La pertinence des essais pressiométriques Ménard (PMT) dans les investigations géotechniques pour l'analyse de la stabilité des fondations profondes

Eduardo Aladim Fonseca[1#], *Carlos Alessandro* Almeida da Silva[1], *Ezequias* Borges de Oliveira[2], *Edgar* Odebrecht[3], and *Fernando* Mantaras[3]

[1]*REDE Engenharia e Sondagens, Geotechnical Engineering, Belo Horizonte-MG, Brazil*
[2]*VALE, Geotechnical Engineering, Belo Horizonte-MG, Brazil*
[3]*GEOFORMA Engenharia, Geotechnical Engineering, Joinvile-SC, Brazil*
[#]*eduardofonseca@redeengenharia.eng.br*

ABSTRACT

The Ménard Pressuremeter Test (PMT) is a versatile in situ geotechnical testing method that provides direct measurements of soil deformability and strength parameters that are essential for prediction soil behavior under load and designing stable deep foundations. This study explores the relevance and reliability of PMT data by comparing it with results from CPTu tests. A comprehensive dataset was compiled, analyzing the consistency of PMT- derived parameters with those obtained through alternative methods . The correlations focus on key geotechnical properties, such as shear strength, modulus of elasticity, and stress-strain behavior, while also evaluating the PMT's capacity to characterize layered soils. The results underline the benefits of PMT, including its ability to measure in situ deformability at stress levels comparable to field conditions, while also highlighting challenges such as equipment sensitivity and operator expertise. When integrated with CPTu and laboratory data, the PMT enhances geotechnical modeling, offering a robust framework for more reliable stability analyses of deep foundations. This study provides practical recommendations for combining PMT with complementary methods, optimizing geotechnical investigation programs for complex soil conditions.

RESUME

L'essai pressiométrique Ménard (PMT) est une méthode d'essai géotechnique in situ polyvalente qui fournit des mesures directes de la déformabilité et des paramètres de résistance des sols, essentiels à la prévision du comportement des sols sous charge et à la conception de fondations profondes stables. Cette étude explore la pertinence et la fiabilité des données du PMT en les comparant aux résultats des essais CPTu. Un ensemble complet de données a été compilé, analysant la cohérence des paramètres dérivés du PMT avec ceux obtenus par d'autres méthodes. Les corrélations se concentrent sur des propriétés géotechniques clés, telles que la résistance au cisaillement, le module d'élasticité et le comportement contrainte-déformation, tout en évaluant la capacité du PMT à caractériser les sols stratifiés. Les résultats soulignent les avantages du PMT, notamment sa capacité à mesurer la déformabilité in situ à des niveaux de contrainte comparables aux conditions de terrain, tout en soulignant les défis tels que la sensibilité des équipements et l'expertise des opérateurs. Intégré aux données CPTu et de laboratoire, le PMT améliore la modélisation géotechnique, offrant un cadre robuste pour des analyses de stabilité plus fiables des fondations profondes. Cette étude fournit des recommandations pratiques pour combiner le PMT avec des méthodes complémentaires, optimisant ainsi les programmes d'investigation géotechnique pour des conditions de sol complexes.

Keywords: ménard pressuremeter test, cptu, deep foundation, geotechnical investigation

1. Introduction

Accurate determination of soil geotechnical parameters is essential for the design and dimensioning of deep foundations, especially in large-scale projects where safety and structural stability are paramount. Brazilian Standard ABNT NBR 6122:2019 defines deep foundations as those in which the load is transmitted to the soil predominantly by lateral friction and/or tip resistance in deeper layers, with a driving depth generally greater than twice the smallest dimension of the cross-section of the foundation element. These foundations are widely used when the surface layers of the soil do not have sufficient capacity to support the loads applied by the structure.

