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EFFECTS OF THE FRICTION REDUCER ON THE STANDARD PENCEL PRESSUREMETER CONE TIP IN SOFT CLAYS

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Abstract: This study was performed to evaluate a standard method of PENCEL pressuremeter (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 deep foundations. Based on the results of a comprehensive testing program the evaluation indicates that the testing procedure is acceptable. A recommended interpretation and procedure are presented. The effects of adding a 1/16-inch friction reducer to the standard PENCEL cone tip used for clay soils were negligible. Dilatometer tests (DMT) were conducted for comparison with PPMT data. From PPMT data, which were reduced to graphs of pressure versus volume and pressure versus relative change in probe radius, soil parameters including the initial pressure, the initial moduli, the reload moduli, and the limit pressure of the clay were determined. The PPMT soil parameters from both types of cone tip show a good agreement with published values. Correlations were found between the PPMT and DMT results, which show consistency in the values of soil parameters. A comparison between PPMT and DMT *p–y* curves was made. The initial slope of the curve 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 to predict the resistance of laterally loaded soil for the purpose of analysis.

LIST OF SYMBOLS

A – lift-off pressure,
B – maximum pressure,
E – Young's modulus,
E_D – DMT modulus,
E_r – reload modulus,
E_0 – initial modulus,
I_D – material index,
K_D – horizontal stress index,

M_{OED} – oedometric 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.

1. INTRODUCTION

1.1. BACKGROUND

The pressuremeter (PMT) consists of a cylindrical probe containing an inflatable membrane, which is lowered into the soil to produce in situ stress–strain responses. It was originally developed in work [8] and modified in [5]. A variety of PMT 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 [4]. 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 [9]. There were some 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 perform PPMT tests [5]. Finally, this device was further advanced by developing a standardized testing procedure as recommended [6] and 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 [6]. PPMT equipment has been successfully used throughout Florida in sands and clays [1], [6].

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.

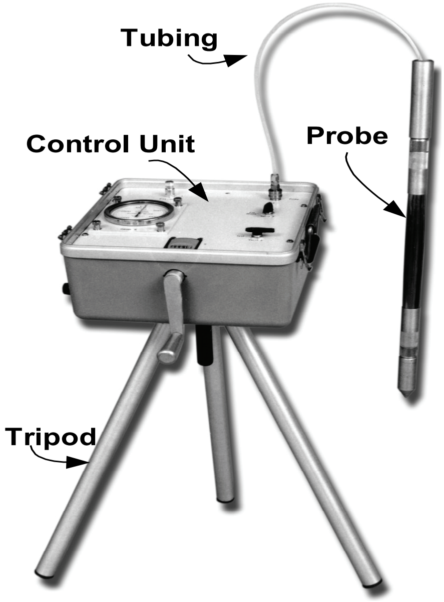

Fig. 1. PENCEL pressuremeter

1.2. TYPICAL OPERATION AND TESTING PROCEDURE

Based on the system saturation requirement, several calibrations are conducted; one that accounts for the inherent membrane resistance, and a second, for expansion of the tubing and thinning of the membrane during pressurization. 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 a recommended 10- to 15-minute standardized test [6] is performed.

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

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

2. Calibration: Two required calibrations are conducted separately, the pressure calibration and the volume loss calibration. The pressure calibration produces the inherent membrane resistance and the volume loss calibration yields the volume loss due to the expansion of the tubing, probe membrane.

3. 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 drilling 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.

4. 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 the water in such a way as to obtain its equal volume 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.

5. Interpretation: Initially the raw PPMT data curve and the corrected PPMT 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:

6. Once the corrected curves are obtained, the initial moduli E_0, lift-off pressure p_0 and limit pressure p_L can be calculated.

7. 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, a digital equipment and data acquisition software, called APMT for Automated Pressuremeter, were incorporated which simplified the process, yielding more precise data while easing operator requirements [6].

The cone penetrometer (CPT) can be used in sands or clays, but not in rock or other extremely dense soils. To perform this test, the electrical cone is advanced into the subsoil at a standard rate of 0.8 inch/sec (20 mm/sec). Wires from transducers are threaded through the center of the rod and continuously give reading of the cone resistance q_c and side resistance f_c.

