Pushed-in PPMT for settlement prediction: insights from indoor test pits in Florida fine sands

PMT poussé pour la prévision des tassements: informations obtenues à partir de puits d'essai intérieurs dans les sables fins de Floride

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ABSTRACT

This study evaluates the performance of three in-situ tests, pushed-in PENCEL Pressuremeter (PPMT), Flat Dilatometer Test (DMT), and Cone Penetration Test (CPT), for predicting shallow foundation settlements in fine Florida sands. Controlled indoor experiments were conducted using Osteen sand (weak) and Starvation Hill sand (strong), compacted at 90%, 95%, and 100% modified Proctor density in segmented test pits. Plate Load Tests (PLT) provided benchmark settlement measurements. The pushed-in PPMT provided settlement predictions closely aligned with PLT results across all conditions, demonstrating its suitability for fine Florida sands. In comparison, the CPT tended to overestimate settlements due to its reliance on ultimate capacity, while DMT underestimated them because of high modulus values at a minimal membrane expansion. These findings highlight the reliability and practicality of the pushed-in PPMT for geotechnical applications in fine sand and silty sand soils.

RESUME

Cette étude évalue les performances de trois tests in situ, le pressiomètre PENCEL enfoncé (PPMT), le test du dilatomètre plat (DMT) et le test de pénétration au cône (CPT), pour prédire les tassements de fondation peu profonds dans les sables fins de Floride. Des expériences intérieures contrôlées ont été menées en utilisant du sable d'Osteen (faible) et du sable de Starvation Hill (fort), compactés à 90 %, 95 % et 100 % de densité Proctor modifiée dans des puits d'essai segmentés. Les tests de charge sur plaque (PLT) ont fourni des mesures de tassement de référence. Le PPMT enfoncé a fourni des prévisions de tassement étroitement alignées sur les résultats du PLT dans toutes les conditions, démontrant son adéquation aux sables fins de Floride. En comparaison, le CPT avait tendance à surestimer les tassements en raison de sa dépendance à la capacité ultime, tandis que le DMT les sous-estimait en raison de valeurs de module élevées à une expansion minimale de la membrane. Ces résultats soulignent la fiabilité et la praticité du PPMT enfoncé pour les applications géotechniques dans les sols de sable fin et de sable limoneux

Keywords: In-situ tests; indoor test pit; shallow foundation; settlement

1. Introduction

In sand and silty sand soils, such as those prevalent in Central Florida, settlement behavior can vary significantly with soil properties and compaction levels. This variability indicates the importance of selecting appropriate in-situ testing methods to support geotechnical design.

Traditional methods like the Standard Penetration Test (SPT) and CPT are widely used to assess soil parameters for settlement prediction. However, these tests typically record data at the soil's ultimate capacity, whereas settlement prediction depends on parameters measured within the elastic range. This reliance on empirical correlations and ultimate strength data often limits their effectiveness for predicting settlements.

Advanced methods, such as pushed-in PPMT, evaluate soil stiffness directly from the stress-strain curve within the elastic range, making them promising alternatives for settlement analysis. The pushed-in PPMT measures soil response over various strains, providing stress-strain data relevant to practical settlement analysis. However, its application has been limited, and its comparative performance relative to other in-situ tests, especially in fine sands, is not well understood.

This study compares PPMT, CPT, and DMT data-based settlement predictions against settlements measured directly from PLT under controlled indoor conditions. Poorly graded Florida fine sands, Osteen sand (OST), and Starvation Hill sand (SH) were selected as fill materials because they are dominantly available in the region and show relatively higher settlement behavior. The gradation curves of these sands, shown in Fig. 1, indicate that SH sands range between sieve #200 and #10, while OST sands fall between sieve #200 and #40, exhibiting narrow banding.

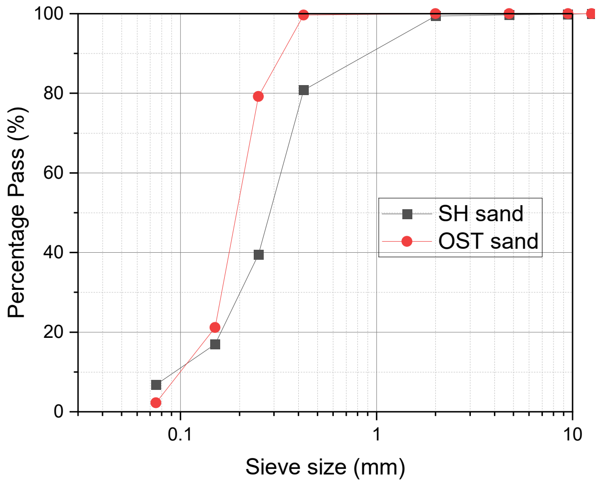

Fig. 1 Particle size distribution for the SH and OST sands

A controlled indoor testing program was established at the Florida Department of Transportation's State Materials Office (FDOT-SMO). Using an overhead 89 kN (20 kips) crane system mounted to a rail, probes for PPMT, DMT, and CPT tests were precisely positioned and pushed to the required depth. The pits, filled with OST and SH sands, were subdivided into compartments with compaction levels of 90%, 95%, and 100% modified Proctor density to replicate field conditions, Fig. 2.

