A View of Pressuremeter Testing in North America

J. Benoît, J.A. Howie

Abstract. The pressuremeter was introduced to North America by Ménard in 1957. It consists of a cylindrical probe which is inserted into the ground in a borehole, by self-boring or by pushing, and is expanded against the soil or rock to obtain a pressure-expansion curve. Interpretation methods based on cavity expansion theory applied to realistic models of soil behavior allow derivation of *in situ* lateral stress, stiffness, strength and volume change characteristics of the material being tested. Since its introduction, the pressuremeter test (PMT) has been a popular topic of research but has not gained wide acceptance in geotechnical engineering site characterization practice which, in North America, is still dominated by the Standard Penetration Test (SPT) and more recently by the piezocone (CPTu). Over the same period, the PMT has become the dominant tool for site investigation and foundation design in France. There, the PMT is used empirically based on a very large amount of load testing and experience. This paper examines the use of the PMT in North American practice, discusses its strengths and weaknesses, identifies trends in its use for site characterization and geotechnical design and identifies possible reasons for its lack of adoption by industry. We conclude that the PMT is not competitive with other techniques such as the CPTu and SPT for general site characterization where such tests are possible but that the PMT offers great potential to provide geotechnical design parameters in problematic materials such as hard, very dense or gravelly soils, residual, saprolitic or lateritic soils, soft and fractured rocks, frozen ground and ice. The PMT also has application in all soils where high consequences of failure require very detailed analysis and design. We also emphasize the need for improvements in the education of geotechnical practitioners on the use of the pressuremeter.

Keywords: Ménard, pressuremeter, self-boring, prebored, pressuremeter design.

1. Introduction

The original concept of the pressuremeter dates back to Kögler in 1933 who developed a device consisting of a rubber bladder clamped at both ends and lowered in a pre-bored hole. The expansion of the device against the sides of the borehole allowed the determination of the stress-strain characteristics of the soil. Without knowledge of Kögler's work, Ménard (1957) developed a much improved pressuremeter (PMT), which has been widely used in engineering practice for more than half a century. In spite of the simplicity of this concept, there are a number of inherent problems associated with inserting an instrument in a pre-bored hole. The pre-drilling of a borehole inevitably induces disturbance due to the drilling process and also allows unloading due to pre-boring the hole. When used in relatively stiff soils and soft rocks, these problems are easily overcome, but in soft clays and cohesionless soils such as sands, these problems are more difficult to circumvent. However, under the assumptions that disturbance and stress relief are minimal when using careful borehole preparation techniques, the cavity expansion measurements and interpreted results can be used directly in a set of design rules, derived empirically but based on theory. The results can also be used indirectly by obtaining soil and rock strength and deformation parameters which can be used in conventional design of geotechnical structures.

Recognizing the effects of pre-boring on the parameters obtained and the corresponding necessity of using empirical correlations, French and English research groups (Baguelin *et al.*, 1972; Wroth & Hughes, 1972) independently developed a self-boring pressuremeter (SBPM) which could be inserted into the ground with minimal disturbance. The SBPM probe is similar in testing concept to the pre-bored pressuremeter except that it is advanced into the ground through a balanced process of pushing while cutting the soil which enters a sharp cutting shoe located at the bottom of the probe. The cuttings are flushed above the probe in the annular space inside the probe body. Results from SBPM tests have been used primarily to obtain soil parameters such as strength and deformation properties for use in conventional design or analytical methods such as finite element analysis. Other types of pressuremeters have been introduced, mostly in an effort to increase productivity especially offshore. Such techniques include push-in and full displacement devices. These methods also induce a consistent and repeatable amount of disturbance and consequently are not as operator dependent.

Regardless of the type of probe used or method of placement into the ground, once the appropriate depth is reached, a pressuremeter test is conducted as follows. The membrane is expanded against the sides of the borehole and the pressure, displacement and, in some cases, porewater pressures are monitored and recorded. Either stress or strain

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controlled expansion tests may be carried out. Each test may generally be conducted in 10 to 30 min depending on the type of material and test procedure.

This paper will review the current use of the pressuremeter as an *in situ* testing tool in North America, highlight its benefits and discuss why its use has been limited compared to other field techniques such as the Standard Penetration Test (SPT) and the Cone Penetration Test (CPT). While emphasis will be placed on the prebored pressuremeter test, other pressuremeter tests will be discussed in terms of applicability and acceptability to engineering practice.

2. Background

The prebored pressuremeter as we know it today is the product of the vision and ingenuity of Louis Ménard while a student at Ecole Nationale des Ponts et Chaussées in Paris. As part of his final project, Ménard and his two colleagues (Gauthier *et al.*, 1954) described the pressuremeter shown in Fig. 1, its use, and a theoretical study governing the interpretation of the test curve. Although the manuscript was only 20 pages, it covered stresses and displacements around the expanding cylindrical cavity for cases of cohesive soils, saturated sands and clays, unsaturated soils and inelastic soils followed by numerical examples for dry and saturated soil. They concluded that the principal advantage of pressuremeter use was to allow the study of pressure-deformation characteristics of soils and that their study was to shed light on the interpretation of those results. At that stage of their study, they also assumed that no remolding of soil occurs as a result of borehole preparation. Ménard's patent application followed and was submitted in Paris on January 19, 1955. The schematic of his probe described in his patent application is as previously shown in Fig. 1.

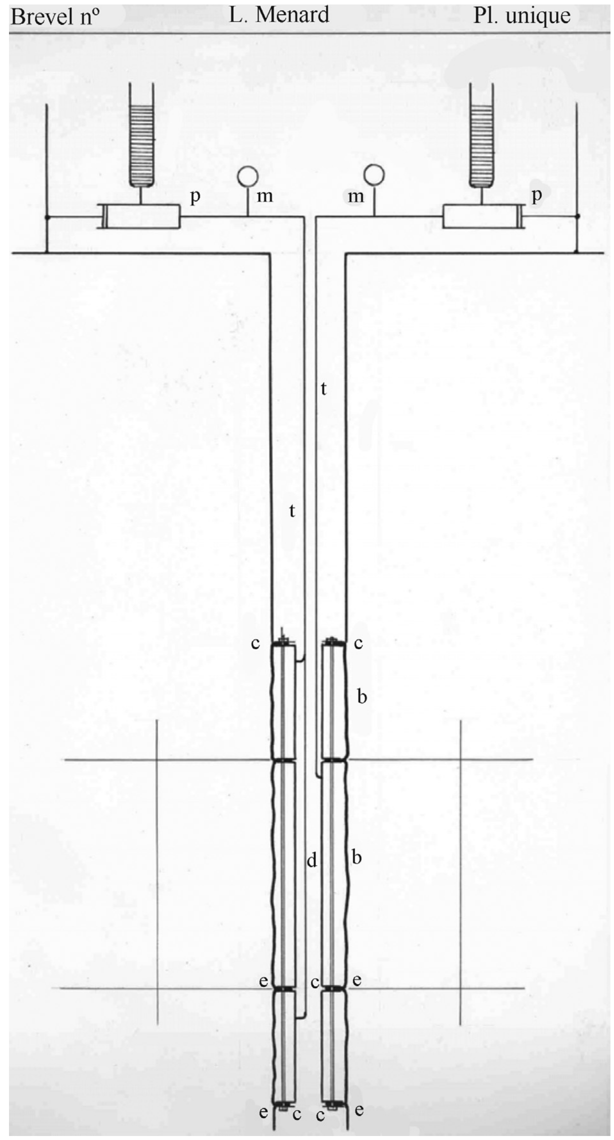


Figure 1 - Schematic description of the original pressuremeter (Gauthier *et al.*, 1954).

Following his studies in Paris, he travelled to the USA to do a Master's thesis under Dr. Ralph Peck. His thesis entitled "An Apparatus for Measuring the Strength of Soils in Place" was completed in 1957 at the University of Illinois. Ménard recognized that his invention, which he coined the "pressiometer" had competition from other field tools such as the field vane in clays and the standard penetration test in sands. However, he recommended his tool because "A theoretical interpretation of the curve "strain versus stress" gives immediately the values of the cohesion, the friction angle and the modulus of elasticity." From his work he concluded the following:

a) The pressiometer is a very precise method of subsurface exploration;

b) The bearing capacity increases with the modulus of elasticity of the soil.

Part of his research work included testing in various soils such as glacial till, fluvial and compacted clays and sand. Figure 2 shows pressuremeter tests done in Chicago clays at shallow depth in an investigation designed to evaluate the remolding due to the driving of H-piles and decompression from the excavation for the Island Steel Building. The test labeled 42 was performed 1 m away from the pile while test 44 was done at the same depth but only 0.3 m away. The results from the tests indicated a decrease in undrained strength of about 40% due to the driving of the piles and unloading from the excavation while the modulus of elasticity varied from 41 kg/cm^2 (4 MPa) for the undisturbed clay compared to only 6 kg/cm^2 (0.6 MPa) for the remolded clay. Through testing at two other sites, Ménard was able to demonstrate good agreement between his theoretical derivations and the experimental results.

