Evaluating the pressuremeter test for determining p-y curves for laterally loaded driven piles in clay

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ABSTRACT
PENCEL Pressuremeter (PPMT) was used to perform tests in clay. This study was performed to evaluate a standard method of PPMT testing to allow engineers to more precisely carry out the standardized tests, and to generate the p-y curves for analysis and design of laterally loaded piles. The results indicate the testing procedure is acceptable. The effects of adding a 1/16 inch friction reducer to the standard PENCEL cone tip used for clay soils were negligible. Dilatometer (DMT) tests were conducted for comparisons with PPMT data. Soil parameters including the lift-off pressure the limit pressure, the initial elastic moduli, and the reload moduli, were determined. The PPMT soil parameters from both types of cone tip, show good agreement with published values. Correlations were developed between the PPMT and DMT results, which show consistency in soil parameters values. Comparison between PPMT and DMT p-y curves were performed. The initial slope shows a good agreement for this comparison. The predicted DMT and PPMT ultimate loads are not similar, while the predicted PPMT and DMT deflections within the elastic range are identical. The PPMT is a suitable in-situ tool to duplicate the pile installation and predict the laterally loaded soil resistance for analysis.

RÉSUMÉ
Le pressiomètre PENCEL (PPMT) était employé pour réaliser des essais dans l'argile. L'étude consiste à évaluer une méthode standard permettant d'effectuer les essais normalisés plus précis, et produisant les courbes p-y pour l'analyse et la conception des pieux chargés latéralement. Les résultats indiquent que la méthode d'essai est acceptable. Les effets d'ajouter un réducteur de friction de 1/16 pouce au cône standard du PENCEL utilisé pour les argiles étaient négligeables. Les essais dilatomètriques (DMT) étaient effectués pour des comparaisons avec ceux du PPMT. Les paramètres du sol comprenant la pression initiale et limite, les modules élastiques initiaux et de rechargement étaient déterminés. Les paramètres du sol du PPMT des deux types de cône, montrent une bonne concordance avec des valeurs publiées. Des corrélations étaient développées entre les résultats PPMT et DMT, montrant l'uniformité en valeurs des paramètres du sol. La comparaison entre les courbes p-y de PPMT et DMT était effectuée. La pente initiale montre une bonne concordance. Les charges ultimes prévues sont différentes, tandis que les déformations prévues de PPMT et DMT, dans l'intervalle élastique, sont identiques. Le PPMT est un outil in-situ approprié pour reproduire l'installation de pieu et présumant la résistance du sol chargée latéralement pour l'analyse.

1 INTRODUCTION

1.1 Background

The pressuremeter consists of a cylindrical probe containing an inflatable balloon, which is lowered into the soil to create in situ stress-strain responses, was originally developed by Ménard (1956) and modified by Briaud and Shields (1979). A variety of pressuremeter models are currently available, although they are typically based on two widths, the standard 3-inch diameter probes lowered into boreholes and the specialty 1.35-inch diameter PENCEL probes pushed when attached to cone rods (Briaud, 1992). In addition to classical geotechnical applications, Briaud and Cosentino (1989) developed procedures for using the PENCEL pressuremeter (PPMT) in pavement design. The PPMT is shown in Figure 1 with the probe connected to the unit through tubing and the pressure and volume gauges for recording data by hand (Roctest, 2005). Anderson and Townsend (1999) saw advantages in connecting the PPMT probe to Cone Penetrometer (CPT) rods and either pushing the cone with the PPMT attached or pushing the PPMT separately to perform PPMT tests. Finally, this device was further advanced by 1) developing a standardized testing procedure as recommended by Cosentino et al (2006) and 2) incorporating digital technology with data acquisition software producing significant time savings and improved accuracy as a fully reduced stress-strain curve is produced during testing (Cosentino et al, 2006). Often thrust pressures monitored by equipment operators are limited to 10 kN to avoid damage.

PPMT equipment has been successfully used throughout Florida in sands and clays (Anderson and Townsend 1999), (Cosentino et al. 2006).

