TOWARDS THE DEVELOPMENT ON NEW HIGH CAPACITY TENSIOMETERS CAPABLE OF MEASURING SOIL MATRIC SUCTION BEYOND 3 MPA

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ABSTRACT

High capacity tensiometers (HCT) are the only type of sensors in existence that can measure soil matric suction directly and are regarded to be the most accurate and reliable technique for the study of suction evolution in unsaturated soils. The measurement with HCTs is possible due to their design, composed of ceramic filter with a specific air entry value (AEV), small water reservoir and pressure transducer. Where, the AEV of the ceramic filter, more precisely the largest pore size within the ceramic, plays the most important role in controlling the measuring range of HCTs. Specifically, decreasing the largest pore size within the ceramic results in an increase in the measuring range. In this work, a new development in HCTs is presented whereby the ceramic filter in HCTs was replaced from the typically used 1.5 MPa AEV ceramic filter with a new alumina ceramic filter with an estimated AEV of 3.5 MPa. To assess the performance of the new ceramic filter, similar designed HCTs were assembled with the Soil Moisture and the new alumina ceramic filters. Early results show that the maximum measuring matric suction range is beyond 3 MPa for HCTs assembled with the new alumina ceramic filter.

KEYWORDS:

Soil suction measurement, High Capacity Tensiometers, Unsaturated Soils

INTRODUCTION

High capacity tensiometers (HCTs) are sensors that can measure both positive (compressive) and negative (tensile) pore-water pressures in soils directly. They are sometimes referred to as “suction sensors” or “suction probes” because HCTs measure the pore suction in soils which, under atmospheric conditions, coincides with the negative pore-water pressure. Different from conventional tensiometers which have threshold in the measuring range of 0 to 80 kPa, HCTs can measure soil suctions beyond this value normally in the range of up to 1.5-2 MPa. HCTs are very versatile sensors as they can be used in different applications from engineering to farming. For example, HCTs have been used both in the field to monitor pore-water pressures inside unstable slopes or agricultural soils (Mendes et al., 2008, Cui et al., 2008, Toll et al. 2011) and in geotechnical laboratories to measure the evolution of soil suction during direct shear tests (Caruso and Tarantino, 2004) or triaxial tests (Cunningham et al., 2003, Mendes and Toll, 2016).

The first HCT was developed in the 1990’s at Imperial College, London, by Ridley and Burland (1993). Shown in Figure 1, the design of the Imperial College HCT (IC-HCT) consisted of a ceramic filter with an Air Entry Value (AEV) of 15 bar (1.5 MPa) and an electronic pressure transducer separated by a small water reservoir (10 mm^3) enabling the direct measurement of soil suction in excess of 1.5 MPa.

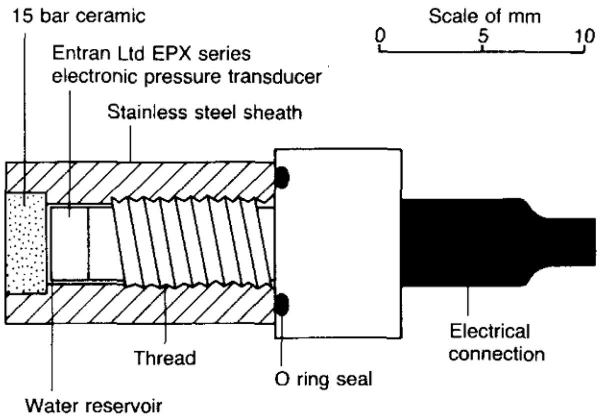

Figure 1. Imperial College HCT (Ridley and Burland, 1993).

Since the development of the IC-HCT, various similar HCT designs have emerged from different research groups around the world (Guan and Fredlund, 1997; Meilani et al. 2002; Take and Bolton 2003; Lourenco et al., 2008; Cui et al., 2008; Mendes and Buzzi 2014; Bagheri et al., 2018; Jacobsz, 2018; Mendes et al., 2020). Bespoke, or commercially available pressure transducers and the same ceramic filter with an AEV of 1.5 MPa as in the IC-HCT was used in these subsequent HCT designs. For a review of the theoretical and practical aspects of suction measurement by means of HCTs, please refer to Marinho et al. (2008).

The ceramic filter is the component that limits the maximum measuring range in HCTs. The measurement of soil suction values beyond -100 kPa (absolute 0 kPa at sea level) with HCTs are only possible because of the AEV of the ceramic filter and due to a proper saturation of the ceramic filter and water reservoir. This second factor ensures the hydraulic continuity of the water inside the HCT and the soil specimen. The AEV prevents air from breaking though the ceramic filter and it is the maximum difference in pressure that can exist between the air and water pressures acting on both sides of the ceramic filter. In the case of measuring suction in a soil specimen, it is the difference in pressure between the pore pressure in the soil and the pressure in the water reservoir. For a properly saturated HCT during point measurements, when this difference in pressure is larger than the AEV of the ceramic filter, cavitation (or water tension breakdown) in the HCT occurs. While the maximum measuring range is directly related to the AEV of the ceramic filter, cavitation in HCTs can occur at pressure values well below the AEV of the ceramic filter due to poor saturation of the HCT and in prolonged continuous measurements on properly saturated HCTs. Regardless, cavitation in HCTs is easily observed in readings from the pressure transducer which show a rapid and immediate decrease in pressure to values close to -100 kPa and it has also been observed through visual instrumentation to occur at the moment when air bubbles emerge in the water reservoir from the ceramic filter, even at pressures below the AEV of the ceramic filter (Mendes and Buzzi, 2013). However, what constitutes the air bubbles that emerge in the water reservoir when cavitation occurs is still unclear (if diffused air from outside the HCT, if entrapped air in the ceramic filter, if water vapour from water cavitation or as combination of the aforementioned). Nevertheless, most HCTs in existence, by using the same ceramic filter with an AEV of 1.5 MPa are theoretically limited to a measuring range of 1.5 MPa. However, as it has been reported by Tarantino and Mongioví (2001), HCTs with this type of ceramic filter are able to measure soil suction well beyond their measuring range where they report measuring suction values in soil specimens in the range of 2.6 MPa. This is in line with observations by Ridley and Burland (1994) and Mendes et al. (2020) where HCTs assembled with similar ceramics were able to sustain pressures beyond 2 MPa. This discrepancy in relation to the measuring range in HCTs is not yet fully understood, but it seems that the actual AEV in this type of ceramics varies greatly and inconsistently for each individual ceramic filter and between the nominal value of 1.5 MPa and 2 MPa.

The water reservoir in the HCT serves only one purpose which is to provide space for the deflection of the pressure transducer. Contrary to previous belief, the water reservoir size does not influence the measuring range of HCTs. As it has been shown previously (Mendes and Buzzi, 2013), large size reservoirs with a volume of 1000 mm^3 assembled with the ceramic filter with an AEV of 1.5 MPa were able to reach the nominal value of 1.5 MPa before cavitation. However, it can be noted that the phase of initial saturation of the HCT is crucial in determining both proper performance and measuring range of HCTs.

The pressure transducer range also does not affect the measuring range of HCTs. When choosing a pressure transducer for an HCT, the measuring range of AEV of the ceramic filter and its symmetrical response should be taken into consideration. A symmetrical response determines the capacity of the pressure transducer to measure both positive and negative pressures (Tarantino and Mongioví, 2002), enabling the calibration of HCTs to be performed in the positive range and then extrapolated to the negative range. Preferably, the pressure transducer measuring range should be above the AEV of the ceramic filter. Despite this, it is possible to use pressure transducers with a pressure range below AEV of the ceramic filter as shown by Lourenco et al. (2008). However, using a pressure transducer with a measuring range similar or higher to the AEV of the ceramic filter, higher water pressures can be applied to the HCT during saturation without damaging it and, in turn, accelerate the saturation of the ceramic filter and water reservoir for the HCT to reach its full measuring range after initial saturation.

Following the aforementioned guidelines, new HCTs (herein N-HCT) assembled with ceramic filters with an estimated AEV of 3.5 MPa and pressure transducers with a 6.8 MPa pressure range were developed at Northumbria University. For assessment and comparison of the new ceramic filter, similar designed HCTs (herein C-HCT), assembled with ceramic filters with an AEV of 1.5 MPa, were also built. Early results show that the N-HCTs can measure soil suction in the range of up to 3.5 MPa, twice the range of C-HCTs. Moreover, it was also found that the response rate when measuring suction in soil specimens with the N-HCT was significantly faster.

The development of HCTs with larger measuring ranges enables the extended study of soil suction using direct methods necessary for the determination of soil water retention curves which, in turn, are crucial in the development of constitutive models for describing the behaviour of unsaturated soils. Moreover, these new HCTs will be important in the development of real-time soil suction monitoring systems, since the extended measuring range can potentially increase the longevity of continuous soil suction measurement, helping in the prevention of early cavitation in HCTs.

