Cone Penetration Testing 2022 – Gottardi & Tonni (eds)

Tensiocone: A cone penetrometer with the facility to measure negative pore-water pressure

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ABSTRACT: CPT sounding initially passes through the vadose zone, that is the zone above the phreatic surface where pore-water pressure is negative and degree of saturation is usually lower than unity. Negative pore-water pressure (suction) significantly affects tip resistance and sleeve friction and lack of knowledge of soil suction in this zone makes CPT data difficult if not impossible to interpret. For the case of Piezocone Cone Penetration Test (CPTU), crossing the vadose zone also exposes the cone tip porous filter to desaturation jeopardising the measurement of positive pore-water pressure once the cone penetrates the saturated zone below the phreatic surface. This paper presents the concept of the Tensiocone, a cone penetrometer with the facility to measure pore-water pressure in both negative and positive range. A first prototype was tested in the laboratory and in the field to investigate one of the major challenges in Tensiocone measurement, that is whether adequate contact can be established between the ground and the tensiometer porous filter during penetration.

1 INTRODUCTION

The Cone Penetration Test (CPT) is a valuable device for characterising soil stratigraphy and estimating soil mechanical properties. The penetrometer is inserted from the ground surface and initially crosses the vadose zone, that is the zone above the phreatic surface where pore-water pressure is negative (suction) and degree of saturation is usually lower than unity. This vadose zone can extend to several meters.

Strength and stiffness of the ground in the vadose zone are significantly affected by suction variations as a result of rainfall and evapotranspiration and so do the tip resistance and sleeve friction. Empirical equations used for characterising soil properties from CPT profiles have been developed from tests conducted in the calibration chamber on soils in dry or saturated states. These equations clearly do not hold for unsaturated soils. Data acquired when crossing the vadose zone are therefore difficult if not impossible to interpret in routine practice.

In recent years, the research groups at the University of New South Wales in Australia (Pournaghiazar et al. 2012; Yang & Russell 2015, 2016) and the University of Oklahoma in the US (Miller et al. 2018; Miller & Collins 2019) have conducted extensive experimental campaigns where CPTs where performed in calibration chambers on unsaturated soils (by controlling or monitoring suction). This has led to a new generation of semi-empirical equations where soil properties can be inferred from tip resistance and sleeve friction by explicitly considering the influence of suction. However, the use of these equations in routine applications remains a challenge due to the difficulty of measuring suction in the field at depths greater than 1-2m.

The most obvious approach to measure suction during penetration is to provide the penetrometer with a High-Capacity Tensiometer to measure pore-water pressure in the negative range (Tarantino 2002; Marinho et al. 2008). A HCT can also measure pore-water pressure in the positive range and this would enable CPT measurements also in the saturated zone below the phreatic surface. The HCT could offer more accurate measurements than Piezocone Cone Penetration Test (CPTU) because it would not suffer from desaturation when passing through the unsaturated vadose zone (Mondelli et al. 2009; Sandven 2010).

This paper presents the development a new cone penetrometer named ‘Tensiocone’, which incorporates a high-capacity tensiometer for the measurement of pore-water tension during cone penetration. The major challenge with this design is to ensure proper contact between the high air-entry porous filter and the

DOI: 10.1201/9781003308829-31

ground. In laboratory measurements using standing-alone high-capacity tensiometers, a soil paste is interposed between the high-capacity tensiometer and the soil to ensure continuity between water in the soil pores and water in the tensiometer water reservoir. This paste cannot be used on the HCT installed on the penetrometer as it would be taken off as soon as the HCT touches the ground.

2 TENSIOCONE CONCEPT AND DESIGN OF FIRST PROTOTYPE

The concept of the Tensiocone is illustrated in Figure 1. An adaptor is placed between the friction sleeve and the cone tip and incorporates a High-Capacity Tensiometer (HCT) (Tarantino & Mongioví, 2002). The first prototype presented in this paper was designed without the cone tip and friction sleeve since the aim was to test the pore-water pressure measurement. However, the same adaptor could be easily incorporated into a fully functional cone penetrometer.

The measurement of pore-water pressure is carried out laterally to minimise the stresses on the porous filter compared to the case of a porous filter located on the penetrometer tip. The major challenge with this new instrument is to ensure proper contact between the porous ceramic filter and the ground.

