Essai pressiométrique Ménard sur géomatériaux provenant de l'industrie minière

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ABSTRACT

The pressuremeter test presents the attractive possibility of being used to derive soil properties to be used in indirect design methods. This article presents some results of PMT tests carried out on mining storages facilities. A procedure for analyzing the expansion of a cylindrical cavity proposed by Mantaras and Schnaid (2002) in cohesive-frictional materials is applied, with the aim of providing a theoretical framework to give rational support for analyses of pressure meter tests. The solution, formulated within the framework of non-associated plasticity and solved with the Euler method, was used to reproduce the measured test data. The Theoretical Simulation Analysis methodology of the pressure curve obtained in the field was used to estimate the set of values of the variables of the likely Mohr-Coulomb model. Application of the proposed approach is particularly relevant in the mining stores facilities. The mathematical interdependence of the variables also allowed us to establish the impact of the uncertainty of each parameter on the model's mathematical response. It is therefore suggested that the Mantaras and Schnaid (2002) solution can represent fundamental features of structured materials, which have not been incorporated in previously proposed models.

RESUME

L'essai pressiométrique offre une possibilité intéressante d'utilisation pour dériver les propriétés du sol et les utiliser dans les méthodes de conception indirecte. Cet article présente quelques résultats d'essais pressiométriques réalisés sur des installations de stockage minier. Une procédure d'analyse de l'expansion d'une cavité cylindrique proposée par Mantaras et Schnaid (2002) dans des matériaux cohésifs-frictionnels est appliquée, afin de fournir un cadre théorique pour étayer rationnellement les analyses des essais pressiométriques. La solution, formulée dans le cadre de la plasticité non associée et résolue par la méthode d'Euler, a été utilisée pour reproduire les données d'essai mesurées. La méthodologie d'analyse par simulation théorique de la courbe de pression obtenue sur le terrain a été utilisée pour estimer l'ensemble des valeurs des variables du modèle probable de Mohr-Coulomb. L'application de l'approche proposée est particulièrement pertinente dans les installations de stockage minier. L'interdépendance mathématique des variables nous a également permis d'établir l'impact de l'incertitude de chaque paramètre sur la réponse mathématique du modèle. Il est donc suggéré que la solution de Mantaras et Schnaid (2002) peut représenter des caractéristiques fondamentales des matériaux structurés, qui n'ont pas été incorporées dans les modèles proposés précédemment.

Keywords: ménard pressuremeter test, iron mining, tailing

1. Introduction

The safety of structures built with iron ore tailings and other minerals such as gold, copper, among others, has been receiving increasing attention, following structural accidents that have caused devastating impacts on the environment and neighboring society. These structures, designed to store waste from mining activities, may be made up of waste of different granulometries, such as fine and granular tailings, whose stability is intrinsically linked to the geotechnical characteristics of the subgrade and the massif. Analyzing this scenario, with in-depth studies of the mechanical properties and deformability of the soil, it is essential to ensure the stability of the structure in compliance with the safety factors (Oliva 2009).

Ménard pressuremeter test (PMT) is a geotechnical methodology for determining soil stress and deformation behaviors. This equipment is widely used in Europe as an associated methodology in research campaigns. It was pioneered by the French engineer Louis Ménard in 1955 to define a cylindrical element designed to apply uniform pressure to the walls of a borehole, through a flexible membrane (Schnaid and Odebrecht 2012). The use of the PMT provides intrinsic data on the deformability and resistance of the constituent materials, including the foundation, (Oliva 2009).

This test, capable of a closed analytical interpretation based on the cylindrical cavity expansion theory, allows a more robust interpretation of the geotechnical parameters and is not so dependent on simplifications, hypotheses and/or the need for empirical factors that often depend on other information coming from other tests.

2. Objective

The general objective of this article is to increase reliability and seek relevance in the use of the Ménard pressuremeter in the mining geotechnical engineering scenario. To achieve the general objective of this work, it was necessary to carry out a broad bibliographic review regarding the Ménard pressuremeter, both in normative aspects, procedure and execution of the test, as well as interpretation of its results. In studies to obtain geotechnical parameters inherent to the pressuremeter test based on robust methodologies founded on cylindrical cavity expansion theories.

3. Justification and Relevance

While Ménard Pressure Meter Tests – PMT are already widespread in Europe, they are still in a very early stage of usage in geotechnical investigation in Brazil. One likely reason is the lack of knowledge about the main concepts and advantages of the test in both academic and technical circles. This lack of knowledge ends up limiting its use and professionals end up presenting poorly detailed and imprecise technical specifications. On the other hand, professionals who use the results of this test are not widely familiar with the use of this important field test and end up avoiding its recommendation and specification.

Given this scenario, this article intends to contribute to the geotechnical community by providing relevant information about the test so that geotechnical designers and consultants can understand its application, procedure, internalization and even its limitations in a mining environment.