The choice between shallow and deep foundations depends on a thorough evaluation of the soil's strength, stiffness, and stress–strain behavior with depth. In this context, in situ tests such as the Ménard Pressuremeter Test (PMT) and the Piezocone Penetration Test (CPTu) play a critical role. The CPTu enables the continuous acquisition of parameters such as cone resistance (q_t), sleeve friction (f_s), and excess pore pressure, allowing the identification of more competent layers suitable for deep foundations and weaker zones where shallow foundations are not recommended (Robertson and Cabal, 2015). The PMT provides parameters such as the pressuremeter modulus (*Em*) and the limit pressure (*pL*), which are essential for estimating settlements of shallow foundations and assessing the load-bearing capacity of deep foundations (Baguelin et al., 1978; Schnaid, 2009).

Among the in situ tests used to characterize soil behavior and obtain reliable parameters for foundation design, the pressuremeter test (PMT - Ménard Pressuremeter) stands out. The first use of the pressuremeter test to determine geotechnical parameters dates to 1933, with the development of the first PBPMT pressuremeter by Kogler. Two decades later, in 1955, Ménard began to develop and build the first pressuremeter model to determine in-situ parameters (Da Silva, 2001). The test measures soil deformability and resistance through the radial expansion of a pressurized cylindrical probe inside a borehole, providing direct parameters such as the pressuremeter modulus, the limiting pressure and the creep coefficient. These parameters are essential for estimating the load capacity and settlements of deep foundations (Schnaid and Odebrecht, 2012).

Furthermore, for shallow foundations, the Em modulus obtained from the PMT can be used to estimate the elastic settlement of footings and blocks, aiding in the verification of whether predicted displacements comply with serviceability criteria. For deep foundations, the limit pressure (*pL*) can be directly applied in the estimation of the load-bearing capacity of isolated or grouped piles, following methodologies such as those proposed by Ménard (1975) , Bustamante and Gianeselli (1982), which relate limit pressure to allowable load through empirical coefficients adapted to the soil type.

The reliability of parameters obtained by in situ tests, such as PMT, has been discussed in the geotechnical literature, especially when compared with laboratory tests and other field tests, such as the CPTu cone penetration test. According to Schnaid and Odebrecht (2012), obtaining parameters directly in the field reduces the uncertainties associated with sampling and soil disturbance, ensuring greater representativeness of the results. In addition, PMT allows the evaluation of the stress-strain response of the soil under conditions closer to reality, which makes it a valuable test for foundation engineering.

In addition to cone resistance and sleeve friction, the CPTu also allows for the inference of properties such as soil type (using classification charts such as Robertson's), sensitivity, and relative stiffness—all of which directly influence the decision between shallow and deep foundations. For instance, in well-compacted granular soils with high cone resistance, shallow foundations may be a viable option. Conversely, in soft or transitional soils, the CPTu profiles may indicate the need for deep foundations to reach more competent layers.

2. Objective

This paper aims to evaluate the applicability and reliability of PMT tests in geotechnical investigation for deep foundations, through an experimental study carried out in a foundation site located in São Gonçalo do Rio Abaixo, Minas Gerais, Brazil. For this purpose, the results obtained in a borehole where a cone test with dissipation of pore pressure (CPTu) was performed were compared with the results of a twin borehole, in which three pressure tests (PMT) were conducted at different depths: 1m, 3m and 9m. The comparative analysis aims to verify the coherence and accuracy of the obtained parameters, contributing to the improvement of deep foundation design practices based on field investigations.

In addition to enabling more accurate geotechnical characterization, the integration of data from these two in situ tests supports the selection of the most appropriate foundation type – shallow or deep – based on allowable bearing capacity, soil deformability, and the depth of competent layers. The CPTu provides continuous information on subsurface stratigraphy through parameters such as cone resistance (*qt*), sleeve friction (*fs*), and pore pressure (*u*), making it an effective tool for estimating the strength of both granular and cohesive soils, as well as for determining the minimum depth required for deep foundations (Robertson, 2016) (Lunne et al., 1997).

The PMT yields parameters directly related to soil stiffness and bearing capacity, such as the pressuremeter modulus (*Em*) and the limit pressure (*pL*), which are essential for settlement analysis and for predicting the behavior of foundations under vertical loads. For shallow foundations, these parameters help verify serviceability limit states (e.g., allowable settlement), while for deep foundations, they are used to define working loads and assess shaft or base integrity (Baguelin et al.1978) (Ménard 1975) (Schnaid, 2009).

