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Friction Reducer Effects to the Pushed Pressuremeter Cone Tip

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Key words

Friction Reducer, Pencel, Dilatometer, Modulus, Deep Foundation.

Abstract: This paper was carried out to evaluate the Pencel Pressuremeter (PPMT) testing to help engineers to execute tests more accurately, and to generate the p-y curves for deep foundations analysis and design. The results derived from the effects of adding a 1/16 inch friction reducer to the standard Pencel cone tip used for soils were insignificant. Dilatometer (DMT) tests were also conducted for comparisons with PPMT data. From PPMT data, which were reduced to graph of pressure versus volume, soil engineering parameters such as the initial pressure, the initial elastic moduli, the reload moduli, and the limit pressure of the soil were determined. The PPMT soil parameters from the two types of cone tip, show good agreement with published values. Correlations were developed between the PPMT and DMT results, which show reliability in soil engineering parameters values. Correlations between PPMT and DMT p-y curves were performed. The initial slope shows a good agreement. The expected DMT and PPMT ultimate loads are not comparing well, while the expected deflections within the elastic range are comparable. The PPMT is an appropriate in-situ device to replicate the pile mechanism and predict the laterally loaded soil resistance for analysis.

Introduction

When conditions are unfavourable for collecting soil specimens for laboratory testing, in-situ tests are used to determine soils properties. The pressuremeter (PMT) is an in-situ device, consists of a cylindrical probe containing an expandable membrane, which is placed into the soil to produce in situ stress-strain responses, was initially developed by Ménard (1956) and adapted by Briaud and Shields (1979). There are many PMT models currently available, but the Pencel PMT (PPMT) has recently been used with cone penetrometer equipment resulting significant time saving. The subject 1.35-inch diameter Pencel probe is pushed when attached to cone rods (Briaud 1992). The PPMT apparatus is shown in Figure 1 including the probe connected to the monitoring unit through tubing, and control valves, for the pressure and volume gauges for manually recording data (Roctest 2005). Anderson and Townsend (1999) observed advantages in connecting the PPMT probe to Cone Penetrometer rods and either pushing the cone with the PPMT attached or pushing the PPMT separately to carry out PPMT tests. Recently, this device was made more advanced by developing a standardized testing procedure and incorporating numerical technology with data acquisition software producing considerable time savings and improved precision as a fully reduced stress-strain curve is formed during testing (Cosentino et al, 2006). PPMT equipment has been successfully used throughout Florida in sands and clays [(Anderson and Townsend, 1999) and (Cosentino et al., 2006)].

Typical Operation

Based on the system saturation requirement, several adjustments are performed. The calibration of the system is conducted in the following steps: First, the membrane correction is determined by inflating the probe in air at the same elevation as the pressure gauge. This is the free air correction for the inherent membrane resistance. The second is the system compliance or volume loss correction, for expansion of the tubing and thinning of the membrane during pressurization, the probe is inserted in a steel tube and inflated. 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

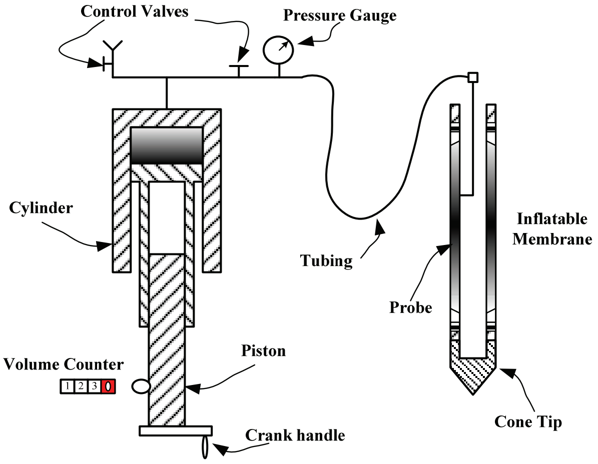

Fig. 1 Pencel Pressure Meter Apparatus

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hydraulically pushed with the equipment in the CPT rig to the preferred depth and the standardized test is performed in 10 to 15 minutes as recommended by Cosentino et al. (2006).