2. Experimental setup and testing methods

2.1. Test pit preparation

Two indoor test pits were constructed at the Florida Department of Transportation's State Materials Office (FDOT-SMO) to simulate controlled conditions for measuring and predicting settlements. Each pit was subdivided into three compartments using wooden partitions, enclosed externally by concrete walls to isolate them from surrounding soils.

The pits measured 2.44 m in length, 2.74 m in width, and 1.52 m in depth. Each layer was compacted to modified Proctor densities of 90%, 95%, and 100%, verified using a nuclear density gauge (NDG).

Fig. 2 (a) and (b) illustrate the pit-filling process and final configurations. 145 tests were performed, distributed across the pits as 36 Pushed-in PPMT, 18 CPT, 71 DMT, and 20 PLT.

2.2. Pushed-in PPMT testing and results

The PPMT tests were conducted using a probe of 24 cm in length, 3.3 cm in diameter, and a length-to-diameter ratio of 7.3. Despite some disturbances while pushing the probe to the intended depth, the pushed-in PPMT minimizes soil disturbance due to borehole collapse or disturbance during preboring, which is common in sand soils. This feature is particularly advantageous in fine sands, where soil disturbance due to borehole preparation can significantly affect measurements. As a result, the modulus values obtained from pushed-in PPMT tests are consistently higher than those from prebored PMTs. Published works by Briaud (1992) confirms that moduli measured by the pushed-in PPMT can exceed those from prebored PMTs by more than double.

The pushed-in PPMT tests were performed at depths of 0.61 m and 1.22 m within each borehole in the test pits, maintaining a uniform vertical spacing of 0.61 m across all tests. Fig. 3 (a) and (b) depict the average stress-strain curves from the PPMT tests for SH and OST sands under the three compaction levels at these depths.

Fig. 2 FDOT-SMO indoor pit during and after fill placement (modified Proctor was adopted)

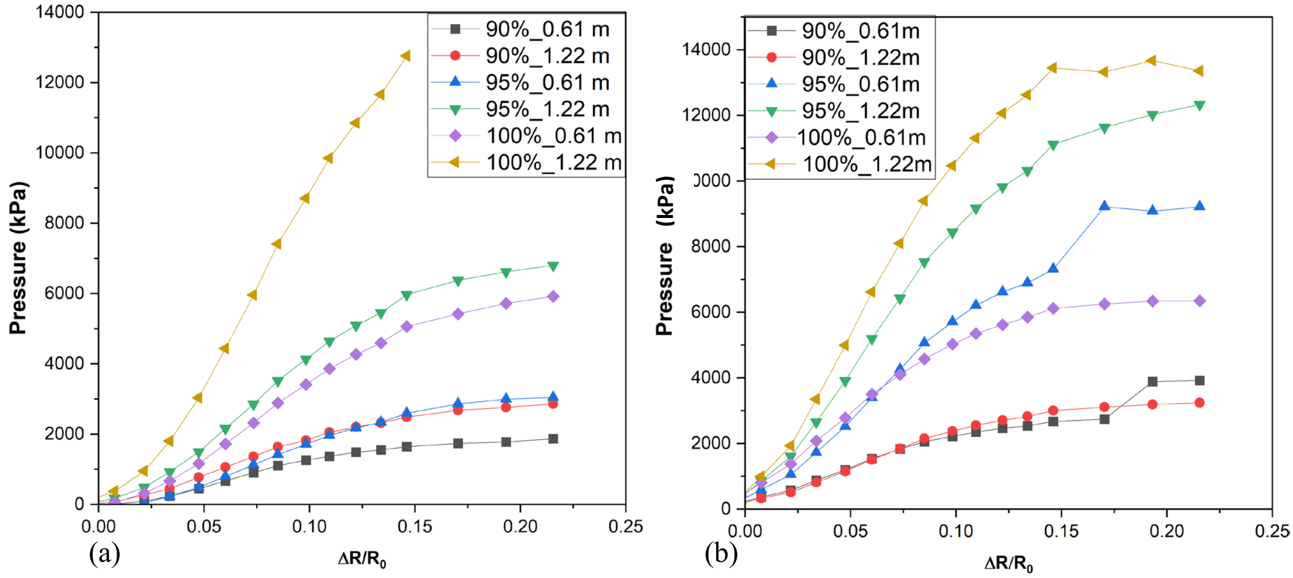

Fig. 3 PPMT Stress-strain data for 90%, 95%, and 100% compaction at 0.61 m and 1.22 m depth for SH (a) and OST (b)

The results reveal a consistent increase in stiffness and strength with greater depth and level of compaction, except for the OST 95% compaction at 0.61 m test depth, which exhibited a stiffer response than the 100% compaction at a similar depth.

