical tests on the tensile strength of water may be classified into several distinct approaches used for applying a tensile stress to liquid water (Guan, 1996). These approaches include thermal contraction methods, superheating methods hydrostatic methods, and dynamic methods. Thermal tests conducted by Jones et al. (1981), measured tensions greater than 500 kPa using a transducer. Tensions up to 1,450 kPa were also directly measured by Sedgewick and Trevena (1976) using piezoelectric transducers in a dynamic stressing test.

The mechanism of cavitation is generally explained using a gas-trapping model (Harvey et al., 1947). According to this model, pre-

pressurization of a water-container system can effectively remove a significant portion of the potential cavitation nuclei and increase the ability of the system to resist cavitation (Apfel, 1970; Winterton, 1977).

Little attention has been given to how long the tensile strength of water can be sustained. Vincent (1941) and Winterton (1977) measured high tensions that were sustained for only a few minutes. Henderson and Speedy (1980) reported a tension of 10,000 kPa that was sustained for over a week. On the other hand, 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, based on a primitive concept of the tensile strength of water. Ridley (1993) pre-pressurized a small volume of water in a tensiometer-type device and measured matric suctions up to 1,500 kPa. More recent studies have shown that the tensile strength of the water in a small chamber can be significantly increased and is fundamentally useful for the direct measurement of high soil suction (Guan, 1996).

3. EQUIPMENT AND METHODS

The developed suction probe consisted of a high pressure transducer and a stainless steel shroud which was precisely machined to embrace the transducer (Fig. 1). The sensing area was a smooth, circular surface with a diameter of 7.0 mm. A 15 bar ceramic was fitted into the shroud. A small volume of water was contained between the ceramic and the transducer diaphragm.

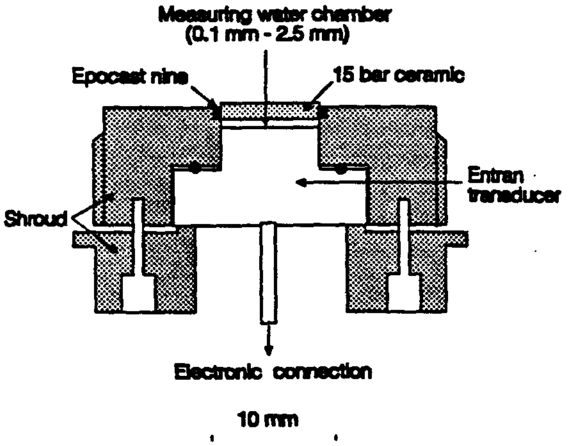

Figure 1: The construction of the suction probe

A pressurization system was built to pre-pressurize the water in the suction probe. An early study indicated that 6 cycles of pressurization produced the maximum sustainable tension (Guan, 1996). Each cycle includes the application of a positive pressure of 12,000 kPa for 1 hour, followed by a negative pressure of -85 kPa for 1 hour. The sustainable tension appeared to be related to the characteristics of the ceramic used. The highest tension measured using the probe was about 1250 kPa.

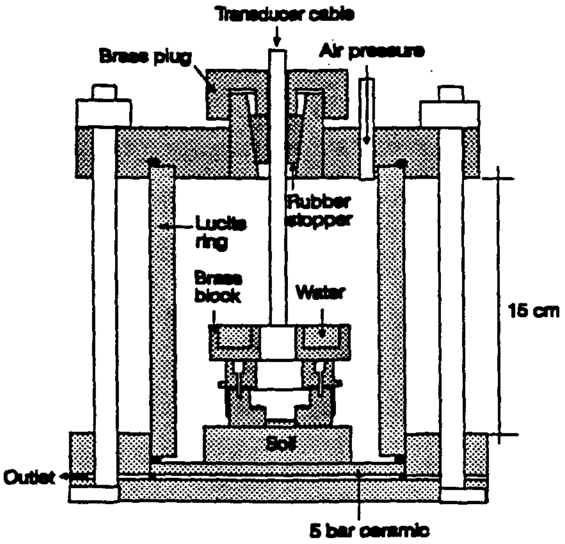

Figure 2: The modified pressure plate for testing the suction probe for negative pressures

3.1 Accuracy and Response Time of the Probe

The accuracy and response time of the suction probe subjected to high tensions were tested in a modified pressure plate, using the axis-translation technique. The experimental setup is illustrated in Fig. 2. A soil specimen was placed on the 5 bar ceramic plate at the bottom of the pressure cell. The suction probe was placed on the soil. A brass block was placed over the probe to ensure good contact between the probe and the soil and to maintain a constant humidity 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. 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 pre-applied air pressure, should be simultaneously established in the soil water and should be measured by the suction probe. Air pressures equal to 200, 300, 400, and 500 kPa were subsequently used.