Thus, this study aims to demonstrate how the combined use of CPTu and PMT provides robust technical input not only for the design of deep foundations but also for critical design decisions, such as the selection of the most efficient and economically viable foundation type based on the actual ground conditions encountered.

3. Justification and Relevance

The use of pressuremeter tests, such as the Ménard Pressuremeter (PMT), is internationally recognized for providing accurate geotechnical parameters, essential for the safe and efficient design of deep foundations. However, in Brazil, the application of this type of test is still limited. This is due, in part, to the cultural predominance of the use of percussion drilling (SPT) and the lack of investment in new technologies for geotechnical investigations (Colaço, 2017).

The limited dissemination of PMT in the country can be attributed to barriers such as the difficulty in interpreting the results and the heterogeneity of the materials tested (Santos, 2021). In addition, the lack of investment in modern equipment and in the training of professionals contributes to the resistance to adopting more advanced soil investigation methods.

In foundation projects, especially those involving complex structures and high loads, accuracy in geotechnical parameters is crucial. Inadequate parameters can lead to oversized or undersized projects, resulting in risks to structural safety and possible financial losses. Therefore, the assertiveness in obtaining these parameters represents a significant gain in terms of safety and economy for the works (Oliveira, 2020).

Given this scenario, this study is justified by the need to promote the application and understanding of pressuremeter tests in Brazil. By comparing the results of the PMT with those of the CPT test in a specific terrain, we seek to demonstrate the effectiveness and relevance of the PMT in obtaining reliable geotechnical parameters.

4. Materials and Methods

The PMT and CPTu tests were conducted following the ASTM D4719-87 (1987) – "Standard Test Method for Pressuremeter Testing in Soils " and ASTM D5778 (2020) – "Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils ". The tests were carried out on a plot of land located in São Gonçalo do Rio Abaixo, where two nearby boreholes were chosen, allowing direct comparison of the results obtained by each method.

The PMT test was performed at three different depths: 1m, 3m and 9m. The procedure involved the introduction of a pressure probe into the borehole, followed by the application of controlled pressure to measure the stress-strain response of the soil. The CPTu test consisted of the continuous driving of an instrumented electronic cone, allowing the measurement of parameters such as tip resistance, lateral friction and dissipation of pore pressure, and was completed at 12m.

After obtaining the field data, the analyses were conducted using different computational tools. The PMT data were processed and interpreted using APAGEO's GEOVISION software and complemented with calculations in Microsoft Excel spreadsheets. In turn, the data obtained in the CPTu test were analyzed using the CPeT -IT software, developed by Geologismiki, allowing detailed interpretation of the soil parameters and their correlation with the pressuremetric results.

4.1. Equipment

To carry out the Ménard Pressuremeter – PMT tests, the following equipment were used: hydraulic diamond rotary drilling machine and automated PMT probe manufactured by APAGEO with a capacity of up to 5Mpa.

To perform the pre-drilling for the PMT tests, the following equipment were used:

- Hydraulic probe;
- Rotary drilling tool with nominal Ø HQ of 3.5”;
- BW barrel;
- AWJ rods;

To perform the Menard Pressuremeter – PMT tests, the following equipment were used:

- GEOPAC 5Mpa equipment;
- Pressure probe with a diameter of 60 mm;
- AWJ rods;
- GEOBOX with pressure application device;
- Twin cables with lengths of 25 to 50 meters;
- Calibration tube;
- Nitrogen gas cylinder;
- GEOVISION software for analysis and interpretation of results.

To perform the CPTu – Cone Penetration Test, the following equipment were used:

- CPT hydraulic driving penetrometer with 200kn capacity;
- CPT hoist assembly;
- Electric cone with an area of 10cm²;
- Data acquisition hardware and software Geologger , Eijkelcamp.

4.2. In-situ Tests Methodology

The PMT tests were performed according to the standard procedure and recommendations of the equipment manufacturer. The steps followed were initial drilling (pre-drilling execution), probe calibration, probe positioning, pressure application and data collection and analysis.

