

The Use of PENCEL Pressuremeter Test for Underground Structures

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Abstract: This paper presents a description of the equipment, testing procedure, and methodology to obtain ground mechanical parameters. The p - y curves for laterally loaded piles are developed. Methods for the development of p - y curves from pressure meter and dilatometer (DMT) test are described. P - y curves are used in the analysis to represent lateral soil-pile interaction. The pressure meter offers an almost ideal in-situ modeling tool for determining directly the p - y curves for the design of deep foundations. As the pressure meter can be driven into the soil, the results can be used to model a displacement pile. DMT tests were performed for comparisons with PPMT tests. Correlations were developed between the PPMT and DMT results, indicating a consistency in soil parameters values. Comparisons between PPMT and DMT p - y curves were developed based on the ultimate soil resistance, the slope of the initial portion of the curves, and the shape of the curves. The initial slope shows a good agreement between PPMT and DMT results. The predicted DMT and PPMT ultimate loads are not similar, while the predicted PPMT and DMT deflections within the elastic range are identical.

Keywords: Pencil Pressuremeter, p - y curves, soil, modulus, interaction.

1. Introduction

The pressuremeter was originally developed by Ménard [1] and modified by Briaud and Shields [2]. 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 [3]. In addition to classical geotechnical applications, 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 [4]. Anderson and Townsend [5] 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 [6] 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 [6]. 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 [5], [6].

The current PPMT as distributed by ROCTEST® consists of three main parts, the operators control unit supported on a tripod stand and placed at the ground surface, the probe inserted into the soil and the tubing connecting the probe to the readout unit. The control unit has pressure and volume displays. A rotation of the handle by the operator moves the piston inside the control unit which forces water through the system that produces a change in the probe volume and a corresponding pressure that can be measured. The PPMT control unit and probe are shown in Figure 1. This equipment was automated and standardized [6].

2. Description of the Equipment

The control unit contains a piston cylinder assembly, pressure gauge of 2500 kPa capacity, volume counter, control valves and tubing

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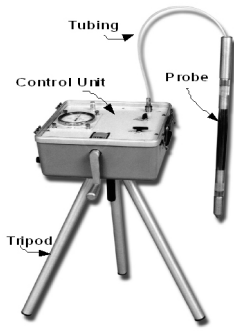


Fig. 1. The PENCEL Pressuremeter

connectors Figure 2. Its function is to control and monitor the expansion of the probe by injecting a certain volume of water and reading the corresponding pressure from the pressure gauge. The maximum volume of the water that can be injected into the unit is 135 cm³. The unit is lightweight and easily transportable. Quick connects are used to allow for the unit, tubing, and probe to be presaturated in the lab or in-situ before running the test. A male quick connect accepts the tubing leading from the pressure-volume control unit.

The probe is a hollow metal cylinder threaded at both ends, designed to accept and seal the inner rubber membrane and the outer (Chinese lantern) metallic sheath. The metallic sheath has longitudinal steel strips fixed to its outer surface and is in direct contact with the borehole walls when the probe is pressurized. The strips overlap in such a way that when inflated, the increased surface area of the sheath remains protected. The

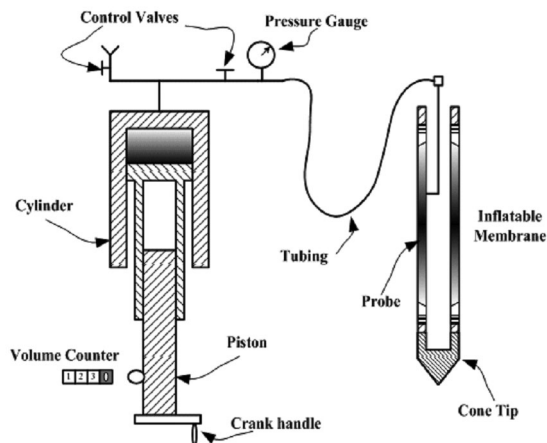


Fig. 2. The PPMT Control Unit

diameter and the length of the probe used for this research were about 32 mm (1.26 in) and 23.6 cm (9.3 in) respectively.