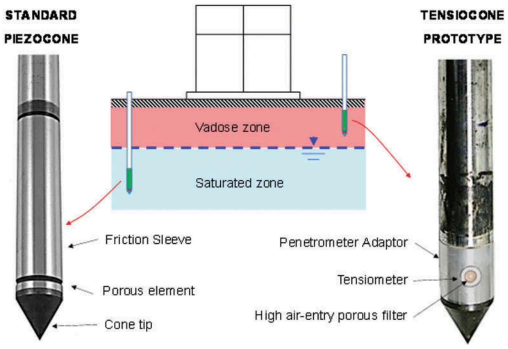

Figure 1. Piezocone and Tensiocone for pore-water pressure measurement below and above the phreatic surface respectively.

2.1 *Tensiocone HCT*

The HCT is installed horizontally into the adaptor and its size must be kept small in order to maintain the rear electrical connections near the axis of the cone and allow the electrical cables to run through the hollow push rods. Figure 2 shows the design concept for the HCT.

It consists of an integral strain-gauge diaphragm and an extension to support a perforated board with four pins to connect the thin strain-gauge wires to the thick cable wires transferring the signal through the hollow push rods. A high air-entry value porous filter (800 kPa) was cut and glued into the HCT using epoxy. The same epoxy was also initially used to fix the tensiometer to the penetrometer adaptor.

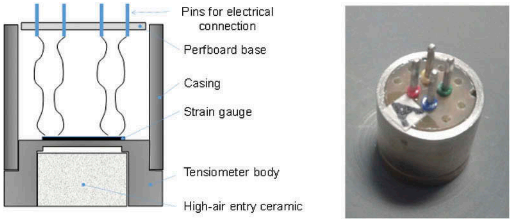

Figure 2. High-Capacity Tensiometer (HCT) installed in the cone penetrometer shaft.

2.2 *Reliability of HCT measurement*

The performance of two tensiocone HCTs was initially tested via simultaneous measurement on a kaolin sample compacted to 300 kPa vertical stress at 30% water content. Measurement was carried out in the suction box described in Tarantino & Mongioví (2003). The box lid has two holes equipped with O-rings to install the two HCTs. O-rings are also interposed between the annular cylinder hosting the sample and the base and lid respectively to prevent evaporation from inside the suction box. A small air gap was present between the top surface of the sample and the lid.

The two HCTs with an initially dry porous filter were subjected to ‘one-shot’ saturation directly in the saturation chamber by pressuring water to 4 MPa for 5 days. The response of the HCTs was then tested by generating water tension up to cavitation (by wiping the porous filter). Cavitation occurred at the air-entry value of the porous ceramic filter. The HCTs were then placed again in the saturation chamber at 4 MPa for 5 days.

The long-term measurement test is shown in Figure 3. The two HCTs successfully measured the same pore-water tension despite the fluctuations due to water drops condensing on the lid and falling periodically on the sample surface. Cavitation occurred as the 800 kPa air-entry value of the porous filter was approached.

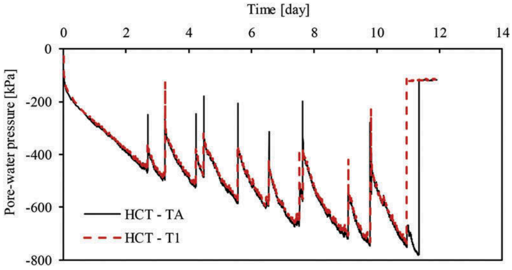

Figure 3. Long term measurement using two High-Capacity Tensiometers installed simultaneously on the same clay sample.

3 TENSIOCONE MESUREMENT IN MOCK-UP LABORATORY TEST

A series of penetration tests were carried out in samples placed in a mould 100 mm diameter and 150 mm height (Figure 4). A transparent lid was used to seal the upper surface of the sample to avoid evaporation during the test. Two holes were made into the lid; the larger one was used to insert the tensiocone equipped with the HCT whereas the smaller one was used to install a HCT on the top of the sample to benchmark the measurement by the Tensiocone HCT. The aim of the test was to verify whether adequate contact could be established between the HCT porous and the soil during penetration in the absence of the clay paste typically used in HCT measurements.

