Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 55 No. 2 June 2024 ISSN 0046-5828

Optimizing Soil Characterization with Automated Pressuremeter Software Integration for the Pencel Pressuremeter in In-situ Testing

F. Messaoud[1], M. S. Nouaouria[2], and P. J. Cosentino[3]
[1]*Laboratory of Civil Engineering and Hydraulic, University 8 Mai 1945, Guelma, Algeria*
[2]*Laboratory of Civil Engineering and Hydraulic, University 8 Mai 1945, Guelma, Algeria*
[3]*Department of Mechanical and Civil Engineering, Florida Institute of Technology, Melbourne, Florida, USA*
E-mail: *f.messaoud@univ-tebessa.dz*

ABSTRACT: The integration of the Pencel Pressuremeter (PPMT) model with the Automated Pressuremeter (APMT) software represents a significant advancement in in-situ soil testing. This combination simplifies the process of data reduction and analysis, resulting in substantial time savings. The APMT software efficiently records digital pressure and volume data, performs necessary calibrations, and offers quick access to essential strength and stiffness properties for engineering analysis. Through extensive testing conducted on various soil types, the integration of a linear potentiometer and a digital pressure transducer into the control unit has significantly improved the accuracy of digital volume measurements and pressure readings. Notably, the Stabilization Time (ST) for volume increments, as estimated by the APMT software, ranges from 20 to 70 seconds depending on the specific soil conditions. The APMT system not only enhances data quality but also minimizes the potential for human recording errors. It drastically reduces the time required for data collection and analysis when compared to manual methods, establishing itself as an efficient and precise tool for evaluating soil properties.

KEYWORDS: Pencel Pressuremeter, Soil Characterization, Data Accuracy, Stabilization Time, and Sensors Integration.

1. INTRODUCTION

The assessment of in-situ strength and deformation characteristics plays a vital role in geotechnical engineering design and evaluation. However, the collection of undisturbed soil samples for thorough laboratory testing poses significant challenges, as highlighted by previous studies (Hight et al., 1992; DeGroot, 2001; DeGroot et al., 2005; and Mayne et al., 2009). To address these challenges, researchers have developed in-situ testing techniques, one of which is the pressuremeter (PMT) test (Wroth & Hughes, 1973). The PMT test involves inserting a cylindrical probe into the soil, applying uniform pressure through a flexible membrane, and measuring the resulting radial deformation of the soil (Baguelin et al., 1978; Mair & Wood, 1987; Briaud, 1992; Clarke, 1995; and Ménard, 1975). This test allows for the measurement of essential soil parameters, providing valuable information for geotechnical engineering design and evaluation processes (Briaud, 1992; Benoît & Howie, 2014; and Messaoud, & Nouaouria, 2010).

Since the development of Ménard's original Pressuremeter, several variations of PMT tests have emerged, including the Pencel Pressuremeter (PPMT), also known as the full displacement pressuremeter (FDPMT). The PPMT involves driving a probe into the ground using specialized equipment, possibly equipped with a friction-reducing ring to protect the membrane during installation (Messaoud, 2008). The installation process, typically conducted at a constant speed, leads to radial soil displacement and some degree of soil disturbance (Withers et al., 1986). It's important to highlight that the installation method can affect the test results. PPMT tests can be conducted in various soil types, as demonstrated by Cosentino et al. (2006) in sands and clays in Florida, showing the PPMT membrane resilience when properly maintained.

The PPMT probe can be connected to standard cone penetration test (CPT) rods, enabling multiple PPMT tests to be performed at a single site (Briaud & Shields, 1979). However, the current testing procedure involves manual data recording from analog pressure and volume gauges, which can be challenging to read accurately. To improve this 25-year-old device, there is a potential enhancement opportunity by integrating digital gauges along with data collection, reduction, and analysis software for more efficient and precise measurements.

In the strain-controlled PPMT test, operators inject 5 cm^3 water volumes into the probe and wait for a 15 to 30 seconds stabilization period before recording pressures (Cosentino et al., 2006). A counter with 0.1 cm^3 increments is used for accurate volume measurements, and a 2500 ± 12.5 analog pressure gauge records pressure. Automation could simplify the process, increasing precision and reducing operator involvement and errors.

In the PPMT test, as seen in Figure 1, adjustments are essential for the raw pressure-volume curve (Cosentino et al., 2006). Two key corrections are made to recorded pressure values: adding hydrostatic pressure in the tubing (unmeasured by the control unit) and reducing for membrane resistance, stemming from pressure-induced tubing expansion and membrane thinning (Messaoud, & Nouaouria, 2010; and Messaoud, & Cosentino, 2016). This ensures accurate representation of soil response, with correction specifics relying on membrane characteristics and equipment calibration (Briaud, 1992; Messaoud, 2008; Roctest, Inc. 2005; and Briaud, 2013).

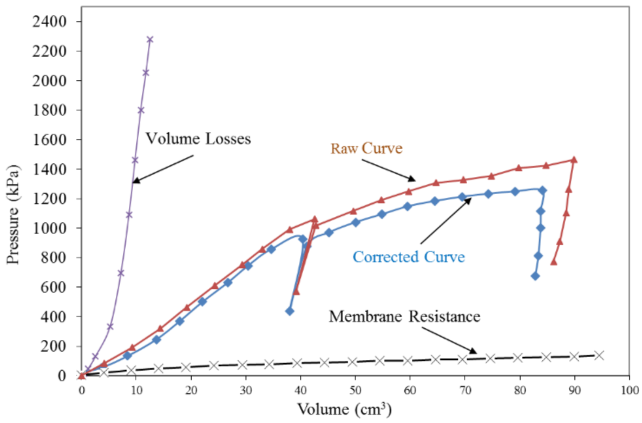


Figure 1 PPMT curves with applied calibrations

Three corrections are applied: 1) Hydrostatic Pressure Correction: To account for the water column's pressure between the control unit and the probe, the hydrostatic pressure (P_h) is added to the raw pressure (P_r); 2) Membrane Resistance Correction: During calibration, a pressure value representing membrane resistance is subtracted from the actual test pressure; and 3) Volumetric Expansion Correction: Calibration provides a volume value accounting for expansion effects due to tubing and membrane; this is subtracted from the actual test volume (Briaud, 1992; Messaoud, 2008; and Roctest, Inc. 2005). These corrections ensure accurate data interpretation in the PPMT test.