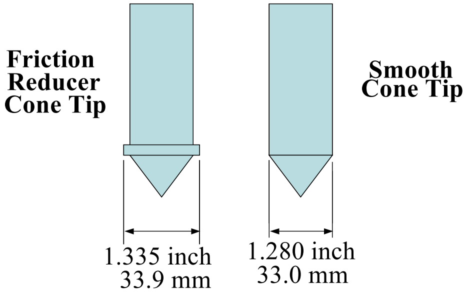

Fig. 2. PPMT cone tip [6]

To determine the effects of the friction reducer, shown schematically in figure 2, on the soil properties, about half of the PPMT tests were conducted with and half without the friction reducer. The 33.9-mm (1.335-inch) diameter of reducing ring was about 3% larger than the 33.0-mm (1.280-inch) diameter of smooth cone tip.

The procedure used during PPMT testing was the recommended FDOT standard [6]. During the strain-controlled test, operators monitored stress versus volume data to determine the pseudo-elastic range. Once this range was complete, unloading to one-half the existing pressure, 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.

1.3. DATA INTERPRETATION AND FIELD TESTING

The corrected pressure versus the volume curve shown in figure 3 is based on the readings taken at the end of each increment of pressure for a pushed-in PPMT test. The curve is composed of three parts. The first part is *OA*, which occurs when the probe pushes the soil back to its original position, called the repositioning phase, from which p_0 is estimated. The second portion of the curve is a straight line from *A* to *B*, called pseudo-elastic phase. Point *A* is considered to be the start of the PMT test in typical theory, and the slope S_i is the initial slope of *AB*, from which the initial elastic modulus E_0 is calculated. On the other hand, the slope S_r is the rebound slope, from which the reload modulus E_r is determined. The last portion is called the plastic phase which starts at *B* and eventually becomes horizontally asymptotic indicating a large deformation of the cavity at minimal pressure increase. The limit pressure p_L is required to be obtained at a double volume of the cavity. Due to limitation on the maximum volume of the PPMT probe, the volume increase at the end of the test is less than twice the cavity volume, and the limit pressure must be obtained by extrapolation. Beyond the limit pressure, the curve is assumed to be horizontal. Other devices have the capacity for determining the limit pressure directly, by recording the pressure at the volume twice that of the cavity (Texam PMT). The portion of the corrected PPMT curve from the beginning of reload through the maximum volume is used to determine the *p–y* curves.

Once the data is collected it is typically plotted on a curve as shown in figure 3. This figure presents both the membrane calibration curve and the volume calibration curve, which are subtracted from the raw data to produce a reduced curve.

In order to determine the critical engineering parameters, figure 4 shows four critical portions of the reduced curve that are used for estimating:

1. The initial pressure or lift-off pressure p_0.
2. The initial modulus E_0, called the pressuremeter modulus.
3. The reload modulus E_r, called the pressuremeter reload modulus.
4. The limit pressure p_L, from which the curve is assumed to be horizontal.

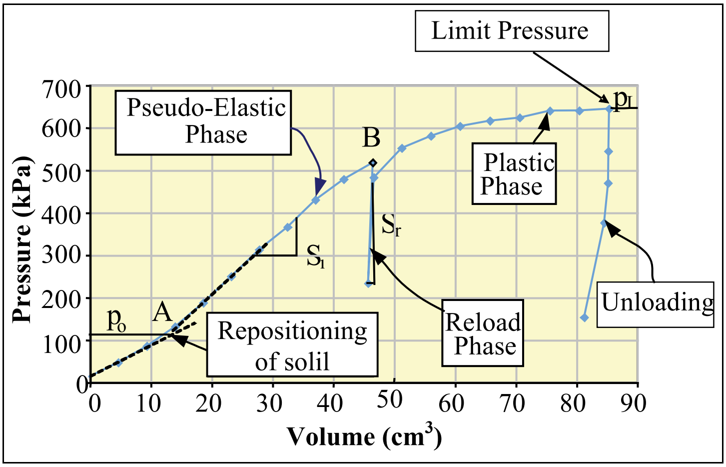

Fig. 3. PPMT curves representing volume and membrane corrections

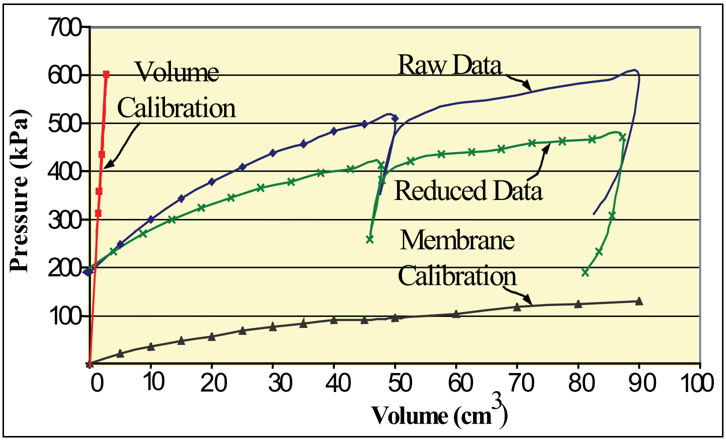

Fig. 4. Engineering parameters obtained from reduced data

The values of Young’s modulus are determined from the following equation [2]:

$$E = 2(1+\nu)\frac{\Delta P}{\Delta V} V_m, \tag{1}$$

where:

E – Young’s modulus,
ΔP – change in pressure,
ΔV – change in volume related to ΔP,
V_m – average volume,
ν – Poisson’s ratio.

