Effect of Loading Duration on the Pressuremeter Test Results

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ABSTRACT

The Menard pressuremeter test is an in situ controlled load-deformation test that is performed on the wall of a borehole using a radial expanded cylindrical probe through incremental loading steps which provides the measurement of stress-strain response of soils. Traditionally, each loading step is maintained for a duration of 60 seconds. The present paper focuses on the evaluation of the impact of varying the loading time, specifically extending it from 60 to 120 seconds. For this purpose, several tests have been carried out across diverse soil types (soft clay, sandy clay, plastic clay, fine silty sand, fine compact clayey sand and compacted clay) at four different sites in Tunisia. The obtained results showed that continued deformations have been observed beyond the 60-second loading period. A reduction of the limit pressure for most of the tested soils have been detected. For all soil types, it was noticed that the obtained pressuremeter modulus EM2 for a loading step of Δt=120s declined particularly with fine soils characterized by low consistency showing the largest decrease but remains below 20% for soils with granular fractions, compacted soils, or those outside the water table.

RESUME

L'essai pressiométrique de Menard est un essai de chargement in situ, qui grace à l'expansion radiale contrôlée d'une sonde insérée dans un forage préalablement réalisé, permet de mesurer la relation contrainte-déformation du sol. Conventionnellement, chaque palier de charge est maintenu pendant 60 secondes. Ce travail présente une étude de l'effet de l'extension de cette durée chargement jusqu'à 120 secondes sur les résultats des essais pressiométriques. Différents essais pressiométriques ont été ainsi effectués sur divers types de sols (des argiles molles, des argiles sableuses, des sables fins et des sols très compactes (argiles raides et sables très compacts) sur quatre sites de la Tunisie. Les principaux résultats montrent qu'au-delà de 60 secondes les déformations se poursuivent et qu'une réduction significative de la pression limite a été observée pour la majorité des sols étudiés. De plus, il a été noté que le module pressiométrique enregistré pour les essais pressiometriques avec un temps de chargement de 120s a diminué. Cette réduction est d'autant plus marquée pour le cas des sols fins ayant de faible consistance mais demeure inférieure à 20% pour les sols contenant des fractions granulaires, les sols compacts ou les sols hors nappe d'eau.

Keywords: Pressuremeter test, extended loading time, limit pressure, pressuremeter modulus.

1. Introduction

Since its creation by Louis Ménard in 1955, the pressuremeter as an in-situ test has attracted a lot of interest and is used in numerous countries (Ménard 1955).

The pressuremeter has developed into a useful instrument for determining strength and deformation characteristics as well as geotechnical structures employing a variety of methods related to retaining wall displacements, bearing capacity, and settlements of shallow and deep foundations, etc. (Baker 2005, Baguelin, et al.1978).

Pressuremeter tests are conducted in prebored boreholes to obtain behaviour curves when the borehole wall is stressed radially by an expandable membrane (Ménard 1955). The test results are usually used for the calculation of pressuremeter modulus (EM) and limit pressure (Pl) which are essential for designing geotechnical structures. Relationships between these parameters and the geotechnical characteristics of soils have been investigated by several researchers (Bouassida and Frikha 2007, Frikha and Bouassida 2013, Gaaloul et al. 2021).

From the patented model (1955) known as type A to later versions B, C, D, E, F, G, etc., the pressuremeter test has undergone numerous improvements over time to improve measurement accuracy (Cassan 2005). To solve the problems of repeatability, accumulation of approximations, and simplifying the work process for operators, an auto-controlled pressuremeter was developed (Frikha and Varaksin 2018).

This investigative instrument has a number of disadvantages despite its benefits and qualities, particularly with regard to soil remoulding, probe placement, deformation assessment, etc. (Tolooiyan et al. 2021). In fact, many researchers have examined and discussed the requirements for performing the pressuremeter test, suggesting changes to improve the accuracy of the results. One of the most important aspects to examine, especially when evaluating the creep behaviour of soil, is the time-dependent behaviour variation as a function of the applied load duration in the pressuremeter test. According to the (ISO 22476-4 2021), the probe is inflated by applying loading steps (pressures). The loading time of each step is fixed at 60 seconds independently of the soil type and volume variations are recorded at 30s and 60s.

