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Highlights

- *The long-term performance of different tensiometer prototypes is compared*
- *A lysimeter with continuous monitoring of soil moisture has been manufactured*
- *Soil suction and moisture are measured in real time under laboratory conditions*
- *The response time of the tensiometers to artificial rainfall events is measured*

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Comparison of high capacity tensiometer designs for long-term suction measurements

Joao Mendes and Domenico Gallipoli

Abstract

This paper investigates the long-term measurement of negative (tensile) pore-water pressures in soils by using high capacity tensiometers (HCTs). Seven different HCT prototypes were designed and manufactured by using different porous filters, pressure transducers, water reservoirs and protective casings. The ability of these prototypes to record negative pore-water pressures over long times was initially assessed by a series of measurements on small clay samples equalized at different suction levels. These tests were followed by two larger scale experiments in which four HCT prototypes were simultaneously installed inside a lysimeter filled with a sandy soil alongside two standard dielectric permittivity sensors measuring suction and water content, respectively. In one experiment, the soil was left to dry until all four HCTs cavitated while, in another test, the soil was allowed to dry up to an intermediate level of suction before triggering a rainfall, after which the soil was left to dry again until all four HCTs cavitated. In each lysimeter experiment, the readings of the HCTs were reasonably consistent, which suggests that sensor design has little effect on the accuracy of measurements. These experiments also indicated that HCTs are more accurate and exhibit a faster response than standard dielectric permittivity sensors. Moreover, the HCTs incorporating a small water reservoir showed a greater ability to sustain suction over long period of time without cavitating.

Keywords

High capacity tensiometers, pore-water tension, soil suction, soil capillarity, laboratory testing, field monitoring.

1. Introduction

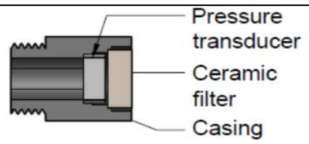
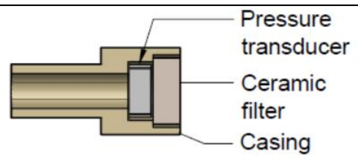
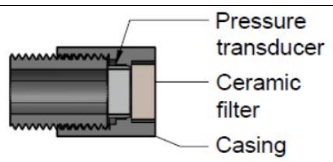
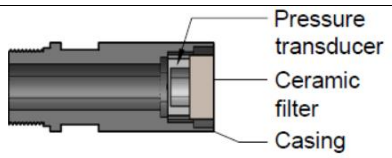
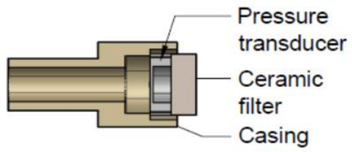
Natural and engineered soil slopes often exist in an unsaturated state and are subjected to negative (tensile) pore-water pressures or pore suctions. The terms "pore-water pressure" and "pore suction" have been interchangeably used in the literature because, under atmospheric conditions, the pore suction coincides with the pore-water pressure changed of sign. A reduction of pore-water suction inside slopes may engender a decrease of material strength and cause the abrupt occurrence of landslides. Moreover, the periodic drying/wetting of unsaturated plastic clays may gradually soften the material and lead to a progressive failure of the slope (Kovacevic et al., 2001).

A number of case studies have recorded the evolution of pore suction in both natural slopes and earth infrastructures such as road and railways embankments. The aim of these studies has been to forecast the occurrence of slope instabilities caused by the attainment of a critical suction threshold inside the soil. For example, Sweeney (1982) and Chipp et al. (1982) used conventional tensiometers, which measure negative pore-water pressures down to -100kPa, to study the effect of rainfall and evaporation on the suction regime of slopes in Hong Kong. Similarly, Pitts and Cy (1987) and Lim et al. (1996) used conventional tensiometers to study the effect of vegetation cover on the suction regime of slopes in Singapore. Other researchers have instead used conventional tensiometers to measure negative pore-water pressures in natural slopes in Italy (Evangelista et al., 2008) and Switzerland (Springman et al., 2003). Only recently, Cui et al. (2008) and Toll et al. (2012), have employed high capacity tensiometers (HCTs), which can measure negative pore-water pressures down to -2000 kPa, to measure suctions inside earth fills in France and the UK. HCTs are relatively new sensors and their use for field monitoring of pore-water suctions is still limited due to uncertainties about the long-term stability of measurements. The first HCT prototype capable of measuring negative pore-water pressures down to -1500kPa was developed three decades ago at Imperial College London by Ridley and Burland (1993). Since then, the designs of a number of HCTs have been published in the literature (Guan and Fredlund, 1997; Meilani et al., 2002; Tarantino and Mongiovì, 2002; Take and Bolton, 2003; Toker et al., 2004; Lourenço et al., 2008; Mendes and Buzzi, 2013; Mendes et al., 2016; Mendes et al., 2019).

The present study aims to optimize the design of high capacity tensiometers (HCTs) for the field measurement of soil suction by assessing the effect of sensor design on the response time and the long-term stability of readings. Seven HCT prototypes, incorporating different porous filters, pressure transducers, water reservoirs and protective casings, were designed and manufactured in the present work. The prototypes are identified in Table 1 by a code having the format VVV – WW(XXXX) – YYYYY [Z], where each field describes a distinct design component. The field VVV indicates the composition of the ceramic filter (i.e. either KCF for Kaolinite Ceramic Filter or ACF for Alumina Ceramic Filter), the field WW indicates the type of pressure transducer (i.e. either FD for Flush Diaphragm or CD for Cavity Diaphragm), the field XXXX indicates the measuring range of the pressure transducer in kPa (i.e. either 500 or 2000), the field YYYYY indicates the casing material (i.e. either SS316 for stainless steel or Al for alumina) and, finally, the field Z indicates a design variant (i.e. either 1 or 2). The design characteristics of each prototype are detailed in a companion paper (Mendes et al., this issue), which focuses on a different aspect of the present research (i.e. the effect of HCT design on the measuring range) and which has been published in this same journal issue.

The next section presents the results of a preliminary series of suction measurements on small kaolin samples performed by using different HCT prototypes to study the effect of sensor design the long-term stability of readings. The subsequent two sections describe instead two larger scale experiments whereby different HCT prototypes were simultaneously installed inside a purposely-built lysimeter containing a sandy soil to compare the response time and the long-term stability of readings. The lysimeter was also fitted with two dielectric permittivity sensors marketed by the company Decagon Devices (now part of Meter Group), namely a MPS2 probe to measure soil suction and an EC-5 probe to measure volumetric water content. These two sensors were chosen because of their planned use for monitoring the suction and the water content of the soil in the field. The lysimeter therefore allowed the comparison of suction readings between the different HCT prototypes and the MPS2 probe. Prior to all tests, the HCTs were saturated and calibrated according to the procedures described in the companion paper by Mendes et al. (this issue).

Table 1. HCT designs (Mendes et al., this issue).

	**Name:** KCF – FD(2000) – SS316 [1] and ACF – FD(2000) – SS316 **Ceramic filter:** KCF and ACF **Size:** 35 mm x Ø26 mm **Water reservoir size:** 40 mm^3 **Pressure transducer:** 2000 kPa ceramic flush diaphragm **Casing material:** Stainless steel SS316 **Special feature:** Water reservoir included in the casing design
	**Name:** KCF – FD(2000) - Al **Ceramic filter:** KCF **Size:** 50 mm x Ø26 mm **Water reservoir size:** 40 mm^3 **Pressure transducer:** 2000 kPa ceramic flush diaphragm **Casing material:** Alumina ceramic **Special feature:** Water reservoir included in the casing design
	**Name:** KCF – FD(2000) – SS316 [2] **Ceramic filter:** KCF **Size:** 45 mm x Ø26 mm **Water reservoir size:** 40 mm^3 **Pressure transducer:** 2000 kPa ceramic flush diaphragm **Casing material:** Stainless steel SS316 **Special features:** small lip in the casing design that separates ceramic filter and pressure transducer; use of a thread adaptor to secure the pressure transducer in place
	**Name:** KCF – CD(2000) – SS316 **Ceramic filter:** KCF **Size:** 60 mm x Ø26 mm **Water reservoir size:** 430 mm^3 **Pressure transducer:** 2000 kPa ceramic cavity diaphragm **Casing material:** Stainless steel SS316 **Special feature:** cavity of the pressure transducer used as water reservoir
	**Name:** KCF – CD(2000) – Al and KCF – CD(500) – Al **Ceramic filter:** KCF **Size:** 55 mm x Ø26 mm **Water reservoir size:** 430 mm^3 **Pressure transducer:** 500 kPa and 2000 kPa ceramic cavity diaphragm **Casing material:** Alumina ceramic **Special feature:** cavity of the pressure transducer used as water reservoir

2. Preliminary tests in clay

An initial series of suction measurements was performed on small cylindrical Speswhite kaolin samples to assess the influence of the HCT ceramic filter and water reservoir size on the long-term stability of readings. The three prototypes chosen for this initial series of tests were ACF – FD(2000) – SS316, KCF – FD(2000) – SS316 [2] and KCF – CD(2000) – SS316. These prototypes differ only for the type of ceramic filter (i.e. either ACF or KCF) and the size of the water reservoir (i.e. either 40 mm^3 or 430 mm^3) while all other design components are the same. The kaolin samples were first equalized at a given suction and then sealed inside a snug-fit plastic container with a small opening to insert the HCT. A saturated kaolin paste was used to ensure a good connection between the ceramic filter of the HCT and the soil sample. After installation, the HCT prototype was connected to a computer, which continuously logged the measurements of soil suction.