During the test, the probe volume is incrementally increased to an additional volume of 90 cm^3. The operators control and determine the extent of the linear stress–strain response range before performing one unload–reload cycle on the soil. This determination requires several complex steps; consequently, digital equipment and data acquisition software was incorporated, called APMT. It was developed by Cosentino et al. (2006), in conjunction with incorporating digital pressure and volume equipment into the Pencel control unit as shown in Figure 2. APMT records four samples per second throughout testing. This sampling rate produces sufficient data points to allow proper engineering analyses.

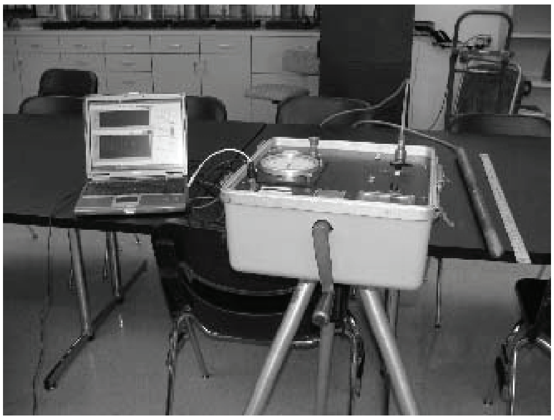


Fig. 2 APMT Connected to PPMT Control Unit

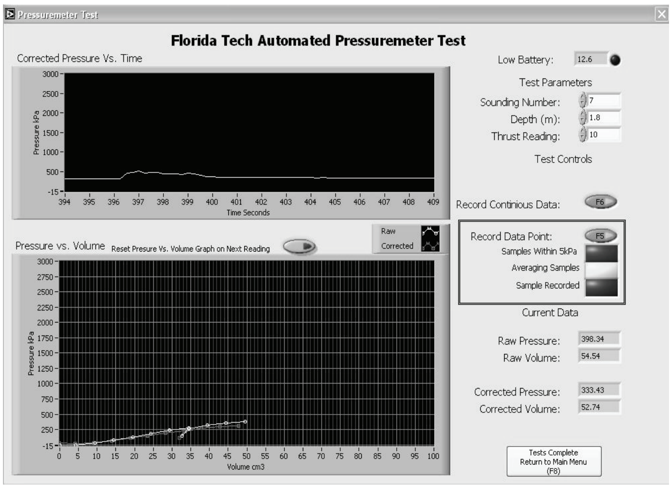
One of the most important operations required during testing is for the operator to wait for 30 seconds after each volume injection and then accurately record pressures as the analogue pressure gage continues to change. Once the volume increment stabilization period (VISP) was defined, APMT data collection software was developed such that the display available to the operator includes a sequence of three lights; red, yellow and green that change, based on the rate of change of successive pressure readings (Figure 3). The screen allows operators' to follow standard testing procedures. This screen allows for determining both initial pressure and limit pressures along with initial and reload moduli. This typical APMT screen includes both the raw and reduced data (Cosentino et al., 2006).

APMT Screen showing the Automatic Recording of Continuous Data Point is presented in Figure 3.

Testing Procedure

The steps that describe testing with the PPMT are as follows:

- Filling and saturation of the control unit: After connection of the tubing and probe, the entire unit is saturated to insure that no air is entrapped in the cylinder, filling lines or the probe. During the saturation period, the pressure gauge is monitored to insure that the pressure stabilizes. If the pressure is not stabilized it signals a leak in the system, which must be fixed before proceeding.



