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ADVANCES IN SUCTION MEASUREMENTS USING HIGH SUCTION TENSIOMETERS

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Abstract

Significant advances in unsaturated soils testing have been gained through the development of high suction tensiometers allowing direct measurement of suction beyond 100kPa. 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.

Keywords

Unsaturated soil, high suction tensiometer, laboratory test, field measurement

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 -100kPa). 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 measurement 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).

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 summarized in Table 1. High suction tensiometers can be classified based on the air entry value of the stones or the form of construction. Nearly half of the tensiometers in Table 1 operate at the high suction range (up to 2000kPa) while the remaining ones operate at lower suctions (up to 500kPa). The high suction tensiometers by Tarantino and Mongiovì (2003), Ridley et al. (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.

Figure 1 shows examples of two designs: a strain gauged diaphragm single-bodied tensiometer (Tarantino and Mongiovì, 2003) and the Durham University device reported by Lourenco *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 of 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).

2.2. Saturation

The reliability and measurement range of high suction tensiometers depends critically on the absence of any trapped air inside the device. The formation of air bubbles either by air entry through the porous stone or by cavitation within the stone and reservoir is the only constraint to the measurement of high suctions. The saturation of the water reservoir and the porous stone is usually performed by applying high values of positive water pressures to force any residual air present to dissolve in water. However, there is still no clear consensus on the degree of pressurisation needed for successful saturation. Guan and Fredlund (1997) applied a pre-pressurisation stage of 12MPa for 24h and measured a cavitation pressure of -1600kPa. Tarantino and Mongiovì (2001) applied a pre-pressurization stage of 4MPa over

24h and measured a cavitation pressure of -2500kPa. Lourenço (2008) used pre-pressurisation of 1.5 MPa and measured a cavitation pressure of -2000kPa. Rojas et al. (2008) showed that pre-pressurisation to only 800kPa was sufficient to obtain cavitation pressures of around -700 kPa.

Take and Bolton (2003) and Lourenço (2008) have identified that it is important to remove air from the device by applying a vacuum, before imposing a high saturation pressure. The following procedure for saturation has been used at Durham University:

- Vacuum stage: the tensiometer was placed in the saturation vessel and vacuum applied for a minimum of 10 minutes.
- Flooding under vacuum stage: while under vacuum, the de-aired water line was opened and left running through the saturation vessel for a few seconds. This ensured that the water was in contact with the porous stone under a pressure close to -100kPa.
- Pressurization stage: 1500kPa was applied for at least 24h in the saturation vessel. Longer periods were often used, depending on the extent of desaturation of the tensiometer. A period of 24 h would be sufficient for re-saturating a transducer that had previously been in use, but had cavitated.

2.3. Additional factors affecting the behaviour of High Suction Tensiometers

Published results indicate that high suction tensiometers are often capable of measuring pore water pressures well beyond the rated air entry value of the porous stone (Tarantino and Mongiovì, 2001). This could be due to the fact that the air entry values of porous stones often exceed the manufacturers' rated value, as noted by Lourenço et al. (2010). It is also possible for a tensiometer in contact with a saturated clay to measure a negative pore water pressure that exceeds the air entry value of the porous stone. This is because air entry cannot occur if the face of porous stone is surrounded by saturated clay, since there will be no air in contact with the face of the porous stone. In this case, the limiting suction that can be measured will be controlled by cavitation.

Recent work has centred on the effect of temperature and long term use of tensiometers. There is evidence that water cavitates at higher tensile strengths at a temperature near 4°C i.e. at its densest state (Richards and Trevena, 1976). To investigate the temperature effect in high suction tensiometers, a series of separate cavitation experiments were carried out at decreasing temperatures (from 20°C to 4°C) with two high suction tensiometers. The results shown in Figure 3 show that higher suctions can be measured with decreasing temperature. It could be argued that the temperature could also affect the calibrations of the devices. To investigate this effect, two calibrations in the positive range at low temperature (4°C) were conducted at increasing air pressures. The calibration factors (i.e. the slope of the calibration relationship in kPa/μV) obtained at 4°C were 0.0112 and 0.0110. The calibration factor at room temperature (21°C) was 0.0112, showing almost no influence of the temperature. Therefore, this confirmed the conclusion that a reduction in temperature leads to an increase in the range of suction it is possible to measure before cavitation (Lourenço et al., 2011a).

Tarantino and Mongiovì (2001) observed that repeated cavitation of high suction tensiometers seemed to improve the measurement range. Results for the Durham University tensiometer over long time scales also suggest that tensiometers perform better (i.e. are able to measure to higher suctions) with increased usage over time. After using a high suction tensiometer for approximately 1 month, Ball (2004) triggered cavitation and read a minimum water pressure of -1231kPa. The same high suction tensiometer was then used for 1 month for testing bentonite-sand mixtures by Hidayat (2006) and was able routinely to measure suctions greater than 600kPa without cavitation occurring. When cavitation was triggered, the minimum water pressure measured was -1537kPa. Therefore, it seems that the prolonged use of high suction tensiometers for pore water pressure measurement on soil samples seemed to improve the measurement range. Jotisankasa (2005) reported similar observations for the Imperial College tensiometer.

2.4. Calibration

Appropriate techniques to calibrate high suction tensiometers must be considered. As tensiometers work in the negative pressure range, calibration should ideally be done by imposing negative pressure values. However, due to the difficulty in generating negative water pressures within the environment of conventional Soil Mechanics laboratories, tensiometers are generally calibrated in the positive range and a linear extrapolation of the calibration equation is assumed to apply to the negative range (Sjoblom, 2000; Meilani et al., 2002; Take and Bolton, 2003).

The only exception to this assumption is the research of Tarantino and Mongiovì (2003) where calibration was done directly by pressurizing the back of the tensiometer. This simulates the outward deflection of the transducer diaphragm, as would occur if the transducer is subjected to negative pressure. They found that the extrapolation error for their tensiometer was 1-1.5% which they concluded was satisfactory, and could justify extrapolation.

Indirect methods for applying a negative pressure have been used to assess the validity of extrapolation. Ridley and Burland (1993), Guan and Fredlund (1997) and Lourenço et al., (2008) have used the axis translation method and the isotropic unloading method to investigate this. Both techniques impose a known suction on an instrumented soil sample. The suction read by a tensiometer attached to the sample using the extrapolated calibration equation is then compared to the applied suction and the accuracy of extrapolation can be determined. Figure 4 shows an example of the isotropic unloading technique (Lourenço et al., 2008). A sample of kaolin was saturated and consolidated by applying a cell pressure of

700kPa and allowing the pore water pressure to dissipate. The drainage system below the porous stone was emptied by blowing dry air through the pedestal of the triaxial cell, to prevent water being sucked into the specimen during unloading. The cell pressure was then reduced rapidly to 100kPa and the tensiometer showed a reduction in value of pore water pressure. When allowance was made for the measured B value of the specimen (which ranged from 0.95 to 0.97), the difference between the tensiometer response and the suction created by unloading indicated an error in the calibration of only 0.81%.