In the first test, prototype ACF – FD(2000) – SS316 (Table 1) was employed to measure the suction of a kaolin sample equalized at a pore-water pressure of -200 kPa. This prototype incorporates an alumina ceramic filter (ACF) with a small water reservoir (40 mm^3), which is built around a flush diaphragm (FD) pressure transducer. The maximum negative pore-water pressure that can be measured by this prototype ranges between -700 kPa and -1000 kPa, which is consistent with the air entry value of the alumina ceramic filter as discussed in the companion paper by Mendes et al. (this issue).

The results in Figure 1 show that the measured negative pore-water pressure steadily increased with time beyond the imposed value of -200 kPa. This steady increase of negative pore-water pressure was due to the ineffective sealing of the plastic container, which caused the progressive drying of the kaolin soil. The fluctuation of readings between days 45 and 48 is the likely consequence of a temporary malfunction of the logging unit (i.e. an insufficient voltage altering the calibration of the sensor).

Results show that the prototype is capable of measuring relatively large values of suction for rather long periods of time up to 57 days before cavitating. Cavitation of HCTs has been generally associated to the formation of gas pockets at a pressure of approximately -100 kPa inside the water reservoir. Consistent with this understanding, Figure 1 shows that the pore-water pressure jumped to value of -100 kPa after cavitation, which confirms that the calibration of the HCT did not drift significantly over the test duration. Inspection of Figure 1 indicates that the maximum negative pore-water pressure was about -475 kPa, which falls short of the HCT measuring range that is between -700 kPa and -1000 kPa (Mendes et al., this issue). This may be explained by the progressive instability of measurements as larger suctions are recorded over longer times, which can induce cavitation well before the attainment of the recording limit.

Figure 2 shows a detail of the initial test stages, which indicates that the imposed pore-water pressure of -200 kPa was attained 3 hours after placing the HCT in contact with the soil. This response is much slower than the one observed during similar experiments in the literature (e.g. Mendes and Buzzi, 2014) and may be explained by the time taken for the equalisation of suction between the saturated kaolin paste and the unsaturated sample. This explanation is also corroborated by the much faster response of the same HCTs when exposed to the atmosphere due to the rapid evaporation of water from the ceramic filter into the air (Mendes et al., this issue).

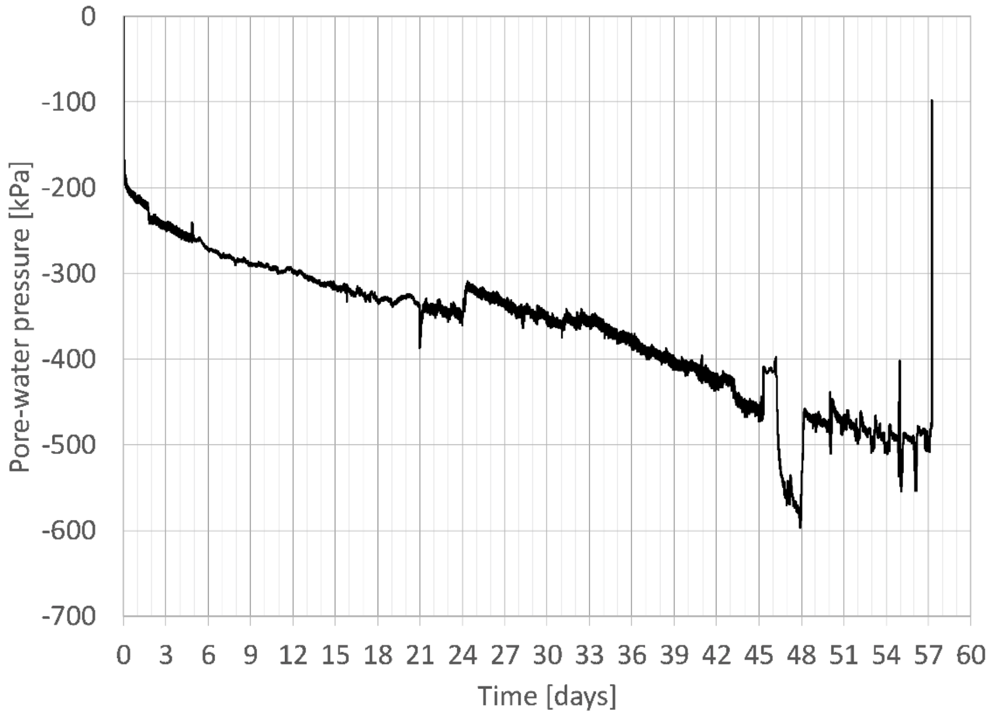


Figure 1. Long-term suction measurements by prototype ACF – FD(2000) – SS316 on a kaolin sample equalised at a pore-water pressure of -200 kPa.

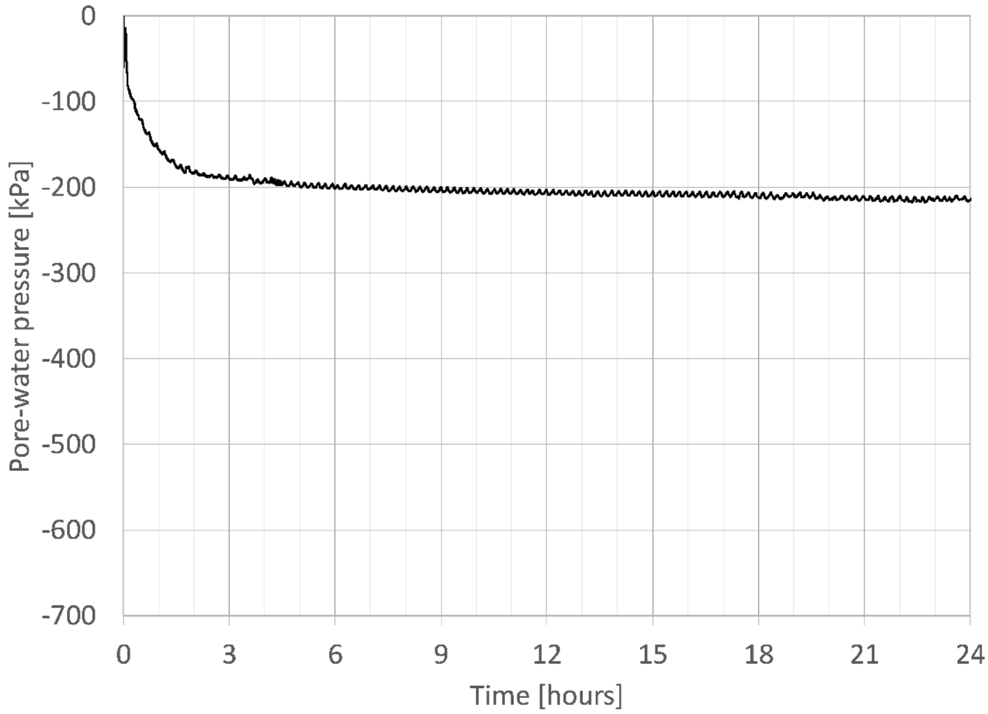


Figure 2. Detail of first 24 hours of suction measurements by prototype ACF – FD(2000) – SS316 on a kaolin sample equalised at a pore-water pressure of -200 kPa.

Next, prototype KCF – FD(2000) – SS316 [2] (Table 1) was employed to measure the suction of a kaolin sample previously equalised at a pore-water pressure of -1200 kPa. This prototype is similar to the previous one but incorporates a kaolinite ceramic filter (KCF) instead of an alumina ceramic filter (ACF).

The kaolinite filter exhibits a higher air entry value than the alumina one, which increases the sensor measuring range to a level between -1500 and -2000 kPa (Mendes et al., this issue). Once again, Figure 3 shows that measurements slowly drifted beyond the target pore-water pressure of -1200 kPa because of the ineffective sealing of the plastic container and the consequent drying of the sample. The prototype could record very large negative pore-water pressures for a relatively long period of 9 days until cavitation occurred at a pore-water pressure of -2280 kPa, which is bigger than the nominal measuring range of the sensor. Figure 4 presents a detail of the initial test stages showing that the target pore-water pressure of -1200 kPa was attained 5 hours after placing the HCT in contact with the soil, which is a similar response time to that observed during the previous test.

