A review of laboratory cone penetration test (CPT) in unsaturated soil

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ABSTRACT

Cone penetration testing (CPT) is a common site investigation method used to determine soil profiles and characterize in-situ soil properties. However, most of the existing interpretations of CPT data are established for dry or saturated soil. In recent years, studies have shown that ignoring the matric suction effect in unsaturated conditions during data interpretation could lead to biased soil characterization and soil property estimates. Still, due to the lack of fundamental understanding of the mechanics during cone penetration in unsaturated soils, accounting for the matric suction effect on the CPT data-soil properties/characterization is not clearly defined, and more laboratory testing in controlled environments is required to fill this gap in knowledge. Existing studies are different in terms of penetrometer diameters (d_{cpt}), chamber dimensions, penetration rate, sample preparation, and suction control techniques. This paper first presents a review of the existing literature on CPTs performed in unsaturated soils in a controlled laboratory environment and discusses the effects of the aforementioned factors on the measured tip resistance. In addition, new results from centrifuge CPTs performed with controlled water levels in a rigid chamber are presented. For the purpose of such experiments, a 12.7 mm diameter miniature cone penetrometer was designed and fabricated to measure tip resistance values. Unsaturated CPT data show that the presence of matric suction in the soil tends to increase the tip resistance measurement during the cone penetration process. More tests are planned in the future to quantify this increase in CPT response with respect to other soil properties.

Keywords: Cone penetration test (CPT); unsaturated soil; matric suction; miniature penetrometer.

1. Introduction

The key component of the CPT is the cone penetrometer device, which consists of a cone tip with an apex angle of 60º and a friction sleeve above the cone tip. When a pore pressure filter is added between the friction sleeve and the cone tip, the instrument is typically referred to as CPTu. For simplicity, tests with or without pore pressure filters are all denoted as CPT in this paper. In practice, the cone penetrometer is pushed into the soil at a constant rate of 20 mm/s (e.g. ASTM D5778-20) until the target depth or refusal is reached, during which three parameters are directly measured: tip resistance (q_c), sleeve friction (f_s), and pore pressure (u) at the filter. Although CPT data interpretation for soil strength and stratification is well-established for dry or saturated soils and is commonly used in practical engineering problems (Robertson and Campanella 1983a; Robertson and Campanella 1983b; Mayne 2007; Robertson and Cabal 2015), the interpretation of CPT measurements in unsaturated soils, which are naturally found in regions of low groundwater, remains unclear.

Pournaghiazar et al. (2013), Yang and Russell (2015), and Miller et al. (2018) investigated the effect of matric suction on measured q_c values in suction-controlled calibration chambers. Test results showed that the measured q_c values increased with higher matric suction, and this effect diminishes with higher confining stress and lower initial void ratio. Ghayoomi et al. (2018), Awad and Sasanakul (2021), and Fioravante et al. (2022) conducted centrifuge CPTs in unsaturated soil and observed similar trends. These studies demonstrate that failing to account for the effects of matric suction in unsaturated soil during data reduction may result in biased soil type characterization and inaccurate estimation of soil property values, ultimately leading to improper geotechnical design (e.g., Russell and Reid 2016; Ghayoomi et al. 2018).

Compared to *in-situ* CPTs, laboratory tests are usually conducted in a highly controlled environment (e.g., relative density, soil type, profile stratification) where parametric studies are possible. However, due to the limited dimensions of the sample container and induced high-stress levels, specifically in the centrifuge test, factors irrelevant to soil properties such as sample container size, penetrometer diameter, penetration rate, sample preparation procedures, and boundary conditions imposed by the calibration chamber also affect the measured data (Ghionna and Jamiolkowski 1991; Gui et al. 1998; Bolton et al. 1999; Huang and Hsu 2005; Schneider et al. 2007; Kim et al. 2016; Lehane et al. 2022). This paper presents a review of factors that could affect the measured q_c in soils with and without matric suction, as well as a review of laboratory CPTs tested in unsaturated soils. Finally, a new test setup and miniature cone penetrometer prepared at HKUST for centrifuge CPTs in unsaturated soils are discussed, and some new test data are presented.