3.2 Measurement of Soils with Pre-Applied Matric Suctions

Matric suctions ranging from 150 up to 550 kPa were applied to soil specimens in a pressure plate. The probe was used to measure the matric suction in the specimens. Aluminum foil and electric tape were used to cover the specimen to reduce moisture loss due to evaporation.

3.3 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 ASTM procedure (D5298 - 92). A set of three filter papers were placed between two soil specimens which were compacted at the same water content and the same dry density. Matric suction of the soil specimen was obtained from the water content of the middle filter paper, based on the calibration curve recommended by ASTM (D5298 - 92) for Schleicher & Schuell No. 589 White Ribbon filter paper. Measurements were repeated on a number of soil specimens.

Following the filter paper measurement, each soil specimen was placed over a saturated 5 bar ceramic disk in a pressure plate cell. "Null flow" condition was obtained by adjusting the magnitude of the applied air pressure. Matric suction in the specimen was assumed to be equal to the applied air pressure at equilibrium.

Matric suction of each specimen was next measured using the new suction probe. A small amount of wet clay paste was applied between the soil and the suction probe to improve soil-ceramic contact.

The thermal conductivity sensors used in this study were 28 mm long and 20 mm in diameter. The sensors had a rigid structure and a stable response. Variations in thermal conductivity among the sensors were relatively small. However, the sensors had a poor sensitivity for matric suctions above 150 kPa.

4. SOIL MATERIALS

Reconstituted specimens of a plastic clay and a fine silt were used to evaluate the performance of the suction probe for measuring soil suction. The clay specimen remains saturated at a suction less than 700 kPa. The prepared silt specimen desaturates at a matric suction of less than 10 kPa and reaches the residual water content at a suction of about 300 kPa.

A compacted glacial till was used for the comparative study between measurements using the suction probe and several other conventional techniques. Five compaction densities and water contents were selected for preparing glacial till specimens (Table 1). All five 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. Matric suction of each specimen was determined using filter paper, null-pressure plate, and the new suction probe in sequence. Matric suction measurements using the thermal conductivity sensor required a separate soil specimen which must be at least 40 mm long.

Table 1: Densities and water contents for 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

5. RESULTS AND DISCUSSIONS

5.1 Testing the Suction Probe for Negative Pressures

Figure 3 shows the changes in water pressure with time from a test on a clay specimen, using the suction probe. When an air pressure of 200 kPa was applied to the pressure chamber, the probe recorded an instantaneous increase in water pressure from 0 to 195 kPa. The water pressure gradually reduced to about 25 kPa after 42 hours. The pressure registered by the probe did not return to zero pressure. This was likely due to the slow rate of soil water flow out of the pressure chamber under a small pressure gradient. Reducing the air pressure from 200 kPa to 0 kPa caused the water pressure to immediately fall below zero and a reading of -158 kPa was obtained. The reduction in air pressure (i.e., -200 kPa) was approximately equal to the reduction in water pressure (i.e., -183 kPa). The water pressure registered by the probe gradually increased because the water below the 5 bar ceramic of the pressure plate 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.

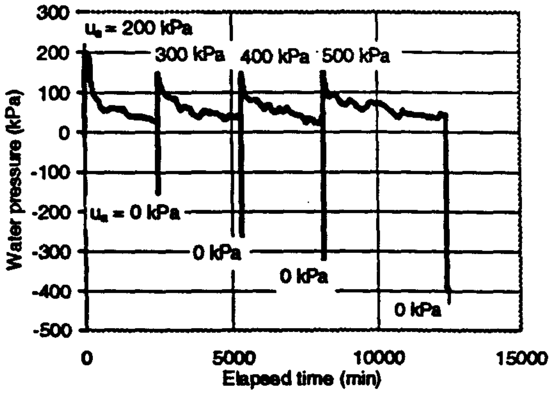

Figure 3: Testing the probe for negative pressure in clay using the axis-translation

Further tests also showed that a change in air pressure in the pressure chamber instantaneously produced an approximately equal amount of change in water pressure in the suction probe. The difference between the change in air pressure in the pressure chamber and the change in water pressure in the suction probe was generally less than 5%. When the air pressure in the pressure chamber was reduced from 500 kPa to zero, the water pressure in the suction probe immediately dropped from 44 kPa to -443 kPa, a change of 487 kPa. The clay remained saturated during the test period.

