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CPT calibration in centrifuge: Effect of partial saturation on cone resistance

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ABSTRACT: When dealing with unsaturated soil conditions, the influence of matric suction on cone tip resistance of the soil above the ground water table is typically neglected in engineering practice, with consequent possible misinterpretation of soil features. In the last decades, various researchers have investigated the influence of suction on cone resistance for sands, whilst still little is known for silty materials, whose contribution can be significant and extended for many meters above the groundwater table. Such issue is especially relevant for compacted earth structures, like river embankments, typically made of a heterogeneous mixture of intermediate soils. With the aim of providing a contribution and stimulating its correct implementation into geotechnical practice, a set of miniature piezocone tests have been carried out in a centrifuge on both saturated and partially saturated silty sand models. The interpretation of CPT results is discussed, highlighting the effect of partial saturation on cone tip resistance.

1 INTRODUCTION

Due to its reliability and time and cost effectiveness, the cone penetration test (CPT) represents a valuable tool for continuous stratigraphy profiling and geotechnical soil properties estimation. Most of the existing approaches for analyzing CPT results are based on fully saturated or dry conditions, for which interpretation methods are well established and have a solid theoretical background (Robertson and Campanella 1983a, b; Lunne et al. 1997; Mayne 2007; Robertson 2009). However, in several cases CPT soundings may cross a vadose zone, conventionally extended from the ground level to the water table, where partially saturated soil states are very likely to occur. Thus, a reliable interpretation of CPT data in unsaturated soil layers is of pivotal importance for the design, optimization and management of the engineering works interacting with soils at shallow depths (e.g. foundations, road pavements) or influenced by infiltration, evapo-transpiration and transient groundwater flow, such as river embankments, earth dams or backfill of retaining walls.

As observed by Yang and Russell (2016), for an accurate analysis of CPT results in partially saturated soils, the in-situ stress state needs to be accurately evaluated, taking into account the variations with depth of the matric suction and the effective degree of saturation of soils. In the current practice, instead, the contribution of suction to the effective stress is frequently neglected, due to difficulties in assessing the in-situ moisture content and in obtaining a reliable pore water pressure distribution, often resulting in excessively conservative design approaches and in the incorrect evaluation of soil features (Russell and Khalili 2006). Various studies have been recently carried out to gain insights on the influence of unsaturated conditions on CPT data, mostly limited to sandy soils (Hryciw and Dowding 1987; Bolton et al. 1999; Russell et al. 2010; Pournaghiazar et al 2013; Jarast and Ghayoomi 2018), all showing evidence that the cone penetration resistance, q_c, can be significantly increased by suction. Conversely, limited research has been carried out on CPTs in unsaturated silty materials (Silva and Bolton 2005; Tan 2005; Yang and Russell 2016), due to the intrinsic complexity related to partial drainage, occurring during penetration at the standard rate of 20 mm/s (Paniagua et al. 2014), and to the microfabric of intermediate soils. Most of these studies have been performed on reconstituted samples, under the controlled laboratory environment of calibration chambers or centrifuges, in order to eliminate the typical uncertainties related to soil heterogeneity and parameters estimation, while only few field tests have been performed so far to evaluate the effect of soil moisture content on the cone resistance, q_c (Lehane et al. 2004; Collins and Miller 2014; Giacheti et al. 2019). The

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present paper aims at contributing to a better understanding of the effect of matric suction on CPT results interpretation. For this purpose, a set of piezocone tests have been carried out on a compacted mixture of sand and finer material in the 240 g-ton geotechnical centrifuge facility at the Experimental Institute for Geotechnical Modelling (Italian acronym: ISMGEO) of Seriate (Bergamo, Italy), in both saturated and partially saturated conditions. The use of monitoring sensors allows to clearly define the pore pressure distribution of the models under different water table depths. Furthermore, implications of using various assumptions on the calculation of the effective stress states during penetration, starting from matric suction measures, are preliminarily discussed and CPT calibration in the centrifuge is attempted.