The tubing consists of a single conduit between the control unit and the probe to allow the water to be sent from the control unit to the probe. This tubing is fitted with shut-off quick connectors to keep the system saturated when detached.

3. Testing Procedure

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 insure that no air is entrapped in the cylinder, filling lines or the probe. During the saturation period, the pressure gage is monitored to insure that the pressure is stabilized. 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, and 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 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 – 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 equal volumes increments. The increment of volume is 5 cm³ 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 cm³ 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 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 the corrected pressure and the corrected volume. Thus the corrected point is obtained by subtracting the volume and the pressure correction from the corresponding raw volume and the 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 Elastic moduli (E), in-situ horizontal stress (σ_{oh}) and limit pressure (P_l) can then 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, [6] incorporated digital equipment and data acquisition software, called APMT for Automated Pressuremeter that simplified the process, yielding more precise data while facilitating operator requirements.

4. Interpretation of Data

The Test and calibration for the PPMT used for this research are based on the [4] Rocctest manual. Following equipment saturation, the calibrations are performed. First, the membrane calibration is determined by inflating the probe in air, at the same elevation as the pressure gage, while recording pressure and volume data.

Second, the system expansion or volume calibration is determined by inserting the probe into a 32 mm diameter steel tube and inflating it while pressures and volumes are recorded. Since there is annular space between the probe and the tube, adjustment are made to the resulting curve

to produce the straight line correction. Calibration should be performed at the start of each testing day, when the protective sheath is replaced, or when it looks worn.

The membrane and system expansion correction are subtracted from the raw data to produce a reduced curve. The hydrostatic pressure developed between the control unit and the center of the probe is added to the raw pressure prior to making these corrections [6].

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

- 1) The lift-off or the initial pressure (p_0) from the repositioning phase,
- 2) An initial elastic modulus (E_0) from the pseudo-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.

The Following expression for determining an elastic modulus from (E) is used [7]:

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

Where, E = Young's modulus,
 ΔP = change in pressure,
 ΔV = change in volume related to ΔP ,
 V_m = average volume,
 ν = Poisson's Ratio

Tucker [8] and Briaud [3] suggested using the

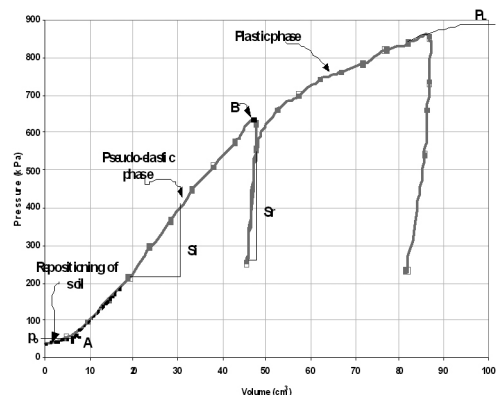


Fig. 3. Engineering parameters obtained from reduced Curve

radial strain to determine moduli. In an effort to normalize the PPMT curve it is recommended that the curve be plotted as pressure versus relative increase on probe radius. Hence, Equation 1 will be:

$$E = (1+\nu) \left[\left(1 + \frac{\Delta R_1}{R_0} \right)^2 + \left(1 + \frac{\Delta R_2}{R_0} \right)^2 \right] \frac{\Delta P}{\left[\left(1 + \frac{\Delta R_2}{R_0} \right)^2 - \left(1 + \frac{\Delta R_1}{R_0} \right)^2 \right]}$$

$$P_0 = 1.05(A - Z_M + \Delta A) - 0.05(B - Z_M - \Delta B) \quad (2)$$

Where:

ΔR_1 = increase in probe radii at the beginning of the pressure increment

ΔR_2 = increase in probe radii at the end of the pressure increment

$$\Delta P = P_1 - P_2$$

P_1 = Radial stress at the cavity at the beginning of the pressure increment

P_2 = Radial stress at the cavity at the end of the pressure increment

R_0 = Initial radius of the probe.