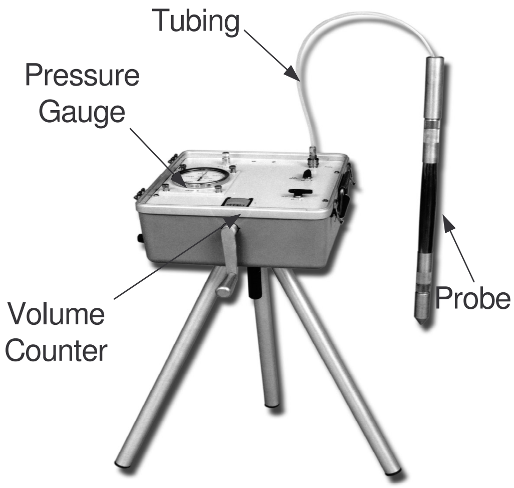

Figure 1. PENCEL Pressuremeter (After Roctest 2005)

1.2 Typical procedure

The system saturation requires several calibrations to be conducted; one that accounts for the inherent membrane resistance termed the membrane calibration, and a second, for expansion of the tubing and thinning of the membrane during pressurization termed the system expansion calibration. Because the test is conducted at a known depth below the pressure gauge, a hydraulic correction is also applied to the pressures. The PPMT probe is hydraulically pushed with the equipment in the (CPT) rig to the desired test depth and the 10-to15-minutes standardized test suggested by Cosentino et al (2006) is performed.

A strain-controlled process is used during this standard test, involving operators to inject equal 5 cm^3 volumes of water into the probe at a desired depth, wait 30 seconds and then record the corresponding pressures to allow the device to be stabilized at that depth.

The probe volume is incrementally increased from its original volume an additional 90 cm^3, or until the limit of the pressure gauge is reached. The operators also determine the extent of the linear stress–strain response range before performing one unload–reload cycle on the soil. This determination needs several complex steps; thus, Cosentino et al (2006) incorporated digital equipment and data acquisition software, called APMT for Automated Pressuremeter that simplified the process, yielding more precise data while easing operator requirements.

1.3 Data Interpretation

Once the data is collected it is typically plotted on a curve as shown in Figure 2. This figure contains both the membrane calibration curve and the volume calibration line, which are subtracted from the raw data to produce a reduced curve.

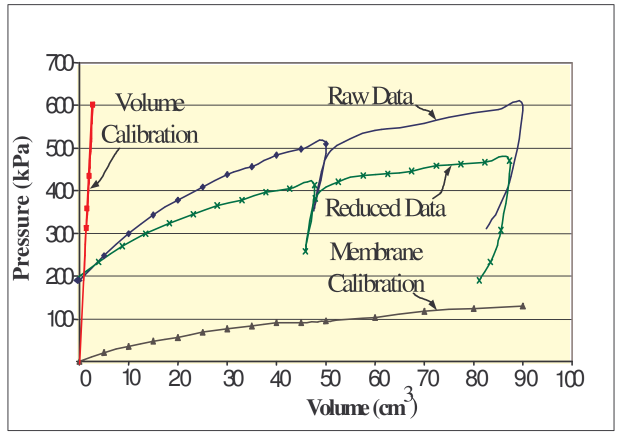

Figure 2. Typical Resulting PPMT Test with Volume and Membrane Corrections (Cosentino et al 2006).

Various portions of the reduced curve are analyzed in sequence to determine the critical engineering parameters, Figure 3 shows four critical portions of the reduced curve that are used for estimating:

1) The initial or the at-rest horizontal pressure (p_0) from the repositioning phase,

2) An initial elastic modulus (E_0) from the elastic phase,

3) An elastic reload modulus (E_r) from the elastic reload phase, and

4) The limit pressure (p_L) from the plastic phase.