After achieving a linear relation, volume correction is subtracted from the recorded volume. This process yields engineering parameters like lift-off pressure (P_0), elastic modulus (E_i), reload modulus (E_R), and limit pressure (P_L) (Messaoud, & Nouaouria, 2010; Messaoud, 2008; and Messaoud, & Cosentino, 2016). Figure 2 shows four critical phases of the PPMT stress-strain reduced curve that are used for estimating:

- Lift-off Pressure: Represents the initial at-rest horizontal pressure in the initial phase.
- Elastic Modulus: Measures soil stiffness during the linear elastic phase.
- Reload Modulus: Describes soil behavior during unloading and reloading phase.
- Limit Pressure: Indicates the soil's ultimate resistance to deformation in the plastic phase.

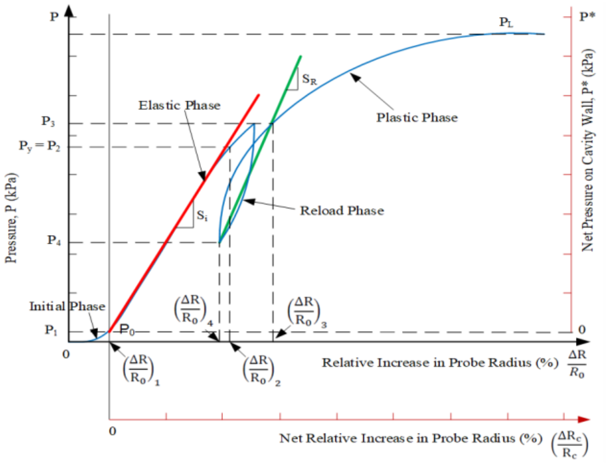


Figure 2 Typical PPMT stress-strain response

Based on Figure 2, Equation for the volume of a soil cavity can be expressed in terms of the relative increase in probe radius:

$$V_c = V_0\left[1+\left(\frac{\Delta R}{R_0}\right)_c\right]^2 \tag{1}$$

E_0 is calculated using the following Equation:

$$E_0 = (1+\upsilon)(P_2-P_1)\frac{\left[1+\left(\frac{\Delta R}{R_0}\right)_2\right]^2+\left[1+\left(\frac{\Delta R}{R_0}\right)_1\right]^2}{\left[1+\left(\frac{\Delta R}{R_0}\right)_2\right]^2-\left[1+\left(\frac{\Delta R}{R_0}\right)_1\right]^2} \tag{2}$$

E_R is calculated using the same way as E_0 employing the following Equation:

$$E_R = (1+\upsilon)(P_3-P_4)\frac{\left[1+\left(\frac{\Delta R}{R_0}\right)_3\right]^2+\left[1+\left(\frac{\Delta R}{R_0}\right)_4\right]^2}{\left[1+\left(\frac{\Delta R}{R_0}\right)_3\right]^2-\left[1+\left(\frac{\Delta R}{R_0}\right)_4\right]^2} \tag{3}$$

2. ENHANCING ENGINEERING TESTING EFFICIENCY WITH DIGITAL INTEGRATION

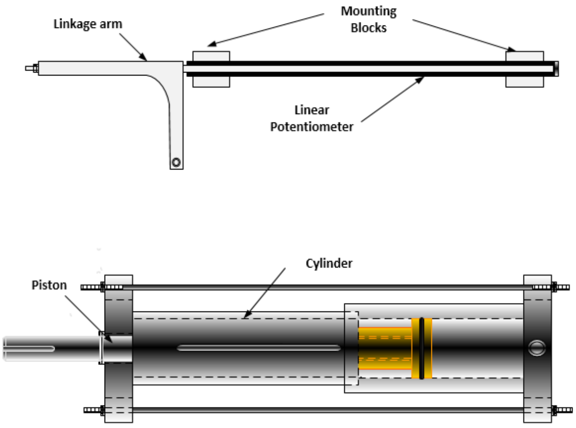
This study focuses on modernizing data collection and analysis in engineering testing. It aims to enhance the efficiency of the testing process, particularly in two key areas: replacing manual data recording with instrumentation and studying the time required for soil pressures to stabilize. These improvements, along with introducing instrumentation to the control unit, seek to achieve various objectives, including reducing test time, minimizing human errors, increasing data accuracy, streamlining data processing, and decreasing manpower required for PPMT testing. Ultimately, this approach aims to improve the understanding of engineering parameters (P_0, E_i, E_R, and P_L).

Incorporating digital data collection and analysis into the PPMT control unit while retaining manual data collection aims to enhance efficiency and accuracy in data processing. This approach allows for precise and consistent measurements of pressures and volumes, minimizing errors and improving data quality. The use of a laptop computer, as depicted in Figure 3, offers advantages such as real-time data analysis, enabling engineers to process and evaluate data on-site immediately.

Figure 3 PPMT control unit connected to laptop computer during field testing

2.1 Improving Data Accuracy through Advanced Sensor Integration

To record pressure accurately, a Setra-Model 522 pressure transducer was integrated with the existing pressure gauge in the PPMT system. This transducer has a pressure range of 3,450 kPa, with excellent stability (less than 0.2% drift per year) and 0.25% full-scale accuracy. It's made of corrosion-resistant 17–4 PH stainless steel, operates on a voltage range of 7–35 V, and produces an output signal from 0–5 V. In contrast, the original 2,500 kPa analog gauge had a ±12.5 kPa reading accuracy. For measuring the injected water volume, three variants were considered: 1) measuring piston displacement and calibrating it to volume, 2) counting rotations of the volume-changing shaft and calibrating rotations to volume, or 3) incorporating a flow meter into the output tubing and calibrating flow to volume. The first option was chosen for its accuracy and compatibility with the existing control unit design. To measure piston displacement with a resolution of 0.1 cc, a CLP-type 6-inch linear-conductive potentiometer from Celesco was selected as depicted in Figure 4. This potentiometer is cost-effective, has a life expectancy of 10 million cycles, and offers an output range of 0–5 V.