Similar results were also obtained from the test on a silt specimen (Fig. 4). These tests indicate that the suction probe is accurate and the response time to a change in the external tension is only a few seconds. The quick response of the suction probe is attributed to the high degree of saturation and the rigidity of the measuring chamber of the probe.

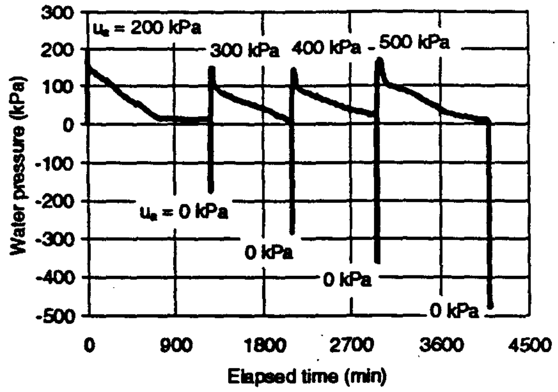

Figure 4: Testing the probe for negative pressure in silt using the axis-translation

The above results also justify the extrapolation of calibration of the transducer from positive to negative pressures. The principle of the axis-translation technique has been proven to be valid for negative pressures as low as -500 kPa.

5.2 Measurement of Pre-Applied Matric Suctions

Figure 5 shows the results of measurements of matric suction in a clay specimen using the new suction probe. The pre-applied matric suctions varied from 150 to 550 kPa in increments of 50 kPa. The recorded curves were in good agreement with the pre-applied matric suctions up to 450 kPa. The recorded negative pressures for pre-applied matric suctions of 500 and 550 kPa developed much slower. This could be due to the occurrence of a tension crack in the central part of the clay specimen when the pre-applied matric suction exceeded 450 kPa. However, the presence of the crack did not appear to influence the matric suction reading at equilibrium.

Figure 6 gives the results of measurements of matric suction on silt specimens. There was an apparent drift in the recorded tension when the pre-applied matric suction exceeded 300 kPa. A matric suction of 300 kPa corresponds to a degree of saturation of about 38% for the silt specimen. The drift was attributed to moisture loss due to evaporation from both the soil and the suction probe during measurement.

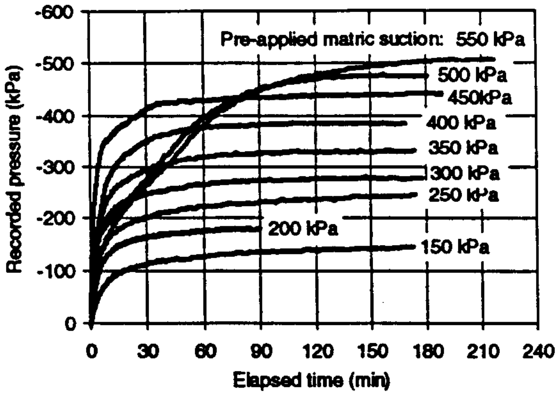

Figure 5: Matric suction measurements on clay

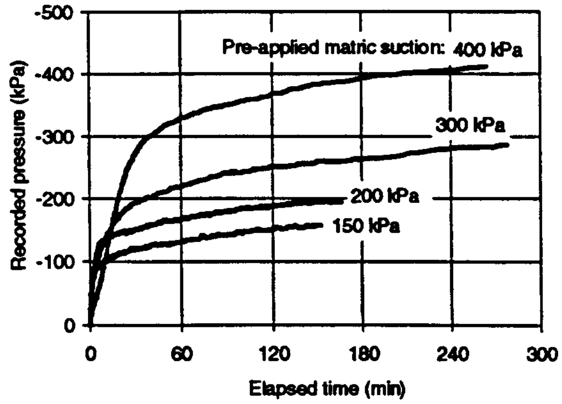

Figure 6: Matric suction measurements on silt

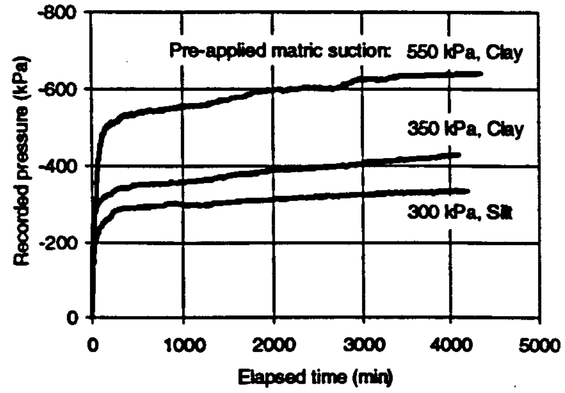

Figure 7: Matric suction measurements on silt and clay

Figure 7 shows three measurements of matric suction on reconstituted silt and Regina clay specimens. Pre-applied matric suctions of 300 kPa, 350 kPa, and 550 kPa were used. The results show that tensions in the probe can be sustained for at least 72 hours. The duration over which a tension can be sustained in the suction probe did not appear to be dependent on the magnitude of the tension.

