USE OF TENSIOMETERS FOR THE MEASUREMENT OF SOIL SUCTION

UTILIZAÇÃO DE TENSIÓMETROS PARA MEDIÇÃO DA SUCÇÃO

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ABSTRACT

Tensiometers are electric transducers capable of measuring negative values of pore water pressure smaller than -100 kPa (*i.e.* capable of measuring soil suctions in excess of 100 kPa). Other common techniques such as the filter paper, the axis-translation and the psychrometer provide indirect measurements of suction and require more complex and lengthy procedures. Tensiometers provide a fast and direct measurement of suction in unsaturated soils and have been used for measuring soil suctions in the field and in the laboratory. This paper presents a new type of tensiometer developed by a collaboration between Durham University and the company Wykeham Farrance Ltd. The paper also focuses on the use of the tensiometer in different geotechnical engineering applications, such as the triaxial testing of unsaturated soils and the determination of the soil water retention curve.

RESUMO

Os tensiómeteros são transdutores de pressão de pequena dimensão para medição de sucções superiores a 100kPa. Os tensiómetros possibilitam uma medição rápida e directa da sucção (pressão intersticial negativa) em solos não saturados. Outras técnicas para a medição da sucção, tal como o papel de filtro, a técnica de translação dos eixos ou o psicrómetro são indirectas e necessitam procedimentos complexos e morosos. Esta comunicação inicia-se pela apresentação de um novo tensiómetro para medição da sucção centrando-se depois nas possíveis aplicações em mecânica dos solos não saturados experimental.

1. INTRODUCTION

Suction is the difference between air pressure and water pressure inside the pores of an unsaturated soil. Usually the air pressure is equal to zero (*i.e.* the atmospheric value) while the water pressure is negative. Suction in soils can be measured directly or indirectly. Direct methods measure the actual values of pressure inside the soil pores (only water pressure is usually measured as the air pressure is assumed to be constant and equal to atmospheric) by having the sample in contact with a measuring device (tensiometer or pressure plate). Indirect methods measure different parameters (*e.g.* moisture content or relative humidity) and subsequently relate these measurements to the value of suction by means of calibration curves (*e.g.* filter paper or psychrometer) [9].

Tensiometers measure suction by allowing the pressure within a miniature water-filled reservoir inside the probe to attain equilibrium with the soil pore water pressure through a high air entry value (HAEV) porous filter placed in contact with the sample (Figure 1). After achieving equilibrium, the corresponding value of negative pressure inside the reservoir is measured by a miniature electric transducer. The tensiometer can also be used to measure negative pore water pressures in saturated samples, *i.e.* samples subjected to a value of suction smaller than the air entry value.

Several tensiometers have been developed so far [10] [3] [11]. They all have a similar structure and the main differences are the dimensions and materials used. The structure comprises (1) a HAEV porous filter, (2) a reservoir of small dimensions and (3) a transducer to measure pressure.