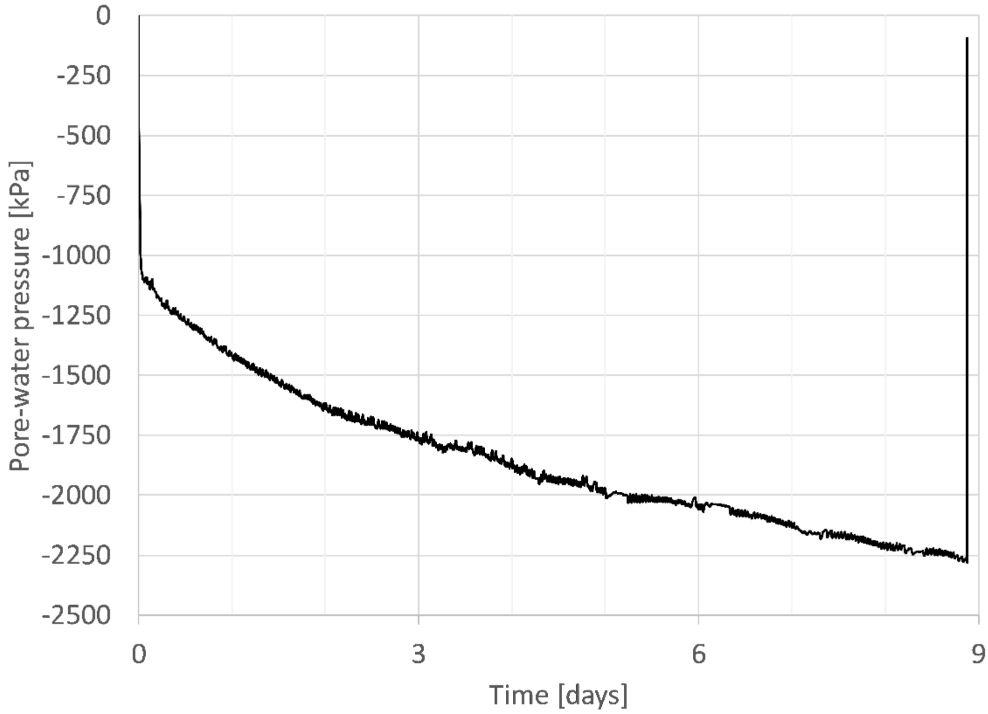


Figure 3. Long-term suction measurements by prototype KCF – FD(2000) – SS316 [2] on a kaolin sample equalised at a pore-water pressure of -1200 kPa.

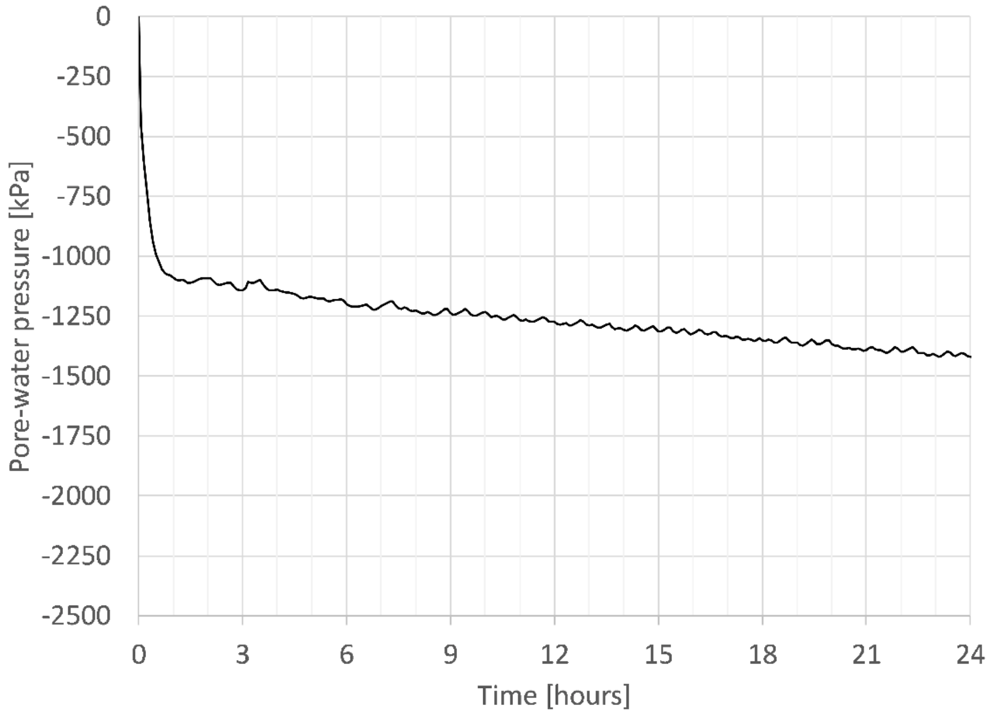


Figure 4. Detail of first 24 hours of suction measurements by prototype KCF – FD(2000) – SS316 [2] on a kaolin sample equalised at a pore-water pressure of -1200 kPa.

A third test was performed using prototype KCF – CD(2000) – SS316 (Table 1) to measure the suction of a kaolin sample equalised at a pore-water pressure of -1200 kPa. This prototype differs from the previous one for the larger capacity of the water reservoir (i.e. 430 mm^3 against 40 mm^3), which is delimited by the inner space of a cavity diaphragm (CD) pressure transducer. Figure 5 shows that the HCT readings stabilised at the target value of -1200 kPa about 3 hours after placing the HCT in contact with the soil while cavitation occurred after about 23 hours, which is much earlier than the previous two tests. A fourth identical test was performed to confirm the above result by using the same prototype KCF – CD(2000) – SS316 (Table 1) to measure the suction of a kaolin sample equalised at the same pore-water pressure of -1200 kPa. Once again, the test ended in early cavitation less than 11 hours after placing the HCT in contact with the soil (Figure 6). The results from these last two tests therefore suggest that the long-term stability of measurements tends to reduce as the reservoir size increases, especially when relatively high suctions are recorded.

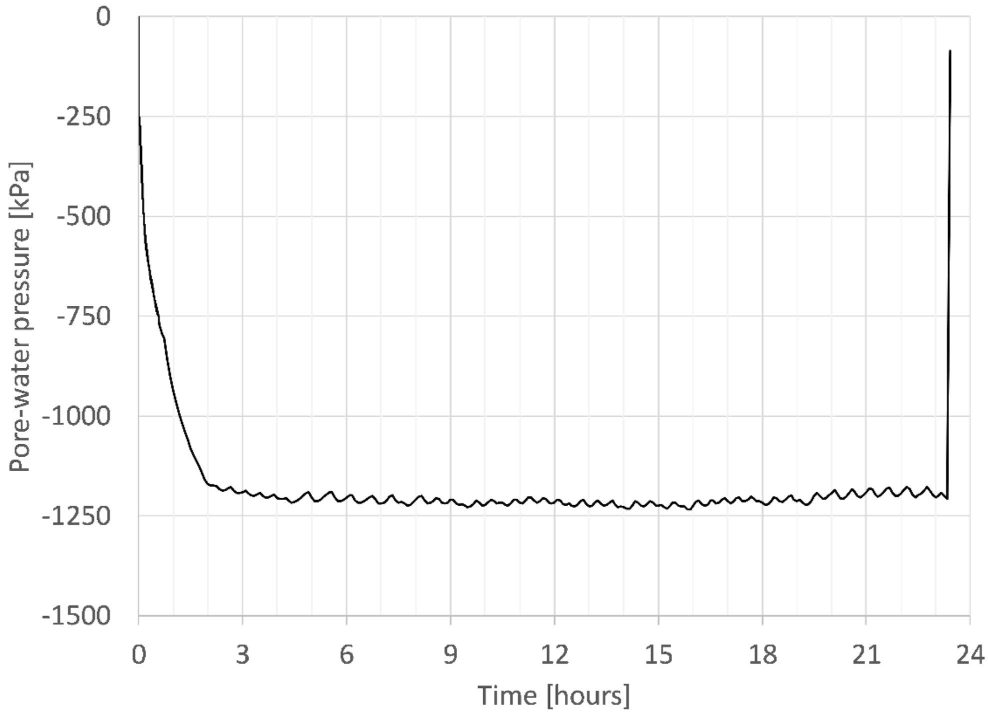


Figure 5. Long-term suction measurements by prototype KCF – CD(2000) – SS316 on a kaolin sample equalised at a pore-water pressure of -1200 kPa.

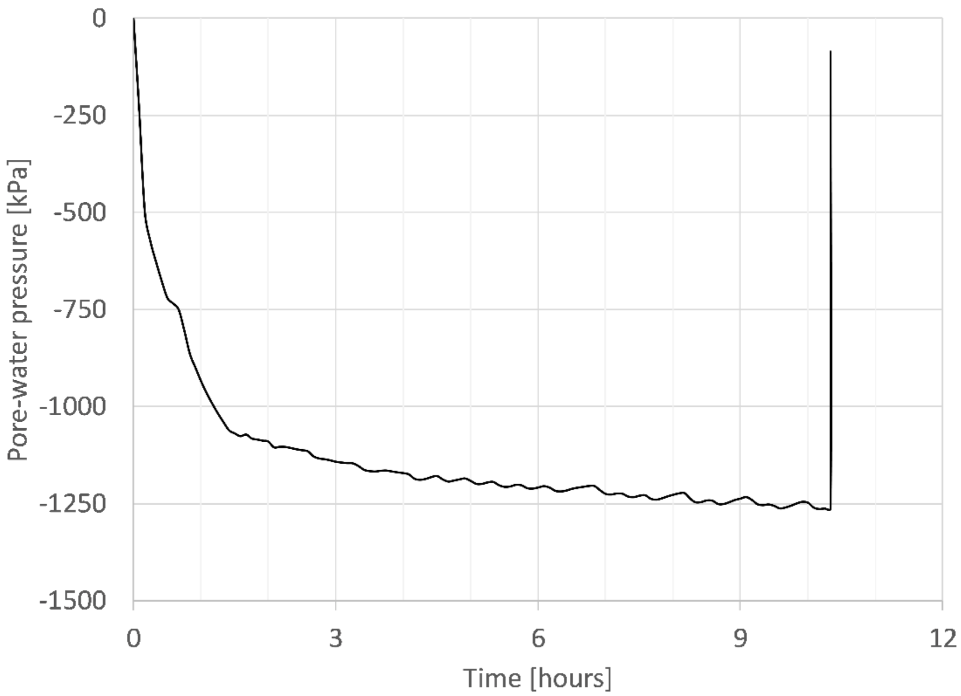


Figure 6. Repeat of long-term suction measurements by prototype KCF – CD(2000) – SS316 on a kaolin sample equalised at a pore-water pressure of -1200 kPa.

