Cone penetration testing in unsaturated silt with matric suction measurements

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ABSTRACT
While most empirical correlations used to interpret Cone Penetration Test (CPT) results have been developed from and for saturated soils, there is a lack of understanding as to their applicability for unsaturated soils. This paper presents the experimental results of Cone Penetration tests in an instrumented chamber filled with an unsaturated silt. The experiments were conducted by advancing a 10 cm^2 piezocone into a 1.6 m tall 0.9 m diameter pipe, which was instrumented with four rapid-response tensiometers. The silt was placed at two different water contents with depth. Two pore pressure dissipation tests (PPD) were conducted after 400mm to 500mm penetration in each layer. Negative pore-water pressures (matric suction) were monitored during advancement of the cone and the PPD tests. The cone resistance, sleeve friction and pore-water pressure were also recorded. The experiment was repeated for seven different water contents. All the results of these Cone Penetration tests indicate that the built-in pore-water pressure transducer was incapable of providing useful information regarding pore pressure and hydraulic properties of the unsaturated soil. Hence, tensiometers ought to be used to obtain pore pressure measurements during and after penetration. Tensiometer readings can also be used to characterize the unsaturated soil, namely the in-situ SWCC, unsaturated hydraulic conductivity, in-situ pore-water pressure profile and the in-situ effective stress. Existing empirical correlations used to interpret the results of Pore Pressure Dissipation test (PPD) and Soil Behaviour Type (SBT) are reviewed.

1 INTRODUCTION

Cone Penetration Test (CPT) is an in-situ testing method used to determine the geotechnical properties of soils. It is conducted by pushing an instrumented metallic cone (piezocone) into the ground at a fixed rate. Physical properties of the subsurface can be estimated empirically using the load cell and friction sleeve readings of the piezocone (Figure 1). In-situ pore-water pressure (u_0) and consolidation parameters of the subsurface can also be evaluated by conducting a pore pressure dissipation test (PPD), which takes place when penetration is temporarily paused during advancement.

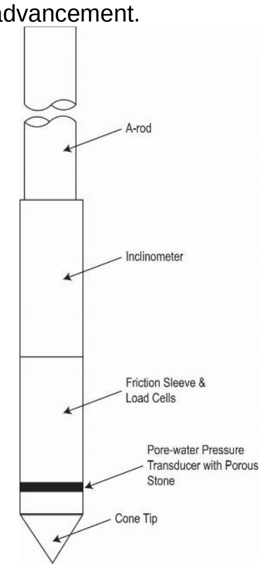

Figure 1: NOVA cone used for unsaturated soil testing

Despite the rapid development of empirical correlations, CPT interpretations have mostly been applied to saturated or completely dry soils only (Robertson & Camapanella, 1983a, 1983b). There are very few publications reporting the use of CPT to evaluate the properties of unsaturated soils. Reasons for this are two-folded. First, most existing empirical correlations were formulated from CPT results in saturated soils, and consequently their applicability to unsaturated soils are unknown, the impact of matric suction on the derived geotechnical parameters in particular. Secondly, to date, there is no known piezocone that can accurately measure matric suction (negative pore-water pressure). Although most pore pressure transducers installed on piezocones can capture negative pore-water pressure, their readings will be inaccurate if the porous stone is desaturated (Campanella & Robertson, 1988). The desaturation of the porous stone can either caused by dilation of an over-consolidated soil or by being in contact with an unsaturated soil. In both cases the hydraulic gradient within the porous stone is higher than the surrounding soil. Fluid within the porous stone will be drawn out resulting in the formation of cavitation nuclei and a discontinuous liquid phase.

Calibration chamber tests were carried out to investigate the applicability of CPT correlations in an unsaturated, moderately dilatant silt. The experiments were conducted by advancing a piezocone (CPTu) into the test chamber, during which, cone resistance; sleeve friction; and pore-water pressure at the u_2 position (cone shoulder) were recorded. Four jet-fill type tensiometers equipped with strain gauge vacuum transducers were installed inside the chamber to various depths to record the change of negative pore-water pressures (matric suction) prior to, during and after cone penetration. Once the piezocone reached the target depth, penetration was halted. Immediately after which, a pore pressure dissipation (PPD) test was conducted.

The objective of this paper is to present the results of these chamber tests, and to demonstrate how to extend CPT applications to unsaturated soils with the use of tensiometers.

2 METHODOLOGY

2.1 Experimental Procedure

The experiment was conducted using a NOVA piezocone (CPTu) to penetrate a cylindrical chamber filled with silt (Figure 2). The inner wall of the chamber was treated to minimize the side wall friction imposed on the specimen. Silt was first pulverized and mixed to a specific gravimetric water content (ranges from 14.5% to 35%) using a concrete mixer (Table 1). The silt was then deposited into the chamber and compacted by hand in 10-centimeter-lifts. Each lift was compacted by dropping a tamper 1 meter from the surface for 30 times. The tamper's base is square in shape and has a length of 254 millimeters (10 inches) and weighs 5.7 kg (12.5 pounds). The compaction effort involved is 25.6 kJ per cubic meter of soil, which is equivalent to 1% compaction effort of a modified proctor test. The relative density of the silt specimen in the chamber tests ranges from 8% to 44%, as shown in Table 1.