2. CPTs in unsaturated soil

Previous 1-**g** calibration chamber tests have been carried out to study cone penetration behavior in unsaturated soils. In these tests, cone penetrometers of different diameters (mostly between 10 to 16 mm) are driven at different penetrating rates into a uniform and unsaturated soil profile prepared in a cylindrical chamber under either controlled soil moisture (e.g. Miller et al. 2018) or matric suction achieved by axis-translation technique (e.g. Pournaghiazar et al. 2013; Yang and Russell 2015). Soil types being tested, in accordance with the Unified Soil Classification System (USCS), are limited to sands (e.g. Hryciw and Dowding 1987; Pournaghiazar et al. 2013 and Ghayoomi et al. 2018), silty sands (Yang and Russell 2015), and clayey silts (Miller et al. 2018). Analytical models based on bearing capacity theory (Miller et al. 2018) and cavity expansion theory (Yang and Russell 2015) have been attempted to draw correlations between CPT results in unsaturated soil and strength parameter values (e.g. friction angle and relative density). The general findings are that q_c increases with increasing matric suction due to the contribution of matric suction to soil effective stress.

Centrifuge CPTs have gained recent attention. High-***g*** CPTs ensure the simulation of the entire penetration process is within a stress regime that is much more representative of field conditions than 1-***g*** laboratory testing. The CPT data obtained, including q_c and f_s, can be scaled to prototype values via relevant scaling laws. Both 'shallow' and 'deep' penetration mechanisms (Gui and Bolton 1998; Puech & Foray 2002) can also be simulated without adding a vertical surcharge to the sample. It should be noted that conducting high-***g*** CPTs is practically more complicated than in 1-**g** conditions. The test setup, including the sample container, actuator, penetrometer, load cell, and sensors, as well as the electrical connections, must be robust enough to ensure proper function during high-speed spinning. Additionally, the q_c profiles obtained directly from high-***g*** environments do not reach a plateau value as easily as 1-***g*** tests. The reason is two-fold: (a) the addition of vertical surcharge in 1-***g*** tests prevents the shallow heave and facilitates the test to enter the 'deep' penetration mode (Gui and Bolton 1998); and (b) increasing effort is required to penetrate deeper under the induced high-stress gradient in a centrifuge environment. Typically, a stress normalization refering to effective stress (Eq. 1) is usually applied to the q_c value obtained from centrifuge CPTs to demonstrate the critical penetration depth (d_{cr}). However, this phenomenon adds additional complexity to the data interpretation for centrifuge CPTs in unsaturated soil, as the computation of effective stress in unsaturated soil is not as straightforward as in dry or saturated soil.

Ghayoomi et al. (2018) used a miniature cone penetrometer equipped with a ceramic filter (Jarast and Ghayoomi 2017) to measure CPT profiles on uniform, loose (i.e. 26% relative density), moist (i.e. 36% degree of saturation) Ottawa sand at 40-***g*** with a penetration rate of 4.25 mm/s. As expected, the values of q_c obtained in the unsaturated soil profile were greater than those obtained from the dry and saturated cases; however, pore-water pressure and suction data during penetration were not reported. Later, Awad and Sasanakul (2021) carried out a series of undrained centrifuge CPTs at a rate of 10 mm/s in unsaturated densely-compacted clayey sand (91% relative density) subjected to wetting (by rainfall) and drying (by evaporation) cycles. To reduce the effect of heterogeneity of the soil samples on the results, three CPT penetrations were carried out in each profile at different locations and at different unsaturated conditions (as-compacted, wetting, or drying). The values of q_c increased and decreased as the soil profile was dried and wetted, respectively. A unique exponential correlation was found between q_c and the degree of saturation, irrespective of the hydraulic path experienced in the soil samples. Fioravante et al. (2022) conducted two centrifuge CPTs in uniform soil profiles made of a sand-silt mixture at 50-***g*** using an 11.3 mm diameter cone penetrometer. The water table was set at the ground surface (saturated case) and mid-depth of the container (unsaturated case). The two CPTs were carried out on the same sample but with 70 mm (i.e. ~$6d_{cpt}$, where d_{cpt} is the cone diameter) separation between the two penetrations. The reasoning for selecting this distance of separation was not provided, but existing works (e.g. Kim et al. 2016) have indicated that a minimum distance of $10d_{cpt}$ should be maintained between two different penetrations to minimize interactions. More recently, a numerical work carried out by Yost et al. (2023) has shown that even at a separation of $10d_{cpt}$, q_c tends to increase with each successive penetration. Finally, Fioravante et al. (2022) concluded that using a single-valued effective stress approach (e.g. Bishop's effective stress) for stress normalization was inadequate to interpret the CPT data in unsaturated soils.