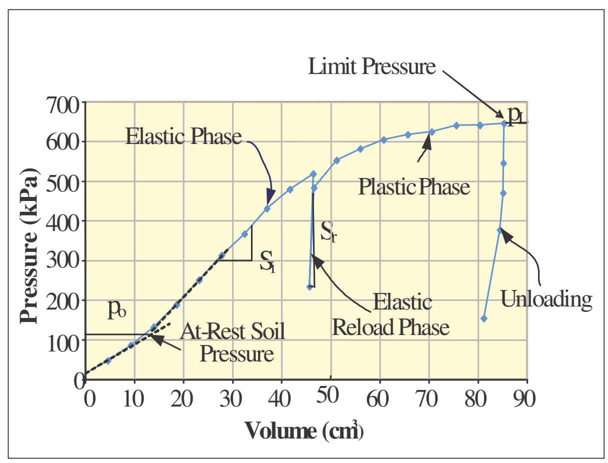

Figure 3. Engineering parameters typically obtained from reduced data.

Elastic moduli are determined from the equation 1 (Baguelin et al. 1978):

$$E = 2(1+\nu)\frac{\Delta P}{\Delta V} V_m \qquad [1]$$

where, E = Young's modulus, ΔP = change in stress, ΔV = change in volume related to ΔP, V_m = average volume, ν = Poisson's Ratio .

Due to soil disturbance, there are concerns about the quality of the engineering parameters obtained from pushed-in PPMT tests. Some operators push the probe with a small friction reducer on the cone tip and others push it without this tool which is thought to help preserve the membranes during a sounding.

2 FIELD TESTING PROGRAM

A complete field-testing program was performed in Cape Canaveral, Florida, enabling clays to be evaluated. In addition to PPMT tests, dilatometer (DMT) Cone and Penetrometer (CPT) tests were conducted. All testing was conducted using the Florida Department of Transportation (FDOT) State Materials Office CPT rig and personnel.

Over 100 PPMT and DMT tests were conducted at this site. To determine the effects the friction reducer, shown schematically in Figure 4, has on the soil properties, about half of the PPMT tests were conducted with friction reducer and half without the friction reducer termed smooth cone tip. The 33.9 mm (1.335 inch) diameter reducing ring was about 3 % larger than the 33.0 mm (1.280 inch) diameter smooth cone point.

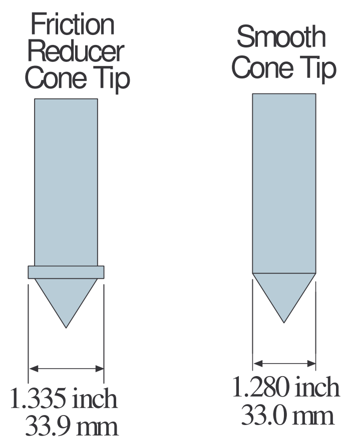

Figure.4 Schematic PPMT cone tip (Cosentino et al 2006)

The Cape Canaveral site consists of interbedded sands and clays. There were two clay layers that were the focus of the research. An upper clay layer approximately 2 m (6 feet) thick was normally consolidated and had an average density of 14.4 kN/m^3 (92 pcf) and a lower normally consolidated layer from the 10 to 15 m (30 to 50 feet) depth with an average density of 15.3 kN/m^3 (97 pcf).

The procedure used during PPMT testing was the recommended FDOT standard (Cosentino et al, 2006). During the strain-controlled test, operators monitored stress versus volume data to determine the extent of the elastic range. Once this range was complete, unloading to one-half the existing pressure then reloading to the original pressure was performed followed by the remainder of the strain-controlled test (Figure 3). The American Society for Testing and Materials (ASTM) procedure D 6635 was followed for all DMT testing, while CPT tests were conducted in accordance with ASTM D 5778.

The flat dilatometer (DMT) developed in Italy by Marchetti (1980) is currently used in over 40 countries, both for research and practical applications. The flat DMT has been shown to be a practical in-situ penetration testing to obtain the data necessary to generate p-y curves for laterally loaded piles (Robertson et al., 1989 and Gabr et al., 1988).