2 EXPERIMENTAL CAMPAIGN

2.1 *Equipment, tested material and test procedure*

A scheme of models tested is presented in Figure 1. The testing soils are Ticino sand (TS, Baldi et al., 1982, 1986, Fioravante, 2000, Jamiolkowski et al., 2003, Fioravante & Giretti, 2016) and Pontida clay (PON, Ventini et al. 2021). TS is a coarse to medium, uniform silica sand, of alluvial origin, mainly composed by angular grains; PON is a low plasticity kaolinitic clayey silt, deposited in a post-glacial lake environment. The overall experimental campaign has been performed considering different mixtures of TS and PON. However, in this contribution, only the results of a test carried out on a mixture of 85% by weight of TS and 15% by weight of PON are discussed. The main physical properties of the mixture, obtained from an accurate laboratory characterization, are listed in Table 1. In particular, the minimum and maximum dry density have been obtained following ASTM 4254 - Method A (2016) and ASTM D1557 - 12e1 (2012) - Modified Proctor method, respectively. Figure 2 compares the grain size distribution of TS, PON and the mix.

Table 1. Main physical properties of the mixed soil 85% TS+15%PON.

SOIL	G_s	d_{50}	C_U	C_C	$\gamma_{d,min}$	$\gamma_{d,max}$
	-	mm	-	-	kN/m^3	kN/m^3
85%TS+15% PON	2,695	0,499	13,2	10,9	13,92	18,15

The ISMGEO miniaturized piezocone used in the tests has a diameter d = 11.3 mm and a total cone area of 100.3 mm^2. It incorporates a 60° cone tip with a load cell to measure tip forces up to 9.8 kN and a 36.9 mm long shaft, which connects to an upper section containing a second 9.8 kN load cell, used to measure tip resistance plus sleeve friction. In addition, the cone has a 35-bar capacity Druck PDCR pressure transducer for interstitial pressure measurements. Physical models were reconstituted in layers of prescribed height to obtain a 1g dry density of 90% of $\gamma_{d,max}$ and using an initial water content of about 17%. The container was a cylindrical box, 400 mm in diameter. With a ratio D/d (D is the container diameter) equal to about 36, boundary side effects were minimized. During the reconstitution, pore pressure transducers (ppts M, P, Q, N, R) and tensiometers (tens 1, 2, 3) were embedded in the model at prescribed heights (Figure 1) and at a distance of 50 mm from the box axis. Once the total height was achieved, the soil saturation was completed applying to the model a continuous vacuum pressure of about -70 kPa for 12 hours. Then a rigid frame which holds a linear displacement transducer to monitor

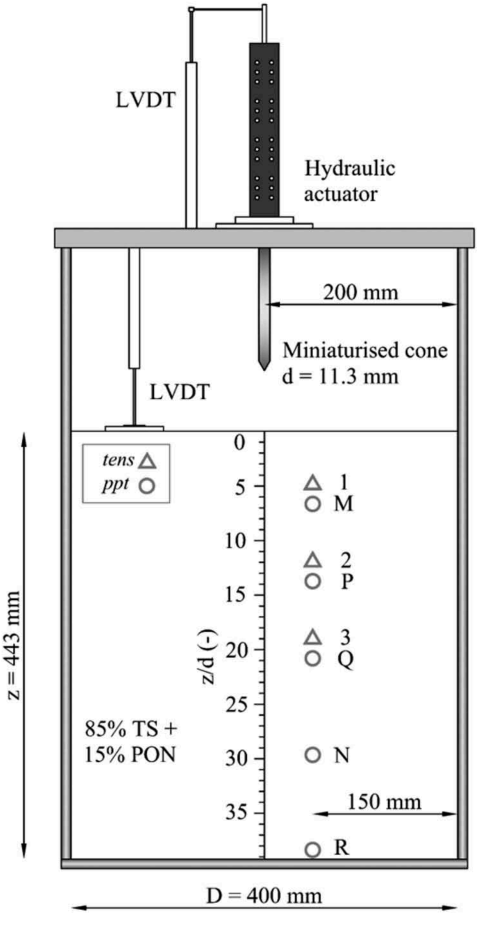

Figure 1. Sketch of the cylindrical strongbox containing details of geometry, transducers and in-flight miniature probe.