Lourenço et al., (2008) also compared readings from the tensiometer against known value of negative pressures (down to -100 kPa) which could be directly imposed on the tensiometer by using a vacuum method. The results revealed that the extrapolation appeared to be satisfactory for the isotropic unloading technique and for the vacuum method (errors of 0.78% and 0.59% respectively). The axis translation technique seems to be the least suited for validating the extrapolation of the calibration equation to the negative range as it is strongly dependent on the water conditions of the underlying porous stone (Lourenço et al., 2008).

High suction tensiometers are now starting to be used as a calibration instrument for other techniques. For instance, there are often uncertainties in the suctions imposed using the osmotic method due to changes in concentration of the PEG solution and the influence of the semi-permeable membrane. Tang et al. (2010) used a tensiometer to calibrate the osmotic technique to take account of temperature.

2.5. Potential improvements

Tensiometers have been used in different applications, from laboratories studies (e.g. oedometer, triaxial, SWRC) to field measurements. No other technique in unsaturated soil testing matches this versatility. However, even if they are able to measure suctions that could potentially reach 2.5 MPa, testing in the geotechnical literature has been limited to lower suctions (up to 1 MPa). It would be useful to continue to extend the range of such devices. Further work to improve the tensiometer behaviour at high suctions (or increase suction at cavitation) could include:

(i) Use of different materials and better control of the porous stone characteristics. Sjoblom (2000) demonstrated that changing from a commercially available porous stone to a different material made in Kochi University (Japan) led to a jump in the measured suction values.

(ii) Placing a flexible membrane in the reservoir to delay or prevent cavitation. Guan (1996) showed that placing a flexible membrane in the reservoir decreases the space for bubbles to grow and led to an increase in the suction at cavitation.

(iii) Improving the affinity of all the internal faces with water could also avoid trapping air and avoid premature cavitation.

3. Soil Water Retention Determination using High Suction Tensiometers

An important advance has been in the determination of the Soil Water Retention Curves (SWRCs) with high suction tensiometers. Suction is measured in samples either dried continuously while exposed to the atmosphere (continuous procedure) or by drying/wetting in stages (discrete procedure). In the discrete procedure, the specimen is sealed and allowed to equalise internally after each period of drying or wetting. Both approaches are quicker than traditional methods for obtaining SWRCs (e.g. pressure plate). For example, Lourenço (2008) reports that tests carried out using a tensiometer by continuous drying took 2 days, discrete drying less than 7 days, whereas a pressure plate test on the same material took 7 weeks to perform. The technique has been trialled for clays, silts and granular soils. Only drying paths are shown in this paper, but wetting tests have also been successfully carried out using the Durham University tensiometer.

Cunningham (2000), Boso et al. (2003), Toker et al. (2004), and Teixeira and Marinho (2006) were the first, to the authors' knowledge, to determine SWRCs by using high suction tensiometers to measure suction and an electronic balance to record water content. Boso et al. (2003) presented a comparison between SWRCs obtained by discrete and continuous drying for samples of reconstituted clayey silt. The evaporation rate during continuous drying was slowed down by wrapping the sample in a porous geotextile. The results revealed no differences between the SWRCs using the two procedures. Cunningham (2000) investigated the influence of the evaporation rate on the measured SWRC for continuously dried samples of reconstituted silty clay. Similar results were obtained suggesting that the evaporation rate had little or no influence on the resulting soil water retention curve.

Lourenço et al. (2007) also compared SWRCs for a sandy clay determined by means of high suction tensiometers following both discrete and continuous drying. The SWRCs obtained by continuous drying showed higher suctions (by as much as 200kPa) than the SWRCs obtained by discrete drying at the same water content (equivalent to higher water contents at the same suction). These results were initially explained by the lack of suction equalization throughout the sample due to: (i) the fast evaporation rate controlled by the low relative humidity inside the laboratory, (ii) the limited surface area of the sample exposed to the atmosphere, (iii) the fact that the measurements of suction were conducted on the exposed sample surface and (iv) possible additional errors introduced by the experimental set-up (e.g. errors in the measurement of the sample mass due to the weight and stiffness of the tensiometer cable).

To avoid the errors due to the stiffness and weight of the tensiometer cable (which can affect the electronic balance reading), Lourenço et al. (2011a) proposed that suction and water content could be measured separately on two identical samples left to dry to the atmosphere next to each other over the same period of time. The results from the different series of tests indicated that this new continuous drying procedure improved the accuracy of the water content measurements. The SWRCs obtained by the new procedure are similar to those obtained by discrete drying, which confirms that suction gradients during continuous drying had limited impact on the measurements (Figure 5).

Figure 5 also shows a comparison with a pressure plate test carried out on the same sandy clay. The pressure plate test shows greater water contents for the same values of suction compared to measurements using the high suction tensiometer. Similarly, Lourenco et al. (2006) noted differences in measurement between axis translation and tensiometer measurements. Tarantino et al. (2011) also report comparisons between pressure plate and tensiometer data where the axis translation tests show higher water contents than those measured by natural drying using tensiometer measurements.

These differences in water content are consistent with the fact that the axis translation technique (used in the pressure plate) prevents cavitation from occurring within the soil and desaturation only occurs by air entry from the sample boundaries. The prevention of cavitation could mean that larger pores within the soil would not desaturate if they were surrounded by smaller pores that would not desaturate at the applied suction level. However, if subject to natural drying (where the pore water pressures become negative) these larger internal pores could cavitate, allowing water to be removed from the pores. Thus natural drying would result in a lower water content at the same value of suction.

Other authors have reported discrepancies between different methods for determining SWRCs. Cunningham (2000) reports a comparison between the SWRCs obtained by continuous drying and the filter paper method. Teixeira and Marinho (2006) compared the SWRC obtained by discrete drying with the pressure plate and by the filter paper method. In both cases the difference in water content at the same suction between these different methods of determining SWRCs tended to be larger than 5%. This confirms that the desaturation processes may be different between direct measurements and testing using the axis translation technique.

4. Suction Control Systems for Laboratory Testing (Air Circulation Technique)

As was noted previously, the use of high suction tensiometers has eliminated the need to use axis translation for suction *measurement*. However, if axis translation is not used then the question arises as to how suction can be *controlled*. Since highly negative water pressures cannot be directly applied to the drainage systems of laboratory equipment without cavitation occurring, an alternative method of suction control is needed. This can be done using the osmotic method (Cui and Delage, 1996) which can be used for control in the suction range 0-10 MPa. However, this method has limitations at low suctions (Blatz et al., 2008) and there can be difficulties with failure of the semi-permeable membrane and penetration of PEG solution into the specimen. Another alternative is the vapour equilibrium technique (Blatz et al., 2008), but the limitation here is the long time scales needed to impose a known suction.