In summary, HCTs can measure moderately large levels of negative pore-water pressure, i.e. up to -500 kPa, for months without cavitating. However, they can only measure very large negative pore-water pressures, i.e. beyond -1000 kPa, for few days. A smaller reservoir size appears to increase the stability of measurements over time, though further research is required to validate this conclusion.

3. Lysimeter tests: material and methods

An upscale version of the previous tests was devised to compare the simultaneous measurements of suction by distinct HCT prototypes inside a purposely-built lysimeter filled with an unsaturated sandy soil. One of the objectives of these experiments was to observe the response of the HCT prototypes during the rapid drying or wetting of the soil and to compare this response to that of commercial dielectric permittivity probes.

3.1 Soil material

A sandy soil was chosen for the lysimeter experiments because of its high permeability, which accelerates the movement of moisture across the relatively large sample. The choice of a sandy soil also allows to explore the measurement of suction inside a significantly different material from the kaolin clay of the previous tests. The sandy soil was sourced from an agricultural farm in Orist, in the south-west of France, where a number of HCTs had been installed in the field for monitoring soil suctions. Organic matter was removed from the soil by hand picking and sieving, followed by submersion in water to segregate biological matter through buoyancy. The particle size distribution of the clean soil was measured twice as shown in Figure 7, which indicates that the material can be classified as a well-graded sandy soil or SW according to the Unified Soil Classification system. The specific gravity of the solid fraction was also measured to be 2.59 while the carbon content was equal to 0.5% of the total mass. The soil was dried in an oven at 105 °C for at least 48 hours and then moistened to attain a gravimetric water content of 0.12. The moist soil was separated into equal portions of about 750 g, which were sealed inside individual plastic bags of half litre capacity and left to equalize for at least 24 hours.

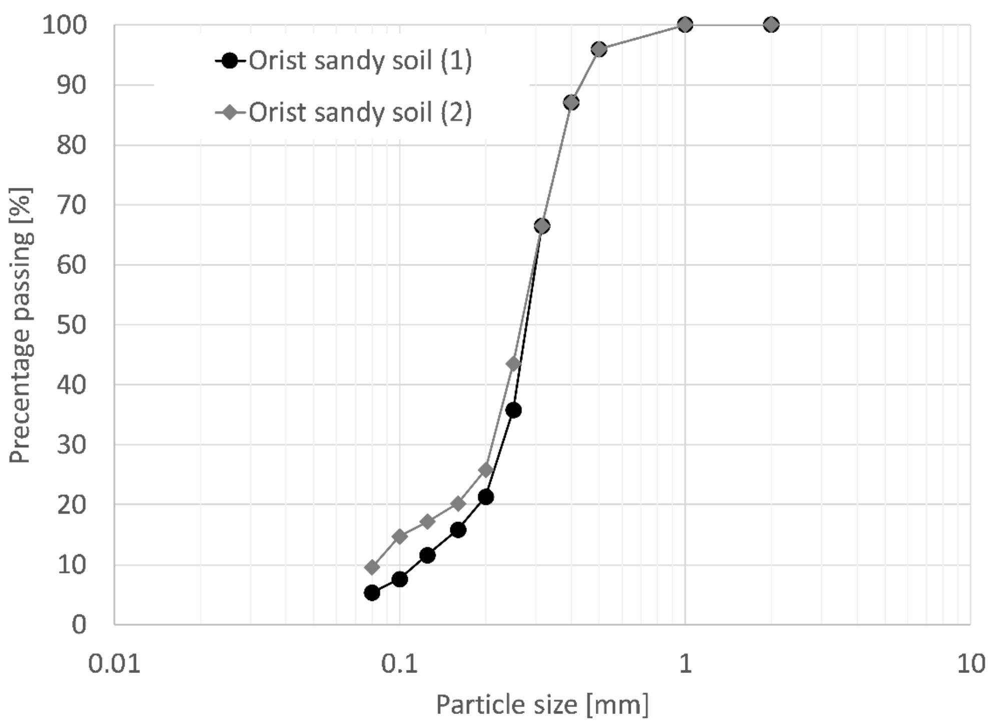


Figure 7. Particle size distribution of Orist sandy soil.

3.2 Lysimeter tests assembly

The lysimeter used in the present work consists of a sealed rectangular plastic container with dimensions 354x325x150 mm^3, whose sides are fitted with four large ports and two small ports (Figures 8a). The four large ports were designed to house four HCT prototypes while the two smaller ports were designed to house two dielectric permittivity probes for the measurement of suction and water content, respectively (Figure 8b). It was subsequently observed that the HCT prototypes tended to detach from the inner soil during the test due to the deformability of the lysimeter walls, which impeded a correct measurement of suction. To avoid this, it was then decided that the four HCTs should be alternatively installed by pushing them from the soil surface down to a depth of 4 cm instead of inserting them through the lateral ports (Figure 8c).

The two dielectric permittivity probes were a MPS2 probe to measure suction and an EC-5 probe to measure volumetric water content, both marketed by the company Decagon Devices (now part of Meter Group). The MPS2 probe measures negative pore-water pressures between -10 kPa and -500 kPa by recording the dielectric permittivity of a porous disk that is in hydraulic equilibrium with the surrounding soil. The measurement of dielectric permittivity is then linked to the suction inside the porous disk, which is assumed to be identical to the suction of the soil under equilibrium conditions. The MPS2 probe is also fitted with a thermal sensor that continuously records the local temperature. In a similar way, the EC-5 probe infers the average volumetric water content of a soil region around the probe from the measurement of the dielectric constant over the same soil region.

The empty lysimeter was initially placed on a PCE-PCS30 electronic balance (Figure 8a) before the MPS2 and EC-5 probes were inserted into the two small ports. The electrical cables of the two probes were fixed with adhesive tape to avoid any potential interference with the balance readings (Figure 8b). Plastic plugs were also inserted in the four large ports to prevent the soil from spilling out of the container. The masses of the empty lysimeter, the six soil sensors (i.e. four HCTs, one MPS2 probe and one EC-5 probe) and all connecting cables were measured so that the soil weight could be subsequently calculated by difference from the balance readings. The dimensions of each sensor were also measured (see Table 1) so that the soil volume could be estimated and the corresponding average values of soil density and porosity could be calculated.

The soil was then carefully spread and lightly compacted in layers using a small spade with special care taken to fill the gaps around the MPS2 and EC-5 probes. The mass of each layer was recorded and double-checked against the readings of the PCE-PCS30 electronic balance. Before adding the next layer, the soil surface was scarified with the spade to avoid strong discontinuities within the sample mass. The target average values of porosity and gravimetric water content were 0.48 and 0.12, respectively, which corresponds to a dry density of 1.33 g/cm^3 and a degree of saturation of 33.1%. After the lysimeter was filled, the four HCTs were gently pushed from the soil surface down to a depth of 4 cm while the electrical cables were suspended in a fixed position to avoid any interference with the balance readings (Figure 8c).

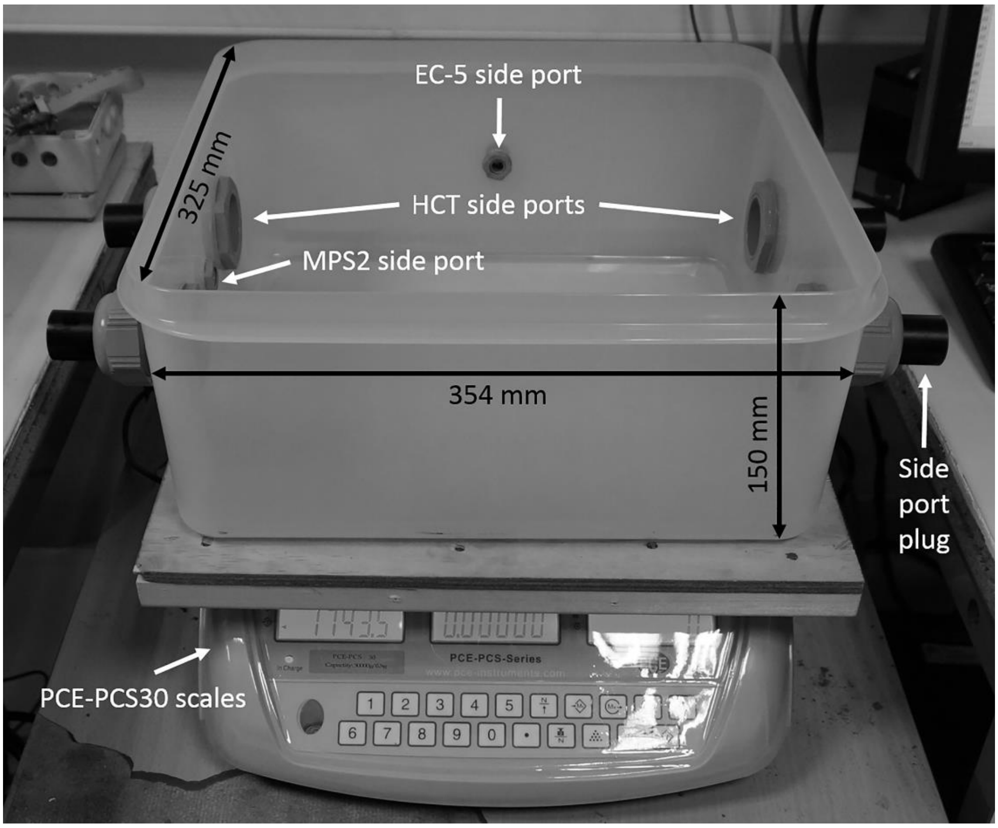


Figure 8a. Empty lysimeter with sensor ports and PCE-PCS30 scale.