The procedure used during PPMT testing was the recommended FDOT standard [6]. 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 [9] is currently used in over 40 countries, both for research and practical applications. The flat DMT has been shown to be as a practical in-situ penetration testing to obtain the data necessary in generating p-y curves for laterally loaded piles [10,11].

The flat DMT consists of a steel blade having a thin, expandable, and 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. 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.

For evaluating DMT data, a test procedure was described by Marchetti [9], presenting equations that requires 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:

$$P_0 = 1.05(A - Z_M + \Delta A) - 0.05(B - Z_M - \Delta B) \quad (3)$$

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:

$$P_1 = B - Z_M - \Delta B \quad (4)$$

The DMT modulus is found from the equation 4:

$$E_D = 34.7(p_1 - p_0) \quad (5)$$

This DMT modulus can be converted to a Young's Elastic Modulus by :

$$M_{DMT} = R_M E_D \quad (6)$$

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:

$$E = M_{DMT} \left[\frac{(1+\nu)(1-2\nu)}{(1-\nu)} \right] \quad (7)$$

5. Geotechnical Conditions at Test Sites

Three sites were chosen. The first site on the

Florida Institute of Technology (FIT) Melbourne campus consisted predominately of sand; the second site, that included two clay layers, was located in Cape Canaveral, Florida, and the third site, the Archer Landfill in Gainesville, Florida.

Testing was conducted using the FDOT SMO Cone Penetrometer rig with FDOT field technicians. To categorize the soils, Standard Penetration (SPT), CPT, Dilatometer (DMT) and PPMT tests were performed. Universal Engineering Services of Melbourne performed SPT tests at both the FIT and Cape Canaveral sites [6].

The soil at the FIT site consisted of three sand layers. The upper medium-dense sand layer, interbedded with silt and clay lenses, varies from the surface to about 2 m (6.6 ft). The second layer, also about 3.05 m (10 feet) thick, consists of very loose to loose silty sand. The third layer beginning at about 6.1 m (20 feet) consists of dense cemented sands.

The stratigraphy at the Cape Canaveral Clay and Sand site, the soil consisted of four layers. The first layer, to 2 m (0–7 ft) was predominantly medium dense sand. The second layer, from 2–3 m (7–10 ft), was soft sandy clay and the third layer from 3–10.5 m (10–32.5 ft), was loose silty sand. The fourth from 10.5 to 16 m (32.5 ft to 50 ft), was predominantly soft clay. This thick clay layer was the focus of the testing. The clay was underlain by medium dense sand to silty sand.

The sands at archer Landfill site displayed consistent which were divided into layers. The first layer to 2.1 m (0 -7ft) consistency of loose silty sand. From 2.1 to 4.2 m (7- 14 ft), the second layer was medium dense silty sand. The third layer from 4.2 -9.1 (14 -30 ft) was predominantly medium dense sand to silty sand.

6. Pressuremeter Data Analysis

6.1. Initial Elastic Moduli Analysis

The PPMT modulus, E_o , is calculated by using the slope of the straight- line portion of the PMT curve. The results of initial elastic modulus versus depth from PPMT tests are shown in Figure 4. A slight but relatively constant increase in modulus occurs with depth throughout the soil

profiles. At 10.5 m (34.5 ft), the high cone value may be the result of testing silty fine sand, which is apparent in the CPT data.

6.2. Reload Moduli Analysis

The PMT reload modulus, E_r , was calculated from the straight- line rebound portion of the PMT curve. The reload modulus increased slightly with depth in the clays, from about 8,000 kPa to about 11,000 kPa, with the exception of a value near 40,000 kPa at 10.5 m (34.5 ft) as shown in Figure 5. Again, at the 10.5 m (34.5 ft) depth, values are high and could indicate loose silty fine sand.