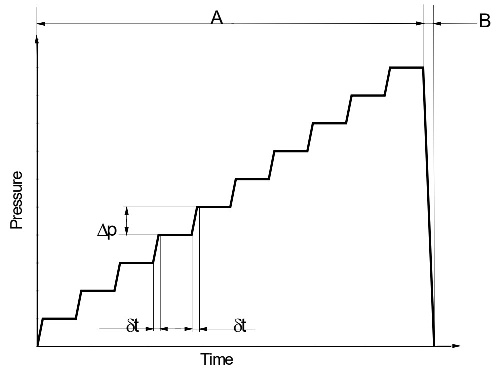
The purpose of this study is to assess how the results of pressuremeter tests can be affected when the loading time is increased to 120 seconds. For that reason, a number of tests have been conducted at four distinct sites in Tunisia across a variety of soil types (soft clay, sandy clay, plastic clay, fine silty sand, fine compact clayey sand and compacted clay).

2. Standard (PMT) and Modified (MPMT) pressuremeter tests

The Ménard pressuremeter (APAGEO®) was used for the in-situ testing in this investigation. There are two main parts to the pressuremeter: the probe and the pressure-volume control device (CPV), connected by a semi-rigid plastic hose (tubing).

The loading program in the PMT involves applying equal internal pressure (Fig. 1). Pressure increments are systematically increased, and each pressure step is maintained for a fixed time interval, Δt = 60 seconds. For every increment, variations in injected volume are recorded at 30 and 60 seconds.

Standard pressuremeter tests (PMT) which refers to Ménard pressuremeter test were conducted in accordance with (ISO 22476-4 2021) standards involving a minimum of 8 loading stages. Adjustments are required to account for hydrostatic water level, membrane resistance, and system compressibility after test readings.



Δt : Time of a uniform pressure level equal to 60s

δt : Time from one level to the next

A : Loading of the soil

B : Unloading of the soil

Figure 1. Step loading program of the pressuremeter test (Ouertani et al. 2025)

The following parameters can be acquired using the pressure volume curves that are obtained from the standard and modified pressuremeter tests:

P_{l1} and P^*_{l1} : limit pressure and net limit pressure measured after 60s' loading stage, respectively.

P_{l2} and P^*_{l2}: limit pressure and net limit pressure measured after 120s' loading stage, respectively.

P_{f1} and P^*_{f1}: creep pressure and net creep pressure obtained from the difference in volumes between the reading at 60 seconds and 30 seconds, respectively.

P_{f21} and P^*_{f21}: creep pressure and net creep pressure obtained from the difference in volumes between the reading at 120 seconds and 60 seconds, respectively.

P_{f22} and P^*_{f22}: the creep pressure and the net creep pressure obtained from the difference in volumes between the reading at 120 seconds and 30 seconds, respectively.

E_{M1}: pressuremeter modulus obtained for a loading step of Δt=60s.

E_{M2}: pressuremeter modulus obtained for a loading step of Δt=120s.

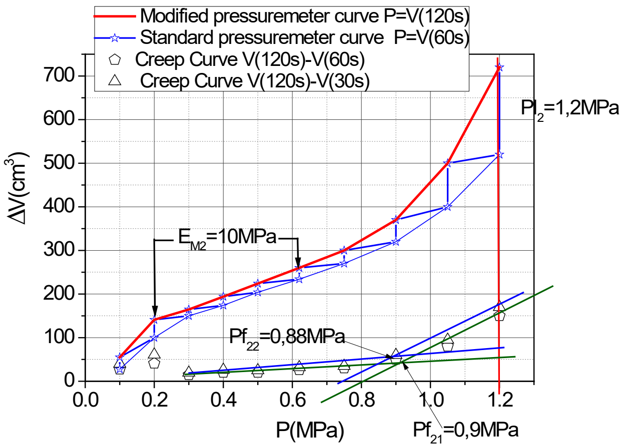


Figure 2. Standard and Modified pressuremeter test curves

The main distinction between the standard pressuremeter test and the modified pressuremeter test, or MPMT, is the testing procedure. Both tests use the same testing apparatus.

In particular, the load steps' duration is extended to two minutes (120 seconds), and the volume variations is also recorded for each step at intervals of 75, 90, and 120 seconds. Fig. 2 illustrates an example of the obtained pressuremeter and creep curves from the Standard and Modified pressuremeter test.

3. Studied soil

As part of a number of geotechnical investigation campaigns, the standard and modified pressuremeter tests were conducted on four sites in Tunisia (Megrine, Rades and Ksar Said in the north and Sfax in the middle of Tunisia) in various soil types.

Table 1 lists the geotechnical properties of the soils that were examined.

4. Result and discussion

The pressuremeter (PMT) and modified pressuremeter (MPMT) curves show consistent patterns with compressed back, pseudo-elastic, and plastic stages in all of the cases that were studied.

