The development of a fully automated pressuremeter

Le développement d'un pressiomètre entièrement automatisé

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ABSTRACT

A prototype fully automated small-diameter pressuremeter, called the "SSMini," is developed to address the limitations of traditional analog pressuremeters. The SSMini integrates advanced automation features, including a data acquisition system, motorized operations, and a software interface. It produces a complete in-situ stress-strain curve with a single digital button operation. The strength and stiffness of the tested material are presented as the limit pressure (p_L) and elastic moduli (E_0). By controlling the probe inflation rate, both continuous and incremental inflation approaches are studied to finalize the optimal inflation rate and timing for the prototype. Hole preparation and probe placement techniques are optimized to minimize surface cracking in compacted sand soils, ensuring reliable and repeatable results.

RESUME

Un prototype de pressiomètre de petit diamètre entièrement automatisé, appelé « SSMini », a été développé pour pallier les limites des pressiomètres analogiques traditionnels. Le SSMini intègre des fonctionnalités d'automatisation avancées, notamment un système d'acquisition de données, des opérations motorisées et une interface logicielle. Il produit une courbe contrainte-déformation in situ complète par simple pression numérique. La résistance et la rigidité du matériau testé sont présentées sous forme de pression limite (p_L) et de modules d'élasticité (E_0). En contrôlant la vitesse de gonflage de la sonde, des approches de gonflage continu et incrémental sont étudiées afin de finaliser la vitesse et le timing de gonflage optimaux pour le prototype. Les techniques de préparation des trous et de placement de la sonde sont optimisées afin de minimiser la fissuration superficielle dans les sols sableux compactés, garantissant ainsi des résultats fiables et reproductibles.

Keywords: SSMini PMT; automated pressuremeter; incremental testing; continuous testing.

1. Early Pressuremeter Development

In the late 1950s, the first pressuremeter (PMT) was developed by Louis Menard, a young intern student at the Ecole Nationale des Ponts et Chaussees (Baguelin, Jézéquel, and Shields 1978). Menard recognized the need for an in-situ testing device that could produce data to allow engineers to evaluate soil stiffness and strength through cylindrical expansion.

Over the decades, the geotechnical community has become more familiar with the PMT. This familiarity has led to the standardization of the testing procedure and the American Society for Testing and Materials (ASTM) Standard for prebored PMT testing (ASTM 2007), which is widely used for geotechnical investigations for onshore and offshore projects worldwide.

Many geotechnical engineers are unaware that Ménard's original work on pressuremeter was for compaction quality control (QC) (Paul J. Cosentino 2024). However, his work did not lead to the standardization of PMT-based compaction QC testing. The compaction QC industry requires a fast and reliable testing method that provides more than just index properties, such as moisture and density. Cosentino et al. (2018) begun developing a miniaturized pressuremeter, known as SSMini, for use in unbound pavement layers as part of a Florida Department of Transportation (FDOT)-funded research project under contract BDV28 977-04. The PMT probes were scaled down to fit within the compaction layer. The PENCEL pressuremeter control unit was instrumented and equipped with automated pressuremeter data acquisition and reduction software (APMT©) designed to improve PMT execution and save time for the industry (Cosentino et al. 2007). However, operator-induced errors continued to be a challenge.

From January 2023 to June 2024, the National Cooperative Research Program (NCHRP) Innovations Deserving Exploratory Analysis (IDEA) funded the idea of developing a compaction quality control standard for the small diameter pressuremeter (SSMini) under grant 232672. In this phase, a prototype of a fully automated SSMini pressuremeter capable of determining soil strength and stiffness was developed.

PMT testing holds significant potential today, as it remains the only in-situ test capable of providing a clear stress-strain curve, making it invaluable for geotechnical analysis.

2. Advantages and Limitations of SSMini PMT

The SSMini PMT test offers several advantages in geotechnical investigations, making it a valuable tool for assessing soil properties. It enables rapid testing, with each testing hole typically completed in the time range shown in **Table 1** at the press of a digital button. The test evaluates a relatively large sample, ranging from 15 to 30 cm, depending on the SSMini probe model used. Test hole preparation is identical to that required for the nuclear density gauge (NDG); the same template and driven pin are used, and the test depths are the same. A QC process for SSMini PMT data is available to assess the testing quality.

