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Calibrations of a high-suction tensiometer

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High-suction tensiometers are able to measure suctions up to 2 MPa. Direct calibration at such high suctions requires the imposition of negative water pressures, which are difficult to achieve using facilities commonly available in soil mechanics laboratories. For this reason, tensiometers are usually calibrated in the positive pressure range, and such calibration is subsequently extrapolated to negative pressures. This paper examines different experimental techniques to assess the accuracy of such extrapolation. Any error in the calibration process would be directly reflected in the measured values of suction, and might be particularly significant (in relative terms) for the measurement of low suctions. In addition, the results of this study show that calibration in the positive range is affected both by the physical configuration of the tensiometer during calibration and by aspects of its design. The paper concludes that linear extrapolation of the calibration from the positive to the negative range is sufficiently accurate provided that calibration is done under conditions that closely match the conditions in which the tensiometer will be used. Owing to structural differences between tensiometers, and also to suction-induced 'calibration hysteresis', at least one check on the accuracy of the extrapolated calibration equation over a range of negative pressure should be performed, even if at low values of suction.

KEYWORDS: laboratory equipment; laboratory testing; partial saturation; suction

Les tensiomètres à aspiration élevée sont en mesure de mesurer des aspirations pouvant atteindre 2 MPa. Le calibrage direct à ces aspirations élevées nécessite l'imposition de pressions d'eau négatives, difficiles à réaliser au moyen des installations dont disposent généralement les laboratoires de mécanique des sols. C'est pour cela que les tensiomètres sont généralement calibrés dans la plage de pressions positives, ce calibrage étant ensuite extrapolé sur des valeurs négatives. La présente communication se penche sur différentes techniques expérimentales permettant d'évaluer la précision ce cette extrapolation. Toute erreur du processus de calibrage serait reflété directement dans les valeurs d'aspiration mesurées, et pourrait être particulièrement significative (de façon relative) pour la mesure de faibles aspirations. En outre, les résultats de ce cette étude montrent que le calibrage dans la plage positive est affecté à la fois par la configuration physique du tensiomètre au cours du calibrage et par des aspects de sa conception. On en conclut, dans la présente communication, que l'extrapolation linéaire du calibrage de la plage positive à la plage négative est suffisamment précise, à condition que ce calibrage soit effectué dans des conditions proches des conditions d'utilisation du tensiomètre. Compte tenu des différences structurelles entre les tensiomètres, et de « l'hystérésis de calibrage » induite par l'aspiration, on doit également effectuer au minimum un contrôle de la précision de l'équation de calibrage extrapolé dans une plage de pressions négatives, même avec de faibles valeurs d'aspiration.

INTRODUCTION

High-suction tensiometers are small transducers able to measure directly water tension below -100 kPa relative to atmospheric pressure. Their applications in unsaturated soil testing are recent and diverse, and include the development of tensiometer-based suction control systems (Jotisankasa *et al.*, 2007), determination of the soil-water retention curve (Toker *et al.*, 2004; Lourenço *et al.*, 2007), direct shear tests (Tarantino & Tombolato, 2005), field suction measurements (Ridley *et al.*, 2003; Mendes *et al.*, 2008) and testing of rammed earth materials (Jaquin *et al.*, 2008). The component parts of a typical tensiometer (of the type used in the research to be described below) are shown in Fig. 1. A closed casing contains a high air entry porous stone, behind which there is a pressure transducer. Between the stone and the transducer is a small reservoir of water. When the tensiometer is placed against a soil surface the water in the stone equilibrates to the pressure of the pore water in the soil. This pressure is also transmitted to the water in the reservoir and hence to the pressure transducer.

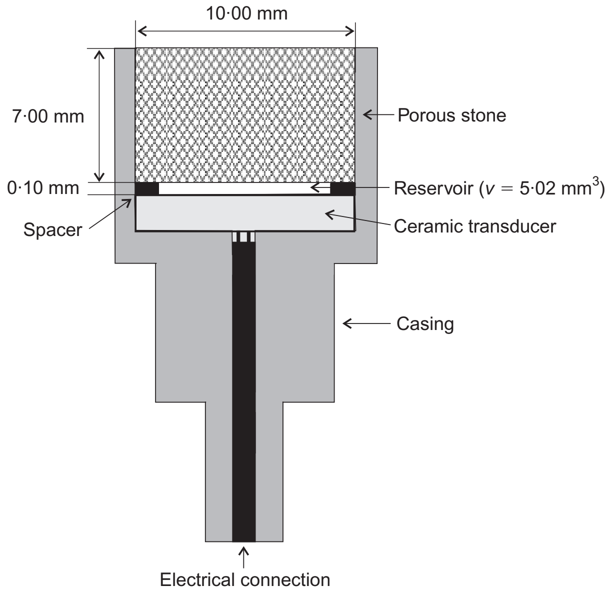

Fig. 1. Component parts of the Durham University–Wykeham Farrance typical tensiometer

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The performance of tensiometers depends strongly on their saturation (as this controls the maximum measurable suction) and their accurate calibration. Recent studies have focused on the former, particularly aspects of the pre-conditioning procedure employed for saturation, such as the magnitude and duration of the positive pre-pressurisation stage and the effect of initial flooding of the tensiometer under vacuum (e.g. Tarantino & Mongiovi, 2001; Take & Bolton, 2003). Calibration has received less attention, however, with only one dedicated study by Tarantino & Mongiovi (2003) to our knowledge.

Calibration is the relation between a known imposed value (input) and the read value (output). For a tensiometer the input is water pressure and the output is a d.c. voltage. A calibration factor *m* is derived (assuming a linear relationship between input and output using a least-squares regression technique) as the ratio of voltage in μV to water pressure in kPa. Calibration error is the difference between an imposed value of suction and the value obtained from the regression equation using the measured output. As tensiometers work in the negative pressure range, calibration should ideally be done by imposing negative pressure values. However, owing to the difficulty of 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 be applicable to the negative range (Sjoblom, 1996; Meilani *et al.*, 2002; Take & Bolton, 2003).