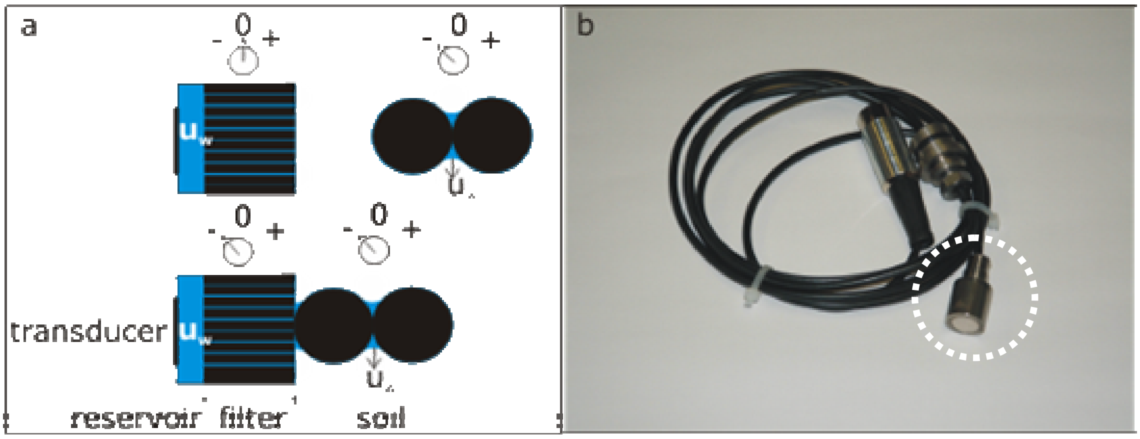

Figure 1 – a) Principle of suction measurement with tensiometers (*after* [12]); b) tensiometer's photo.

This paper presents a new type of tensiometer developed in collaboration by Durham University and Wykeham Farrance Limited. The paper also focuses on the use of such probe for different applications in geotechnical engineering, including the measurements of suction in triaxial testing of unsaturated soils and the determination of the soil water retention curve.

2. THE TENSIOMETER

The Durham University – Wykeham Farrance (DU-WF) tensiometer consists of a HAEV porous filter, a water reservoir with a capacity of 10.3 mm^3 and a miniature gauge for measuring negative water pressure inside the reservoir with a capacity of 15bar. The tensiometer has a diameter of 14mm and is 26mm long.

The ability of the tensiometer to measure suctions in excess of 100kPa depends on the degree of water saturation of both the porous filter and the miniature reservoir inside the probe. Well-saturated tensiometers are capable of measuring suctions higher than 100kPa and the maximum measurable suction is limited by the cavitation of water inside the miniature reservoir. Cavitation is the process of rupturing a liquid by decrease in pressure at constant liquid temperature [1]. Cavitation is triggered as soon as gas bubbles form in the water reservoir, usually in correspondence of pre-existing microbubbles, hydrophobic surfaces and crevices [4]. It is therefore very important to eliminate any air present inside the porous filter and reservoir, which may help to prevent the occurrence of cavitation at low suction and to extend the range of measurement of the probe.

Saturation of tensiometers is commonly performed in a similar way as in soil samples, by applying high values of positive water pressures to force any residual air volume present in the porous stone and reservoir to dissolve in water.

In this work the saturation of the DU-WF tensiometer was achieved by the application of high positive water pressures (800 kPa) for at least 24hr. This procedure is similar to that used by other authors [10] [3]. After such pre-pressurization, the measurement range was checked by subjecting the device to increasingly higher values of suction until cavitation (Figure 2). This was achieved by placing a small amount of soil in contact with the porous filter and leaving it to dry to the atmosphere or, alternatively, by leaving the water inside the porous filter to evaporate directly to the atmosphere without the application of any soil paste. The latter method resulted in a faster rate of suction increase during the test. The maximum suction measured by the device varied between 800 kPa and 1000kPa.

Due to its small dimensions, the tensiometer is not suitable for the measurement of suction in coarse and highly porous heteregenous soils. The use in chemically active soils (with $CaCO_3$, for example) should also be avoided, as it leads to clogging of the porous stone and reservoir, decreasing the response time.

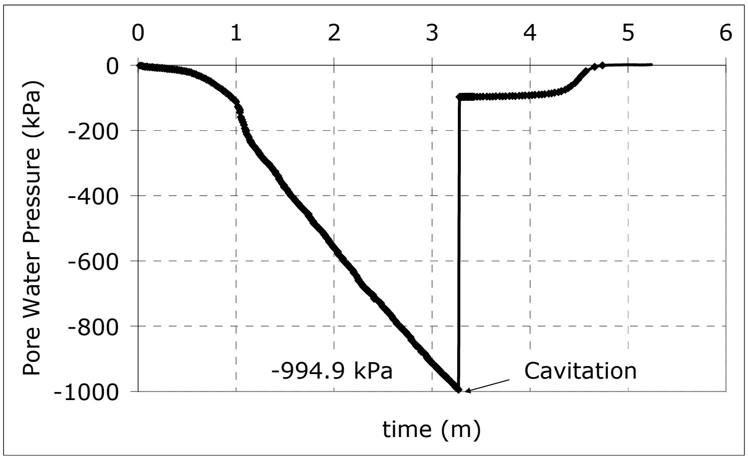

Figure 2 – Typical response curve of a tensiometer showing sudden cavitation.