The SSMini PMT testing process is relatively straightforward and measures both the strength and stiffness of the soil. The equipment is more logistically compatible than the NDG.

Table 1 Total time for both automated SSMini PMT approaches

SSMini Probe Model	Time for Automated Continuous SSMini PMT (min: sec)	Time for Automated Incremental SSMini PMT (min: sec)
SSMini-15	1:10	4:40
SSMini-20	1:30	5:50
SSMini-25	1:45	7:00
SSMini-30	2:00	8:10

However, SSMini PMT also has limitations. Proper test hole preparation is critical, as any errors in preparation may compromise results. Membrane failures can cause delays. Fully assembling the SSMini probe can take up to one hour, depending on tool availability

3. Objective and Approach

One of the objectives is to develop a prototype of a fully automated pressuremeter.
To achieve this objective, the automation includes:

- Motor-driven operations for calibrations and PMT testing execution.
- Data Acquisition (DAQ) and Automated Data Reduction after each test.

The following tasks were performed:

1. Selection and integration of key hardware components, including the motor, cylinder, tubing, connectors, and valves
2. Development of a DAQ system using LabView® to record pressure and volume data, store it, and display a pressure-volume graph in real time.
3. Programming motor control for automated test execution.
4. Assembly of an all-in-one control unit integrating mechanical and electronic subsystems.
5. Field evaluation of the system through comparative testing of manual (hand-operated) and automated control units.

4. Overview of SSMini PMT

Like other pressuremeter types, the SSMini PMT operates by expanding a cylindrical probe within a preformed borehole and measuring the corresponding pressure as a function of the volume change, as shown in **Fig. 1**. Before placing the probe in the hole, the SSMini control unit is fully saturated with de-aired water, and both membrane and system calibrations are performed. **Fig. 1** illustrates the raw stress-strain SSMini PMT curve. During the initial 15 cc of volume expansion, there is no contact between the membrane and the soil; this stage represents the free inflation of the probe. Once contact is established, a soil repositioning occurs, and radial strain in the probe cavity (i.e., the test hole) starts to develop. In this region, the pressuremeter modulus (E_0) can be estimated. As the test progresses, the response transitions into the plastic phase, where the curve flattens. This transition into the plastic phase follows, leading to the determination of the limit pressure (p_L), which characterizes the soil's strength under expansion.

The SSMini test is conducted at shallow depths, where the center of the probe is positioned above the critical depth, defined as 30 times the probe diameter (30 × D) (Briaud and Jordan, 1983). The critical depth represents the threshold above which SSMini PMT testing may not yield reliable results due to insufficient confinement, as the test pushes the soil laterally.

Even if the soil is equally compacted at depths of 0.5 m and 1 m, the limit pressure results will differ, despite any normalization for depth. This is because the PMT test applies lateral pressure, and the soil tends to move horizontally at shallow depths at first. Without sufficient confining pressure from overlying soil or surcharge, the soil may begin to slide upward toward the surface as the test progresses. However, the 15-cm SSMini probe (SSMini-15) consistently performs in measuring strength and stiffness when used in a 30-cm prebored hole, with no signs of surface cracking observed—even in the absence of a surcharge load.

Two testing procedures were studied for the SSMini PMT. The classical incremental testing involves the operator applying equal water volume increments of approximately 2.5 cm^3 and recording the corresponding pressure. Pressure readings are taken after 30 seconds of stabilization at each 2.5 cm^3 volume increment. A minimum of 20 data points per sounding is recommended regardless of probe length.

Continuous testing requires the operator to continually inject water into the probe at a constant rate (0.5 cm^3/sec or 1 cm^3/sec) to minimize inertia effects caused by water movement within the system.

Once the maximum volume is injected and data is recorded for either procedure, the probe is slowly deflated back to its zero point.