N-HCT AND C-HCT DESIGNS

The design of the N-HCT followed a similar design principle to the IC-HCT in Figure 1, comprising of a ceramic filter, water reservoir and pressure transducer encapsulated in a stainless-steel sheath. As shown in Figure 2, the dimensions of the N-HCT are 20 mm in diameter and about 20 mm in height (when accounting with the back extension of the pressure transducer).

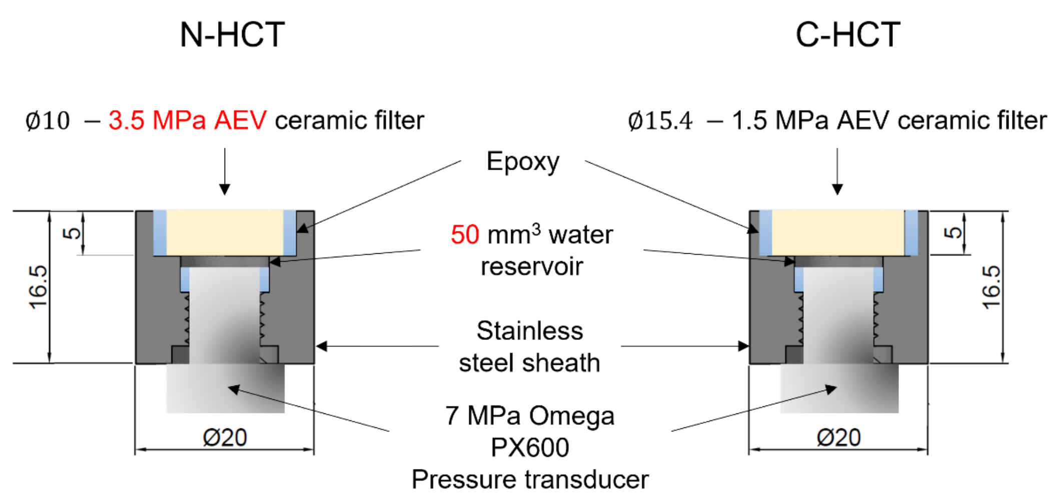

Figure 2. Schematics for the N-HCT (left) and the C-HCT (right). Sizes in mm.

The most important component in an HCT is the ceramic filter, more precisely its AEV, as it defines the upper bound limit of the maximum suction attainable by the HCT. The AEV is inversely related to the largest pore size in the ceramic filter, where a smaller largest pore size relates to a higher AEV and therefore, to a greater maximum suction range attainable by the HCT. In the N-HCT design, the ceramic filter used in the assembly was a 10 mm in diameter by 5 mm in height >99.9% alumina ceramic filter with the largest pore size diameter of 75-92 nm (see Figure 3) determined by mercury intrusion porosimetry (MIP) using a Micromeritrics AutoPore IV device. This is about 2 times smaller to the largest pore size diameter of 165 – 220 nm (see Figure 3) in the 1.5 MPa AEV ceramic filter (Mendes et al., 2020) commonly used in most HCT designs. A rough estimation of about 3.5 MPa for the AEV of the new ceramic filter was obtained using Young-Laplace equation (Equation 1).

$$AEV = \frac{4\sigma_w \cos\theta_w}{d_{max}} \qquad \text{[Equation 1]}$$

Where, σ_w is the air-water surface tension (72.8 mN/m at 293°K) and θ_w is the contact angle between the filter material and the water. Note that, for simplicity the material of the filter was considered to be perfectly wettable, meaning the contact angle used in the estimation of the AEV was kept equal to zero.

As aforementioned, the pressure transducer range of an HCT should be at least equal to the AEV of the ceramic filter to allow a faster saturation of the ceramic filter at a pressure level matching the AEV. Although not considered in this study, it is also possible to achieve a satisfactory saturation of ceramic filter of the HCT at a pressure level below the AEV of the ceramic filter if preceded by good saturation (see Take and Bolton, 2003). Thus, for an estimated AEV of 3.5 MPa of the ceramic filter, the pressure transducer used in the assembly of the N-HCTs was the PX600 flush diaphragm subminiature pressure transducer with a pressure range of 6.8 MPa by Omega Engineering. The PX600 pressure transducer is designed with a thread just below the sensing face and is made of stainless steel, two features that are important when assembling and using the HCT. The thread in pressure transducer simplifies the manufacture of the N-HCT, but also, allows for an accurate positioning of the pressure transducer inside the sheath. Because it is made of stainless steel, the same material as in the protective sheath, the influence of temperature in the measurement is expected to reduce. The latter can be particularly important when considering the use of HCTs outside of the temperature-controlled environment of the laboratory.

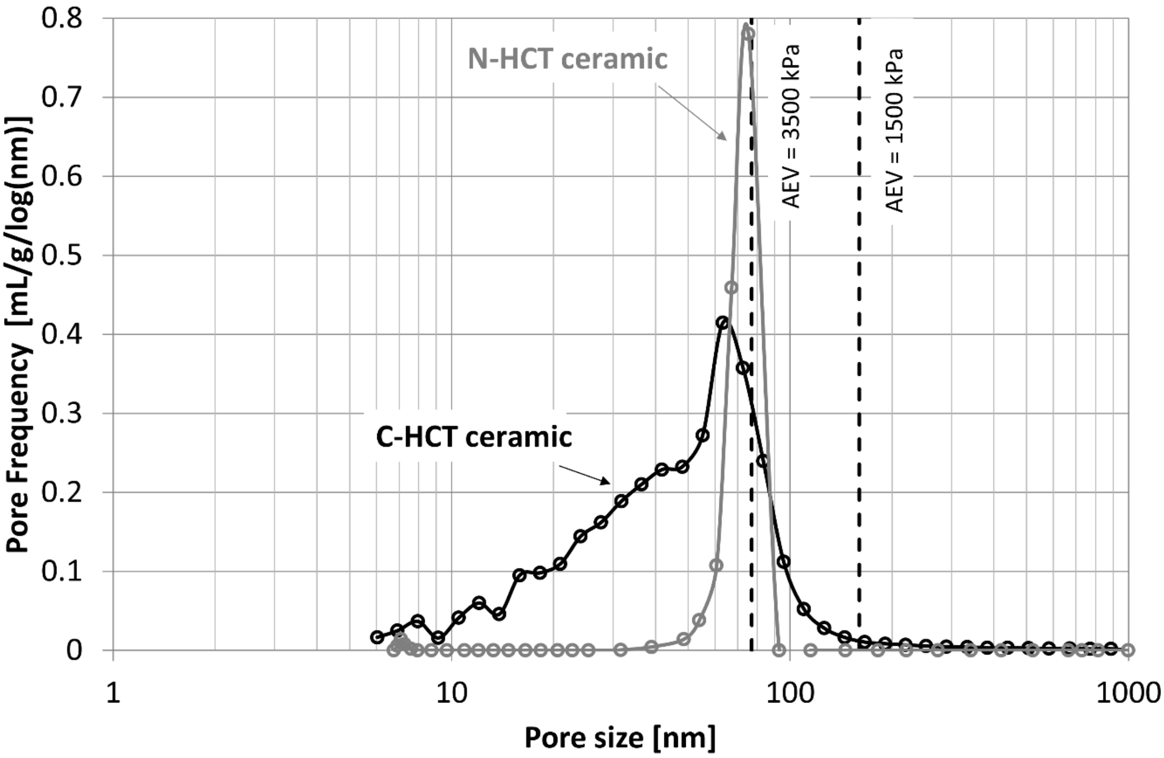

Figure 3. Pore size distribution of the ceramic filters used in both N-HCT and C-HCT obtained from mercury intrusion porosimetry (MIP) tests.

The water reservoir, built within the protective stainless-steel sheath, was designed to be 50 mm^3. This was considered to be large enough to allow deflection of the pressure transducer when under tension. Finally, clear epoxy with good performance for bonding metals and ceramics was used to secure and seal the ceramic filter and pressure transducer inside the protective sheath.

Overall, four N-HCTs were assembled at Northumbria University according to the design specifications and used in this study, two N-HCTs were tested at Northumbria University, UK, while the other two were tested at UPC-Barcelona Tech, Spain. To assess the performance of the new ceramic filter in the

N-HCTs, two C-HCTs were also assembled with the more commonly used 1.5 MPa ceramic filter. Comparatively with the N-HCTs, in the C-HCT design, the only difference was the size of the ceramic filter measuring 15.4mm in diameter while maintaining the 5 mm in height. The overall dimension, pressure transducer and water reservoir size were the same as in the N-HCT design.