Previous penetration tests carried out in dry and saturated soils have identified the significance of (a) chamber dimensions, (b) penetration rate, and (c) penetrometer size on the measured CPT data. Subsequent sections of this paper present a review of such effects on CPT response in dry or saturated soil. To the best of the authors' knowledge, no study has been conducted to investigate these effects in unsaturated soils. However, the presence of matric suction is believed to further complicate data interpretation. Extended discussions regarding the effects in unsaturated soils will be provided in subsequent sections. Table 1 summarizes the relevant test conditions for the aforementioned laboratory CPTs in unsaturated soil.

2.1. Boundary effect

The term 'boundary effect' refers to the restraint imposed by the soil container's boundary on the development of the shear band that forms around the cone penetrometer during penetration. The presence of the boundary effect usually leads to higher q_c values. In the case of a cylindrical container, the boundary effect is indicated by the ratio of the container diameter to the cone diameter (D/d_{cpt}) when the penetration is carried out at the geometric center of the container. Bolton et al. (1999) suggested that for dense sand, the boundary effect on the measurement diminishes after a D/d_{cpt} and has no significant effect after a ratio of 30. Honardar (2019) noted that a D/d_{cpt} ratio of 30 has minor boundary effects, and a ratio of 40 has no boundary effects.

For penetrations conducted away from the geometric center of the container, Gui et al. (1998) recommend an S/d_{cpt} ratio greater than 11 to minimize the boundary effect in dense sand, where S is the distance from the cone to the nearest side of the container. Later, Kim et al. (2016) discovered that q_c profiles obtained from the same sample under the same centrifugal g level but at different locations of the container (S/d_{cpt} = 7, 10, and 12) are in acceptable agreement with each other.

In cases where multiple penetrations are carried out on the same sample, a minimum distance of 10d_{cpt} should be maintained between each penetration to minimize disturbance from prior penetrations (Kim et al. 2016). However, a more recent numerical study by Yost et al. (2023) has shown an increasing trend in the q_c profile with each successive penetration, even if a separation of 10d_{cpt} is maintained. It is reasonable to conclude that as the density and confining pressure of the sample increase, the disturbance zone of penetration tends to be smaller due to the higher likelihood of local soil failure around the cone tip. Therefore, the requirement to prevent boundary effects in unsaturated soil should be more generous than that developed for dry or saturated soil, as the presence of matric suction increases the shear strength and stiffness of the soil. However, to ensure the absence of boundary effects for CPTs in unsaturated samples, it is still recommended to maintain a minimum D/d_{cpt} ratio of 30, unless future research indicates otherwise. When multiple penetrations are required in unsaturated soil, the authors of the present paper recommend performing sensitivity analysis on the specific soil samples to determine an appropriate separation distance.

Table 1. Summary of reviewed references that performed laboratory CPTs in unsaturated soil