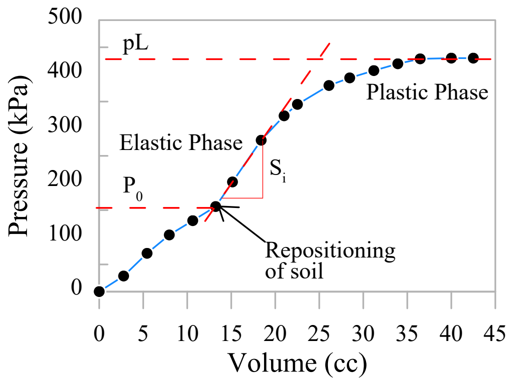

Fig. 1 SSMini PMT stress-strain curve

The SSMini probes, **Fig. 2**, have a diameter of 1.9 cm and are designed to fit within the compaction layer. **Table 2** presents the available probe lengths and their corresponding initial probe volume (V_0).

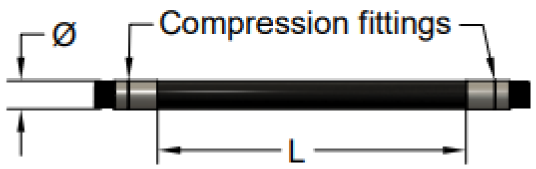

Fig. 2 SSMini probe visual design

Table 2. SSMini probe lengths and initial volume values

Probe Length (cm)	Initial Probe Volume (cm^3)
15	43
20	57
25	71
30	85

a. Data Reduction and QC Procedure

Once the raw data is obtained from the field PMT testing, the data reduction and data QC procedure follows five steps are presented:

- Subtract the membrane's inherent pressure loss from the raw pressure values to account for the resistance of the probe's membrane.
- Subtract the system's tubing and membrane volume loss from the raw volume values to compensate for tubing expansion and the compressibility of various components in the testing equipment.
- Add the pressure values for hydrostatic pressure.
- Calculate the PMT modulus from the initial linear slope (**Fig. 1**) and measure the limit pressure.
- Perform QC on the finalized data by evaluating the E_0/p_L ratio and the linear regression coefficient (R^2) from the relationship between E_0 and p_L.

b. Membrane Calibration

Pressure losses (P_c), as shown in **Fig. 3**, occur due to the inherent rigidity of the probe's rubber membrane. During testing, the pressure readings displayed on the readout device include the pressure required to expand the probe walls. This membrane resistance must be subtracted to obtain the actual pressure applied to the soil. Membrane resistance is calibrated by inflating the probe while it is positioned at the same height as the control unit pressure gauge, fully exposed to the atmosphere. The probe is inflated to volumes exceeding those expected during testing to ensure accurate resistance measurement.

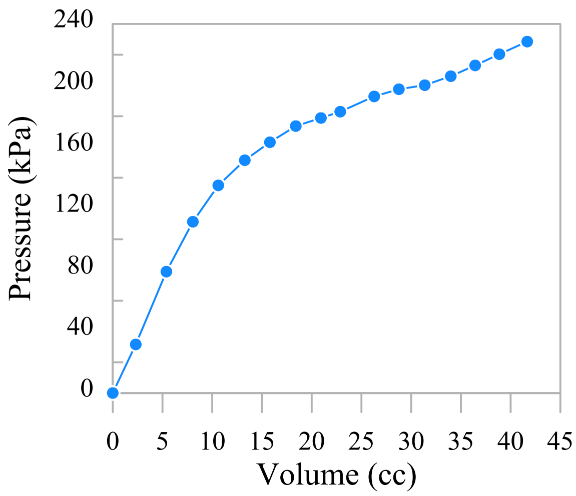

Fig. 3 Membrane resistance plot

c. Volume or System Expansion Calibration

Volume losses (V_c) occur due to tubing expansion and the compressibility of various components of the testing equipment, including the probe and the liquid used in the system. To account for these losses, calibration is performed by pressurizing the equipment with the probe placed loosely inside a heavy-duty steel casing or pipe with a thickness of approximately 3 mm and an inner diameter of 1.9 cm. A recommended procedure involves increasing the pressure incrementally by 100 kPa or 500 kPa, depending on whether the probe is designed for a maximum expansion pressure of 2500 kPa or 5000 kPa, respectively. Each pressure increment should be held constant for 30 seconds, and then the volume value is recorded. Alternatively, a continuous calibration approach may be employed, where the pressure is gradually increased, without stabilization pauses, up to the target pressure. Whether the end user chooses to execute the SSMini PMT continuously or incrementally, two system calibration methods can be selected based on the test execution approach.