(a) PPMT Cylinder and linear-conductive potentiometer

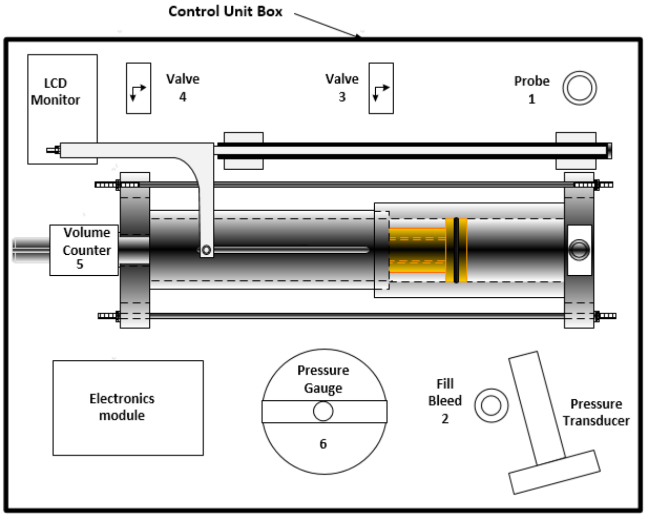


Figure 4 Advanced sensor integration assembly for PPMT control unit instrumentation

2.2 Control Unit Space and Sensor Integration

The control unit's interior space was evaluated to accommodate a pressure transducer and linear potentiometer. Electrical connections were established, linking these sensors to an electronics module, which, in turn, connected to a laptop computer via a serial port. The electronics module, as shown in Figure 5, featuring a microprocessor and serial interface chip, powered and collected data from both sensors. This data was converted into digital values, transmitted to the laptop in RS232 format, and displayed in chart format through a stand-alone data acquisition serial visa module. An LCD monitor on the PPMT control unit also displayed digital readings in case the laptop was disconnected.

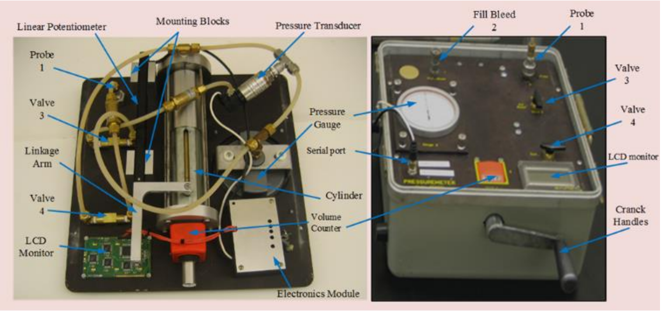
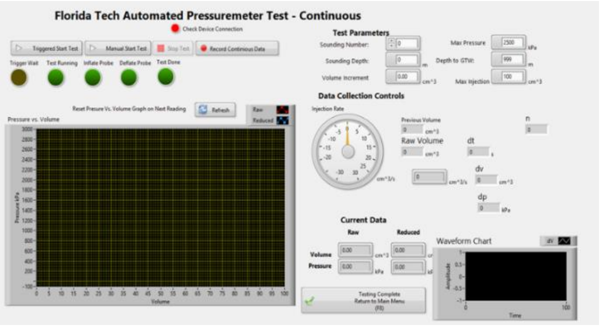


Figure 5 Front and back instrumented PPMT control unit

2.3 Enhancing Data Collection and Analysis with APMT Software in PPMT Testing

An independent data acquisition program, APMT, was developed to enhance data collection accuracy and simplify operator tasks during testing (Figure 6).


Florida Tech Automated Pressuremeter Test - Continuous

Test Parameters
Sounding Number: 0
Sounding Depth: 0 m
Volume Increment 0.00 cm^3
Max Pressure 2500 kPa
Depth to GTW: 999 m
Max Injection 100 cm^3

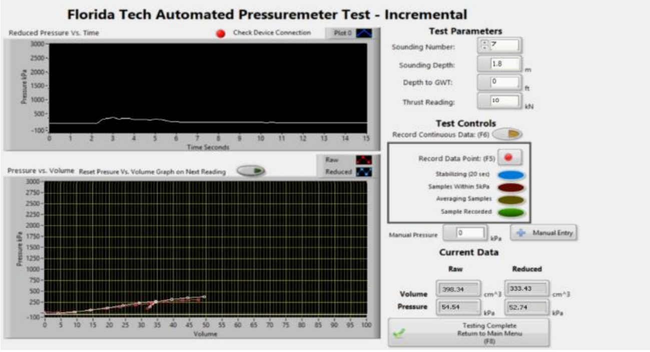
Data Collection Controls
Injection Rate 0 cm^3/s
Previous Volume 0 cm^3
Raw Volume 0 cm^3
n 0
dt 0 s
dv 0 cm^3
dp 0 kPa

Current Data
Volume: Raw 0.00 cm^3, Reduced 0.00
Pressure: Raw 0.00 kPa, Reduced 0.00

Figure 6 APMT test screen interface for PPMT testing

APMT digitally records pressure and volume data, streamlining the process of reducing test data and determining critical engineering parameters (P_0, E_i, E_R, and P_L). The system's sampling rate ensures sufficient data points for accurate analysis, and operators can choose different data visualization formats, including pressure versus volume, volumetric strain, or radial strain during testing for improved data analysis.