Table 1: Test plan for chamber tests

Test #	1	2		3		4	
Zone		Dry	Wet	Dry	Wet	Dry	Wet
Bulk Density (kN/m^3)	19.0	13.0	18.5	18.0	18.5	14.0	18.0
Degree of Saturation	100	32.3	89.9	75.0	85.0	36.4	89.2
Void Ratio	0.93	1.22	0.90	0.87	0.86	1.26	1.00
Grav. Water Content (%)	35	14.5	30	24	27	17	33
Matric Suction (kPa)	9.4	70.7	20.4	24.6	16.0	53.5	14.1
PPD depth (m)	1.24	0.46	1.26	0.52	1.23	0.44	1.19
Relative Density (%)	37	8	40	43	44	4	30

Each chamber test was conducted with two layers of silt, placed at two different water contents, of which the drier layer overlaid the wetter one (Except Test 1 which was tested at one water content). After compacting the last lift of each silt layer, one soil sample was extracted using a 1-inch-shelby tube, using which bulk density and gravimetric water content were measured.

The advancement rate of the piezocone was controlled at a constant rate of 15 millimeters per second in accordance with ASTM D5778. During penetration, cone resistance; sleeve friction; matric suction; and pore-water pressure were recorded. A pore-water pressure dissipation test (PPDs) was conducted near the bottom of each silt layer, beside the installed tensiometer (Figure 2). Every PPD was conducted until the tensiometer readings (matric suction) recovered to their initial values. The chamber test was repeated four times at seven different gravimetric water contents.

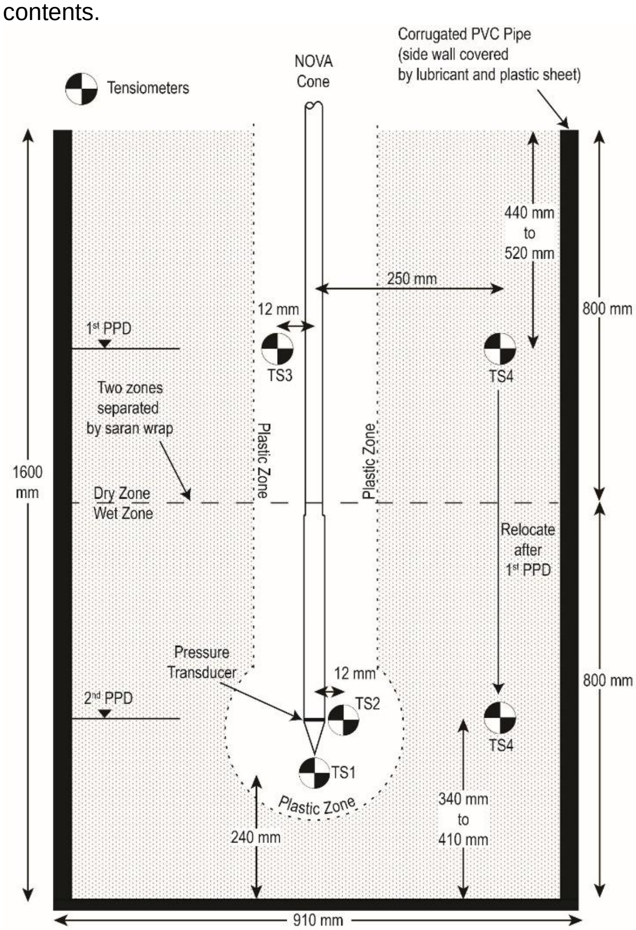

Figure 2: General Layout of Chamber testing

2.1.1 Tensiometers

A tensiometer is a tubular-Plexiglas instrument used to measure the water potential (matric suction) of unsaturated soils. Each tensiometer has a high-air-entry value (HAEV) ceramic tip on one end and a jet-fill type water reservoir and a strain-gauge type vacuum pressure transducer on the other (Figure 3).

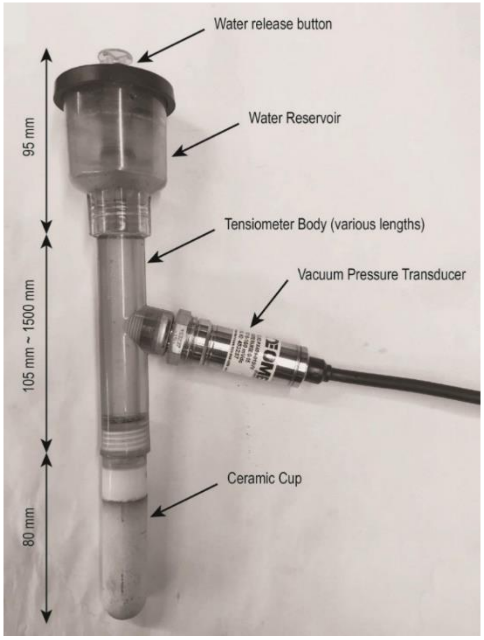

Figure 3: Jet-fill type tensiometer

Before installing the tensiometer into the unsaturated soil, the tensiometer was first filled with de-aired water and the ceramic tip was saturated by immersing in de-aired water inside a vacuum chamber for a minimum of 24 hours. Once all the components of the tensiometer were saturated, it was planted within the unsaturated soil. To measure the water potential (matric suction) accurately, the ceramic tip must be in intimate contact with the surrounding soil. In the chamber test, tensiometers (diameter of 22 millimeters) were inserted into 18-millimeter-auger-holes drilled to the desired depth.