The flat DMT consists of a steel blade having a thin, expandable, circular steel membrane mounted on the face. When at rest, the membrane is flush with the surrounding flat surface of the blade. The blade is connected, by an electric-pneumatic tube running through the insertion rods, to a control unit on the surface (Figure 5). The control unit is equipped with pressure gauges, an audio-visual signal, a valve for regulating gas flow, and vent valves. The blade is advanced into the ground using common field equipment i.e. push rigs normally used for CPT tests or drill rigs. The type of blade used for this program testing was blade # 61370 with a thickness of 15 mm and the membrane face was oriented to the West.

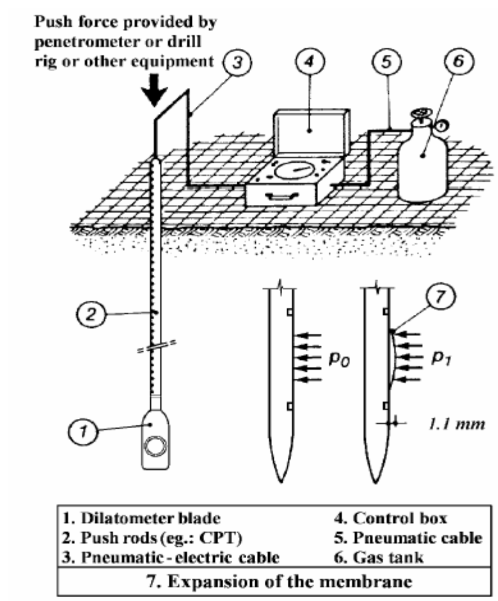

Figure 5. General Layout of the DMT Test

For evaluating DMT data, a test procedure was described by Marchetti (1980), presented equations requiring several preliminary calculations to determine a Young's modulus of elasticity (E). After obtaining the two basic test parameters; the lift-off pressure (A) or the pressure on the DMT membrane once it is pushed to the desired depth and the maximum pressure at 1.1 mm of movement (B), a corrected contact stress is found using the equation 2:

$$p_0 = 1.05(A - Z_M + \Delta A) - 0.05(B - Z_M - \Delta B) \qquad [2]$$

where, Z_M is the gauge pressure when vented to the atmosphere, while ΔA and ΔB are calibration pressures subtracted from the lift-off and maximum readings. A corrected expansion stress is then found using the equation 3:

$$p_1 = B - Z_M - \Delta B \quad [3]$$

The DMT modulus, not Young's Modulus, is then found from the equation 4:

$$E_D = 34.7\left(p_1 - p_0\right) \quad [4]$$

This DMT modulus can be converted to a Young's Elastic Modulus by first determining a constrained modulus from equation 5:

$$M_{DMT} = R_M E_D \quad [5]$$

Where,

R_M is an empirical value that is a function of either the horizontal stress index (K_D) defined as $(p_{0-} u_0)/(\sigma'_{v0})$ or the material index (I_D) defined as $I_D = (p_1 - p_0)/(p_0 - u_0)$.

Note that u_0 is the pore water pressure and σ'_{v0} is the vertical effective stress. The constrained modulus is used in the following equation "Eq.6", based on Poisson's ratio (ν) to determine the elastic modulus:

$$E = M_{DMT}\left[\frac{(1+\nu)(1-2\nu)}{(1-\nu)}\right] \quad [6]$$

3 DATA REDUCTION AND ANALYSIS

The stand-alone data acquisition program, called APMT, was developed for this research (Cosentino et al, 2006), in conjunction with incorporating digital pressure and volume equipment into the PENCEL control unit. This software uses the digital calibration data to continuously reduce the digital field data producing a stress-strain plot on the operators' computer screen throughout testing as see in Figure 6. This plot allows operators' to follow standardized testing procedures. APMT also has built-in modules that yield the critical stress-deformation information i.e., p_0, E_0, E_r and p_L. Results obtained using the APMT package were compared to hand and spreadsheet calculations. Once the output was verified this package was used to determine the four key engineering parameters obtained during PPMT testing (i.e., p_0, E_0, E_r, p_L).