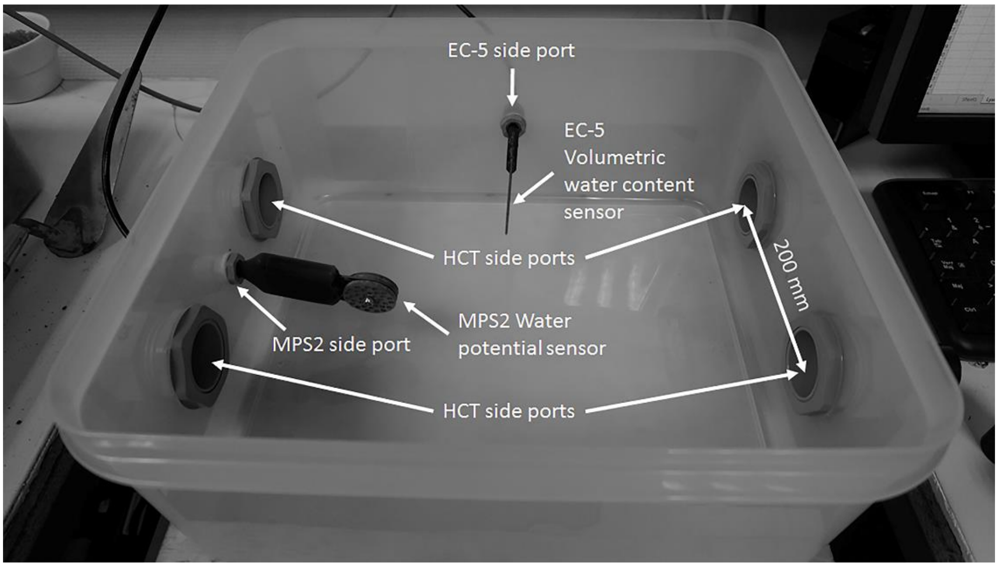


Figure 8b. Installation of MPS2 and EC-5 probes inside the lysimeter.

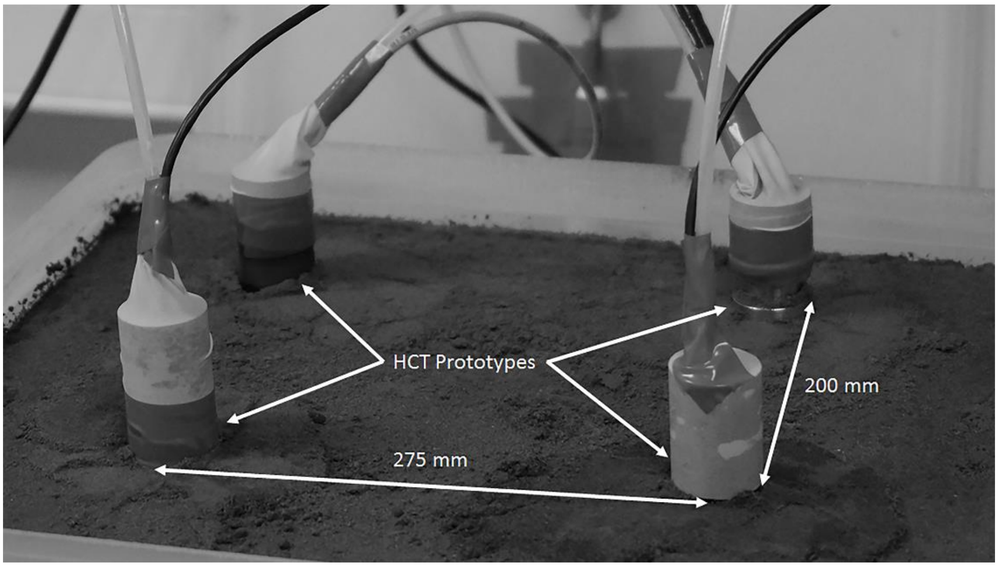


Figure 8c. HCTs installed down to a soil depth of 4 cm.

4. Lysimeter tests: results

Two distinct tests were performed to compare the response of the HCT prototypes during both drying and wetting of the soil. In these tests, the measurements of the HCTs were compared against those of the MPS2 probe while the weight recorded by the electronic balance was compared against the volumetric water content measured by the EC-5 probe. The HCT prototypes used in the lysimeter tests were selected to explore the effects of reservoir size, protective casing and transducer range on the long-term measurement of suction. Only prototypes incorporating a kaolinite ceramic filter (KCF) were used to take advantage of their larger measuring limit which is comprised between -1500 and -2000 kPa (Mendes et al., this issue).

4.1 First lysimeter test

In the first experiment, prototypes KCF – FD(2000) – SS316 [1], KCF – FD(2000) – SS316 [2], KCF – CD(2000) – SS316 and KCF – CD(500) – Al were installed inside the lysimeter. A MPS2 suction probe and an EC-5 volumetric water content probe were also installed inside the small ports of the lysimeter. Two of the four HCT prototypes, namely prototypes KCF – FD(2000) – SS316 [1] and KCF – FD(2000) – SS316 [2], incorporate a small water reservoir of 40 mm^3 built around a flush diaphragm (FD) pressure transducer (Table 1). The other two prototypes, namely prototypes KCF – CD(2000) – SS316 and KCF – CD(500) – Al, incorporate instead a large water reservoir of 430 mm^3 delimited by a cavity diaphragm (CD) pressure transducer (Table 1). All prototypes are encased in a stainless steel sheath and are fitted with a pressure transducer with a measuring range of 2000 kPa with the exception of prototype KCF – CD(500) – Al, which is encased in an alumina ceramic sheath and is fitted with a pressure transducer with a range of 500 kPa.

Figures 9a and 9b shows the suctions measured by the HCTs and MPS2 probe as the soil is progressively dried from the initial state (Section 3) by surface evaporation until cavitation of the last HCT prototype after about 13 days. Figure 9a also shows the temperature measured by the MPS2 probe and in Figure 9b the volumetric water content measured by the EC-5 probe. In particular, inspection of Figure 9a indicates that the HCTs and the MPS2 probes measured an almost identical value of the initial pore-water pressure equal to -200 kPa. The four HCTs also showed very similar readings until day 6 when the pore-water pressure was about -450 kPa. At this point, the measurements of the four HTCs started to diverge with prototypes KCF – CD(2000) – SS316 and KCF – FD(2000) – SS316 [2] reading larger suctions than prototypes KCF – FD(2000) – SS316 [1] and KCF – CD(500) – Al. The former two prototypes continued to show similar readings until day 9 when the recorded pore-water pressure was about -900 kPa. At this point, prototype KCF – FD(2000) – SS316 [2] started to read larger values of suction than prototype KCF – CD(2000) – SS316. These slight differences between HCT measurements may be explained by a small heterogeneity of water content inside the soil sample, whose effect on the measured suction augments as the soil becomes drier. This is illustrated in Figure 10, which plots the retention curves resulting from the combination of the suction measurements by the HCT prototypes and MPS2 probe with the water content measurements by the EC-5 probe (Figure 9b). Inspection of Figure 10 indicates that the retention curves measured by the four HCT prototypes are almost identical until a pore-water pressure of -450 kPa is attained but they become flatter and start to diverge as suction increases beyond this value. In the flat portion of the curve, a small difference of water content corresponds to a large difference of pore-water pressure, which may explain the discrepancy between HCT measurements in the high suction range.

The two HCTs with small water reservoirs of 40 mm^3, namely prototypes KCF – FD(2000) – SS316 [1] and KCF – FD(2000) – SS316 [2], sustained larger suctions for longer times before cavitating. The former prototype cavitated after more than 13 days, when it attained a pore-water pressure of -1866 kPa, while the latter prototype cavitated after about 11 days, when it attained a pore-water pressure of -1582 kPa. On the contrary, the two HCTs with larger water reservoirs of 430 mm^3, namely prototypes KCF – CD(2000) – SS316 and KCF – CD(500) – Al, cavitated at relatively low suctions. In particular, the former prototype cavitated after about 11 days at a pore-water pressure of -1384 kPa while the latter prototype cavitated after less than 9 days at a pore-water pressure of -704 kPa. These results are consistent with those of the preliminary tests on kaolin clay as they show that the HCT prototypes with smaller water reservoirs can sustain larger suctions for longer times. An alternative explanation for the early cavitation of prototype KCF – CD(500) – Al may reside in the lower pressurization of this prototype during the initial saturation. The application of a lower saturation pressure was necessary in this case to avoid damaging the transducer, whose measuring range is only 500 kPa compared to 2000 kPa for the other three prototypes. The application of a low saturation pressure increases, however, the likelihood of air pockets in the water reservoir and ceramic filter, thus heightening the probability of early cavitation. After cavitation, all HCTs recorded the same pore-water pressure of about -100 kPa, which suggests that calibration did not drift significantly during the course of the test.