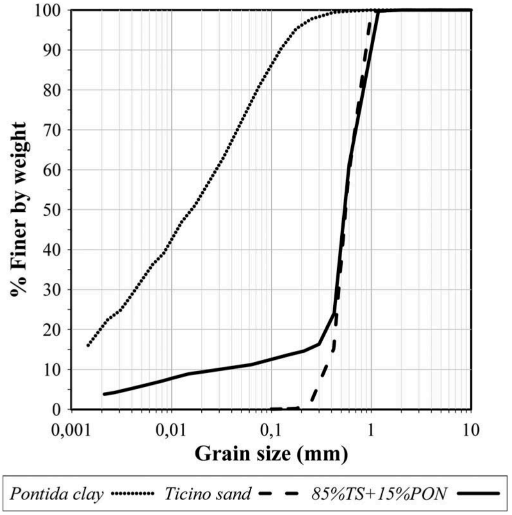

Figure 2. Grain size distribution of the tested soils.

the soils surface settlement, the miniaturized piezocone and the actuator was fixed to the top of the container.

The container was loaded onto the centrifuge and accelerated to the target (50g at the soil surface). After the in-flight consolidation, a first CPTU was carried out in the central axis of the model. At the end of penetration, the penetrometer was lifted, the centrifuge was stopped, the equipment was moved 70 mm from the original position and the model was re-accelerated. When the pore pressure equilibrium was achieved again, as identified by real-time pore pressure monitoring data, an outflow was imposed to the soil model by opening a hydraulic valve placed at the bottom of the cylindrical box. The outflow was interrupted when the water table reached almost mid depth. Following pore pressure stabilization, a second CPTU was carried out in a model partially saturated in the upper part and saturated below, with matric suction and pore pressure data continuously recorded. It has to be noticed that, due to settlement induced by saturation, centrifuge accelerations and desaturation of the model, the soil sample underwent a progressive increase in density, with an average void index value equal to 0.480 (at the beginning of the test in saturated conditions) and to 0.475 (at the beginning of the test in partially saturated conditions).

3 CENTRIFUGE TEST RESULTS

The data recorded during the piezocone advancement in both fully saturated soil conditions (continuous lines) and with the phreatic surface below the ground level (dotted lines) are presented in Figure 3. To take into account the progressive mobilization of the cone resistance from the free model surface (Schmertmann, 1978), the data registered in the first 10 d of penetration from the ground level were removed (Gui and Bolton 1998). The plot shows the variation with the dimensionless depth (i.e. the ratio between penetration depth, *z*, and cone diameter, *d*) of the sleeve friction resistance, f_s, and of the corrected cone tip resistance, q_t, this latter expressed as:

$$q_t = q_c + u_2(1 - a) \tag{1}$$

where q_c is the measured cone tip resistance, a = 0.785 is the net area ratio, determined from laboratory calibration, and u_2 is the pore pressure generated during cone penetration and measured just behind the cone. In addition, the pore pressure values measured by ppts (in the positive range) and tensiometers (both in positive and negative ranges) are also plotted, with circles and triangles, respectively, together with u_2 data. The dimensionless depth of the water level has been determined from the measures of the ppt placed at the bottom of the