The pushed-in PPMT captures soil behavior across the elastic and plastic ranges through its real-time load and deformation sensors.

The relative increase in probe radius with pressure changes, as described by Briaud et al. (1986), can be used to predict PMT modulus (E_0) through Eq. (1).

$$E_0 = (1+\nu)\left[\left(1+\frac{\Delta R_1}{R_o}\right)^2 + \left(1+\frac{\Delta R_2}{R_o}\right)^2\right]\frac{\Delta P}{\left(1+\frac{\Delta R_1}{R_o}\right)^2 - \left(1+\frac{\Delta R_2}{R_o}\right)^2} \quad (1)$$

Where ΔR_1 and ΔR_2 are increases in probe radius at points 1 and 2, respectively, R_0 is the initial probe radius, and ΔP is the change in pressure. The E_0 values for all test pits at 0.61 m and 1.22 m depths are summarized in Table 1. These values align with expectations, showing increased stiffness with higher compaction levels and greater depth. However, tests conducted above the critical depth, approximately 1 m for this probe, exhibited deviations. The critical depth for sand soil is determined as 30·D (Baguelin, Jézéquel, and Shields 1978), where D is the diameter of the probe and becomes more influential in strong soils at high compaction levels, emphasizing the importance of maintaining test depths below this threshold or using an external surcharge load during testing. Keeping the testing depth below the critical depth, especially for densely compacted strong sand soil, the pushed-in PPMT is suitable to test the SP-fine Florida sands.

Table 1. PMT moduli for the two pits at 0.61 m and 1.22 m depth

Pit	% Compaction	E_0 (kPa)							
		Borehole-1		Borehole-2		Borehole-3		Borehole-4	
		0.61 m	1.22 m	0.61 m	1.22 m	0.61 m	1.22 m	0.61 m	1.22 m
SH	90%	10198	3868	8522	6723	8391	6709		
	95%	19616	24946	19244	23464	10873	25973		
	100%	13128	27415	11853	29979	14569	38212		
OST	90%	3399	4302	3275	5640	4158	6074	5530	6081
	95%	4978	14259	5419	12342	6861	12177		
	100%	10777	28635	9736	31434	11246	33020		

2.3. CPT testing and results

CPT tests were conducted using a 10 cm² cone rod to evaluate soil resistance and estimate stiffness parameters. Three CPT tests were performed for each sub-pit, penetrating from the surface to a depth of 1.52 m. Fig. 4 illustrates the tip resistance (q_c) profiles, which show a trend of increasing q_c with greater compaction levels and depth, reflecting the densification and stiffness improvement of the sands.