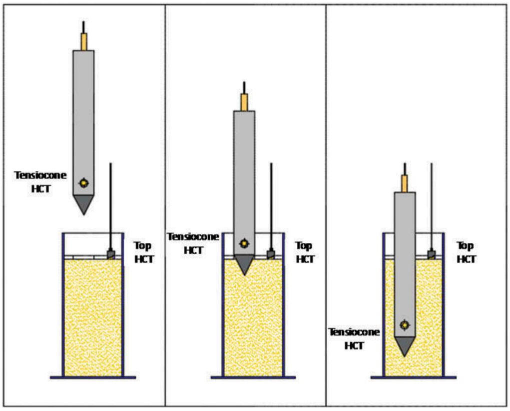

Figure 4. Mock-up scale test to simulate measurement during penetration.

3.1 *Lightly compacted sample*

The first test was made on a lightly compacted sample, which should represent the worst case scenario (the lower the density, the lower is the radial pressure pushing the soil against the HCT porous filter). The sample was prepared using 80% of coarse fraction (sand) and 20 % of fine fraction (Speswhite kaolin clay) humidified at 30% water content calculated with respect to the dry mass of kaolinite clay only (corresponding to 6% overall water content). The two fractions were mixed dry and water was then sprayed over the mix. After mixing, the humidified soil was sealed in a plastic bag for at least 24h for water content equilibration.

In this test, the soil was placed in the mould in a single layer and compacted manually. After closing the mould with the transparent lid, the tensiocone was penetrated for about 100 mm into the sample. Another HCT was installed on the top surface of the sample. To improve the contact between the top HCT and the sample surface, a thin layer of kaolin paste (water content 100%) was interposed between the top HCT and the soil. Figure 5 shows the results of the pore-water pressure measurements of the two HCTs installed on the tensiocone and top surface respectively.

There was a lowest value of water pressure detected by the tensiocone HCT during penetration. Following penetration, pore-water pressure increased to -550 kPa and equalised to this value. The top HCT equalised to a slightly lower pressure (-560 kPa) therefore showing that adequate contact could be established between the porous ceramic filter of the tensiocone HCT and the sample.

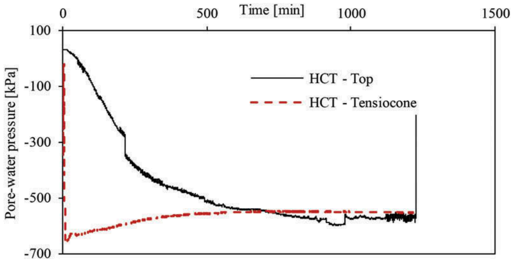

Figure 5. Penetration test on lightly compacted sample (20% clay/ 80% sand).

3.2 *Moderately compacted samples*

The second part of the experimental program involved moderately compacted samples. Three samples with different coarse/fine fraction ratio and compaction water content were prepared for this purpose. The soil was first humidified and cured for at least 24h in sealed plastic bags and then compacted in three layers inside the mould using a loading frame until reaching the target dry density of 1.4 g/cm^3.

Figure 6 shows the pore-water pressure measurements during penetration in a sample composed of 80% of sand, 20% of kaolin and humidified at 40% water content calculated with respect to the mass of the fine fraction (corresponding to an overall water content equal to 8%). Similar to the lightly compacted sample, the tensiocone pore-water pressure decreased during penetration and increased once penetration was stopped until achieving equilibrium. The top HCT converged to similar values (the drop at the end of the measurement was due to the loss of contact with the sample).

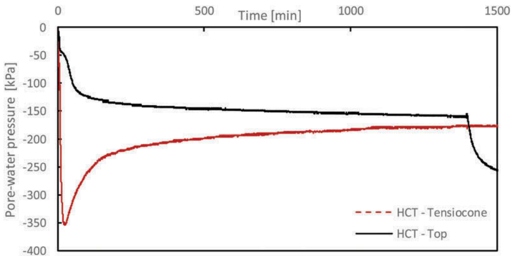

Figure 6. Penetration test on moderately compacted sample (80% sand, 20% kaolin, 40% water content to kaolin dry mass).

The second compacted sample was prepared using only Speswhite kaolin humidified at 32% water content. The as-compacted suction was measured using the top HCT before starting the penetration of the tensiocone. Once the top HCT measurement reached equilibrium, the tensiocone penetration was started. Figure 7 shows the results of the measurement of the pore-water pressure of the two tensiometers during the last part of the tensiocone penetration. Again, once penetration stopped, the measurement of the tensiocone HCT attained the same value recorded by the top HCT.