Since the ceramic tip was saturated, the water potential of the unsaturated soil is lower than that within the tensiometer. The potential difference induces a tensile stress on the water within the tensiometer, which is measured by the strain-gauge type vacuum pressure transducer at a rate of once per second. However, when the water within the tensiometer is under tensile stress, air bubbles can form as a result of cavitation nuclei provided the water potential of the soil is less than the atmospheric pressure. In the event that air bubbles were observed within the water column, the water release button on the jet-fill reservoir was pressed and the negative pressure within the water column was vented.

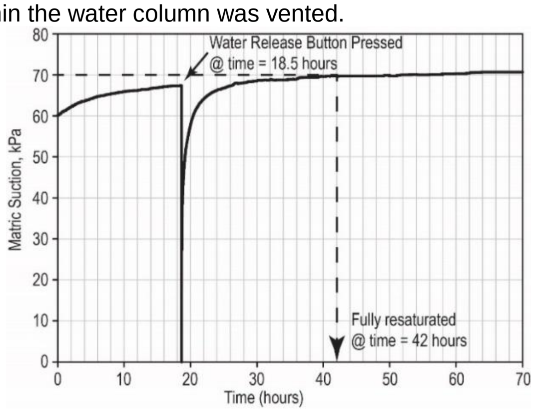

Figure 4: Re-saturation of tensiometer before Test 3

The tensiometers were left in place until the matric suction measurements suggested that equilibrium with the soil had been achieved and that no visible air bubbles existed within the tensiometer. Depending on the water potential of the soil, the time to reach equilibrium was observed to take up to 24 hours (Figure 4).

During the chamber test, ceramic tips rated at 100 kPa (1 ATM) air-entry value were used. This air-entry value rating represents the maximum allowable difference in water potential a saturated ceramic tip can withstand before the intrusion of air into the pore space of the ceramic. The rating of the ceramic tip should be greater than or equal to on the residual suction of the unsaturated soil.

The locations of these tensiometers are summarized in Table 1 and Figure 2. As shown, one tensiometer was buried near the centerline of the chamber, which was used to record the matric suction change at the tip of the piezocone in the wet zone (TS1). Whereas, three tensiometers were inserted away from the centerline at different radii to record the matric suction change near the piezocone shoulder in the wet zone (TS2) and the dry zone (TS3), and in the assumed elastic region (TS4). The locations of these tensiometer were chosen such that tensiometers measuring the matric suction within the plastic zone (TS1, TS2, and TS3) are within ~80 millimeters radius from the pore pressure transducer (Burns & Mayne, 1998a); while the tensiometer measuring the matric suction within the assumed elastic zone (TS4) is at least 200 milimeters from the wall of the chamber.

2.1.2 The Test Chamber

Results of a CPT conducted in a chamber could be significantly different than that conducted in the field due to different boundary conditions. The boundary effects are particularly difficult to quantify as it could vary with many factors. Parkin & Lunne (1982) studied the minimum size of a sand filled test chamber required to have negligible boundary effects. They reported that boundary effects are negligible provided that the chamber diameter is a minimum of 50 times the cone penetrometer for tests conducted in a dense sand (Relative density of ~90%); and 20 times larger than the cone for tests conducted in a loose sand (Relative density of ~30%). Yu & Mitchell (1998) stated that the rigidity of the chamber wall could also affect the cone penetrometer readings. For a chamber with flexible walls (constant pressure), the cone resistance measured tends to be lower than that measured in the field; whereas, a higher cone resistance is usually measured in chambers with rigid walls (zero deformation). Although there is no intention to quantify the boundary effects of the chamber tests in this research, efforts were made to ensure that the boundary effects were minimized where possible. Pore-water pressure changes measured in the tensiometer installed within the assumed elastic region suggested that there was negligible measured change and that the wall treatment and chamber size appeared sufficient to minimize any boundary effects.