FIRST SATURATION, CALIBRATION AND FIRST CAVITATION AT NORTHUMBRIA UNIVERSITY

Whereas the proper implementation of first saturation is often overlooked, it cannot be stressed enough how important this procedure is and how it influences the performance of HCTs. HCT performance is highly dependent on the water saturation level (the relation between air and water present within the voids) of the ceramic filter and water reservoir.

After assembly, the four completely dry HCTs (2 N-HCTs and 2 C-HCTs) were placed and sealed inside a saturation vessel to undergo the first saturation. On one end, the saturation vessel was connected by hydraulic valves to a Pfeiffer DUO 11 two stage rotary vane vacuum pump, delivering an absolute pressure of 3.10^{-4} kPa. The other end the saturation vessel was connected to a beaker with deaired deionised water at atmospheric pressure and a 4 MPa GDS Instruments pressure volume controller.

The procedure for the first saturation of the N-HCTs and C-HCTs can be described in the following sequential stages: vacuum, zero-pressure, and pressurisation. In the vacuum stage, the HCTs were initially subjected to vacuum for about 1 hour. During this stage the valves connected to the beaker with water and to the pressure volume controller were kept closed. This process allows the vacuum pump to evacuate most of the air entrapped within the ceramic filter. After 1 hour, in the zero-pressure stage, the valve to the vacuum pump was closed, while the valve connecting to the beaker containing deaired deionised water at atmospheric pressure was open for about 2-5 seconds to rapidly flood the empty space and increase the pressure to atmospheric inside the saturation vessel. This stage is important for two reasons. Firstly, the pressure controller is not able to cope with negative pressures. And secondly, even with the rapid flow setting, the water flowrate of the pressure controller is inadequate to rapidly flood the empty volume of the saturation vessel. Immediately after the zero-pressure stage, in the pressurisation stage, the valve to the beaker with water was closed, while the valve to the pressure controller, set to the water pressure of 3.5 MPa, was open. The HCTs were then left inside the saturation vessel overnight under a water pressure of 3.5 MPa.

Following the stage of first saturation, calibration of the HCTs was performed. Calibration of the N-HCTs and C-HCTs was performed on the positive pressure range and extrapolated to the negative as suggested by Tarantino and Mongioví (2002). Voltage readings from the HCTs were recorded at specific water pressures (3500 – 3000 – 2500 – 2000 – 1500 – 1000 – 500 – 250 – 100 – 50 – 25 – 50 – 100 – 250 – 500 – 1000 – 1500 – 2000 – 3000 – 3500 kPa) applied with the pressure volume controlled. The typical regression lines of voltage versus pressure for the two types of HCTs are presented in Figure 4. As it can be observed in Figure 4, the calibration curves did not show significant hysteresis in obtained readings from the HCTs within the applied pressure range. Moreover, the obtained calibration curves with the N-HCT and C-HCT suggests that the ceramic filter does not seem to influence the performance of the PX600 pressure transducer. Comparatively, the obtained slope values of the linear regression lines were very similar in value for both sensors (0.5904 kPa/μV for the N-HCT and 0.6089 kPa/μV for the C-HCT).

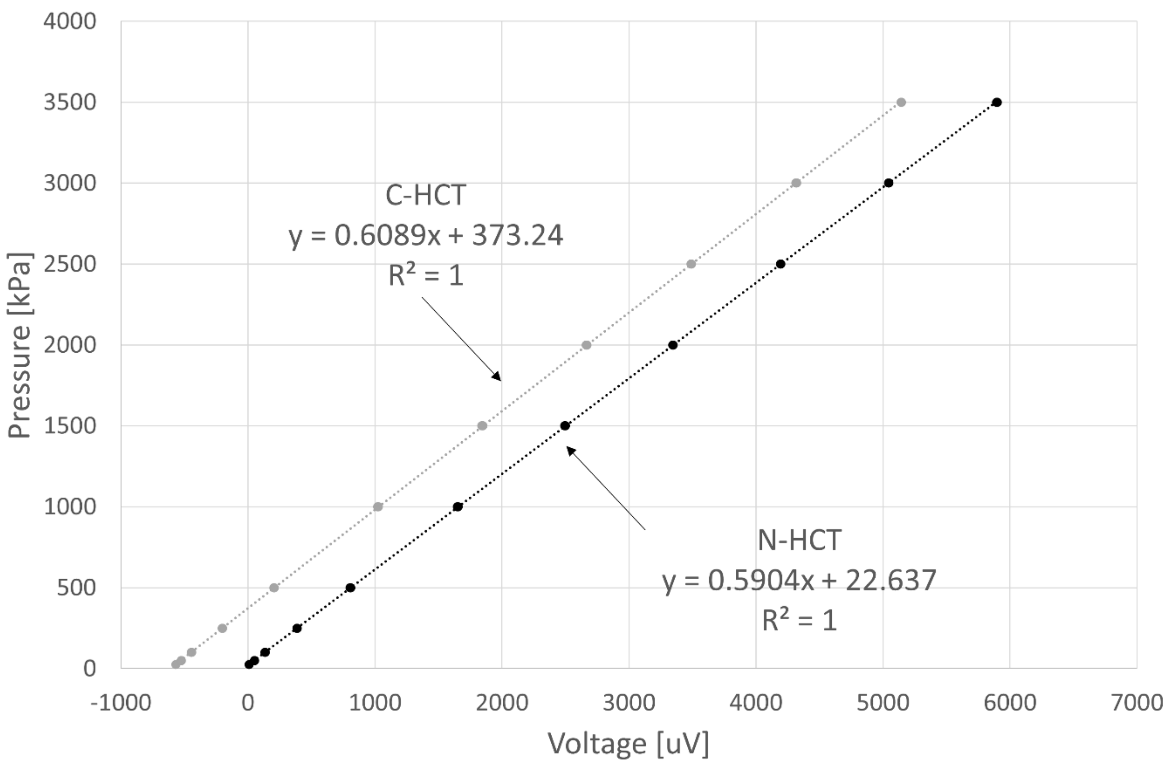

Figure 4. Calibration curves for C-HCT (left) and N-HCT (right).

After calibration, the HCTs were removed from the saturation vessel and placed in a beaker of free standing deaired deionised water. After the readings from the sensors equalised with water pressure in the beaker (close to atmospheric) the HCTs were subjected to their first evaporation tests (sometimes referred to as cavitation test).

Evaporation tests are normally used to determine the maximum attainable measuring range of HCTs and are performed by exposing the sensing face of the HCT to atmosphere. During an evaporation test, as water from the ceramic filter starts to evaporate, the readings from the HCT will decrease in value in an attempt to match the relative humidity (RH) in the laboratory. Current HCTs are not able to measure RH below 98%, which means that at some point the HCTs will eventually cavitate. Nevertheless, the value immediately before cavitation is taken and considered to be the maximum attainable suction range of the HCT.

Figure 5 presents the results obtained in the first evaporation test of two N-HCTs and two C-HCTs carried out at open laboratory atmosphere conditions. As it can be observed in Figure 5, the value immediately before cavitation or measuring suction range for the HCTs was in the range of 2-2.25 MPa and 3.36-3.39 MPa for the C-HCTs and N-HCTs, respectively.

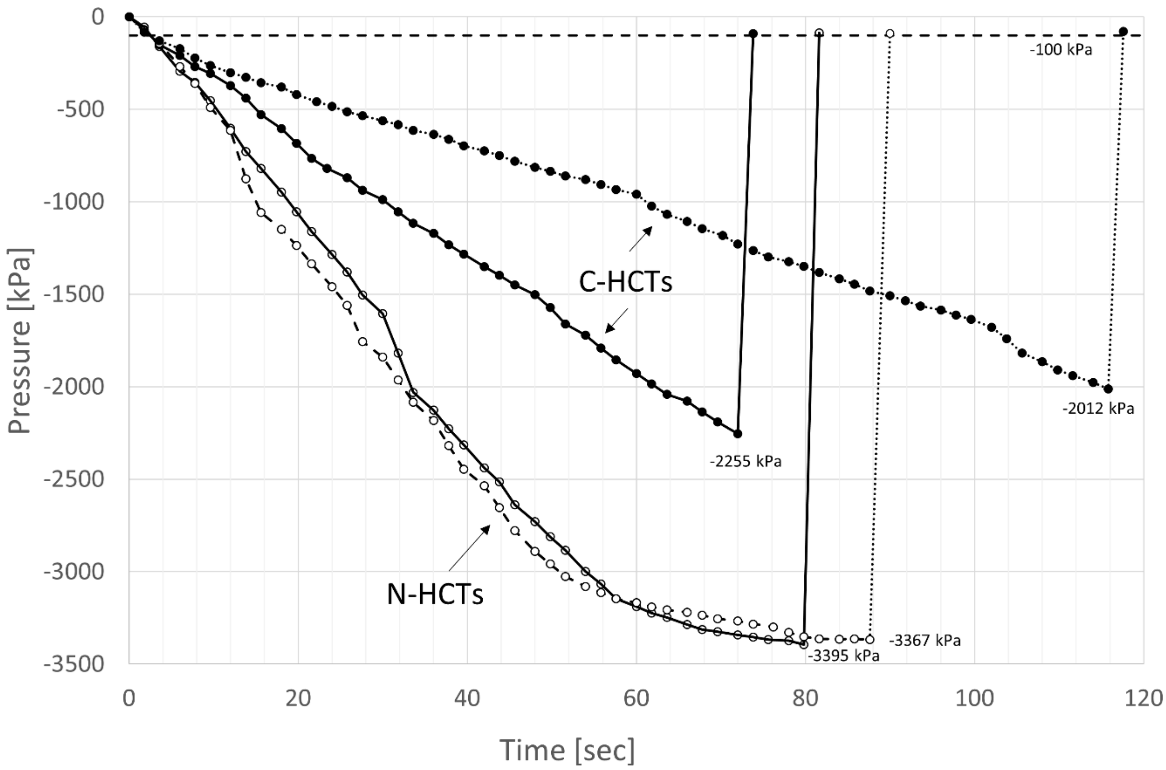

Figure 5. Evaporation test with N-HCT and C-HCT after initial saturation.

