Pencel Pressuremeter Testing to Determining P-Y Curves for Laterally Loaded Deep Foundations

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Abstract

The pressuremeter used was essentially the PENCEL pressuremeter (PPMT), manufactured by ROCTEST, Inc. This paper offers a description of the equipment, testing procedure, theory to obtain parameters of the ground and to develop the p-y curves for laterally loaded piles. From PPMT data reduced to graphs of pressure versus volume, soil parameters including the lift-off pressure, the initial elastic and reload moduli, and the limit pressure were determined. Methods developed to determine p-y curves from pressuremeter and dilatometer (DMT) test. P-y curves are used in the analysis to represent lateral soil-pile interaction. The pressuremeter offers an almost ideal in-situ modelling tool for determining directly the p-y curves for the design of deep foundations. As the pressuremeter 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, show consistency in soil parameters values. Comparison between PPMT and DMT p-y curves were developed based on the ultimate soil resistance, the slope of the initial portion of the curves, the shape of the curves. 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.

Keywords: p-y curves; deep foundation; piles; pressuremeter; dilatometer.
1. Introduction

The pressuremeter was originally developed by Ménard (1956) and modified by Briaud and Shields (1979). The subject 1.35-inch diameter PENCEL probes pushed when attached to cone rods as suggested by Briaud (1992). In addition to classical geotechnical applications, Cosentino and Briaud (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 by Roctest (2005). The PPMT probe is connected to Cone Penetrometer (CPT) rods and either pushing the cone with the PPMT attached or pushing the PPMT separately to perform PPMT tests as demonstrated Anderson and Townsend (1999). Recently this device was more advanced by developing a standardized testing procedure as recommended by Cosentino et al (2006) 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 (Cosentino et al. 2006). Often thrust pressures monitored by equipment operators are limited to 10 kN to avoid damage.

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.

![Figure 1. The PENCEL Pressuremeter](image)
1.1. PMT Description

It was developed for 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.

![Figure 2. APMT connected to PPMT Control Unit](image)

One of the most complex 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 as shown in Figure 3. The screen allows operators to follow standardized testing procedures. This screen allows for determining both an initial and limits pressure along with initial and reloads moduli. This typical APMT screen includes both the raw and reduced data (Cosentino et al. 2006).

![Figure 3. APMT Screen showing the Automatic Recording of Continuous Data Point](image)
1.2. Testing 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 cm³ 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 cm³, 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.

2. Data Interpretation

Once the data is collected it is typically plotted on a graph containing 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.
From this graph, the points are selected for PMT initial modulus and PMT rebound modulus determination, using the following equation, (Baguelin et al, 1978).

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

Where:
- $E$ = Young’s modulus,
- $\Delta P$ = Change in pressure,
- $\Delta V$ = Change in volume related to $\Delta P$,
- $V_m$ = Average volume,
- $\nu$ = Poisson’s Ratio

Tucker (1987) and Messaoud (2008) suggested using the 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:

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

Where:
- $\Delta R_1$ = increase in probe radii at the beginning of the pressure increment
- $\Delta R_2$ = increase in probe radii at the end of the pressure increment
- $\Delta P = P_2 - P_1$
- $P_1$ = 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 (Cosentino et al. 2006). CPT tests were conducted in accordance with the American Society for Testing and Materials (ASTM) D 5778.
3. Field Testing Program

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) as described by Marchetti (1980) and PPMT tests were performed. Universal Engineering Services of Melbourne performed SPT tests at both the FIT and Cape Canaveral sites (Cosentino et al. 2006).

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. The second layer, also about 3.05 m thick, consists of very loose to loose silty sand. The third layer beginning at about 6.1 m 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 was predominantly medium dense sand. The second layer, from 2 to 3 m, was soft sandy clay and the third layer from 3 to 10.5 m, was loose silty sand. The fourth from 10.5 to 16 m, 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 consists of loose silty sand. From 2.1 to 4.2 m, the second layer was medium dense silty sand. The third layer from 4.2 to 9.1 m was predominantly medium dense sand to silty sand.