The results can be divided into three categories based on the comparison of the obtained curves:

- Type I: There is no appreciable difference between the PMT and MPMT curves, and loading duration has little effect on the pressuremeter test results.

It corresponds especially on sand, silt and clay outside out water ground table. As an example, Fig.3 illustrates the pressuremeter curves for fine silty sand performed at 5.5 m depth in Rades site.

- Type II: The volumetric deformation in MPMT for a given pressure P is significantly greater than that in PMT (VMPMT > VPMT). Limit pressures are quasi-similar. In this instance, the soils continue to deform for longer than the standard loading time of 60 seconds. It is particularly appropriate for soft clay soils as illustrated in Fig.4.
- Type III: For a given pressure P, VMPMT > VPMT. Compared to PMT, MPMT's limit pressure is significantly higher. It corresponds especially on clayey soils (silty clay, sandy clay, Plastic clay). As an example, Fig.5 illustrates the pressuremeter curves for plastic clay at 5.5 m depth in Rades site.

The detailed results are provided in Ouertani et al. (2025).

Table 1. Geotechnical characteristics of tested soils (Ouertani et al.2025)

Site and survey	Soil type	IP(%)	WL(%)	Cc	FC (%)
Megrine SP1	Soft clay	17	37	0.28	96
	Soft clay	20	45	0.4	92
	Silty sandy clay	15	32	0.18	83
Megrine SP2	Silty sandy clay	15	28	0.15	79
	Silty sandy clay	18	25	0.17	85
	Plastic clay	26	42	0.34	97
Rades SP8	Silty sand	-	-	-	22
	Soft clay	28	58	0.4	90
	Silty clay	22	46	0.43	57
	Plastic clay	25	52	0.36	98
Rades SP6	Silty sand	-	15	-	16.9
	Soft clay	29	60	0.37	97
	Soft clay	35	50	0.46	96
	Silty sand	-	-	-	21
	Plastic clay	27	44	0.43	92
Sfax SP19	Compact Silty clayey fine sand	15	33	0.10	41
Ksar Said SP1	Silty clay outside of water table	29	61	0.26	86

(PI: Plasticity index. WL: Liquid limit. Cc: Compression index. FC: fine content)

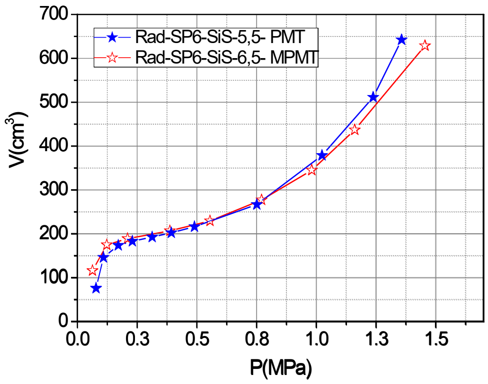


Figure 3. Pressuremeter curves obtained from standard and modified tests carried out in Rades site for fine silty sand at 5.5 m depth

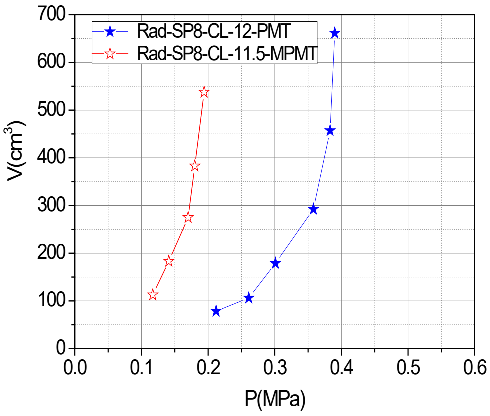


Figure 4. Pressuremeter curves obtained from standard and modified tests carried out in Rades site for soft clay at 12 m depth

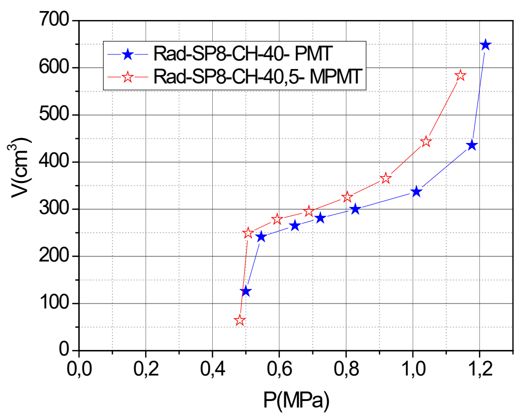


Figure 5. Pressuremeter curves obtained from standard and modified tests carried out in Rades site for plastic clay at 40 m depth

4.1. Influence of the Fine Content FC

The evolution of the pressuremeter modulus ratio E_{M2}/E_{M1} and the limit pressure ratio P_{l2}/P_{l1} as a function of the fine fraction content are shown in Figs. 6 and 7, respectively.