Reference	**Hryciw & Dowding (1987)**	**Yang & Russell (2015)**	**Pournaghiazar et al. (2013)**	**Miller et al. (2018)**	**Fioravante et al. (2022)**	**Ghayoomi et al. (2018)**	**Awad & Sasanakul (2021)**
Gravity condition	1 **g**	1 **g**	1 **g**	1 **g**	Centrifuge	Centrifuge	Centrifuge
Cone size (d_{cpt})	12.7mm	16mm	16mm	17.8mm	11.3mm	12.7mm	6mm
[1]Container size	⌀229mm	⌀460mm	⌀460mm	⌀610mm	⌀400mm	360mm x 180mm	385mm x 360mm
[2]B/ d_{cpt} or S/ d_{cpt}	18.0	28.7	28.7	34.3	35.4	7.1	11.7
Penetration Rate	5 mm/s	10 mm/s	20 mm/s	5 mm/s	20 mm/s	4.25 mm/s	10 mm/s
Soil type	20-30 Ottawa Sand	Nonplasticity SM	Quartz SP	CL-ML	Sand-clay mixture	F-75 Ottawa sand	Sand-clay mixture
d_{cpt}/d_{50}	[3]17.9	53.3	51.6	-	-	63.0	-
Suction Control	Varying CO_2 pressure	Axis-Translation	Axis-Translation	As compacted	Lowering water table	Steady-state infiltration	Steady-state infiltration
Comment	[1] Diameter (⌀) or length by width [2] B = diamter of the container; S = distance from the cone penetrometer to the nearest side [3] Mean grain size value obtained from Polito et al. (2013)						

2.2. Penetration rate effect

It is typically assumed that CPT performed at a standard rate of 20 mm/s (ASTM D5778-20) corresponds to fully drained penetration in coarse-grained soil and undrained penetration in fine-grained soil (Robertson & Campanella 1983a and 1983b). However, in either a 1-**g** calibration chamber test or a centrifuge test, the penetration rate may differ from the industrial standard. Danziger and Lunne (2012) compared available studies regarding CPTs in sand with varying penetration rates (mostly between 2mm/s to 20mm/s). They concluded that excess pore pressure can reduce the recorded q_c. In fully drained penetration or dry conditions, the rate effect on the measured q_c can be negligible for loose sand. For dense sand, grain crushing at high-stress levels leads to an increase in the recorded q_c. This effect is more pronounced in samples with a higher susceptibility to grain crushing. Kim et al. (2016) conducted centrifuge CPTs in two types of medium-dense saturated sand samples with three different penetration rates (SM: 5, 10, and 20mm/s; SP: 1, 10, and 20m/s) at 50 **g**. It was then found that varying penetration rates do not significantly affect the measured q_c, indicating a fully drained condition and negligible grain crushing during penetration. For other soil types, particularly soils with higher fine or silt content, the standard penetration rate typically refers to partially drained penetration. The relationship between the q_c values returned from partially drained penetration is usually characterized by a backbone curve as a function of a normalized penetration rate (i.e., Kim et al. 2006; Ceccato et al. 2016). The normalized penetration rate is calculated as a function of penetration rate, d_{cpt} and the coefficient of vertical consolidation (c_v). Therefore, the penetration rate effect in coarse-grained soil essentially can be related to the problem of soil consolidation (hydraulic conductivity) and susceptibility of grain crush. In the case of penetrating into unsaturated soils, because the soil hydraulic conductivity reduces with increasing matric suction, the drainage condition can be different compared to penetrating the same soil in dry or saturated status. Further studies on the effects of cone penetration rate in unsaturated soils are needed.

2.3. Particle size and cone diameter effect

The particle size effect refers to the relationship between the size of the cone penetrometer and the mean grain diameter (d_{50}) of the soil sample. A lower ratio of d_{cpt}/d_{50} (i.e. relatively larger soil grain size) is expected to alter the soil-cone interaction, which could result in biased q_c measurements. The standard cone penetrometer used in the industry typically has a vertical projected area of 10 or 15 cm^2 (ASTM D5778-20). However, laboratory-used penetrometers are usually smaller in 1-**g** and will be scaled to a much greater prototype scale size in the centrifuge environment (Table 1). This discrepancy in the cone size leads to different development of shear bands, resulting in different q_c measurements and locations of d_{cr}.