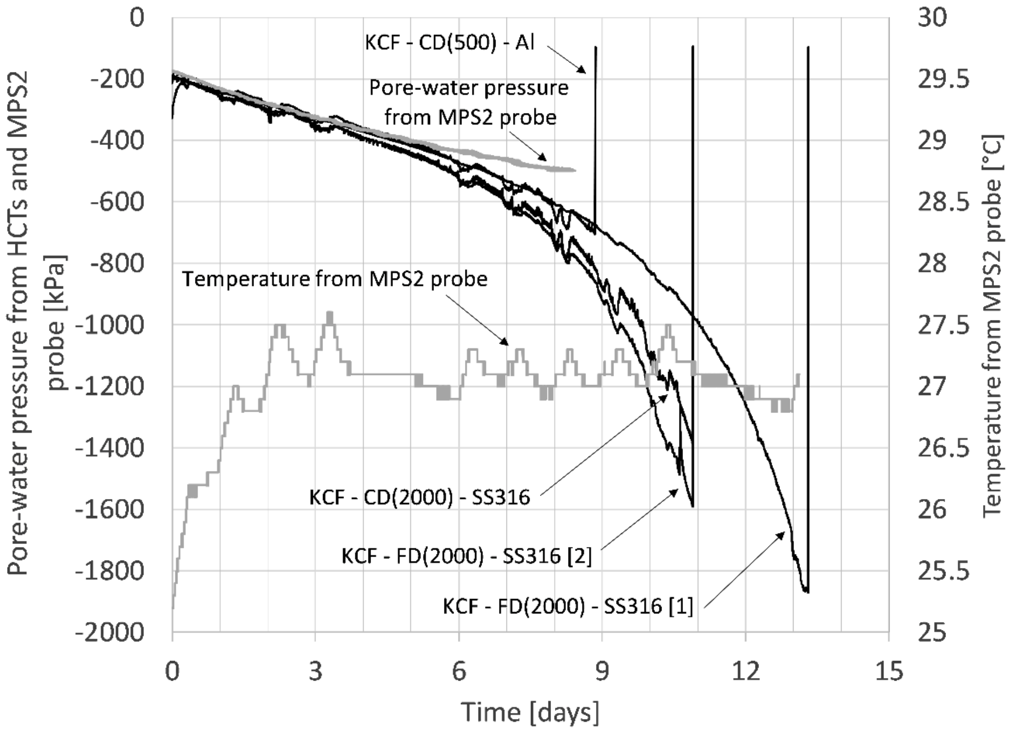


Figure 9a. Pore-water pressures (measured by HCTs and MPS2 probe) and temperature (measured by MPS2 probe).

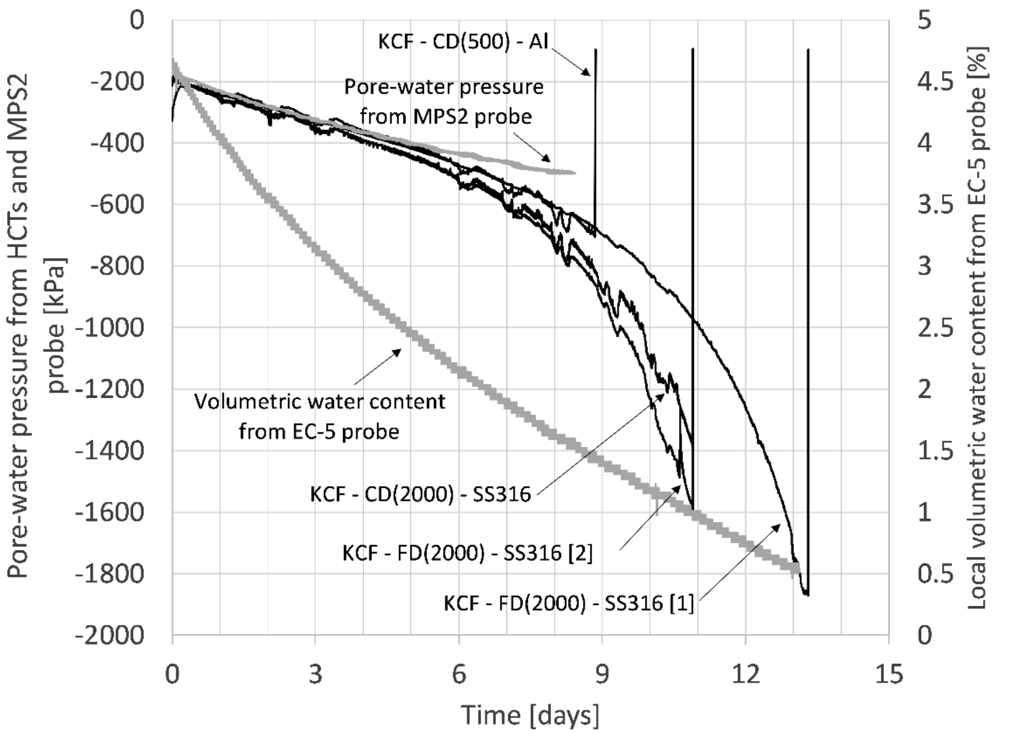


Figure 9b. Pore-water pressures (measured by HCTs and MPS2 probe) and volumetric water content (measured by EC-5 probe).

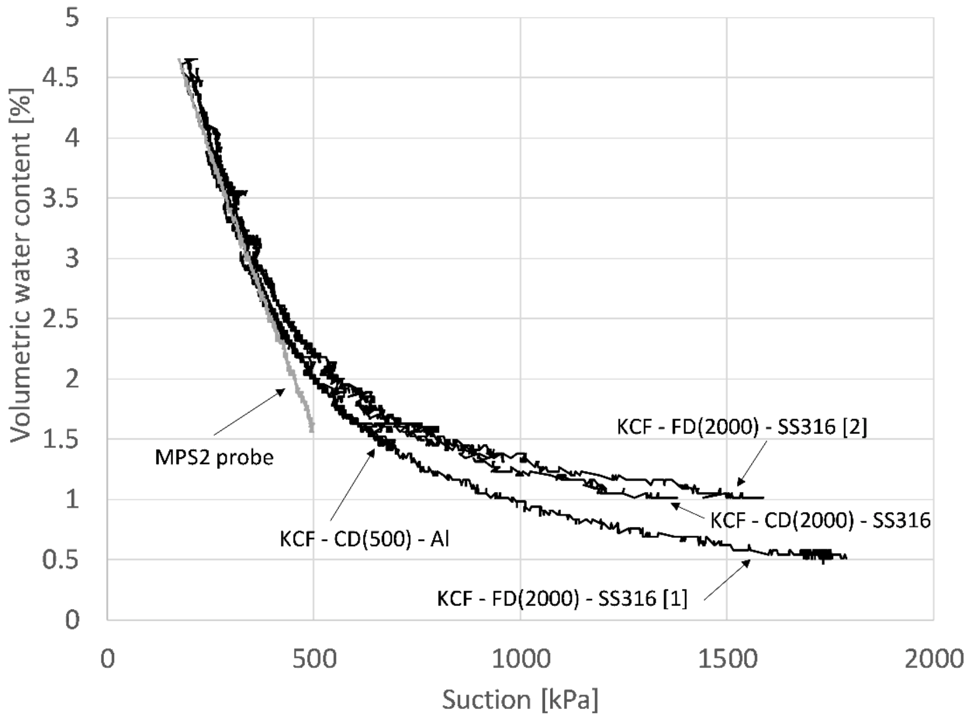


Figure 10. Retention curves obtained by combining suction measurements by HCT prototypes and MPS2 probe with water content measurements by EC-5 probe.

Figures 9a and 9b shows that all four HCT prototypes exhibited a faster growth of negative pore-water pressure as the test progressed. The slight fluctuations of pore-water pressure are the likely consequence of small thermal changes inside the soil as it can be inferred by comparing the measurements of pore-water pressure and temperature. This comparison indicates that even a small temperature change of 0.5 °C can produce a marked variation of pore-water pressure in excess of 10 kPa, which suggests that HCT measurements should be compensated for temperature changes, especially in field applications. The impact of temperature fluctuations on suction measurements is particularly evident for prototypes KCF – FD(2000) – SS316 [2], KCF – CD(2000) – SS316 and KCF – CD(500) – Al while prototype KCF – FD(2000) – SS316 [1] records a relatively smooth curve.

Figures 9a, 9b and 10 show that the readings of the MPS2 probe compare well with those of the four HCTs up to a value of -400 kPa but, beyond this point, the MPS2 probe underestimates the suction compared to the HCTs. This discrepancy is somewhat expected because MPS2 readings become less accurate as the probe measuring limit of -500 kPa is approached. This loss of accuracy is caused by the progressive withdrawal of water within the smaller voids of the porous disk of the MPS2 probe, which delays the exchange of moisture with the surrounding soil.

The variation of the soil water content throughout the test was monitored by the PCE-PCS30 electronic balance and the EC-5 probe. The electronic balance provided a continuous measurement of the average gravimetric water content across the entire sample volume (about 11550 cm^3). Conversely, the EC-5 probe measured the average volumetric water content of a cylindrical soil region, with a diameter of 5.5 cm and an overall volume of 360 cm^3, which is eccentrically located along the probe axis (Figure 11).

