NOTE

Mini suction probe for matric suction measurements

Inge Meilani, Harianto Rahardjo, Eng-Choon Leong, and Delwyn G. Fredlund

Abstract: A modified triaxial apparatus with mini suction probes was fabricated to study the matric suction along the specimen height during unsaturated triaxial testing. Three mini suction probes were placed at 3/4, 1/2, and 1/4 height of the specimen, each at 120° apart in the lateral direction. This paper presents the development of the mini probe for matric suction measurements. Evaluation of the performance shows that the fabricated mini probe provides a rapid response and accurate reading under negative and positive pore-water pressure changes. Matric suctions as high as 400 kPa were successfully measured on soil specimens over a time span of 15 h. On the other hand, the mini suction probes were also found to be able to measure a matric suction of 200 kPa for a longer period of 155 h.

Key words: matric suction, mini suction probe, triaxial, unsaturated soils, mid-height pore-water pressure measurement.

Résumé : Un appareil triaxial modifié avec des minisondes à succion a été fabriqué pour étudier la succion matricielle le long de la hauteur d'un spécimen durant un essai triaxial non saturé. Trois minisondes à succion ont été placées à 3/4, 1/2, et 1/4 de la hauteur du spécimen, chacun à 120° l'un de l'autres dans la direction latérale. Cet article présente le développement de la minisonde pour la mesure de la succion matricielle. L'évaluation de la performance montre que la minisonde fabriquée fournit une réponse rapide et des lectures précises des changements négatifs et positifs des pressions interstitielles. Des succions matricielles aussi élevées que 400 kPa ont été mesurées avec succès sur un spécimen de sol au cours d'une période de temps de 15 h. Par ailleurs, on a aussi trouvé que les minisondes à succion pouvaient mesurer une succion matricielle de 200 kPa pour un période plus longue de 155 h.

Mots clés : succion matricielle, minisonde à succion, triaxial, sols non saturés, mesure de pression interstitielle à mi-hauteur.

[Traduit par la Rédaction]

Introduction

One of the two stress state variables for unsaturated soils is matric suction. There are various matric suction measurement devices, which have been broadly categorized into two methods: direct and indirect. Some examples of the direct method of measuring matric suction are the tensiometer and the null-type pressure plate. Examples of the indirect measurement devices are the filter paper technique and the thermal conductivity sensor (Fredlund and Rahardjo 1993).

The direct measurement of matric suction is preferred in unsaturated soil tests since measured pore-water pressures are more rapidly reflected. Ridley and Burland (1993) and Guan and Fredlund (1997) showed that it was relatively simple and convenient to make direct measurements of matric suction using a suction probe. Basically, a suction probe consists of a pressure transducer with a high-air entry ceramic disk mounted at the tip of the transducer. The diaphragm of the pressure transducer responds to the pressure applied. A small gap between the ceramic disk and the diaphragm is filled with water to give a continuous water phase between the ceramic disk and the pressure transducer. The principle of making suction measurements using a suction probe is based on the equilibrium between the pore-water pressure in the soil and the pore-water pressure in the water compartment. Before equilibrium is attained, water flows from the water compartment into the soil, or vice versa. In an unsaturated soil specimen, negative pore-water pressure causes the flow of water from the water compartment into the soil. On the other hand, in a saturated specimen, positive pore-water pressure causes the flow of water from the soil into the water compartment.

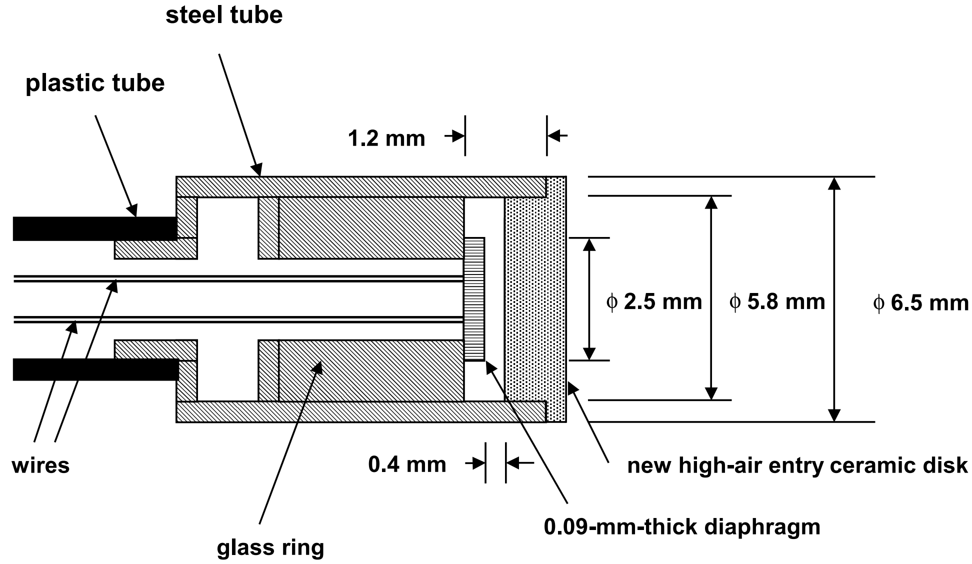
Received 6 July 2001. Accepted 19 June 2002. Published on the NRC Research Press Web site at http://cgj.nrc.ca on 18 November 2002.