Fig. 4 demonstrates the system calibration curve. The pressure increase follows a linear trend once the probe is in full contact with the steel pipe. The volume loss (V_c) is determined by extrapolating a straight-line extension of the curve to zero pressure. The slope (a) of this line is then used to correct for volumetric losses using **Eq. (1).**

$$V_c = V_r - (P_r/a) \qquad (1)$$

Where:
V_r = injected volume
P_r = corresponding pressure to the injected volume (Vr)
a = slope value (kPa/cc)

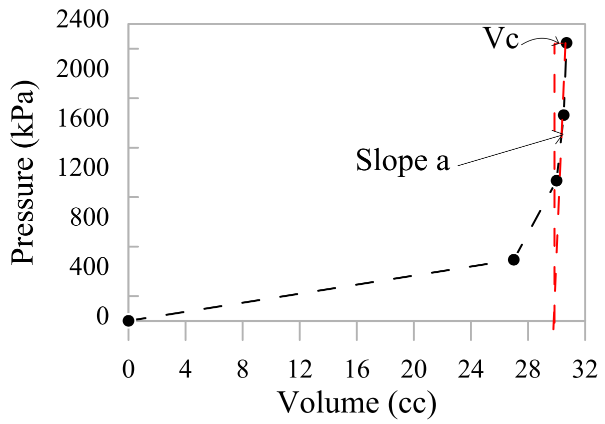

Fig. 4 Typical SSMini system expansion plot

Table 3 presents the typical slope values for different SSMini probe sizes, all connected to a 3-meter tubing. The values are provided for incremental and continuous system calibration approaches. As shown, larger probe sizes correspond to lower slope values, and the continuous approach consistently yields higher slope values than the incremental method.

Table 3 Typical slope values for SSMini probes

Probe Size (cm)	Slope Values Incremental Approach (kPa/cc)	Slope Values Continuous Approach (kPa/cc)
15	1700	3000
20	1600	2800
25	1500	2600
30	1400	2400

Table 4 provides an example of system expansion at different pressure levels (1000, 1500, and 2500 kPa) using a 15-cm SSMini probe connected to a 3-meter tubing. The calculated expansion is based on the slope values for both calibration approaches: 1700 kPa/cc for the incremental method and 3000 kPa/cc for the continuous method. The resulting system expansion values differ slightly between the two approaches, but the difference is minimal and practically negligible.

Table 4 An example of system expansion at different pressure levels

Pressure (kPa)	System Expansion – Incremental Method (cc)	System Expansion – Continuous Method (cc)
1000	0.59	0.33
1500	0.88	0.50
2500	1.47	0.83

d. Hydrostatic Correction

The hydrostatic pressure (p_h) must be accounted for to ensure accurate data reduction. A typical hydrostatic pressure difference is approximately 5 kPa per 0.5-meter height difference between the control unit and the test depth. Since compaction testing setups are often standardized, **Eq. 2** is used to calculate the hydrostatic pressure correction based on this height difference. As shown in **Table 5**, when the test depth is held constant at 0.3 meters, increasing the control unit height from 0.5 m to 2.0 m results in a corresponding pressure increase from 8 kPa to 23 kPa, illustrating the linear relationship between height difference and hydrostatic pressure.

Table 5 Hydrostatic pressure example

Control Unit Height (m)	Test Depth (m)	Hydrostatic Pressure (kPa)
0.5	0.3	8
1	0.3	13
1.5	0.3	18
2	0.3	23

$$p_h = H \times \gamma_w \qquad (2)$$

Where:
H = the depth in meters to the center of the probe from the height of the control unit pressure gauge.
γ_w = unit weight in kN/m^3 of the test liquid.

e. Determining Modulus and Limit Pressure

Fig. 5 shows an example of the raw and reduced PMT stress-strain curve after applying membrane, system, and hydrostatic pressure corrections. The majority of the difference results from the membrane correction.