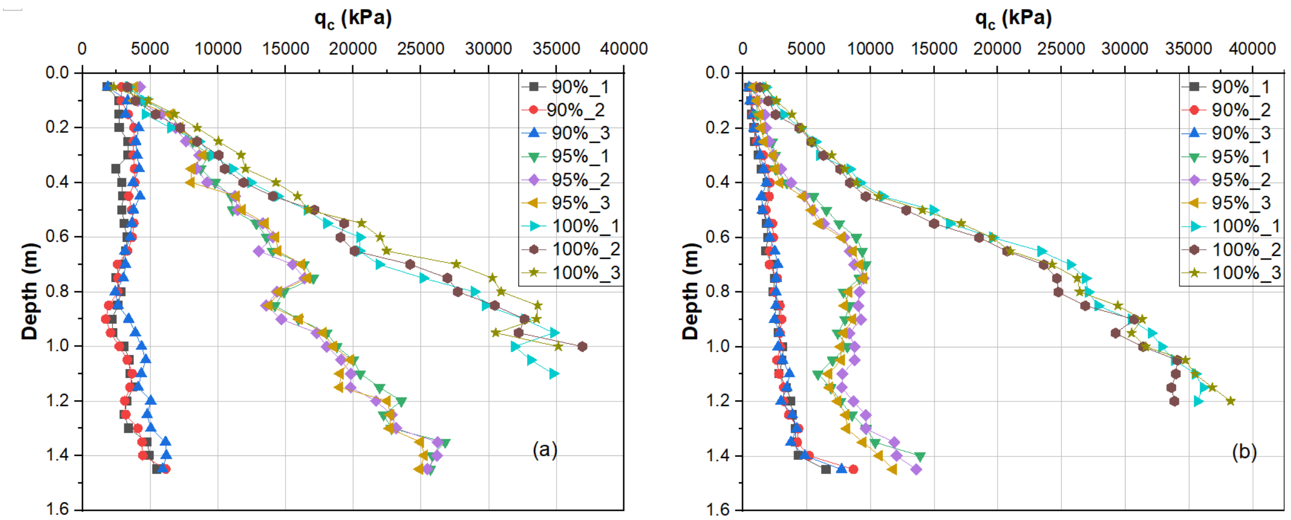

Fig. 4 CPT results for (a) SH test pit and (b) OST test pit

Anomalies were observed in the OST sand pit, where a sharp increase in q_c near 1.37 m depth was attributed to a stiff subgrade material beneath the compacted sand. In contrast, SH sand pit profiles were smoother, indicating that the stiffness in its compacted fill material is at least the same as the existing subgrade material.

Unlike PPMT, where the elastic modulus is directly calculated from the stress-strain response, CPT infers the elastic modulus (E_s) using empirical correlations. Table 2 summarizes seven commonly used methods for estimating E_s from q_c. Settlement analysis based on CPT data for sand and silty sand soils applies either directly q_c or correlations provided in Table 2. All seven methods are employed when correlations are not specified, and settlements are computed based on the resulting stiffness predictions.

Table 2. Correlations between q_c and elastic modulus (kPa)

Methods	Equation	Reference
Method-1	$E_s = 144q_c$, q_c>2586 kPa $E_s = 287q_c$, q_c<2586 kPa	(DeBeer 1965)
Method 2	$E_s = 192q_c$	(Schmertmann 1970)
Method3	$E_s = 239q_c$ L/B=1 to 2 $E_s = 335q_c$ L/B$\geq$10	(Schmertmann et al. 1978)
Method 4	$E_s = \alpha q_c$ $\alpha = 287-1149$	(Thomas 1968)
Method 5	$E_s = 239(q_c + 30)$	(Webb 1970)
Method 6	$E_s = 144q_c$	(Buisman, A. S. K. 1940)
Method 7	$E_s = \alpha q_c$ α = 192 for q_c<4788 kPa α = 144 for q_c>4788 kPa	(Sanglerat 1972)

2.4. DMT testing and results

DMT tests were performed by pushing the blade from the surface to a depth of 1.22 m. For 90% and 95% compaction levels, DMT tests were conducted at 0.3, 0.61, 0.91, and 1.22 m depth. For the 100% compaction level, tests were limited to depths of 0.3 and 0.61 m. The modulus values derived from DMT are typically higher than those obtained from other in-situ methods because they are measured at a relatively small membrane expansion (1.1 mm).

Fig. 5 presents the dilatometer modulus (E_D) and confined modulus (M) for SH and OST sands. The dilatometer modulus (E_D) is calculated using Eq. (2) (Marchetti et al. 2001).

$$E_D = 34.7 * (P_1 - P_0) \quad (2)$$

Where P_0 is the initial pressure, and P_1 is the limit pressure.

Confined or oedometer modulus (M) is predicted from E_D using Eq. (3) correlation.

$$M = R_M * E_D \quad (3)$$

Where R_M is a correlation factor (Marchetti et al. 2001).

Furthermore, the vertical elastic modulus (E_s) is commonly derived from M using Eq. (4).

$$E_s = \frac{(1+\upsilon)(1-2\upsilon)}{(1-\upsilon)} * M \quad (4)$$

The values of E_D and M, displayed in Fig. 5, demonstrate a clear trend of increasing moduli with higher degrees of compaction and depth, except for the

SH at a 90% compaction level. These trends validate the controlled preparation of the sub-pits and highlight the consistency of DMT in assessing soil stiffness under different compaction conditions.