I. Meilani, H. Rahardjo,[1] and E.-C. Leong. Nanyang Technological University, School of Civil and Environmental Engineering, 50 Nanyang Avenue, Block N1, #1A-02, 639798 Singapore.
D.G. Fredlund. Department of Civil Engineering, University of Saskatchewan, Saskatoon, SK S7N 5A9, Canada.

[1]Corresponding author (e-mail: chrahardjo@ntu.edu.sg).

 DOI: 10.1139/T02-101

Fig. 1. Schematic diagram of the mini suction probe.



The suction probe measures the pore-water pressure (u_w). The matric suction can be computed since the applied air pressure (u_a) is known, and the matric suction is the difference between the pore-air pressure and the pore-water pressure ($u_a - u_w$).

Mid-height pore-water pressure measurement in the triaxial testing of *saturated* specimens has been widely used for various studies (Hight 1982). However, few studies have been done on mid-height pore-water pressure measurement in triaxial tests on unsaturated soils. The suction probe developed by Ridley and Burland (1993) and Guan and Fredlund (1997) used an Entran pressure transducer that is not submersible under water for long durations of time (Wong 2000). Hence, these suction probes are not suitable for pore-water pressure measurements in triaxial testing. Previous mid-height pore-water pressure measurements on unsaturated soil specimens have had limitations in terms of response time (Toll 1988) and cavitation under high matric suctions (Wong 2000). The objective of this study is to develop a mini suction probe for triaxial tests on unsaturated soils. The mini suction probe has to provide a fast response and can be used under high matric suction conditions for a long period of testing time.

Fabrication of the mini suction probe

Description of the mini suction probe

The mini suction probe developed at the Nanyang Technological University uses a 15-bar miniature pore-water pressure transducer, PDCR 81, manufactured by Druck Ltd. (Leicester, England). The PDCR 81 pore-water pressure transducer is attached to a high-air entry ceramic disk as shown in Fig. 1. The mini suction probe consists of a 0.09-mm thick silicon diaphragm mounted in a cylindrical housing. The outer and inner diameters of the steel tube of the probe are 6.5 and 5.8 mm, respectively. The total space between the diaphragm and the edge of the steel tube is 1.2 mm. The probe has negligible weight (i.e., 3 g with a cable of 20 cm length) and is provided with an integral Teflon cable that allows the probe to be immersed in water in a triaxial cell.

The air-entry value of the original ceramic disk was found to be less than 100 kPa (Wong 2000), whereas it was supposed to be in the 200 kPa range of matric suction for this study. Hence, the original ceramic disk was removed and replaced with a new high-air entry ceramic disk. The mini suction probe was connected to a data logger and readings were obtained using a personal computer. A computer control program, Triax 4.0 (Toll 1999), was used for data acquisition.

Modification of high-air entry ceramic disk design

The high-air entry ceramic disk for the mini suction probe was cut from a standard 5-bar high-air entry ceramic disk. A standard 5-bar high-air entry ceramic disk from Soilmoisture Equipment Corporation has a coefficient of permeability with respect to water of approximately 1.21×10^{-9} m/s (Soilmoisture Equipment Corp. 1996). To overcome the problem of slow response due to the low permeability of the ceramic disk, the high-air entry ceramic disk was thinned down to 1 mm thick.