Low Battery: 12.6

Sounding Number: 7

Depth (m): 1.8

Thrust Reading: 10

Raw Pressure: 398.34

Raw Volume: 54.54

Corrected Pressure: 333.43

Corrected Volume: 52.74

Fig. 3 APMT Screen showing the Automatic Recording of Continuous Data Point

- Calibration: Two required calibrations are performed separately, the Pressure Calibration which produces the inherent membrane resistance and the Volume Loss Calibration which yields the volume loss due to the expansion of the tubing, probe membrane.
- Probe Insertion: In addition to lowering into a prebored hole, the probe is designed for positioning in place by pushing or light hammering. If a CPT drill rig is used, the probe is connected to hollow EW drill rods with an external diameter of 32 mm and internal diameter varying from 12.7 mm to 16 mm. The rod is then pushed into the soil.
- Test Execution: Once the probe has reached the desired depth, the valves on the top of the reading unit are turned to "Test" position. The testing is conducted by rotating the crank to inject equal volumes increments. The increment of volume is 5 cm^3 and the corresponding pressure is usually noted after 30 seconds of having injected the specified volume. The maximum volume injected for a test is usually 90 cm^3 in order to avoid membrane failure. Generally the test duration is about 15 minutes. When the test is completed, prior to either removing the probe from the hole or advancing it to the next depth, the probe must be deflated, which is accomplished by returning the water to the cylinder.
- Interpretation: Initially the raw PMT data curve and the corrected PMT curve are plotted. For each point on the raw curve there is a corresponding point on the corrected curve with coordinates of corrected pressure and corrected

volume. Thus the corrected point is obtained by subtracting the volume and pressure correction from the corresponding raw volume and pressure data. In correcting the pressure, hydrostatic pressure exerted on the probe is also taken into consideration. Thus, the following calculations are performed on the data points;

- > Once the corrected curves are obtained, the Elastic moduli (E), initial pressure (p_0) and limit pressure (p_L) can then be calculated.
- > The operators also determine the extent of the linear stress-strain response range before performing one unload-reload cycle on the soil.

Data Interpretation

Once the data is collected it is typically plotted on a graph as shown in Figure 4. This figure contains both the membrane calibration curve and the volume calibration curve, which are subtracted from the raw data to produce a reduced data. The calibration tests should be performed at the start of each testing day or when the protective sheath is replaced or has been used for large number of tests. In this instance the tubing must also be saturated. It should be noted that calibration tests are necessary if one wants to come up with representative results.

With the aim of determining the soil engineering parameters from PPMT reduced data, Figure 5 shows four major portions of the reduced curve that are used for estimating the initial pressure (p_0), the initial elastic modulus (E_0) called the Pressuremeter modulus, the elastic reload modulus (E_r) called the pressuremeter rebound modulus, and the limit pressure (p_L) from which the curve is assumed to be horizontal.

Once the data has been corrected and the volume changed to a hoop strain, the plot of pressure versus volume is developed as shown in Figure 4. From this graph, the points are selected for PMT initial modulus and PMT rebound modulus determination, using the following equation, (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 pressure, ΔV = change in volume

V_m = average volume, ν = Poisson's Ratio

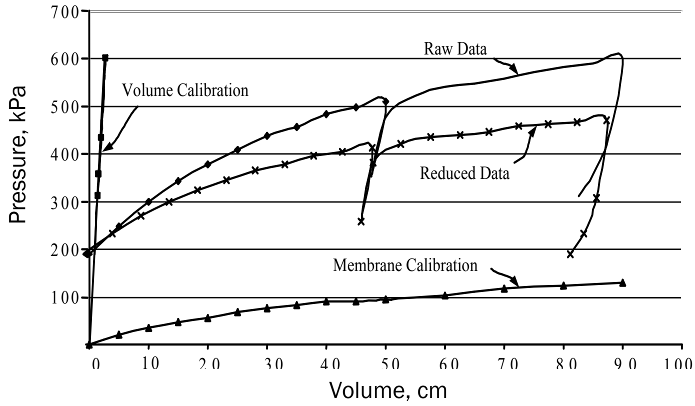


Fig. 4 PPMT Curves with Volume and Membrane Calibrations

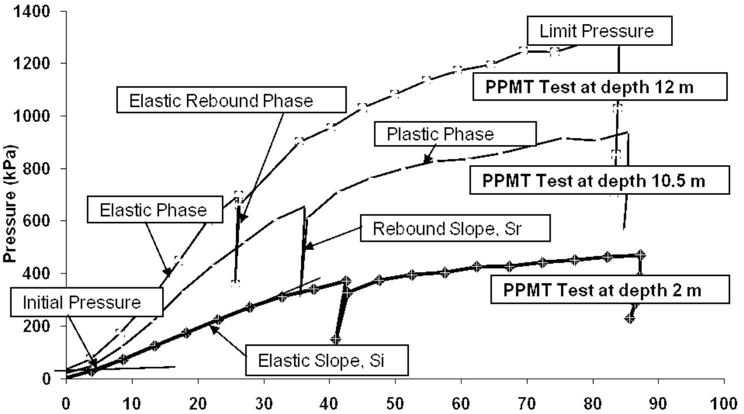


Fig. 5 Engineering Parameters Obtained from PPMT Test @ Depths: 2 m, 10.5 m and 12 m

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.