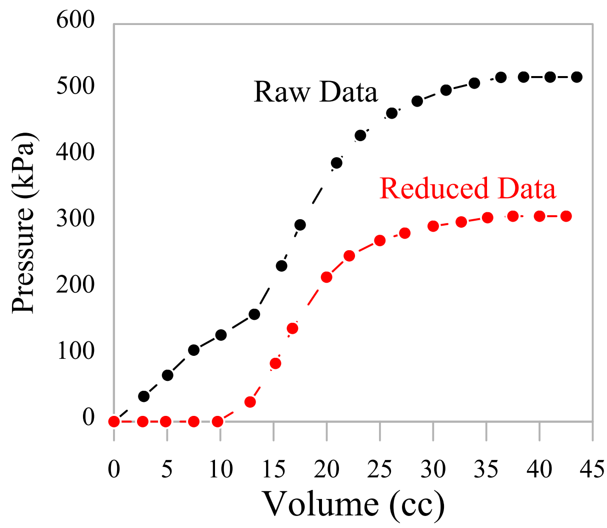

Fig. 5 SSMini stress-strain curve after applying pressure and volume corrections

After the PMT data reduction, the theory of elasticity is applied to the elastic zone shown as a slope S_i in **Fig. 1** of the PMT stress-strain curve to calculate Young's modulus using **Eq. 3**. The PMT modulus is based on volumetric strain, and it increases with higher Poisson's ratio, assuming all other variables remain constant.

$$E_0 = 2(1+\nu)\frac{\Delta P}{\Delta V}(V_m + V_0) \quad (3)$$

Where:

E_0 = Young's modulus
ΔP = change in stress between two points within the elastic zone
ΔV = change in volume related to ΔP
V_m = average total probe volume over ΔP
V_0 = initial volume of probe
ν = Poisson's ratio

To determine the strength of the tested soil or the limit pressure, it is essential to capture the transition from the elastic to the plastic phase (**Fig. 1**) by performing all necessary steps of the PMT test.

Suppose the PMT test is not fully executed and only a small portion of the elastic-to-plastic transition is recorded. In that case, the limit pressure is estimated by extrapolating the PMT curve to twice the initial borehole cavity volume ($2V_0c$). The pressure corresponding to this volume is then taken as the limit pressure (p_L).

f. Data QC Evaluation

The ratio between soil strength and stiffness provides valuable information for evaluating the quality and consistency of test data. During the NCHRP IDEA Type 2 project, the expansion of the soil test database offered deeper insights into the relationship between E_0 and p_L, particularly through analysis of their ratio and corresponding linear regression performance. **Table 6** summarizes the results for various soil types, including the number of tests conducted, the average E_0/p_L ratio, and the coefficient of determination (R^2) for the linear regression.

Table 6 Summary of E_0/p_L ratios and linear regression results for various soil types

Soil Description	USCS Classification	No. of Tests	E_0/p_L ratio	R^2
Poorly graded sand	SP	82	13.4:1	0.89
Lean clay	CL	14	18.6:1	0.84
Clayey Silt	ML	5	12.8:1	0.91
Clayey sand	SC	21	15.5:1	0.91
Silty sand	SM	13	12.2:1	0.97
Clayey gravel	GC	12	16.3:1	0.90
Well-graded gravel with clay	GW-GC	4	14.1:1	0.96

As shown, R^2 values remain consistently high across all soil classifications, ranging from 0.84 to 0.97, indicating a strong linear correlation between E_0 and p_L, independent of soil type.

Once the engineer calculates E_0 and p_L, a QC procedure is applied to verify the reliability of the results. A key step in this process involves plotting E_0 versus p_L, evaluating the E_0/p_L ratio, and assessing the R^2 value from the linear regression. A high R^2 and a ratio falling within expected limits suggest the test was executed correctly and the soil behavior was consistent. In contrast, a low R^2 or outlying E_0/p_L ratio may indicate issues such as borehole disturbance, pressure or volume measurement errors, unusual soil response, or equipment calibration problems.