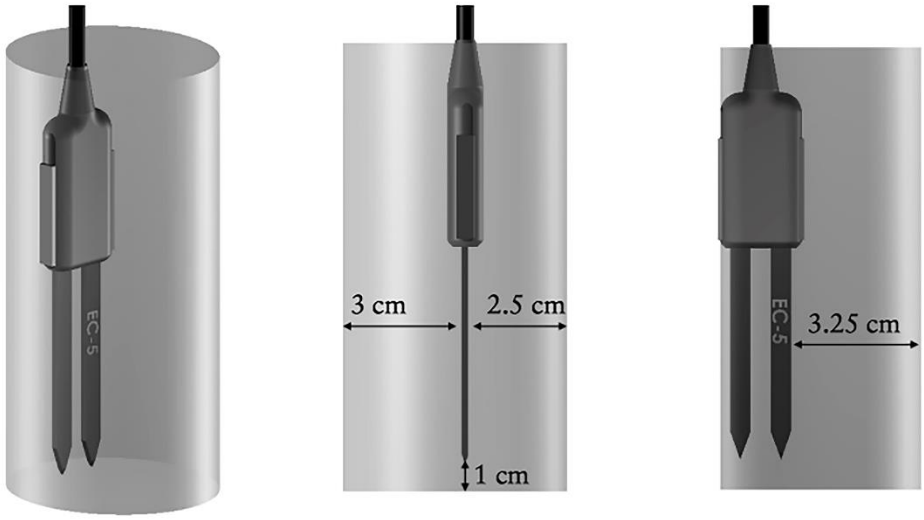


Figure 11. Region of influence covered by the EC-5 volumetric water content probe (after Cobos, 2015).

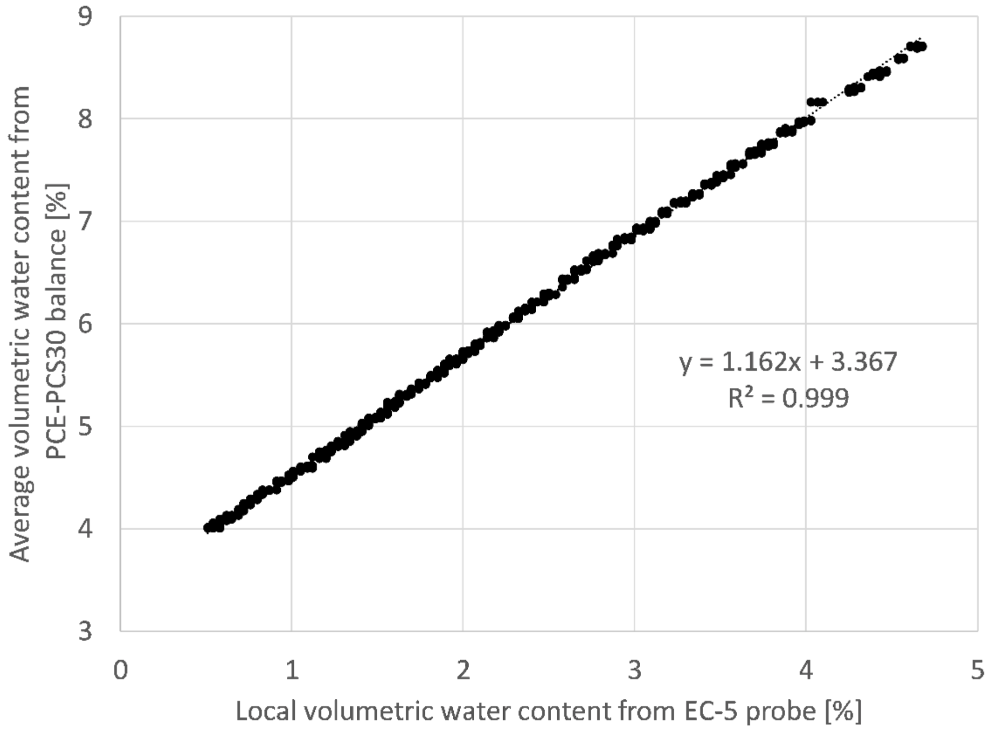


Figure 12. Average water content measured by the electronic balance versus local water content measured by the EC-5 probe.

If the dry density of the soil is fixed to 1.33 g/cm^3, the gravimetric water content can be converted into volumetric water content, which allows a direct comparison between the readings of the electronic balance and the EC-5 probe (Figure 12). Note that the assumption of a constant dry density during the test is plausible given the sandy nature of the soil. Figure 12 shows a linear correlation between the local and average values of volumetric water content measured by the EC-5 probe and the electronic balance, respectively. The volumetric water contents measured by the EC-5 probe are smaller than those measured by the electronic balance because of surface evaporation, which generates a gradient of water content across the soil depth. The EC-5 probe is located in the shallow drier layer and therefore measures a local value of water content that is smaller than the average value measured by the electronic balance across the entire sample mass.

4.2 Second lysimeter test

The same HCT prototypes of the first experiment were used during the second experiment with the only exception of prototype KCF – CD(500) – Al, which was replaced by prototype KCF – CD(2000) – Al. These two prototypes differ only for the measuring range of the pressure transducer, which is equal to 500 kPa in the former case and 2000 kPa in the latter case (Table 1). This replacement was intended to eliminate any potential effect of the saturation procedure on the cavitation limit of the sensor as discussed in the previous section. Similar to the first experiment, a MPS2 suction probe and an EC-5 volumetric water content probe were also installed in the small ports of the lysimeter.

In this test, the soil was left to dry to the atmosphere from the initial state (Section 3) until the MPS2 probe recorded a pore-water pressure of -400 kPa. At this point, an intense rainfall corresponding to a precipitation of 7.6 mm over a period of 30 minutes was uniformly applied to the soil surface by means of a spray bottle. The soil was then left to dry again by surface evaporation until all HCTs cavitated. The only difference with respect to the previous experiment therefore consists in the application of the intermediate rainfall, whose purpose was to explore the response of the HCTs during the rapid wetting of the soil.

Figure 13 shows the suction measured by the HCT prototypes and MPS probe together with the volumetric water content measured by the EC-5 probe throughout the duration of the test, which was equal to 27 days until cavitation of the last HCT. Similar to the previous experiment, the MPS2 probe recorded the same suction trend of the HCT prototypes during the first week of the test (i.e. until the application of the rainfall), though there was a small offset between the readings of the MPS2 probe and those of the HCT prototypes. The three prototypes KCF – FD(2000) – SS316 [1], KCF – FD(2000) – SS316 [2] and KCF – CD(2000) – SS316 HCTs showed highly consistent readings during the initial stages of the test while prototype KCF – CD(2000) – Al recorded lower suctions and exhibited significant fluctuations. These fluctuations are still unexplained but they significantly reduced during the subsequent drying stage after the rainfall.

Similar to the previous test, it took less than 7 days for the pore-water pressure recorded by the MPS2 probe to attain a value of -400 kPa. At this point, just before the start of the rainfall, the readings of prototypes KCF – FD(2000) – SS316 [1], KCF – FD(2000) – SS316 [2], KCF – CD(2000) – SS316 and KCF – CD(2000) – Al were -431 kPa, -427 kPa, -473 kPa and -390 kPa, respectively. Figure 14 presents an expanded view of the response of all sensors after the rainfall, which indicates that the HCT readings remained unchanged for about 20 minutes following the end of the precipitation. A delayed response is expected because some time is required for the wetting front to advance through the soil down to the depth of 4 cm where the sensors are located. The four HCTs responded with an initially slow increase of pore-water pressure, which was a precursor of the imminent arrival of the wetting front. After few minutes, the arrival of the wetting front was marked by a sudden jump of the pore-water pressure to zero, indicating the full saturation of the upper soil layer. The response of the MPS2 probe was considerably slower than that of the HCTs, with the first signs of an increase of pore-water pressure recorded about 2 hours after the end of the rainfall. The readings of the MPS2 probe continued to increase gradually for another 2 days (Figure 14) well into the subsequent drying stage. This behaviour suggests that dielectric permittivity sensors, such as the MPS2 probe, can significantly overestimate the value of suction during the rapid wetting of the soil.

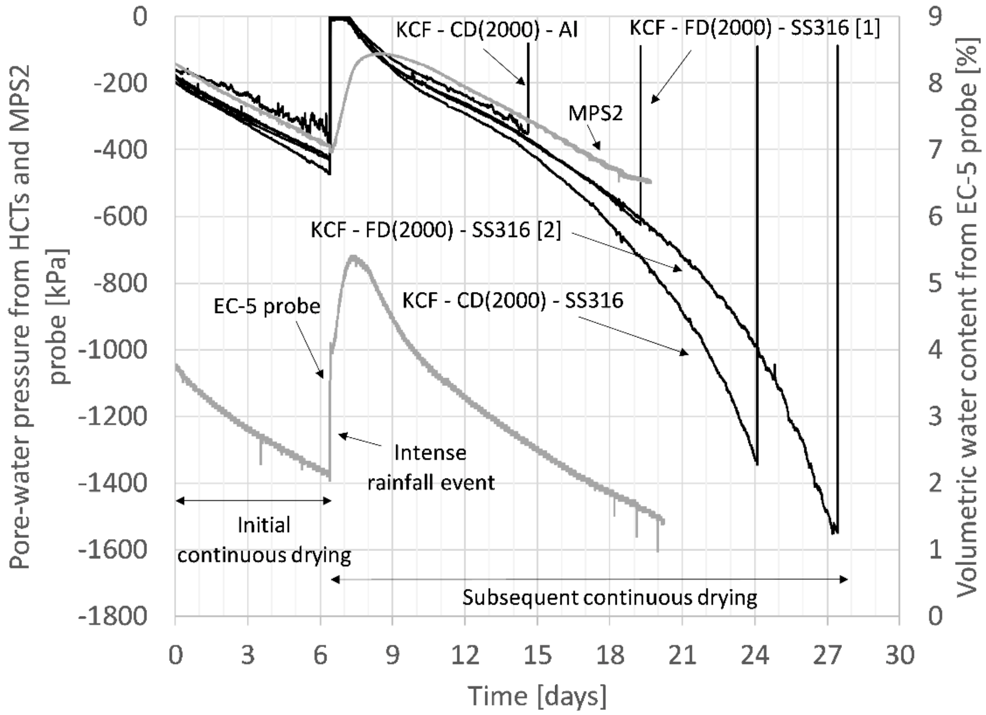


Figure 13. Pore-water pressures (measured by HCTs and MPS2 probe) and volumetric water content (measured by EC-5 probe).