Geotechnical Investigation

A thorough field-testing program was performed in Cape Canaveral, Florida, enabling clays to be evaluated. Apart from the PPMT tests, Cone Penetrometer (CPT) and dilatometer (DMT) tests were conducted. The Florida Department of Transportation (FDOT) State Materials Office CPT rig and personnel was used to perform all testing. Over 100 PPMT and DMT tests were accomplished at this site which 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 thick was normally consolidated and had an average density of 14.4 kN/m^3 and a lower normally consolidated layer from the 10 to 15 m depth with an average density of 15.3 kN/m^3.

To determine the effects, two types of the cone tip shown in Figure 6, has been used for evaluating the soil properties, about half of the PPMT tests were conducted with friction reducer and half with smooth cone tip. The 33.9 mm diameter reducing ring was about 3% larger than the 33.0 mm diameter smooth cone point.

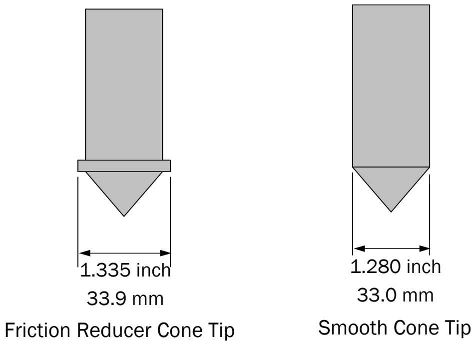


Fig. 6 Two Types of PPMT Cone Tip (Cosentino el.2006)

The procedure used during PPMT testing was the recommended FDOT standard (Cosentino et al. 2006). During the strain-controlled test, operators monitored pressure versus volume data to determine the degree of the elastic range. Once this range was reached, 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 5). 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. This device 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 7). 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.

This test procedure requires an experienced operator. Following three calibrations, the first step is the insertion of the DMT into the ground as described in Figure 8. About one minute after penetration, the membrane is inflated and two readings are taken: the pressure required beginning to move the membrane (lift-off) ‘A’ and the pressure required to move the center of the membrane 1.1 mm against the soil ‘B’. A third reading ‘C’ (closing pressure) can optionally be taken by slowly deflating the membrane soon after ‘B’ is reached. The first correction, ΔA, is the external pressure which must be applied to the membrane in free air, to collapse it against its seating. The second correction, ΔB, is the internal pressure, which in free air lifts the membrane center 1.1 mm (0.04 in) from its seating. The third correction, Z_M, is the gauge offset or gauge reading when vented to the atmosphere. The blade is then advanced to the next depth increment (typically 200 mm). The pressure readings ‘A’ and ‘B’ are corrected by the values ΔA and ΔB determined through two calibrations that take into account the membrane stiffness.

For evaluating DMT data, equations were presented requiring some preliminary calculations to determine a Young’s modulus of elasticity (E) (Marchetti 1980). After obtaining the basic test parameters as mentioned above; a corrected contact pressure is found using the following equation:

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

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.

Fig. 7 Layout of the DMT Apparatus

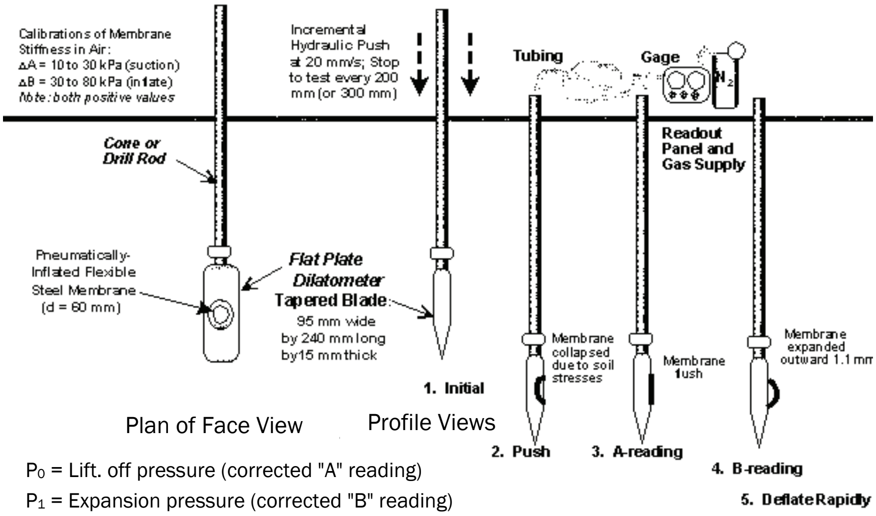


Fig. 8 Flat Dilatometer Test (DMT)