3. APPLICATIONS

Some of the potential applications of the tensiometer are presented and discussed below. Most of the applications are still at an initial stage of development.

3.1 Suction measurements by using the tensiometer

The initial suction of a soil sample can be inferred by the water retention curve of the soil once the water content is known. Equally the initial suction can be measured by the axis translation technique where a positive air pressure is applied to the sample while the water pressure is measured by a conventional pressure transducer (the application of a positive air pressure is necessary in order to ensure that the water pressure is also in the positive range). However, the tensiometer has the advantage of measuring directly the initial suction at the start of a test in an unsaturated soil.

The suction of an unsaturated soil sample can be determined by placing the tensiometer in contact with the soil. A good contact, by forcing the probe into the soil, is necessary to ensure that there is a continuation of the water phase from the soil to the tensiometer's filter. Suction then increases until it stabilizes at a value equal to that present in the soil. The measurements should be done in an environment where the relative humidity is controlled to prevent the sample from drying or wetting during the measurement. Measurements of suction performed in an impermeable clayey material have required more than 4hrs to read a value of pressure of -400kPa as shown in Figure 3 [6].

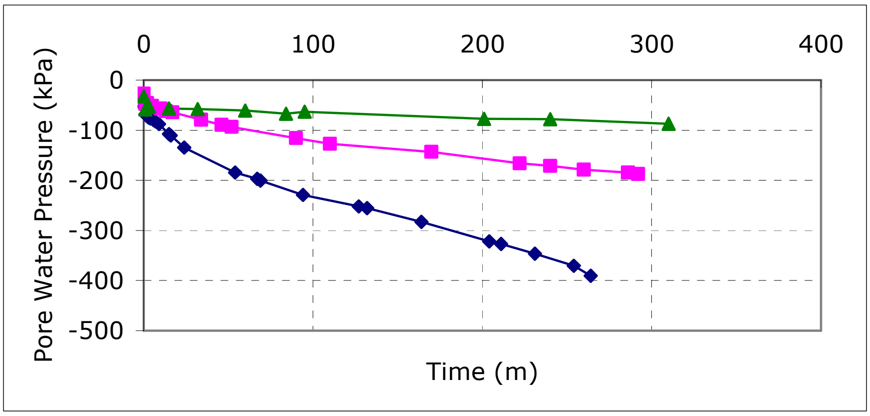

Figure 3 – Suction measured with the tensiometer in different soil samples compacted in the field under different loads [6].

3.2 Soil water retention curve

The determination of the soil water retention curve by using conventional techniques, such as the axis-translation and the filter paper, involves the simultaneous measurement of the values of water content and suction at a discrete number of stages during wetting or drying of a soil sample. In the filter paper case, suction is inferred by measuring the water content of the filter paper, which should have been previously calibrated. These procedures might result lengthy and inaccurate. A quick and reliable technique for the evaluation of the water retention curve by using tensiometers has recently been proposed [14] as an alternative to conventional methods. An electronic balance is used to record the progressive decrease of water content of a soil sample left to dry to the atmosphere while measuring the suction by means of a tensiometer placed in contact with the sample. In this way it is possible to obtain the water retention curve as a continuous relationship between water content and suction. This technique has been successfully used in silty soils [14].