To execute the pre-drilling process, up to the depth for performing the tests, the drilling was carried out using the rotary diamond drilling method with HQ diameter tools (3.5"). After reaching the test section, the drilled diameter was changed to 2.5" (nominal diameter BWL) to ensure that there was a minimum difference between the diameter of the hole and the PMT probe (diameter suitable for inserting the pressure probe). This procedure was made to ensure that during the pressurization of the equipment it would be possible to measure exactly the point of contact with the ground.

After the initial drilling was completed, the equipment was calibrated to ensure the accuracy of the measurements, following the manufacturer's recommendations. The calibration process was carried out in two stages, the first being calibration by pressurizing a rigid steel cylinder, where pressures are applied at increments every 60 seconds and monitoring is performed to plot a pressure-displacement curve, called an expansion curve. The second stage consists of calibration in air, with the probe in a vertical position, to correct the pressures based on the membrane resistance. The resulting pressure and deformation curve is plotted and from this, the pressure correction resulting from the membrane resistance can be obtained for each injected volume (Fig.1).

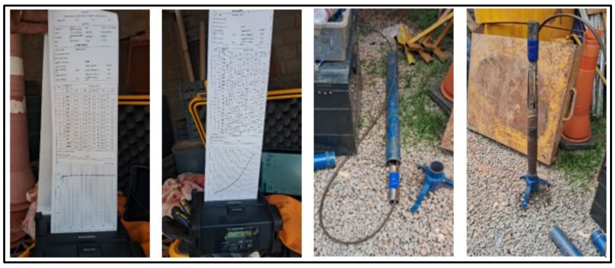

Figure 1. Pressure probe calibration process. Source: REDE Engenharia.

The pressure probe must be positioned carefully by inserting threaded rod columns. During the process, care must be taken to ensure that the position of the tooling is in accordance with the depth of interest for the test. (Fig. 2).

Figure 2. PMT Assay Preparation and Probe Positioning. - Source: REDE Engenharia.

As the GEOPAC equipment is fully automatic, the entire pressurization process is carried out in a controlled and digital manner, respecting the normative pressure increments from ASTM D4719-87 (1987), with the soil's stress-deformation response being recorded in real time. Once the test stoppage criterion is reached (reaching the volumetric limit and/or applied pressure limits), the test is terminated, and the data is stored for later processing and analysis in specific software.

The CPTu test was performed according to the ASTM D5778-20 (2020) standard procedure, with continuous driving of the electronic cone to a depth of 12 m. During driving, the tip resistance, lateral friction and pore pressure were recorded.

5. Results

Test performed at a depth of 1.38 meters in contact with soil presenting mature residual characteristics, with little preserved relict structure and fragments of laterite conglomerate and presenting no resistance in the loading cycles and reaching a maximum limit pressure *PLm* 0.041Mpa and presenting a result of Ménard modulus of 0.271Mpa. From pressure *P2*, an increase in the ascending curve is observed, which refers to material with sandier granulometry.

The first field test result was not considered conclusive, it has been caused by an unconsolidated material layer at shallow depth that could have led to a possible wall collapse during the test execution.

The second test was conducted at a depth of 3.36 meters, where the soil exhibited mature residual characteristics with preserved relic structure. The soil also contained kaolinitic intercalations and millimetric quartz fragments, showing a sandy texture with fine to coarse sand fractions observable through tactile inspection In the more pronounced pseudo-elastic phase, the curve advances into a more horizontal trend, indicative of materials with finer granulometry, attributed to the presence of silt and kaolin. The maximum limiting pressure (*Pl*) is 1.249 MPa, with an Ménard modulus of 10.65 MPa. After reaching pressure *P2*, an increase in the ascending curve is observed, showing the transition of the material into the plasticization phase. (Fig. 3).