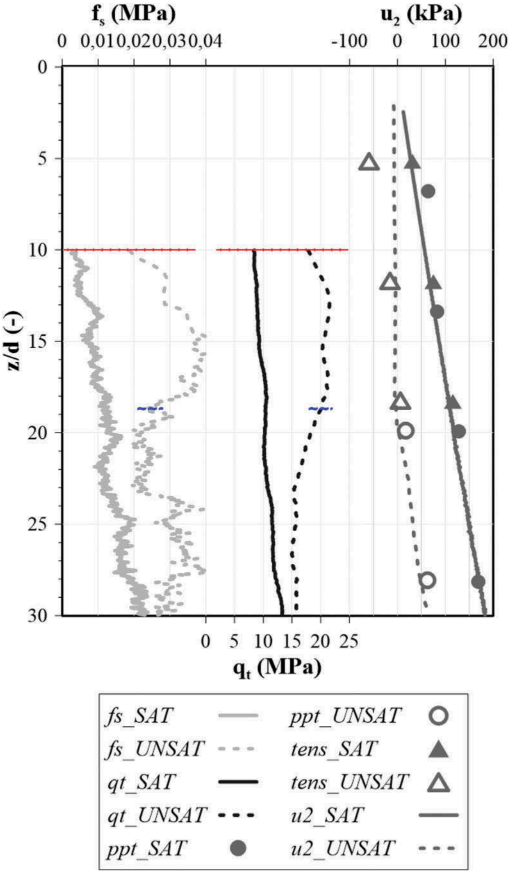

Figure 3. Variation with the dimensionless depth, z/d, of the sleeve friction resistance, fs, of the pore pressure generated during cone penetration, u_2, together with the pore pressure measurements (circles and triangles) and of corrected cone tip resistance, q_t.

model; for the test in unsaturated conditions, its value, $z/d_{w,UNSAT}$, is equal to 18.7 and is drawn in bold hatched line (Figure 3).

The ppts and tensiometers monitoring data fit quite well the u_2 measured during penetration, showing a hydrostatic distribution of pore pressures in the positive range of values in both experiments (*SAT* and *UNSAT*) and a less than hydrostatic distribution in the unsaturated area (UNSAT model), highlighting that the process of lowering the water table led to a hydraulic equilibrium of pore pressure in the saturated soil area also for the unsaturated test. On the other hand, distributions of q_t and f_s show significant differences between the two tests, i.e. higher cone tip resistance and sleeve friction in the area where desaturation occurred, where the suction effect is clearly tangible. It should be noticed that, since the cone tip and sleeve friction resistances vary with the relevant overburden stress for the same material, the CPT data plotted in Figure 3 require a stress normalization for a proper interpretation and comparison of resistance profiles.

4 STRESS NORMALIZATION

Stress conditions are significantly different in the two tests. The change in the water table depth, in fact, leads to a variation of the saturation level and produces suction states in the partially saturated soil in the *UNSAT* experiment and subsequent effects on the test results. At least two independent stress state variables should be considered for an accurate description of the relevant soil behaviour (i.e. Morgenstern, 1979; Fredlund et al., 2012); however, it is also well known that the most commonly used CPT charts and correlations are based on a single-valued effective stress approach. To show the implications of adopting a single-valued effective stress approach, the Bishop's effective stress equation (1959) for unsaturated soils has been here used, such as:

$$\sigma' = (\sigma - u_a) + S_r(u_a - u_w) \tag{2}$$

with $(\sigma - u_a)$ being the net stress, S_r the degree of saturation and $(u_a - u_w)$ the matric suction. For such test interpretation, it is therefore required the knowledge of the distribution of S_r and of $(u_a - u_w)$, typically not readily available in traditional engineering applications. Two different assumptions have been thus made here, with a first simplified case (*UNSAT,1*) considering a hydrostatic distribution of pore pressure above the groundwater line and a constant degree of saturation equal to 0.5, while a second case (*UNSAT,2*) aims at representing the experimental conditions closely, with a matric suction distribution determined on the base of tensiometer measurements and a variable degree of saturation, provided by the water retention curve obtained from physical soil properties through the procedure suggested in Aubertin et al. (2003). For both cases, the calculated values of total stress, σ_v, and effective stress, σ'_v, the pore pressure, u_0, and the degree of saturation are plotted with dimensionless depth in Figure 4. Considering a constant 0.5 value of the degree of saturation (*UNSAT,1*), a noticeable increase in the effective stress distribution is produced. Instead, due to the significant percentage of sand in the tested material, the degree of saturation tends to rapidly reduce with the increase of matric suction (absolute) values, evidencing in case *UNSAT,2*, a limited impact on the effective stress as calculated with equation (2). It is now possible to try to determine general trends in the soil response to CPT advancement.