During load testing, determining the appropriate duration for each load increment is vital and can vary depending on soil type, density, saturation, and response (Roctest, Inc. 1980; Baguelin et al., 1986; and Cosentino, 1987). The APMT software was developed to address this issue by providing visual feedback to operators through three distinct lights: Burgundy, Dark Brown, and Green. These lights as seen in Figure 7. change based on the rate of change of successive pressure readings, indicating the system's stabilization at the desired pressure. The software's evaluation confirmed that when successive readings are within 5 kPa (burgundy light), stability at the desired pressure is achieved. The dark brown light (within 1 kPa) triggers data recording, averaging, and saving, while the green light indicates that the data has been successfully saved, allowing testing to proceed. Upon test completion, operators gain access to a new screen that offers estimations for lift-off and limit pressure (P_0, P_L), as well as initial and reload moduli (E_i, E_R).


Florida Tech Automated Pressuremeter Test - Incremental

Test Parameters
Sounding Number: 7
Sounding Depth: 1.8 m
Depth to GWT: 0 ft
Thrust Reading: 10 kN

Manual Pressure 0 kPa

Current Data
Volume: Raw 398.34 cm^3, Reduced 333.43 cm^3
Pressure: Raw 54.54 kPa, Reduced 52.74 kPa

Figure 7 APMT screen displaying automatic data points recording and pressure time

2.4 Precision Calibration of Sensor Integration for Accurate Digital Measurements

Following installation, the pressure transducer and potentiometer underwent calibration to ensure precise measurements within the 0–5 V analog signal range. To enable digital signal processing, the APMT device connected to the computer's serial port converted these signals into bits. A permeability control panel was employed to further validate the calibration of both the pressure transducer and gauge as illustrated in Figure 8.

Figure 8 Optimizing PPMT pressure transducer calibration with permeability control panel

By increasing pressure in the control panel, a corresponding change in the pressure transducer's bit readings was observed and recorded during multiple trials. This data facilitated calibration of the pressure transducer against the control panel, resulting in a highly correlated relationship with an R^2 value of 0.99. Ultimately, the pressure readings from the control panel aligned consistently with digital readings and measurements from the PPMT gauge, confirming the accuracy of the calibration process.

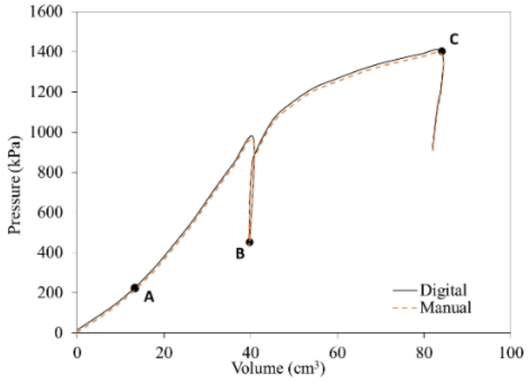
Calibrating the potentiometer involved establishing a correlation between the digital bit readings obtained through APMT and the PPMT volume counter. This calibration process resulted in highly accurate digitally calibrated volumes, with precision reaching less than 0.06 cm^3. An interesting observation during extensive testing revealed that the control unit counter had to display a volume greater than 0.7 cm^3 before any water was collected in the burettes. Further analysis showed that the initial 1.0 cm^3 volume counter increment only produced a 0.3 cm^3 change in the burette level, attributed to backlash between mating gears in the system. Using the linear potentiometer to measure piston displacement, which is directly connected to the piston, resolved this issue, ensuring reliable volume readings and reducing errors in the measurement system.

3. ASSESSING PPMT INSTRUMENTATION THROUGH FIELD TESTING PROGRAM

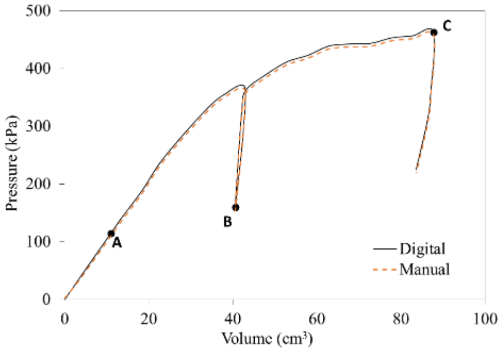
Three field testing sites were chosen for assessing the PPMT instrumentation's performance. The first site, located within the Florida Institute of Technology (FIT) campus in Melbourne, primarily consisted of sand with a top layer of 3.05 m thick and was composed of medium-dense sand interspersed with silt and clay lenses, having an average density of 17 kN/m^3 and a friction angle ranging from 32 to 35 degrees. Below, from 3.05 m to 6.1 m, was loose silty sand with an average density of 16 kN/m^3 and friction angles between 27 to 32 degrees. The third layer, starting at a depth of 6.1 m, comprised very dense sand with an average density of 17.4 kN/m^3 and friction angles ranging from 32 to 38 degrees. The second site, in Cape Canaveral, featured interbedded sands and clays, focusing on two clay layers. The upper clay layer, spanning 2 to 4 m, was normally consolidated and had an average density of 14.4 kN/m^3. A lower normally consolidated clay layer was found between 10 to 15 m depths with an average density of 15.3 kN/m^3. The third site, the Archer Landfill site, showed consistent soil properties from Cone Penetration Tests (CPT) performed by FDOT (Schmertmann, 1978). These soils were divided into three layers based on CPT data: the first layer up to 2 m consisted of silty clay, the second layer from 2 to 4.5 m was silty sand, and the third layer from 4.5 to 9 m was primarily sand to silty sand. A total of eighty PPMT tests were conducted in sand and clay soils at these sites, comparing results from conventional (Digital) and instrumented (manual) systems, with complementary Standard Penetration (SPT) and CPT tests to classify the soils accurately. Universal Engineering Services conducted SPT and CPT tests at FIT and Cape Canaveral sites, while FDOT conducted CPT tests at the Archer Landfill site.