Based on the type of soil that was examined, the results are grouped.

Both ratios show comparatively little variance for soils with fine fractions < 40%. In particular, the E_{M2}/E_{M1} ratio remains between 0.8 and 1.0, suggesting that there is little decrease in the soil's stiffness over time.

Comparably, the P_{l2}/P_{l1}ratio varies between 0.9 and 1.0, indicating that the limit pressure only slightly changes when the loading period is increased from 60 to 120 seconds.

However, the E_{M2}/E_{M1} ratio drastically decreases and varies between 0.25 and 0.8 for soils with fine fractions higher than 80%.

Under sustained loading, this shows a significant drop in the pressuremeter modulus, which reflects the increasing time-dependent deformation in fine-grained soils.

On the other hand, the P_{l2}/P_{l1}ratio, which ranges from 0.7 to 0.9, is comparatively less impacted. This suggests that while the limit pressure decreases, the impact is less severe than the reduction in stiffness.

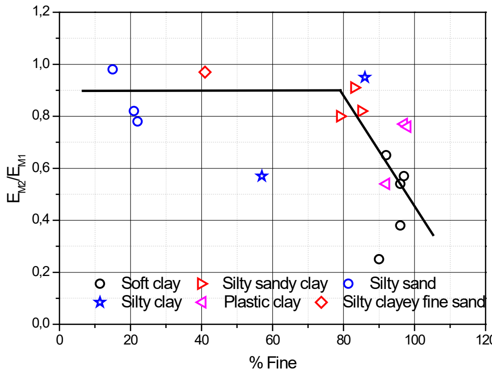


Figure 6. Effect of fine content on the variation of the pressuremeter modulus' ratio E_{M2}/E_{M1}

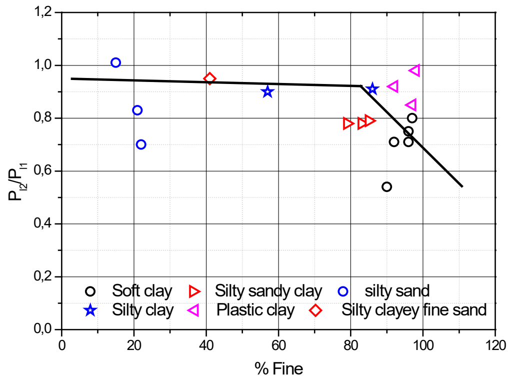


Figure 7. Effect of fine content on the variation of the limit pressures' ratio P_{l2}/P_{l1}

4.2. Influence of the Compression index Cc

The correlation between the compression index (Cc) and the ratios $E_{M2}/E_{M1}$and P_{l2}/P_{l1} is shown in Fig. 8 and 9, respectively.

As predicted, both ratios show more noticeable decreases in soils with higher Cc values, which signify a greater tendency for volumetric compression under load.

The E_{M2}/E_{M1} ratio drastically decreases for soils with Cc values above 0.35, falling between 0.25 and 0.8, suggesting that highly compressible soils lose a significant amount of stiffness under prolonged loading periods.

The P_{l2}/P_{l1} ratio in these soils' ranges from 0.7 to 0.9, reflecting a more moderate reduction in the limit pressure.

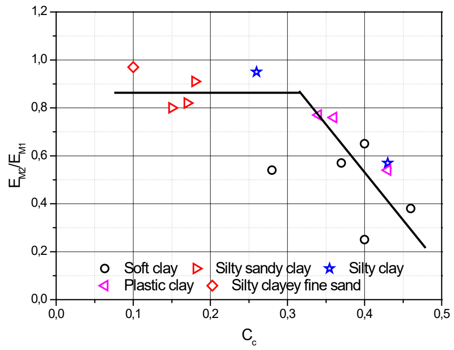
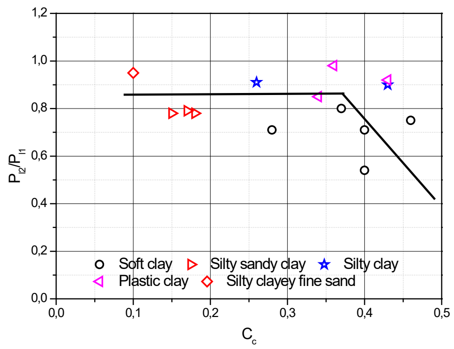