To provide a technique to control suction in the range of measurement of the high suction tensiometers (<2MPa), a suction control system based on the air circulation method has been developed. The approach described is an extension of the techniques first used by Cunningham (2000) and Jotisankasa (2005).

The technique is based on circulating air around or through the specimen. The air pressure is close to the atmospheric value (pressure gradients of 5-10 kPa are sufficient), thus avoiding the need for elevated air pressures as in the axis translation technique. In the work by Cunningham (2000) and Cunningham et al. (2003), the soil was dried by circulating air through the base of the sample while measuring pore water pressure with two tensiometers at the side and top of the sample. Jotisankasa (2005) and Jotisankasa et al. (2007a) proposed an improved suction control system by including water content estimation. In their system, relative humidity was measured at the inlet and outlet of the air circulation line at the base of the sample. Any difference between these two measurements was attributed to moisture exchange with the sample, thus enabling an estimation of water content during tests. Jotisankasa (2005) also extended the system to allow wetting of the sample. An attempt to wet the soil by circulating moist air proved ineffective so a manual system of injecting a known volume of water into the air circulation line was adopted.

New developments of a tensiometer based suction control system for laboratory testing on unsaturated soil were reported by Lourenço et al. (2011b). The major improvement over the work of Cunningham and Jotisankasa was the use of a closed-loop circulation system that provides continuous measurement of water content, as well as automation of the control system (Figure 6). The control system was implemented within a triaxial cell (a double cell triaxial set-up described by Lourenço (2008) and Mendes (2011)) and was used for imposing drying-wetting paths on compacted soil samples.

Samples (76 mm high by 38mm diameter) were dried by circulating air through a desiccant (silica gel) within a closed-loop system. Wetting was carried out by directly injecting water. The silica gel desiccant was placed on an electronic balance so that the change in mass of the desiccant could be continuously monitored. Changes in the sample water content were measured as the difference between the water injected and that adsorbed by the silica gel. The specimen was surrounded by a geotextile to allow air flow to take place from top to base around the specimen (not simply below the base of the specimen), ensuring uniform drying conditions. An open weave geotextile was used that would not retain water at the suctions being investigated.

Figure 7 shows a sandy clay specimen being dried to a required suction of 800 kPa, which was achieved in about 12 h. The system was able to dry and wet to a required pore water pressure; however wetting was not as easily controlled as drying. During wetting, tensiometer measurements tended to overshoot significantly the target pressure. It was possible to use the system with manual intervention to prevent overshoot, but the automated wetting system still needs further improvement. To overcome this, it is preferable to operate the system for wetting using water content control; injecting water at a controlled rate and measuring the suction response.

5. Field Measurements using High Suction Tensiometers

High suction tensiometers also have great potential for field measurements. However, it is important to recognise that these tensiometers can cavitate if subject to high suctions for a long period. A technique was developed by Ridley and Burland (1996) for placing such tensiometers at depths up to 5 m. However, to resaturate the tensiometers using the pressurisation technique, it is necessary to remove them from the ground. Recent developments by Cui et al. (2008) and Mendes et al. (2008) show that tensiometers can be used for long-term measurements.

The installation technique used by Cui et al. (2008) allowed installation of a single tensiometer at the base of a hole (Figure 8) whereas Mendes et al. (2008) devised an arrangement where multiple tensiometers can be installed at different depths in a borehole (Figure 9). However, in both cases it is possible to remove the tensiometer from the ground, when resaturation is necessary.

The experimental set-up described by Mendes et al. (2008) has been used for real-time continuous measurements of suction inside an embankment. The tensiometers were installed with the help of a *probe locator*, which consists of a 3 m long PVC cylinder installed in a borehole (Figure 10). The tensiometers were fitted with a nylon tube over the electrical cable so they could be easily removed from the ground by pulling the nylon tube. The nylon tube was also sufficiently stiff to prevent buckling, thus allowing tensiometers to be pushed into place, down guide tubes provided in the probe locator, to ensure good contact with the soil.

Cui et al. (2008) report the results of field monitoring near the village of Boissy-le-Châtel, France. The field suction was monitored at two depths (0.25 and 0.45 m) during May and June 2004 and the results are presented in Figure 11a. The tensiometer was changed every two or three weeks for re-saturation in the laboratory and reinstallation resulted in a suction reduction as shown by the points where the suction drops to zero in Figure 11a. The overall trend is for an increase in suction with values approaching 200kPa, beyond the range that would be possible to measure using conventional tensiometers.

Field monitoring was performed using tensiometers at an instrumented embankment near Newcastle, UK (Toll et al., 2011). Figure 12(a) shows continuous measurements for the period of November 2007 to March 2009 whereas Figure 12(b) shows data for February to April 2008 on an expanded timescale. Again the tensiometers were removed regularly (about every two weeks) to check the calibrations (Mendes, 2011). These points of change are shown by vertical dotted lines in Figure 12. The transducers were placed in free water to check the zero values. In some cases, removal and replacement of a tensiometer caused a change in reading that might take several hours before the general trend of pore water pressure change was re-established.

Although high suctions (>150 kPa) were measured on the embankment during construction in 2005 (Hughes et al., 2007) the values since November 2007 were small (less than 20 kPa) as might be expected as the period May-July 2007 was the wettest on record for 250 years and caused extensive flooding in the UK. It does demonstrate that the tensiometers were able to record positive pore water pressures as well as suctions. Figure 12(b) shows small increases in pore water pressure of 2-5kPa after small rainfall events with 2-3 mm of precipitation. After a larger rainfall event starting on 15 April 2008, the pore water pressure rise is larger, of the order of 10 kPa.

The results from the tensiometers indicate a general increase in pore water pressure down to 3m depth with zero pressure conditions suggesting a water table at 0.5-1.0m. However, flushable piezometers installed deeper in the embankment at 4.5m depth indicated suctions of 20-30 kPa at this depth (Hughes et al., 2009) meaning that a perched water table was present within the embankment.

6. Conclusions

A major advance in unsaturated soil testing has been the incorporation of high suction tensiometers into laboratory testing procedures. The devices potentially allow direct measurement of suctions up to 2.5 MPa, although most measurements on soils have generally been limited to around 1 MPa. It is possible to use these probes to measure suctions in a variety of apparatus (from the shear box to the centrifuge). Procedures for saturation and calibration of the devices need particular attention. However, it is shown that it is acceptable to extrapolate a calibration determined for the positive range of pressure to the negative (suction) range.

High suction tensiometers have also been used to determine the soil water retention behaviour. This can be done using continuous drying techniques, when the water content is monitored using an electronic balance as the soil dries out naturally. Discrete drying can also be used, where the specimen is sealed after a period of drying or wetting to ensure equalisation before measuring the suction using the tensiometer. Both techniques involve considerably shorter periods of time than conventional methods such as the pressure plate.

