Engineering Geology 165 (2013) 29–37

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Advances in suction measurements using high suction tensiometers

David G. Toll [a,*], Sérgio D.N. Lourenço [b,1], João Mendes [c,1]

[a] School of Engineering and Computing Sciences, Durham University, South Road, Durham DH1 3LE, UK
[b] School of Earth and Ocean Sciences, Cardiff University, Park Place, Cardiff CF10 3AT, UK
[c] Centre for Geotechnical and Materials Modelling, The University of Newcastle, University Drive, Callaghan, NSW 2308, Australia

ARTICLE INFO

Article history:
Accepted 24 April 2012
Available online 9 May 2012

Keywords:
Unsaturated soil
High suction tensiometer
Laboratory test
Field measurement

ABSTRACT

Significant advances in unsaturated soils testing have been gained through the development of high suction tensiometers allowing direct measurement of suction beyond 100 kPa. This has allowed the implementation of techniques that measure and control suction directly, where the soil is tested in the same conditions as in nature. Previously, much reliance had been placed on indirect measurements of suction and on control of suction using the axis translation technique. It is argued that this technique should be avoided as the use of an elevated air pressure does not replicate natural conditions. This paper presents advances resulting from the use of high suction tensiometers for laboratory testing and field measurements. It also describes an automated suction control system using the air circulation method that can impose controlled cycles of drying and wetting.

1. Introduction

Critical advances in testing of unsaturated soils in recent years have been in the development of techniques to measure and control suction directly. This allows soil specimens to be tested in conditions similar to nature, with the air pressure at atmospheric conditions, rather than using axis translation techniques where the air pressure is artificially elevated. Direct measurement of suction and water content in unsaturated soils in the laboratory is now a reality and relies on the measurement of suction with high suction tensiometers and water content through mass measurements with an electronic balance.

The benefit of using high suction tensiometers in laboratory testing is that suction measurements can be carried out with the sample maintained at atmospheric air pressure. Prior to the development of high suction tensiometers, the only alternative for *direct* measurement of suction was to use the axis translation technique where the pore air pressure was elevated so that a positive pore water pressure was obtained, which could be measured using conventional transducers. It is important to recognise that the use of the axis translation technique prevents cavitation from taking place in soil samples. The pore water pressure is always maintained above absolute pressure (gauge pressure of −100 kPa). In contrast, a soil that dries in a natural condition in the field will be subject to negative pore water pressures, when cavitation might be induced in larger pores within the soil. It will be shown that a sample subjected to a suction applied through axis translation can exist at a higher water content (or degree of saturation) than the same soil that is subject to the same suction induced by natural drying. Being able to measure the negative pressure directly using a high suction tensiometer allows measurements to be obtained on soils at atmospheric air pressure, replicating the natural state.

Tensiometers have many uses for laboratory testing and in field measurement and these are discussed in the paper. A particular use is the determination of Soil Water Retention behaviour, where much faster testing can be achieved compared to conventional pressure plate techniques. Lourenço (2008) reports that tests carried out using a tensiometer took less than 7 days (in some cases as little as 2 days), whereas a pressure plate test on the same material took 7 weeks to perform.

To eliminate the need for axis translation techniques requires the development of alternative forms of suction control. A novel technique using air circulation is presented in the paper, which uses high suction tensiometers for measurement. This technique is particularly suited to suction control in the range where high suction tensiometers can operate (<2 MPa).

This paper examines the use of high suction tensiometers in laboratory and field measurements for unsaturated soils, presenting developments in their design and procedures for their saturation and calibration. It identifies some of the difficulties involved such as the requirements for a high level of saturation and the difficulty in calibrating these devices in the negative pressure range. It is not intended to be a review of unsaturated soil testing. Extensive reviews are given elsewhere: Fredlund and Rahardjo (1993), Lee and Wray (1995), Ridley and Wray (1996), Rahardjo and Leong (2006), Bulut and Leong (2008), Tarantino et al. (2008) and Delage et al. (2008).

* Corresponding author.
E-mail addresses: d.g.toll@durham.ac.uk (D.G. Toll), LourencoSD@cardiff.ac.uk (S.D.N. Lourenço), Joao.Mendes@newcastle.edu.au (J. Mendes).
[1] Formerly Durham University.

0013-7952/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.enggeo.2012.04.013

2. High suction tensiometers

2.1. Overview

A potential shift in laboratory testing for unsaturated soils has been brought about by the development of high suction tensiometers. Since the first device developed by Ridley and Burland (1993), there have been a number of devices using the same concept, as outlined in Table 1. Delage et al. (2008) provides a detailed review of the high suction tensiometers developed to date.