A corrected expansion pressure is then found out using the equation:

$$p_1 = B - Z_M - \Delta B \tag{3}$$

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

$$E_D = 34.7(p_1 - p_0) \tag{4}$$

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

$$M_{DMT} = R_M E_D \tag{5}$$

where R_M is an empirical value that is a function of either:

the horizontal stress index (K_D):

$$K_D = \frac{p_0 - u_0}{\sigma'_{v0}} \tag{6}$$

- or the material index (I_D) :

$$I_D = \frac{p_1 - p_0}{p_0 - u_0} \tag{7}$$

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, based on Poisson's ratio (ν) to determine the elastic modulus:

$$E = M_{DMT}\left[\frac{(1+\nu)(1-2\nu)}{(1-\nu)}\right] \tag{8}$$

Cone Tip Comparison to Engineering Parameters

To evaluate the effects of using a friction reducer, 80 tests were conducted at the Cape Canaveral Site. The tests were performed in 16 soundings, 8 PPMT soundings with a smooth cone tip probe, and 8 PPMT soundings with a friction reducer cone tip. Five depths were tested in each PPMT sounding at 2.5 m, 10.5m, 12m, 13.5m, and 15m. All PPMT tests at this site were performed with probes calibrated using a 32 mm diameter calibration tube. A comparison was developed between the smooth cone data and the friction cone data using the initial elastic moduli (E_0) and reload elastic moduli (E_r), plus the initial pressures (p_0) and the limit pressures (p_L).

Ratios of these four parameters at five depths are shown in Table 1. This data was erratic in the two upper depths due to inconsistencies 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 (Figure 9), indicating that in soft clay there is very little difference between the results conducted with and without the friction reducer. Of the four parameters evaluated, the initial modulus was most affected by the use of a friction reducer.

Table 1 Values of Engineering Parameters at Cape Canaveral Site

Depth [m]	Type of cone tip	E_0 [kPa]	E_r [kPa]	p_0 [kPa]	p_L [kPa]
2.5	Smooth	2680	8610	72	155
	Friction Reducer	2146	8004	62	121
10.5	Smooth	3592	41254	195	524
	Friction Reducer	2710	38904	184	492
12	Smooth	2969	11918	285	411
	Friction Reducer	2710	11501	282	406
13.5	Smooth	2962	10231	338	438
	Friction Reducer	2736	10208	335	440
15	Smooth	3588	10508	383	487
	Friction Reducer	3380	10609	380	494

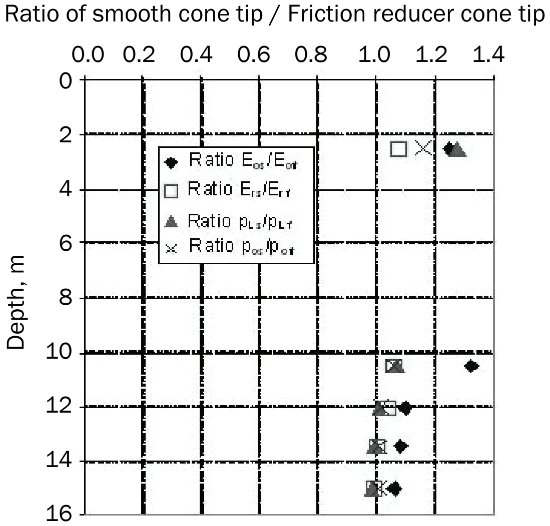


Fig. 9 Ratio of Soil Properties using Two Different Cone Tips

To further evaluate the need of a friction reducer cone tip, correlated results from some references concerning the initial elastic modulus, E_0, to the limit pressure, p_L, (Ménard and Rousseau 1962), and concerning the initial elastic modulus, E_0, to the point resistance, q_c, (Schmertmann 1978) and (Bergado and A.Khaleque 1986), and the point resistance, q_c, to the limit pressure, p_L, (Schmertmann 1978) are discussed below with the help of Tables and Figures.