6.3. Initial or Lift-off Pressure

The initial or lift-off pressure, p_o , corresponds to the pressure at which the probe contacts the borehole wall and balances the static earth pressure in the ground. This initial pressure indicates the first stress within the clay before the expansion of the PPMT probe occurs.

The data points drawn on this graph tend to vary linearly and display a straight line passing through the origin, which indicates that the lift-off pressure in clays is linear and increases with depth. The results at 10.5 m (34.5 ft) are in silty sand and, therefore, do not follow the trend, which may be a result of the soil change.

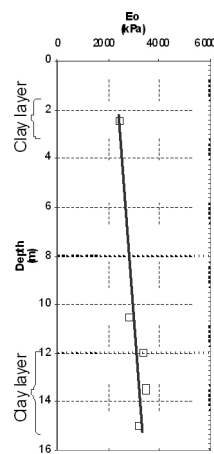


Fig. 4. Initial Moduli Vs Depth

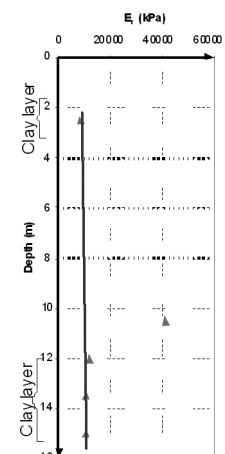


Fig. 5. Reload Moduli Vs Depth

6.4. Limit Pressure

The pressure at which the cavity has doubled its volume is defined as limit pressure, p_L . The test cannot directly measure the limit pressure due to a limited water reservoir and the risk of damaging the tubing and the probe. In this case, the PPMT curve has to be extrapolated to estimate the limit pressure.

These extrapolation results show that within the clay, the limit pressure linearly increased with depth. These values showed similar trends to the other parameters and again at 10.5 m (34.5 ft), the limit pressure is slightly higher, indicating this could be a different soil.

7. Correlation from PPMT Engineering Parameters

The initial elastic modulus was compared to the limit pressures using the engineering parameters from 96 PPMT tests in the silty sands at the FIT and Archer sites. These soils ranged from very loose to dense silty sands. An excellent correlation exists when modeled nonlinearly shown in “Figure 6”. A nonlinear relationship would be expected because the limit pressure cannot increase infinitely as stiffness increases. Briaud [3] presented linear correlations based on over 400 records, between the limit pressure and initial elastic modulus of $p_L = 0.125 E_o$ for sands and $p_L = 0.071 E_o$ for clays. He specifically states that the wide scatter in the data used to develop them, “makes these correlations essentially useless for design;” however, they give the engineers a relative feel for the engineering parameters [12]. When a linear regression through the origin was used to describe this data the equation becomes $p_L = 0.079 E_o$. In conclusion, this nonlinear relationship shows that PPMT data are realistic and can be used by engineers.

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A nonlinear correlation was developed between the initial elastic modulus and the reload modulus “Figure 7”. Using data from 36 tests performed in silty sands from both the FIT and Archer sites. Twenty of the 36 tests were performed and recorded using the digital system [12]. When only digital information was evaluated the regression equation became $E_r = 0.15E_o^{1.4864}$ and had a corresponding regression coefficient (i.e. R^2) of 0.93. This improved

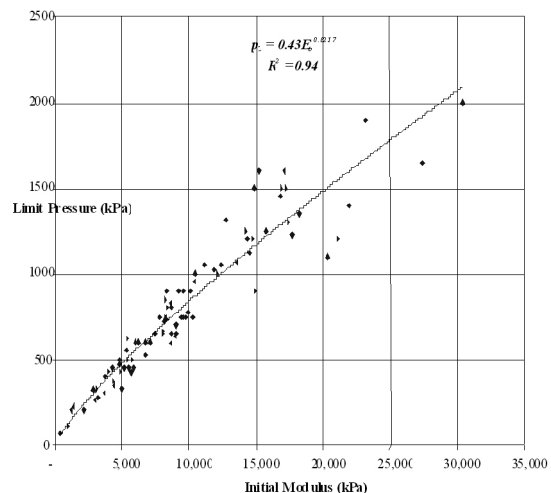


Fig. 6. Correlation between Limit Pressure and Initial Elastic Modulus in Silty Sands.