The use of the high suction tensiometer has removed the need to use the axis translation technique in laboratory testing. Since axis translation prevents cavitation taking place within the inner soil pores, it does not represent the same condition as a soil will achieve by drying naturally, where cavitation can take place. However, alternative methods for controlling suctions are needed if axis translation is not used. The air circulation technique provides such a method. An automated system for suction control is described that can dry and wet a specimen to a required suction. It also provides continuous measurements of water content.

The devices have also been used in the field to obtain long-term measurements of suction *in situ*. Methods of installation are discussed that either involve installing a single tensiometer at the base of a borehole, or ways to incorporate multiple tensiometers at different depths within the same borehole. In either case it is essential to have a system by which the tensiometer can be removed and re-installed in case the device cavitates.

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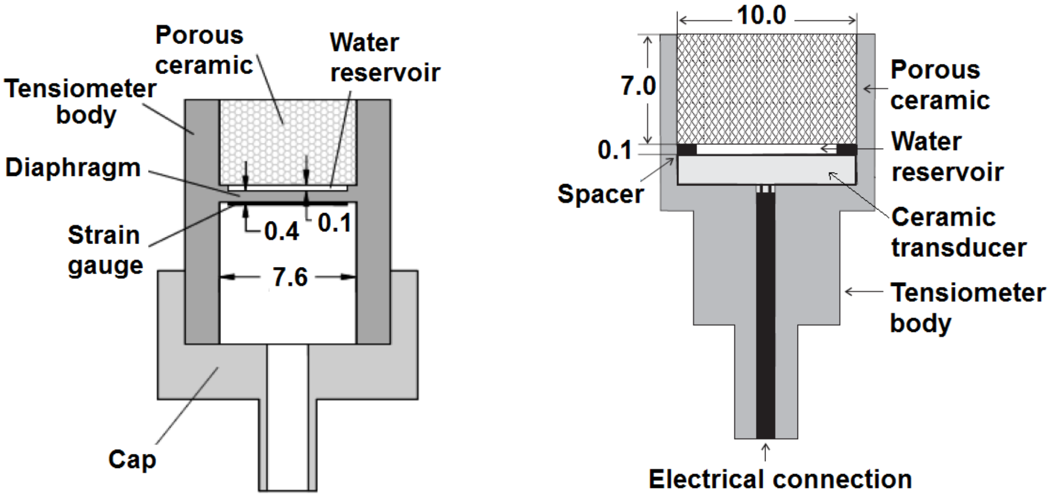
Table 1. Characteristics of tensiometers

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	15000	~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	1mm 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



(a) (b)