Table 2 contains correlation relating E_0 to p_L from PPMT tests and published values. It is obvious that with either smooth cone tip or the friction reducer cone tip the average ratio for E_0/p_L is still within range of published values of 6 to 16 (Ménard and Rousseau 1962) as shown in Figure 10.

Table 2 Correlation of PPMT Engineering Parameters (E_0/p_L)

Depth [m]	E_0/p_L from PPMT	
	Smooth Cone Tip	Friction Reducer Cone Tip
2.5	16	14
10.5	8	6
12	8	6
13.5	7	8
15	8	8

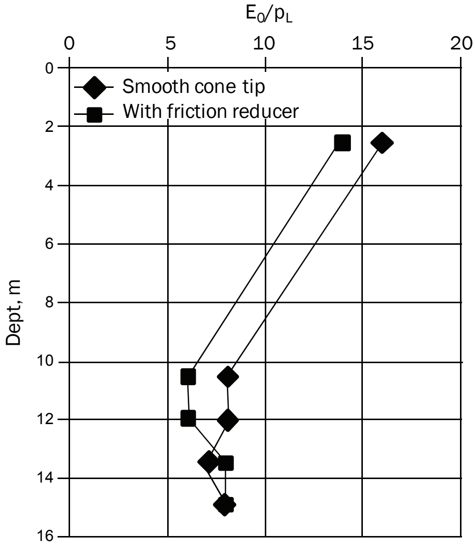


Fig. 10 Correlation relating E_0 to p_L from PPMT Test using Two Different Cone Tips

Figure 11 shows that the average ratio for q_c/p_L was 1.5 to 6 (Schmertmann 1978) The ratios between the PPMT initial elastic 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).

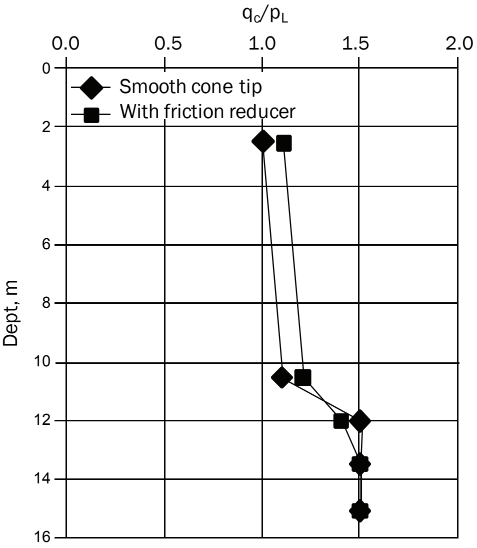


Fig. 11 Correlation relating q_c to p_L from PPMT Test using Two Different Cone Tips

Figure 12 shows that the average ratio for E_0/q_c based on tests results was between 3 to 20 for clay or 4.5 to 9 for fine sand using both the friction reducer and smooth cone tip, respectively (Schmertmann 1978) and (Bergado and A.Khaleque 1986).

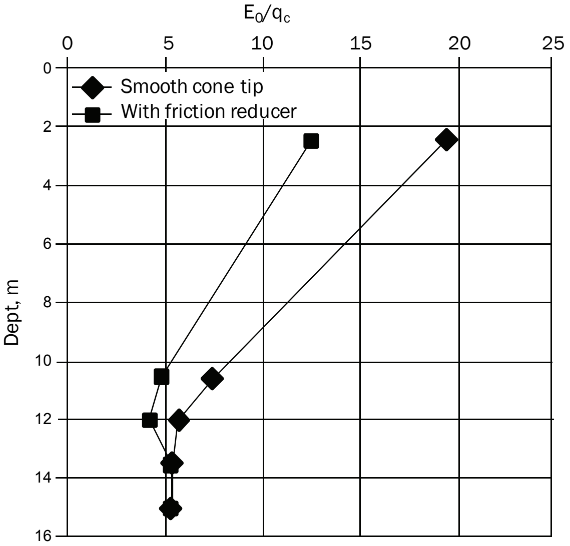


Fig. 12 Correlation relating E_0 to q_c from PPMT Test using Two Different Cone Tips

Figures 10 to 12 show that for the first two depths the comparisons are not consistent, on the other hand, 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 also indicate that reliable engineering parameters can be obtained from PPMT testing and the parameters obtained with the smooth cone tip are slightly higher than that from the friction reducer cone tip. This difference indicates that the additional soil disturbance associated with the friction reducer decrease the engineering parameters.