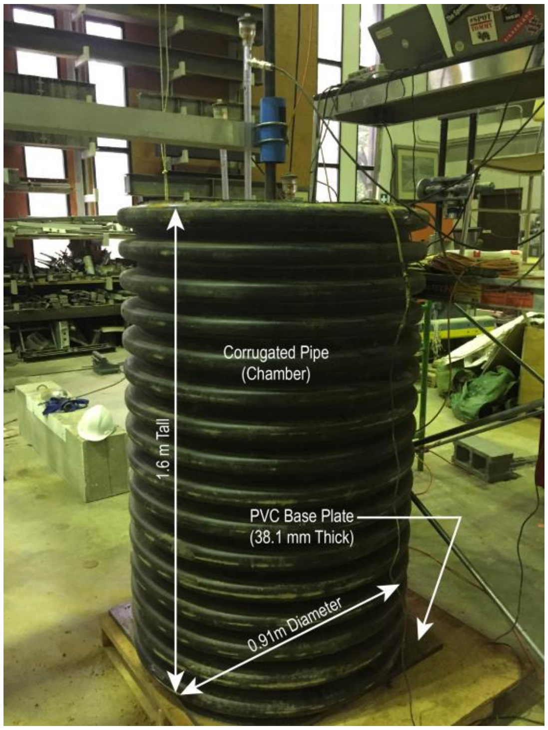

Figure 5: Photo of Chamber Test Set-up

The chamber (Figure 5) used in this experiment is a corrugated pipe made of High Density Polyethylene (HDPE), with dimensions of 0.9 meters x 1.63 meters x 6.4 millimeters (diameter x height x thickness) and corrugated thickness of 63.5 millimeters. The bottom rim of the pipe sits in a groove milled into a 38.1 millimeter (1.5 inches) thick PVC base plate. The groove was sealed with plumber's wax to ensure water tightness. While the piezocone used for the chamber tests has a diameter of 3.6 centimeters, the chamber size is only 25 times larger than that of the cone diameter. In addition, since the silt specimen was at a relative density higher than 20% (refer to Table 1), therefore boundary effect should be expected (Parkin & Lunne, 1982). With the chamber wall being reinforced with corrugated ribs, it is reasonable to assume a zero-deformation boundary condition on the sidewall and the bottom face of the chamber (referred to as "Type B2 chamber" by Parkin & Lunne (1982)). As a result, the cone resistance values obtained in the chamber tests should be higher than that under field conditions.

Prior to deposition of the silt, a layer of silicone lubricant followed by a thin plastic film was applied to the inner wall of the chamber. Such preparation works are intended to reduce the interface friction between the chamber wall and the silt therein, as suggested by Rieke & Chilingarian (1974). The top face of the chamber was also covered by a plastic film immediately after soil depostion and cone penetration in order to reduce the loss of water content through evaporation.

3 RESULTS & INTERPRETATIONS

3.1 In-situ SWCC

Fredlund & Houston (2013) reported that the SWCC may differ if the porosity of the soil sample changes. This suggests a hysteresis between laboratory SWCC data and in-situ SWCC data due to the difference in sample preparation (hence, different porosities). To obtain the in-situ SWCC, tensiometers were used to measure the matric suction after the unsaturated silt was deposited into the chamber. The bulk density and gravimetric water content of the silt layer was measured from the silt sample extracted after compaction. From these measurements, degree of saturation and void ratio were calculated. The calculated values of degree of saturation were then plotted against the matric suction value, and curve fitted using Fredlund & Xing (1994) to obtain the in-situ SWCC. Figure 6 presents the SWCC obtained from a pressure plate cell (lab data) and from tensiometer measurements (in-situ).

It is observed that the in-situ SWCC shifted to the right (Figure 6), meaning the soil is able to sustain higher suction before desaturation. As a result, the air-entry value also shifted from ~9.5 kPa (lab condition) to ~15 kPa (in-situ measurement).

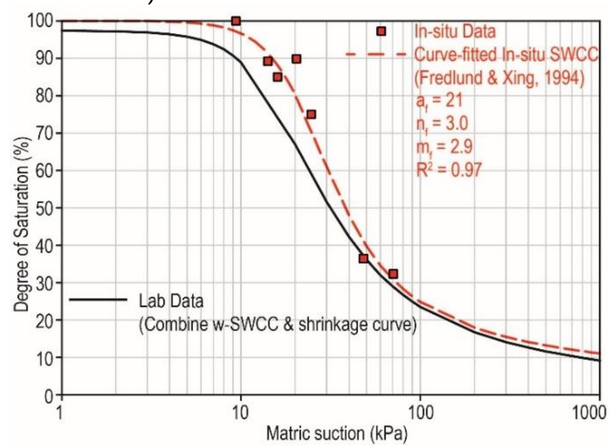

Figure 6: Lab and In-situ SWCC

3.2 Correction for Cone Resistance & Sleeve Friction

Due to the different geometry of the friction sleeve and the cone tip load cell, the cone resistance could be affected by the excess pore-water pressure. This effect is referred to as the "unequal end area effect" (Campanella et al., 1982). A correction factor can be applied to the measured cone resistance (q_c) to obtain a corrected cone resistance value (q_t):

Equation (1) $$q_t = q_c + u_2(1-a)$$

q_t = Corrected cone resistance;
q_c = Uncorrected cone resistance;
u_2 = Excess pore-water pressure measured by pore pressure transducer at cone shoulder (u_2 location);
a = Net area ratio (instrument-specific calibration value, determined to be 0.842 by the manufacturer).

The continuous measurement of cone resistance and sleeve friction with depth of the four chamber tests were averaged (cone resistance values being corrected as well) and are presented in Figure 7 with the in-situ SWCC overlain. It can be generalized that cone resistance measured in unsaturated soils tends to increase with matric suction. Whereas, sleeve friction attains a maximum value near the air-entry value (AEV) of the soil. The result is expected as cone resistance is known to varies with the shear strength of the soil (Nash & Duffin, 1982; Lunne et al., 1986; Aas et al., 1986). And while the shear strength of the unsaturated soil also increases with increasing matric suction (Bishop, 1959; Fredlund & Rahardjo, 1993), it is within expectation that cone resistance increases with increasing matric suction (Yang & Russell, 2015).