correlation suggests that the digital instrumentation combined with the APMT software improves the PPMT data. Briaud [3] presents a linear correlation between these two parameters where $E_r = 8 E_o$ in sands. If the data in Figure 6 is represented linearly a regression of $E_r = 16 E_o$ results with an R^2 value of 0.76 and if only digital data is used the equation becomes $E_r = 21 E_o$ results with an R^2 of 0.79. These linear results indicate that digital testing should be used to improve pressuremeter data.

Similar correlations between the lift-off or initial pressure and limit pressure were developed; however the data were not well represented statistically as shown in the equation and corresponding correlation coefficient below.

$$P_L = 24.2 (P_o)^{0.9685} \quad R^2 = 0.62$$

9. Development of p-y Curves

Several methods have been proposed for the design of laterally loaded pile using PMT data [7] and [13]. Most of these methods were based on preboring PMT results. More recently, methods have been proposed which develop the p-y curves from pushed in PMT tests [14].

10. Pressuremeter p-y Curves

Robertson [15] suggested a method that used the results of a pushed-in pressuremeter to

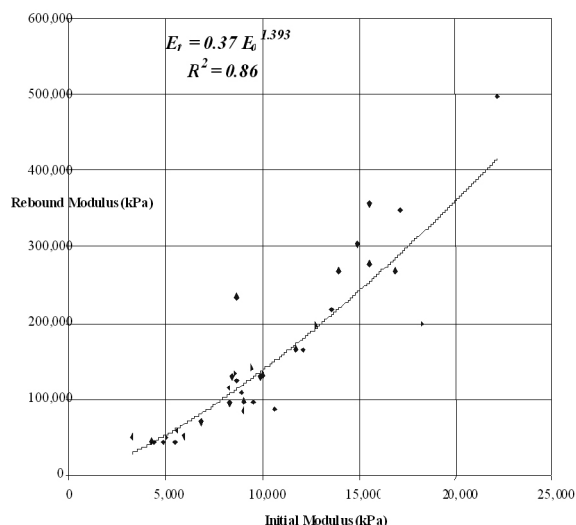


Fig. 7. Correlation between Initial Modulus and Reload Modulus for Silty Sands.

evaluate p-y curves of a driven displacement pile. They multiplied the pressure component of the PMT curve by an α factor to obtain the correct p-y curve. The critical depth was assumed to be four pile diameters

The following steps outline the Robertson [15] method for determination of p-y curves from cone-pressuremeter data:

- a) Determine the initial radius of the probe:
- b) Calculate the initial volume of the probe:

$$V_{op} = \pi \times R_p^2 \times L_m \quad (8)$$

Where R_p = Initial Radius of the probe
 L_m = Membrane Length

- c) Determine P in units of force/length:

$$P = (P_{PPMT})^* \times B_{pile} \times \alpha \quad (9)$$

Where B_{pile} = Pile Diameter
 $(P_{ppmt})^*$ = Corrected Pressure from pressuremeter
 α Reduction Factor

- d) A reduction factor, α , is applied to the P.

If $X/B_{pile} > 4$, $\alpha = 2$ for Clay and $\alpha = 1.5$ for Sand

Else $\alpha = \frac{1.5 \times D_{cm}}{4 \times B_{pile}}$ for Sand; Or $\alpha = \frac{2 \times D_{cm}}{4 \times B_{pile}}$ for Sand; Or for Clay

- e) Determine Y in units of Length

$$Y = \frac{(V_{PPMT})^*}{2 \times V_{op}} \times \frac{B_{pile}}{2} \quad (10)$$

$(V_{PPMT})^*$ = Corrected Volume from pressuremeter

D_{cm} = depth from the ground surface to the center of the pressuremeter membrane.

Figure 8 shows p-y curves Typical based on a Pencil Pressuremeter Test driving at the one sounding of Cape Canaveral Test site.