Figure 13 shows that the average ratio of E_r/E_0, 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_0 ratio was about 10 at 10.5 m, corresponding to fine sand Briaud (1992). These ratios compare well with the 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_0, E_0/p_L, E_0/q_c and p_L/q_c can serve as indicators for soil identification Briaud (1992).

Comparison of PPMT and DMT Engineering Parameters

Comparison between DMT and PPMT soils parameters was based on the initial elastic moduli and lift-off pressures because the DMT data does not produce limit pressure or reload moduli.

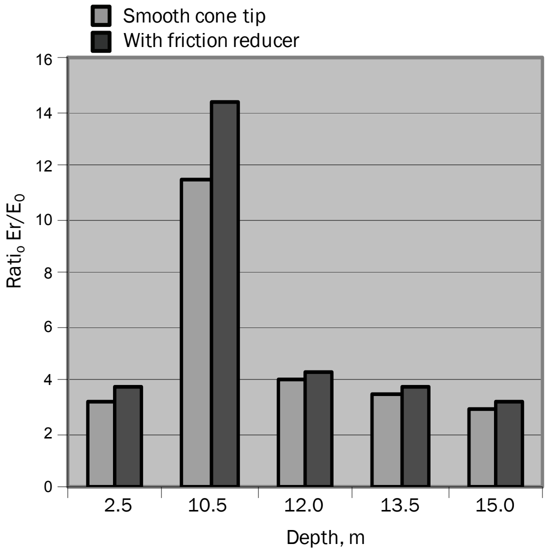


Fig. 13 Ratio of Initial Moduli to Reload Moduli using Two Different Cone Tips

The initial pressure from the DMT and PPMT are summarized in Table 3, and also plotted and compared in Figure 14. The plot shows that as the DMT lift-off pressure increases, the PPMT lift-off pressures increase. Two trend lines were used to describe the data. A linear trend line indicates the data was offset at the origin by about 50 kPa while the one-to-one correlation line shows that the lift-off pressures from these two cone tips may be linearly related in clays.

Table 3 DMT and PPMT Lift-off Pressures using Two Different Cone Tips

Depth [m]	p$_0$(kPa)		
	DMT	PPMT	
		Smooth Cone Tip	Friction Reducer Cone Tip
2.5	167.75	72	62
10.5	362.5	195	184
12	401	285	282
13.5	403	338	335
15	496.25	383	380

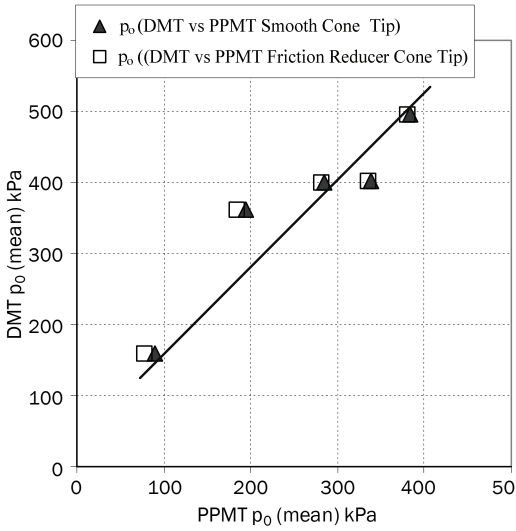


Fig. 14 DMT versus PPMT Initial Pressures

The initial elastic moduli from the DMT and PPMT are summarized in Table 4 and then plotted in Figure 15. A one-to-one correlation line was placed on the plot. The data shows very little difference between data from the two insertion techniques when compared to the DMT moduli

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 initial pressures varied from 1.2 to 2.7.these ranges were based on data from PPMT tests and 20 DMT tests at 5 depths.