Figure 8. Effect of compression index C_c on the variation of the pressuremeter modulus' ratio E_{M2}/E_{M1}



Figures 9. Effect of compression index C_c on the variation of the limit pressures' ratio P_{l2}/P_{l1}

4.3. Influence of the plasticity index IP

The variation of $E_{M2}/E_{M1}$and P_{l2}/P_{l1} with the plasticity index (IP) are illustrated in Figs.10 and 11, respectively. Soils with higher plasticity show a significant reduction in E_{M2}/E_{M1}, with the ratio decreasing to values as low as 0.4. This is indicative of plastic clays' high time-dependent deformation, where creep intensifies as soil plasticity increases. The P_{l2}/P_{l1}ratio follows a similar, though less dramatic, trend, with values mast ranging between 0.75 and 1.0 for high-plasticity soils. This shows that when plasticity increases, both stiffness and limit pressure decrease, but the effect is more noticeable in terms of stiffness loss (modulus).

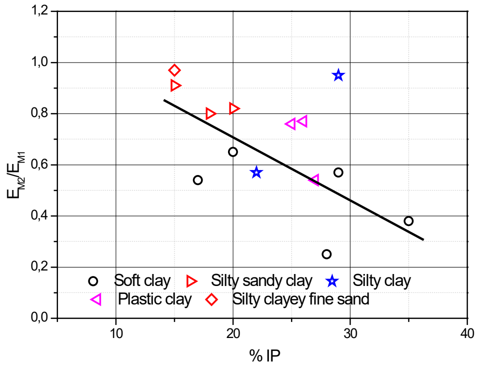


Figure 10. Effect of the plasticity index (IP) on the variation of (a) the pressuremeter modulus' ratio E_{M2}/E_{M1}

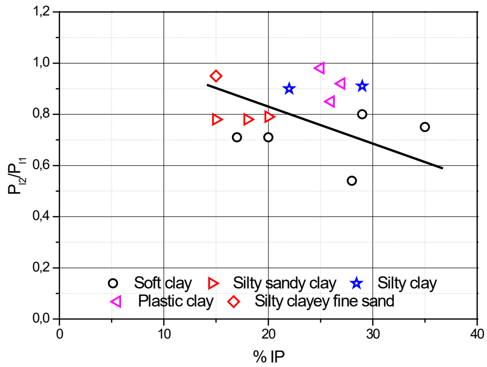


Figure 11. Effect of the plasticity index (IP) on the variation of the limit pressures' ratio P_{l2}/P_{l1}

5. Conclusions

The current study focuses on the evaluation of the impact of varying the loading time, specifically extending it from 60 to 120 seconds on the interpretation of pressuremeter test results.

The following conclusions were reached after comparing the results of modified pressuremeter tests (MPMT) with standard pressuremeter tests (PMT) conducted within the same horizons:

- For soils characterized by a significant granular fraction (sand, fine silty sand, or clayey sand) and compacted clays, the curves from standard tests (PMT) and modified tests (MPMT) roughly match. On the other hand, MPMT curves consistently exceed PMT curves for soft and plastic clay soils, indicating an augmented volume consumption with increased loading time, especially in clayey soils.
- Soils having a larger proportion of fine particles and less consistency are more sensitive to loading time.

With extended loading times, the limit pressure decreases; for soft and sandy clays, the decrease is more noticeable (2–30%). For compact silty clayey fine sand, the difference between P_{l1} and P_{l2} is less noticeable.

The modified pressuremeter modulus E_{M2} experiences a reduction for each soil type. This decrease is less than 20% for soils with granular fractions, compacted soils, or soils outside the water table, while it is more significant (50%) for fine soils with low consistency.

Although the limit pressure is less impacted, the general trend shows that soils with a higher fine content (more than 80%) are more susceptible to time-dependent behaviour, which causes noticeable decreases in their modulus with time.

This demonstrates how sensitive fine-grained soils are to prolonged loading time, particularly in terms of stiffness degradation. The ratio of pressuremeter modulus ratios E_{M2}/E_{M1} decreases with an increasing compression index (Cc), especially for Cc values above 0.30. On the other hand, the evolution of the limit pressure ratio P_{l2}/P_{l1} is less significantly impacted by the compression index.

- Higher plasticity significantly impacts the stiffness and strength characteristics of soils.

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