The obtained results in Figure 5 show that the C-HCTs were able to sustain a negative pressure below -2 MPa, well beyond the AEV of the ceramic filter of 1.5 MPa. This value suggests what has been mentioned before, that the AEV of the 1.5 MPa ceramic filter is only nominal and each individual ceramic filter may have a higher AEV than specified by the manufacturer. The N-HCTs were able to reach a value lower than -3.3 MPa, significantly less than the C-HCTs, and close to the estimated AEV of the ceramic filter of 3.5 MPa. As shown in Figure 5, the N-HCTs were still able to surpass the C-HCTs in terms of measuring suction range by more than 1 MPa. Finally, the response rates of the N-HCTs were similar for both sensors and significantly faster when compared with the C-HCTs, even though the largest pore size within the ceramic filter of the N-HCTs is smaller than the largest pore size of the ceramic filter of the C-HCTs. The observed behaviours could be explained by the effective pore size distribution and the difference in hydraulic conductivity of both ceramic types. The pore size distribution for a 1.5 MPa ceramic filter typically ranges between 2 nm and 220 nm (Mendes et al., 2020). This wide range of pore sizes within the ceramic filter is hypothesized to be responsible for the observed slower flow and transmition of pressure within the ceramic filter of C-HCTs, but also, responsible for the different response rate observed for the two C-HCTs due to diffferent pore volume distribution in each ceramic. While the pore size distribution for the ceramic filter used in N-HCT the pore size distribution range is monomodal within 40 and 92 nm (see Figure 3) resulting in an increased flow and transmition of pressure, and, in turn, resulting in the much quicker and comparable response rates of both N-HCTs in Figure 5.

RESATURATION AND RESATURATION TIMES AT NORTHUMBRIA UNIVERSITY

As it can be observed in Figure 5, when cavitation occurs there is an immediate jump to values of -80 to -90 kPa (close to absolute zero pressure at sea level) in the HCTs readings. As shown by Mendes and Buzzi (2013), this corresponds to the time that air bubbles emerge in the water reservoir, resulting in the loss of hydraulic connection between the soil and pressure transducer. The presence of these air bubbles in the water reservoir prevents any further measure of soil suction to take place and resaturation of the HCTs is therefore required. Depending on the saturation level of the ceramic filter of the HCT, resaturation may involve only re-pressurisation of the HCT or a repeat of the first saturation procedure. If immediately placed in free water after cavitation, preventing the desaturation of the ceramic filter, re-pressurisation of the HCTs is sufficient to achieve satisfactory resaturation. However, if after cavitation the ceramic filter of the HCT is left to desaturate beyond the point in which the readings of the HCT start to increase from around -90 kPa to atmospheric pressure (when an air continuum between the water reservoir and ceramic filter is reached), resaturation of HCTs will require the full desaturation of the ceramic filter, either by the use of silica gel and/or oven drying at low temperatures (preferably within the working temperature of the components used in the HCT assembly such as pressure transducer and epoxy), followed by a repeat of the first saturation procedure.

In this work the HCTs were regularly monitored and placed in free water as soon as cavitation occurred. Thus, for the resaturation process, the HCTs were placed in the saturation vessel and were re-pressurised at 3.5 MPa with deaired deionised water delivered by the 4 MPa GDS Instruments pressure volume controller. In contrast to the initial saturation, vacuum is not required and, in fact, should be avoided as the change in phase of the water (from liquid water to solid ice) due to the low pressure applied by the vacuum pump could damage the ceramic filter. Initially the N-HCTs and C-HCTs were subject to regular (almost daily) evaporation tests to observe any changes in the measuring range. At the end of each evaporation test, after cavitation had occurred, the HCTs were placed in the saturation vessel to be resaturated.

Figure 6 reports the best results obtained for each of the N-HCTs and C-HCTs. As it can be observed in Figure 6, the measuring range of C-HCTs increased from 2.2 MPa to values closed to 2.8 MPa. Although only recorded once, this result shows that the maximum measuring range of HCTs can be almost twice the value of the 1.5 MPa AEV ceramic filter used in their assembly. The measuring range of the N-HCTs did not vary significantly from initial saturation values presented in Figure 5, increasing from 3.3 MPa to values close to the estimated AEV of the ceramic filter of 3.5 MPa. The main difference in the behaviour from part of the N-HCTs was in the time they took to cavitate from 1.3 minutes to almost 30 minutes, as shown in Figure 6. Water tension, however, was not maintained during this time, where after reaching -3.48 MPa, the readings of the N-HCT started to increase, plateauing at about -2.8 MPa before decreasing once more until cavitation occurred at -3.48 MPa. This kind of behaviour was observed before by Mendes and Buzzi (2013), where they hypothesise that even with the application of high vacuum and high-water pressures during first saturation and resaturation, air pockets will still be present inside the ceramic filter, influencing the ability of the HCT to maintain the value of water tension and, in turn, the ability to accurately measure soil suction at pressure values close to the AEV of the ceramic filter.

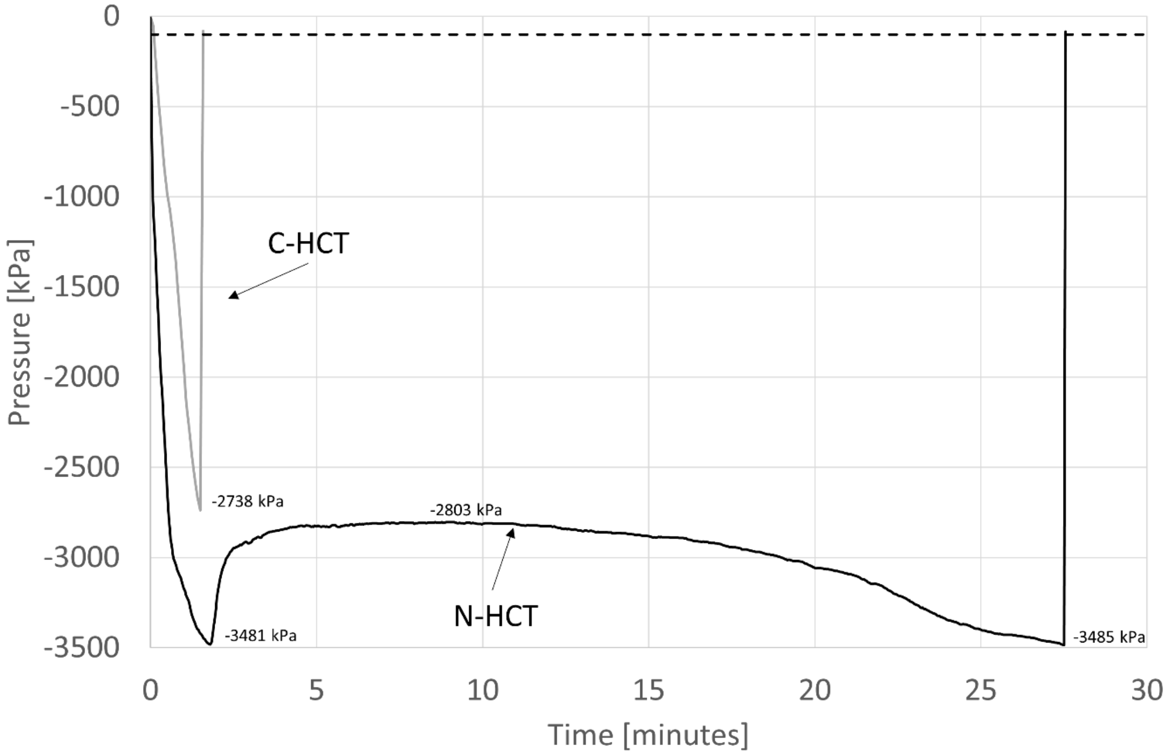

Figure 6. Evaporation test results with N-HCT and C-HCT.