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

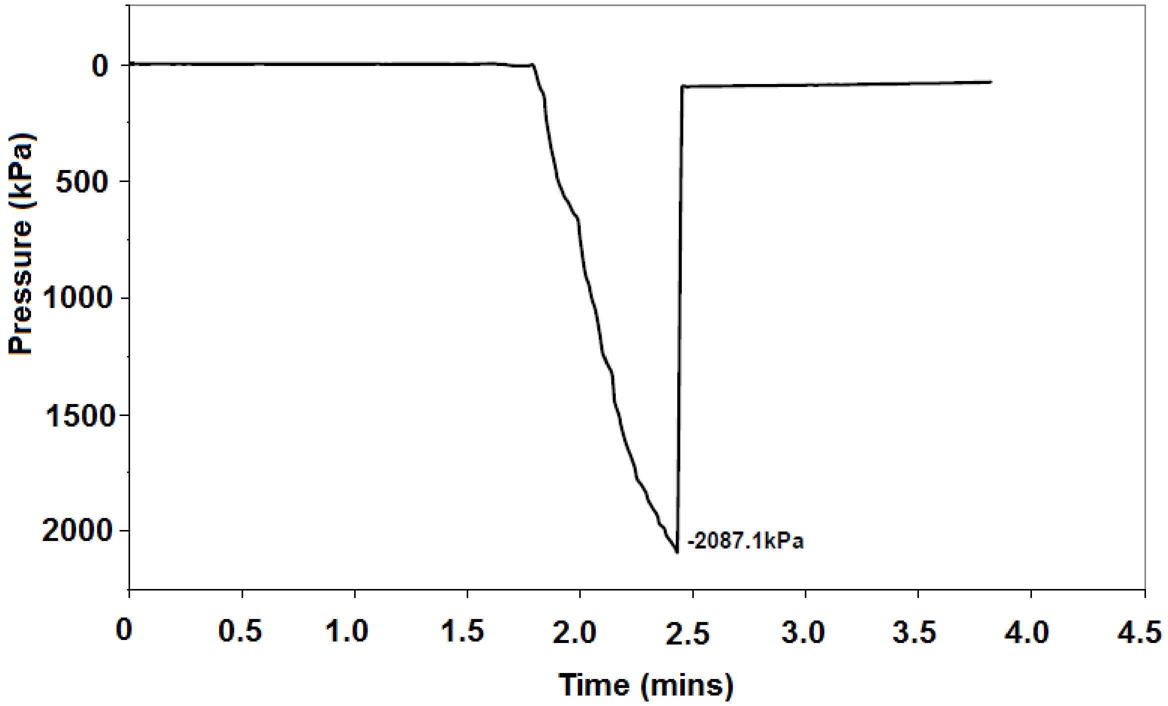


Figure 2. Cavitation of a high suction tensiometer

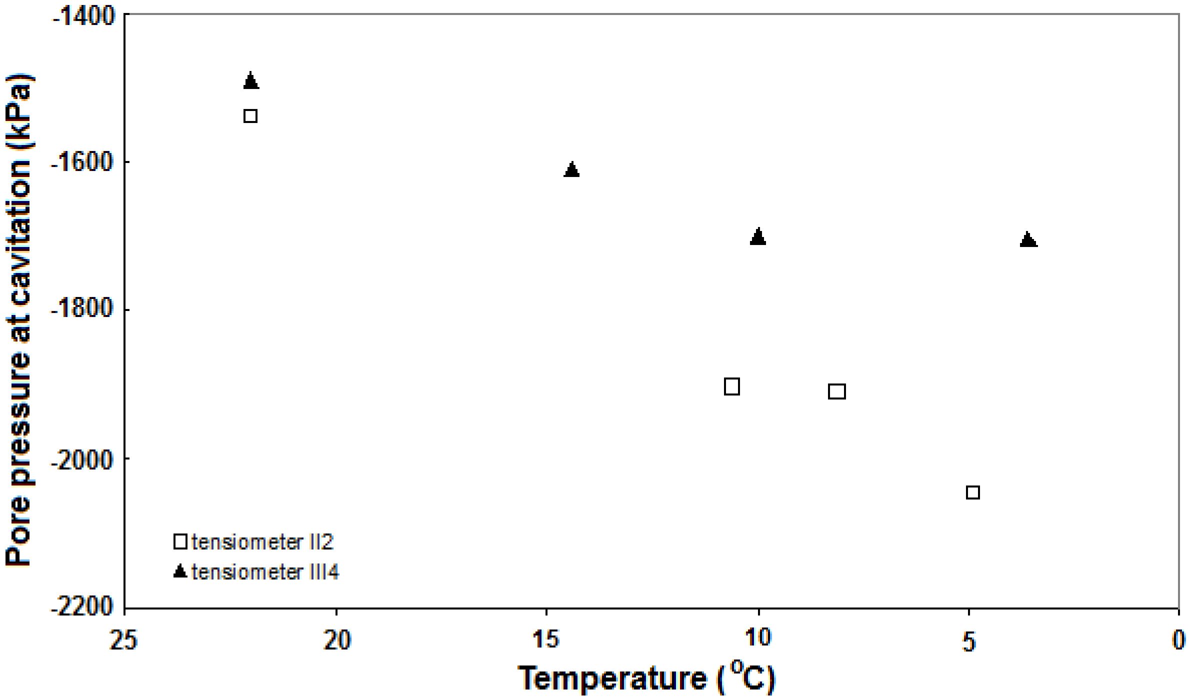


Figure 3 : Temperature effect on pore water pressure at cavitation

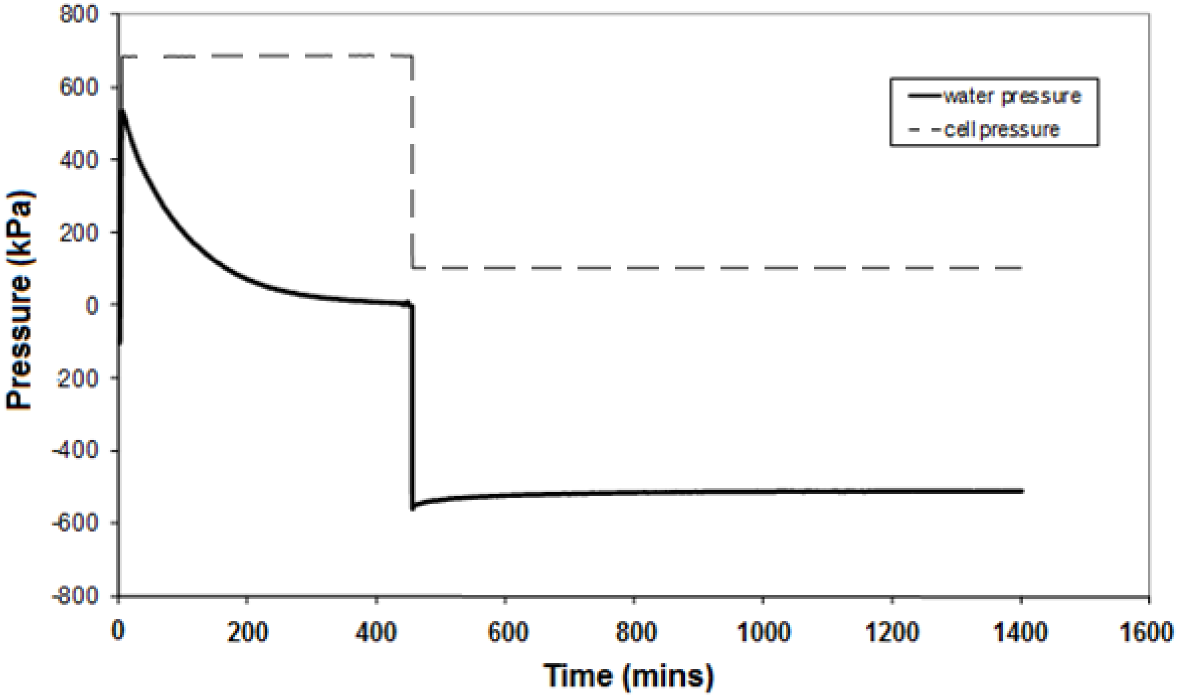


Figure 4 : Tensiometer calibration by isotropic unloading of a saturated kaolin sample; decrease in pore water pressure (measured by tensiometer) is compared to the decrease in cell pressure

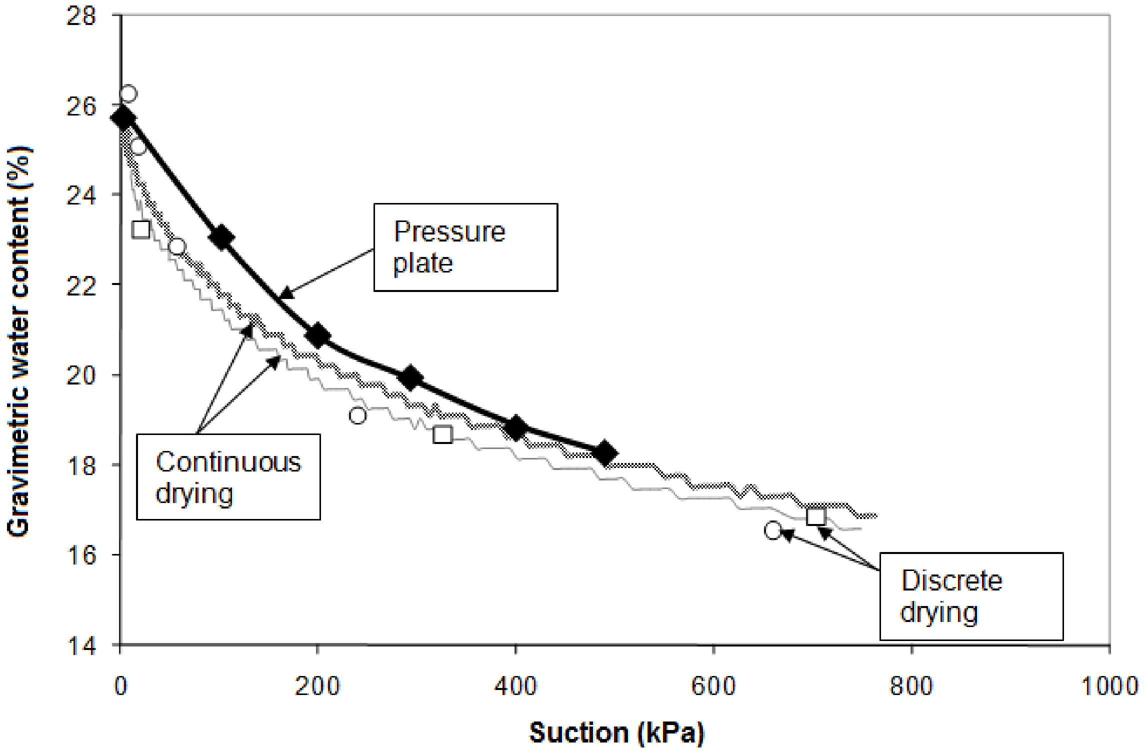


Figure 5 : Soil water retention curve determined with high suction tensiometers by discrete drying (dots and squares) and continuous drying (lines) of sandy clay samples. A pressure plate test on the same soil is shown for comparison.