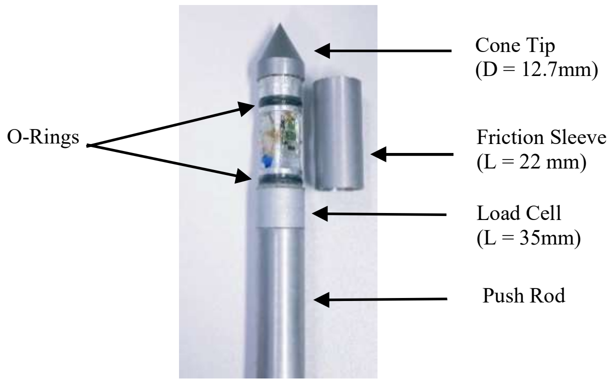
Bałachowski (2007) studied the particle size and cone size effects by applying different g levels to a single cone penetrometer to model different prototype cone sizes. It was observed that both grain size and cone size affect the CPT responses, with a more pronounced effect in shallow penetration depths (i.e., shallower than the d_{cr}), which tends to attenuate as the d_{cr} is reached. This finding is consistent with more recent studies conducted by Kim et al. (2016) and Lehane et al. (2022) using the same approach. Although the q_c values are higher for higher g levels at the same model penetration depth, the stress-normalized q_c converges to a similar steady-state value after reaching the depth of d_{cr}, regardless of the cone size in the prototype scale. Xu (2007) conducted CPTs using penetrometers of three different diameters under the same g level. Using the same stress-normalization approach as Lehane et al. (2022), q_c stabilizes to a similar value after d_{cr}.

To study the particle size effect separately, the 'modelling of models' procedure (Schofield 1980) can be used. This involves scaling penetrometers from different model diameters to the same prototype diameter under corresponding g levels. According to centrifuge tests conducted by Bolton et al. (1999), a d_{cpt}/d_{50} ratio of at least 20 is required to prevent the particle size effect from affecting the CPT responses. Kim et al. (2016), following the 'modelling of the models' procedure, used three cone penetrometers and two types of sand. Results demonstrated a negligible particle size effect with a d_{cpt}/d_{50} value of 87.5 for silty sand and 47.2 for clean silica sand.

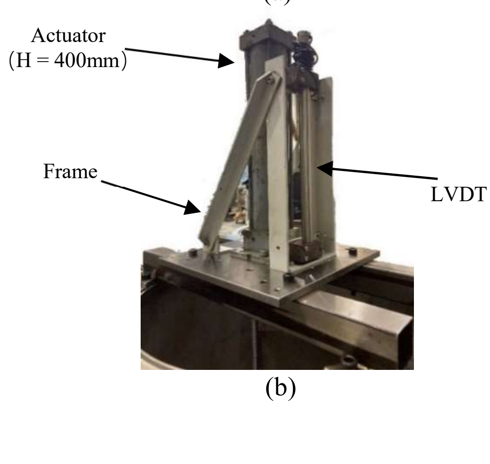
In the case of penetrating into unsaturated soil, the existing d_{cpt}/d_{50} limit required to prevent particle size effect continues to apply from the perspective of solid-solid interaction. The cone diameter effect is expected to be more complicated before reaching the location of d_{cr} due to the presence of matric suction and might be negligible after d_{cpt}. Future centrifuge test programs will be designed to confirm the convergence of stress-normalized q_c values returned from different cone diameters in the prototype scale.

3. New testing equipment and experiment setup

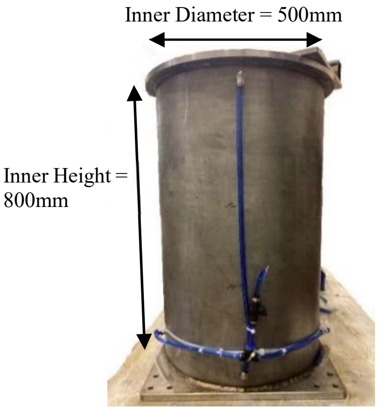
A set of new centrifuge CPTs have been conducted at the HKUST centrifuge center with a 400 g-ton beam centrifuge with a rotating arm of 4.2 m in radius. A 12.7-mm diameter cone penetrometer with a vertical projected area of 126.67 mm^2 for q_c measurement has been designed and manufactured for the purpose of this study (Figure 1a). The cone tip and push rod are made of 304 stainless steel, and the load cell is made of 7075-T6 aluminum alloy with a yield strength of 503 MPa. The load cell was calibrated using an MTS 858 axial loading machine. Samples are prepared in a cylindrical container with an inner diameter of 500 mm and an inner height of 800 mm (Figure 1c). A frame and a displacement-controlled actuator are mounted on top of the container, with the penetrometer fixed at the bottom of the actuator inside the container (Figure 1b). The container has three openings near the bottom and one near the top. This design allows for the saturation or desaturation of samples by adjusting the water level through the bottom openings. The water table in the sample can be observed through the standpipe mounted vertically outside the container (Figure 1c).