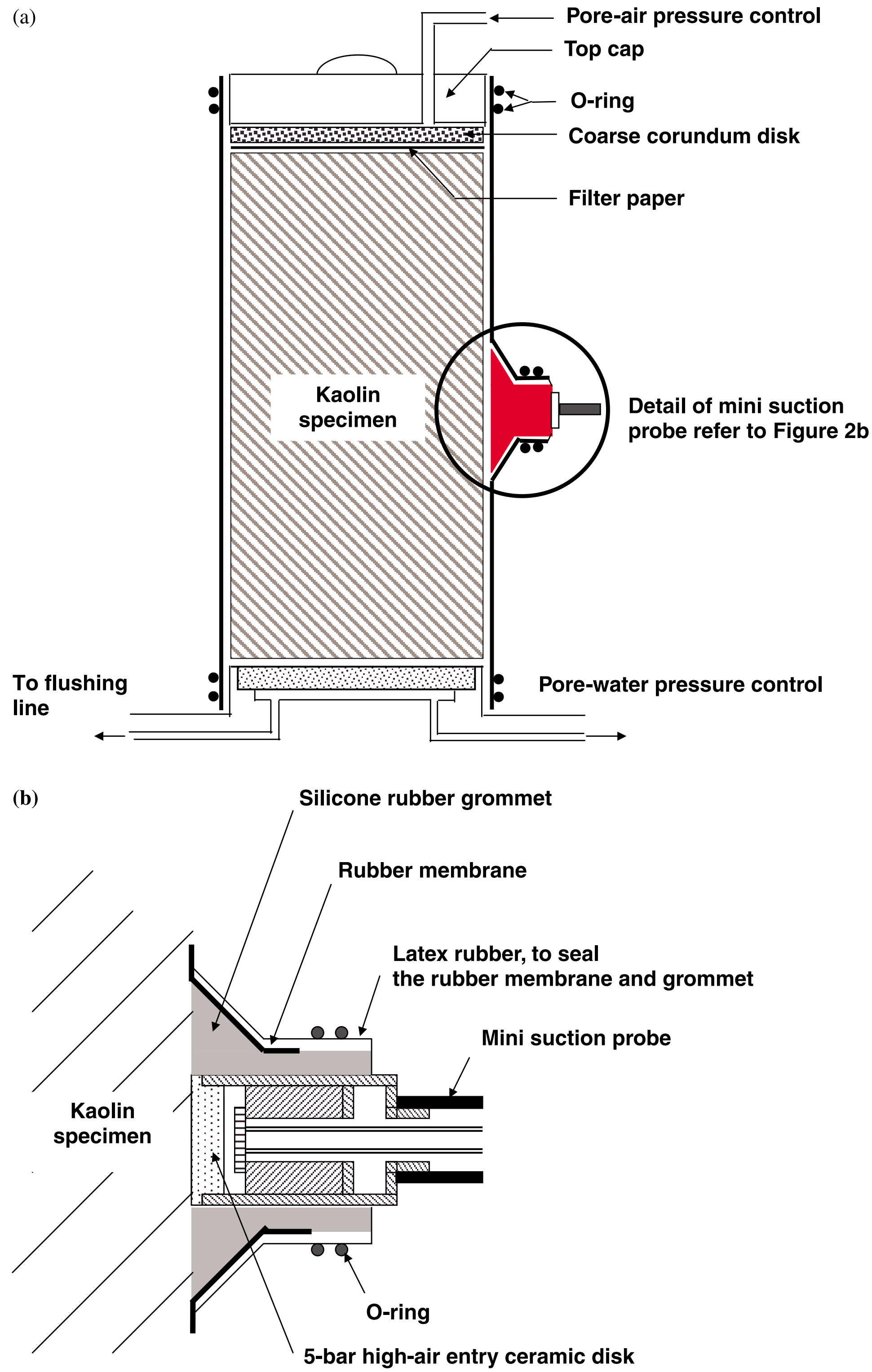
The gap between the disk and the diaphragm was made as small as possible to obtain high accuracy and sensitivity of the pore-water pressure measurement. A T-shaped configuration was selected as the shape for the edge of the ceramic disk. The diameter and thickness of the web of the new high-air entry ceramic disk were 5.7 and 0.7 mm, whereas the diameter and thickness of the flange were 7 and 0.3 mm, respectively. The thickness of the ceramic disk that enters the steel tube is 0.7 mm, giving a small gap of 0.4 mm between the diaphragm and the bottom of the ceramic disk (Fig. 1). The T-shape allows the disk to be glued to the steel tube from the outside of the steel tube, preventing the glue from dripping onto the diaphragm. The ceramic disk was glued onto the probe using Araldite 2021 epoxy.