The time required for resaturation at high water pressures of HCTs after cavitation is normally stipulated to be in the range of 12 hours (overnight) up to several days. To study the time HCTs spent pressurised during resaturation and the effect it has on their performance, a series of tests were conducted subjecting both N-HCTs and C-HCTs to short pressurisation times. In these tests, the HCTs were initially kept under high water pressure overnight inside the saturation vessel before the initial evaporation test was conducted. As soon as cavitation occurred, the HCTs were placed in a beaker with deaired deionised water before being placed back inside the saturation vessel where the HCTs were pressurised to 3.5 MPa for 10 minutes, followed once again by an evaporation test. This cycle of evaporation test followed by short resaturation was then repeated at sequential shortened time periods (5, 2.5, 1 minutes) until the HCTs were not able to record pressures below -100 kPa. The sequence was then reversed to verify the resaturation time period required to reactivate the HCTs. In summary, these tests were performed to establish the shortest resaturation time period required to reactivate the HCTs after cavitation.

Three tests were conducted where the results were found to be similar, for clarity and brevity only the result from a single test is presented in Figure 7. As it can be observed in Figure 7, in the initial evaporation test (Ei), the recorded values for the N-HCT and C-HCT before cavitation were -3132 KPa and -1887 kPa, respectively. After 10 minutes of resaturation at 3.5 MPa (R1) and during the evaporation test (E1), the readings of both sensors increased to -3392 KPa and -1978 kPa for the N-HCT and C-HCT, respectively. Similar results were obtained for the resaturation-evaporation test cycles R2-E2 and R3-E3 showing that it is possible to reactivate freshly cavitated HCTs after only 2.5 minutes of water pressurisation at 3.5 MPa. When the resaturation period time was reduced to 1 minute (R1) both HCTs were unable to measure pressure values below -100 kPa, as it can be observed in Figure 7 to the evaporation test E4. After being unable to reactivate the HCTs, the resaturation time period was then reversed. Both HCTs failed to record pressures below -100 kPa to 2.5 minutes and 5 minutes resaturation-evaporation cycles (R5-E5 and R6-E6 in Figure 7, respectively). Only when the resaturation period was extended to 10 minutes (R7) did the HCTs responded by being able to record values of -2541 kPa and -2036 kPa for both N-HCT and C-HCT, respectively.

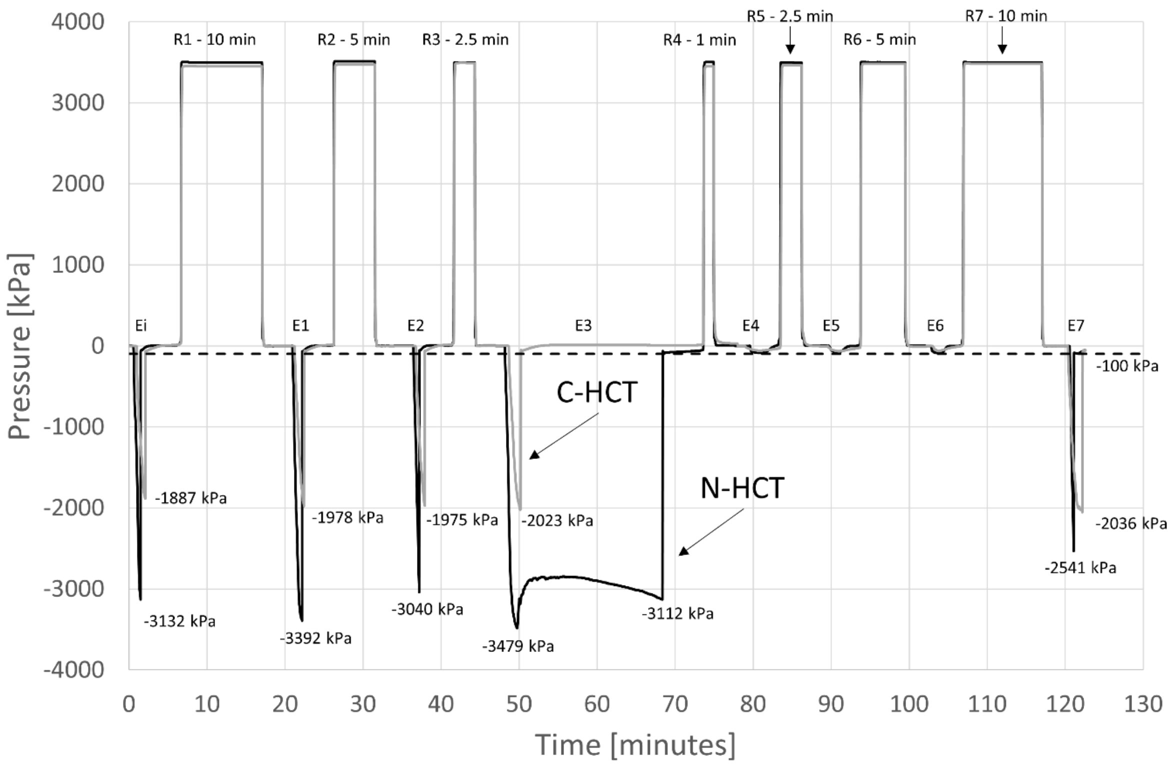

Figure 7. Evaporation and short resaturation cycles with N-HCT and C-HCT.
Ei – initial evaporation cycle after overnight saturation; EX – evaporation cycle after short resaturation (X represents cycle number); RX – Y.Y min – Resaturation cycle of HCTs at 3.5 MPa for short period of time (X represents cycle number and Y.Y min represents the period)

From the obtained results in Figure 7 it was possible to establish that freshly cavitated HCTs can be reactivated in about 10 minutes of resaturation at high water pressure, a significant reduction in the resaturation time, provided that HCTs are placed under pressure immediately after cavitation preventing the desaturation of the ceramic filter. These results can be of particular interest to researchers performing point suction measurements in multiple soil specimens in the laboratory. For researchers intending to use HCTs in field installations note that the resaturation-evaporation cycles presented in Figure 7 were performed on HCTs that were placed in free water immediately after cavitation, something that is unlikely to be possible in field installations. Moreover, the impact of short resaturation periods on the long-term performance of HCTs was also not studied.

POINT SUCTION MEASUREMENTS AT NORTHUMBRIA UNIVERSITY

The N-HCT and C-HCT performance was also studied in relation to the measurement of suction in soil specimens. Point suction measurements with the best performing N-HCT and C-HCT were carried on soil samples prepared at specific water contents. The soil used for the point suction measurement tests was a well graded sandy clay soil of intermediate plasticity, single sourced from a stockpile in

County Durham (Hughes et al., 2009), sieved to 2.8 mm in particle size and with Atterberg limits of 43.3% and 19.6% for the liquid limit and plasticity index, respectively.

For the point suction measurements, samples with the dimensions of 50 mm in diameter by 20 mm in height were cut from larger dynamically compacted soil specimens prepared at 25% of water content following the Mendes and Toll (2016) sample preparation procedure. These were then dried to target water contents corresponding to known suction values. For reference, the gravimetric water versus matric suction relationship obtained using direct methods (HCTs) and indirect methods (in-contact filter paper) by Mendes and Toll (2016) is shown in Figure 8. When the target water content was reached, the small samples were then wrapped in cling film for 24 hours for the water content to equalise inside the samples. After 24 hours of equalisation, the samples were unwrapped and placed inside a sealed chamber where an HCT was placed in contact with the top of the sample surface to allow the measurement of suction, as shown schematically in Figure 9. A 200 gr load was applied to the back of the HCT to ensure an intimate contact was established between soil sample surface and the sensing face of the HCT.

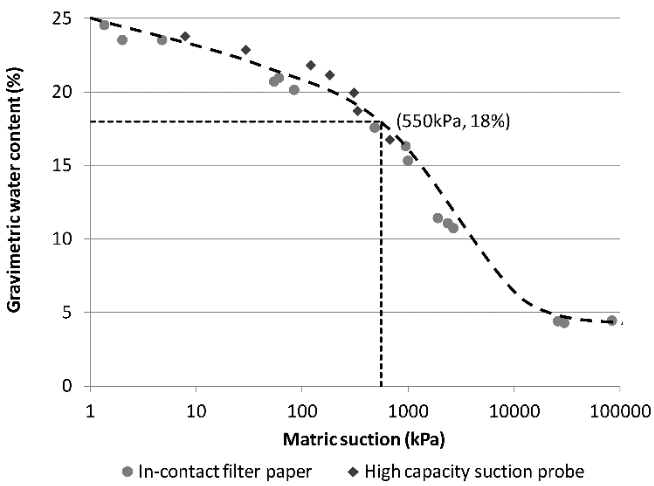

Figure 8. Gravimetric water content versus matric suction for compacted samples dried from 25% of water content, after Mendes and Toll (2016).