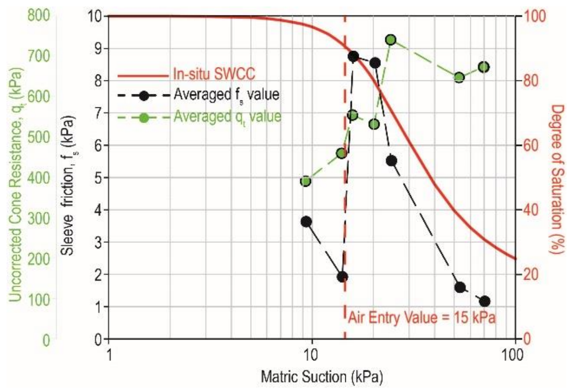

Figure 7: Matric suction against averaged sleeve friction & averaged corrected cone resistance

3.3 Pore Pressure Response

3.3.1 Pore Pressure Dissipation test

As the piezocone advances, the pore pressure transducer measures the excess pore-water pressure generated with depth. When the piezocone has advanced to the target depth, penetration stops and a Pore Pressure Dissipation test (PPD) is conducted. During a PPD test, the pore-water pressure transducer (Figure 1) records the pore-water pressure around the piezocone as it is being dissipated with time. In granular soils, a complete PPD may only takes several minutes, whereas a PPD in fine-grained soils could takes days to complete. Very often, a PPD in fine-grained soil is terminated as soon as half of the excess pore-water pressure has been dissipated, the time required for which is known as the t_{50} value. Empirical correlations have been developed to estimate the hydraulic properties of the subsurface using t_{50}, namely the hydraulic conductivity and coefficient of consolidation. The in-situ pore-water pressure can also be estimated from a PPD, which will be discussed in subsequent section.

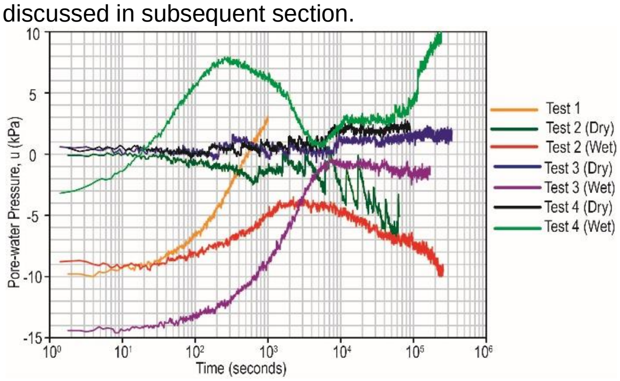

Figure 8: PPD Curves of chamber tests

Pore pressure dissipation tests (PPD) were conducted twice in most chamber tests (except Test 1): Once in the dry zone and once in the wet zone. Figure 8 presented the PPD curves obtained in all the chamber tests. It is observed that the pore pressure transducer does not always record a change of pore pressure during PPDs. In fact, when the in-situ suction is higher than ~ 24.6 kPa (Deg. Of Saturation: 75%), the pore pressure transducer shows little to no change of pressure.

For PPDs that recorded a dissipating pressure, the trend of PPD curves shows an exponential increase of pore pressure with time. Once the pore pressure reaches a maximum value, it either remains constant (Test 1 and Test 3) or decreases with time (Test 2 and Test 4). However, the decrease of pore pressure after peak values are likely the results of hydraulic head difference between the Wet Zone and the Dry Zone. Hence, it can be assumed that the pore pressures are fully recovered at peak value. Table 2 below summarized the measured t_{50} values.

Table 2: t_{50} values and estimated hydraulic properties

Test # /Zone	Matric Suction (kPa)	q_t-σ_{v0} (kPa)	PPD Results (Tensiometer Results)		
			t_{50} (s)	k ($\times10^{-9}$ m/s)	c_h ($\times10^{-6}$ m^2/s)
1	9.36	376.5	426 (415)	8.30 (8.52)	2.63 (2.7)
2/ Wet	20.4	530.1	628 (176)	4.00 (14.3)	1.78 (6.36)
3/ Wet	15.96	552.5	1305 (73)	1.85 (33)	0.86 (15.3)
4/ Wet*	14.1	457.9	40 (752)	73.1 (3.87)	28.1 (1.49)

*Tensiometer damaged by piezocone, leakage may have affected the PPD readings. Tensiometer's t_{50} value was estimated base on other tensiometers

3.3.2 Tensiometer Readings

In the chamber test, tensiometers were also used to monitor the pore pressure change during and after cone penetration. Similar to the results of the PPD tests, the tensiometer measurements were mostly unresponsive to cone penetration when the degree of saturation of the soil is less than 75% (matric suction > 25 kPa); a drastic change of tensiometer readings with cone insertion when the degree of saturation of the soil is higher than 75% (matric suction < 25 kPa).