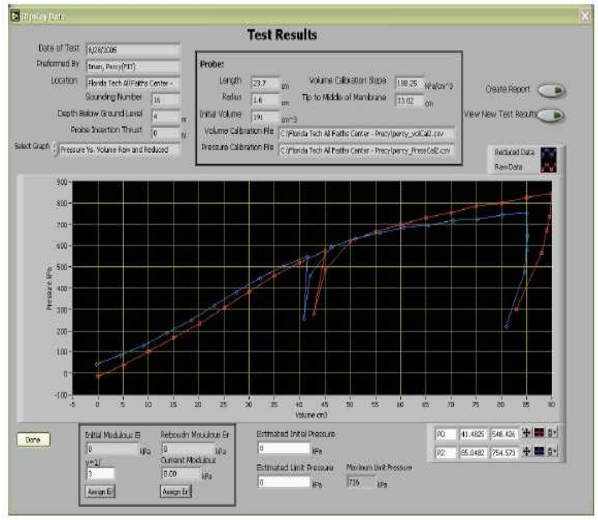

Figure 6. APMT screen used to perform all analysis of the data (Cosentino et al 2006).

4 DEVELOPMENT OF CORRELATIONS

4.1 Correlations to Engineering Parameters from PPMT

To evaluate the effects of using a friction reducer, 80 tests were conducted at the Cape Canaveral Site, 40 were performed with friction reducer and 40 with out friction reducer (smooth cone tip). The tests were performed in 16 soundings (i.e., a series of tests performed in one location while advancing the PENCEL probe to the desired depths), with eight being conducted with friction reducer and eight smooth cone tip.

A comparison was developed between the smooth cone data and the friction cone data using the initial and reload moduli, plus the initial or lift-off pressures and the limit pressures. Ratios of these four parameters at five depths are shown in Table 1. This data was inconsistent in the two upper depths due to irregularities in the soil types as the PENCEL probe was moved between soundings. However, once the soft clay was encountered the ratios between the smooth and friction reducer probes were nearly 1.00, indicating that in soft clay there is very little difference between the results conducted with smooth cone tip and with the friction reducer. Of the four parameters evaluated, the initial modulus was most affected by the use of a friction reducer.

Table 1. Ratio between PPMT Engineering Parameters at Cape Canaveral Site

Depth [m]	Soil Type	Engineering Parameters			
		$\frac{E_{0(sm)}}{E_{0(fr)}}$	$\frac{E_{r\,(sm)}}{E_{r\,(fr)}}$	$\frac{p_{L\,(sm)}}{p_{L\,(fr)}}$	$\frac{p_{o\,(sm)}}{p_{o\,(fr)}}$
2.5	Soft Sandy Clay	1.25	1.08	1.28	1.16
10.5	Loose Silty Fine Sand	1.33	1.06	1.07	1.06
12	Soft Clay	1.10	1.04	1.01	1.01
13.5	Soft Clay	1.08	1.00	1.00	1.01
15	Soft Clay	1.06	0.99	0.99	1.01

To more evaluate the need of a friction reducer cone tip, tables 2 to 4, present the correlated results from various references relating elastic modulus, E_o, to limit pressure, p_L, and relating point resistance (q_c), to elastic modulus, E_o, and to limit pressure, p_L.

Table 2 includes correlation relating E_o to p_L from PPMT tests in clay at the Puerto Del Rio site and published values from Ménard and Rousseau (1962). It is obvious that with either smooth cone tip or the friction reducer cone tip the average ratio for E_o/p_L is still within range of Ménard and Rousseau's published values of 6 to 16.

Table 2 Comparisons of PPMT and CPT Engineering Parameters (E_o/p_L)

Depth [m]	E_o/p_L		
	PPMT		CPT
	Smooth	Friction	Ref A
2.5	16	14	6 to 16
10.5	8	6	
12	8	6	
13.5	7	8	
15	8	8	
Reference A : Ménard and Rousseau (1962)			

Table 3 shows the average ratio for E_o/q_c based on tests results was between 3 to 20 or 4.5 to 9 for clay or fine sand using both the friction reducer and smooth cone tip, respectively (Schmertmann, 1978; Bergado and A.Khaleque, 1986).