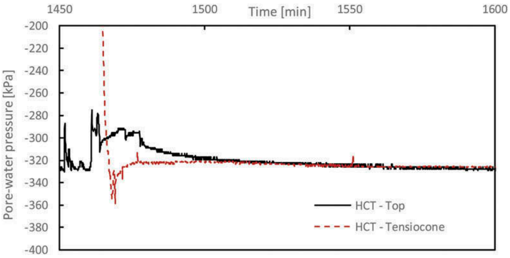

Figure 7. Penetration test on moderately compacted sample (0% sand, 100% kaolin, 32% water content to kaolin dry mass).

The third sample was prepared with 60% coarse fraction and 40% fine fraction. The water content calculated with respect to the dry mass of the fine fraction was 40%, corresponding to an overall water content equal to 16%. The results of this test are shown in Figure 8. The tensiocone pore-water pressure decreased during penetration and then increased up to -145 kPa. This value was markedly different from the top HCT that equalised at about -40 kPa. This discrepancy was also observed in other tests not reported herein.

The reason for such a discrepancy was not due to poor contact between the soil and the HCT porous filter. The pore-water pressure recorded by the tensiocone HCT levelled off suggesting that adequate contact could be established. In fact, if an air gap had formed between the soil and the porous ceramic filter, water from the ceramic filter would have evaporated into the air gap and pore-water pressure would have started declining rapidly over time.

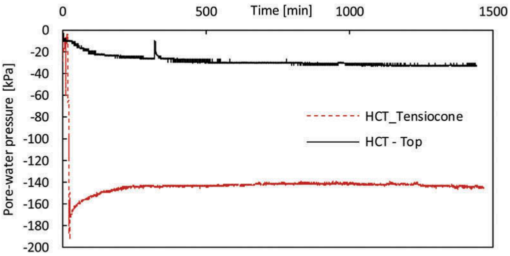

Figure 8. Penetration test on moderately compacted sample (60% sand, 40% kaolin, 40% water content pect to kaolin dry mass).

4 TENSIOCONE MESUREMENT IN THE FIELD

The tensiocone prototype (only equipped with a lateral HCT) was tested on the crest of the Adige river embankment at about 1 km downriver from the bridge that connects the local railway station to the town of Egna (BZ), Italy. The embankment made of a silty material was instrumented with two series of conventional tensiometers at depths of 1.8 m, 3.25 m, and -4.7 m and depths of -2 m, -3.45 m, and -4.5 m respectively. At the time of the CPT, these tensiometers showed a pore-water pressure profile nearly hydrostatic at depths greater than 3 m (associated with the phreatic surface located at 7m below the embankment crest). These field measurements were aimed to provide a reference to benchmark the measurements by the tensiocone HCT.

The tensiometer installed in the tensiocone was preliminarily saturated for more than 24 hours using a portable saturation chamber (at the constant pressure of 4MPa). The pressure in the saturation chamber was applied via a piston screw pump (Figure 9a). The tensiocone was then removed from the saturation chamber and placed in water for zeroing (Figure 9b). Finally, the tensiocone was removed from water and screwed onto the first push rod. Once removed from water, the porous filter was immediately covered with kaolin paste to prevent cavitation during the short period of time where the HCT remained exposed to air before penetrating the ground (Figure 9c). This kaolin paste was chipped off once the tip started penetrating the embankment.

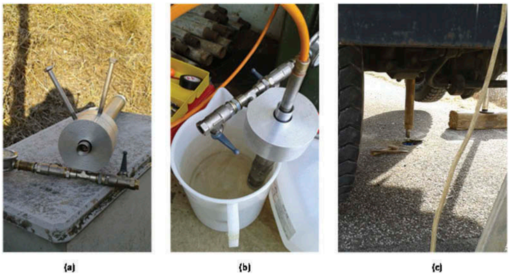
(a) (b) (c)

Figure 9. Field test. (a) Tensiocone in the pre-pressuration chamber. (b) Tensiocone in free water before installation. (c) Tensiocone at the onset of penetration.

The pore-water pressure measured at different depths is shown in Figure 10. The thrust system was stopped four times at four different depths. During penetration, pore-water pressure always tended to decrease whereas equilibrium was established in a relatively short time after penetration was stopped. The pore-water pressure levelling off once penetration was stopped was taken as an indication that adequate contact could be established between the ground and the HCT porous filter.