According to Ladanyi (1995), Ménard recognized some limitations in his initial theoretical approach to interpretation of the test and began to develop empirical rules governing the use of the pressuremeter results for founda-

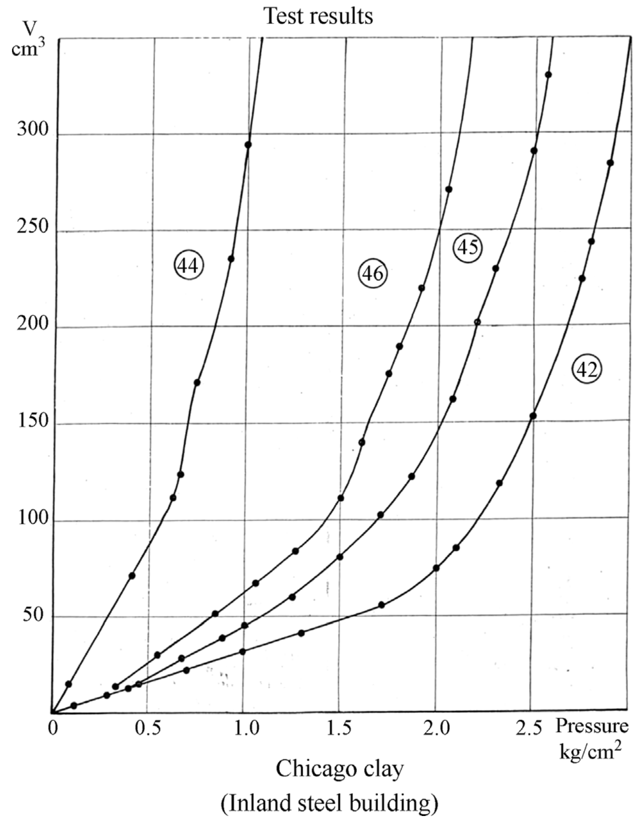


Figure 2 - Pressuremeter tests performed by Ménard in Chicago clays (Ménard, 1957).

tion design. The approach was validated initially by comparison to full-scale load tests and has been improved and extended by research and practice in the years since, particularly in France where it has become the dominant tool for site investigation and foundation design. Although the original pressuremeter shown in Fig. 1 required a borehole diameter of 140 mm, the second prototype was reduced to 50 mm (Cassan, 2005). A series of improvements and modifications in the guard cells' design and pressurization, volume and pressure measurement systems, membrane protection, and control unit for conducting and recording the test were continuously implemented in an effort to make the pressuremeter a more reliable and accurate test method. These changes also allowed the pressuremeter to be used at greater depths and higher pressures. Dimensions of the pressuremeter also evolved to improve on the length to diameter ratio. Other groups outside France have also modified the details of the pressuremeter and the system used to measure expansion of the pressuremeter membrane by using various displacement sensors instead of volume measurements.

The prebored pressuremeter has been successfully used in hard soils and soft or weak rocks where other *in situ* tools cannot penetrate these materials or lack the capacity to measure geotechnical parameters in these formations. Special probes with rugged membranes can acquire pressure-expansion curves which can be interpreted to estimate material stiffness properties and, in some cases, strength parameters in carefully prepared boreholes.

Ménard protected his invention from outside influence for 10 years through patent protection but in 1969 began to sell and license its use to others (Ladanyi, 1995). This opened the pressuremeter concept to much research. In an effort to eliminate the disturbance effects of preboring, the self-boring pressuremeter was developed by research groups in France (Baguelin *et al.*, 1972) and England (Wroth & Hughes, 1972). Differences exist between the French system (PAFSOR) and the British system (CamKoMeter) but the objectives are the same. Insertion of the probe into the ground occurs using a cutter system located inside a cutting or driving shoe to minimize disturbance. As the probe is pushed into the ground, the soil which enters the cutting shoe is cut by the rotating cutter and flushed to the ground surface through the annular space inside the probe body. Other systems of advance have been successfully used, *e.g.* jetting (Benoît *et al.*, 1995) and have proved to often be more time-effective in soils. Once the testing depth is reached, the membrane is expanded against the sides of the borehole and the pressure, displacements (or volume) and, in some cases, porewater pressures, are measured continuously and automatically. The SBPM test can be conducted in a stress or strain controlled manner. Because the SBPM is inserted with minimal disturbance, the cavity expansion measurements can be analyzed using basic continuum mechanics of cavity expansion and consequently engineers need not rely on empirical correlations to obtain soil parameters for use in foundation design.

Other types of pressuremeter were introduced in an effort to circumvent the requirements to produce a prepared hole for testing or to use an often time consuming method of advance in the case of self-boring by using pushing as the method of insertion. The need for pressuremeter testing offshore was the major catalyst for these innovations. One approach developed was the Push-in Pressuremeter (Reid *et al.*, 1982) which comprised an expansion unit mounted around a tube similar to a sample tube. However, Bandis & Lacasse (1986) showed that the insertion of this unit caused considerable disturbance and the fact that the probe had to be withdrawn from the hole between tests did not offer significant improvement in productivity. Another development aimed at the offshore market was the Cone Pressuremeter which was also known as the Full-Displacement Pressuremeter (Hughes & Robertson, 1985; Withers *et al.*, 1986). The Pencel Pressuremeter was an adaptation of the pavement evaluation tool described by Briaud & Shields (1979) which was also pushed into place for testing. These tools were based on the concept that it was better to create a consistent, repeatable degree of disturbance in the soil adjacent to the expansion unit. An additional advantage of this method is an increased production rate.

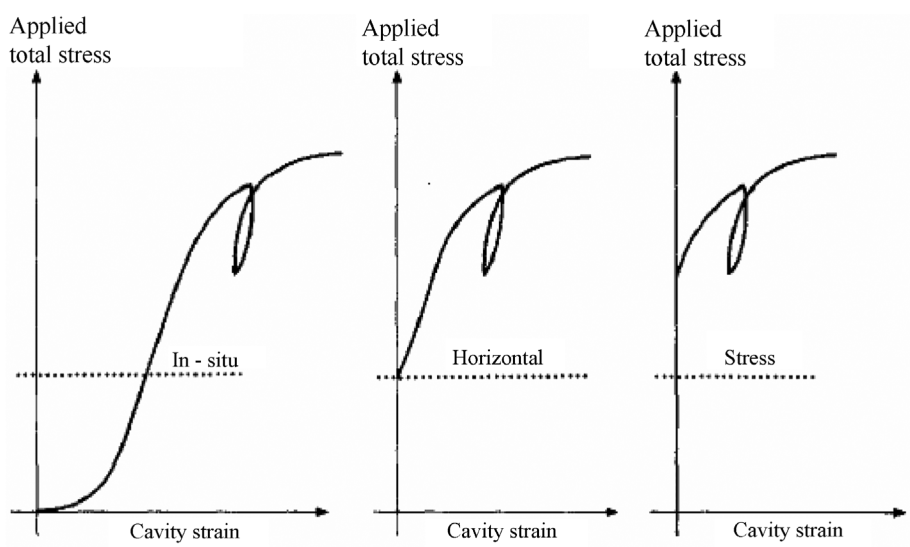
3. Approaches to Analysis and Interpretation of Test Curves

In a report by the ISSMGE Committee TC 16 on pressuremeter testing in onshore ground investigations, Clarke & Gambin (1998) noted that two approaches to interpretation and use of pressuremeter results had evolved. One was based on analytical methods used to derive basic soil properties (strength, stiffness etc.) from the test curves and the other was based on the development of a set of empirical design rules based on measurements made in a very standard way with a standard instrument. They also hinted at a strong diversity of opinion between proponents of the two approaches but regarded such differences as healthy.

Figure 3 from Clayton *et al.* (1995) shows schematic pressuremeter curves obtained using the three principal methods of insertion. The differences are readily seen. For the prebored test, the wall of the test pocket has been unloaded by the drilling and will have relaxed inwards. The pressure increase and deflection required to re-establish contact between the probe and the cavity wall and to exceed the *in situ* lateral stress to begin expansion will depend on the material type and properties, the relative diameters of the borehole and the probe, the quality of the drilling and the expertise of the pressuremeter test field crew in installation of the probe. This results in an S-shaped expansion curve. For the full displacement probe, since it is pushed into the ground, the initial deformation results in the expansion curve starting at a higher stress. In principle, for the self-boring advance, the stresses *in situ* are theoretically unchanged by the probe insertion and thus the beginning of the expansion curve should represent the *in situ* lateral stress.

In reality, no probe can be installed without some disturbance of the soil. For example, a 0.5 mm expansion of a 76 mm diameter pressuremeter represents 1.3% cavity strain ($\Delta r/r_o$ where r_o is the initial cavity radius and Δr is the change in radius). With full scale expansion of a typical SBPM test being only 10% cavity strain, small movements induced during installation can have a large effect on the measured expansion curve. For most soils, such a deformation would lead to the formation of a zone immediately adjacent to the pressuremeter that has reached yield. For saturated fine grained soils, this will be a zone exhibiting excess pore pressure and in free-draining soils, will be a zone of volume change. From Fig. 3(b), it can be seen that there is the potential for disturbance to cause large stress changes from the *in situ* stress even for SBPM testing in relatively soft soils. In stiff soils, the potential stress changes are very large. Consequently, "lift-off" pressures are unreliable measures of *in situ* stress even in a test conducted after expert installation of the probe. Much research effort has been expended in an attempt to clarify the effects of such disturbance on subsequent test curves but the fundamental problem is that it is not possible to reliably assess from the measured test curve the degree of disturbance caused by installation of the probe.

The schematic test curves in Fig. 3 all include unload-reload loops. Palmer (1972) showed that the slope of the initial part of an ideal expansion curve is twice the shear modulus. To avoid the effects of disturbance on the initial part of the expansion curve, unload-reload loops can be interpreted to give the elastic shear modulus of the soil or rock. Such loops are considered to be little affected by disturbance as is shown in Fig. 3 where the slopes of the unload-reload loops are similar in all three cases.



(a) Borehole pressuremeter (b) Self-boring pressuremeter (c) Full displacement pressuremeter

Figure 3 - Schematic differences in stress-strain curves as a result of pressuremeter installation procedures (Clayton *et al.*, 1995).

3.1. Interpretation to derive soil properties

The analysis of pressuremeter test results based on theory requires the following assumptions:

- The probe can be installed without disturbing the soil to be deformed by the test (or in the case of the cone pressuremeter, the degree of disturbance is consistent),
- The assumed soil model is representative of the stress-strain response of the soil being deformed by the pressuremeter expansion,
- Deformation occurs under plane strain conditions.

The analysis is dependent on the type of soil and whether the cavity expansion is conducted drained or undrained. If the test is undertaken in a saturated fine-grained soil and the test is conducted fast enough to prevent drainage, then the soil will deform at constant volume and all elements surrounding the probe will have the same stress-strain behavior. However, if the soil is a free draining granular material, the stress-strain curve will no longer be unique with radius but rather a function of the stress level. In other words, near the walls of the cavity the stresses will be high and hence the shear resistance will be high. Both stresses and strength will decrease with radial distance. Furthermore, because the volume is allowed to change during the test, as the sand shears, the material will expand or dilate depending on its initial stress level and initial density. If the material is a rock then the interpretation becomes even more complex because of the tensile strength of the rock, the presence of discontinuities and planes of weakness and the determination of a suitable failure criterion.