Table 4 shows the average ratio for q_c/p_L was about 1.5 to 6 (Schmertmann, 1978). The ratios between the PPMT initial moduli and the CPT point resistances (q_c) were estimated along with ratios of the PPMT limit pressures and q_c. The E/q_c ratios are commonly used for settlements of sands (Schmertmann et al, 1978).

Table 3 Comparisons of PPMT and CPT Engineering Parameters (E_o/q_c)

Depth [m]	E_o/q_c		
	PPMT		CPT
	Smooth	Friction	Ref s B, C
2.5	19.4	12.4	3 to 20
10.5	7.4	4.7	4.5 to 8.9
12	5.7	4.1	
13.5	5	5.2	
15	5.1	5.2	
Reference B: Schmertmann (1978)			
Reference C: Bergado and A. Khaleque (1986)			

Table 4 Comparisons of PPMT and CPT Engineering Parameters (q_c/p_L)

Depth	q_c/p_L		
	PPMT		CPT
[m]	Smooth	Friction	Ref B
2.5	1	1.1	1.5 to 6
10.5	1.1	1.2	
12	1.5	1.4	
13.5	1.5	1.5	
15	1.5	1.5	
Reference B: Schmertmann (1978)			

Again, for the first two depths the comparisons are not consistent, however, for the last three depths the values indicate that there is very little difference between the results from tests conducted with and without the friction reducer.

The correlations in Tables 2 to 4 also indicate that reliable engineering parameters can be obtained from PPMT testing. Data in tables show that parameters obtained with the smooth cone are slightly higher than that from the cone with the friction reducer.
This difference indicates that the additional soil disturbance associated with the friction reducer decrease the engineering parameters.

Figure 7 shows that the average ratio of E_r/E_o, based on tests results in clay, was approximately 3.4 using the smooth cone tip and 3.7 using the friction reducer. The E_r/E_o ratio was about 10 at 10.5 m (34.5 ft), corresponding to fine sand, according to Briaud (1992). These ratios compare well to published values of 1.5 to 5 in clay and 3 to 10 in sand (Briaud, 1992). Therefore, the common values of initial modulus, limit pressure and the ratios of E_r/E_o, E_o/p_L, E_o/q_c and p_L/q_c can serve as indicators for soil identification (Briaud, 1992).

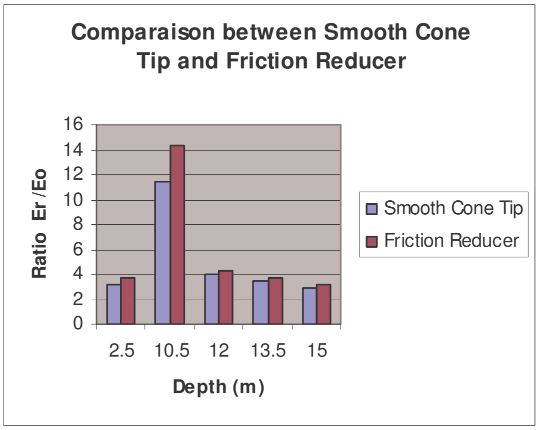

Figure 7. Ratio of Initial Moduli to Reload Moduli using Two Different Cone Tips

4.2 Correlations to Engineering Parameters from Other Instruments

Correlations were performed between DMT lift-off pressures and PPMT lift-off (Figure 8) plus the DMT and PPMT initial moduli (Figure 9) from the Cape Canaveral site. Correlations between these parameters were not quite conclusive; however, ratios between the DMT and PPMT parameters were developed to provide engineers with a probable range, the DMT/PPMT elastic moduli ratios varied from 0.9 to 1.4, while The ratio of the DMT/PPMT lift-off pressures varied from 1.2 to 2.7.these ranges were based on data from PPMT tests and 20 DMT tests at 5 depths.