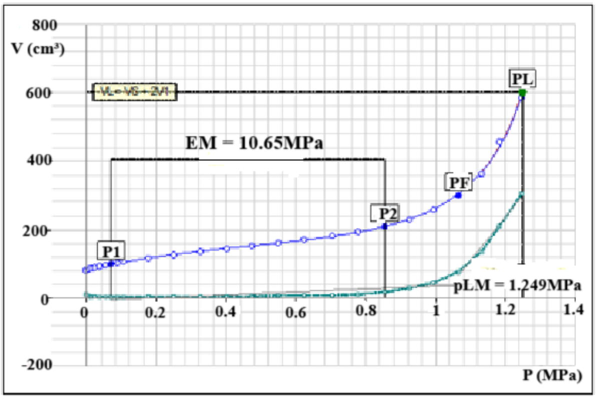

Figure 3. PMT Test Result – Depth 3.36m. - Source: REDE Engenharia.

The test was conducted at a depth of 9.32 meters, where the soil exhibited mature residual characteristics with preserved relic structure. The soil also contained kaolinitic intercalations and millimetric quartz fragments, with a sandy texture featuring fine to coarse sand fractions observable through tactile inspection. In the more pronounced pseudo-elastic phase, the curve advances into a more horizontal trend, indicative of materials with finer granulometry, attributed to the presence of silt and kaolin. The maximum limiting pressure (*pL*) is 1.677 MPa, with a Ménard modulus of 11.88 MPa. After reaching pressure *P2*, an increase in the ascending curve is observed, signaling the transition of the material into the plasticization phase. The test exhibited behavior similar to that conducted at a depth of 3.36 meters. (Fig. 4).

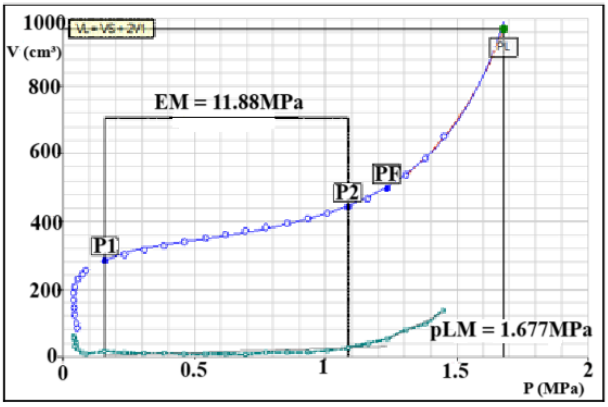

Figure 4. PMT Test Result – Depth 9.32m. - Source: REDE Engenharia.

The results of the CPTu test with dilatant material behaviors falling within the Mod. SBTn classification (Robertson, 2016) in predominantly unsaturated horizons with increased tip resistance and lateral friction from 7.50 meters. Test completed at a depth of 12.13 meters due to impenetrability in the residual material.

The analysis of the geotechnical tests carried out at different depths allowed a detailed understanding of the mechanical behavior of the soil and its granulometric variations. The results highlighted the influence of soil composition on the response to applied loads, providing important subsidies for the geotechnical characterization of the studied depths.

The results obtained by comparing the PMT and CPTu tests were compiled on “Table 1” and “Table 2”.

Table 1. PMT Results – Geotechnical Parameters

Borehole	Depth	p_f (MPa)	p_{lm} (MPa)	E_M (MPa)
PMT-01	3,36m	1,07	1,25	10,6
PMT-01	9,32m	1,23	1,68	11,9

The tests carried out at depths of 3.36m and 9.32m showed significant variations in the soil structure. In the test at 3.36 m, the preservation of the relict structure and the presence of kaolinic intercalations were observed, resulting in a significant increase in the maximum limit pressure and Ménard modulus.

Table 2. CPTu Results – Geotechnical Parameters

Borehole	Depth	*qt* (MPa)	*fs* (kPa)	*u* (kPa)
PMT-01	3,36m	4,33	204,16	-3,82
PMT-01	9,32m	18,89	558,08	-44,83

The behavior observed in the 9.32 m test was similar to that of the 3.36 m test, reinforcing the tendency of greater resistance with increasing depth. The CPTu test (Fig. 5) indicated the presence of dilatant materials, classified according to the Mod. SBTn methodology (Robertson, 2016), highlighting predominantly unsaturated horizons and increased resistance from 7.50 m, ending at 12.13 m due to the impenetrability of the residual material.