For chamber tests with initial matric suction of 25 kPa or lower, matric suction changes with cone penetration. As demonstrated in Figure 9, there is a slight increase of matric suction (~1 to 2 kPa) as the piezocone approaches the depth of tensiometers. This increase of suction is immediately followed by a sharp decrease of matric suction until the shoulder of the piezocone reaches the same depth as the tip of the tensiometer. Penetration is halted for PPD test at this instance, and the matric suction slowly rises to its initial value. Full recovery of matric suction was generally observed within 3 to 5 hours after the beginning of PPD. Since the tensiometers were located close to the pore pressure transducer unit of the piezocone, partial amount of the dissipating pore pressure was also recorded by the tensiometers. The t_{50} values measured by the tensiometers are also presented in Table 2.

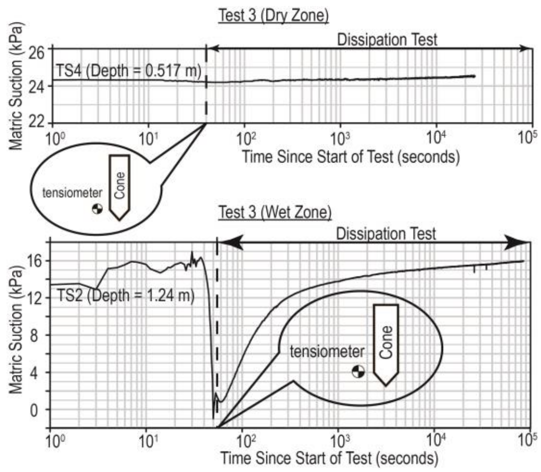

Figure 9: Two Types of Matric Suction Responses (Test 3)

3.4 Estimation of Hydraulic Properties

Typically, the hydraulic properties of the subsurface, namely hydraulic conductivity and coefficient of consolidation, can be evaluated using the dissipation rate from PPD. The following Terzaghi type consolidation equation is commonly used to calculate coefficient of consolidation using the PPD data (Campanella & Robertson, 1988; Houlsby et al., 1989) :

Equation (3)
$$T = \frac{c_h t}{r_0^2 \sqrt{I_R}}$$

Where,

t = Time to reach a certain degree of consolidation ($\Delta u/u_0$);

r_0 = Radius of the piezocone = 1.8 cm;

c_h = Coefficient of consolidation;

T = Time factor that depends on degree of consolidation, tip geometry of piezocone, porous element location;

I_R = Rigidity index ($I_R = G/S_u = 200$)

Torstensson (1977) realized that the degree of pore pressure dissipation ($\Delta u/u_0$) is related to rigidity index (I_R) and the quantity r_o^2/c_h in Equation (3). Using the method of finite difference, Teh & Houlsby (1991) created a tabulated solution to obtain the time factor (T) in Equation (3). A time factor of 0.245 is usually used in the t_{50} method, at which 50% of the excess pore-water pressure have been dissipated.

Burns & Mayne (1998b) proposed an empirical correlation to coefficient of volume compressibility (m_h) and hydraulic conductivity (k) using corrected cone tip resistance (q_t):

Equation (4)
$$k = \frac{c_h \gamma_w}{1/m_h} = \frac{c_h \gamma_w}{8.25(q_t - \sigma_{vo})}$$

Where,

k = Hydraulic conductivity;

m_h = Coefficient of volume compressibility;

q_t = Corrected cone tip resistance;

c_h = Coefficient of consolidation;

σ_{v0} = Vertical total stress;

γ_w = Unit weight of water

Equation (4) was developed based on the database of cone penetration tests in saturated soils. At which, the equation assumed that the constrained modulus ($1/m_h$) is 8.25 time of the net cone resistance (q_t- σ_{v0}). While unsaturated soils are generally more compressible than saturated ones (due to compressibility of air), there is no evidence indicating to what degree is this equation applicable to unsaturated soils. Using Equation (3) and Equation (4), the hydraulic conductivity and coefficient of consolidation of the unsaturated soils can be estimated using the t_{50} values obtained from the PPDs and tensiometers (Table 2).

The hydraulic conductivity of unsaturated soil varies with both degree of saturation and void ratio (Fredlund & Rahardjo, 1993), and are always lower than that of saturated soils. The typical t_{50} method is only applicable to unsaturated soils at low suction (close to air-entry value) since at higher matric suction (>25 k) there is no dissipation response. In addition, the hydraulic properties of silt with higher than 75% saturation are also overestimated.

Aside from using the aforementioned empirical correlations, the in-situ SWCC can also be used to estimate the hydraulic conductivity of unsaturated soils. Brooks & Corey (1964) proposed the following equations, in junction with a pore-size distribution index (λ), to estimate the unsaturated hydraulic conductivity.

Equation (5):
$$k_{unsat} = k_{sat} \left(\frac{AEV}{u_a - u_w}\right)^{2+3\lambda} \qquad for\ u_a - u_w > AEV$$
$$k_{unsat} = k_{sat} \qquad for\ u_a - u_w \le AEV$$

The pore-size distribution index (λ) is defined as the negative slope of a SWCC (degree of saturation against suction). The λ parameter can be obtained by curve fitting the Brooks & Corey SWCC model (Equation (6)) to the in-situ SWCC (Figure 6). The results are presented in Figure 10.