4. Data Analysis and Discussion

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.

The initial pressure from the DMT and PPMT are summarized in Table 1, so the data was plotted and compared in Figure 5. 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 1. DMT and PPMT lift-off pressures using two different cone tips

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>DMT</th>
<th>PPMT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Series 1</td>
</tr>
<tr>
<td>2.5</td>
<td>167.75</td>
<td>72</td>
</tr>
<tr>
<td>10.5</td>
<td>362.5</td>
<td>195</td>
</tr>
<tr>
<td>12</td>
<td>401</td>
<td>285</td>
</tr>
<tr>
<td>13.5</td>
<td>403</td>
<td>338</td>
</tr>
<tr>
<td>15</td>
<td>496.25</td>
<td>383</td>
</tr>
</tbody>
</table>

Figure 5. DMT versus PPMT Initial Pressures

The initial elastic moduli from the DMT and PPMT are summarized in Table 2 and then plotted in Figure 6. 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.

Table 2. DMT and PPMT initial moduli

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>DMT</th>
<th>PPMT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Series 1</td>
</tr>
<tr>
<td>2.5</td>
<td>2400</td>
<td>2680</td>
</tr>
<tr>
<td>10.5</td>
<td>3358</td>
<td>3592</td>
</tr>
<tr>
<td>12</td>
<td>3816</td>
<td>2969</td>
</tr>
<tr>
<td>13.5</td>
<td>3160</td>
<td>2962</td>
</tr>
<tr>
<td>15</td>
<td>3286</td>
<td>3588</td>
</tr>
</tbody>
</table>
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.

4.1. Development of p-y Curves

Several methods have been proposed for the design of laterally loaded piles using PMT data as demonstrated (Baguelin et al. 1978; Robertson et al. 1983; Robertson et al. 1985). 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 by Robertson et al. (Robertson et al. 1985).

4.1.1. Pressuremeter p-y Curves

Robertson et al. (Robertson et al. 1986) suggested a method that used the results of a pushed-in pressuremeter to evaluate p-y curves of a driven displacement pile. They multiplied the pressure component of the PMT curve by “a” factor to obtain the correct p-y curve. The critical depth was assumed to be four pile diameters.

The following steps outline the Robertson et al (Robertson et al. 1986) 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:

\[ V_{0p} = \pi \times R_p^2 \times L_m \]  

(3)

where:

\[ R_p = \text{Initial Radius of the probe} \]

\[ L_m = \text{Membrane Length} \]
c) Determine P in units of force/length:
\[ P = (p_{PPMT})^* \times B_{pile} \times \alpha \]  
(4)

where:
- \( B_{pile} \) = Pile Diameter
- \( (p_{PPMT})^* \) = Corrected Pressure from pressuremeter
- \( \alpha \) = Reduction Factor

d) A reduction factor, \( \alpha \), 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 Clay

e) Determine Y in units of Length
\[ Y = \frac{(V_{PPMT})^*}{2 \times V_{op}} \times \frac{B_{pile}}{2} \]  
(5)

where:
- \( (V_{PPMT})^* \) = Corrected Volume from pressuremeter
- \( D_{cm} \) = depth from the ground surface to the center of the pressuremeter membrane.

Figure 7 shows p-y curves based on a Pencel Pressuremeter Test driving at the one sounding of Cape Canaveral Test site.

![Figure 7. Typical PPMT p-y Curves](image-url)
4.1.2. 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 et al. (Robertson et al. 1989).