The purpose of the research presented here is to study and validate the extrapolation of calibration from the positive range to the negative range for high-suction tensiometers. A series of tests were carried out in which target negative pressures (suctions) were applied to a tensiometer and compared with the values derived from a calibration curve extrapolated from the positive pressure range. This paper discusses features of the tests themselves as well as the effect of cyclical variation of pressure on tensiometer performance. Following this, a comparison is made with calibrations in the positive range to assess the accuracy of extrapolation. Throughout the following the error *e* in using extrapolation is the ratio

$$e = \frac{\left|(u_\mathrm{w})_\mathrm{e} - (u_\mathrm{w})_\mathrm{a}\right|}{\left|(u_\mathrm{w})_\mathrm{a}\right|} \times 100\% \qquad (1)$$

where $(u_\mathrm{w})_\mathrm{a}$ is the *applied* target negative pressure and $(u_\mathrm{w})_\mathrm{e}$ is the *estimated* pressure measured by the tensiometer using the extrapolation of the positive calibration curve to the negative pressure range.

TENSIOMETER CALIBRATION METHODS

Table 1 contains a summary of tensiometer calibration methods that will be examined in turn below. The only direct method to calibrate in the negative pressure range (suitable for high-suction tensiometers) employs pressurisation from the back of the tensiometer. This technique has the advantage of replicating the exact conditions in which the tensiometer will be used. Pressurisation from the back of the tensiometer induces a deflection of the transducer diaphragm in the direction of the soil, that is, in the same direction as that induced by a negative pressure in the reservoir. In Tarantino & Mongiovi (2003) a tensiometer of the general form of Fig. 1 was used, but with a strain-gauged diaphragm replacing the transducer, behind which was a sealed chamber that could be pressurised. The extrapolation error was found to be 1–1·5%, which, the authors state, justifies extrapolation in this case.

The technique proposed by Tarantino & Mongiovi (2003) is probably the most suitable for calibration since it replicates almost exactly the effect of a negative pressure on the transducer. However, the technique requires adaptation of the tensiometer for air pressure application from the back, which implies that each tensiometer has to be designed and built so that it can easily be switched between calibration, saturation and use. In the case of the tensiometer used for this research, it was not possible to pressurise the back of the tensiometer because a cement sealant completely isolates the electrical wires connected to the transducer (see Fig. 1). This is a necessary feature for a tensiometer that may be used in a submersible environment, such as inside a triaxial cell.

Indirect methods to assess the validity of the extrapolated calibration have greater applicability than the direct method described above, and have been more widely used in the past. These include the axis-translation technique and the isotropic unloading technique. Both techniques impose a target suction on a soil sample. The suction read by a tensiometer in contact with the sample using the extrapolated calibration equation is compared with the applied target suction, and the accuracy of extrapolation is measured. In addition, it is possible to apply small negative pressures (down to -100 kPa) using a vacuum pump attached to a triaxial cell, but this has limited application for high-suction tensiometers.

The axis-translation technique imposes a known value of suction on an unsaturated soil sample by elevating the pore air pressure while keeping the pore water pressure at atmospheric value. The air pressure is subsequently reduced while a tensiometer in contact with the soil sample measures the corresponding decreases of pore water pressure (in the negative range). Assuming that equilibrium is attained at the imposed value of suction, the tensiometer should read a negative value of pore water pressure identical to the corresponding reduction in pore air pressure. Guan & Fredlund (1997) used this technique to investigate the accuracy

Table 1. Methods of tensiometer calibration

Range	Name of technique		Direct or indirect?	Imposed	Medium in which measurement is taken
Positive	Transducer	Saturation manifold Isotropic Anisotropic	Direct	Water pressure	Water
Negative	Vacuum		Direct	Water pressure (> -100 kPa)	Water
	Isotropic unloading		Indirect	Cell pressure	Saturated soil
	Axis translation		Indirect	Air pressure	Saturated/unsaturated soil
	Back pressurisation		Direct	Air pressure	Air

of the extrapolated calibration on clay and silt samples in the pressure plate. The calibration error was between 0·5% and 8·5%. Previous data by the authors (Lourenço *et al.*, 2006) using the axis-translation technique showed an error of approximately 5%, that is, within the same range as reported by Guan & Fredlund (1997). In both studies the observed tendency was for the suction to stabilise at smaller values than those imposed, after each drop of the air pressure. This was interpreted as water transfer from the porous stone of the pressure plate to the sample.

The isotropic unloading technique uses a tensiometer to read the negative pore water pressure imposed by undrained unloading of a saturated soil sample initially consolidated to a given effective stress under a back-pressure equal to or greater than zero. According to the effective stress principle, any change in mean total stresses in undrained conditions should generate an equal pore water pressure change. Ridley & Burland (1993) tested kaolin samples consolidated to different values of effective stresses (up to ~1500 kPa) with a constant back-pressure of 200 kPa. The samples were then unloaded with the drainage line closed while the generated soil suction was measured by the tensiometer. Subsequently the samples were reloaded, still under undrained conditions, to the same initial total stress, and the back-pressure was again measured to calculate the corresponding effective stress (which was in general different from the value initially imposed). The error was calculated as the difference between the suction measured by the tensiometer and the imposed effective stress. Ridley & Burland (1993) found that the error was smaller if the effective stress measured after reloading was used in the calculation, as the suction read by the tensiometer was noticeably smaller than the effective stress initially imposed (i.e. before unloading of the sample).

The indirect methods outlined above use equipment easily available in laboratories (e.g. a triaxial cell with a porous stone) for assessing the accuracy of the extrapolated calibration equation, and do not require a tensiometer with a specific design. Previous work (cited above) made use of these techniques, but such studies were focused on introducing new tensiometers to the geotechnical community, and it remains unclear which of these two techniques provides the most accurate way of validating the extrapolated calibration equation. In the light of these limitations, the present research was initiated to provide a consistent set of data relating to the techniques available to assess the accuracy of the extrapolated calibration equation. The testing programme consisted of calibrating a tensiometer in the positive range (by a variety of methods) and then comparing the suction measured by the tensiometer using the extrapolated calibration equation against target values of suction imposed on a soil sample by using the axis-translation and isotropic unloading techniques. An additional comparison was also performed against negative pressures down to −100 kPa imposed via a vacuum pump and measured by the same transducer used for the calibration in the positive range. Calibration equations were obtained for single or several cycles of imposed pressure (to study any hysteretical effect of the calibration equation). Related aspects are discussed, namely the influence of external forces, error calculation, hysteresis of the calibration equation, and alternative techniques to assess the accuracy of the extrapolated calibration.