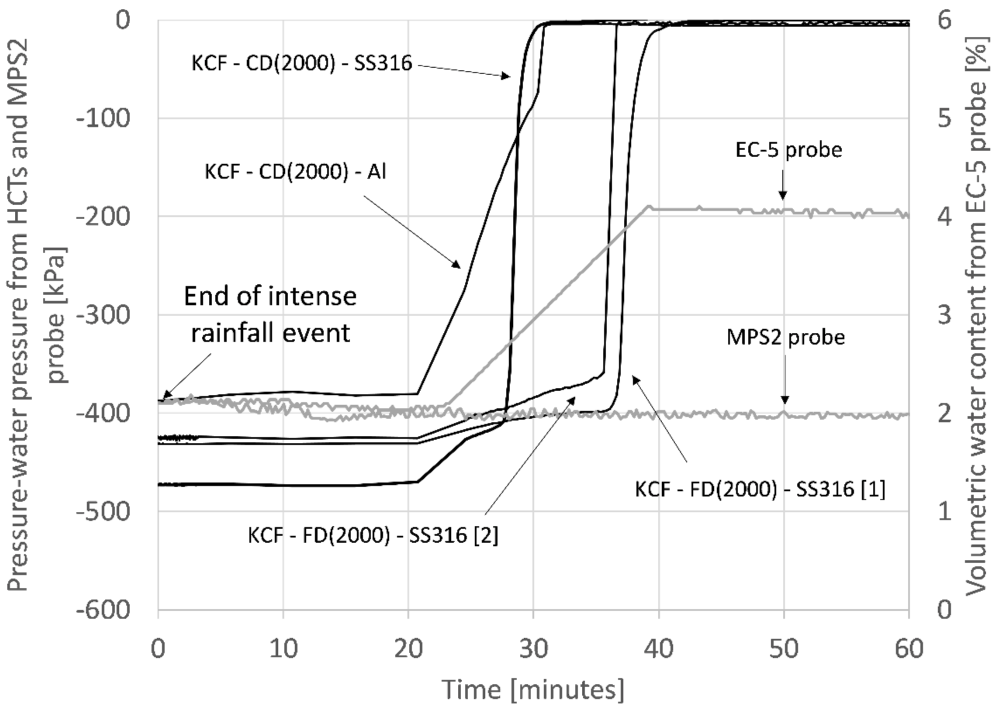


Figure 14. Expanded view of pore-water pressures (measured by HCTs and MPS2 probe) and volumetric water content (measured by EC-5 probe) after the rainfall.

As for the water content, the EC-5 probe reacted relatively quickly, i.e. about 20 minutes after the end of the rainfall. This fast response is similar to that of the HCT prototypes (Figure 14), though the subsequent readings showed a more gradual increase of volumetric water content alike the MPS2 probe (Figure 13).

Inspection of Figure 13 also confirms a good consistency between water content measurements from the EC-5 probe and suction measurements from the HCT prototypes as the former attain a peak of 5.3% while the latter are still zero.

As the soil started drying again, all HCTs begun to read increasingly larger suctions at the same time when the EC-5 probe commenced to record smaller values of water content, which is again consistent with physical expectation. Likewise the previous experiment, all HCTs showed similar readings until attaining a pore-water pressure of about -400 kPa. After this point, a small divergence of measurements was registered, which may be explained by the sensitivity of suction measurements to the spatial heterogeneity of water content as discussed earlier. The first HCT prototype to cavitate, on day 14, was KCF – CD(2000) – Al in correspondence of a pore-water pressure of -347 kPa. This was followed, on day 19, by prototype KCF – FD(2000) – SS316 [1] in correspondence of a pore-water pressure of -624 kPa. On day 24, prototype KCF – CD(2000) – SS316 cavitated after attaining a pore-water pressure of -1342 kPa. Lastly, on day 27, prototype KCF – FD(2000) – SS316 [2] cavitated after reaching a pore-water pressure of -1547 kPa. The early cavitation of prototypes KCF – CD(2000) – Al and KCF – FD(2000) – SS316 [1] is particularly surprising as it occurs well before attaining the ultimate measuring limit of these two sensors, which is comprised between -1500 kPa and -2000 kPa. This behaviour also contradicts the results of the initial tests on kaolin clay (Figure 1), in which prototype ACF – FD(2000) – SS316 recorded negative pore-water pressures in excess of -300 kPa for more than 50 days before cavitating at a pressure of -475 kPa (despite the smaller measuring range of prototype ACF – FD(2000) – SS316 compared to prototypes KCF – CD(2000) – Al and KCF – FD(2000) – SS316 [1]). One possible explanation of this behaviour may be found in the inadequate saturation of prototypes KCF – CD(2000) – Al and KCF – FD(2000) – SS316 [1] prior to the test or in the non-monotonic variation of soil suction. A non-monotonic variation of suction, during drying-wetting cycles, may somehow limit the measuring range of HCTs and hence trigger early cavitation. However, at this stage, these are speculative hypotheses and further investigation is necessary to understand the actual reasons of this behaviour.

Based on all tests, including the preliminary ones on small kaolin samples, prototype KCF – FD(2000) – SS316 [2] appears to exhibit the best performance. This prototype incorporates a small water reservoir of 40 mm^3 built around a flush diaphragm (FD) pressure transducer and a kaolin ceramic filter (KCF), which are encapsulated inside a SS316 stainless steel protective casing (Table 1). One specific characteristic of this prototype is the presence of an adjustable compression screw at the back of the sensor, which helps preventing any displacement of the pressure transducer during application of the saturation pressure or during measurements, thus increasing the stiffness of the water reservoir (Mendes et al., this issue). Overall, this prototype was capable of measuring very large negative pore-water pressures in excess of -1500 kPa for long periods of time up to 27 days.

5. Conclusions

This paper has investigated the ability of high capacity tensiometers (HCTs) to measure pore-water suctions in soils over long periods of time without cavitating. A number of HCT prototypes were designed and manufactured incorporating different ceramic filters, water reservoir sizes, pressure transducers and protective casings. The performance of these prototypes was initially assessed by measuring the suction of small kaolin clay samples equalised at two distinct pore-water pressures of -200 kPa and -1200 kPa. This was followed by a second experimental campaign at a larger scale, which made use of a purposely-built lysimeter filled with a sandy soil. Four different HCT prototypes were simultaneously installed inside the lysimeter together with two commercial dielectric permittivity probes to measure suction and water content, respectively. The lysimeter tests indicated a good consistency of measurements between different HCT prototypes, especially in the low suction range. Larger discrepancies were, however, observed as suction increased but this was possibly caused by the heterogeneity of water content across the relatively large sample rather than by the malfunctioning of the sensors. In general, HCTs design seems to have a relatively small influence on the accuracy of readings while it tends to affect the range and stability of measurements.

The results from the above experimental campaign suggest that the stability of measurements over time is inversely related to the magnitude of the recorded suction, with the measurement of larger suctions leading to earlier cavitation. Moreover, a smaller water reservoir enables the measurement of higher suctions over longer times before cavitation. This trend has been inferred from the majority of tests performed in this work, though some contradictory evidence is present and requires further investigation.

The results from the study also indicate that the HCT design has no effect on response time. All HCT prototypes exhibit a faster response to suction changes compared to the dielectric permittivity sensor. This constitutes a significant advantage of HCTs with respect to dielectric permittivity sensors, especially for field warning systems where the timely detection of suction changes is very important. Another disadvantage of dielectric permittivity probes is their tendency to underestimate suction over the high range of values close to the measuring limit of the probe.

Lysimeter tests have also demonstrated a sensitivity of HCT readings to temperature changes with a small temperature change of half degree centigrade potentially resulting in suction fluctuations of the order of ten kilopascals. No clear correlation exists, however, between sensor design and thermal sensitivity, though suction fluctuations were less evident for prototype KCF – FD(2000) – SS316 [1] which incorporates a small water reservoir of 40 mm^3.

On the basis of all tests, prototype KCF – FD(2000) – SS316 HCT [2] exhibited the best performance in terms of measurement stability at high suctions as it was capable of measuring negative pore-water pressures in excess of -1500 kPa for up to 27 days. This prototype incorporates a small water reservoir of 40 mm^3 with a flush diaphragm pressure transducer and a kaolin ceramic filter, all enclosed inside a stainless steel casing. Another distinctive characteristic of this prototype is the presence of an adjustable compression screw at the back of the casing, which pushes the pressure transducer against the water reservoir, thus preventing any dislocation of the transducer during application of the saturation pressure or during measurements.

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