In general, from a pressuremeter test, it is possible to obtain, empirically, theoretically or analytically, the lateral stress in the ground, the stress-strain behavior, the strength and in some cases the consolidation characteristics. Several interpretation techniques are available to evaluate these various parameters.

The early approaches to pressuremeter interpretation based on cavity expansion theories used graphical manipulations of the test curves to derive soil parameters. Table 1 from Yu (2004) gives examples of available methods to interpret fundamental soil parameters from *in situ* testing. In the initial attempts at interpretation, parameters were treated separately. The total lateral stress was taken to be the stress at first movement of the membrane ("lift-off" pressure), the shear modulus was derived from unload-reload loops or from an inferred stress-strain curve and shear strength was obtained from graphical manipulation of the test curve. As noted by Ladanyi (1995), with the advent of the PC-age, the whole pressuremeter curve could be analyzed using computer-aided modeling. Shuttle & Jefferies (1995) refer to the process as Iterative Forward Modeling. The ability to simulate complete pressuremeter curves, both loading and unloading, using realistic soil models has led to attempts to use comparisons between simulated and measured pressuremeter curves to obtain estimates of geotechnical parameters. Both expansion and contraction curves can be modeled. To use the approach, a group of relevant parameters is selected based on the assumed constitutive model and is used to predict a theoretical curve. The parameters are adjusted until good agreement is achieved between the measured and calculated curves. Figure 4(a) shows an example of curve fitting for a clay soil from Jefferies (1988) and Fig. 4(b) is an example for sand from Roy *et al.* (2002). Both of these examples are based on SBPM data. However, modeling can also be applied to prebored or full-displacement pressuremeter test data, provided the curve-matching focuses on the latter part of the expansion curve or the unloading curve (*e.g.* Ferreira & Robertson, 1992). Schnaid *et al.* (2000) suggested that in a lightly structured granite saprolite, the curve fitting technique applied to the loading curve of a SBPM test provided

Table 1 - Examples of the capabilities of *in situ* tests for measuring soil properties (Yu, 2004).

Test	Measured Properties	Selected References
Cone penetration tests (CPT/CPTU)	Soil profiling; Stress history (OCR); Consolidation coefficient; In situ state parameter for sand; Undrained shear strength; Hydrostatic pore pressure	Robertson (1986), Wroth (1984), Mayne (1993), Baligh and Levadoux (1986), Teh (1987), Been *et al.* (1987), Yu and Mitchell (1998), Lunne *et al.* (1997)
Self-boring pressuremeter tests (SBPMT)	Horizontal in situ stress; Shear modulus; Shear strength; Stress-strain curve; In situ state parameter for sand; Consolidation coefficient; Small strain stiffness	Jamiolkowski *et al.* (1985), Wroth (1982), Gibson and Anderson (1961), Hughes *et al.* (1977), Palmer (1972), Manassero (1989), Yu (1994, 1996, 2000), Clarke *et al.* (1979), Byrne *et al.* (1990), Jardine (1992), Fahey and Carter (1993), Bolton and Whittle (1999)
Cone pressuremeter tests (CPMT)	Horizontal in situ stress; Shear modulus; Shear strength; In situ state parameter for sand	Houlsby and Withers (1988), Schnaid (1990), Yu (1990), Yu *et al.* (1996)
Flat dilatometer tests (DMT)	Soil profiling; Horizontal in situ stress; Stress history (OCR); Shear strength; In situ state parameter for sand	Marchetti (1980), Mayne and Martin (1998), Finno (1993), Huang (1989), Yu (2004)

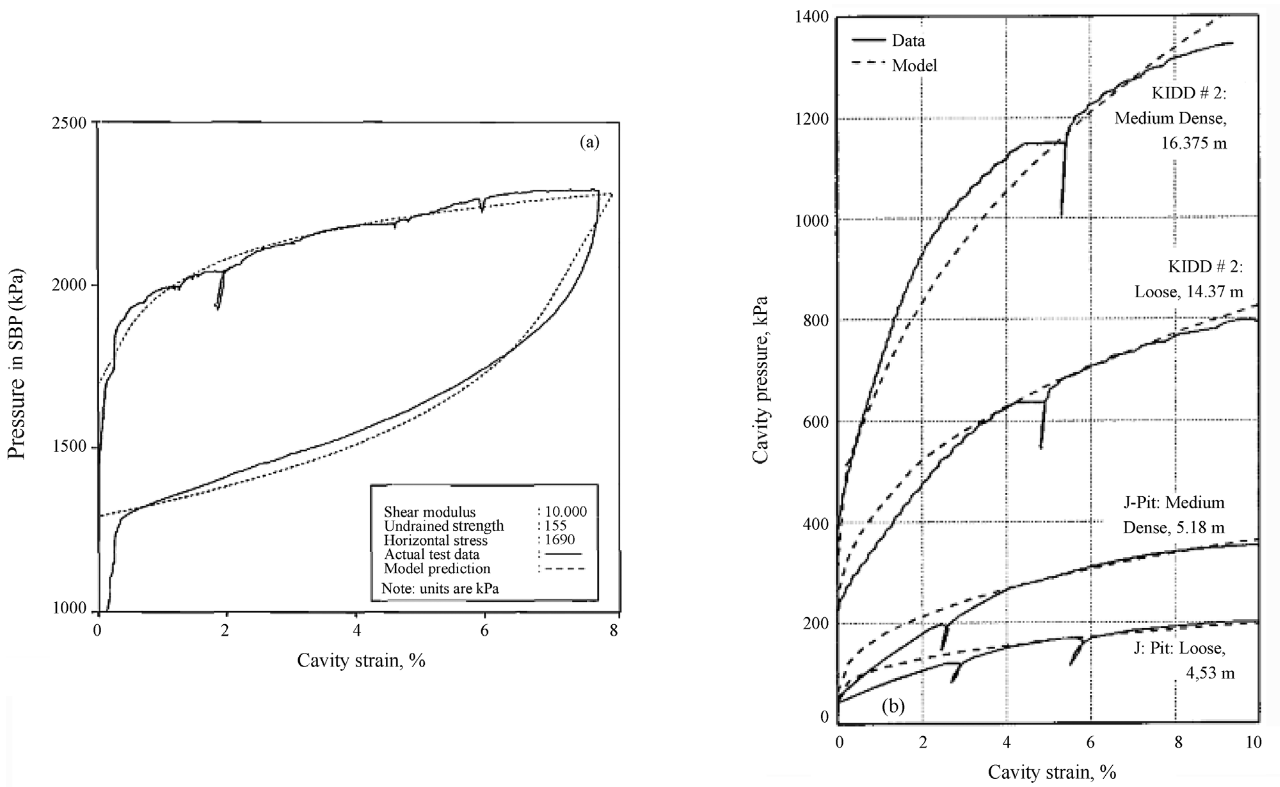


Figure 4 - (a): Example of curve fitting in clay (after Jefferies 1988). (b): Example of curve fitting in sand (Roy *et al.*, 2002).

properties typical of peak shear strength parameters, whereas those obtained from the unloading portion were more typical of the critical state behavior.

This approach has the advantage that parameters are related to each other and can be checked for consistency with those of soils that are typical of the soil being tested. For example, for a linear elastic, perfectly plastic soil, the parameters assumed would be the total horizontal stress, shear modulus (G) and undrained shear strength (s_u). Whether the resulting derived soil parameters are typical of the soil being tested can be assessed. Similarly, the estimated total lateral stress and equilibrium pore pressure can be used to derive the coefficient of earth pressure at-rest, K_o. This value can be assessed against values typical of soils with similar geological history. As the soil models increase in complexity, the number of soil parameters that have to be adjusted may become large.

Numerical analysis also allows the influence of departures from the ideal case to be assessed. For example, Yeung & Carter (1990), Houlsby & Carter (1993) and Jefferies & Shuttle (1995) discuss the effect of the finite length of the probe on the shear strength and rigidity index derived from approaches based on assumption of an infinitely long cavity and linear elastic, perfectly plastic soil behavior. These authors show that the effects of the finite length should be considered in the interpretation of the pressuremeter curves and indicate that such effects could result in errors in interpreted undrained shear strength of up to 40%.

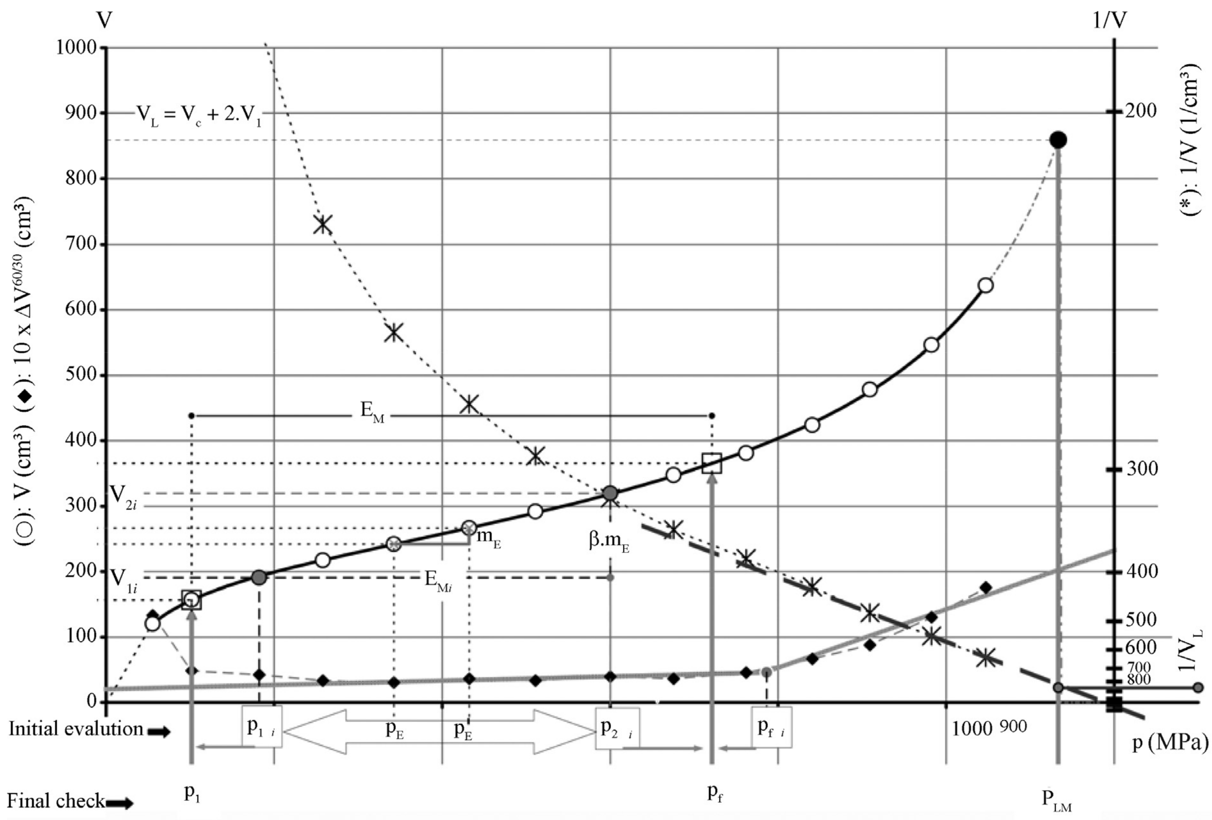
It is clear that computer aided modeling provides great potential for the interpretation of pressuremeter test curves to determine the characteristic behavior of the soil tested. However, the interpretation must be considered together with other available geotechnical and geological information about the material and requires the application of engineering judgment based on an appreciation of the factors affecting the results.