5.3 Comparison with Other Methods

Figure 8 plots measurements obtained using the suction probe and filter paper method. Each data point for the suction probe method is the mean value of measurements on two specimens at the same water content. The determination of equilibrium condition was difficult for the till specimens prepared at degree of saturation of 43.7%. Figure 9 plots the measurements obtained using the suction probe, null-pressure plate, and thermal conductivity sensor. The results indicated that the measurements of matric suction were reproducible except for the filter paper method.

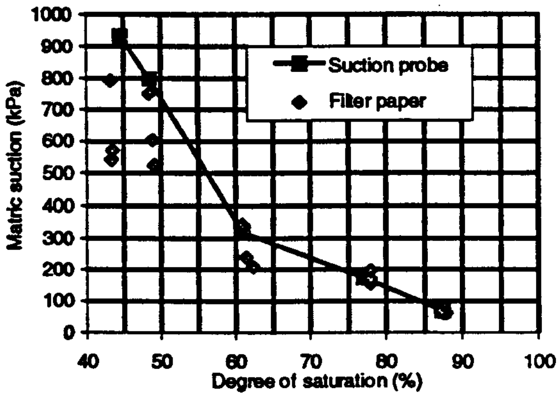

Figure 8: Matric suction measurements on glacial till using the probe and filter paper

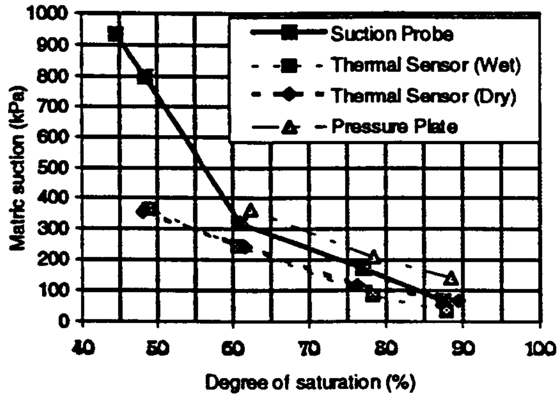

Figure 9: Matric suction measurements on glacial till using the probe, pressure plate, and thermal conductivity sensor

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 and widely scattered values. Similar conclusions were also obtained by Ridley (1993). The low values from the filter paper method is probably because equilibrium is not achieved in seven days, particularly for soils at low degrees of saturation. Deka et al. (1995) suggested that equalization periods longer than seven days are required for dry soils when using the filter paper method.

The thermal conductivity sensor produced measurements which are relatively close to the suction probe measurements for matric suctions less than 100 kPa. The thermal conductivity sensor, either initially dry or wet, appeared to under-estimate the matric suction at values exceeding 100 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 suction measured using the pressure plate method, particularly for soils with a high degree of saturation, was 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. Theoretical analysis made by Bocking and Fredlund (1980) indicated that occluded air bubbles in a soil can result in an over-estimation of matric suction when using the null-pressure plate technique. Soils near or above the optimum water content (i.e., degree of saturation above about 80%) usually contain occluded air bubbles and the axis-translation may produce significant errors in the suction measurement.

6. CONCLUSIONS

The newly developed suction probe is suitable for measuring matric suctions up to 1000 kPa in both saturated and unsaturated soils with satisfactory accuracy. The principle of the axis-translation technique was proved to be correct for negative pore-water pressures as low as -500 kPa.

The suction probe is most suited to soils for which evaporation from the 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. Difficulties were encountered in measuring soils with a degree of saturation less than 40%.

Reasonable agreements were observed between measurements using the suction probe, and those using the filter paper method and the thermal conductivity sensor for soils with a relatively high degree of saturation of the soil. The discrepancies in the measurements using the suction probe, the filter paper and the thermal conductivity sensor became more pronounced with decreasing degree of saturation. 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 smaller as the degree of saturation of the soil was reduced.

A soil-water system provides an excellent system for studying the behavior of water subjected to high tensions. It appears that a tension in water can be sustained for a relatively long period of time.

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