The values of Young's modulus are determined from the slopes S shown in figure 3, while the other parameters are estimated. The initial pressure p_0 can be estimated from the initial segment of the curve using tangents as shown in figure 3. The PPMT limit pressure p_L, defined as the pressure associated with doubling the initial probe volume, is never reached during testing, since the initial PPMT probe volume is about 200 cm^3 and there are only 138 cm^3 of water in cylinder used to expand the probe. Therefore, the plastic segment of the curve is extrapolated to a volume or strain associated with doubling the initial volume.

A complete field-testing program was carried out at Cape Canaveral, Florida, enabling clays to be evaluated. In addition to PPMT tests, cone penetrometer (CPT) and dilatometer (DMT) tests were conducted [6]. All testing was conducted using CPT rig and personnel from the Florida Department of Transportation (FDOT) State Materials Office.

Over 100 PPMT and DMT tests were conducted at the Cape Canaveral site which consists of interbedded sands and clays. Two clay layers 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 of the depth ranging from the 10 to 15 m (30 to 50 feet) with an average density of 15.3 kN/m^3 (97 pcf).

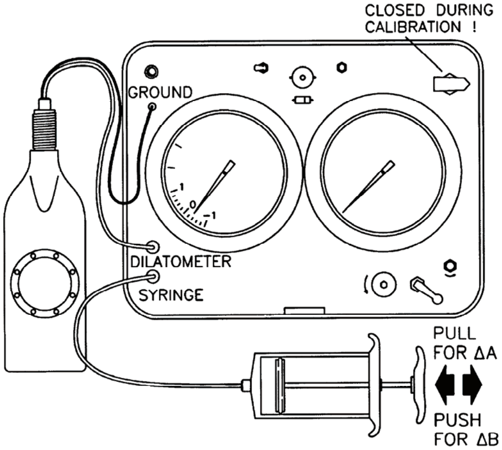

Fig. 5. Layout of the connections during membrane calibration (blade accessible)

For evaluating DMT data, equations were presented requiring several preliminary calculations to determine a Young's modulus of elasticity E [7]. After obtaining the two basic test parameters, i.e., 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:

$$p_0 = 1.05(A - Z_M + \Delta A) - 0.05(B - Z_M - \Delta B), \tag{2}$$

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 as shown in figure 5.

A corrected expansion stress is then found using the equation:

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

The DMT modulus, not Young's modulus, is then found 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 oedometric modulus from:

$$M_{\text{OED}} = R_M E_D\,, \tag{5}$$

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 oedometric modulus is used in the following equation, based on Poisson's ratio ν to determine the elastic Young's modulus:

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

2. DATA REDUCTION AND ANALYSIS

The stand-alone data acquisition program, called APMT, was developed for this research [6] 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. 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. Once the output was verified, this package was used to determine the four key engineering parameters obtained during PPMT testing.

2.1. CORRELATIONS BETWEEN ENGINEERING PARAMETERS FROM PPMT

To evaluate the effects of using a friction reducer, 80 tests were conducted at the Cape Canaveral site as shown in table 1. 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). A comparison was made 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. The ratios of these four parameters at five depths are shown in table 2. 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, indicating that in soft clay there existed very little difference between the results obtained 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 in clays at Cape Canaveral site

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

Table 2

Ratios between PPMT engineering parameters

Depth (m)	Soil type	Engineering parameters			
		$\frac{E_{0(sm)}}{E_{0(fr)}}$	$\frac{E_{r(sm)}}{E_{r(fr)}}$	$\frac{p_{L(sm)}}{p_{L(fr)}}$	$\frac{p_{0(sm)}}{p_{0(fr)}}$
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

sm – smooth cone tip and *fr* – friction reducer cone tip.

To make the evaluation of the need of a friction reducer cone tip more thorough, tables 3 to 5 present the correlated results from various references relating initial modulus E_0 to limit pressure p_L (table 3), and to point resistance q_c (table 4), and relating point resistance q_c to limit pressure p_L (table 5).