3.2. Interpretation by Ménard rules

The alternative to interpreting the curves to obtain fundamental properties and the attendant problems arising from the many uncertainties in both the test curve and the interpretation is the one followed by Ménard and developed by his collaborators and successors. A prebored pressuremeter test is conducted using a standard probe, installed according to restrictive drilling requirements governing the formation of the test pocket, and expanded according to a standard test procedure. The resulting test curves are analyzed in a prescribed way and specific parameters are derived from them.

From a conventional pressuremeter expansion, three basic parameters are obtained: the creep pressure p_f, the Ménard modulus E_M and the limit pressure p_{LM}. Figure 5 shows the analysis procedure from the current international draft standard, ISO 22476 4, which is used to define the three main pressuremeter parameters: p_f, E_M, and p_{LM}. The quality of the test is evaluated using the number of data points available to define each portion of the expanding cavity as well as the scatter of the test points. The test curve shown in Fig. 5 is an ideal test. The first part of the curve is a recompression zone, followed by a quasi-linear zone which transforms to a non-linear third portion as the cavity volume approaches twice its initial volume. The test curve has been corrected for pressure and volume losses per standard calibration procedures outlined in the standard.

A test where test points are found in the first two groups only may indicate that the test hole was too large while a test with only the last two groups of points is generally indicative of the hole being too small or the presence of swelling ground. This approach has been in existence for decades as previously reported by Kastman (1978) using PMT tests carried out in the USA. Below the test curve is the corrected creep curve resulting from the differences in volume between the 30 s and 60 s readings from each pressure increment. This creep curve is used to define the various sections of the test. For example, the creep pressure is



Key:

(○) Corrected pressuremeter test data points fitted with double hyperbolic curve

(◆) Pressuremeter creep data points (volume scale enlarged ten times)

(✱) Corrected pressuremeter test data points on 1/V scale (volume reciprocal scale on the vertical axis, right hand side)

(□) Points retained to obtain E_M after final check for p_{LM} and p_f

(●) The Black point retained for p_{LM} (D.4.2)

(●) The 2 grey points initially limiting the pseudo-elastic range (D.5.1)

(*i*) Stands for "initial"

Double hyperbolic fitted curve

Inverse volume straight line fitting the last three values

Example of creep data points fitting

Figure 5 - Pressuremeter test curve analysis (ISO/FDIS 22476-4:2009 (E)).

located between the values p_{2i} and p_{fi} which are estimated using a graphical procedure. It has been shown that the quality of the test is reflected in the closeness of those two values.

The limit pressure is also obtained from the test but typically using an extrapolation technique. The limit pressure is defined as the pressure required for doubling the initial borehole cavity. In practice, this pressure is rarely attained because of the risk of membrane burst at higher expansion. Consequently, the limit pressure is obtained by extrapolation using a variety of methods. Often the value is obtained visually using the test curve. However, more reproducible methods should be used such as the reciprocal method (1/V from ASTM and ISO 22476-4) or the double hyperbolic method. Figure 5 illustrates both techniques.

Finally, the pressuremeter modulus, often referred to as the Ménard modulus, is generally defined as the slope of the linear portion of the expansion curve prior to the creep pressure. This pseudo-elastic range is defined by points p_{1i} and p_{2i} in Fig. 5. The modulus obtained using the pressuremeter test is often quoted as being an elastic modulus equal to Young's modulus since it is obtained from Eq. 1 which is based on the theory of linear elasticity (Gambin *et al.*, 1996).

$$E_M = 2(1+\nu)\left[V_c + \left(\frac{V_1 + V_2}{2}\right)\right]\frac{(p_2 - p_1)}{(V_2 - V_1)} \qquad (1)$$

with Poisson's ratio ν = 0.33, where E_M = pressuremeter modulus and V_c = volume of initial cavity.

However, as stated by Gambin *et al.* (1996), Ménard recognized that the modulus of the soil was dependent on the stress path and strain level. It is clear from Gambin *et al.* (1996) and Briaud (1992) that the slope of the curve used to derive the modulus E_M obtained using the pressuremeter is influenced by the various parameters and conditions including the coefficient of earth pressure at-rest, K_o, the friction angle, soil stiffness, the length to diameter ratio of the pressuremeter probe, the stress path, the disturbance of the borehole wall and the test expansion strain rate. The pressuremeter modulus, E_M, is more appropriately referred to as a modulus of deformation. Gambin *et al.* (1996) conclude that in analyses of deformation based on linear elasticity where a modulus is required, E_M should likely be multiplied by a factor of 5 to 10 if it is going to be used as a Young's modulus.

Interpretation of the pressuremeter test is well-detailed in the standard but is still subject to variability. Reiffsteck (2009) reports that pressuremeter test curves provided to 9 individuals as part of a pile prediction exercise during the International Symposium on Pressuremeters (ISP5) yielded an acceptable range of pressuremeter modulus and limit pressure. Figure 6 shows the results in terms of limit pressure for a total of 42 PMT tests. Reiffsteck states that the mean error is in the order of 24% which is consistent with errors observed with other *in situ* tests such as the CPT as reported by Long (2008).

Because these parameters are obtained by a standard procedure in all materials, their values can be used in a similar manner to the standard parameters measured in the CPTu (tip, friction and pore pressure), *i.e.* by comparison with data from other similar materials, it is possible to make qualitative assessments of the likely soil characteristics. The parameters can also be used to design foundations by following strict design rules. From the onset, design rules have been devised in France using the pressuremeter results directly in the assessment of bearing capacity of shallow foundations, deep foundations including lateral loading, settlement evaluation of shallow and deep foundations as

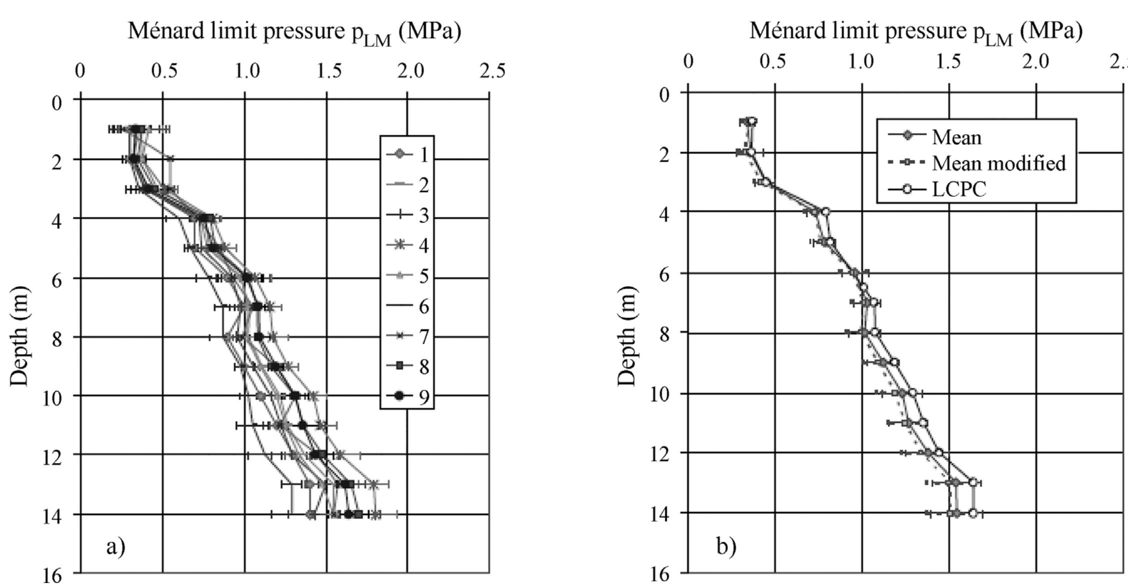


Figure 6 - Limit pressure from 9 participants on 3 boreholes for a total of 42 tests (Reiffsteck, 2009).

well as a panoply of applications to geotechnical structures and methods. From the pressuremeter deformation modulus, it is possible to assess settlement of foundations and displacement of laterally loaded piles while with the limit pressure, the bearing capacity can be evaluated for shallow and deep foundations. These rules are based on theory as well as observations and measurements of numerous instrumented experiments carried out at well documented test sites located in a variety of geological materials. The rules are not described in this paper but can be found in numerous documents (Briaud, 1992). However, many are in French. Work is ongoing to incorporate these design rules into the Eurocode which would make them significantly more accessible.

The majority of design work in France is done using the PMT and the well-established design rules. With improvements in testing techniques, equipment, additional observations and advanced numerical modeling, the rules are constantly revised to provide more versatile, accurate and safe design procedures. Expanding these rules through the Eurocode will also lead to improvements.