EQUIPMENT AND MATERIAL

The tensiometer used had a porous stone with an air entry value of 1500 kPa. Details of the tensiometer characteristics and saturation procedures can be found in Lourenço *et al.* (2006). The calibration was performed in the positive range against a standard transducer (maximum capacity of 2000 kPa), previously calibrated against a dead load machine. This same transducer was used as the reference measure for the air pressure imposed in the axis-translation technique, for the cell pressure or back-pressure imposed in the isotropic unloading technique, and for the negative pressure imposed by the vacuum pump. The axis-translation tests and isotropic unloading tests were conducted in a triaxial cell fitted with a pedestal containing a porous stone with an air entry value of 500 kPa. This allowed easier control of the water conditions below the porous stone, compared with the pressure plate used by Guan & Fredlund (1997). Calibrations in the positive range were conducted in a purpose-built saturation manifold (Donoghue, 2006) and in a triaxial cell. In the saturation manifold the tensiometer is fastened from the back and sealed on the sides by an O-ring and a metallic ring (the metallic ring was designed to improve the sealing at high pressures). A labelled photograph of the manifold is shown in Fig. 2. The TRIAX software was used for data acquisition (Toll, 1999).

Reconstituted Speswhite kaolin samples were used for the tests using the isotropic unloading and axis-translation techniques. Speswhite kaolin was chosen for its availability, its homogeneity (ensuring reproducibility), and its ability to cover the suction range of the tensiometer with a relatively high cavitation limit. It is also non-expansive and reasonably permeable (for a clay), avoids effects related to temperature fluctuations, and enables relatively fast equalisation of pore water pressure. Kaolin was initially mixed with distilled water at a water content of 200% to form a slurry and placed in a Rowe cell for one-dimensional consolidation at 250 kPa. Samples were then cored using 38 mm samplers, and coated with liquid paraffin wax in several layers to prevent moisture losses. All samples had a water content of approximately 42%, initial void ratio of 1·13, and degree of saturation of 98·7%.

CALIBRATION IN THE POSITIVE RANGE

In order to study the validity of extrapolation, it was first necessary to obtain a calibration in the positive range for the tensiometer used. This calibration was performed in three ways (Table 1). Calibrations were carried out in the saturation manifold (Fig. 2), with different holding-down forces applied to the tensiometer in the seating. Two further calibrations were then carried out with the tensiometer inside a triaxial cell. First, a calibration was carried out in what we term 'isotropic' conditions, by submerging the probe in water and increasing the cell pressure in steps. This calibration method corresponds to a condition where the pressure applied to the inner transducer through the ceramic stone is the same as the pressure applied externally to the probe's body. Second, a calibration was carried out in what we term 'anisotropic' conditions, by consolidating a soil sample at a

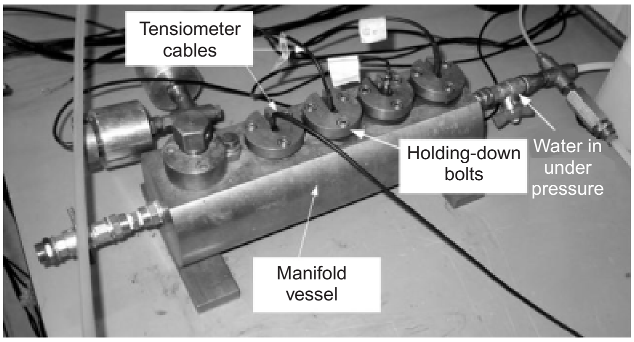

Fig. 2. Saturation manifold (Donoghue, 2006)

given cell pressure and applying increasing back-pressures until reaching an effective stress of approximately zero. At the same time, the tensiometer was maintained directly in contact with the soil through a grommet on the sample's side, sealed by O-rings and painted with several layers of liquid latex rubber. The procedure for placing the tensiometer in contact with the sample is similar to that described by Hight (1982) for sealing a piezometer probe on a sample's side during saturated triaxial tests, and has been used frequently since (e.g. Wong *et al.*, 2001; Jotisankasa, 2005). This calibration method corresponds to a condition where the pressure applied to the transducer through the ceramic stone was equal to the back-pressure inside the sample, and different from the cell pressure applied externally to the tensiometer's body.

The calibration factors *m* obtained for the four cases described above are shown in Fig. 3 together with the plots of voltage against applied pressure. There is a clear difference between these calibration methods. The effect of loose or tight fitting in the saturation manifold is significant, while tests conducted with the tensiometer in 'isotropic' or 'anisotropic' conditions inside the triaxial cell show closer calibration factors. The two calibration factors that differed most (i.e. for the tensiometer fixed tightly in the saturation manifold and in 'isotropic' conditions respectively) show a difference of 9·8%, indicating that, in order to obtain accurate measurement of suctions, the tensiometer should ideally be calibrated using a method that resembles conditions of use. Further possible evidence for this can be found in the study by Jotisankasa (2005). Given the authors' findings here, the calibration factor used later to check extrapolation to the negative pressure range was that obtained under 'isotropic' conditions.

Hysteretic effects due to imposed positive pressure changes were also studied. The procedure followed consisted of submerging the tensiometer in water in a triaxial cell and applying five cycles of cell pressure between zero and 600 kPa. The increments of cell pressure were applied in steps followed by waiting periods to ensure that the tensiometer readings achieved equilibrium. Data for these pressure cycles are shown in Fig. 4, where the series of loops corresponding to consecutive increments of cell pressure could be attributed to the low permeability of the stone causing a delay in the tensiometer response. As the diaphragm deflects, a small amount of water flows inwards or outwards, depending on whether pressure increases or decreases respectively. After each increase of pressure a period of time of 1 to 2 min is necessary for this flow process to be completed and for tensiometer readings to stabilise. By considering only the final equilibrium points for each increment of cell pressure, the same calibration factor as given in Fig. 3 for 'isotropic' conditions is obtained.