However, the equilibrium values where not consistent qualitatively and quantitatively with a hydrostatic pore-water pressure profile controlled by the phreatic surface at 7m depth. It was then speculated that the HCT readings were affected by spurious mechanical deformation of the HCT sensing diaphragm. Two types of stresses can influence the measurement, the radial stress due to the ground lateral compression and the axial stresses imposed by the thrust system.

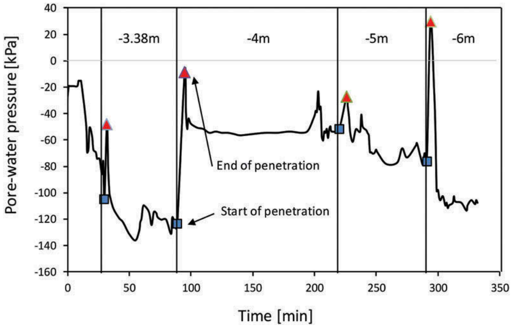

Figure 10. Results of field test.

5 LOADING EFFECTS

To investigate whether the tensiocone HCT readings were affected by spurious mechanical deformation of the sensing diaphragm, the tensiocone was placed in a loading frame. The tensiocone HCT porous filter was air dried for several days so that the HCT should have measured zero-gauge pressure throughout the mechanical axial compression of the tensiocone.

Figure 11 shows the results of the axial loading test. The tensiocone was compressed in steps up to 10 kN (0kN, 2 kN, 5 kN and 10 kN) and then unloaded in steps (10kN, 5 kN, 2 kN and 0 kN). Step duration was 15 seconds. The HCT recorded significant 'false' changes in pressure up to 180 kPa. In the field test, circumferential stresses might have also generated additional spurious readings.

The first HCT prototype was designed as an integral strain gauge diaphragm and any deformation of the HCT body due to the compression of the shaft directly affected the response of the sensing diaphragm. This design is clearly not suitable for the HCT to be incorporated into the tensiocone.

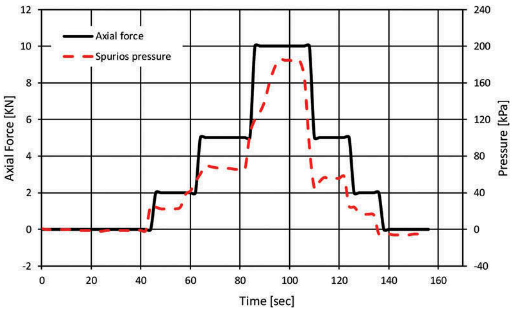

Figure 11. Mechanical effect on the HCT of the first tensiocone prototype.

6 CONCLUSIONS

This paper has presented the concept of the Tensiocone, a cone penetrometer with the facility to measure pore-water pressure in both negative and positive range. A first prototype was tested in the laboratory and the field to investigate one of the major challenges in tensiocone measurement, i.e. whether adequate contact can be established between the ground and the HCT porous filter during penetration.

The clay paste usually applied to the high air-entry porous filter of standing alone HCTs to ensure adequate hydraulic continuity between the pore-water and the water in the HCT reservoir cannot be used in CPT. The measurement of the negative pore-water pressure during penetration has to rely on the contact generated by the radial compression during penetration of the CPT shaft.

Laboratory tests showed that adequate contact could be established even under unfavourable conditions, i.e. high fraction of course-grained material (this makes the contact more difficult to achieve) and lower soil density (low radial stresses develop in a lightly compacted sample). The field test also showed that equilibrium could be reached after stopping the penetration, indicating that adequate contact could be established between the penetrometer HCT and the ground in a real case scenario.

However, it was observed that the compression of the shaft induced deformations in the HCT resulting in false pressure readings. This explains the almost random values recorded during the field penetration test and the discrepancy between the suction measured by the tensiocone HCT and the HCT placed at the top of the sample in the laboratory tests. The next challenge in the design of the penetrometer shaft is therefore to isolate mechanically the HCT from the shaft and this will be the focus of future tensiocone design developments.

ACKNOWLEDGEMENTS

The financial contribution of the European Commission to this research through the Marie Curie Industry-Academia Partnership and Pathways Network MAGIC (Monitoring systems to Assess Geotechnical Infrastructure subjected to Climatic hazards) – PIAPP-GA-2012-324426 – is gratefully acknowledged.

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