The main characteristics of the tensiometers in use are summarised in Table 1. High suction tensiometers can be classified based on the air entry value of the porous stone or the form of construction. Nearly half of the tensiometers in Table 1 operate at the high suction range (up to 2000 kPa) while the remaining ones operate at lower suctions (up to 500 kPa). The high suction tensiometers by Ridley et al. (2003), Tarantino and Mongiovì (2003) and Mantho (2005) are strain gauged tensiometers, where a strain gauge was attached to the back of a flexible diaphragm. In the case of Tarantino and Mongiovì (2003) and Mantho (2005) the tensiometer body was made of a single piece and the diaphragm was machined as part of the body. Most of the devices listed in Table 1 are built from commercial transducers, which have been slightly modified to improve their response at high suctions. For example, Ridley and Burland (1993) used the model Entran EPX-500, Meilani et al. (2002) the model Druck PCDR-81 and Take and Bolton (2003) Entran EPB-C1. Some designs use commercial transducers enclosed in a stainless steel housing and fitted with a detachable porous stone, hence three separate parts (transducer, housing and stone) are combined to make up the tensiometer.

Fig. 1 shows examples of two designs: a strain gauged diaphragm single-bodied tensiometer (Tarantino and Mongiovì, 2003) and the Durham University device reported by Lourenço et al. (2006) using a ceramic transducer. Low cost tensiometers have been developed by Mahler and Diene (2007), using an acrylic body instead of the usual stainless steel, and Jotisankasa et al. (2007b), using a piezoresistive pressure sensor instead of usual resistive transducers.

The success of the high suction tensiometer is due to the prevention of cavitation, by using a small volume water reservoir. The cavitation limit of the device imposes an upper limit on the suction that can be measured. The maximum suctions that have been directly measured by high suction tensiometers are those reported by Tarantino and Mongiovì (2001) who achieved 2.6 MPa and Lourenço et al. (2008) who achieved 2.1 MPa (Figure 2). As tensiometers measure pore water pressure directly, errors related to indirect calibration curves are avoided, such as those used for electrical or thermal conductivity sensors or for filter paper techniques.

There has been considerable interest in high suction tensiometers due to their fast response time, easy manoeuvrability and because measurement errors are reduced because they involve a direct measurement of suction, rather than relying on indirect calibrations. The time to obtain readings with high suction tensiometers can be of the order of minutes, compared to days for the filter paper and axis translation techniques (Rahardjo and Leong, 2006). Due to their relatively small size, high suction tensiometers can be easily transported and fitted to any device requiring suction measurements, e.g. shear box (Caruso and Tarantino, 2004; Tarantino and Tombolato, 2005), centrifuge (Chiu et al., 2005), triaxial cell (Jotisankasa, 2005; Mendes, 2011), oedometer (Jotisankasa, 2005; Le et al., 2011), physical models (Tang et al., 2009), field probe (Cui et al., 2008; Mendes et al., 2008; Toll et al., 2011) or simply for pore water pressure measurements in sealed soil samples (Teixeira and Marinho, 2006).

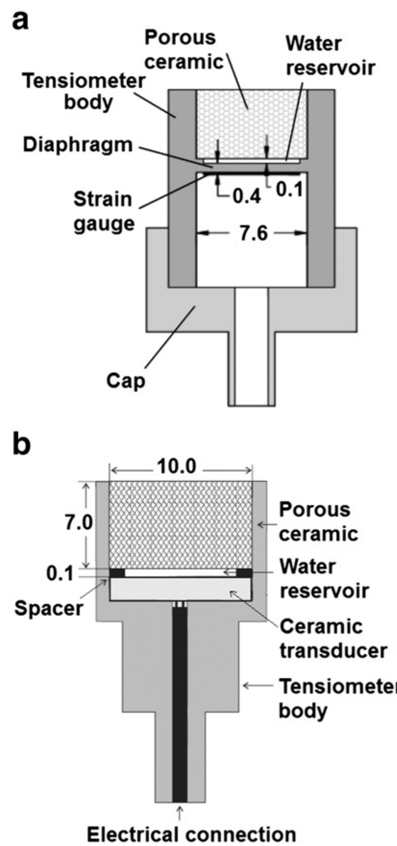

Fig. 1. Tensiometer designs (a) Tarantino and Mongiovì (2003) and (b) Lourenço et al. (2006) (dimensions in mm).

Table 1
Characteristics of tensiometers.

Source	Air entry value of porous stone (kPa)	Pressure transducer range (kPa)	Water reservoir volume (mm^3)	Design	Notes
Ridley and Burland (1993)	1500	3500	–	Modified commercial transducer	–
Guan and Fredlund (1997)	1500	15,000	~20	Modified commercial transducer	–
Sjoblom (2000)	–	1380	–	Modified commercial transducer	Stone made of sintered silica gels
Tarantino and Mongiovì (2003)	1500	–	<4.5	Strain gauged diaphragm, single body	–
Mantho (2005)	1500	–	Height 0.1 mm	Strain gauged diaphragm single body	–
Lourenço et al. (2006)	1500	2000	5	Ceramic transducer	–
Meilani et al. (2002)	500	1500	–	Modified commercial transducer	1 mm thick porous stone
Ridley et al. (2003)	1500	8000	~3	Strain gauged diaphragm	–
Take and Bolton (2003)	300	700	–	Modified commercial transducer	–
Poirier et al. (2005)	500	1380	–	Modified commercial transducer	–
Mahler and Diene (2007)	500 & 1500	–	5–112	Modified commercial transducer	Tensiometer body in acrylic
Jotisankasa et al. (2007b)	500	–	60	Modified commercial transducer	Piezoresistive pressure sensor