(a)



(b)



(c)

Figure 1. Experiment setup: (a) 12.7mm diameter cone penetrometer; (b) actuator and frame; and (c) sample container

4. Sample preparation and test program

Two of the centrifuge CPT results are presented. Tests were carried out at a steady penetration rate of 10mm/s. Both tests were conducted on Toyoura sand (Toyoura Keiseki Kogyo Co., Ltd) with a d_{50} of 0.242 mm, maximum void ratio (e_{max}) of 0.95, and minimum void ratio (e_{min}) of 0.59 (Liu et al. 2022). The current experiment setup (Figure 1) resulted in a d_{cpt}/d_{50} ratio of 52 and a D/d_{cpt} ratio of 39 to prevent the presence of particle size and boundary effects. Sand samples with a relative density of 80% were prepared by dry pluviation with a lift of 0.5 to 1 cm to ensure profile uniformity. The main drying soil water retention curve (SWRC) of Toyoura sand (Figure 2) was described by the van Genuchten model (Van Genuchten 1980) using data measured by Liu et al. 2022. The air entry value is 2 kPa, and the residual value is approximately 7 kPa.

The sample height inside the container is 480 mm to allow space for the setup of the penetrometer. One test was conducted in a dry sample and another one in an unsaturated sample. The unsaturated sample was prepared from an initially saturated sample by lowering the water table, creating an unsaturated zone above the water table in the container. Figure 3 presents a schematic of the experimental setup and designated water surface in the unsaturated sample before penetration. At equilibrium, the matric suction distribution above the water table is hydrostatic (Figure 4), and the degree of soil saturation (or water content) can be estimated based on the SWRC.

The CPT in a dry sample with a centrifugal acceleration of 40***g*** was conducted prior to the unsaturated sample test. The penetration depth in model scale is 220 mm (Figure 3), which is approximately 90% of the maximum measurement range of the LVDT. A 40-***g*** centrifugal acceleration renders an 8.8-m penetration on prototype scale. This penetration depth is determined based on Fioravante et al. (1991), where a series of 1-***g*** calibration chamber CPTs on Toyoura sand were carried out. One of the tests was conducted with a 20-mm diameter cone on very dense sand (relative density = 84.7% and γ_d = 15.58kN/m^3). With the addition of a 110 kPa vertical surcharge, the depth of d_{cr} reached at about 20 cm, which is equivalent to 7.2 m deep without any vertical surcharge. The centrifugal acceleration of 40***g*** was selected to ensure the detection of d_{cr} in the new tests. It should be noted that it is not strictly correct to equate the depth in 1-**g** tests to the prototype depth in centrifuge tests without considering the boundary condition and penetration rate. This method was adopted to simply obtain a reference value to perform the first centrifuge test. It was then found that the maximum reaction force recorded during the dry sample test was about 7500 N, which reached the designed capacity of the load cell. To prevent damage to the load cell, the centrifugal acceleration was reduced to 20***g*** for the subsequent unsaturated CPT, as the amount of load was expected to be higher. In the unsaturated sample, the designated water table is reduced to 200 mm below the sample surface. The depth of the water table is selected to ensure most of the penetration occurs in unsaturated zone with a small portion of the saturated penetration as the reference.

It took approximately 6 hours to fully saturate the dry sample at 1***g*** to prevent the phenomenon of wetting-induced collapse of the sand bed. Four pore water pressure transducers (PPT) with a measuring range of +/- 100 kPa were placed inside the saturated sample near the body of the container. One PPT was located below the designated water level, and the other three were in the unsaturated zone. While preparing the unsaturated sample, a hole was opened on the standpipe at the level of the designated water level before spinning the centrifuge assembly. It was observed that the outflow of water at 1***g*** was slower than expected. This observation was reasonable considering the time needed for the water level to equilibrate inside of the soil sample with only one water outlet. Therefore, the centrifuge test was conducted with the hole open to first speed up the pore pressure equilibrium. During spinning at 20***g***, the water level inside the sample gradually reached the designed depth due to centrifugal force. The stabilization of the PPT signals below the water table indicates the equilibrium of the unsaturated zone inside the sample. The penetration test can then be continued at the same g level.