4. Materials and Methods

The PMT and CPTu tests were conducted following The studies were performed following the normative aspects ASTM D4719–87 (American Society of Testing and Materials 1987) on a mining area in order to understand the behavior of stress and deformation at different depths and compare the results obtained with the results of the CPTu tests performed according to ASTM D5778-2020 (American Society of Testing and Materials 2020).

The results of the tests for treatment and discussion were determined through investigation islands with results at different depths equidistant to 1 meter between the Ménard pressuremeter tests - PMT and CPTu. With these data, we seek to highlight the advantages and limitations of the test and provide greater familiarity, among the technical environment, with this important field test tool and eliminate possible effects of undeformed samples disturbance caused by the transportation or during laboratory opening to determine stiffness and resistance parameters that can be obtained through the execution of the Ménard pressuremeter tests - PMT.

4.1. Equipment

To carry out the Ménard Pressuremeter – PMT, it was used a hydraulic hollow auger drilling machine and a fully automated PMT equipment (Geopac) with capacity of up to 5Mpa consisting of the following equipment and tools:

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.

4.2. In-situ Tests Methodology

The test method carried out followed the studies developed by Louis Ménard, engineer and creator of the PMT – Menárd Pressumeter test.

Initially, calibration is performed with pressurization inside a rigid steel cylinder, when pressures are applied with increments every 60 seconds and monitoring is carried out with the aim of drawing a pressure-displacement curve, called an expansion curve. Subsequently, the second calibration is performed in air with the probe in the vertical position to correct the pressures according to the membrane resistance. The resulting pressure and deformation curve is plotted and from it the pressure correction resulting from the membrane resistance for pressure correction resulting from the membrane resistance for each injected volume can be obtained (Fig. 1).

Figure 1. Volume loss and pressure loss probe calibration. - Source: REDE Engenharia.

To begin the execution of the tests, drillings were carried out using the Hollow Auger equipment (Fig. 2), with an hydraulic probe (Fig. 3) up to one meter of the test depth and then a barrel with diameter BW was introduced and advanced 1.50 meters carefully in order to avoid disturbances in the borehole wall and thus be able to obtain the stress and deformation curve while performing the Ménard pressuremeter test. According to Schnaid and Odebrecht (2012), it is essential to control the relationship between the hole diameter (*Df*) and the diameter of the probe with the flexible membrane (*Ds*), where the recommended value is less than 1.15 due to the expansion limitations of the pressuremeter probe.

Figure 2. Drilling equipment, Minas Gerais, Brazil. - Source: REDE Engenharia.

Pressure probe consists of three compartments equipment, the two lateral are filled with nitrogen gas and the central cell is filled with pressurized water called a guard cell, aiming to centralize the expansion of the cavity in the central region of the pressure probe.

Figure 3. Hydraulic probe insertion for in-situ test. - Source: REDE Engenharia.

According to Louis Ménard, the test procedure involves applying equal pressure increments and recording the volumes obtained every 15 seconds, 30 seconds and 60 seconds after each pressure increment. After 60 seconds, a new pressure increment is performed, resulting in a pressure curve where the volume injected at the end of 60 seconds is presented in a graph as a function of the pressure applied.

The tests were executed using the GEOPAC (Apageo 2020), executed in a borehole pre-drilled by a hydraulic drilling machine. The test procedure using this equipment is started by executing a pilot bore until the intended depth, removing the drilling tools from the borehole, inserting the GEOPAC probe, setting the test parameters in the software, executing the automatic testing and removing the probe from the borehole after the test is completed.

5. Results

Test first test was carried out at a depth of 6.21 meters resulting in a maximum limit pressure (*PLm*) of 0.986Mpa. This pressure value is way below the equipment's loading capacity, that could reach the maximum of 5 MPa. This result, at this depth, indicate a very low resistance material. By the graph result (Fig. 4) it is possible to observe that, during the plastic soil phase, not many points were obtained, while the Ménard modulus was very close to *PLm* 0.986 MPa.

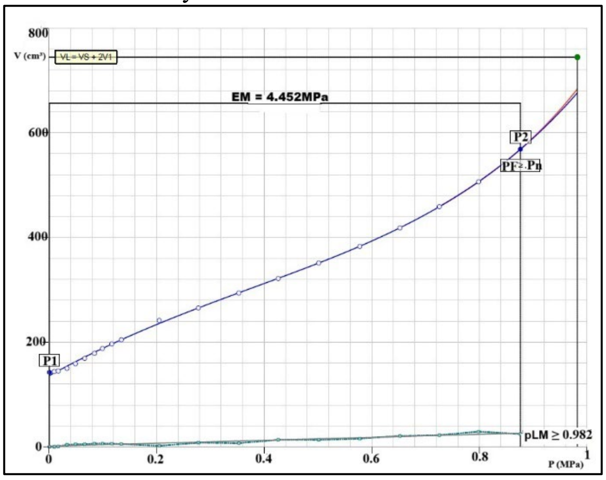

Figure 4. PMT Test Result – Depth 6.21m. - Source: VALE.