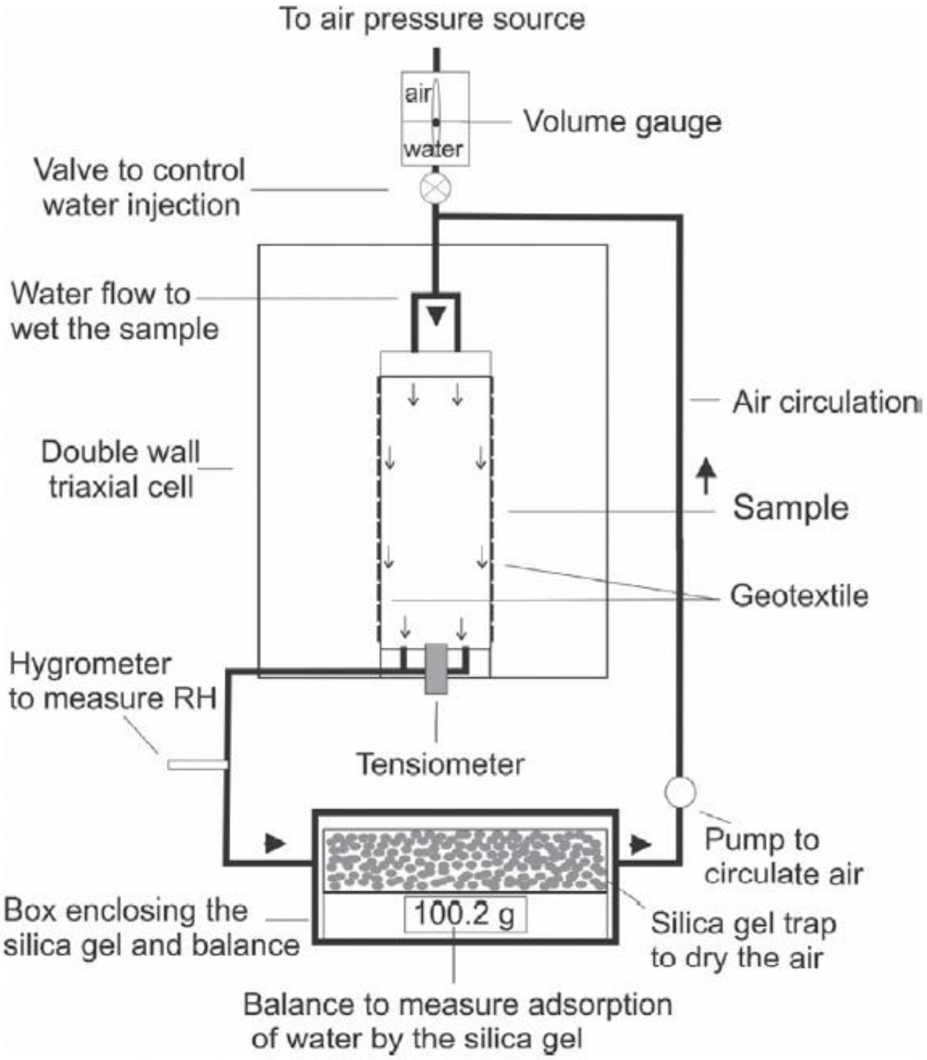


Figure 6 : Air circulation system for suction controlled drying and wetting of soils.

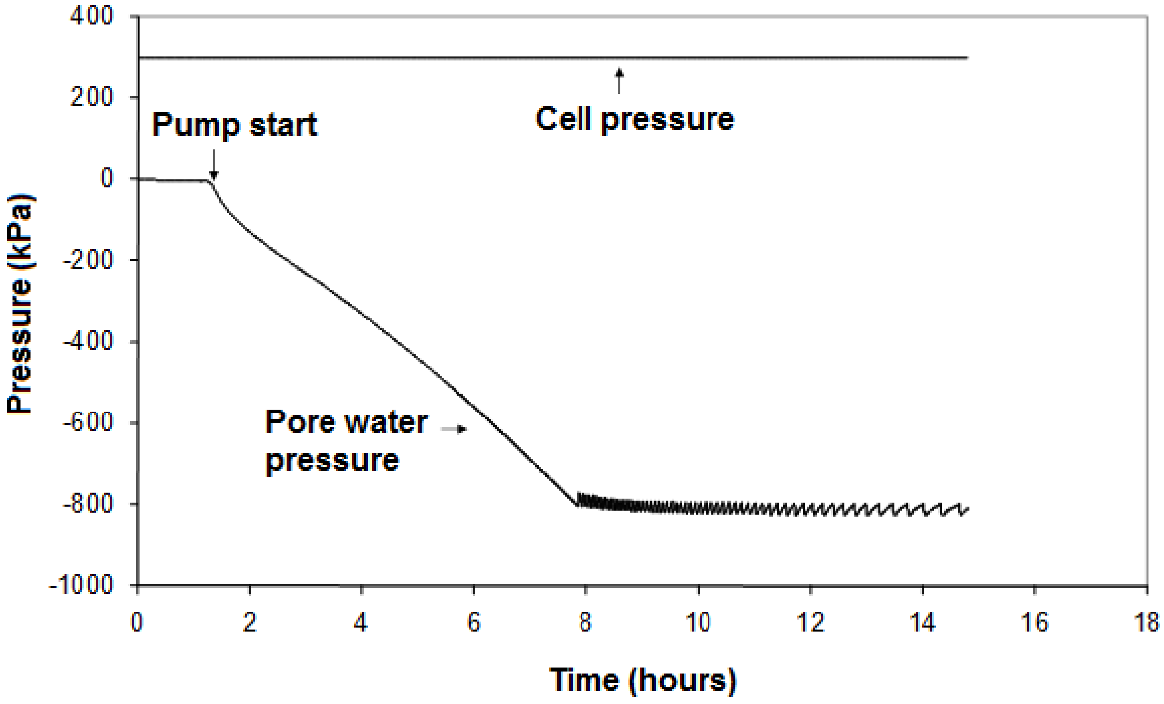


Figure 7 : Controlled drying by air circulation of a sandy clay sample; pore water pressure measured by a high suction tensiometer; a target value of pore water pressure was set and the sample was dried until reaching the target value (-800kPa)