5. SSMini Pressuremeter Automation

The SSMini PMT automation process started with studying the ASTM D4719-07 standard for prebored pressuremeter (ASTM 2007). Many field tests were done to identify the limitations of the existing pressuremeter control units. The Florida Tech research team attended many local and national conferences across the United States to gather feedback from PMT users. The key automation outlines were:

1. PMT consistency by controlled execution.
2. Data analysis, monitoring, and decision-making.
3. Selecting the proper hardware and automation tools for cost-effectiveness.

a. Data Acquisition System

Among various Data Acquisition Systems (DAQs), the team opted for National Instruments (NI) due to the user-friendly, plug-and-play solutions suitable for the SSMini PM application. NI's LabView® software facilitates the conversion of analog and digital signals into user-interface displayable values. Development began by identifying key pressuremeter output variables such as pressure and volume, which are crucial for pressuremeter testing and data interpretation. APMT® software was upgraded for the fully automated SSMini PMT test. This software also includes features such as graphical representation and automatic data reduction, which processes raw test data using the data reduction process described in Section 4, and outputs calculated E_0 and p_L parameters for each performed PMT test. Additionally, it supports post-testing. report which contains raw, reduced data and general test parameters (sounding #, control unit height, etc.).

The APMT software requires the end user to:

- Select the SSMini probe size: 15,20,25, or 30 cm SSMini probe.
- Input the general test parameters
- Press a digital start button to perform the automated SSMini PMT test

b. Motor Driven Operations

i. Determining Motor Torque Requirements

Given the variable soil strength limits encountered during pressuremeter testing of various types and densities of soils, the team searched for a motor capable of producing torque that would generate pressures of up to 5000 kPa. Specialized pressuremeter tests were initially conducted using a torque wrench to establish the design relationship between pressure and torque, allowing the team to establish both nominal and maximum torque requirements.

ii. Determining Motor Controller Features

The automation requires a motor driver capable of actuating and stopping the motor based on specific scenarios encountered during pressuremeter testing, such as changes in pressure or volume. The motor driver was configured to operate the motor using selected pulse-width modulation settings and to drive it until the piston reached its programmed start and end positions. The chosen motor controller's diagnostic features were essential, as they provided error detection and remedied issues such as overcurrent, internal errors, or configuration discrepancies. These capabilities ensure system reliability and fast corrective action for the motor driver.

iii. State Machine Diagrams

The state machine flowcharts developed for the automated SSMini PMT were designed for incremental testing, aligning with standard industry practices.

The automated incremental SSMini PMT state transition diagram is shown in **Fig. 6**. The system begins with the APMT© setup, where the user selects the probe. Once initialized, the DAQ system continuously measures and records volume and pressure outputs throughout the test. The motor then incrementally increases the volume output by 2.5 cm^3 at each step, pausing for 30 seconds to allow stabilization before proceeding. This cycle continues until the injected volume reaches the maximum volume limit (Vmax), which is automatically adjusted in the software based on the selected probe size as given in **Table 7**. When the volume threshold is met, the system reverses, gradually decreasing the volume to 0 cm^3 before saving both raw and reduced data. If another PMT test is required, the process restarts; otherwise, the state is closed.