It should be pointed out that after the spinning for the unsaturated CPT, two of the PPTs installed above the water level experienced mechanical issues and did not provide any data. The other two PPTs were dragged down to below the water level by the centrifugal force and returned similar pore pressure values. Additional mitigation measures will be implemented to ensure proper fixation of PPTs at the designed location before and after the spinning. What can be concluded from available pore pressure data and standpipe observation is that the water level is stabilized at the designated depth before and after the spinning, and the distribution of matric suction in unsaturated soil is considered hydrostatic (Figure 4).

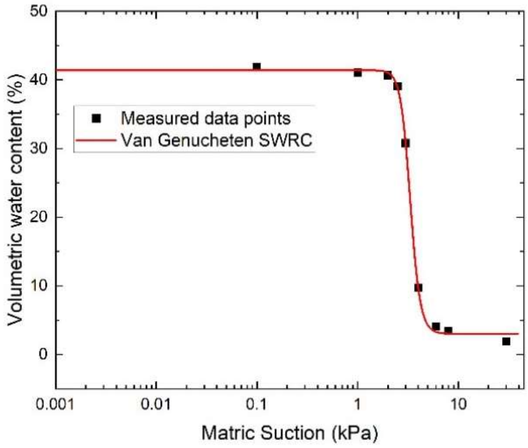


Figure 2. Drying SWRC of Toyoura sand.

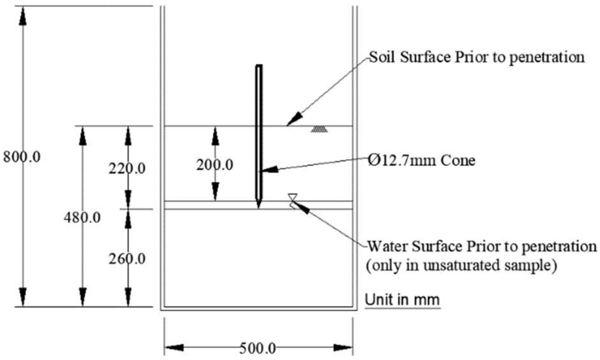


Figure 3. Schematic of experimental setup of high-***g*** CPT. Dimensions are all in model scale

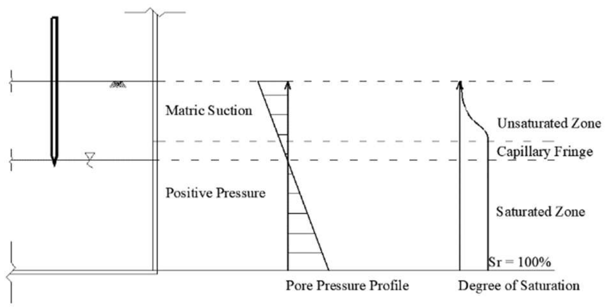


Figure 4. Schematic of hydraulic state of soil sample below and above the water table (Modified from Jarast 2017)

5. Test results and discussion

Figure 5 shows the q_c profile obtained from the dry and unsaturated cone penetration tests. A stress normalization procedure (Kulhawy and Mayne 1990) is applied to the measured q_c to reduce the influence of overburden pressure induced by high-**g** level (Eq. 1):

$$q_{c1N} = (\frac{q_c}{p_a})(\frac{p_a}{\sigma'_v})^n \quad (1)$$

where q_c is the measured tip resistance, p_a is the atmospheric pressure and n = 0.7 for silica sand (Lehane et al. 2022).