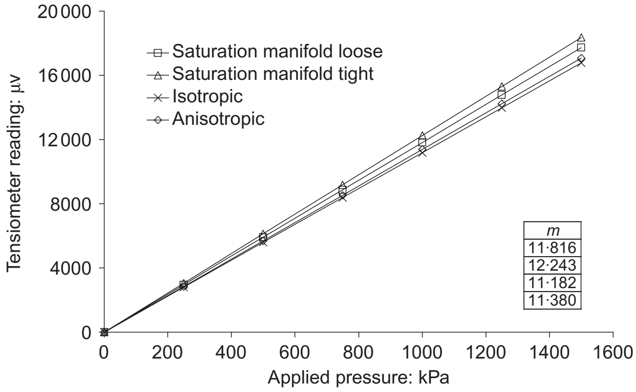

Fig. 3. Calibration in the positive range

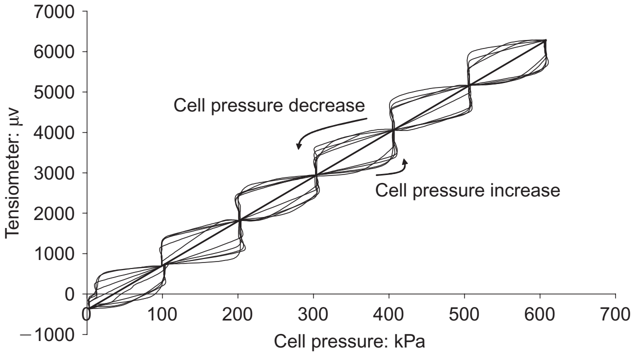

Fig. 4. Hysteretic effects in the positive range

METHODS OF CHECKING EXTRAPOLATION

Having obtained a calibration in the positive pressure range, three methods (one direct and two indirect) were investigated to check the extrapolation of such calibration to the negative pressure range. This also included the study of some aspects of the methods themselves such as, for example, the study of hysteretic effects.

Application of vacuum

The first extrapolation check used a direct method of applying negative pressures down to −100 kPa by means of a vacuum pump. Despite its limitations for high-suction tensiometers, it was thought useful to include such a method in this study as a comparison with other indirect techniques. The tensiometer was submerged in a cup in free water placed inside a triaxial cell. Vacuum was applied inside the cell in three different cycles and maintained constant for short periods of time at different stages during each cycle (see Fig. 5). Tensiometer readings (using the calibration factor extrapolated from the 'isotropic' method in the positive range) were compared against the imposed negative pressure (measured by the same transducer used during the calibration in the positive range). The results in Fig. 5 show that the pressure transducer controlling the vacuum returns to zero after each cycle, whereas the tensiometer shows a slight shift in measurements throughout the three cycles. With the cell pressure at zero, the tensiometer reading after the second cycle was approximately 2 kPa and after the third was 3 kPa. This suggests that calibration could be drifting as pressures are ranged between zero and −100 kPa, but there is no evidence of a change of the calibration factor *m*.

Suction-induced hysteresis of this nature has also been seen in studies involving the continuous use of a tensiometer for soil testing, such as the experimental programme de-

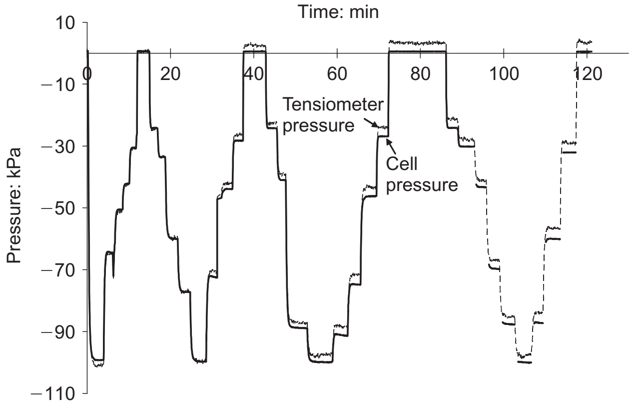

Fig. 5. Cycles of pressure by application of vacuum

scribed in Lourenço *et al.* (2007), where values read by the tensiometer, when plunged in free water before and after a test, were seen to change by as much as 14 kPa, although values were usually below 5 kPa. This might be explained by a small calibration drift when the tensiometer is working in the negative range, which, however, would be significant only at very low suctions, given that the calibration factor *m* remains unchanged. There is also the possibility that this phenomenon appears only when using tensiometers at low suctions, but this seems unlikely, as it has been seen in tensiometers used continuously for a period of one year, regardless of the suctions measured. While the nature of this drift is unclear, it seems to be restricted to the negative pressure range. When pressure was cycled in the positive range between zero and 600 kPa, as previously described, the tensiometer reading always returned to zero at the end of each cycle. Tarantino & Mongiovi (2003) also found a change in the calibration when tensiometers were used in the negative range. For those authors quick cycles of negative pressure were seen to improve the measurement accuracy.

Isotropic unloading

The procedure followed for the isotropic unloading test in this research had one difference from that described by Ridley & Burland (1993). A zero pore water pressure, instead of 200 kPa, was imposed on the sample before unloading. Therefore the suction read by the tensiometer was compared with the initial total stress applied to the sample (which in this case is equal to the effective stresses). A sample was enclosed in a latex membrane and mounted in the triaxial cell, with the drainage line open to the atmosphere to ensure a zero pore water pressure. The tensiometer was set directly in contact with the sample through a grommet, as in the 'anisotropic' positive pressure calibration described above. The arrangement for the isotropic unloading tests is shown in Fig. 6. Cell pressure was then quickly increased, producing a build-up of excess pore water pressures read by the tensiometer. After dissipation of the excess pore water pressure, and with the tensiometer reading zero, the back-pressure drainage line was shut and the cell pressure was decreased while the tensiometer measurements were recorded (using the extrapolated positive calibration).