Some examples are provided herein to illustrate the efforts undertaken by various French research groups to advance the Ménard design rules. For example, Bustamante *et al.* (2009) in a paper describing pile design using the PMT, states that the current method is based on 561 pile load tests on more than 400 piles instrumented to measure skin friction and end bearing. These piles have been installed using more than 26 different techniques. They also show that the PMT is often more versatile than other *in situ* tests such as the CPT, the SPT and coring for laboratory testing as shown in Table 2. The tests were carried out in various materials including weathered or fragmented rock and cemented or very fine cohesionless formations. Their results led to improvements in design charts for unit skin friction, q_s, and a simplification of tip bearing factors, k_p, for 26 pile types. The work was further simplified as part of the drafting of the French standard for deep foundations for implementation in Eurocode 7 (AFNOR, 2012; Reiffsteck & Burlon, 2012). Using results from 159 load tests, a chart as shown in Fig. 7 was developed for determining the unit skin friction, q_s. Each curve represents a different pile type and installation method and was validated using, on average, 30 load tests. The values for f_{sol}, equivalent to the normalized unit frictional resistance, f_s, are given in tabular form in the standard NF P94-262 as a function of soil type. The unit skin friction, q_s, is then determined using f_{sol} multiplied by a soil-structure coefficient which is a function of pile type and installation method as well as soil type. The standard also provides limiting values for q_s for each case. The methods are straightforward, reliable considering the number of load tests used in their development, and useful especially for cases with similar geological conditions.

4. Pressuremeter Testing in North America

Based on a review of North American literature, it seems that most pressuremeter testing has been of the prebored variety. Early SBPM research was conducted in soils conducive to the installation of the SBPM with minimal disturbance which are also the soils that are suited to investigation by other *in situ* tests such as the SPT, the CPTu, the field vane and the flat plate dilatometer (DMT). In such soils, the pressuremeter offers no significant advantages for

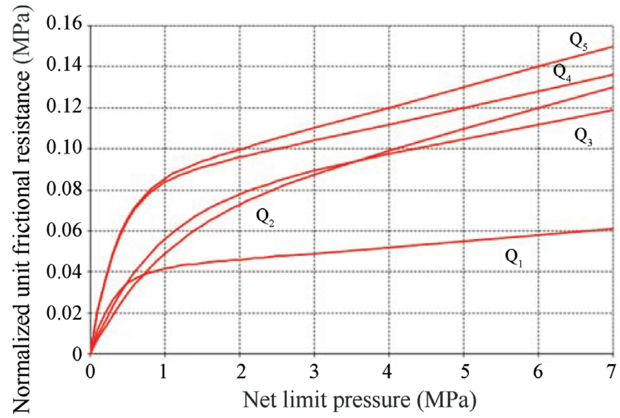


Figure 7 - Design chart for evaluating the unit skin friction q_s from pressuremeter test limit pressure (in Reiffsteck & Burlon, 2012; AFNOR (2012) Standard NF P94-262).

Table 2 - Comparison of *in situ* test and coring feasibility at 204 sites (Bustamante *et al.*, 2009).

Type of test	Number of sites as a function of test feasibility[1]			
	Tests completed[2]	Insufficient no. of tests[3]	Tests possible but curtailed	Tests inadequate[4]
PMT (p_{LM})	155 Sites (76%)	3 Sites (1.5%)	46 Sites (22.5%)	0 Site (0%)
CPT (q_c)	60 Sites (29.4%)	79 Sites (38.7%)	23 Sites (11.3%)	42 Sites (20.6%)
SPT (N)	26 Sites (12.7%)	54 Sites (26.5%)	72 Sites (35.3%)	52 Sites (25.5%)
Coring for laboratory (c' and φ')	21 Sites (10.3%)	67 Sites (32.8%)	69 Sites (33.8%)	47 Sites (23.1%)

[1]It is assumed that a PMT or an SPT log includes a test every meter. [2]Throughout the whole pile depth at least. [3]Insufficient No. of tests (PMT), premature refusal (CPT), excessive blow count (SPT) or sample badly recovered. [4]Tests deemed inadequate beforehand due either to soil type or to soil resistance.

geotechnical characterization over these other tests and so the other tools dominate. In the research sphere, the PMT has continued to be of great interest. The PMT has also found use in what Ladanyi (1995) termed "non-standard" materials. He was primarily referring to testing in frozen soils, ice and in soft and hard rock but there has also been considerable testing in other hard-to-investigate soils such as glacial tills, hard clays, residual soils and municipal wastes.

4.1. ASTM standards

The only ASTM standard related to pressuremeter testing in North America is ASTM Standard D4719. The current version was published in 2007 and is concerned with prebored pressuremeter testing. The scope of this standard is summarized in the following excerpts from ASTM:

> *This test method covers pressuremeter testing of soils. A pressuremeter test is an in situ stress-strain test performed on the wall of a borehole using a cylindrical probe that is expanded radially. To obtain viable test results, disturbance to the borehole wall must be minimized.*
>
> *This test method includes the procedure for drilling the borehole, inserting the probe, and conducting pressuremeter tests in both granular and cohesive soils, but does not include high pressure testing in rock. Knowledge of the type of soil in which each pressuremeter test is to be made is necessary for assessment of (1) the method of boring or probe placement, or both, (2) the interpretation of the test data, and (3) the reasonableness of the test results.*

It goes on to state that the method does not cover the self-boring pressuremeter and is limited to the pressuremeter which is inserted into predrilled boreholes or, under certain circumstances, is inserted by driving. There is no current ASTM Standard for versions of the test focused on the derivation of basic soil parameters.

Elsewhere, pressuremeter testing and test interpretation are provided by the international draft standard ISO 22476-4 prepared by the Technical Committee ISO/TC 182 (*Geotechnics*, Subcommittee SC 1, and by Technical Committee CEN/TC 341, *Geotechnical investigation and testing*) which provides a more complete set of procedures. The international standard is not limited to using the PMT in soils only but includes weak rocks. It is interesting to note that this standard refers to the prebored pressuremeter as the Ménard Pressuremeter Test (MPT). Figure 8 shows a schematic of the MPT.

The ASTM standard outlines the test procedures as well as making suggestions on best practices for borehole preparation based on soil types as shown in Table 3. In Table 4 are the recommendations from the international stan-

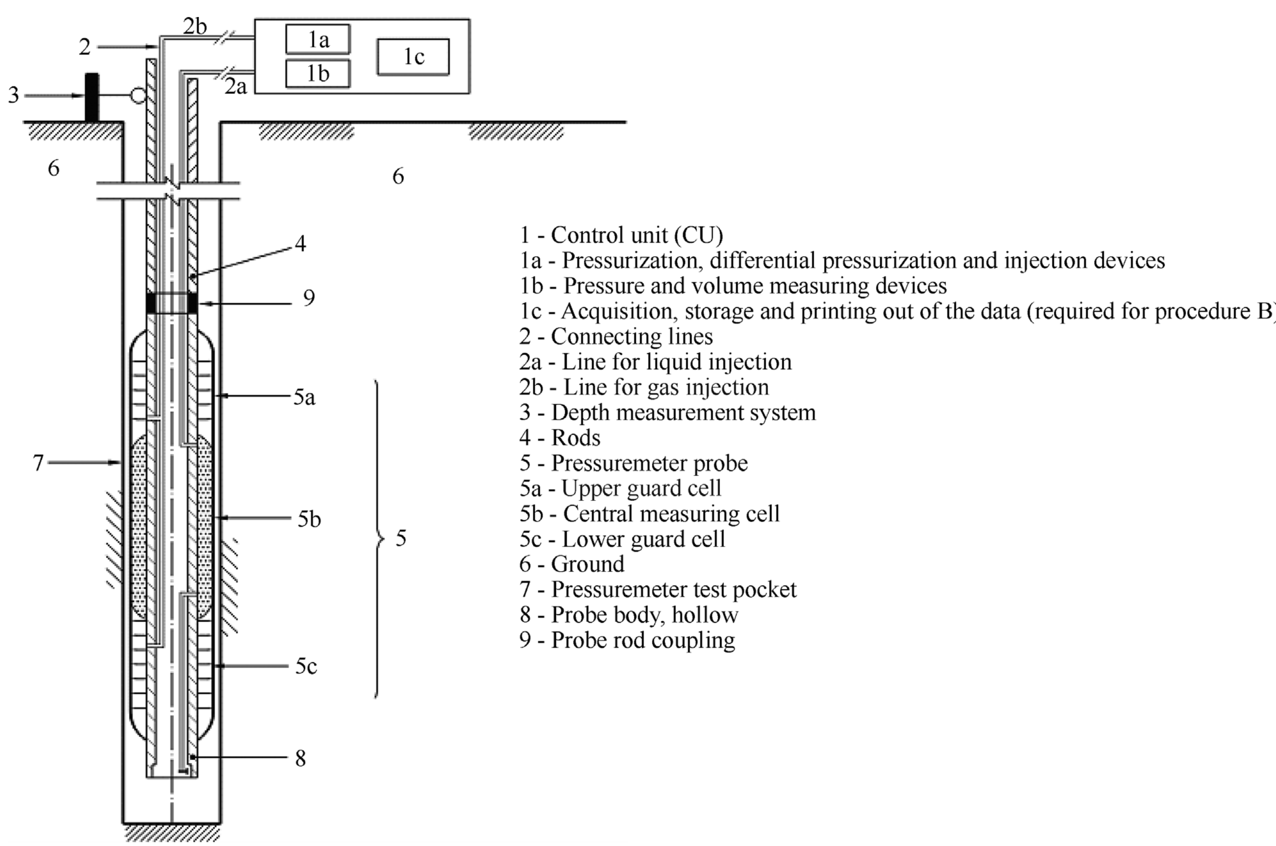


Figure 8 - Schematic of the prebored or Ménard pressuremeter (ISO, 2009).

Table 3 - Guidelines for Selection of Borehole Preparation Methods and Tools (ASTM D4719).