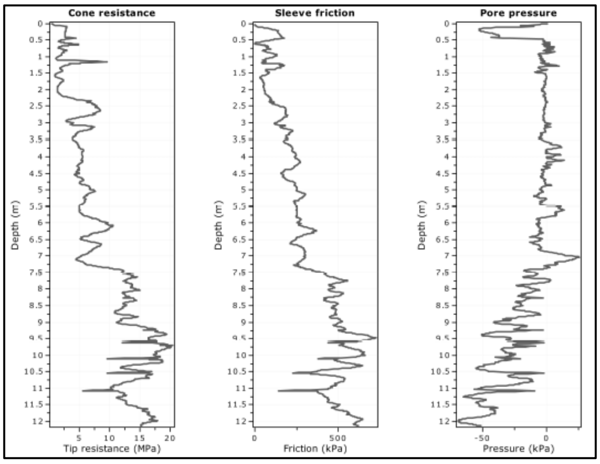

Figure 5. CPTu Test Result – From 0 to 12.13m. - Source: VALE.

Analyzing the results and applying them to hypothetical scenarios for shallow and deep foundation applications and designs, the following considerations can be made based on the obtained test results from PMT on "Table 1" and CPTu on "Table 2". The Ménard modulus (*Em*) of 10.6 MPa indicates good rigidity, making it suitable for pile support. The maximum limiting pressure (*pLm*) of 1.25 MPa demonstrates strong resistance to concentrated loads.

The point resistance (*qt* = 4.33 MPa) suggests compacted to moderately compacted sand or silt. The lateral friction (*fs* = 204.16 kPa) is compatible with moderately compact granular material. The negative pore pressure (*u* = -3.82 kPa) may indicate suction in partially saturated soils or the presence of dry sand.

In a hypothetical case, the application of shallow foundation projects at a depth of 3.36 meters is considered. The suggested foundation types for this scenario are either continuous or isolated footings. The estimated allowable load is calculated based on the data obtained from the Ménard pressuremeter (pLm). According to the Ménard method, the allowable bearing capacity (q_adm) is given by the Eq.(1) :

$$q\ (adm) = \frac{plm}{2.5} = \frac{1.25}{2.5} = 0.50MPa = 500KPa \quad (1)$$

Additionally, the elastic settlement (s) for a footing with a width of 1.0 m and an applied load of 400 kPa is estimated as follows on Eq.(2):

$$s = \alpha.\frac{q.B}{Em} = 1.0\,\frac{400.1}{10.600} = 0.038m = 3.8cm \quad (2)$$

This settlement value is within the acceptable range for typical structures. Therefore, the foundation design is considered appropriate for the given soil conditions, ensuring adequate support and minimal settlement.

In a hypothetical scenario involving deep foundation design at a depth of 9.32 meters, data obtained from both the Ménard Pressuremeter Test (PMT) and the Cone Penetration Test with pore pressure measurement (CPTu) were analyzed to assess soil performance under concentrated loading conditions.

According to the PMT results, the soil exhibited an Ménard modulus (*Em*) of 11.9 MPa, indicating good stiffness and mechanical compatibility for pile support. The limiting pressure (*pLm*) reached a value of 1.68 MPa, which reflects a high capacity to resist concentrated loads, further supporting the feasibility of deep foundation elements such as bored or driven piles in this stratum.

Complementary data from the CPTu test confirmed the presence of a very dense granular material at the same depth. The measured point resistance (*qt*) of 18.89 MPa suggests a compacted sand layer or sand with natural cementation, providing substantial end-bearing capacity. The lateral friction value (*fs*) of 558.08 kPa supports the interpretation of high shaft resistance, favorable for load transfer through skin friction. Furthermore, the observed negative pore pressure (*u* = –44.83 kPa) may indicate an extremely well-drained condition, potentially associated with dry dense sand or, in rare cases, the presence of partial vacuum within the soil matrix.

Together, these geotechnical parameters highlight the suitability of the layer at 9.32m for deep foundation applications, particularly for high-capacity piles that rely on both tip resistance and shaft friction for load transfer.