The second test was carried out at a depth of 16.14 meters resulting in a maximum limit pressure (*PLm*) of 2.595 MPa, at this point it is possible to observe pseudo-elastic phases with higher values and the Ménard modulus between the range of 0.56MPa and 1.43MPa, continuing up to *PLm* 2.595MPa (Fig. 5). Both results are presented on “Table 1” and “Table 2”.

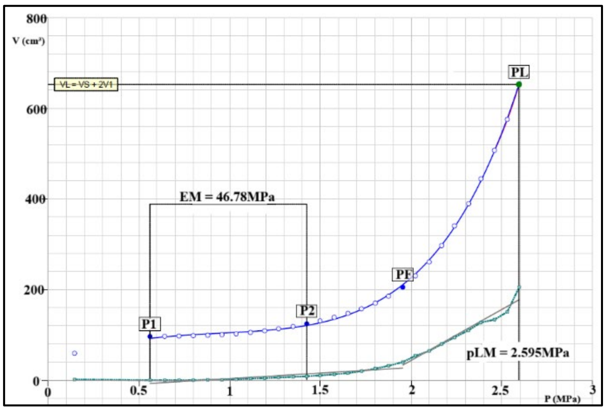

Figure 5. PMT Test Result – Depth 16.14m. - Source: VALE.

Table 1. PMT Results – Geotechnical Parameters

Depth	p_f (MPa)	p_{lm} (MPa)	E_M (MPa)
6,21m	≥ 0.876	≥ 0.982	4.52
16,14m	1.95	2.60	46.78

CPTu result with dilatant material behaviors fitting the Mod. SBTn classification (Robertson and Cabal, 2022) in predominantly unsaturated horizons and intercalations of point pore pressure peaks in materials layers with fine grain size at depths of 0.85 meters and 10.30 meters.

The results of the CPTu (Fig. 6) test show dilatant behavior of the material, falling within the Mod. SBTn classification (Robertson and Campanella, 1983). The soil predominantly presents unsaturated horizons, with specific pore pressure peaks in thin layers at 0.85 meters and 10.30 meters depth. The correlation between the tests suggests that, in regions of lower resistance detected by the pressuremeter, the CPTu also records lower values of tip resistance and lateral friction, confirming the presence of less competent soils. At depths where the pressuremeter indicates greater rigidity, the CPTu values also reflect an increase in resistance, corroborating the transition to a more resistant material.

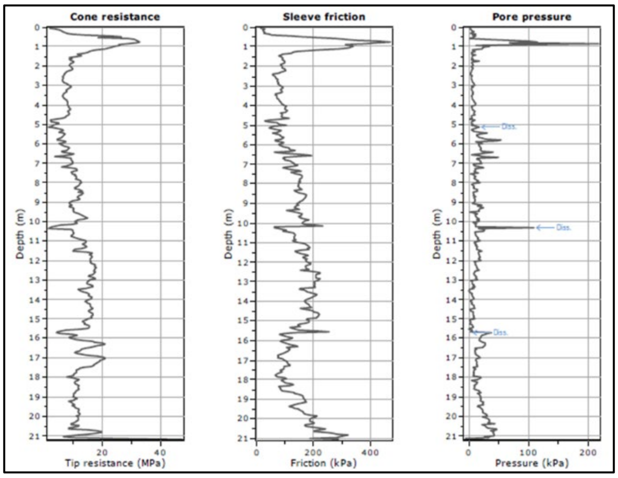

Figure 6. CPTu Test Result – From 0 to 21m. - Source: VALE.

Table 2. PMT and CPTu Results – Geotechnical Parameters

	PMT Parameters			CPTu Parameters		
Depth	*Pf* (MPa)	*Plm* (MPa)	*Em* (MPa)	*qt* (MPa)	*fs* (kPa)	*u* (kPa)
6,21m	≥ 0.876	≥ 0.982	4,5	8,52	0,1139	0,020
16,14m	1,95	2,60	46,8	15,92	0,1024	0,021

Considering the relative stiffness analysis its difference indicates greater density in the depth of 16,14m. The relative stiffness on "Table 3" was calculated by dividing Ménard modulus (EM) by cone resistance (q_t) as discussed by Ménard (1975). This correlation between Ménard modulus (EM) and cone resistance (qt) is a way of comparing soil resistance parameters obtained in different tests.