Soil	Type	Rotary Drilling with bottom discharge of prepared mud	Pushed thin wall sampler	Pilot hole drilling and subsequent sampler pushing	Pilot hole drilling and simultaneous shaving	Continuous flight auger	Hand auger in the dry	Hand auger with bottom discharge of prepared mud	Driven or vibro-driven sampler	Core barrel drilling	Rotary percussion	Driven vibro-driven or pushed slotted tube
Clayey soils												
	Soft	2[B]	2[B]	2	2	NR	NR	1	NR	NR	NR	NR
	Firm to stiff	1[B]	1	2	2	1[B]	1	1	NR	NR	NR	NR
	Stiff to hard	1	2	1	1	1[B]	NA	NA	NA	1[B]	2[B]	NR
Silty soils												
	Above GWL[C]	1[B]	2[B]	2	2[B]	1	1	2	2	NR	NR	NR
	Under GWL[C]	1[B]	NR	NR	2[B]	NR	NR	1	NR	NR	NR	NR
Sandy soils												
	Loose and above GWL[C]	1[B]	NR	NR	2	2	2	1	2	NA	NR	NR
	Loose and below GWL[C]	1[B]	NR	NR	2	NR	NR	1	NR	NA	NR	NR
	Medium to dense	1[B]	NR	NR	2	1	1	1	2	NR	2[B]	NR
Sandy gravel or gravely sands below GWL												
	Loose	2	NA	NA	NA	NA	NA	NA	NR	NA	2	2
	Dense	NR	NA	NA	NA	NR	NA	NA	NR	NA	2	1[D]
Weathered rock		1	NA	2[B]	NA	1	NA	NA	1	2	2	NR

[A] 1 is first choice; 2 is second choice; NR is not recommended; and NA is nonapplicable.
[B] Method is applicable only under certain conditions (see text for details).
[C] GWL is groundwater level.
[D] Pilot hole drilling required beforehand.

dard. The international standard also defines the maximum time allowed between formation of the test pocket and the actual testing as well as the length of opened borehole permitted between tests to avoid further disturbance of the soil or rock. Table 5 shows these recommendations.

The ASTM specifications were originally developed using the French standards as a template. The new international standard includes contributions from several countries and users with diverse experiences making the document more useable and consistent. The ASTM standard often lags behind where updates are required only every 7 years and is revised by a smaller pool of users. Using the international standard as a working document for North American practice would help promote exchange of information and results that could be used in developing improved methods of insertion, testing and interpretation.

A difference between ASTM and the ISO 22476-4 standards should also be pointed out. The international committee does not mention the use of unload-reload loops as part of the Ménard pressuremeter test while ASTM indicates that such a loop is acceptable and that the resulting modulus should be clearly identified as an unload-reload modulus. However, D4719 gives little guidance as to how such an unload-reload loop should be conducted and interpreted. In his Ménard lecture, Briaud (2013) states that he "would strongly discourage the use of the reload modulus" in the prebored PMT because it is not a "standard modulus" and "is not precisely defined".

However, one of the most significant benefits of pressuremeter testing in soils and rocks is the ability to evaluate a modulus *in situ* from the resulting stress-strain measurement during expansion of the test cavity and unload-reload cycles. As shown in Table 6 from Clarke (1995), the moduli obtained from pressuremeter tests are quoted several different ways, making it difficult to arrive at consistent and pertinent use of the pressuremeter moduli in analyses of deformation. It has been shown that the unload-reload modulus appears to be relatively unaffected by the method of insertion since this unloading and reloading is essentially elastic. However, it is necessary to perform the unload-reload loops carefully to ensure that they can be interpreted reliably. For example, Wroth (1984) argued that the stress decrement in an unload-reload loop should be limited to twice the undrained shear strength in undrained PM tests. In sands, the stress decrement should be limited to approximately 40% of the initial effective stress at the start of unloading (Fahey, 1991). In addition, the strain increment level associated with the modulus needs to be reported since the modulus reduces with increasing strain increment level (Clarke, 1995). In drained expansion, the effect of stress level at the start of unloading also needs to be considered as stiffness increases with stress level.

Table 4 - Guidelines for pressuremeter probe placement techniques (adapted from ISO, 2009).

	Probe placing without soil displacement $1 < dt/dc \leq 1.15$										Probe placing by direct driving ($dt/dc \approx 0$)
	Rotary drilling				Rotary percussion			Tube pushing, driving or vibrodriving			Driven slotted tube
	OHD *	HA/HAM*	CFA	CD	RP	RPM	STDTM	PT	DT	VDT	DST
Sludge and soft clay	S°	R°	-	-$^{\$}$		-	-$^{\$}$	R TWT	-		A$^{\$}$
Soft to firm clayey soils	R°	R°	S$^{\$}$	S$^{\$}$	-	A$^{\$}$°	A°	A$^{\$}$	A	-	
Stiff clayey soils	R°	S$^{\$}$°	R	R°	A$^{\$}$	S°	S$^{\$}$°	-	A$^{\$}$	-	
Silty soils:											
- above water table	S°	R°	S	S$^{\$}$°	-	A°	S°	A$^{\$}$	A	A	-
- below water table	A$^{\$}$°	S$^{\$}$°	-	A$^{\$}$°	-	A°	S$^{\$}$°	-	-	-	A$^{\$}$
Loose sandy soils:											
- above water table	S°	R$^{\$}$°	S	A	-	A°	A°	-$^{\$}$	-	-	-
- below water table	A$^{\$}$°	S°	-	-$^{\$}$	-	A°	A$^{\$}$°	-$^{\$}$	-	-	A$^{\$}$+
Medium dense and dense sandy soils	R°	R°	R	A°	A	S°	S$^{\$}$°	-	A	A	S$^{\$}$+
Gravels, cobbles	S°	-$^{\$}$°	-$^{\$}$	-$^{\$}$	A	R°	A$^{\$}$°		A	A	R$^{\$}$+
Cohesive non homogeneous soils (*e.g.* boulder clay)	S°	A°	A	S$^{\$}$°	A	R°	A$^{\$}$°		A	A	
Loose non homogeneous soils, other soils not specified above (e.g. tills, some alluvial deposits, manmade soils, treated or untreated fills)	S°	A°	A	A°	A	S°	S$^{\$}$°	-	A	A	S$^{\$}$+
Weathered rock, weak rock	R°	S°	S	S$^{\$}$°	A$^{\$}$	S°	S$^{\$}$°		A$^{\$}$	A$^{\$}$	

R	Recommended	OHD	Open hole drilling.	PT	Pushed tube
S	Suited	HA	OHD performed with a hand auger	TWT	Thin wall tube, pushed
A	Acceptable	HAM	OHD performed with a hand auger and mud	DT	Driven tube
-	Not suited	CFA	Continuous flight auger	VDT	Vibro driven tube
(grey)	Not covered by this standard	CD	Core drilling	DST	Driven slotted tube
*d*t	drilling tool diameter	RP	Rotary percussion		
*d*c	probe outside diameter	RPM	Rotary percussion with mud		
		STDTM	Slotted tube with inside disintegrating tool and mud circulation		

$ Depending on the actual site conditions and on the evaluation of the operator -

* Rotation speed should not exceed 60rpm and tool diameter not be more than 1.15*dc*

° Slurry circulation: pressure should not exceed 500kPa and the flow rate 15l/min. The flow can be temporarily interrupted if necessary

\+ Pilot hole with possible preboring techniques: DST, RP and RPM

4.2. Examples of pressuremeter testing

Although Ménard carried out his first pressuremeter tests in the USA, acceptance and utilization of the test has been overall relatively slow compared to other *in situ* tools and techniques such as the cone penetration test. Nevertheless, several firms make use of the PMT either as soil testing services for various clients or directly by geotechnical consultants for site characterization and design of foundations. The use of the PMT in the USA and Canada appears to be localized and is highly dependent on historical use and experience.

One of the early uses of the prebored PMT was in the Chicago area as shown in the original work of Ménard and then later in publications by Kastman (1978), Baker (2005) and Lukas (2010). A paper by Kastman (1978) uses the ratio between the Ménard modulus and the net limit pressure E_M/p_{LM} as an indicator of test quality (or disturbance) and for identifying soils. Figure 9 shows results from Kastman (1978) for a variety of soils tested using the PMT in the USA using the ratio E_M/p_{LM} as a function of the logarithm of the pressuremeter modulus. The summary of results clearly shows a strong linear relationship for each soil type. The ratio was found to be in the range of 8 to 12 for normally consolidated soils and 12 to 20 for overconsolidated soils.

Lukas (2010) discusses his experience with the PMT in Chicago clays which are heavily overconsolidated and cannot be penetrated by the CPT or by sampling with thin walled Shelby tubes. Up to the 1970's, properties were obtained from the SPT where penetration values N were generally greater than 50 to 100. The use of the pressuremeter was well-received as it was easily deployed in the field and far less expensive than full scale load tests. Bearing capacity and settlement predictions in 35 years of experience have correlated reasonably well. In his paper he discusses two cases. Settlement of a sixty-one story building founded on drilled piers in "hardpan" was estimated using pressure-

Table 6 - Terms used to define moduli taken from pressuremeter tests (Clarke, 1995).

Symbol	Definition
G_i	Initial secant shear modulus
E_M	Ménard modulus
G_{ur}	Secant shear modulus from an unload/reload cycle
G_u	Secant shear modulus from an unloading curve
G_r	Secant shear modulus from a reloading curve
E_m	Secant elastic modulus from an unloading curve
E_{m*}	Secant elastic modulus from a reloading curve
E_{mo}	Maximum elastic modulus from an unloading curve
E_{ro}	Maximum elastic modulus from a reloading curve
G_n	Secant shear modulus measured over strain range n%
G_o	Maximum shear modulus
G_s	Equivalent element modulus
G_{uro}	Equivalent shear modulus at the in-situ effective stress

Table 5 - Maximum continuous drilling or driving stage length before testing (adapted from ISO, 2009).