Equation (6):
$$\frac{S - S_r}{1 - S_r} = \left(\frac{AEV}{u_a - u_w}\right)^{\lambda} \qquad for\ u_a - u_w > AEV$$
$$S = 1 \qquad for\ u_a - u_w \le AEV$$

Where,

k_{unsat} = Unsaturated hydraulic conductivity;

k_{sat} = Saturated hydraulic conductivity;

AEV = Air-entry value obtained from in-situ SWCC;

S = Instantaneous degree of saturation;

S_r = Residual degree of saturation

u_a-u_w = Matric suction;

λ = Pore-size distribution index

The estimated unsaturated hydraulic conductivity using Brooks' & Corey's (1964) method is presented in Figure 10, where the hydraulic conductivity estimated with the empirical correlations are also plotted.

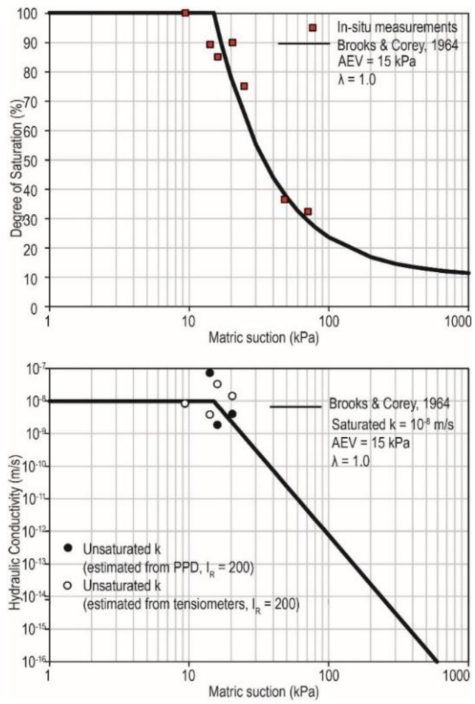

Figure 10: Estimated unsaturated hydraulic conductivity (In-situ condition)

3.5 Estimation of In-situ Pore-water Pressure

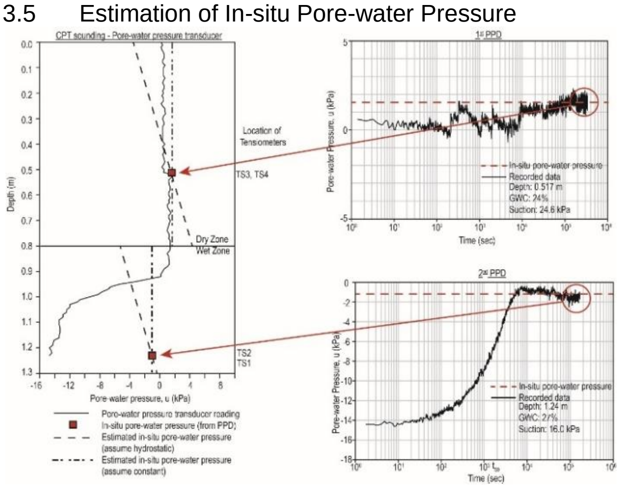

Figure 11: Interpreting in-situ pore-water pressure from PPD results

During a PPD test, the excess pore-water pressure generated by cone penetration dissipates until in-situ level. Therefore, it is reasonable to assume the terminal value of a PPD equals the in-situ pore-water pressure (Figure 11). For saturated soils, the pore-water pressure often exhibits hydrostatic condition (steady increases with depth). The same condition, however, cannot be assumed for this chamber test since the water content of soil column was controlled and kept constant. And as verified by the tensiometer readings at various depths of the same zone, the pore-water pressure was, in fact, a constant value with depth. The in-situ pore-water pressure of each test is summarized in Table 3.

Table 3: Pore-water pressure profile of each chamber test

	In-situ Pore-water pressure (kPa)		
	Estimated from PPDs	Estimated using tensiometers	% Diff.
Test 1	8	-9.4	185
Test 2 Dry Zone	-0.1	-70.7	100
Test 2 Wet Zone	-3.5	-20.4	83
Test 3 Dry Zone	0.6	-24.6	102
Test 3 Wet Zone	-0.5	-16.0	97
Test 4 Dry Zone	2.5	-53.5	105
Test 4 Wet Zone	-3.2	-14.1	77

While air-pressure is not controlled during all chamber tests (remain atmospheric), the matric suction values measured by the tensiometers equal to the in-situ pore-water pressure (negative pore-water pressure) (axis translation technique by Hilf (1956)). However, the in-situ pore-water pressures estimated using PPD and tensiometer are very different (greater than 77%). The different pore-water pressure could be the result of desaturation of the pore-pressure transducer.