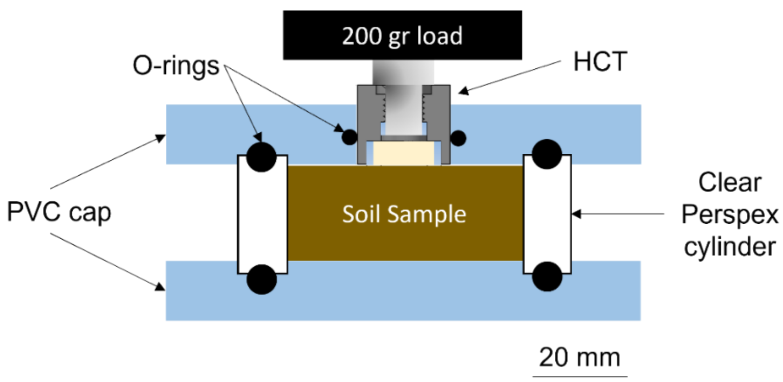

Figure 9. Schematic of the sealed chamber used in the point measurements with N-HCTs and C-HCTs.

Four samples that were initially prepared at a gravimetric water content of 25% were dried to 17.5%, 15%, 13% and 10%. According to Figure 8, the corresponding soil matric suction values for the different water contents are 700 kPa for 17.5%, 1000 kPa for 15%, 1600 kPa for 13%, and 3000 kPa for 10%.

Figures 10 and 11 present the matric suction readings obtained with the N-HCT and C-HCT for point measurement tests performed on samples prepared at the aforementioned water contents.

In Figure 10, the equalised suction reading from the N-HCT and C-HCT for the soil sample tested at 15% water content (solid lines in Figure 10) were 925 kPa and 956 kPa, respectively. For the sample tested at 10% water content (dashed lines in Figure 10), equalisation with the soil sample was reached at 2865 kPa for the N-HCT, while cavitation occurred in the C-HCT when measuring a suction value of 1825 kPa. On both tests presented in Figure 10, the readings from the N-HCT equalised with suction in soil within the first 7 minutes; whereas, for the only successful test with the C-HCT (for the sample tested at 15%) equalisation occurred after 14 minutes. Thus, the N-HCT was able to measure comparable high suctions to the C-HCT, while reaching equalisation with the suction in soil sample in half of the time.

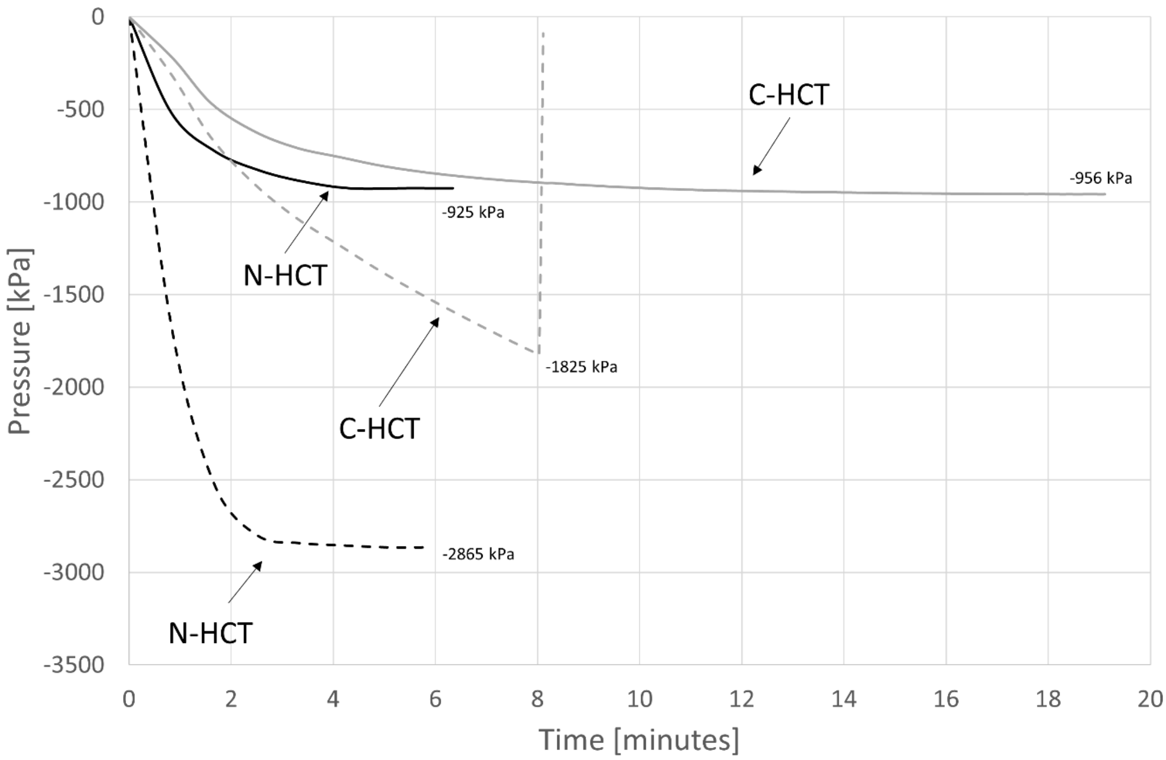

Figure 10. Comparison of the response rate of N-HCT and C-HCT during measurement of suction in soil specimens prepared at a water content of 15% (solid lines) and 10% (dashed lines) and without the use of a soil paste in the HCT sensing face.

In Figure 11, the equalised suction reading from the N-HCT and C-HCT for the soil sample tested at 17.5% water content (solid lines in Figure 11) were 573 kPa and 645 kPa, respectively. While, for the sample tested at 13% water content (dashed lines in Figure 11), equalisation with the soil sample was reached at 1650 kPa and 1591 kPa for the N-HCT and C-HCT respectively. In the two tests presented in Figure 11, the adopted procedure was changed slightly with the addition of soil paste (prepared at the liquid limit of the soil of 43.3%) applied to the sensing face of the HCTs. The use of soil paste, as suggested by Oliveira and Marinho (2008), is highly recommended since it minimises the risk of poor contact between the sensing face of the HCT and soil sample. However, the soil paste, normally prepared at a wetter state than the soil, increases the equalisation time between the soil sample and HCT since time is now required for the soil sample, soil paste and HCT to reach an equilibrium corroborating the findings of Oliveira and Marinho (2008). This is evident in Figure 11, where for both the N-HCT and C-HCT the equalisation time increased significantly to 20-30 minutes.

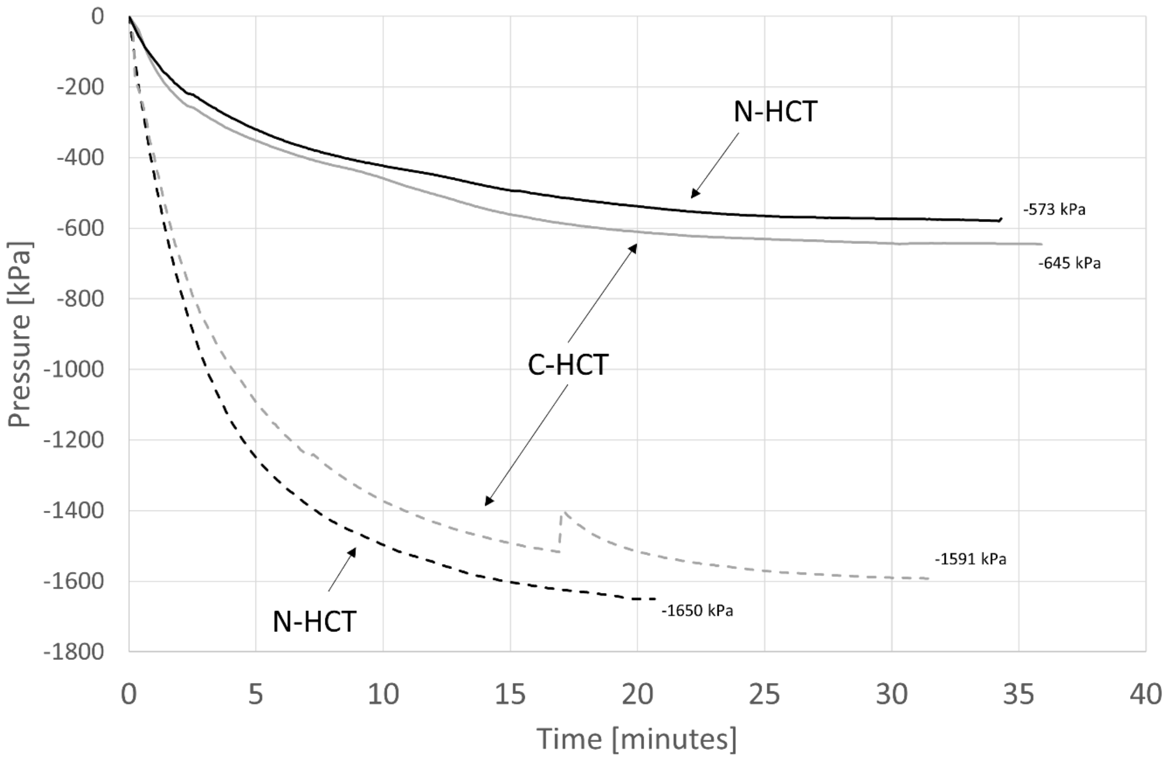

Figure 11. Comparison of response rate of N-HCT and C-HCT during measurement of suction in soil specimens with soil paste at a water content of 17.5% (solid lines) and 13% (dashed lines) and with the use of a soil paste in the HCT sensing face.