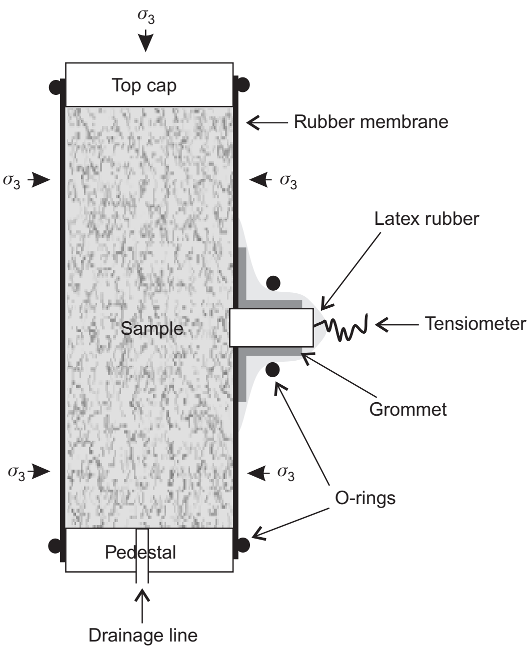

Fig. 6. Arrangement for isotropic unloading tests

Results from an initial test are shown in Fig. 7. Owing to the high degree of saturation (98·7%), it was considered unnecessary to saturate the sample under a back-pressure. The sample was initially consolidated to 454 kPa of effective stress, and, with the tensiometer reading zero, the drainage line was closed before decreasing the cell pressure first to 252·6 kPa and then to zero. For the first drop the cell pressure decreased by 201·4 kPa, while the suction measured by the tensiometer was equal to 190·2 kPa. The ratio between the target and measured values of suction is therefore 0·944, and the extrapolation error is about 5·6%. For the second drop in cell pressure the error is similar, that is, about 5·4%. Both errors are quite large but comparable to those obtained by Guan & Fredlund (1997) and Lourenço *et al.* (2006) by using the axis-translation technique.

The results also revealed an unexpected increase of the pore water pressure after unloading, and this was attributed to water adsorption from the sample. After ending the test it was found that the latex rubber had detached from the sample's membrane, which could have led to water infiltrating from the cell to the sample through the grommet. Water imbibition could have also occurred from the porous stone, or from the reservoir below the porous stone in the pedestal of the triaxial cell. Also, as water pressure decreases below the −100 kPa threshold, cavitation could have occurred in the drainage tubing. There is also the possibility that cavitation could have occurred within the pores of the kaolin, resulting in a decrease of suction due to the formation of small air bubbles.

To overcome some of these problems, a second test was carried out in which the sealing of the sample was improved by eliminating the tube connecting the top cap to the triaxial base. A system was also introduced for blowing dry air through the drainage system below the porous stone in the pedestal of the triaxial cell before unloading. This follows the example of Bishop *et al.* (1975), who modified a triaxial cell base so that water could be removed when required. To avoid the water leaks through the grommet the entire sample (including the grommet) was painted with the liquid latex in several layers, and was then sealed with extra O-rings at the top cap and pedestal, and around the grommet. The improved sealing removed the suction decrease after unloading, but resulted in a similar extrapolation error of approximately 5·0% (Fig. 8).

In Ridley (1993) specimens were reloaded after the unloading stage, and the changes in pore water pressure during unloading were compared with that during reloading. The difference observed by Ridley (1993) was 2·2% up to 1200 kPa and increasing afterwards, but was still better than the 5% value from this research. However, so far, the pore water pressure change has been compared with the total stress change during unloading. This makes the implicit

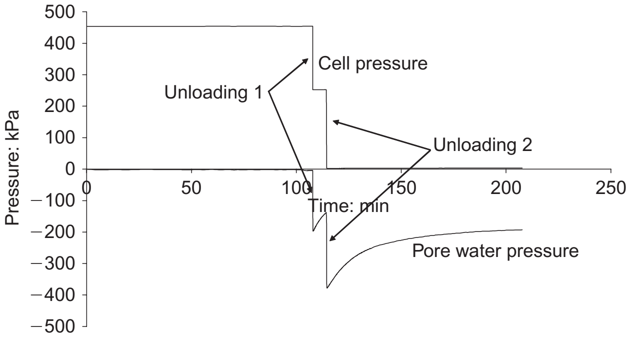

Fig. 7. Initial isotropic unloading test

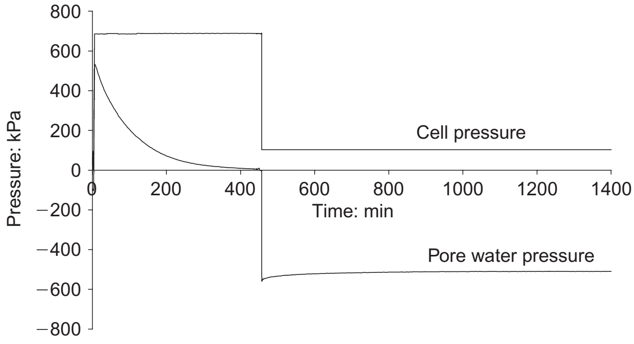

Fig. 8. Isotropic unloading test with improved sealing

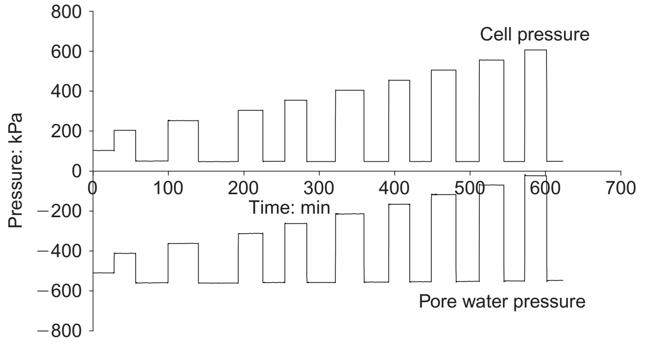

Fig. 9. Cycles of loading and unloading

assumption that the pore pressure parameter B is equal to unity, so that no change of effective stress occurs in the solid skeleton, and the pore water pressure change equals the total stress change. However, the assumption of $B = 1$ is incorrect, as the degree of saturation was not 100%, but 98·7% as stated above, and measured B values were approximately 0·96. (Note that, while the samples were not fully saturated, the B values were above the limit of 0·95 as prescribed by BS 1377. Using a back-pressure saturation technique would only cause air to dissolve in the pore water. This dissolved air would probably come out of solution during unloading, thus giving differential B values between loading and unloading, which is undesirable.) To allow for this, we assume that the same proportion of the total stress change is transferred to the solid skeleton when the soil is loaded or unloaded, and in this case the extrapolation error can be calculated as the difference between the B value for unloading (denoted B_u) and the B value for loading (denoted B_l) divided by B_l. To demonstrate this new procedure for error calculation, the test shown in Fig. 8 was continued by cycling the cell pressure at increasing total stresses, where the values of B_l and B_u are obtained for each cycle. The results are plotted in Fig. 9 with the corresponding values of B_l and B_u for the first eight cycles given in Table 2. Using this procedure for error calculation, the agreement between imposed and measured values is very good, with errors smaller than 0·81% (Table 2).