Despite pore pressure transducers are mostly used to measure a positive pore-water pressure response, literatures have suggested that it is also capable of measuring pore-water pressure in the negative range (Burns & Mayne, 1998a; Burns & Mayne, 1998b; Robertson & Cabal, 2015; Robertson et al., 2017). However, the measurements of negative pore-water pressure become inaccurate if the instrument is not fully saturated (Campanella & Robertson, 1988; Fredlund et al., 2012). This is very likely to be the case while conducting CPT test in unsaturated soils, since the porous stone could be desaturated due to hydraulic head difference or air diffusion. Since the readings from the pore pressure transducer obtained in an unsaturated soil generally do not reflect the actual negative pore-water pressure (suction), if it was used to characterize the in-situ condition of the soil, the results are erred.

3.6 Effective Stress of Unsaturated Soils

One of the erred interpretation as a result of inaccurate pore pressure measurements is effective stress. In saturated soils, the effective stress (σ') was considered as the difference between total stress (σ) and pore-water pressure (u_w) (Terzaghi, 1925):

Equation (7) $$\sigma' = \sigma - u_w$$

Terzaghi's effective stress equation assumes the soil contains only solids and water. However, in unsaturated state, the soil is a three-phase material which also contains air. Bishop (1959) proposed an expression for effective stress (σ') in unsaturated soil, which also account for the pore-air pressure (u_a):

Equation (8) $$\sigma' = \sigma - u_a + \chi(u_a - u_w)$$

σ' = Effective stress;
σ = Total stress;
u_a = Pore-air pressure;

u_w = Pore-water pressure;

χ = Effective stress parameter.

The term u_a-u_w is also known as matric suction, which was defined by Hilf (1956) using the axis-translation method. The effective stress parameter (χ) is known to be dependent on the degree of saturation. For practical purposes, the χ parameter is sometimes assumed to be the degree of saturation (S) (Leroueil & Hight, 2003). Jennings & Burland (1962) summarized the results of different unsaturated soil testing from literatures and provided a graphical solution to χ (Figure 12). They demonstrated that the parameter χ is not only quite different from the degree of saturation, it also varies with different type of materials. The χ parameter of the red silt (as shown in Figure 12) was estimated using unsaturated triaxial tests.

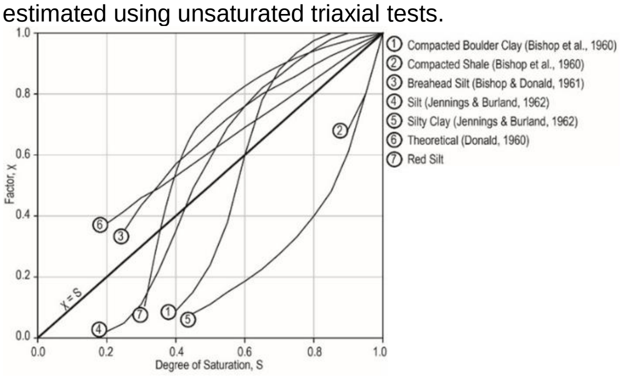

Figure 12: The χ parameter against degree of saturation for various soils (After Jennings & Burland, 1962)

By substituting the vertical overburden stress, pore air pressure (equals to atmospheric, hence, 0) and matric suction (measured from tensiometers) into Equation (8), the effective stress of the unsaturated soil can be estimated. With the pore-water pressures estimated using PPD and tensiometers being significantly different (Table 3), the calculated values for in-situ effective stress also differs. Figure 13 presented different values of effective stresses estimated with the two transducers. The result indicates that the effective stress evaluated using the results of PPDs tend to underestimate the suction hardening effect.

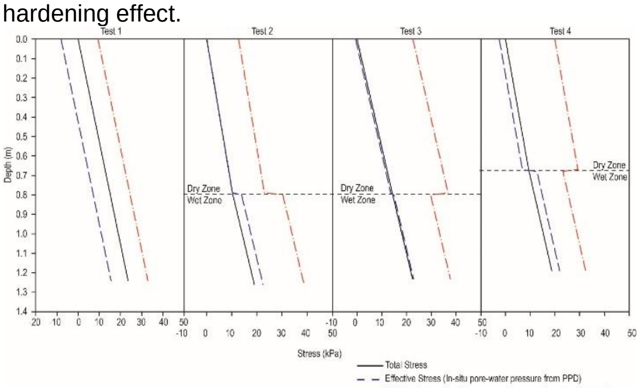

Figure 13: Calculated effective stresses for chamber tests

4 CONCLUSION

A research study was carried out to investigate the validity of the existing empirical correlations for CPT in unsaturated soils. Unsaturated silt specimens of controlled water contents were deposited into a 1.6 m tall 0.9 m diameter pipe and penetrated by a 10 cm^2 piezocone. Aside from cone resistance, sleeve friction and pore-water pressure, the matric suction was also measured with the use of tensiometers. Chamber test results indicate that a conventional pore pressure transducer with a brass porous stone was not capable of capturing the matric suction in unsaturated soils, hence, tensiometers ought to be used to obtain pore pressure measurements during and after penetration.

While the pore pressure transducer unit is incapable of providing any useful information within unsaturated soils since its porous element desaturates, tensiometers ought to be used to evaluate the pore pressures. Using the tensiometer readings, one can estimate in-situ SWCC, unsaturated hydraulic conductivity, in-situ pore-water pressure profile and in-situ effective stress, as demonstrated in this paper.

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