Overall, the results in Figures 10 and 11 show a good agreement between the readings obtained with the two different HCT designs. Where, if soil paste is not applied to the sensing face of the HCT, then the N-HCT is able to reach equilibrium with the soil in half the time of the C-HCT, corroborating the behaviour observed during the evaporation tests presented before. Moreover, the obtained results with the N-HCT, by being very close to the expected suction values and the readings of the C-HCT, demonstrate that the new alumina ceramic filter is suitable for use in HCT designs for measurement of soil suction.

CONTINUOUS SUCTION MEASUREMENTS AT UPC-BARCELONA TECH

Continuous drying tests with N-HCTs were conducted in UPC-Barcelona Tech, Spain. In a continuous drying test, as the name suggests, soil samples are placed in contact with the N-HCTs and are exposed to atmosphere allowing progressive drying of the soil sample. The samples are left to dry until cavitation in the N-HCTs occurs.

Before performing the continuous drying tests, the N-HCTs were initially saturated and calibrated following the procedure presented earlier. However, the maximum applied pressure was limited to 3 MPa due to unavailability of a pressure controller with sufficient pressure range of the estimated AEV of the ceramic filter.

A series of evaporation tests were then performed to assess the N-HCTs maximum suction measuring range. The best overall results from the series of evaporation tests with the N-HCTs are presented in Figure 12. As it can be observed from Figure 12, the two N-HCTs were able to reach pressures in the range of the saturation pressure applied of about 3 MPa and showing a similar behaviour pattern as in Figures 5 and 6. After reaching a value close to -3 MPa, the readings from the N-HCTs started to increase and plateauing before cavitation occurred at higher pressure of about -2.7 to -2.9 MPa.

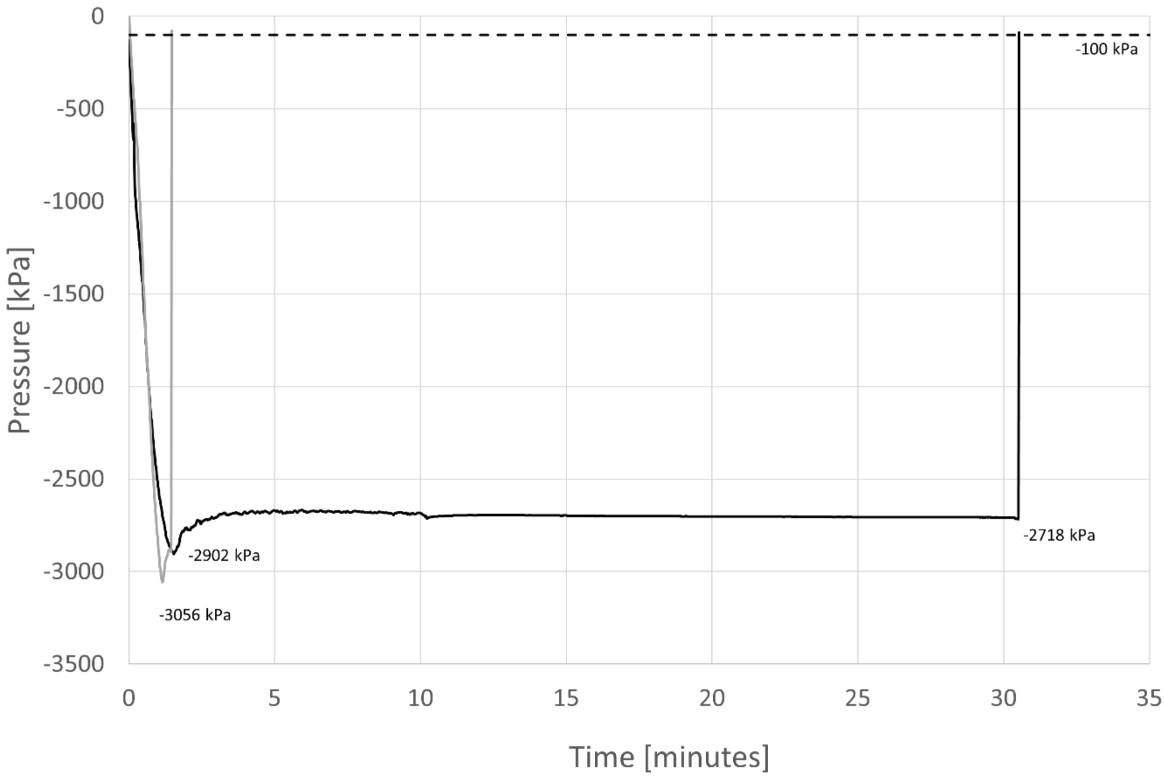

Figure 12. Best overall evaporation test results with the N-HCTs at UPC-Barcelona Tech.

Comparing the results in Figures 6 and 12 suggests that the maximum measuring range for the N-HCTs is highly dependent on the applied pressure during saturation. In both cases, the N-HCTs were able to read pressure values equivalent to the applied pressures demonstrating that N-HCTs saturated at lower water pressures are still able to perform.

After assessing the expected performance of the N-HCTs, two continuous drying tests were performed with two different low plasticity clays locally sourced in Barcelona, Spain. One of the continuous drying tests was conducted in a soil sample prepared from slurry with the well-known Barcelona silty clay that was sieved below 2 mm and with Atterberg limits of 32% and 16% for the liquid limit and plasticity index, respectively (Gens et al., 1995; Barrera, 2002). The second continuous drying test was conducted in a soil sample cut from a dynamically compacted larger sample, using the proctor hammer, at a water content of 19% (equivalent to a degree of saturation of 92%) with the locally sourced Agropolis clay that was sieved below 2 mm and with Atterberg limits of 29% and 12% for the liquid limit and plasticity index, respectively (Cordero et al., 2020). These tests were performed by clamping the N-HCTs to a support platform where the soil samples, with initial dimensions of 50 mm in diameter and 20 mm in height, were placed on top of the N-HCT as shown schematically in Figure 13. To ensure a good contact between the soil samples and sensing face of the N-HCT, an indentation of 5 mm in depth and 20 mm in diameter (same diameter as the N-HCT) was cut in the soil samples. The indentation was supplemented, in the case of the sample prepared with the Agropolis clay, with soil paste (prepared at the liquid limit water content of 29%). The paste was used in order to seal any existing gaps and crevices that might have been created during the cutting of the indentation in the soil sample. The drying of the soil sample was produced at open laboratory atmosphere conditions.

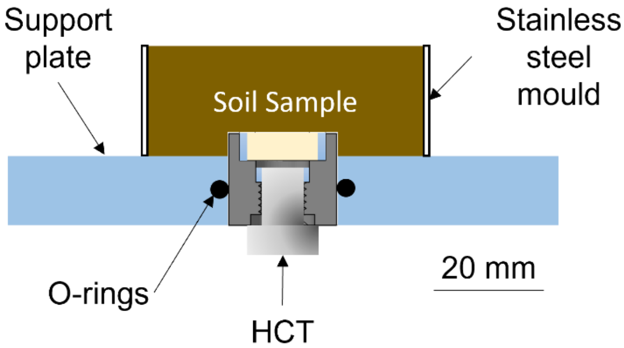

Figure 13. Schematics of the setup used the for continuous drying test.