Axis translation

The second indirect method of checking extrapolation used the axis-translation technique. A sample was placed on a previously saturated porous stone (with air entry value of 500 kPa) in the triaxial cell. The tensiometer was gently pushed 2–3 mm inside the top surface of the soil sample to ensure a good contact, and so that it could stand vertically by itself. No membrane was used to contain the sample, and the pore air pressure was applied directly within the cell. The arrangement for the axis-translation tests is shown in Fig. 10. The advantage of using a triaxial cell instead of a pressure plate for the axis-translation technique is that it allowed a better control of the water conditions within and below the porous stone.

Similar problems to those observed in the isotropic unloading tests were observed during axis-translation tests. On releasing the air pressure there would be an immediate decrease of pore water pressure, but thereafter the pore water pressure would increase back with time. In order to over-

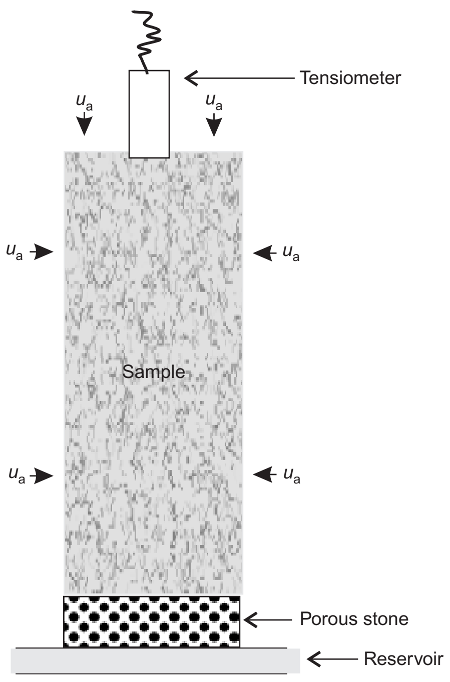

Fig. 10. Arrangement for axis-translation tests

Table 2. Cycles of loading and unloading in the isotropic unloading test

Imposed change in cell pressure, Δp: kPa	Difference in pore water pressure read by tensiometer during loading, Δu_l: kPa	Difference in pore water pressure read by tensiometer during unloading, Δu_u: kPa)	Pore pressure parameter during loading, $B_\mathrm{l} = \frac{\Delta u_\mathrm{l}}{\Delta p}$	Pore pressure parameter during unloading, $B_\mathrm{u} = \frac{\Delta u_\mathrm{u}}{\Delta p}$	Extrapolation error, $e = \frac{\lvert B_u - B_l \rvert}{B_l}$: %
±101	97·9	−97·7	0·969	0·967	0·20
±203	197·3	−197	0·972	0·970	0·15
±256	246·3	−248·3	0·962	0·970	0·81
±306	295·2	−295·1	0·965	0·964	0·03
±357	342·7	−343·5	0·960	0·962	0·23
±407	390·3	−389·7	0·959	0·957	0·15
±457	435·1	−436·9	0·952	0·956	0·41
±509	485·2	−482·3	0·953	0·948	0·60

come such problems, cycling of pore air pressure was used, after having removed all water from below the porous stone of the triaxial cell by flushing air through the back-pressure line. The pore air pressure was changed in several steps (e.g. reducing from 600 kPa to zero then increasing in similar steps back to 600 kPa). A series of three cycles were imposed on the sample, and the pore water pressure read by the tensiometer was compared against the pore air pressure read by the same pressure transducer as used for the calibration of the tensiometer in the positive range. Plots of the pore air pressure applied within the cell and the negative pore water pressure measured by the tensiometer using the extrapolated calibration curve are given in Fig. 11(a), and show the following.

(*a*) After each decrease of pore air pressure, the pore water pressure instantaneously decreased. However, it subsequently increased back while pore air pressure was held constant. This can be clearly seen in the first two unloading steps in cycle 1, where, although the tensiometer reading dropped immediately on reducing pressure, it then started to move back towards zero. The same effect can be seen in Fig. 11(b), which shows cycle 3 on an expanded timescale. The likely reason for this is that water is being drawn out of the porous stone of the triaxial cell into the sample. This effect disappeared as pore air pressure decreased, suggesting that all free water had been removed by this stage. Progressive evaporation of water from the porous stone of the triaxial cell and the sample is also expected to happen throughout the test as a consequence of the low relative humidity of the compressor air feed to the cell compared with the equilibrium relative humidity at such low suctions. If the mixing ratio vapour/dry air provided by the compressor is assumed to be constant, the evaporation rate will also tend to accelerate after each reduction of pressure, because each reduction of pressure would cause a proportional decrease of the vapour partial pressure, and hence a drop of the relative humidity inside the cell. The progressive evaporation from the porous stone of the triaxial cell, combined with the sucking up of water from the sample, will eventually reduce the availability of free water inside the stone, and will result in the disappearance of the tendency for the pore water pressure to increase back after each air pressure drop. However, at the end of each cycle water pressure becomes positive, as shown in Fig. 11(a), resulting in some of the water previously sucked by the sample to be released back into the porous stone of the triaxial cell. As a consequence, free water is available again when pressure is decreased at the start of the next cycle, and once more the pore water pressure tends to increase after an air pressure drop.