11. Dilatometer p-y Curves

Unlike the PMT, which produces a comparatively large radial deformation (approximately 3.5 mm over 24 cm in length), the DMT only produces 1.1 mm of lateral deformation at the center of a 60 mm ring. The deformation is produced by a single volume injection; therefore, there are no increments of pressure with which to develop a load-deformation curve.

The basic soil properties, determined from the DMT indices, are used in conjunction with a parabolic function to develop p-y curves. For this research, curves determined from DMT tests were developed based on the method presented by Robertson [10].

The following steps outline the Robertson [10] method for determination of p-y curves from dilatometer data:

1. For cohesive soils the following cubic parabola, originally proposed by Matlock [16] is suggested:

$$\frac{P}{P_u} = 0.5 \left(\frac{y}{y_c} \right)^{0.33} \quad (11)$$

$$\text{Where: } y_c = \frac{23.67 S_u B_{pile}^{0.5}}{F_c E_D} \quad (12)$$

With y_c in cm, B_{pile} = pile diameter, cm, and an empirical stiffness factor, $F_c \approx 10$. The

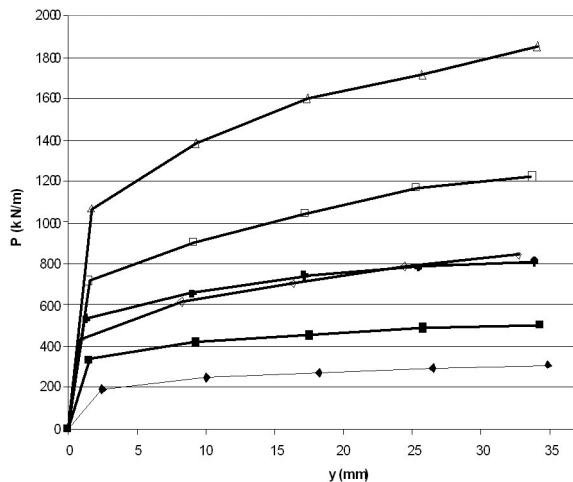


Fig. 8. Typical PPMT p-y Curves

evaluation of the ultimate lateral resistance P_u is again given in a bearing capacity format as:

$$P_u = N_p S_u B_{pile} \quad (13)$$

At considerable depths $N_p \approx 9$, but near the surface it reduces to 2 to 4; the non-dimensional factor is calculated as:

$$N_p = 3 + \frac{\sigma_{vo}}{S_u} + \left(J \frac{z}{B_{pile}} \right) < 9.0 \quad (14)$$

Where z = depth,

σ_{vo} = effective stress at depth z , and

J = empirical stiffness factor set to 0.5 for soft clay and 0.25 for stiff clay.

The value of S_u can either be obtained from DMT values, or PMT estimates as

$$S_{uPMT} = 0.67 (p_L)^{0.75} \quad (15)$$

With S_u and p_L in kPa.

2. For cohesionless soils, use the Matlock's [16] cubic parabola, where P_u is based on the findings of Reese [17] and is the lesser of:

$$P_u = \sigma_{vo}' [B_{pile} (K_p - K_a) + z K_p \tan \phi' \tan \beta] \quad (16)$$

and y_c is:

$$y_c = \frac{4.17 \sin \phi' \sigma_{vo}'}{E_D F_\phi (1 - \sin \phi')} B_{pile} \quad (17)$$

where F_ϕ is an empirical factor equal to 1 for cohesionless soil. The evaluation of the ultimate lateral resistance P_u is again given in a bearing capacity.

Figure 9 shows p-y curves Typical based on a dilatometer Test driving at the one sounding of Cape Canaveral Test site.