Experimental setup

Modified triaxial apparatus for unsaturated soil tests

The modified triaxial apparatus consists of a triaxial cell, three mini suction probes, a force actuator for shearing the

Fig. 2. Installation of the mini suction probe to the specimen. (*a*) Only the mid-level mini suction probe is shown. (*b*) Details of the mini suction probe placed on a kaolin specimen.



soil specimen, two digital pressure and volume controllers (DPVC), a diffused-air volume indicator (DAVI), a data acquisition unit, and a personal computer. The modified triaxial cell for testing unsaturated soils is described in more detail in Fredlund and Rahardjo (1993).

Saturation method for the mini suction probes

The mini suction probes can be used to measure negative pore-water pressure provided a complete saturation of the probes is achieved. In this study, the saturation of the mini suction probes was performed by filling the triaxial cell con-

Table 1. Stress conditions on the triaxial tests on statically compacted kaolin.

Specimen	Net confining pressure (kPa)	Matric suction (kPa)
TU 25–100	25	100
TU 25–200	25	200
TU 100–400	100	400

taining the mini suction probes with de-aired water and subsequently applying a cell pressure of 800 kPa for a period of four days.

The response of the mini suction probes to negative water pressure was observed to verify the saturation of the mini suction probes. If the mini suction probes have achieved saturation (i.e., water compartment totally filled with water), the probes should respond quickly to the applied negative water pressure. The procedure of ensuring the response of the mini suction probes to negative water pressure was carried out by immersing the probes in the cell, which was filled with water up to one-third of the total height of the cell. A vacuum pressure was subsequently used to impose a negative water pressure from the top-port hole. During the application of vacuum pressure, the valve connected to the top cap was opened and a pressure transducer attached to the valve measured the vacuum pressure as a reference pressure.

There were small fluctuations of vacuum pressure from –82 to –92 kPa due to the mechanism of the vacuum pump and the inability of the vacuum regulator to maintain a constant vacuum pressure. The mini suction probes did not show any response to the changes in the vacuum pressure when there were air bubbles in the water compartment, even though a negative pressure reading was found in the mini suction probes. However, when saturation of the probe was achieved, the mini suction probe could precisely capture the small fluctuations of the applied vacuum pressure.

Calibration procedure

The mini suction probe was calibrated after saturation. The probe was always calibrated to check its response prior to usage. The results of the six calibrations fell into the same regression line, indicating that the mini suction probe was in good working condition.

Installation procedure for the mini suction probe

Three mini suction probes were used to measure the pore-water pressure along the height of a specimen. The probes were placed at 3/4 (i.e., "top"), 1/2 (i.e., "middle), and 1/4 (i.e., "bottom") height of the specimen from its base and at 120° apart in the lateral direction (Fig. 2*a*). Figure 2*b* shows the installation of a mini suction probe onto a soil specimen. The installation procedure described by Hight (1982) was adopted.

Specimen preparation

To test the mini suction probes compacted specimens of kaolin with a grain size distribution of 85% of silt (75–2 μm) and 15% of clay (finer than 2 μm) were used in this study. The coarse kaolin has a liquid limit of 51%, a plastic limit of 35%, an optimum water content of 22% (standard Proctor), and a maximum dry density of 1.35 Mg/m^3 (standard Proctor). According to the plasticity chart of the Unified Soil Classification System (ASTM D 2487–93), kaolin is classified as silt with high plasticity (MH). The soil specimen was prepared by static compaction at its optimum water content and maximum dry density using a compression machine.

Testing procedure

A consolidated drained (CD) triaxial test on an unsaturated kaolin specimen was conducted to observe the performance of the mini suction probes in the triaxial apparatus. The CD triaxial test consists of four stages (i.e., saturation, consolidation, matric suction equalization, and shearing). Saturation was achieved by applying a cell pressure and a back pressure until a pore pressure parameter, B of 0.95 was reached (Head 1986). The pore pressure parameter, B is defined as

$$[1] \qquad B = \frac{\Delta u_w}{\Delta \sigma_3}$$

where Δu_w is the change in pore-water pressure and $\Delta\sigma_3$ is the change in total confining pressure.

The kaolin specimen was then consolidated under an applied effective confining pressure. Water was drained from the top cap through a coarse porous stone to enhance the consolidation process. The axis translation technique was used during matric suction equalization (Hilf 1956). A specific air pressure (u_a) was applied through the top cap while a constant water pressure (u_w) was maintained at the bottom of the specimen. Water would drain from the bottom of the specimen. Matric suction equalization was achieved when there was no further change in water volume and the pore-water pressure was equalized throughout the specimen.