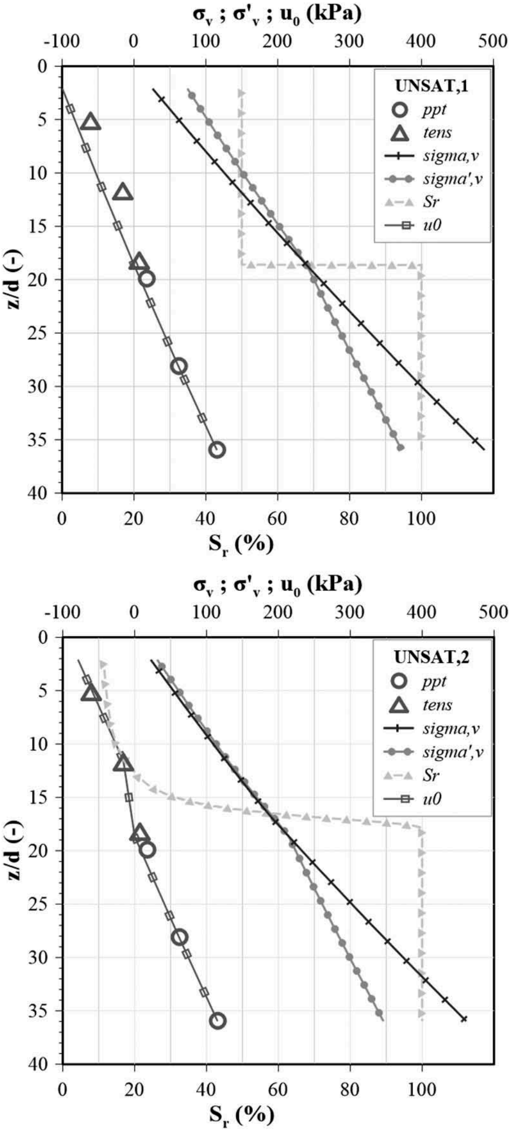

Figure 4. Calculated values of total, σ_v, and effective, σ'_v, stresses acting on vertical direction, pore pressure, u_0, and degree of saturation, S_r, are plotted with dimensionless depth, z/d, under a simplified assumption (UNSAT,1 top graph) and based on tensiometer data (UNSAT,2 bottom graph).

According to Robertson's (2009) very popular unified approach, the normalized cone resistance, Q_{tn}, and the Soil Behavior Type index, I_{cn}, are calculated using a stress exponent, n, that varies with soil type and stress level. Specifically:

$$Q_{tn} = \left(\frac{q_t - \sigma_v}{p_{a2}}\right)\left(\frac{p_a}{\sigma'_v}\right)^n \tag{3}$$

$$I_{cn} = \left[(3.47 - logQ_{tn})^2 + (logF + 1.22)^2\right]^{0.5} \tag{4}$$

$$n = 0.381(I_{cn}) + 0.05\left(\frac{\sigma'_v}{P_a}\right) - 0.15 \tag{5}$$

$$F = f_s/[(q_t - \sigma_v)] \tag{6}$$

where p_a and p_{a2} are reference pressures in the same units of q_c, σ_v and σ'_v, while F is the normalized friction ratio. Results obtained from the present CPT tests performed before (*SAT*) and after (*UNSAT*) the water table lowering are plotted in Figure 5, in terms of Q_{tn} and I_{cn}, considering both the simplified (*UNSAT,1*) and the more accurate (*UNSAT,2*) assumptions for the calculation of stress conditions (see Figure 4). Considering the test conducted in fully saturated conditions (*SAT*), values of Q_{tn} and I_{cn} tend to be relatively constant with depth and typical of sandy materials, in good agreement with Robertson's approach.