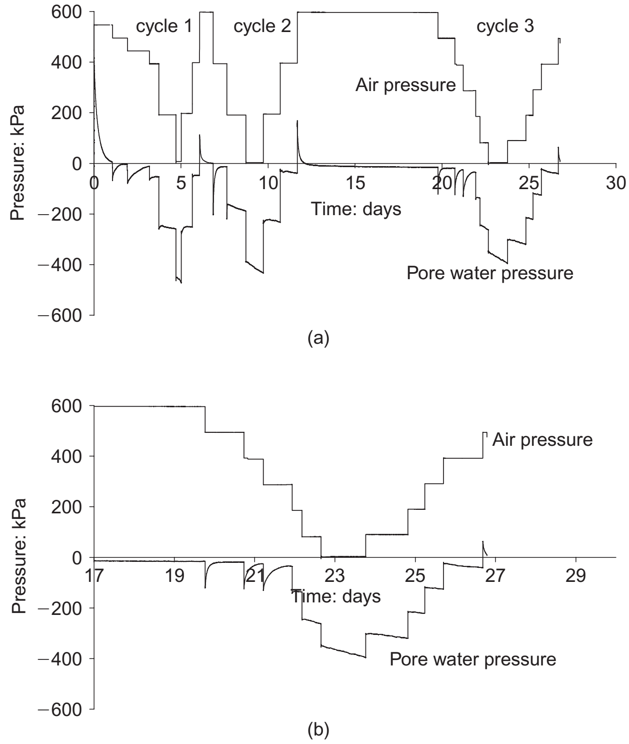

Fig. 11. Axis-translation test: (a) all cycles; (b) cycle 3 only

(*b*) During the ascending part of the curves the pore water pressure increased instantaneously after an increase of pore air pressure, showing a tendency to reduce slowly with time while air pressure was kept constant after each stage. Again, this effect can be explained by the fact that water evaporates from the sample in an attempt to establish hygroscopic equilibrium inside the cell. In this case, the evaporation rate will tend to slow down after each increase of pressure, because an increase of pressure produces an increase of vapour partial pressure, and hence an increase of relative humidity, inside the cell. As a note, the degree of saturation at the end of the test was 92·3%. Table 3 shows the results in terms of the change of pore water pressure instantaneously measured after each step change of air pressure for cycle 3 shown in Fig. 11(b). The error is rather large, with the measured change of pore water pressure tending to be generally greater than the imposed change of air pressure by an amount that could be as big as 8%. The error is also seen to increase at higher suctions. Only at the end of the first cycle was a change of water pressure significantly smaller than the increase of air pressure observed. This can be explained by the fact that in this case the pore air pressure was slowly increased to 600 kPa, and the pore water pressure started dissipating as it became positive. Since the water channels below the porous stone of the triaxial cell had been blown dry, water under positive pressure would be able to flow out of the specimen and into space below the porous stone.

In contrast to the above, previous tests by Lourenço *et al.* (2006) showed changes of pore water pressures whose magnitude was always smaller than the corresponding changes of air pressure. These tests were performed in a pressure plate rather than in a triaxial cell, and a further difference was that air pressure was released to zero in a

Table 3. Results for cycle 3 of axis-translation test

Decrease (D) or increase (I)	Imposed difference in air pressure: kPa	Difference in pore water pressure measured by tensiometer: kPa	Error, *e*: %
D	102·2	103·1	0·88
D	101·3	104·5	3·16
D	102·5	105·0	2·44
D	102·4	109·0	6·45
D	85·5	89·9	5·15
I	87·3	94·2	7·90
I	99·9	104·4	4·50
I	97·5	104·6	7·28
I	101·1	104·2	3·07
I	101·3	105·0	3·65

single stage. The water channels beneath the porous stone of the pressure plate were also filled with free water, rather than being blown dry. Guan & Fredlund (1997) reported similar results to this study for some tests where the pore water pressure increase measured by the tensiometer was higher than the air pressure increase by about 5%. The authors give no reason for such behaviour.

A possible explanation for the fact that the magnitude of pore water pressure change was generally greater than the imposed change of pore air pressure could be the movement of water from the porous stone of the triaxial cell to the soil, and rearrangement of water within the pores of the stone. The top surface of the porous stone is subject to the applied air pressure, but the bottom surface is subject to atmospheric pressure. Initially there is likely to be a film of free water on this bottom surface. During the first drops in pore air pressure there will be water transfer from the stone to the soil (limiting the corresponding decrease of pore water pressure). Further decreases of air pressure will eventually remove all free water from the bottom surface of the stone.

When air pressure in the cell is decreasing, there would be a tendency for the pressure difference between the air pressure on the top surface and the water pressure inside the stone to decrease. However, this tendency will progressively reduce as the availability of free water vanishes and negative pore water pressures are generated inside the stone. At the same time, at the base of the stone, the pressure difference between the atmospheric air pressure and the water pressure inside the stone is increasing. This could lead to water rearrangement within the porous stone of the triaxial, potentially increasing suction even more. While this might explain the descending part of the curves it does not explain the ascending parts.

There is also the possibility that the sample dried during unloading; however, this is unlikely to have any effect, because pore air pressure is changed rapidly (in a few seconds) so there would be no time for the sample to dry. Nevertheless, it could be that drying during the equalisation periods between pressure drops has an effect on the following pressure reduction phase.

DISCUSSION

The previous sections have discussed aspects of the individual direct and indirect methods of calibrating tensiometers in the negative range. They have assumed that extrapolation from the positive range is acceptable in order to observe features of the tests in isolation, and to express results in terms of pressures. In the following we shall compare these methods of obtaining a calibration factor with extrapolation, now working in terms of the raw output from the tensiometer, the d.c. voltage.

Technique selection

The results in previous sections indicate that, from a practical point of view, the isotropic unloading method of checking extrapolation for tensiometer calibration is most suitable and, while slightly more complicated to carry out, provides fewer disadvantages than the axis-translation method.

Figure 12 shows plots of the *applied* target negative pressures (i.e. not the *estimated* pressures measured by the tensiometer using the extrapolation of the positive calibration curve to the negative pressure range) against tensiometer transducer output voltages for the three methods described above. For isotropic unloading the imposed values were corrected by B_1. Also shown is the regression line extrapolated from the positive range for the 'isotropic' calibration. All results shown here use the same tensiometer (including the positive extrapolation), but are different from the results discussed in previous sections (which used a different tensiometer). Table 4 shows the calibration factors for the three methods used in the negative range, and compares them with the assumption of extrapolation from the positive range using an error measure similar to equation (1) in terms of *m*. While the vacuum method is clearly the best, it has limited use for high-suction tensiometers, and the isotropic unloading method appears to be optimal.