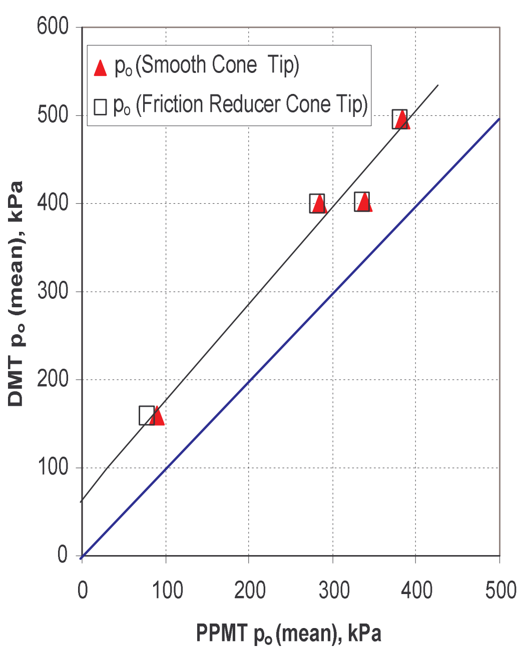

Figure 8. DMT versus PPMT Lift-off Pressures in Clay

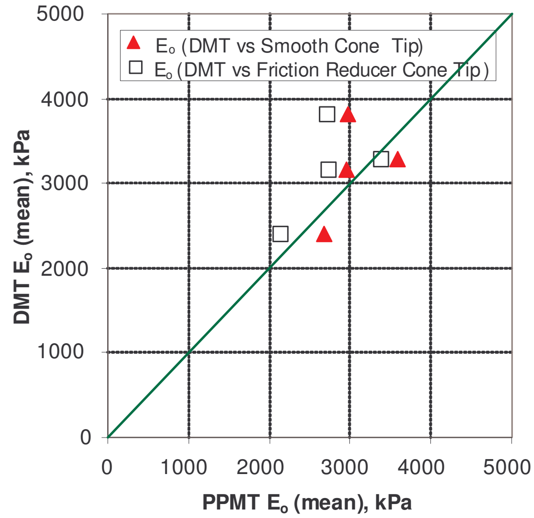

Figure 9. DMT versus PPMT Initial Moduli in Clay

4.3 Evaluation of p-y curves

Roberston's et al (1986) PPMT-based p-y curves produce comparable Values, P_u, with Roberston's et al (1989) DMT-based p-y curves in soft clays and fine sands. The p-y curves derived from PPMT and DMT tests at this site are performed. The ultimate loads are defined as P_{u1} and P_{u2}, which are termed the lower and higher ultimate loads, respectively as seen in Figure 10. The lower ultimate load is determined at the end of the straight line portion of the p-y curve, representing the end of the elastic soil response. The higher ultimate load is defined as the intersection of the elastic-plastic response of the soil. Therefore P_{u2} is found when the extension line the elastic portion meets the plastic portion of the curve as seen in Figure 10.

The maximum ultimate load is defined as P_{u1}, which correspond to the end of the elastic phase of the soil. At this point deformation of the soil is irreversible and failure results. The slope, k_s, is determined from the difference between the ultimate soil resistance, P_{u1}, and the lift-off pressure, p_o, of the elastic phase of the soil to the deflection, y_1.

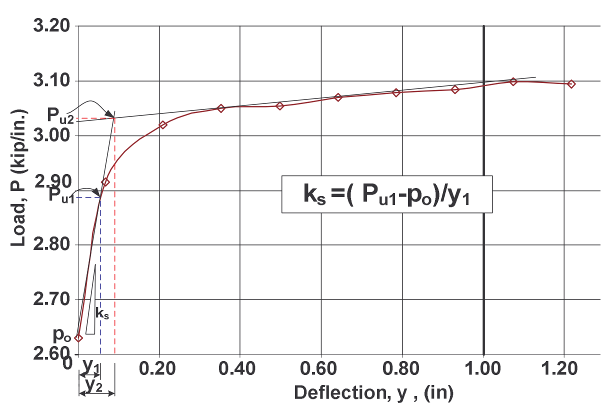

Figure 10. Depiction of Ultimate Loads and the corresponding Lateral Defections in Clays