3.1 Comparison of Manual and Digital Systems for Reliable Data Collection

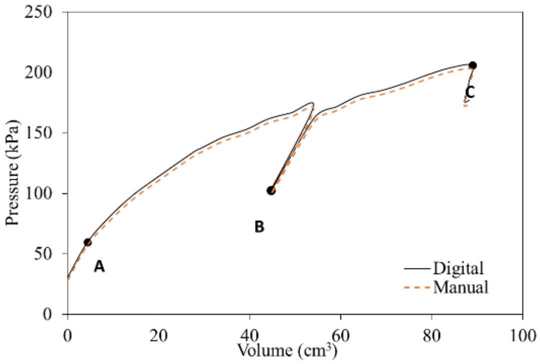
The field evaluation conducted after installing digital equipment aimed to compare the accuracy of data collected by the digital instrument with manual data recording. This involved a comprehensive analysis of raw data from both conventional and instrumented systems. Graphs (Figure 9) illustrated the comparison of raw pressure and volume data for three soil types: medium dense sand, loose silty sand, and clay. These graphs revealed slight disparities between the instrumented and conventional system data. To facilitate a detailed comparison, three specific points (A, B, and C) were chosen on each curve, representing different pressure levels and significant testing stages. For instance, in Figure 9(a), point A showed that the manual reading recorded a volume 0.67 cm^3 higher than the digital reading. Similar differences were observed at points B and C, consistently across different soil types.



(a) Medium Dense Sand



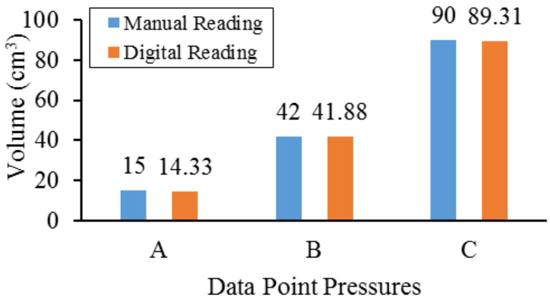
(b) Loose silty Sand



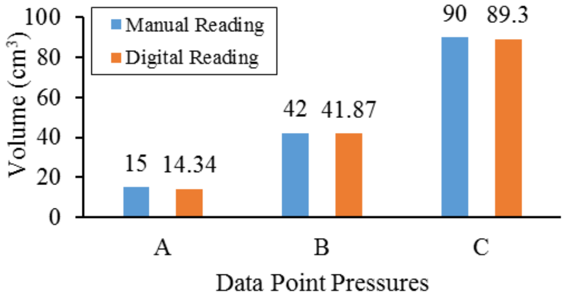
(c) Clay

Figure 9 Comparing manual and digital raw data from PPMT field testing

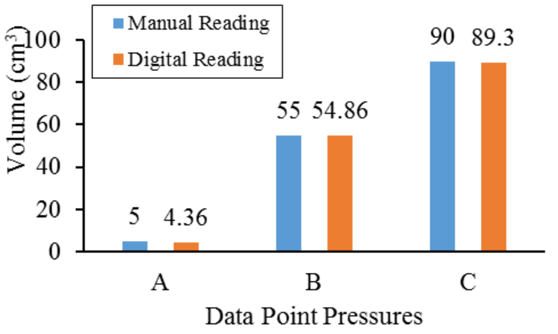
Figures 10 (a), (b), and (c) offer graphical comparisons of volume readings obtained from the digital system and the manual system at designated key points A, B, and C. These comparisons reveal a consistent change in volume, regardless of the stress level at which the measurements were taken. This consistency is attributed to the initial backlash present in the volume counter apparatus. However, it's noteworthy that smaller volume differences observed at point B result from gear movements reversing. Across all three soil types, the graphs show that the volume changes at points A and C closely align with the calibration error. Additionally, digital readings consistently report smaller values compared to manual readings. The results suggest that the digital data recording system offers greater accuracy in representing the PPMT curve compared to conventional data collection methods.



(a) Medium Dense Sand



(b) Loose silty Sand



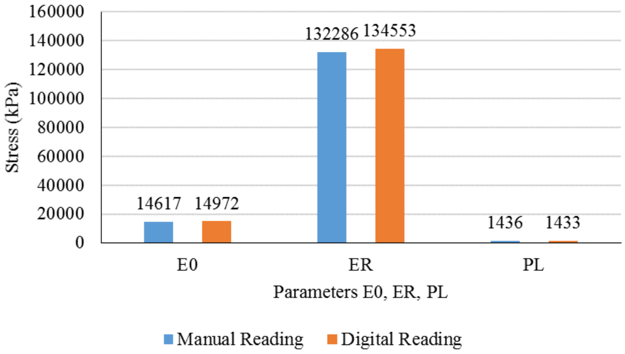
(c) Clay

Figure 10 Volume comparison between the conventional and instrumented system at key points A, B and C on PPMT curves for each type of soil

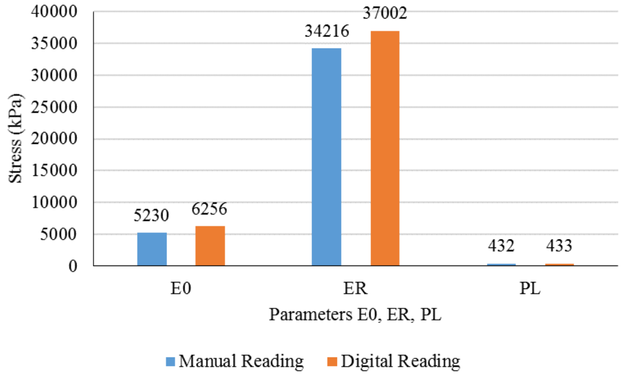
The APMT software offers engineers the flexibility to select specific points on the PPMT curve, facilitating the calculation of initial and reload slopes (S_i and S_R) and the estimation of the limit pressure (P_L). To determine P_L, APMT uses the last two digitally recorded data points from the PPMT curve, extending a straight line to the required volume (approximately 200 cm^3) representing P_L(max). A parallel lower line is drawn using the last point of the PMT curve, representing P_L(min). The average of P_L(max) and P_L(min) provides the estimated soil limit pressure P_L.