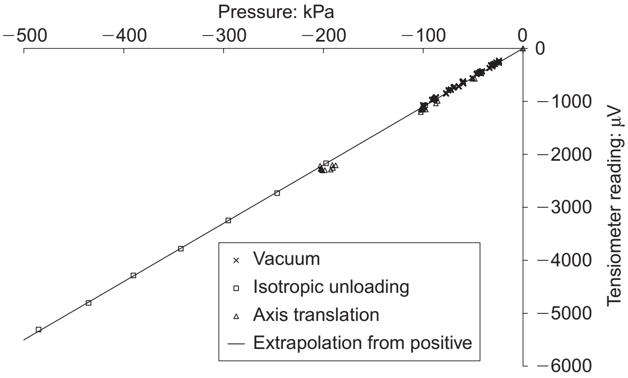

Fig. 12. Comparisons of calibration in the negative range with extrapolation from the positive range

The high sensitivity of the axis-translation technique to the presence of water in the porous stone underneath the sample is an indication that it probably should not be used to calibrate tensiometers in the negative range. Isotropic unloading and the vacuum method give smaller errors and seem to be less dependent on external factors. It also suggests that calibration in the positive range with extrapolation to the negative could be accurate enough, but only if the tensiometer is calibrated in the same conditions as those in which it will be used.

Application of these results to other tensiometers might not be straightforward because of design differences among tensiometers. Differences in dimensions, materials, sealants and construction would certainly affect the calibration in both the positive and negative pressure ranges, as forces would be transmitted differently through the body. For instance, tensiometers developed by Tarantino & Mongiovi (2003) and Ridley *et al.* (2003) have the diaphragm embodied in the casing as a single piece, whereas Guan & Fredlund (1997) and Lourenço *et al.* (2006) have tensiometers with separate transducers that are glued or fixed to the casing. It is therefore advisable that at least one calibration in the negative range is carried out.

Fast assessment of calibration

A good indication of the accuracy of the calibration is given by the pressure the tensiometer reads immediately

Table 4. Comparing calibration in the negative range with extrapolation from the positive range

Test	Calibration factor	Error if extrapolation used: %
Vacuum	11·071	0·59
Isotropic unloading	10·921	0·78
Axis translation	11·438	3·78
(Extrapolation from the positive)	(11·006)	

after cavitation, which should be approximately −100 kPa. If the tensiometer does not give this reading, then there has been a shift in the calibration, or the calibration is not correct. Published data on the air-entry characteristics of the Imperial College tensiometer by Ridley & Wray (1996) show the same response. Cavitation following the measurement of high suctions for one of the tensiometers used in this study is shown in Fig. 13, and an indication of correct calibration can be seen in the very small deviation of the tensiometer reading from −100 kPa following cavitation.

A procedure was also used in this work for assessing any hysteresis of the calibration factor at pressures less than −100 kPa. This consisted in performing several suction measurements on the same sample and, after each measurement, removing the tensiometer from the sample and plunging it in water. Fig. 14 shows a good agreement in the suction measured several times on a sandy clayey soil sample, and this is an indication that the calibration is not drifting with time.

CONCLUSION

Techniques to validate the extrapolation of the calibration of high-capacity tensiometers from the positive to the negative range have been studied. The tensiometers have been calibrated in the positive pressure range (against a standard transducer in three different ways: in a saturation manifold and in a triaxial cell under ‘isotropic’ and ‘anisotropic’ conditions). The results show that calibration in the positive pressure range using a saturation manifold is sensitive to the way the tensiometer is fixed, since the biggest source of error is due to the external forces holding the device in place. The immediate implication is that the calibration should be conducted under the same external force regime as will be applied to the body of the tensiometer when it is to be used.

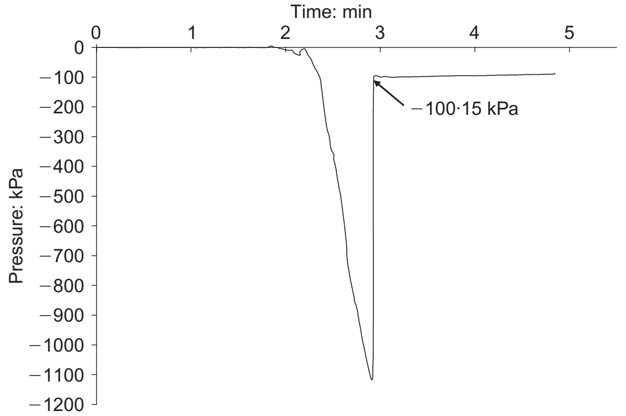

Fig. 13. Tensiometer performance after cavitation

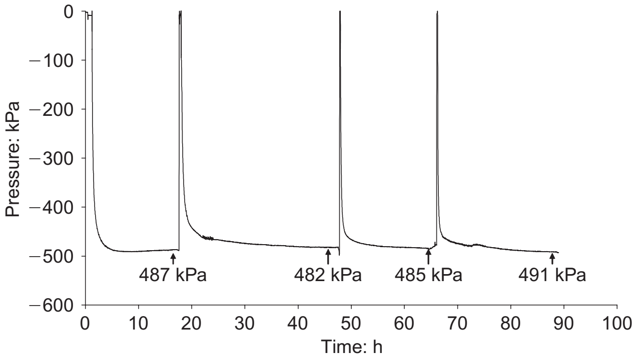

Fig. 14. Repeated readings to assess calibration hysteresis

The extrapolated calibration has then been used to read applied target values of suction imposed on soil samples by using two different techniques: the axis-translation technique and isotropic unloading. Readings from the tensiometer have also been compared against known values of negative pressure (down to −100 kPa), which have been directly imposed on the tensiometer by using a vacuum pump. The extrapolated calibration curve appeared to provide suction measurements that are consistent with the target suction values imposed by the isotropic unloading technique and by application of vacuum. For isotropic unloading allowance has to be made for a value of the pore pressure parameter *B* that may not equal unity. If this is allowed for, calibration errors were less than 0·81%. 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.

Long-term monitoring of the use of tensiometers shows that calibration changes do occur with time or with use. This is seen as a non-zero value at the end of a test when the tensiometer is submerged in free water. These calibration shifts occur in the negative pressure range but not in the positive pressure range. The variations are generally low (about 5 kPa), and are likely to pose a problem only if the tensiometer is used at low suctions, when such a shift might be significant.

It is suggested that differences between tensiometer types could lead to different results from those observed for the particular tensiometer used in this study, so at least one check on the validity of the extrapolated calibration equation should be done. Isotropic unloading and the direct application of negative pressures down to −100 kPa seem to be the best options for checking whether an extrapolation from the positive pressure range is sufficiently accurate for the intended use.

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