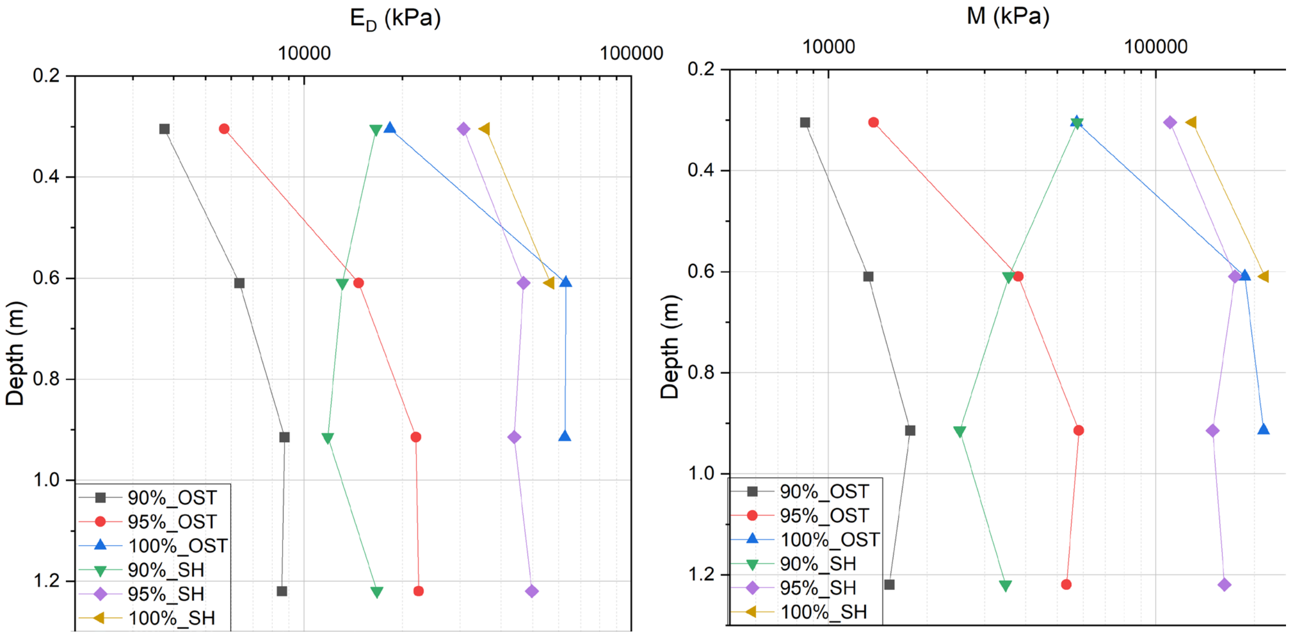

Fig. 5 DMT E_D and M results for OST and SH test pit at 90%, 95%, and 100% compaction levels

2.5. PLT testing and results

PLT tests were carried out using a 30 cm diameter steel plate as a footing when the settlements were measured under incremental loading. The diameter of the plate is fixed at 30 cm because of the hydraulic jack's capacity. Three Linear Variable Differential Transformers (LVDTs) were positioned around the plate to capture settlement readings at each load increment, adhering to Florida Plate Load Test standards.

A sample PLT setup, Fig. 6, and resulting load-settlement curves, Fig. 7, for the two sands at different compaction levels are provided. The results indicate a progressive increase in stiffness and load-bearing capacity with higher degrees of compaction. SH sands consistently exhibited greater stiffness than OST sands, reflecting their superior mechanical properties.

For sand compacted to 100% modified proctor density, settlements were significantly lower compared to 90% and 95% compaction levels, underscoring the influence of compaction on soil stiffness and deformation behavior, as shown in the other tests. In contrast, loosely compacted sands with a 90% compaction level exhibited more variability in settlement measurements, attributable to surface sensitivity and potential heterogeneity in compaction.

Fig. 6 PLT setup during testing

The data obtained from PLT provides a critical reference for validating settlement predictions derived from the in-situ testing methods (PPMT, CPT, and DMT). The direct measurement of settlements under controlled conditions establishes PLT as a reliable benchmark for evaluating the applicability and limitations of predictive models in fine sand and silty sand soils.

3. Settlement predictions and comparison with measured values

Settlements were analyzed at two representative load levels: 10 kN, corresponding to loosely compacted soils, and 45 kN, representing densely compacted soils. These load levels were selected based on the results of the PLT load-settlement behavior and provided the basis for comparing across compaction levels. The PLT full load-settlement curves for both pits at each compaction level are depicted in Fig. 7.

3.1. Settlement predictions based on data from the in-situ test

For settlement calculations using PPMT data, established methods such as those proposed by Ménard and Rousseau (1962), Ménard (1967), and Briaud (2007) are widely used and suitable for a range of footing sizes. However, while Briaud (2007) applies to all footing sizes and foundation depths, the other methods at least need modulus data at the base of the foundation. However, in this study, the foundation base, based on the PLT, is located at the surface, where conducting a PMT test is impossible. Due to its flexibility, Briaud (2007) approach was selected for this experimental setup, ensuring reliable settlement predictions.