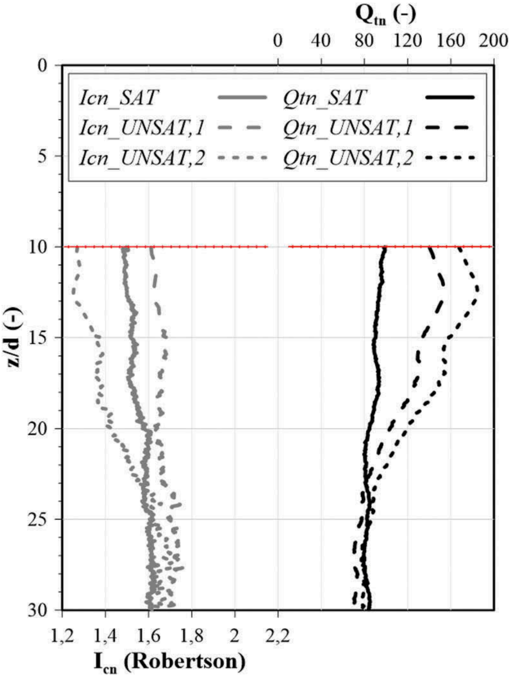

Figure 5. Variation with the dimensionless depth, z/d, of the normalized cone resistance, Q_{tn}, and the Soil Behavior Type index, I_{cn}, calculated using the stress exponent, n.

However, for the test performed after the water table lowering, significant variations can be found in the values of Q_{tn} when comparing the advancement in the saturated versus the unsaturated zones. For dimensionless depths lower than $z/d_{w,UNSAT}$ (18.7), none of the two assumptions on the effective stress and saturation degree provide uniform Q_{tn} profiles, despite the material is essentially the same in the two experiments, showing higher normalized cone resistances in the unsaturated with respect to the saturated zone. Indeed, below the water table, the assumption based on monitoring data (*UNSAT,2*) tends to produce similar values to the test performed in fully saturated conditions, rather than for the case of a simplified assumption (*UNSAT,1*). Analogous observations can be done for the I_{cn} data, always within the range of sandy materials (1.31 – 2.05), but with substantial differences between the saturated and the unsaturated zones.

Hence, adopting a single-valued effective stress approach for stress normalization to interpret the CPT data in the unsaturated zone appears to be not fully reliable.

5 CONCLUSIONS

Results from small-scale laboratory tests, which included CPT execution with pore pressure and suction measurements in a centrifuge environment, have been presented herein. The experiments described are referred to a soil mixture, made of mainly coarse-grained particles with a limited fine fraction, tested under different saturation conditions. In fact, the only variation in the two presented cases was related to their water table depth, either at almost the ground surface or at a lower level, obtained through a dewatering process. Monitoring sensors, pore pressure transducers and tensiometers, located along the model depth, played an essential role in determining the soil suction distribution above the water table and in identifying the hydraulic equilibrium reached at the end of the outflow phase. Data measured during cone penetration tests (f_s, q_t and u_2), before and after the dewatering process, show only limited differences in the saturated zones, further reduced by adopting the stress normalization of Robertson's unified approach.

On the other side, when comparing cone penetration data measured in the unsaturated versus the saturated zones, substantial differences in the selected stress-normalized results (Q_{tn} and I_{cn}), regardless of the assumption on suction and saturation degree profiles above the water table, can be detected. Therefore, from the data presented herein, it would appear that the effect of partial saturation on cone tip resistance provided by the matric suction is not duly taken into account by simply applying a stress normalization by the Bishop's equation for unsaturated soils. In other terms, it seems that the combined use of a single effective stress variable (as typically assumed when more specific information on unsaturated soil behavior is lacking) with the standard CPT charts and correlations cannot produce a similarly reliable data interpretation. Additional investigations, including the use of other materials, are clearly required to better define such critical issue.

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