In the application of deep foundations, the recommended foundation type consists of either driven or small-displacement bored piles. A hypothetical case is considered, where the pile base area is 0.3 m². According to the method proposed by Bustamante and Gianeselli (1982), the point load capacity is calculated as showed on Eq.(3):

$$Qb = qt\,.Ab = 18{,}89\,.0{,}3 = 5{,}67MN \quad (3)$$

Additionally, the total lateral friction is estimated by assuming a 6-meter pile shaft with a perimeter of 1 meter as in Eq.(4):

$$Qs = fs\,.A = 558\,.(6.1) = 3{,}348KN \qquad (4)$$

The total estimated load capacity is the sum of the point load and the lateral friction as in Eq.(5):

$$Qult = Qb + Qs = 5{,}670 + 3{,}348 = 9{,}018KN \qquad (5)$$

To ensure the safety of the design, a safety factor of 2.5 is applied, resulting in an allowable load capacity as in Eq.(6):

$$Qadm \approx 3{,}607\ KN \qquad (6)$$

This calculation demonstrates the high capacity of the proposed deep foundation, with the pile supporting substantial axial and lateral loads.

The following table summarizes the estimated capacity and settlement for shallow and deep foundations at different depths "Table 3":

Table 3. Estimated Capacity and Settlement for Shallow and Deep Foundation

Foundation Type	Depth	Estimated Capacity	Settlement
Shallow	3,36m	~500 kPa	~3.8cm
Deep	9,32m	~3,600 kN (pile)	-

The table reflects that at 3.36 m depth, the shallow foundation provides a moderate settlement of approximately 3.8 cm, which is typical for competent soils. At 9.32 m depth, the deep foundation demonstrates high capacity with minimal expected settlement, suitable for high-load applications due to the dense soil.

6. Conclusions

The results obtained at two considered depths (3,36m and 9,32m) evaluated by means of the PMT test demonstrated coherence when compared to the results of the CPTu test. A significant similarity was observed between the soil resistance parameters, reinforcing the reliability of the PMT for geotechnical characterization.

Furthermore, the use of the PMT test is a viable alternative in cases where the CPTu test cannot be performed due to equipment limitations. The PMT makes it possible to obtain parameters in deeper and more resistant layers, expanding the scope of geotechnical investigation and ensuring essential information for the design of deep foundations.

Another relevant aspect observed is the applicability of the PMT test in heterogeneous terrains, where there are layers with different degrees of resistance. Obtaining reliable parameters in these cases allows for more precise dimensioning of the foundations, ensuring greater safety and efficiency in geotechnical projects.

Based on the results obtained from the Ménard Pressuremeter Test (PMT) and the Piezocone Penetration Test (CPTu), the evaluated geotechnical profile presents favorable conditions for the use of both shallow and deep foundations.

At a depth of 3.36 m, the limit pressure and pressuremeter modulus values indicate a soil with adequate strength and stiffness for shallow foundations, with an estimated allowable bearing capacity on the order of 500 kPa and settlements within acceptable limits. CPTu interpretation at this level further confirms the presence of medium-dense sandy soils with good drained response, supporting the use of shallow foundations with controlled deformation.

At a depth of 9.32 m, the results indicate a very competent soil, with cone resistance exceeding 18 MPa and significant sleeve friction. These characteristics make this layer highly suitable for deep foundations, such as bored or continuous flight auger piles, offering high load-bearing capacity through both end bearing and skin friction.

According to Ménard (1975), the use of pressuremeter-derived parameters allows for a reliable assessment of both bearing capacity and elastic settlements for various foundation types. Additionally, CPTu-based correlations follow well-established methodologies, such as those by Schmertmann (1978) and Bustamante & Gianeselli (1982), providing confidence in the estimation of load capacity through both tip and side resistance.

Therefore, it can be concluded that the investigated subsoil is technically suitable for both shallow foundations in upper layers and deep foundations at greater depths. The final foundation type should be selected by the structural designer, taking into account the applied loads and the desired safety factors.

Thus, the results of this study highlight the relevance of the PMT test as a valuable tool for geotechnical investigations, contributing to the improvement of foundation engineering practices.

7. Acknowledgements

The authors are grateful for the support of REDE Engenharia and GEOFORMA for sharing the test raw data, results and analysis for this case study.