It is obvious that with either smooth cone tip or the friction reducer cone tip the average ratio of E_0/p_L is still within the range of published values, i.e. from 6 to 16 [8].

Table 3

Comparisons of PPMT with CPT engineering parameters (E_0/p_L)

Depth (m)	E_0/p_L		
	Smooth cone tip	Friction reducer cone tip	Reference [8]
2.5	16	14	6–16
10.5	8	6	
12	8	6	
13.5	7	8	
15	8	8	

Table 4

Comparisons of PPMT and CPT engineering parameters (E_0/q_c)

Depth (m)	E_0/q_c		
	Smooth cone tip	Friction reducer cone tip	References [10], [3]
2.5	19.4	12.4	3–20
10.5	7.4	4.7	4.5–8.9
12	5.7	4.1	
13.5	5	5.2	
15	5.1	5.2	

Table 4 shows the average ratio of E_0/q_c based on test results varying between 3 and 20 or 4.5 and 8.9 for clay or fine sand using both the friction reducer and smooth cone tip, respectively, [10] and [3].

Table 5 shows that the average ratio of q_c/p_L ranges from about 1.5 to 6 [10]. 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 [11].

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 3 to 5 also indicate that reliable engineering parameters can be obtained from PPMT testing. Data in tables show that the values of the parameters obtained with the smooth cone are slightly higher than those with the friction reducer cone. This difference indicates that an additional soil disturbance associated with the friction reducer decreases the engineering parameters.

Table 5

Comparisons of PPMT and CPT engineering parameters (q_c/p_L)

Depth (m)	q_c/p_L		
	Smooth cone tip	Friction reducer cone tip	Reference [10]
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	

Figure 6 shows that the average ratios of E_r/E_0, based on the tests' results in clay, were approximately 3.4 (for the smooth cone tip) and 3.7 (for the friction reducer). The E_r/E_0 ratio approached 10 at 10.5 m (34.5 ft), corresponding to fine sand [4]. These ratios compare well to those published, i.e. 1.5–5 in clay and 3–10 in sand [4]. 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 [4].

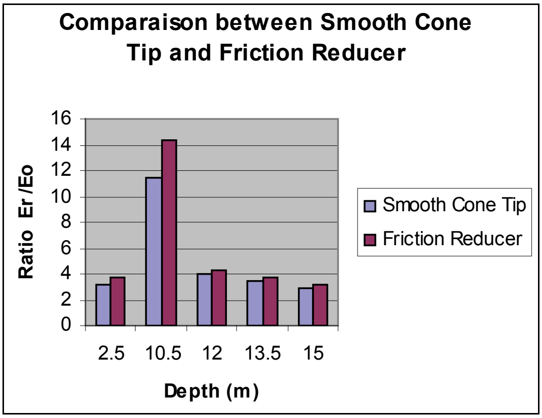

Fig. 6. Ratio of initial moduli to reload moduli using two different cone tips

2.2. CORRELATIONS BETWEEN ENGINEERING PARAMETERS FROM DILATOMETER TESTS

Correlations were found between DMT lift-off pressures and PPMT lift-off (figure 7) plus the DMT and PPMT initial moduli (figure 8) from the Cape Canaveral site. The correlations between these parameters were not quite conclusive; however, the ratios between the DMT and PPMT parameters were calculated to provide engineers with a probable range, the DMT/PPMT initial 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 DMT tests at 5 depths.