The comparison between DMT and PPMT p-y curves was based on the slope of the initial portion of the curve, the ultimate soil resistance and the curve shape. The initial slopes were determined by constructing tangents through the average initial slopes for the p-y data and the average ultimate loads were determined from the p-y curves at one-inch (2.5 cm) deflection. The values shown in table 5 for the initial slopes show several trends. First, the 10.5 m data produced higher values than the other layers due to the influence of the sandy layer at this depth. Second, the DMT slopes in the lower clay layers (12 to 15 m) are somewhat higher than the corresponding slopes from either PPMT tests. Third, the slopes have a much higher variability than the ultimate loads as evidence by the standard deviations in the table 5.

Table 5. Comparison of Average Initial Slope and Average Ultimate Loads at One-Inch (2.5 cm) Deflection from DMT and PPMT p-y Curves

	Initial Slopes			Ultimate Loads		
Depth (m)	DMT ($Kips/in^2$)	PPMT Friction Cone ($Kips/in^2$)	PPMT Smooth Cone ($Kips/in^2$)	DMT (Kips/in)	PPMT Friction Cone (Kips/in)	PPMT Smooth Cone (Kips/in)
2.5	3.43	3.83	3.5	0.95	0.95	1
10.5	16	14	16	4.4	3	3.3
12	7.5	4.7	4.1	2.3	2.7	2.75
13.5	6.1	3.9	3.4	2.2	3	3
15	10	2.9	3.5	2.75	3.3	3.3
Average	**8.61**	**5.87**	**6.10**	**2.52**	**2.59**	**2.67**
Std Dev	**4.8**	**4.6**	**5.5**	**1.2**	**0.9**	**1.0**

The ultimate loads for all depths were fairly similar. The data in this table was also used to determine ratios which could be evaluated to further clarify the findings. This data is shown in Table 6. Again, the initial slopes showed higher variability and the ultimate loads were more consistent. This discrepancy in the result is based on that the DMT-based equations are a cube root polynomial that will follow an increasing curve shape, while the PPMT-based equations will follow the same shape as the reduced PPMT plot. So the parameter ratios presented are quite constant for soil condition. Further researches can improve it.

Table 6. Ratios of PPMT and DMT p-y Curves

Depth [m]	Initial slopes DMT/PPMT		Ultimate loads DMT/PPMT	
	Friction	Smooth	Friction	Smooth
2.5	0.9	0.98	1	0.95
10.5	1.14	1	1.47	1.33
12	1.6	1.83	0.85	0.84
13.5	1.56	1.79	0.73	0.73
15	3.45	2.86	0.83	0.83
Average	1.73	1.69	0.98	0.94
Std Dev	1	0.8	0.3	0.2

5 SUMMARY

The data from this research indicates there is no need for a friction reducer on the cone tip of the PENCEL probe.

PPMT data produces more engineering parameters (i.e., p_0, E_0, E_r, p_L) than either DMT or CPT data.

A reliable nonlinear correlation was developed between the PPMT initial elastic and the reload moduli in clays. This correlation improved when digital information along with the APMT software was used.

Several correlations between PPMT data and CPT data were confirmed and shown to be very consistent. Probable ratios between PPMT and DMT parameters were presented and should be improved with further research.

The pushed-in PPMT test is much faster than conventional pressuremeter testing and is recommended for use in determining the soils stress-strain response and the associated engineering parameters.

Robertson's et al (1986) PPMT based p-y curves produce comparable ultimate values, P_u, with Robertson's et al (1989) DMT based p-y curves in soft clays.

The DMT equations yield a polynomial that continually increases while the PPMT equations yield curves that resemble the corresponding reduced curves.

In sands both sets of equations may yield similar curves, while in clays the PPMT curves display clear limit pressures as they approach a horizontal asymptote.

A database of PPMT and DMT p-y curves should be developed for instrumented piles in various soils. Included within the data base should be methodology for conducting PPMT tests.

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