8. References

ABNT NBR 6122:2019. "*Projeto e Execução de Fundações.*" Rio de Janeiro, Brazil, ABNT, 2019.

Apageo, 2020, *Ménard pressuremeter test according to the ISO 22476-4 and ASTM D4719-07 standards*" Avaliable at: https://en.apageo.com/storage/upload/pdf/geopac-uk-2020.pdf accessed 03/06/2025.

ASTM D4719–87. "*Standard test method for pressuremeter testing in soils.*", American Society for Testing and Materials, Annual book of ASTM Standards, 1987.

ASTM D5778–20. "*Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils*, American Society for Testing and Materials, Annual book of ASTM Standards, 2020.

Baguelin, F., Jezequel, J.F., & Shields, D.H. (1978). "*The Pressuremeter and Foundation Engineering.*" Trans Tech Publications.

Bustamante, M., and Gianeselli, L. (1982). *"Pile Bearing Capacity Prediction by Means of Static Penetrometer CPT."* Proceedings of the 2nd European Symposium on Penetration Testing.

Colaço, A.S, 2017. "*Desenvolvimento e análise de um método simplificado para estimativa de recalques de fundações em solos arenosos utilizando ensaios pressiométricos."* Dissertação (Mestrado em Geotecnia – Universidade de Brasília, Brasília, Brasil).

Da Silva, E. M. D. J., 2001 "*Ensaio pressiométrico: metodologia de entail e calibração do equipamento".* Tecnovisão - Faro: Escola Superior de Tecnologia, 1994. - ISSN 0872-752X. - N. 11 (Jan. 2001), p. 23-28

Lunne, T.; Robertson, P.K. and Powell, J.J.M. (1997). *"Cone penetration testing in geotechnical practice*", Blackie Academic & Professional, 312p.

Menard, L., 1975 "*The Menard pressuremeter: Interpretation and application of the pressuremeter test results to foundations design."* General Memorandum, Sols Soils, 26, pp. 5-43. Avaliable at: https://insitusoil.com/wp-content/uploads/2022/02/French-2018-update-for-interpretation-and-foundation-design-from-pressuremeter-tests.pdf accessed: 03/06/2025.

Oliva, R. R. R. S., "*Caracterização do Comportamento de Materiais a partir do Ensaio Pressiométrico" (in portuguese) "Material Behavior Characterization from Pressiometric Test*", Doctoral Dissertation, Universidade Técnica de Lisboa, 2009. Available at: https://scholar.tecnico.ulisboa.pt/ records/ am8Wx5fEZK790lMKpqro-TDxZgdJgxksHmCY, accessed: 03/06/2025.

Oliveira, J. M., 2020., *"A importância dos projetos geotécnicos na engenharia civil."* Revista Engenharia e Construção, v. 28, n. 3, p. 45-58, 2020.

Santos, R., 2021. *"Simulação numérica de ensaios pressiométricos executados no campo experimental da UFG."* 2021. Dissertação (Mestrado em Engenharia Civil – Universidade Federal de Goiás, Goiânia, 2021.)

Robertson, P.K., and Cabal, K.L. (2015). *"Guide to Cone Penetration Testing for Geotechnical Engineering"* (6th ed.). Gregg Drilling & Testing.

Robertson, P.K. (2016) *"Cone Penetration Test (CPT)-Based Soil Behaviour Type (SBT) Classification System—An Update"*. Canadian Geotechnical Journal, 53, 1910-1927. https://doi.org/10.1139/cgj-2016-0044

Schmertmann, John H. *"Guidelines for cone penetration test: performance and design."* No. FHWA-TS-78-209. United States. Federal Highway Administration, 1978.

Schnaid, F., and Odebrecht, E., "*Ensaios de Campo e suas aplicações à Engenharia de Fundações"* (in portuguese) "Field Tests and its Application to Foundation Engineering" 2nd ed, Oficina de Textos, São Paulo, Brazil, 2012, ISBN 978-85-7975-059-5.

Schnaid F. (2009) *"In Situ Testing in Geomechanics*", 1st Edition, Taylor and Francis, London, New York. https://doi.org/10.1201/9781482266054