The following steps outline the Robertson et al (1986) method for determination of p-y curves from dilatometer data:

1. For cohesive soils the following cubic parabola, originally proposed by Matlock (Matlock 1970) is suggested:

\[
\frac{p}{p_u} = 0.5 \left( \frac{\gamma_c}{\gamma_c} \right)^{0.33}
\]

Where:

\[
\gamma_c = \frac{23.67 S_u B_{pile}^{0.5}}{F_c E_D}
\]

With \( \gamma_c \) in cm, \( B_{pile} \) = pile diameter, cm, and an empirical stiffness factor, \( F_c \approx 10 \). The evaluation of the ultimate lateral resistance \( P_u \) is again given in a bearing capacity format as:

\[
P_u = N_p S_u B_{pile}
\] (8)

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

\[
N_p = 3 + \frac{\sigma_v}{S_u} + \left( J \frac{z}{B_{pile}} \right)< 9.0
\]

where:

\( z \) = depth

\( \sigma_v \) = effective stress at depth \( z \)

\( J \) = 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

\[
S_{uPMT} = 0.67 (p_L)^{0.75}
\] (10)

With \( S_u \) and \( p_L \) in kPa.

2. For cohesionless soils, use the Matlock’s (1970) cubic parabola, where \( P_u \) is based on the findings of Reese et al. (1974) and is the lesser of:

\[
P_u = \sigma_{v0} ' \left[ B_{pile} (K_p - K_a) + z K_p \tan \theta' \tan \beta \right]
\]

(11)
and $y_c$ is:

$$y_c = \frac{4.17 \sin \phi' \sigma_{vo}'}{E_D F_0 (1 - \sin \phi')} B_{pile}$$  \hspace{1cm} (12)

where $F_0$ 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 8 shows p-y curves based on a dilatometer Test driving at the one sounding of Cape Canaveral Test site.

![Figure 8. Typical DMT p-y Curves](image)

4.2. PPMT and DMT p-y Curves Analysis

Roberston’s et al (1986) PPMT-based p-y curves produce comparable Values, $P_u$, with Robertson’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 9. 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 as demonstrated (Cosentino et al. 2006; Messaoud 2008) 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 9.

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, $y_1$. 
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 3 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 evidenced by the standard deviations in the Table 3.

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>Initial slopes</th>
<th>Ultimate loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.98</td>
<td>0.95</td>
</tr>
<tr>
<td>10.5</td>
<td>1</td>
<td>1.33</td>
</tr>
<tr>
<td>12</td>
<td>1.83</td>
<td>0.84</td>
</tr>
<tr>
<td>13.5</td>
<td>1.79</td>
<td>0.73</td>
</tr>
<tr>
<td>15</td>
<td>2.86</td>
<td>0.83</td>
</tr>
<tr>
<td>Average</td>
<td>1.69</td>
<td>0.94</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.8</td>
<td>0.2</td>
</tr>
</tbody>
</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 4.
Table 4. Comparison of average initial slope and average ultimate loads at one inch deflection from PPMT and DMT P-y (2.5 cm)

<table>
<thead>
<tr>
<th>Depth</th>
<th>Initial Slopes</th>
<th>Ultimate Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DMT</td>
<td>PPMT</td>
</tr>
<tr>
<td>[m]</td>
<td>[ft]</td>
<td>[kips/in²]</td>
</tr>
<tr>
<td>2.5</td>
<td>8</td>
<td>3.43</td>
</tr>
<tr>
<td>10.5</td>
<td>34.5</td>
<td>16</td>
</tr>
<tr>
<td>12</td>
<td>39.5</td>
<td>7.5</td>
</tr>
<tr>
<td>13.5</td>
<td>44.5</td>
<td>6.1</td>
</tr>
<tr>
<td>15</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>Avg</td>
<td>8.61</td>
<td>5.87</td>
</tr>
<tr>
<td>Std Dev</td>
<td>4.8</td>
<td>4.6</td>
</tr>
</tbody>
</table>

5. 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., p₀, E₀, Eᵣ, p_L) than either DMT data.

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, Pu, with Robertson’s et al. (1986) 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.

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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References