Table 3. Relative Stiffness

Depth	$\frac{EM}{qt}$
6,21m	$\frac{4,5}{8,52} \approx 0,53$
16,14m	$\frac{46,80}{15,92} \approx 2,94$

Besides the greater depth, the lateral friction fs is a bit lower, indicating a granular denser soil with less relative lateral friction, indicating a compaction variability.

The porepressure levels are very low in both depths (≈0,02Mpa), suggesting non cohesive soil or partially drained during the test in response of the CPT test. In both cases it is possible to estimate the undrained shear strenght (*Su*) by the CPTu results, using as reference studies by Schmertmann (1978) and by the PMT results using as reference studies by Ménard (1975). Both results are presented on "Table 4".

Table 4. Undrained Shear Strenght results from PMT (Su^1) and from CPTu (Su^2) results.

Depth	Su^1 (MPa)	Su^2 (MPa)	$\frac{Su^2}{Su^1}$
6,21m	0,087	0,561	6,44
16,14m	0,231	1,042	4,51

The undrained shear strenght (*Su*) obtained by PMT results (Ménard, 1975) was calulated as Eq. (1):

$$Su = \alpha \cdot (pL - \sigma_{v0}) \quad (1)$$

considering α ≈ 0,10 (for sands) and γ≈18 kN/m (estimated density by soil characteristics). The undrained shear strenght (*Su*) obtained by CPTu results (Schmertmann and Robertson (1978, 1983) as Eq. (2):

$$Su = \frac{(qt - \sigma_{v0})}{Nkt} \quad (2)$$

considering *Nkt* ≈ 15 (medium *Nkt*).

A comparison was performed between the internal friction angle values obtained from the Cunha (1985) method using the PMT results and those estimated using the correlation proposed by Robertson (2022) based on CPTu results. This comparison aimed to evaluate the consistency between the interpretations derived from different in situ testing methods applied to the same geotechnical profile.

The internal friction angle (ϕ) estimated from the pressuremeter test (ϕ^1) was calculated using the empirical method proposed by Cunha (1975), that relates the yield pressure (*pf*) and the limit pressure (*pL*) obtained from the pressure-expansion curve. The internal friction angle (ϕ) estimated from the CPTu test (ϕ^2) was calculated using the empirical correlation proposed by Robertson (2022) for granular soils, based on normalized cone resistance. Both results are presented on "Table 5".

Table 5. Internal friction angle results from PMT (ϕ^1) and from CPTu (ϕ^2) results.

Depth	ϕ^1 (º)	ϕ^2 (º)	$\frac{\phi^2}{\phi^1}$
6,21m	29,8	30,7	1,03
16,14m	29,9	31,8	1,06

6. Conclusions

The integrated analysis of pressuremeter tests (PMT) and piezocone tests (CPTu) enabled a consistent assessment of the geotechnical characteristics of the investigated subsoil. The data indicate a significant variation in the relative stiffness ratio (*EM/q*t), with values of approximately 0.53 at a depth of 6.21 m and 2.94 at 16.14 m, suggesting an increase in soil density and stiffness with depth, which is in accordance with the interpretations of Ménard (1975).

Despite the greater depth reached in the second test (depth of 16.14m), the sleeve friction (*fs*) was slightly lower than that of the first test (depth of 6.21m), which may be related to a more granular and dense soil composition, with local variations in compaction. The very low pore pressure values (≈ 0.02 MPa) at both depths reinforce the hypothesis of a predominantly sandy and non-cohesive or partially drained soil, consistent with the studies of Schmertmann (1978), Robertson and Campanella (1983).

The undrained shear strength (*Su*) estimated from the pressuremeter test yielded values considerably lower than those calculated based on CPTu. The ratio between Su from CPTu and PMT was 6.44 at 6.21 m and 4.51 at 16.14 m, which is typical for sandy materials, where CPTu tends to overestimate strength due to the lack of effective cohesion. The draining behavior of the material, combined with the different test methodology, was a determining factor for the observed discrepancy.

The estimation of the internal friction angle (ϕ) showed good agreement between the pressuremeter and piezocone test methods, with only minor variations observed between the obtained values. This convergence is attributed to the relative homogeneity of the tested soil and the predominance of frictional behavior, which is characteristic of predominantly granular soils. In contrast, the undrained shear strength (*Su*) exhibited greater variability, which is consistent with the granular nature of the investigated profile and the influence of local heterogeneities under undrained conditions.

In summary, the results support the interpretation of a granular soil profile exhibiting a progressive increase in density and stiffness with depth, low pore pressure, and predominantly non-cohesive behavior. The combined use of PMT and CPTu proved to be effective for characterizing such soils, as these methods provide complementary data that enhance the understanding of the subsoil's geomechanical behavior. This integrated approach serves as a valuable source of additional information, contributing to more accurate slope stability analyses and design, especially in deep and heterogeneous structures such as mining dams and pile foundation.

7. Acknowledgements

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