The readings obtained with the N-HCTs during the continuous drying tests with the Barcelona silty clay and the Agropolis clay are presented in Figure 14. As it can be observed in Figure 14, the pressure readings obtained with N-HCTs seem to follow the expected evolution of soil suction during continuous drying in both tests. The Agropolis clay sample was dynamically compacted using the Proctor hammer with a starting water content of 19% equivalent to a degree of saturation of 92% (grey line in Figure 14). After the initial equalisation of N-HCT with the matric suction in the sample, the pressure readings from the N-HCT were progressively decreasing in time as the soil sample desaturated and until a value of -2830 kPa was achieved. Beyond this value, the pressure readings from the N-HCT diverged in pattern. Specifically, an increase was observed initially, followed by a decrease in the pressure readings before cavitation of the N-HCT occurred, while recording a pressure value of -2963 kPa. The Barcelona silty clay sample was prepared from an unconsolidated slurry at 34% (black line in Figure 14). The initial pressure readings from the N-HCT were close to 0 kPa, for the first 3 days, before significant desaturation in the soil sample occurred as the pressure readings of the N-HCT started to progressively decrease with desaturation of the soil sample down to -2811 kPa. Beyond this point, much like the observed behaviour of the N-HCT in the continuous drying test performed with the Agropolis clay sample, a small increase in the pressure readings was observed initially before decreasing until cavitation of the N-HCT occurred, while recording a pressure value of -3101 kPa.

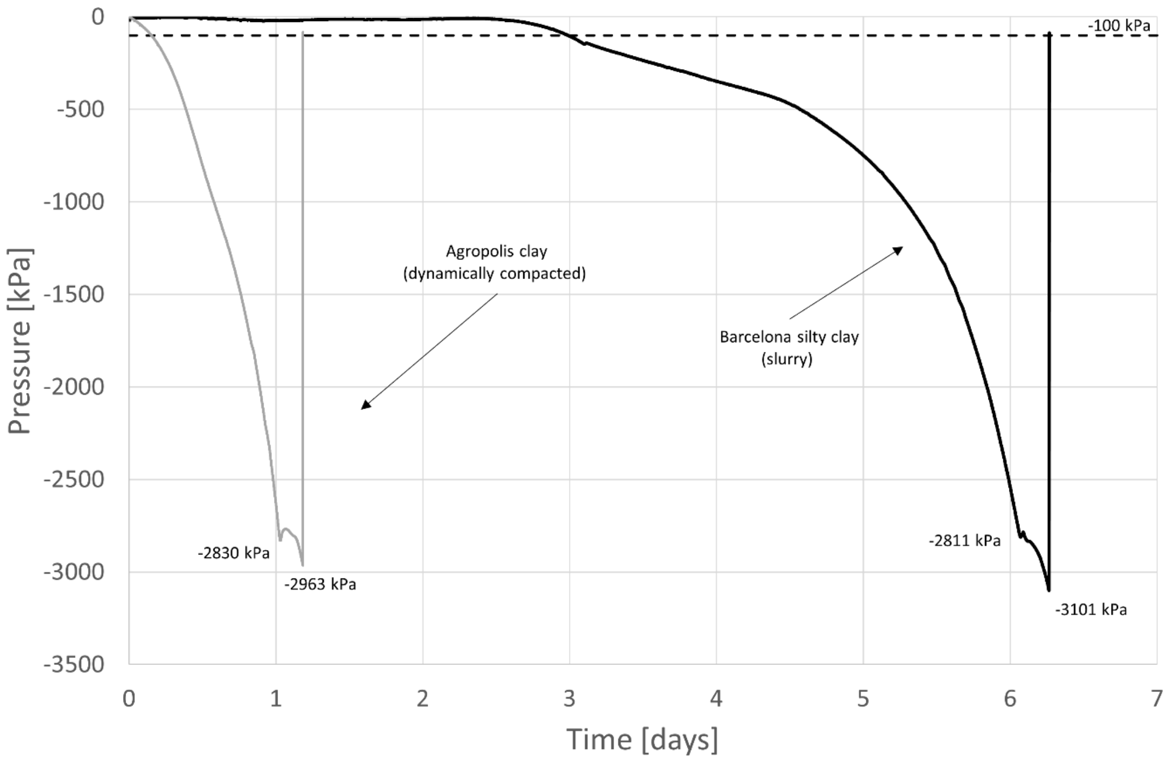

Figure 14. Continuous drying test with N-HCTs on the Barcelona silty clay sample prepared from slurry with an initial water content of 34% (black line) and on the Agropolis clay sample dynamically compacted using the Proctor hammer with an initial water content of 19%.

From Figure 14 it is evident that, while the N-HCTs were still able to consistently record decreasing pressure values, the pattern of the suction recordings with the N-HCTs beyond 2.8 MPa appeared to be influenced by something other than the actual suction in the soil samples. This suggests that the reliability of the measurement with N-HCTs when recording suction values close to the pressure applied during saturation, much like the observed behaviour observed by Mendes and Buzzi (2013) in their evaporation tests, is not only influenced by the AEV of the ceramic filter, but also by the water pressure applied during saturation. Nevertheless, the obtained results with the N-HCTs during the continuous drying tests show that by applying a saturation pressure of 3 MPa to the N-HCTs it is possible to reliably monitor soil suction evolution in soil samples during drying to values up to 2.8 MPa. A value that is already a significant increase in the measuring range for HCTs, but also, an important step towards the development of new HCTs capable of measuring soil matric suction beyond 3 MPa.

CONCLUSIONS

High capacity tensiometers (HCT) are sensors that are increasingly used in the monitoring of pore water pressures, both positive and negative (suction). They are systematically employed in field installations to monitor the evolution of pore water pressures and in the study of unsaturated soils in the laboratory. HCTs, uniquely enable the direct measurement of soil suction and also respond faster to changes in soil suction, which are both major limitations in indirect methods of suction measurement (e.g., inferred suction from soil moisture content). However, HCTs have two major limitations: cavitation and insufficient measuring range.

In this manuscript a new HCT design (N-HCT) was presented, incorporating a new alumina ceramic filter with a largest pore size of 75-92 nm, estimated to have an AEV of 3.5 MPa. The performance of the N-HCT was assessed in relation to maximum measuring suction range and measurement reliability. Specifically, the performance comparison was made with the more common 1.5 MPa AEV ceramic filter HCTs (C-HCTs) which were also assembled in the laboratory.

From the evaporation tests conducted at Northumbria University, it was possible to establish that with the new alumina ceramic filter, the N-HCTs maximum measuring suction range is close to 3.5 MPa, resulting in an almost twofold increase in the measuring range when compared with other HCTs built with the more commonly used 1.5 MPa AEV ceramic filter found in the literature. Comparatively, the N-HCTs measuring suction range of 3.5MPa was still significantly higher than the maximum measuring range achieved by the C-HCTs, of about 2.8 MPa even when high vacuum and high-water pressure (of 3.5 MPa) was applied during the initial saturation.

From the point suction measurement tests performed with both N-HCTs and C-HCTs in sandy clay soil samples it was found that the obtained results were comparable between the two different HCT designs, with a difference of less than 70 kPa during high suction measurements. In the test performed with soil sample dried to 10% water content, the N-HCT was able to reach an equilibrium with the suction in the soil sample at a suction value close to 2.9 MPa, whereas the C-HCT cavitated at around 1.8 MPa. The later result shows that N-HCTs can be used for soil suction measurements within a higher suction range than C-HCTs. Moreover, the obtained results were comparable with previous experimental results obtained with indirect methods showing the reliability and confidence in the measurements made with the two different HCT designs.

The use of soil paste prepared at the soil liquid limit, applied to improve the contact between soil and HCT, was found to influence the time required to reach suction equilibrium between the soil sample and HCT: without the use of soil paste on the sensing face, the time that the N-HCTs required to reach an equilibrium was found to be less than 10 minutes, half the time when compared with the C-HCTs; when soil paste was applied to the sensing face, the time to reach suction equilibrium was comparable for both HCT designs at about 20-30 minutes.

Continuous soil suction measurements were also conducted with N-HCTs on two low plasticity clays at the UPC-Barcelona Tech. The obtained results show that the N-HCTs were able to successfully record suction changes as the soil samples progressively dried up to a value of soil suction of 2.8 MPa. Although still able to read lower pressure values (higher suction), down to -3.1 MPa, during the continuous suction measurement tests, the observed pattern of the readings from part of the N-HCTs suggests that the water pressure of 3 MPa applied during saturation may have affected the N-HCTs measuring range. However, it is important to consider the observed performance of the N-HCTs in continuous drying tests is quite relevant for the general adoption of HCTs designed with this new alumina ceramic filters since it is more common to find, typically as part of other testing equipment, pressure controllers with 3 MPa pressure range in most geotechnical laboratories than pressure controllers with higher pressure ranges.

The results obtained with the N-HCTs presented in this paper are an important step towards the development of HCTs capable of measuring soil matric suction beyond 3 MPa. With an extended measuring suction range, the N-HCTs already enable the extended study of soil suction using direct methods necessary for the determination of soil water retention curves that are crucial in the development of constitutive models for describing the behaviour of unsaturated soils; but also, in the development of more reliable real-time soil suction field monitoring systems, preventing or, at least, delaying cavitation in HCTs at soil suctions below the AEV of the ceramic filter during prolonged continuous monitoring.

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