Table 4 DMT and PPMT Initial Moduli using Two Different Cone Tips

Depth [m]	E$_0$(kPa)		
	DMT	PPMT	
		Smooth Cone Tip	Friction Reducer Cone Tip
2.5	2400	2680	2146
10.5	3358	3592	2710
12	3816	2969	2710
13.5	3160	2962	2736
15	3286	3588	3380

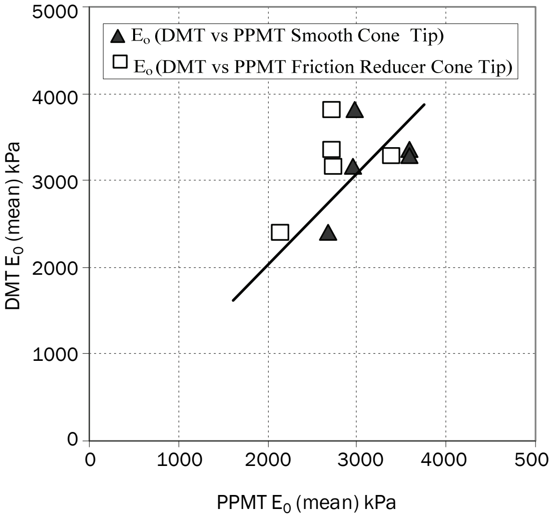


Fig. 15 DMT versus PPMT Initial Elastic Moduli

Comparison of predicted p-y curves from PPMT and DMT Data

The p-y curves derived from PPMT and DMT tests at this site were performed. The ultimate load defined as P_{u1} and P_{u2}, which are termed the lower and higher ultimate loads, respectively as seen in Figure 16.

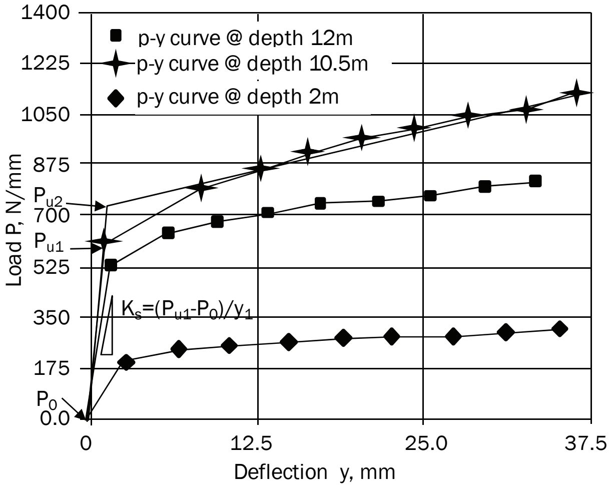


Fig. 16 Depiction of P-y curves from PPMT Test at Depths: 2 m, 10.5 m and 12 m

The comparison between PPMT and DMT 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 deflection. The values shown 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. 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 5.

Table 5 Comparison of PPMT and DMT p-y Curves

Depth [m]	Initial slopes [N/mm²]			Ultimate loads [N/mm]		
	DMT	PPMT Fr	PPMT Sm	DMT	PPMT Fr	PPMT Sm
2.5	24	26	24	166	166	175
10.5	110	97	110	771	525	578
12	52	32	28	403	473	482
13.5	42	27	23	385	525	525
15	69	20	24	482	578	578
Average	59	40	42	441	454	468
Std Dev	33	32	38	218	165	168

Conclusion

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.

Several correlations between PPMT data and CPT data were confirmed and shown to be very consistent.

Possible ratios between PPMT and DMT parameters were presented and should be enhanced with more research.

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

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.

List of Symbols

A= Lift-off Pressure

B = Maximum Pressure

E = Young's Modulus

E_D = DMT Modulus

E_0 = Initial Elastic Modulus

E_r = Reload Modulus

I_D = Material index

K_D = Horizontal stress index

M_{DMT} = Constrained Modulus

p_0 = Initial Pressure

p_1 = Corrected Expansion Pressure

p_L = Limit Pressure

P_{u1} = Lower Ultimate Loads

P_{u2} = Higher Ultimate Loads

q_c = Point Resistances

u_0 = Pore water pressure

V_m = Average Volume,

Z_M = Gauge Pressure

ΔA, ΔB = Calibration Pressures

ΔP = Change in Pressure

ΔV = Change in Volume

ν = Poisson's Ratio

σ'_{v0} = Vertical effective stress

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