Results and discussion

Response to positive pressure

The response of the mini suction probes to positive water pressure needs to be observed to evaluate the response of the probes in the positive pressure range. The triaxial cell was filled with de-aired water and the cell pressure was varied using the DPVC. The test results indicate that the mini suction probes are responsive to increases and decreases in cell pressure.

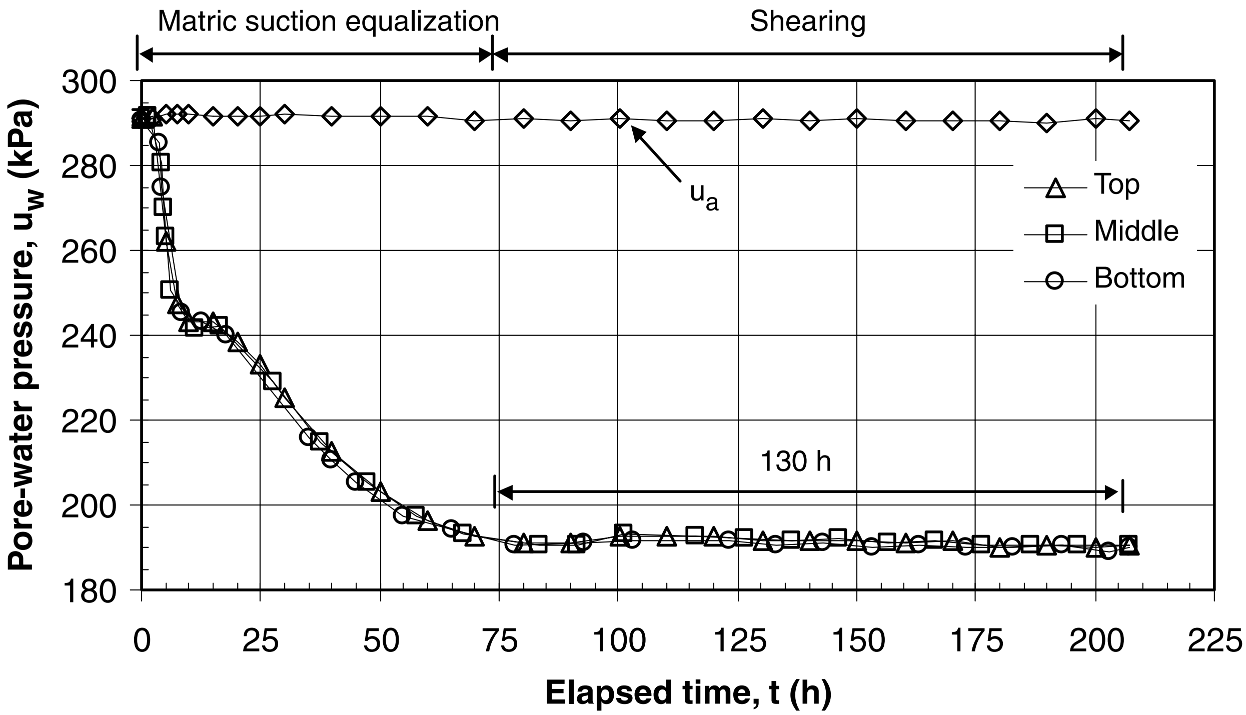
Response to a sudden cell pressure change

A rapid response time is important to capture pore-water pressure changes in a soil specimen. A sudden increase in pressure of 500 kPa was applied to the triaxial cell and the mini probes showed a short response time of less than 3 s.

Air entry value of the new ceramic probe

The air entry value of the ceramic disk of the mini suction probes was measured using the "free evaporation" tests proposed by Guan (1996). Three mini suction probes were subjected to the evaporation test and the response of the probes was monitored. The "top," "middle," and "bottom" probe measurements decreased to –426, –400, and –495 kPa, respectively, before increasing rapidly to approximately –100 kPa (i.e., atmospheric pressure) when the air entry values of the disks

Fig. 3. Mini suction probe measurement versus elapsed time during matric suction equalization and the shearing stage on specimen TU 25–100 under a net confining pressure of 25 kPa and a matric suction of 100 kPa.



were exceeded. Therefore, the air entry values of the disks in the "top," "middle," and "bottom" probes were assessed to be 426, 400, and 495 kPa, respectively.