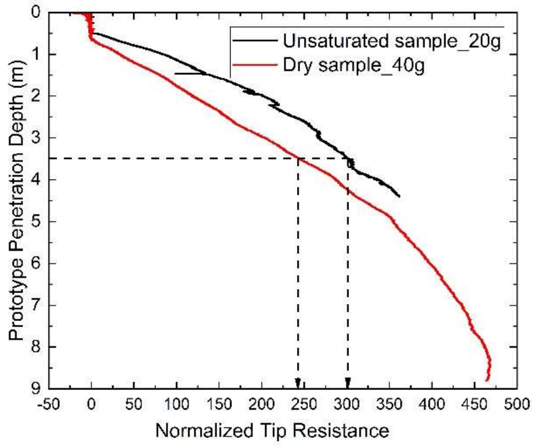


Figure 5. Cone penetration test results for unsaturated and dry sample

The Bishop's effective stress (Bishop 1959) is used to account for the effects of matric suction on soil shear strength (Eq.2).

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \quad (2)$$

Where $(\sigma - u_a)$ is the net stress, $(u_a - u_w)$ is the matric suction, and χ is the effective stress parameter. The value of χ is soil SWRC dependent, and can be assumed to the value of soil degree of saturation (S_r). The value of S_r is estimated from the SWRC. It is observed that the existence of matric suction results in higher q_c value during penetration of the unsaturated sample compared to the dry sample. For example, as indicated by the dashed line in Figure 5, at a prototype depth of 3.5 m with a suction of 4.9 kPa, the normalized q_c returned from the unsaturated sample is about 20% higher than the dry sample.

Soil samples located between the prototype depths of 3.3 m (i.e. matric suction = 7 kPa) and 3.8 m (i.e. matric suction = 2 kPa) below the soil surface in the prototype scale are situated in the transition zone with respect to the soil hydraulic state. Tip resistance values obtained from this transition zone of the unsaturated sample are expected to be larger than that of the dry sample. Shallower than a depth of 3.3 m, the sample is considered dry, while deeper than a depth of 3.8 m, it is considered saturated. Therefore, the q_c in the unsaturated sample is expected to be approximately the same as that in the dry sample at depths shallower than 3.3 m and lower below the depth of 3.8 m.

However, it should be noted that although the q_c is normalized with the vertical effective stress, the entire resistance profile for the unsaturated sample is larger than that of the dry sample (Figure 5). Based on this single set of tests, no decisive conclusions can be drawn regarding the mismatch between the expectation and the obtained results. It may be necessary to use a more appropriate effective stress parameter (χ) in Eq. 2 to better distinguish the soil's transition zone. Alternatively, an additional term for matric suction normalization may be derived for q_c returned in unsaturated soil. In addition, as stated in section 2.3, the cone diameter effect is not negligible above the critical depth (i.e. d_{cr}). The q_c profile obtained from the unsaturated sample indicates a complete shallow penetration mode. The discrepancy between the actual and expected results may also be due to the cone diameter effect. Therefore, future CPTs should be conducted in samples with smaller relative density to allow the same centrifugal **g** level in dry and unsaturated samples. If tests on samples with higher relative density are still planned, reference CPTs should be conducted to dry and unsaturated samples separately with the same relative density but different g levels to study the cone diameter effect. If cone diameter effect exists for Toyoura sand with the target relative density, another soil that returns smaller overall q_c should be selected.

6. Conclusion

This paper presents an updated review of laboratory CPTs conducted in unsaturated soil, discussing the effects of the physical dimensions of the test setup, penetration rate, particle size, and stress level (specifically in centrifuge tests) on the measured q_c and providing insights into the applications in CPTs in unsaturated soils. A new experiment setup and cone penetrometer prepared at HKUST for centrifuge CPTs is introduced. The results from two tests performed on dry Toyoura sand at 40***g*** and unsaturated Toyoura sand at 20***g*** are presented. To reduce the impact of large stress gradients within the soil sample induced by centrifuge acceleration, the returned q_c is normalized with vertical effective stress. Although the normalized q_c of the unsaturated sand is higher than that of the dry sand at the same prototype penetration depth, the detailed shape of the profile returned from the unsaturated sample does not fully match expectations. To fully examine this observation, more CPTs with different relative densities and centrifugal accelerations will be carried out. A more appropriate normalization scheme may be derived specifically for the q_c returned from unsaturated soil.

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