Soil type	Maximum continuous drilling or tube driving stage length (m)		
	Adapted rotary drilling[b]	Rotary percussive drilling[b]	Tube pushing, driving and vibrodriving[c]
Sludge and soft clay, soft clayey soil	1[a]	-	1[a]
Firm clayey soils	2	2	3
Stiff clayey soils	5	4	4
Silty soils: above ground water table	4	3	3
Silty soils: below water table	2[a]	1[a]	-
Loose sandy soils: above ground water table	3	2	-
Loose sandy soils: below water table	1[a]	1[a]	-
Medium dense and dense sandy soils	5	5	4
Coarse soils: gravels, cobbles	3	5	3
Coarse soils with cohesion	4	5	3
Loose non homogeneous soils, other soils not specified above (*e.g.* tills, etc.)	2	3	2
Weathered rock, weak rock	4	5	3

[a]: Or the required interval between two successive tests.
[b]: Refer to Table C.2 for acceptable techniques.
[c]: Not applicable to STDTM technique (see C.2.6.3).

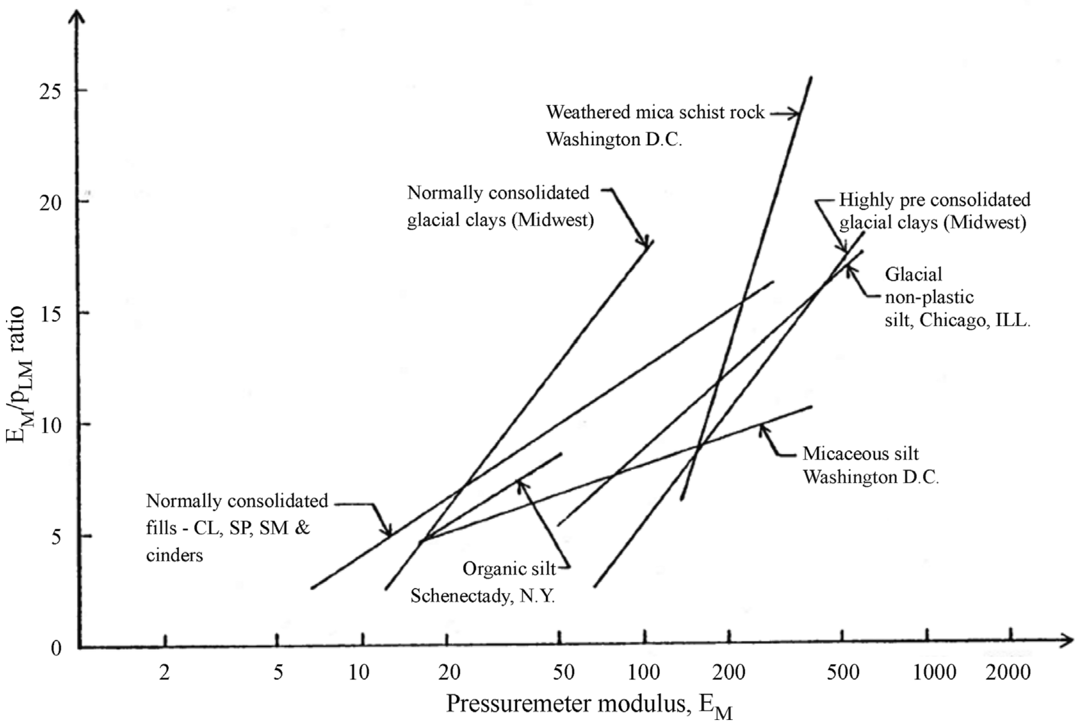


Figure 9 - Pressuremeter ratio E_M/p_{LM} as a function of the pressuremeter modulus E_M (Kastman, 1978).

meter data. The estimated movements agreed well with the measurements in the field when the bearing pressures were below the creep pressure and the pressuremeter modulus was used in settlement calculations. The second case dealt with bearing capacity of a mat foundation for a high rise to be founded on the overconsolidated clay. Using the pressuremeter results, the calculated bearing capacity agreed well with that obtained by more conventional approaches to design when using undrained shear strengths derived from the PM test.

Similarly to Lukas (2010), Baker (2005) describes his experience with the pressuremeter in the Chicago area soils as well as in other parts of the world. The PMT has been used in Chicago since 1969 and has allowed less conservative design of drilled piers and caissons than is obtained using parameters derived from SPT and unconfined compression tests, increasing allowable pressures by more than 50%. From his experiences in highly consolidated glacial tills and medium dense to dense deposits, using the pressuremeter theory and appropriate PMT results allows reliable predictions of settlement magnitudes of deep foundations under working load. The confidence in reliably predicting settlements has afforded them to be more innovative in their designs. Baker suggests that for reliable settlement predictions, the dead load bearing stress plus the overburden pressure should not exceed the average creep pressure. However, there are cases where such an approach is not applicable, *e.g.* weakly cemented sandstone. Their settlement evaluation is done either using the Ménard rules or elastic theory with an equivalent Young's modulus derived from the PMT. Their approach has been based on local experience and performance monitoring of other similar foundations in similar soils. This often leads to company-specific empirical relationships.

Pressuremeter testing has also been carried out extensively in the Miocene clay in the Richmond, Virginia area (Martin & Drahos, 1986). This clay is highly preconsolidated and hard in consistency. This material is also sensitive and highly plastic. From their work they developed a relationship between the constrained modulus from the reload portion of their consolidation tests and the pressuremeter modulus, E_M. The results shown in Fig. 10 were found to be much different than what was previously published by Lukas & DeBussy (1976) for Chicago clays. They also developed a correlation between the PMT creep pressure and the preconsolidation pressure (p_c) and recommended a conservative estimate of p_c could be obtained from the expression: $p_c = 0.6\ p_f$.

Based on the technical literature and geotechnical reports reviewed by the authors, a number of different versions of the pressuremeter are in use as outlined in Table 7. By far the most common encountered was the Texam pressuremeter. This is a monocellular version of the prebored PM developed by Briaud and his co-workers (Briaud, 1992). There is also a high capacity version of this probe, the Probex, designed for testing in rock. According to Briaud (2005), the Texam was designed:

> *"to simplify and make safer (no pressurized gas bottle) the operation and the repairing of the Ménard*

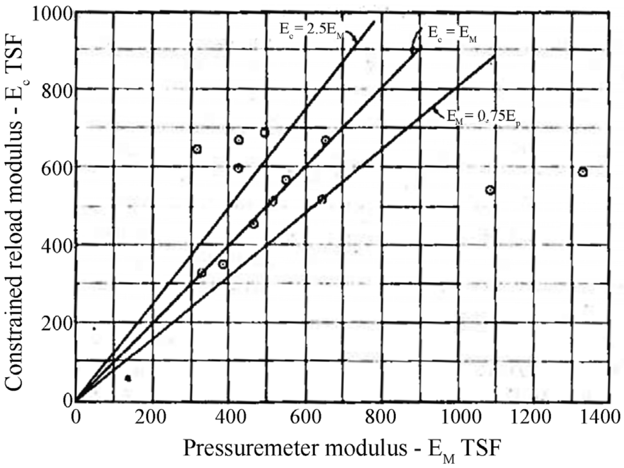


Figure 10 - Relationship between Constrained Reload Modulus from consolidation tests and Pressuremeter Modulus (after Martin & Drahos, 1986) (Note: 1 TSF = 95.76 kPa).

pressuremeter while allowing for more versatility in the types of possible PMT tests (e.g.: cyclic tests).”

Briaud (1992) stated that comparison testing between the Texam and the triple cell Ménard probes showed that the results were comparable provided the length to diameter ratio (*L*/*D*) of the monocell probe exceeded 6. Since then, the Texam probe appears to have become the most common version of the probe in published case histories of prebored testing. However, the standard GAM model series is the preferred tool in Europe and complies with European standards. The Pencel probe has also been the subject of considerable research, particularly in Florida (Cosentino *et al.*, 2006; Messaoud & Nouaouria, 2010; Messaoud *et al.*, 2011). At 35 mm diameter, it is much smaller than most other probes. A major focus of this work has been the derivation of p-y curves for the design of piles under lateral loads.

Some testing has also been done using a Cambridge style monocell probe installed in a prebored hole which is inflated by gas and has strain feeler arms at 120 degree intervals at mid-height of the probe. Test curves obtained with this probe only expand to 10% to 15% cavity strain and so cannot be continued to sufficient cavity strain to achieve a doubling of the cavity volume. Consequently, Ménard-type limit pressures also have to be obtained by extrapolation for this tool. However, most of the cases involving this approach to pressuremeter testing were based on test procedures that did not follow ASTM D4719 and were analyzed and interpreted using computer aided modelling (CAM) based on simple constitutive models of soil behavior. The tests were interpreted to obtain the fundamental properties of the materials tested which were then considered in conjunction with other geotechnical and geological information collected by the site characterization.

Jefferies *et al.* (1987) used CAM and SBPM testing to determine a profile of effective stress in Beaufort Sea clays. They argued that the lateral stress profile did not agree with estimates based on overconsolidation ratios obtained from consolidation tests and emphasized the importance of field testing. A similar recent example of such an approach is presented in Hoopes & Hughes (2014) in which pressuremeter test results were used in the estimation of the *in situ* lateral stress profile of glacially over-ridden glaciolacustrine clay by seeking a pressure during unloading at which no expansion or contraction occurred.

In a paper on the use of *in situ* tests for design of drilled shafts in coarse granular deposits, Rabab’ah *et al.* (2012) described an ingenious solution developed by Durkee *et al.* (2007) to the preparation of a test pocket in such challenging soil conditions. They drilled an oversized hole (127 mm) using a down-hole air hammer and left a casing in place. They then tremie-grouted the hole with a weak grout placed through a central tube while withdrawing the casing. After a curing period of 2 weeks, they drilled a 76 mm diameter hole through the grout which left a 20 mm annulus around the wall of the pocket in which the PM was installed. The cement grout was designed to be brittle and to fracture early in the expansion of the pressuremeter. The test pocket preparation sequence is illustrated in Fig. 11. A total of 45 pressuremeter tests carried out in this way using a Cambridge-style monocell probe were considered to be of good to excellent quality and were interpreted to give geotechnical properties of the soil. The interpretation took ac-

Table 7 - Most common pressuremeters encountered in north american document review.