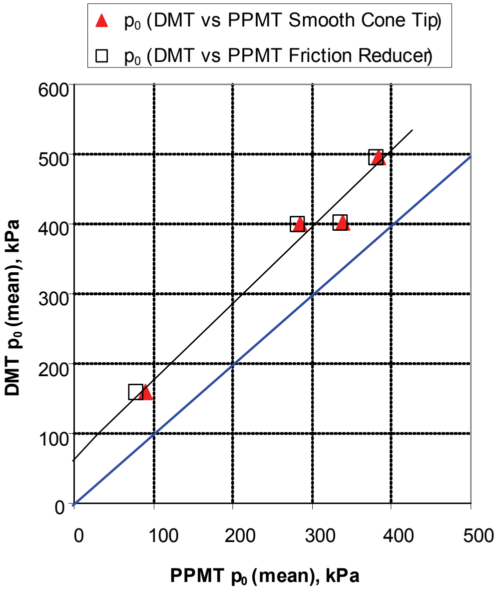

Fig. 7. DMT versus PPMT lift-off pressures in clay

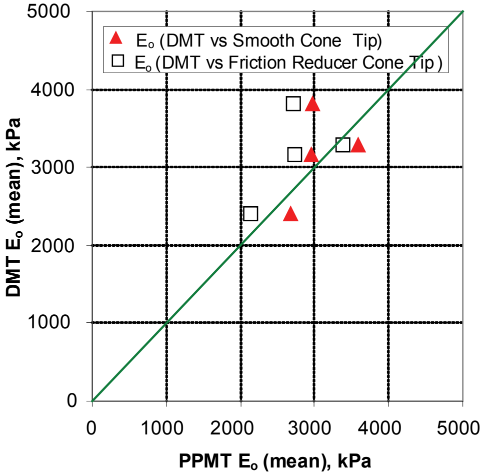

Fig. 8. DMT versus PPMT initial moduli in clay

2.3. EVALUATION OF *P–y* CURVES

The analysis and design of laterally loaded piles used to resist earth pressures are complex because the soil's load deformation behaviour in this case is highly nonlinear. That is, the governing differential equation relating the lateral force P to the soil and pile deflection y at any point along a pile is a fourth-order equation, requiring the use of numerical methods and/or simplifying assumptions. This model allows us to establish the load–deformation behaviour as a *P–y* curve using in situ test data. In situ tests can be used directly or indirectly to determine more accurate load transfer curves. The *P–y* curves can be estimated indirectly through CPT and SPT tests and directly through DMT and PMT tests. The latter can provide better predictions of lateral pile response. The *P–y* curves derived from PPMT and DMT tests at this site are performed. The ultimate loads defined as P_{u1} and P_{u2}, i.e. the lower and higher ultimate loads, respectively (figure 9), correspond to the end of the elastic phase of the soil, which means that the deformation of the soil is irreversible and failure occurs. The slope k_s is determined from the ratio of the difference between the ultimate soil resistance P_{u1} and lift-off pressure p_0 of the elastic phase of the soil to the deflection y_1.

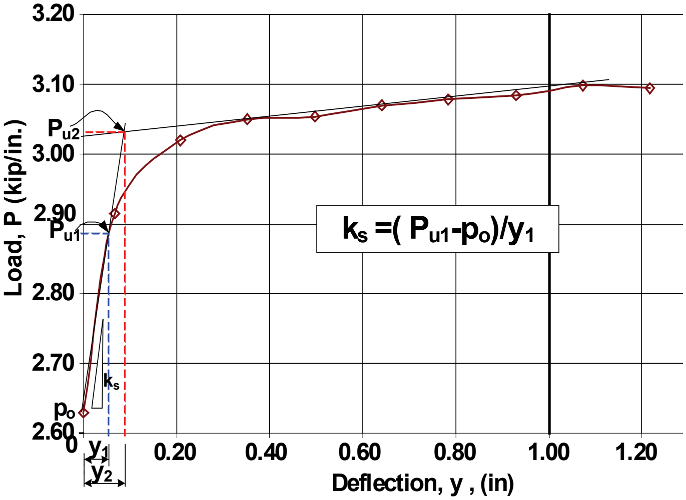

Fig. 9. Ultimate loads and the corresponding lateral defections

The comparison between the DMT and PPMT *P–y* curves was based on the slope of the initial segment 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 follow several trends. First, the values from 10.5-m depth are higher than those from other layers due to the influence of the sandy layer at this depth. Second, the DMT slopes in the lower clay layers (from 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 evidenced by the standard deviations in table 6. The ultimate loads for all depths were fairly similar. The data in table 6 was also used to determine the ratios which could be evaluated for further clarifying the findings.

Table 6

Comparison between DMT and PPMT *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	1.67	1.83	0.85	0.84
13.5	1.56	1.79	0.73	0.73
15	3.05	2.86	0.83	0.83
Average	1.73	1.69	0.98	0.94
Std Dev	1	0.8	0.3	0.2

3. CONCLUSION

- Evaluation of the soil parameters obtained from PPMT testing in clays revealed that the friction reducer increases the disturbance in the soil surrounding the PENCEL probe and subsequently causes a slight decrease in engineering parameters and, therefore, is not recommended.
- 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 found between the PPMT initial elastic modulus and the reload modulus in clays. This correlation improved when digital information along with the APMT software was used.
- The 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 in further research.
- The pushed-in PPMT test is much faster than conventional pressuremeter testing, thus its use in determining the soils stress–strain response and the associated engineering parameters is highly recommended.
- A database of the PPMT and DMT *P–y* curves should be developed for instrumented piles in various soils. The methodology for conducting PPMT tests should be included within the data base.

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