Table 7 Vmax values for different SSMini PMT probes

SSMini Probe Model	Vmax (cc)
SSMini-15	40
SSMini-20	50
SSMini-25	60
SSMini-30	70

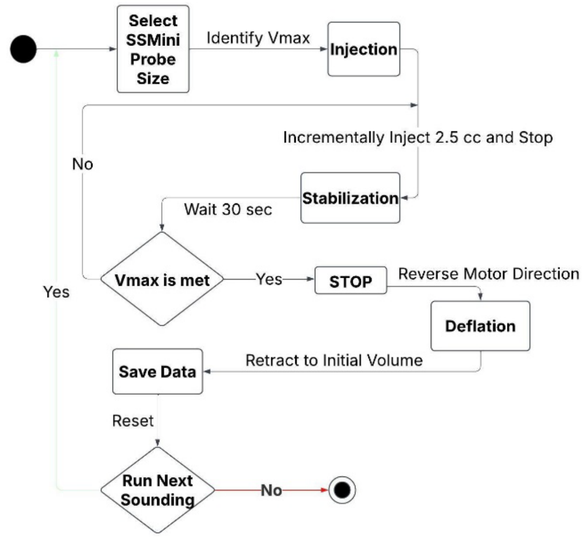

Fig. 6 State machine for automated SSMini PMT

Fig. 7 illustrates the state machine logic for the automated continuous execution of the SSMini PMT test. The process begins with selecting the probe size, which determines the Vmax based on predefined values (**Table 7**). Once selected, the system initiates continuous injection, where the motor gradually inflates the probe while the DAQ records the injected volume and pressure in real time.

Upon reaching Vmax, the system automatically stops injection, reverses the motor direction, and initiates deflation to return the probe to its initial volume. The recorded data is then saved. A decision point follows, prompting whether to proceed with the next sounding. If yes, the process resets and loops back to the beginning. If no further tests are required, the system exits the cycle.

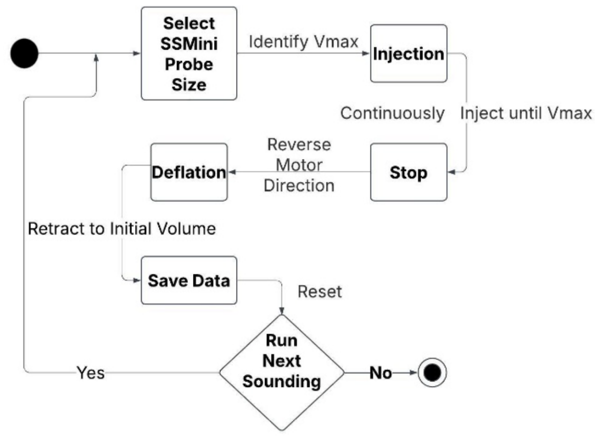

Fig. 7 State machine diagram for automated continuous PMT testing

6. Proof of concept

For many decades, the incremental PMT method has been widely used for geotechnical soil investigations, particularly in prebored holes, as outlined in ASTM D4719 – Standard Test Method for Prebored Pressuremeter Testing in Soils. This method requires the end user to:

- Record site-specific and test-specific parameters.
- Apply equal pressure or volume increments,
- Hold for 30 seconds before proceeding to the next increment, and
- Record and analyze the pressure and volume data.

With the hand-operated control unit, a trained specialist can complete an incremental test in less than 15 minutes, depending on the probe length.

To validate the automated SSMini incremental PMT, testing was conducted outside the Frueauff Building at Florida Tech. The goal was to compare the existing instrumented, hand-operated PMT control unit with the fully automated SSMini PMT prototype (**Fig. 8**). The testing protocol is shown in **Fig. 9**. The 15-cm SSMini probes were used for both control units to ensure consistency with previous PMT tests.

Fig. 8 The prototype of a fully automated SSMini PMT control unit

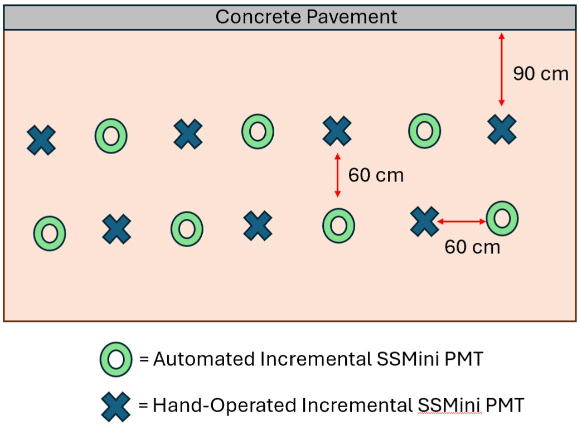

Fig. 9 Testing protocol for outdoor SSMini PMT testing

The SSMini pressuremeter was programmed to execute the incremental PMT procedure automatically. On average, the automated PMT test required only 3 minutes per sounding, achieved with a single button press, significantly reducing testing time and improving data consistency compared to manual operation. **Fig. 10** presents one of the stress-strain curves obtained from the incremental PMT testing comparison, highlighting the consistency of the automated SSMini PMT control unit.