3.3 Triaxial testing

3.3.1 Saturated soils

Standard triaxial undrained tests on saturated strongly dilative samples have the inconvenient of developing high suctions, which standard pressure transducers are unable to measure. For example, if a sample is sheared starting from an initial pore water pressure of 0 kPa, it is likely that, as the sample dilates, the water will end up cavitating inside the tubing and pressure transducers of the experimental apparatus. One way to overcome this limitation is to increase the initial pore water pressure by applying a positive backpressure (as well as a corresponding increase of cell pressure to maintain the mean effective stress constant). In this way any decrease of pore water pressure during shearing takes place while the absolute value of pore water pressure remains positive. This translation of the initial value of pore water pressure to the positive range is similar to the axis translation technique used for measuring or controlling suction in unsaturated soils. For both situations the purpose is to avoid the development of negative pore water pressures (Figure 4). By using a tensiometer instead of a conventional pressure transducer, it would be possible to measure negative pore water pressure during shearing and, therefore, to avoid the application of an initial backpressure to the sample. Tensiometers can also be used to measure positive pore water pressures and, provided that they are well saturated, they give the same accuracy and similar response times as conventional pressure transducer.

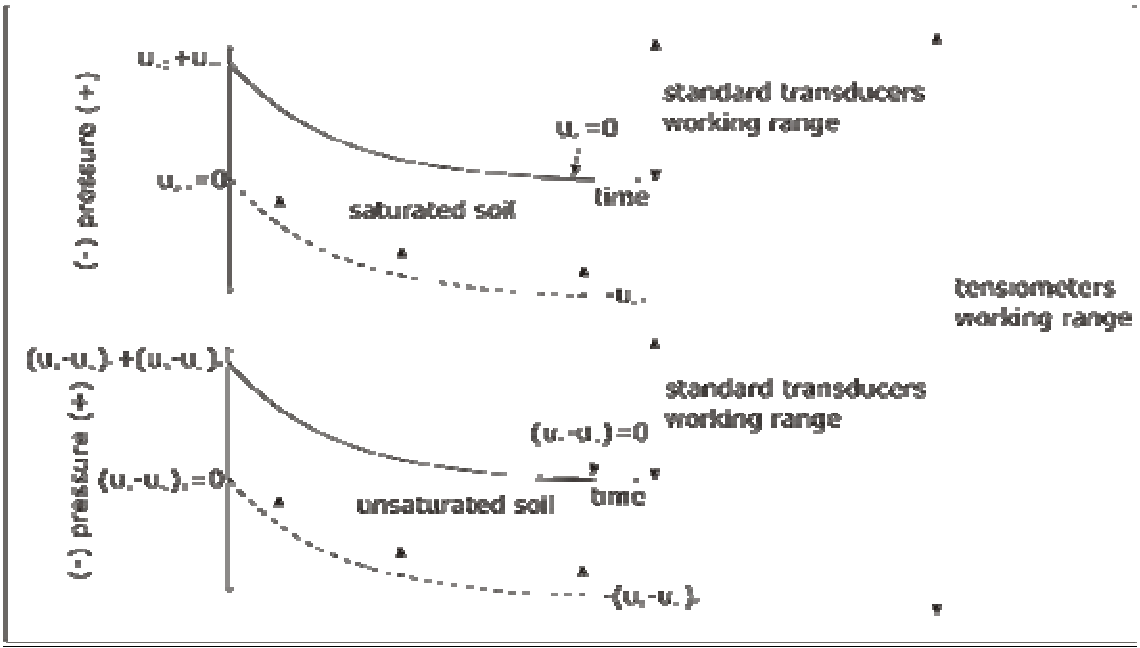

Figure 4 – Y-axis translation for saturated and unsaturated soils.

3.3.2 Unsaturated soils

Tensiometers could be used to monitor suction directly in an unsaturated sample set in a triaxial cell, by using the vapour equilibrium technique [5], the axis translation technique [15] or the air circulation technique [2].