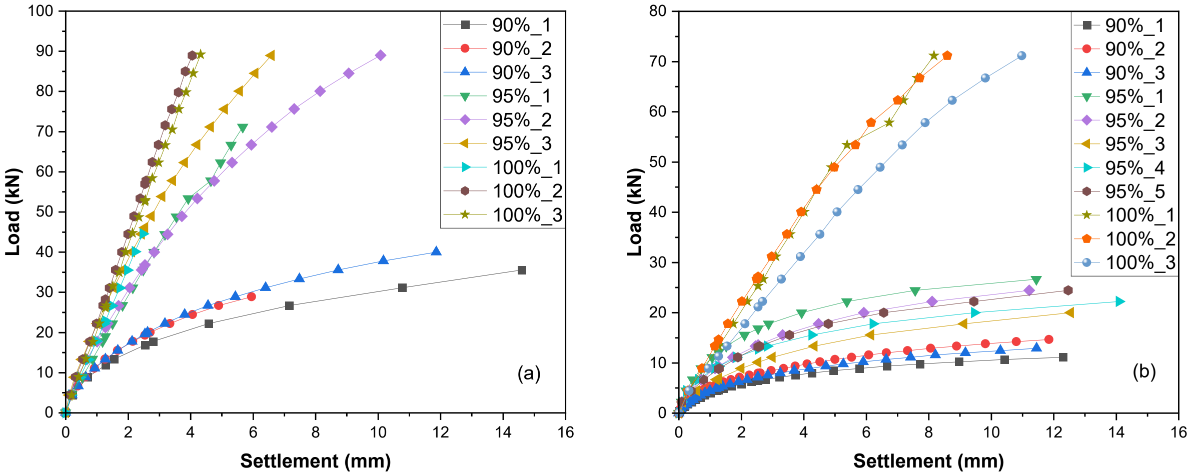

Fig. 7 Load-settlement curves from PLT for SH pit (a) and OST pit (b) at 90%, 95%, and 100% degree of compaction

The settlement results from the pushed-in PPMT demonstrate that pushed-in PPMT predictions closely match the measured PLT settlements, Fig. 8 Loosely compacted sands exhibited noticeable settlements under lower loads, while densely compacted sands showed significantly reduced settlements, underscoring the influence of compaction.

CPT-based settlements were estimated using stiffness parameters (E_s) derived based on four analytical (Das and Sivakugan 2018; Poulos and Davis 1974; Schleicher 1926; Tschebotarioff 1973) and three empirical (Bowles 1987; Meyerhof 1965; Schmertmann 1978) methods. Compared to PLT-measured settlements, CPT-based predictions were generally higher, particularly for loosely compacted sands, reflecting a tendency to overestimate settlement due to reliance of the elastic modulus on correlations based on ultimate capacity rather than using direct elastic parameters.

Settlements predicted using DMT data were calculated based on methods proposed by Leonards and Frost (1988) and Schmertmann (1986). DMT-based predictions are typically lower than all other settlements. This discrepancy is attributed to the higher stiffness values derived from DMT tests, which capture low-strain soil behavior but may underestimate settlement under higher applied loads.

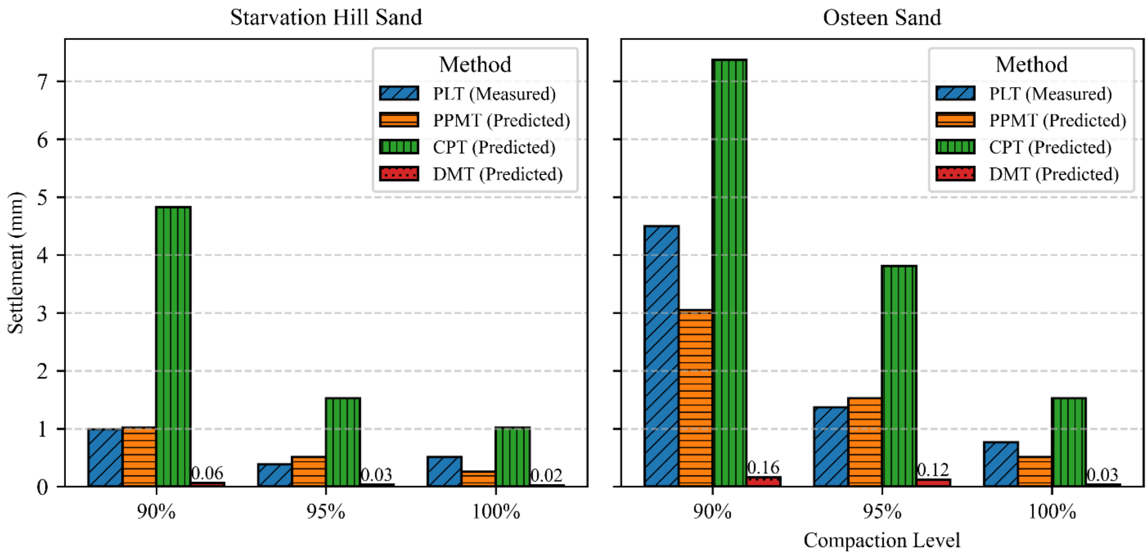

Fig. 8 Comparison of measured and predicted settlement at different compaction levels for 10 kN load