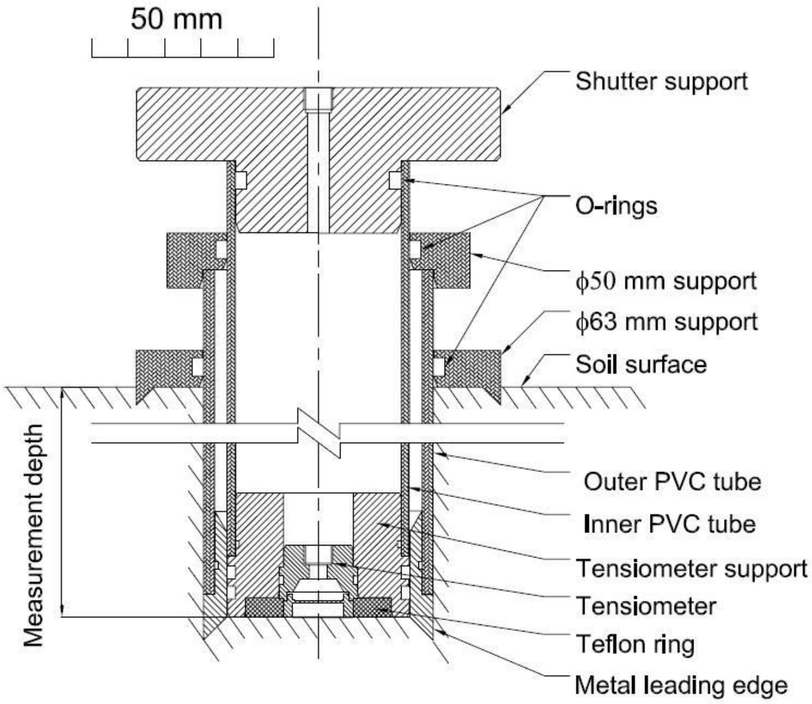


Figure 8. Schematic view of the field installation of the ENPC tensiometer (Cui et al., 2008)

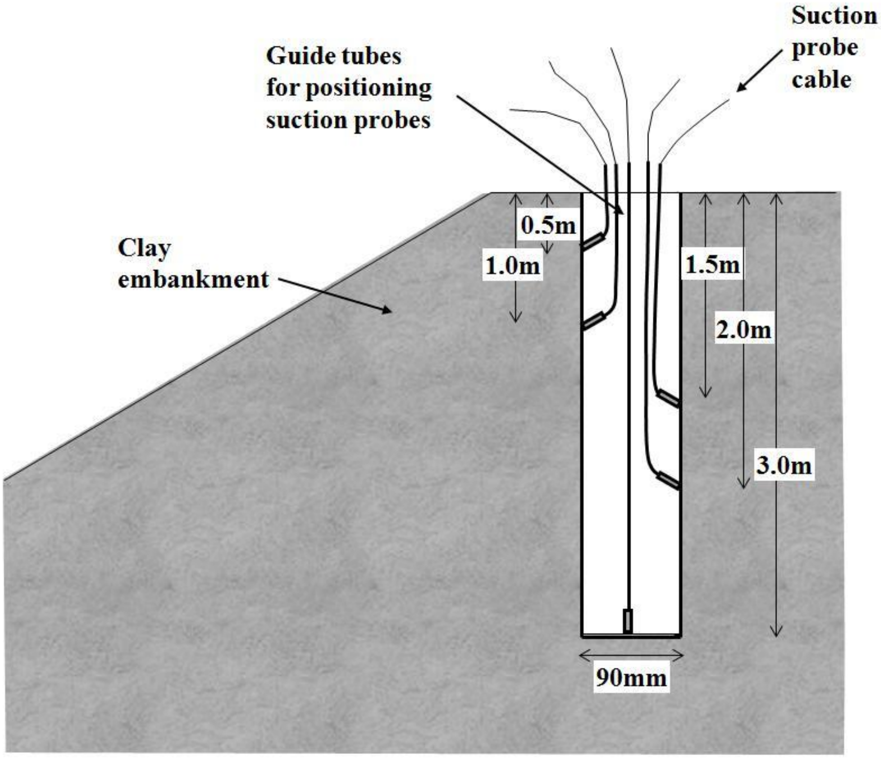


Figure 9. Schematic of the Durham University multi-tensiometer installation (depths in metres)

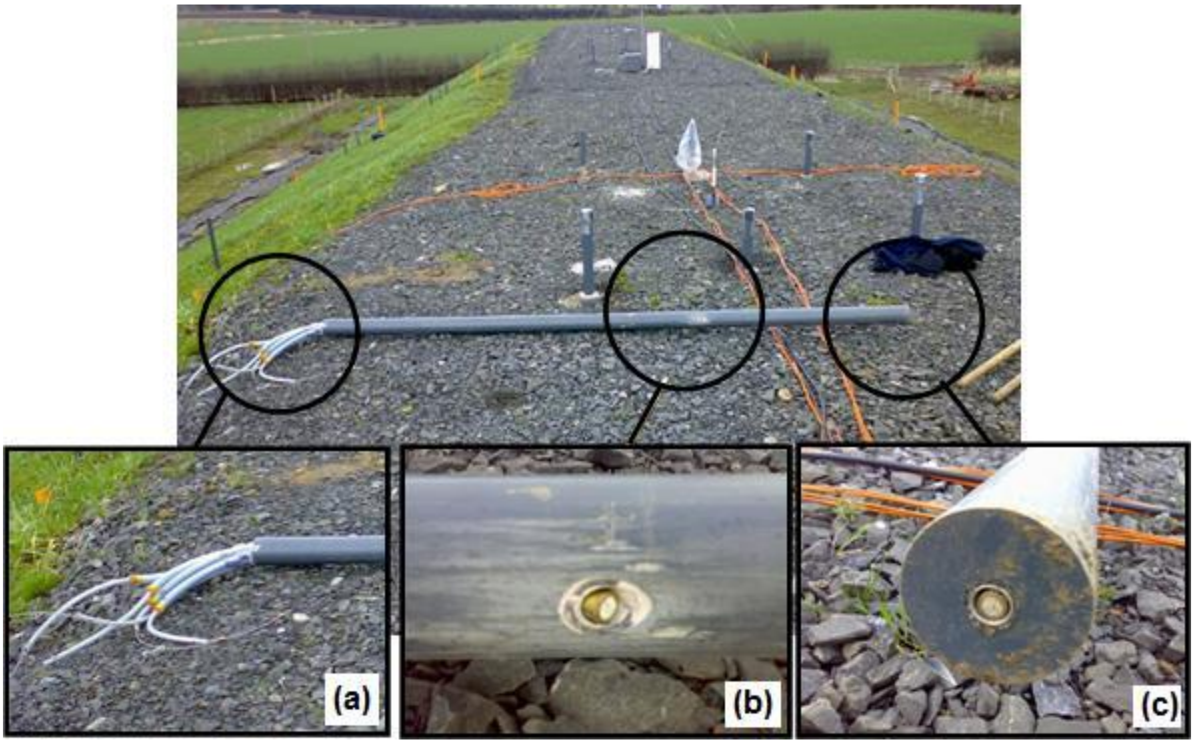


Figure 10. A probe locator before installation (a) detail of the guide tubes emanating from the top (b) detail of the side suction station (c) detail of the base suction station