The air circulation system being developed at Durham University aims to control suction (measured by the tensiometer) in the soil sample, by letting air at different relative humidity's to circulate through it (the corresponding changes in water content of the sample can be measured by an electronic scale connected to a logging unit). The tensiometer is inserted in the pedestal from the exterior and set directly in contact with the sample. The system includes a wet air and dry air source; the tensiometer for direct measurement of suction; a scale to weight any moisture gain or loss by the sample; and a control system. The system is regulated by valves to switch the dry air or wet air circulation through the sample, and a pump to force the air circulation. Figure 5 shows a preliminary test conducted by circulating dry air with a pump through a porous sample made of 80% medium-sized sand and 20% kaolin. The test revealed that when the pump was on, suction increased but when switched off it would decrease and tended to equalize, suggesting that the sample was drying faster on the surface than in the internal part.

For tests requiring the axis translation technique, where a null or positive water pressure is imposed through a HAEV disk, there would be no need to use the tensiometer as the standard transducer set below the HAEV disk would be sufficient to measure the positive water pressure. However, constant water content tests could be performed by keeping the air and water phases undrained. The initial negative suction would be measured by the tensiometer as well as the variations during shear. Possible air pressures developing during shear would be small due to the air higher compressibility.

For those experimental techniques where suction is imposed by controlling the relative humidity of the air around the sample (*e.g.,* the vapour equilibrium technique) the use of tensiometers is feasible depending on the applied range of suction values. In the vapour equilibrium technique, the levels of suction imposed to the sample are usually higher than 2 MPa and this would exceed the upper limit of the measurement range for existing tensiometers.
Another difficulty is that tensiometers usually measure only the matric component of suction whereas the vapour equilibrium technique is used to control the value of total suction (including both the osmotic and matric components of suction). Only if the cations dissolved in the pore water would remain absorbed to the HAEV porous filter and would not diffuse inside the miniature reservoir, the additional (osmotic) component of suction would be measured by the tensiometer [7] but there is not yet experimental evidence of this behaviour.

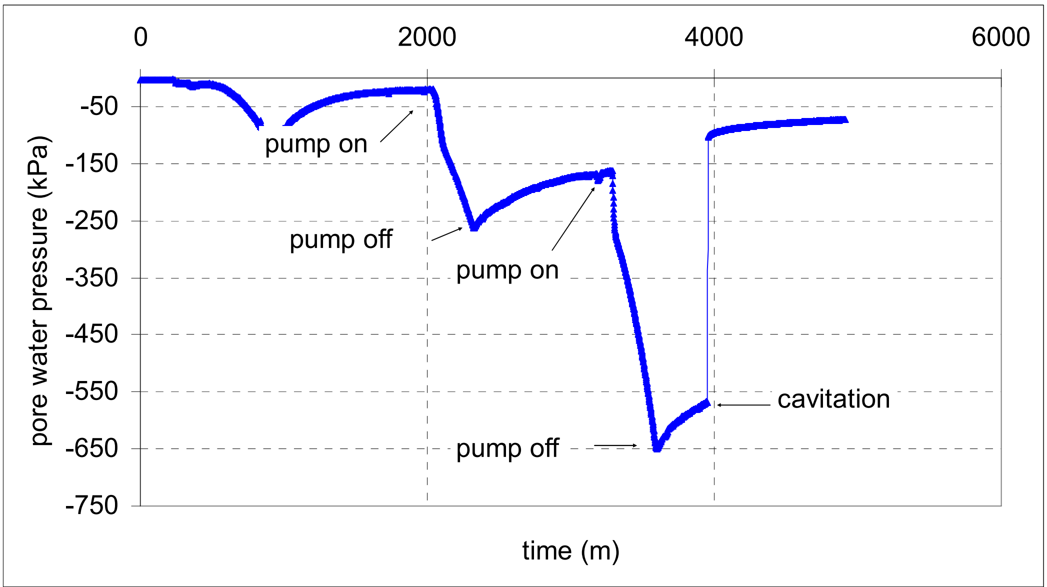

Figure 5 – Increasing suction by circulating dry air through a sample.