12. PPMT and DMT p-y Curves Analysis

Robertson's [14] PPMT-based p-y curves produce comparable Values, P_u , with Robertson's [10] 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 [18]. The higher ultimate load is defined as the

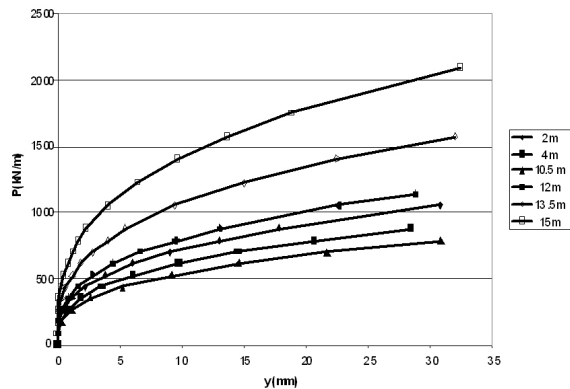


Fig. 9. Typical DMT p-y Curves

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 could be seen in Figure 10.

The maximum ultimate load is defined as P_{u1} , which corresponds 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_0 , of the elastic phase of the soil to the deflection, y_1 .

The comparison between DMT and PPMT p-y curves was performed 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

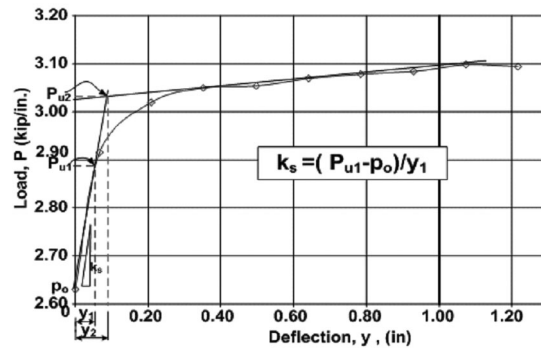


Fig. 10. Depiction of Ultimate Loads and the corresponding Lateral Deflections in Clays

tests. Third, the slopes have a much higher variability than the ultimate loads as evidence by the standard deviations in the Table 1.

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 2.

13. Conclusion

P-y curves are used to represent horizontal soil-pile interaction in conventional analysis of deep foundations under lateral load. PPMT data produces more engineering parameters (i.e., p_0 , E_0 , E_r , pL) than DMT data. A reliable nonlinear correlation was developed between the PPMT initial elastic and the reload moduli in clays. It is shown that 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. The DMT equations yield a polynomial that continually increases

Table 1. Ratio of PPMT and DMT P-Y Curves

| Depth | | Initial slopes | Ultimate loads |
|---------|------|----------------|----------------|
| [m] | [ft] | DMT/PPMT | DMT/PPMT |
| 2.5 | 8 | 0.98 | 0.95 |
| 10.5 | 34.5 | 1 | 1.33 |
| 12 | 39.5 | 1.83 | 0.84 |
| 13.5 | 44.5 | 1.79 | 0.73 |
| 15 | 50 | 2.86 | 0.83 |
| Average | | 1.69 | 0.94 |
| Std Dev | | 0.8 | 0.2 |

Table 2. Comparison of average initial Slope and average Ultimate Loads at One Inch Deflection from PPMT and DMT P-y (2.5 cm)

| Depth | | Initial Slopes | | Ultimate Loads | |
|---------|------|-------------------------|------|----------------|------|
| [m] | [ft] | DMT | PPMT | DMT | PPMT |
| | | [kips/in ²] | | [kips/in] | |
| 2.5 | 8 | 3.43 | 3.83 | 0.95 | 1 |
| 10.5 | 34.5 | 16 | 14 | 4.4 | 3.3 |
| 12 | 39.5 | 7.5 | 4.7 | 2.3 | 2.75 |
| 13.5 | 44.5 | 6.1 | 3.9 | 2.2 | 3 |
| 15 | 50 | 10 | 2.9 | 2.75 | 3.3 |
| Avg | | 8.61 | 5.87 | 2.52 | 2.67 |
| Std Dev | | 4.8 | 4.6 | 1.2 | 1.0 |

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. The predictions made with pressuremeter and dilatometer tests were also good. Thus, both the pressuremeter and the dilatometer are promising methods of modeling lateral soil-pile interaction of deep foundations.

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