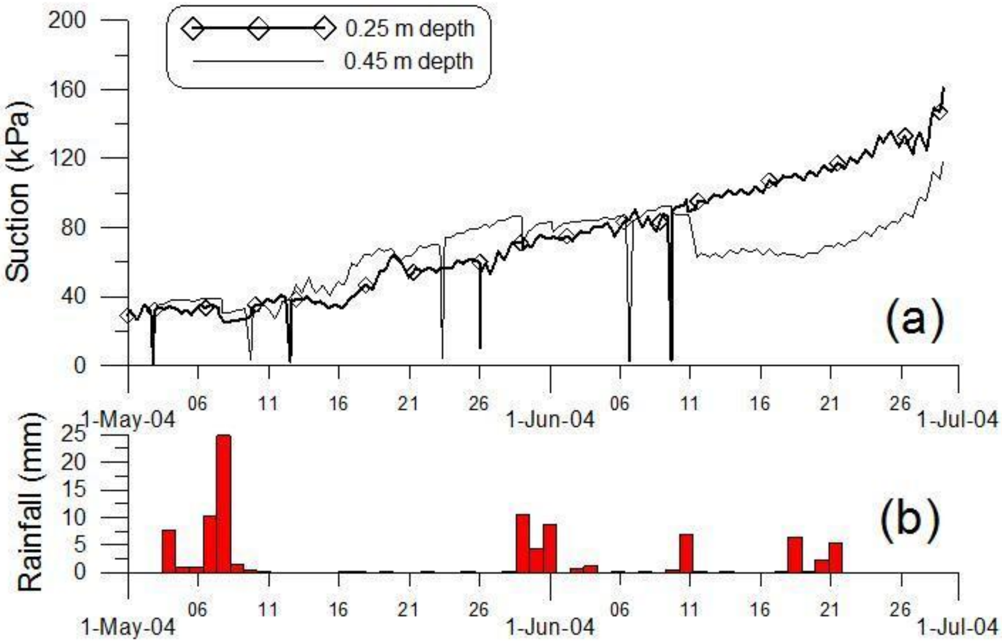


Figure 11. (a) Suction measurements at Boissy-le-Châtel (b) daily rainfall records (Cui et al., 2008)

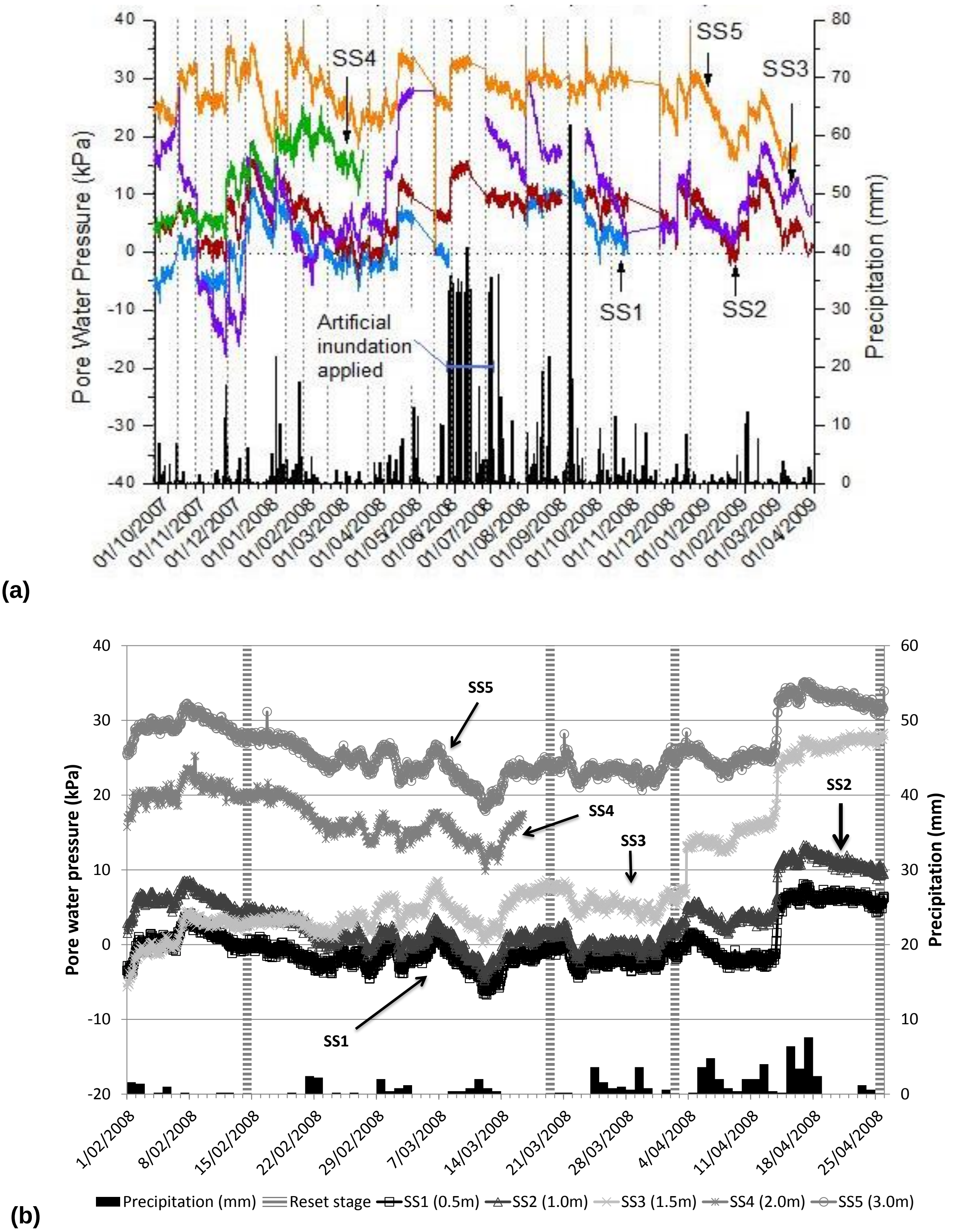


Figure 12. Results of field monitoring at an instrumented embankment near Newcastle, UK (a) complete record 2007-2009 (b) February to April 2008. (SS- suction station) SS1 (0.5m), SS2 (1.0m), SS3 (1.5m), SS4 (2.0m), SS5 (3.0m). Bar graph shows precipitation. Vertical dotted lines indicate the tensiometers were removed and reset.