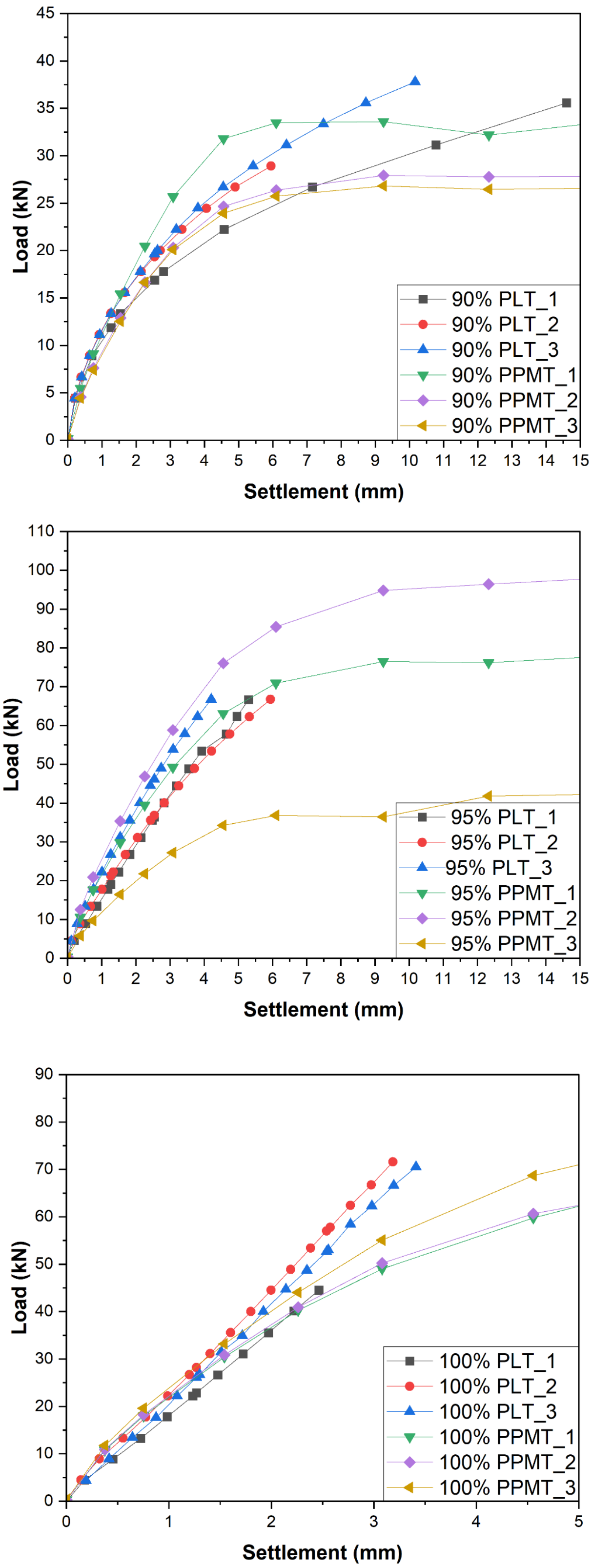

Fig. 9 PLT and PPMT Load-Settlement curves for SH sand pit at 90%, 95%, and 100% compaction level

3.2. Comparison of predicted and measured settlements

Fig. 8 elaborates further on the settlement comparisons of the measured and predicted settlements at 10 kN load, where the predictions from the PPMT and