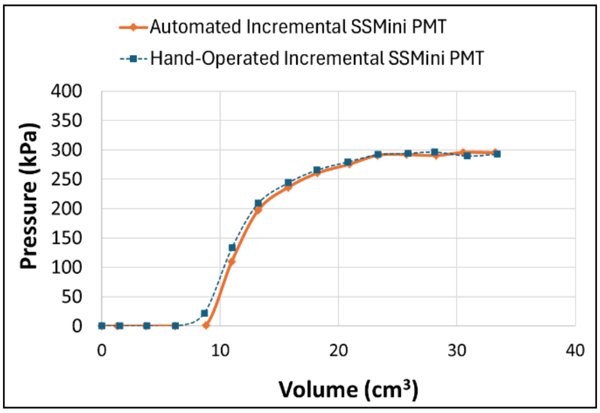

Fig. 10 Stress-strain curve from hand-operated incremental and automated incremental SSMini PMTs

Table 8 summarizes average results from comparison tests between the two SSMini PMT testing approaches. Specifically, it shows the average initial modulus and limit pressure values obtained from seven PMT tests conducted with each method. While both testing approaches were conducted with the same number of repetitions, they produced slightly different results. The hand-operated incremental method tended to capture higher initial stiffness, whereas the automated method resulted in higher limit pressure.

Table 8 Summary of average initial modulus and limit pressure from the SSMini PMT tests

Type of SSMini PMT Test	Avg. E_0	Avg. p_L	Number of tests
Automated Incremental	4001	316	7
Hand-Operated Incremental	4799	271	7

Fig. 11 illustrates the relationship between E_0 and p_L based on field testing conducted using both control units. A total of 14 PMT tests were performed, with 7 using the hand-operated control unit and 7 using the automated control unit. The data shows high linear correlation for both systems, with R^2=0.99.

Despite the strong correlations, a noticeable difference exists in the E_0/p_L ratio: the hand-operated tests yielded a ratio of E_0=17.7 p_L, while the automated tests followed E_0=12.8 p_L. This difference highlights a key observation in the proof-of-concept phase: although both systems produce consistent and high-quality data, they do not currently align in E_0/p_L ratios.

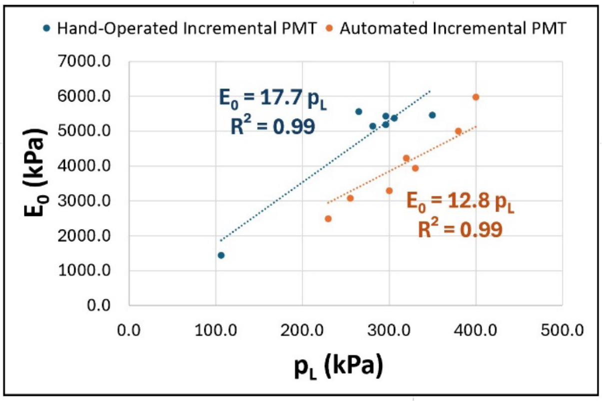

Fig.11 Comparison of R^2 and the E_0 and p_L relationship between motor drive and hand-operated incremental PMT

One possible reason for this discrepancy is the manual rotation of the handle in the hand-operated control unit. Because the operator controlled the volume increments, variations in rotation speed and timing likely caused uneven stress application on the soil. In contrast, the automated system delivers uniform volume increments at a 0.57 cc/sec rate.

7. Conclusions

The fully automated SSMini Pressuremeter prototype was successfully developed and validated at Florida Tech. The system underwent several design iterations and field testing to ensure reliability. Both incremental and continuous PMT methods are now fully automated and can be executed with a single button press. The integration of motor-driven operations, data acquisition, and automated data reduction into the SSMini prototype was successfully validated. The automated incremental SSMini PMT testing showed consistency in the field and reduced the execution time by 75%.

8. Acknowledgements

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