3.4 Imposing an initial value of suction

Suction can also be imposed by the axis translation technique, by applying an initial air pressure with the water pressure at atmospheric value. If the air pressure is subsequently decreased to atmospheric value while preventing any drainage of water from the sample, the decrease in air pressure should lead to an equal decrease of water pressure, *i.e.* negative water pressure generates in the sample, as shown in Figure 5. The tensiometer set in contact with the soil should measure the negative water pressure in the sample corresponding to the value of suction initially imposed. However, for the test shown in Figure 6 the suction measured by the tensiometer is 66.2kPa instead of 100kPa. This was possibly due to the sample sucking water from the HAEV disk.

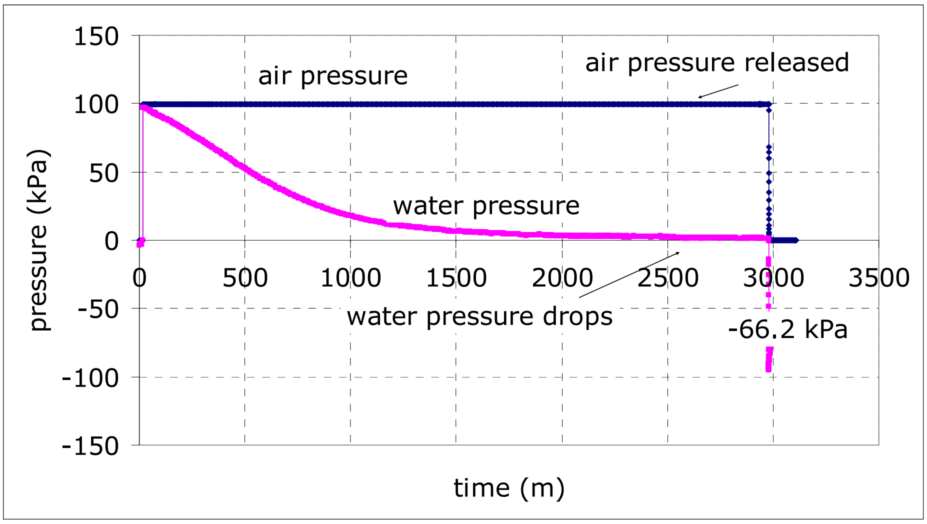

Figure 6 – Imposing an initial suction of 66.2kPa to a sample. Water pressure measured with the tensiometer.

3.5 Other tests

Tensiometers have been used in centrifuge tests to monitor pore pressure fluctuations [13]. The author in reference [13] conducted an experimental investigation using the accelerated time-scaling for seepage flow provided by centrifuge modelling to observe the behaviour of overconsolidated clay embankments during seasonal pore pressure cycles. The tests were conducted in a controlled RH chamber and the seasonal pore pressure cycles were measured by tensiometers. Up to 11 tensiometers were used in a small embankment made of a clay cake. The tensiometers measured pore pressure fluctuations between 20kPa and -70kPa.

The tensiometer can be used as a non-destructive technique to assess sample disturbance [8]. The magnitude of suction produced depends on the in situ stress state, pore size and distribution, drilling and sampling procedures, and sample handling. Suction measurements have been conducted in the field and lab in remolded samples and high quality block samples. The measurements in the clayey soils revealed that the high quality samples reached higher suctions than the poor quality samples.

4. CONCLUSIONS

The new DU-WF tensiometer, which has been developed in collaboration by Durham University and Wykeham Farrance Limited, has been presented in the paper. The tensiometer is able to measure suctions up to 1000kPa, depending on the initial degree of saturation of the probe. Possible applications of the tensiometer have been discussed. These include: (1) measurements of suction by placing the tensiometer in contact with an unsaturated soil sample; (2) determination of the soil water retention curve, by simultaneous measurements of suction and water content on a soil sample left to dry to the atmosphere; (3) triaxial testing of saturated and unsaturated soils with direct measurement of negative pore water pressures; (4) negative pressures measurement in centrifuge tests and soil disturbance studies.

5. REFERENCES

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6. ACKNOWLEDGEMENTS

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