Laboratory test results on soil specimens

The results of three laboratory triaxial tests are presented as tests, TU 25–100, TU 25–200, and TU 100–400. All soil specimens were tested under net confining pressures and matric suctions as shown in Table 1.

Figure 3 shows the pore-water pressure measurements along the height of specimen TU 25–100, for the matric suction equalization and shearing stage. A matric suction of 100 kPa was applied by imposing an air pressure of 290 kPa to the top of the soil specimen and subsequently lowering the water pressure at the bottom of the specimen from 290 to 190 kPa. The difference between the pore-air and the pore-water pressures (or matric suction) is 100 kPa. The mini suction probe could sustain 100 kPa of matric suction for about 130 h until the shearing stage was complete. During shearing, the matric suction decreased slightly. Since the specimen was sheared quite rapidly (0.001 mm/min), the pore-water pressure increased slightly. The pore-water pressure became stable after the strain rate was reduced to 0.0008 mm/min.

For soil specimen TU 25–200, the measurements on the "top" mini suction probe resulted in an error due to air diffusion that took place about 30 h after shearing was started. However, the "middle" and the "bottom" mini suction probes continued to work well for 155 h during shearing.

The mini suction probe readings on soil specimen TU 100–400 indicate that the "middle" suction probe reading had errors due to air diffusion even before the shearing commenced. The "top" and "bottom" probes showed signs of air diffusion 15 h from the beginning of shearing.

Conclusions

(1) Mini suction probes for unsaturated soil triaxial testing have been designed, fabricated, and shown to perform satisfactorily for a series of tests. The probes can be used to measure matric suctions up to 400 kPa (i.e., 4 bar). In one test, the probe was found to be able to measure a matric suction of 200 kPa for 155 h. In another test, a matric suction of 400 kPa was maintained for 15 h.

(2) The response of the mini suction probe to fluctuations in applied negative pressures can be used as an indicator to verify the saturation condition of the mini suction probe.

(3) The testing time has to be as short as possible to avoid diffusion that causes cavitation. It is recommended that an optimum strain rate should be used during the shearing stage to reduce the testing duration in a triaxial test on an unsaturated specimen.

Acknowledgements

This study was funded by the National Science and Technology Board of Singapore (NSTB 17/6/16: Rainfall-induced slope failures). The authors are indebted to Dr. D.G. Toll for his kind permission to use the Triax 4.0 programme. Discussions with Dr. D.G. Toll and Mr. Wong J.C. regarding their studies on mid-height pore-water pressure measurements are appreciated. The first author gratefully acknowledges the research scholarship provided by the Nanyang Technological University.

References

Fredlund, D.G., and Rahardjo, H. 1993. Soil mechanics for unsaturated soils. John Wiley & Sons Inc., New York, NY.

Guan, Y. 1996. The measurement of soil suction. Ph.D. thesis, University of Saskatchewan, Saskatoon, SK.

Guan, Y., and Fredlund, D.G. 1997. Use of the tensile strength of water for the direct measurement of high soil suction. Canadian Geotechnical Journal, **34**: 604–614.

Head, K.H. 1986. Manual of soil laboratory testing. John Wiley & Sons, Inc., New York, NY, Vol. 3, pp. 942–945.

Hight, D.W. 1982. A simple piezometer probe for the routine measurement of pore pressure in triaxial tests on saturated soils. Géotechnique, **32**(3): 396–401.

Hilf, J.W. 1956. An investigation of pore-water pressure in compacted cohesive soils. Ph.D. dissertation, Technical Memorandum No. 654, U.S. Department of the Interior, Bureau of Reclamation, Design and Construction Division, Denver, CO.

Ridley, A.M., and Burland, J.B. 1993. A new instrument for the measurement of soil moisture suction. Géotechnique, **43**(2): 321–324.

Soilmoisture Equipment Corp. 1996. Catalog of porous ceramics of 600 series. Santa Barbara, CA.

Toll, D.G. 1988. The behaviour of unsaturated compacted naturally occurring gravel. Ph.D. dissertation, Imperial College, London, U.K.

Toll, D.G. 1999. A data acquisition and control system for geotechnical testing. *In* Computing developments in civil and structural engineering. *Edited by* B. Kumar and B.H.V. Topping. Civil-Comp Press, Edinburgh, Scotland, pp. 237–242.

Wong, J.C. 2000. Shear strength of residual soil under infiltration condition. M. Eng. thesis, Nanyang Technological University, Singapore.