Engineering parameters obtained manually and digitally for three distinct soils are depicted in Figures 11 (a, b, and c). Notably, digitally obtained initial and reload moduli surpass their manual counterparts. The elastic modulus of soil depends on the slope of the curve, and since the manual system typically records a volume 0.7 cm^3 greater than the digital system at the same pressure, the conventional modulus tends to be lower. Consequently, this results in slightly higher values for the initial modulus E_0 and significantly higher values for the reload modulus E_R.

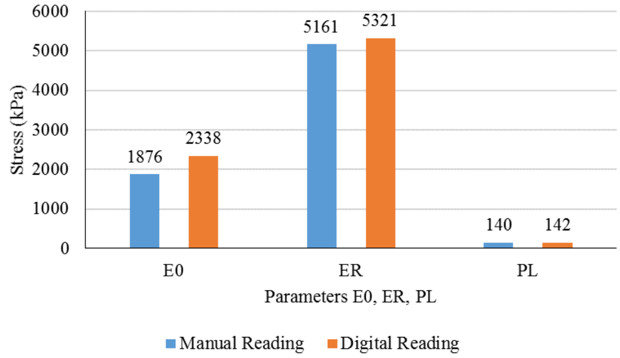
In the case of the stiffest soil among the three, the reload modulus exhibits the most substantial disparity between digital and manual measurements, as illustrated in Figures 11 (a, b). This difference was expected due to two primary factors: a greater pressure change associated with the unload-reload loop for this soil and a smaller volume change or strain during the cycle, including the 0.7 cm^3 gear backlash loss. Similarly, both loose silty sand and clay display significant differences in their initial moduli between digital and manual values, attributed to the backlash volume loss relative to the volume change in the initial portion of the curves. However, it's noteworthy that the limit pressures obtained from both systems remain very similar, as volume errors become negligible at larger volumes required for estimating this parameter.



(a) Medium Dense Sand



(b) Loose silty Sand



(c) Clay

Figure 11 Comparison of engineering parameters obtained through manual and digital PPMT data collection for each type of soil

3.2 Improving Time Efficiency in Field Testing

Engineers prioritize time efficiency in PMT field testing and data analysis, aiming to reduce drilling, manual data tasks, and engineering parameter determination. FDOT has already saved time by using a push probe instead of drilling boreholes. The introduction of digital technology and APMT software further accelerates data collection, reduction, and parameter analysis. These improvements modernize the process, allowing quicker results, timely decisions, and more efficient project progress. Table 1 illustrates significant time savings with the digital system, emphasizing its efficiency.

Table 1 A comparative analysis of task times in manual and automated PPMT tests

Task	Measured time per task	
	Manual system	Automated system
Read and record data collection	5 minutes	Automated entry and recording
Data transfer and reduction	25 minutes	Automated reduction
Engineering parameters evaluation	20 minutes	10 minutes
Total	50 minutes	10 minutes

Table 1 reveals that the implemented digital system saves approximately 40 minutes per test for specific tasks. This time-saving benefit allows engineers to promptly evaluate field test results and assess data rationality. Additionally, the digital system reduces field data collection time and eliminates the need for office data processing and report preparation, resulting in valuable time savings. Manual data recording can still serve as a backup, ensuring data redundancy and added assurance.

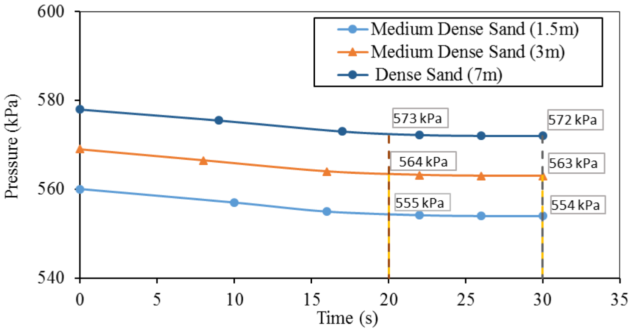
4. OPTIMIZATION OF STABILIZATION TIME FOR PRESSURE MEASUREMENTS ACCURACY

Pressure and volume readings are recorded after a designated Stabilization Time (ST) period, during which the soil relaxes, resulting in a gradual pressure decrease until it stabilizes. The APMT software simplifies the analysis by automatically evaluating pressure-versus-volume data for each incremental measurement. It monitors pressure readings over time, displaying them on the screen (refer to Figure 7). As pressure stabilizes and reaches a constant state, the APMT automatically saves the data in a designated file. This automated process ensures accurate and consistent data collection. A green light indicator signals the operator to proceed to the next reading, streamlining workflow and enhancing measurement efficiency.

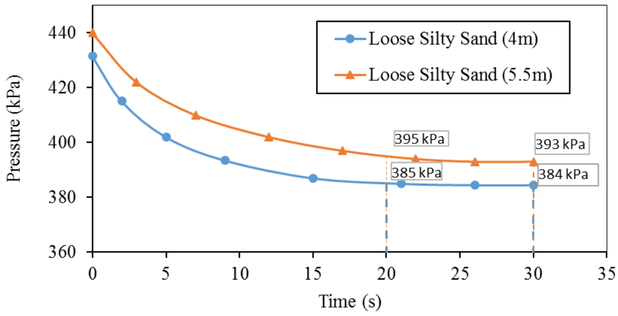
Selecting the appropriate Stabilization Time (ST) for different soils is a challenge with conventional PPMT systems. Typically, a common value of 15 seconds for sands and 30 seconds for clays is used (Roctest, Inc. 1980; and Cosentino et al., 2006). However, the implemented system was used at three sites to investigate ST variations across different soils. Findings revealed that ST can range from 20 to 70 seconds for various soil types as illustrated in Figures 12, 13, and 14.