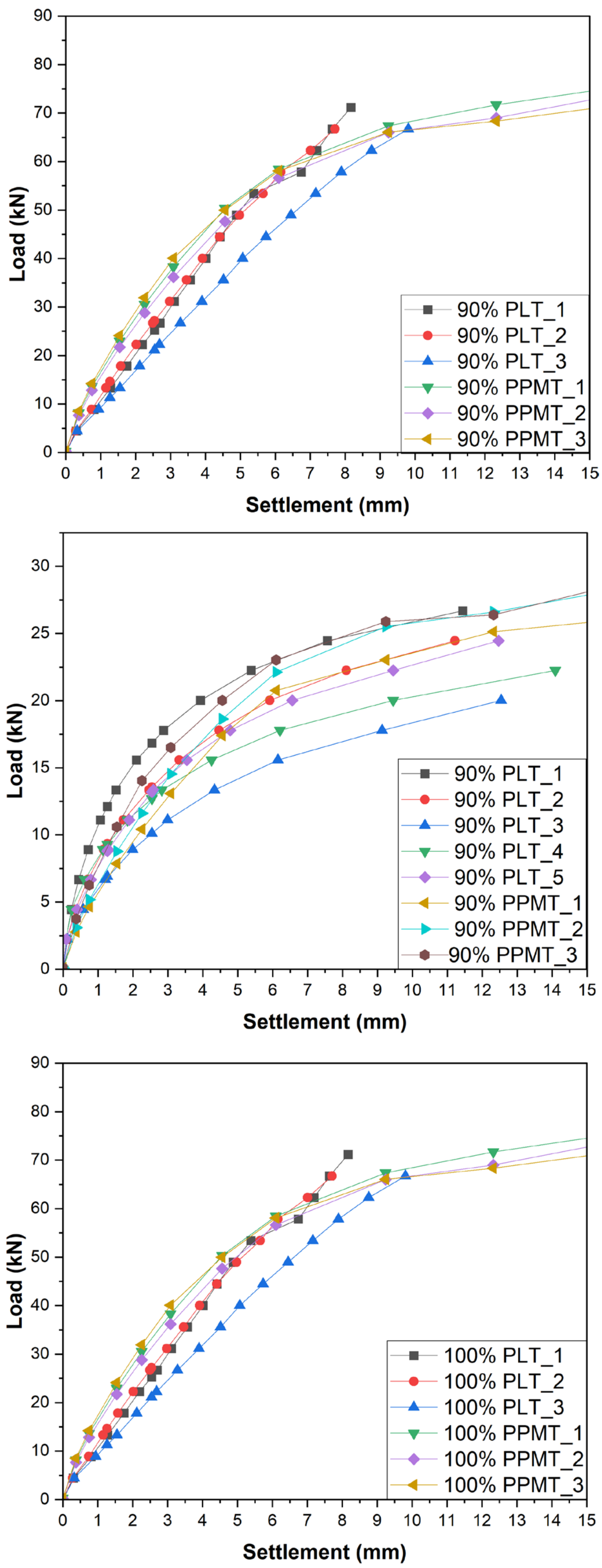

Fig. 10 PLT and PPMT Load-Settlement curves for OST sand pit at 90%, 95%, and 100% compaction level

PLT settlements are close to each other in most cases. The comparison shows that PPMT predictions align closely with PLT data, with an average underestimation of 11%. CPT predictions overestimate the settlements by as much as 153%, particularly in loosely compacted soils, while DMT predictions underestimate the settlements by approximately 94%.

Fig. 9 and Fig. 10 illustrate the average load-settlement curves for each degree of compaction derived from PLT and PPMT data for SH and OST sands. These curves indicate a strong agreement between PPMT and PLT results at different load levels. The discrepancies observed in CPT and DMT predictions largely stem from the testing methods' inherent nature.

The findings confirm PPMT as a reliable method for predicting settlements in the Florida fine sands and silty sands, consistently aligning with measured PLT data across all compaction levels. While settlement predictions based on data from CPT and DMT are adopted in the industry, they have inherent limitations of the testing methods that introduce variability in settlement predictions.

4. Conclusions

Based on this study, the following summaries and conclusions have been drawn.

1. The stiffness and strength are directly computed from the real-time stress-strain curve for a pressuremeter test. Accordingly, settlement predictions based on the pushed-in PPMT data closely matched the measured PLT settlements across all compaction levels and test pits. This establishes the push-in PPMT as an effective tool for settlement prediction, particularly in Florida's fine and silty sands.
2. CPT data-based predictions deviated more significantly from measured PLT settlements than PPMT. The discrepancy arises from the CPT's reliance on the ultimate tip resistance of the soil rather than directly computed stiffness values. While empirical correlations exist to estimate E_s from q_c, the lack of direct stiffness calculation and qc being an ultimate soil resistance introduces variabilities and limits the method's performance in settlement prediction.
3. Predictions from DMT data were notably lower than measured PLT settlements, particularly in this indoor setup with a 30 cm plate diameter. The high modulus values derived from small membrane expansions during DMT testing result in underestimated settlements, suggesting limitations for its application under similar testing conditions.

Among the in-situ test methods considered in this study, the pushed-in PPMT provided the most consistent results, closely aligning with measured PLT settlements and demonstrating its potential for shallow foundation settlement analysis in fine and silty sands.

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