For medium dense sand and dense sand at depths of 1.5 m, 3 m, and 7 m (Figure 12.a), the APMT showed that ST for these soils ranged from 20 to 30 seconds. Pressure readings corresponding to an ST of 20 seconds varied between 555 kPa and 564 kPa for medium dense sand and had a value of 573 kPa for dense sand. When pressure reached a constant state at an actual ST of 30 seconds, readings ranged between 554 kPa and 563 kPa for medium dense sand and 572 kPa for dense sand. The average ST was approximately 28 seconds with a standard deviation of 7 seconds.

Similarly, for loose silty sand at depths of 4 m and 5.5 m (Figure 12(b)), pressure readings corresponding to an ST of 20 seconds varied between 385 kPa and 395 kPa. When pressure reached a constant state at an actual ST of 30 seconds, readings ranged between 384 kPa and 393 kPa. These measurements were taken when there was no further change in pressure with time. Using a manual system with a fixed ST of 15 seconds instead of real-time measurements with the instrumented unit resulted in a 4% induced change in pressure values. This highlights the importance of accurately determining ST using the APMT, as it significantly impacts data reliability and accuracy.



(a) Medium Dense Sand



(b) Loose silty Sand

Figure 12 Pressure vs. Time at selected volume in FIT site

As seen in Figure 13, the analysis of soil at the Cape Canaveral site showed that the Stabilization Time (ST) for clayey silt and clay soils ranged from 30 to 70 seconds, significantly longer than the recommended 30 seconds by Roctest, Inc. (2005). This suggests that the soil at this site takes longer to stabilize before pressure becomes relatively constant.

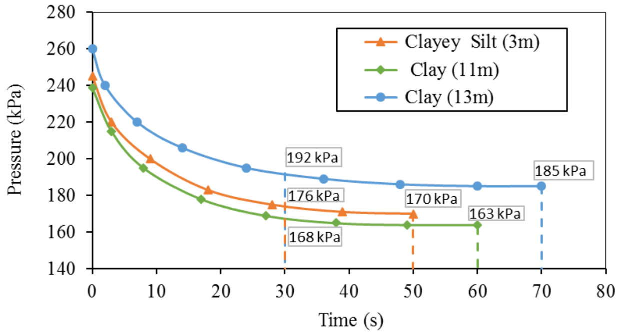


Figure 13 Pressure vs Time at selected volume in cape canaveral site

The analysis of soil at the Archer Landfill site (Figure 15) showed that the Stabilization Time (ST) for silty clay soil ranged from approximately 20 to 50 seconds, with an average ST of about 31 seconds, in line with the recommended 30 seconds. Similarly, for silty sand and sand to silty sand soil, the ST varied from 20 to 35 seconds, with an average ST of approximately 29 seconds, also aligning with the recommended 30-second ST (Roctest, Inc. 2005).

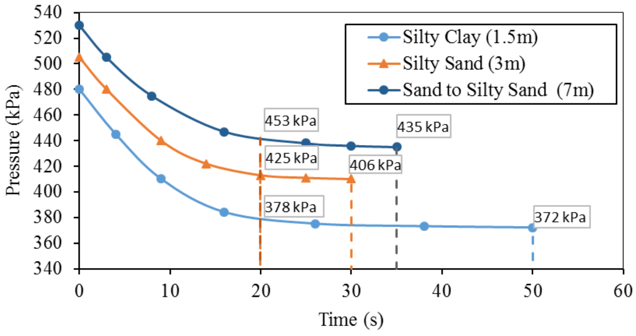


Figure 14 Pressure vs. Time at selected volume in archer landfill site

Histograms of Stabilization Times (ST) were generated for various soil types by conducting tests at different sites. The data from these histograms, which include the ST range, average, and standard deviation for each soil type, are summarized in Table 2.

Table 2 Summary of stabilization time for different soil types

Site	Soil Type	ST		
		Range	Average	Standard Deviation
Florida Institute of Technology	Medium dense sand	20–30	28.2	7.2
	Loose silty sand	20–30	27.3	7.0
	Dense sand	20–30	29.1	7.1
Cape Canaveral	Clayey silt	30–50	43.9	5.7
	Clay	30–60	46.3	6.8
	Clay	30–70	48.1	6.9
Archer Landfill	Silty clay	20–50	30.8	7.1
	Silty sand	20–35	26.9	6.9
	Sand to silty sand	20–35	31.6	7.3

5. NOMENCLATURE

APMT	Automated pressuremeter
FDPMT	Full displacement pressuremeter
CLP	Linear-Conductive Potentiometer
CPT	Cone Penetration Test
E_i	Initial elastic modulus
E_R	Reload modulus
FDOT	Florida Department of Transportation
FIT	Florida Institute of Technology
LCD	Liquid Crystal Display
LVDT	Linear Variable Differential Transformer
P_h	Hydrostatic pressure
P_L	Limit pressure
PMT	Pressuremeter
PPMT	Pencel pressuremeter
P*	Net pressure
P_{r0}	Raw pressure
P_0	Lift-off pressure
R_0	Initial cavity radius
S_i	Initial slope to estimate the elastic modulus
SMO	State Materials Office
SPT	Standard Penetration
SR	Reload slope to estimate the reload modulus
ST	Stabilization Time
v	Poisson's ratio
P_1 ; P_2	Radial pressure at the start and end of the initial phase.
P_3 ; P_4	Radial pressure at the start and end of the unloading cycle.
ΔR_1 ; ΔR_2	Variation of probe radius at the start and end during the initial phase.
ΔR_3 ; ΔR_4	Variation of probe radius at the start and the end of unloading cycle
$\Delta R/R$	Relative increase in probe radius
$\Delta R_c/R_c$	Net relative increase in probe radius
V_c	Volume of the cavity
V_0	Initial volume

6. CONCLUSIONS

The successful integration of the PPMT control unit with digital devices and APMT software has yielded numerous benefits. This includes the generation of high-quality digital pressure and volume data, leading to substantial time savings during data acquisition. The APMT software offers rapid assessment of critical soil parameters such as lift-off pressure (P_0), initial elastic modulus (E_i), reload modulus (E_R), and limit pressure (P_L). Raw data obtained from APMT aligns closely with conventional PPMT measurements, enhancing data quality while reducing the time required for data collection and analysis to a fraction of the manual process.

The observed volume discrepancies, primarily caused by backlash in gear mechanisms, particularly affecting unload-reload moduli, have been effectively addressed by selecting a high-precision pressure gauge and a potentiometer that eliminates gear backlash impact. Furthermore, the recommended Stabilization Times (ST) of 15 seconds for sands and 30 seconds for clays may not always hold true, as the APMT software has revealed ST variations ranging from 20 to 70 seconds across different soils. Precisely determining the ST using APMT results in more accurate pressure readings.

In summary, the instrumented control unit, in conjunction with the stand-alone Data Acquisition package APMT, is highly recommended for obtaining efficient and accurate in situ stress-strain data. Further evaluations of the PPMT with the instrumented control unit across diverse soil types and conditions are essential. This automated approach streamlines data interpretation and evaluation, leading to more efficient analysis and informed decision-making. Additionally, it not only reduces field data collection time but also eliminates the need for extensive office processing and report preparation, resulting in significant time savings throughout the testing process.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge the following people for their invaluable guidance and help in the completion of this study; Todd Britton and John Shoucair of the Florida Department of Transportation State Materials Office.

8. REFERENCES

Baguelin, F., Bustamante, M., and Frank, R. A. (1986). "The Pressuremeter and Foundations: French Experience. Use of In-situ Tests in Geotechnical Engineering." *Reston, Virginia, ASCE Geotechnical Special Publication 6.*

Baguelin, F., Jézéquel, J. F., and Shields, D. H. (1978). "The Pressuremeter and Foundation Engineering." *Trans Tech Publications,* Causthal-Zellerfeld, W. Germany.

Benoît, J., and Howie, J. A. (2014). "View of Pressuremeter Testing in North America." *Soils Rocks,* 37(3), 211–231.

Briaud J. L. (1992). "The Pressuremeter." *A. A Balkema, Brookfield, Vermont.*

Briaud, J. L. (2013). "The Pressuremeter Test: Expanding its Use." *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris,* 107-126.

Briaud, J. L., and Shields, D. H. (1979). "A Special Pressuremeter and Pressuremeter Test for Pavement Evaluation and Design." *Geotechnical Testing Journal,* ASTM 2:3.

Clarke, B. G. (1995). "Pressuremeters in Geotechnical Design." *Blackie Academic & Professional,* 364.

Cosentino, P. J. (1987). “Pressuremeter Moduli for Airport Pavement Design.” *Ph.D. Dissertation, Department of Civil Engineering, Texas A&M University.*

Cosentino, P. J., Kalajian, E., Anderson, B. J., Messaoud, F., and Cottingham, M. (2006). “Standardizing the Pressuremeter Test for Determining p-y Curves for Laterally Loaded Piles.” *FDOT Research Report,* Contract BD 658.

DeGroot, D. J. (2001). “Laboratory Measurement and Interpretation of Soft Clay Mechanical Behaviour, Soil Behaviour and Soft Ground Construction.” *ASCE GSP*, 119, 167-200.

DeGroot, D. J., Poirer, S. E. and Landon, M. M. (2005). “Sample Disturbance of Soft Clays.” *Studia Geotechnica,* XXVII (3-4), 91-105.

Hight, D. W., Boesse, R., Butcher, A. P., Clayton, C. R. I., and Smith, P. R. (1992). “Disturbance of the Bothkennar Clay Prior to Laboratory Testing.” *Geotechnique,* 42(2), 199-217.

Mair, R. J., and Wood, D. M. (1987). “Pressuremeter Testing-Methods and Interpretation.” *Construction Industry Research and Information Association (CIRIA)*, Buttersworth, Great Britain.

Mayne, P. W., Coop, M. R., Springman, S. M., Huang, A. B., and Zornberg, J. G. (2009). “Geomaterial Behavior and Testing.” *Proceedings of the 17th ICSMFE, (Alexandria, Egypt),* Millpress/IOS Press Rotterdam: (4) 2777-2872.

Ménard, L. (1975). “The Menard Pressuremeter: Interpretation and Application of the Pressuremeter Test Result to the Foundations Design.” *Sols-Soils,* no. 26.

Messaoud, F. (2008). “Pressuremeter Test Evaluation for Developing P-Y Curves for Driven Piles.” *Proceedings of the 11th Baltic Sea Geotechnical Conference, Geotechnic in Maritime Engineering. Gdansk, Poland,* 271-278.

Messaoud, F., and Cosentino, P. J. (2016). “Practice of the Pencel Pressuremeter in Foundations Design.” *Proceedings of the 5th International Conference on Geotechnical and Geophysical Site Characterization, ISC5.*

Messaoud, F. and Nouaouria, M. S. (2010). “The Use of Pencel Pressuremeter Test for Underground Structures.” *International Journal of Civil Engineering,* Vol. 8 no. 1, 33-43.

Roctest, Inc. (2005). “Pencel Pressuremeter Instruction Manual.” *Plattsburgh, N.Y.*

Roctest, Inc. (1980). “Texam Pressuremeter Instruction Manual.” *Plattsburgh, N.Y.*

Schmertmann, J. H. (1978). “Guidelines for the Cone Penetration Test Performance and Design.” Washington, D.C., U.S. Department of Transportation, Federal Highway Administration Report FHWA-TS-78209.

Withers, N. J., Schaap, L. H. J., and Dalton, C. P. (1986). “The Development of a Full Displacement Pressuremeter.” in: *Briaud et Audibert (Eds.), International Symposium on Pressuremeter and its Marine Applications,* ASTM STP 950, Texan, 38–56.

Wroth, C. P., and Hughes, J. (1973). “An Instrument for the In-situ Measurement of the Properties of Soft Clays.” *Inter. Conference Soil Mechanics and Foundation Engineering, Moscow.*