Model	Design	Method of insertion	Method of inflation	Method of strain measurement
Menard	Triple cell	Prebored	Hydraulic	Volume
Texam	Monocell	Prebored	Hydraulic	Volume
Probex*	Monocell	Prebored	Hydraulic	Volume
Cambridge type	Monocell	Prebored (some self-boring)	Gas	3/6 strain arms
Pencel	Monocell	Driven or pushed	Hydraulic	Volume
Oyo elastometer 100	Monocell	Prebored	Gas	2 feeler arms

*High capacity version of Texam.

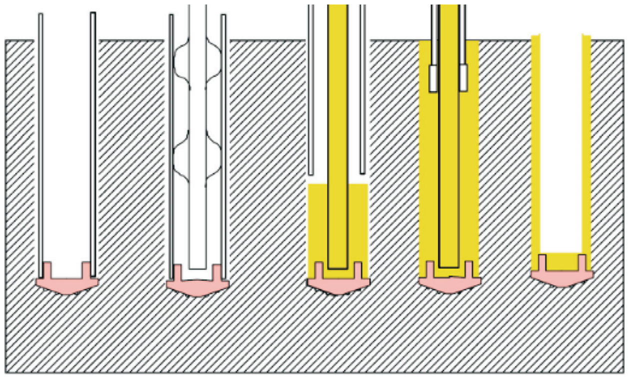


Figure 11 - Schematic of drilling procedure in gravelly soils (After Durkee *et al.*, 2007).

count of the presence of the grout. Despite the likelihood of some disturbance of the soil tested, this procedure allowed some assessment of soil properties which would have otherwise been impossible given the difficulty of drilling and sampling in such soils.

The pressuremeter continues to be of interest to researchers. Dafni (2013) presents a study of pressuremeter testing in weak rock using a Cambridge-type monocell instrument in which he applies CAM based on representative constitutive models for rock. A comparison of measured data and a curve simulated using the Hoek-Brown model initiated by Yang and Zou (2011) is shown in Fig. 12. Jacobs (2003) carried out Ménard-style PMTs to study the use of the pressuremeter for estimating the side shear capacity of drilled shafts in Florida limestone. An example of his test results is shown in Fig. 13. The existing approach was based on laboratory testing of intact rock core and there was interest in determining whether the PMT would give data more representative of the rock mass. He found that an empirical design method for side shear capacity by the Laboratoire Central des Ponts et Chaussées (LCPC) performed reasonably well and recommended that it be studied further. He observed that the method required further calibration by comparison with load testing before design use in Florida.

5. Discussion

Pressuremeter testing has not yet attained widespread acceptance in North American geotechnical engineering practice. It tends to be seen as being too expensive for routine practice. A common view of the test is expressed by the Nevada Department of Transportation as follows:

> *The pressuremeter test is a delicate tool, and the test is very sensitive to borehole disturbance. The data may be difficult to interpret for some soils, but it provides the advantage that due to the large size of the pressuremeter cell it is less likely to be adversely affected by gravel in the soil. This test requires a high level of technical expertise to perform, and is time consuming.*

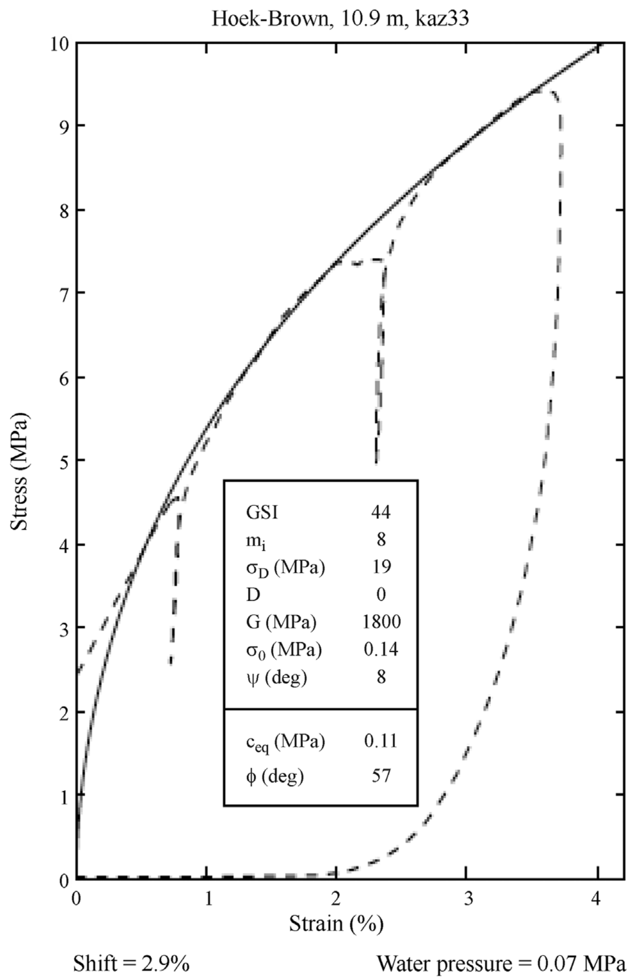


Figure 12 - Measured and simulated PMT curves in Weak Rock (Dafni, 2013).

The situation is complicated by the fact that a range of instruments and test procedures are in use. The shape of the pressuremeter test curve in any soil or rock is affected by the insertion method, the geometry of the instrument and by details of the test procedures. Consequently, tests carried out with different instruments and procedures will obtain different test curves in a given material, with the magnitude of the variation being material-dependent. There is evidence that engineers continue to interpret their test results using the Ménard rules despite their test data not being obtained by instruments and procedures conforming to those rules.

For conventional foundation engineering in sands and finer soils which are normally to moderately overconsolidated, the pressuremeter offers no advantage over faster and more robust *in situ* tests such as the seismic CPTu and DMT except in unusual cases where pressuremeter data can provide additional insight. However, the prebored PMT is better-suited than conventional penetration tests or drilling and sampling to the characterization of the mechanical behavior of hard or very dense soils, coarse grained soils, re-

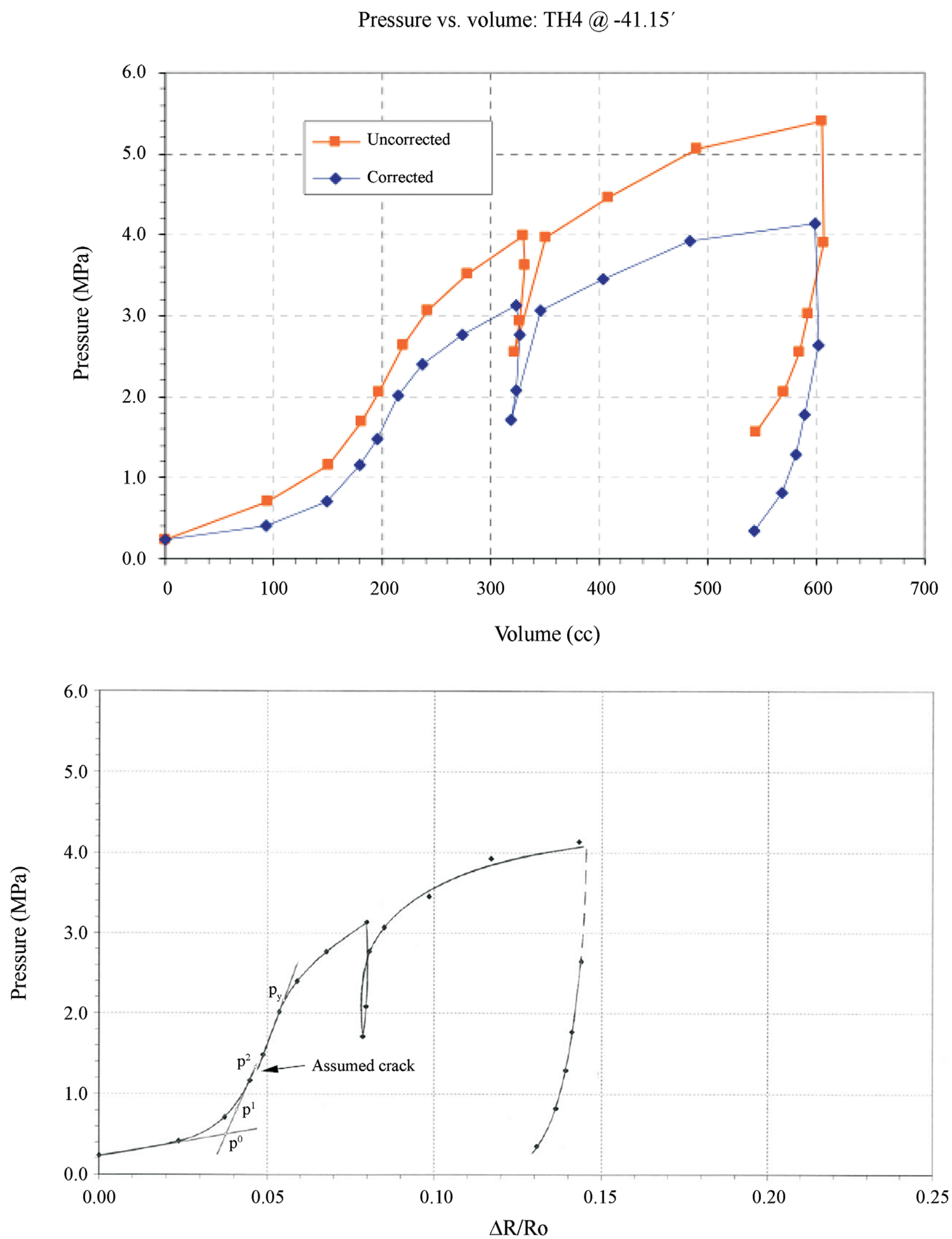


Figure 13 - Example of PMT in Limestone (Jacobs, 2003).

sidual, saprolitic or lateritic soils, soft and fractured rocks, frozen ground and ice.. The challenge then becomes to drill a suitable test pocket to allow pressuremeter tests to be carried out successfully. Briaud (2013) emphasizes that this is "the most important and most difficult step in a quality pressuremeter test".

Where pressuremeter testing is carried out, the procedures set out in the current version of the ASTM standard on prebored pressuremeter testing are not consistent with those of the European standard. The major difference is the option to include an unload-reload loop at some stage of the expansion. The latter guidelines are based on the decades of experience in France of successful use of PMT parameters directly for foundation design. This difference compromises the ability of engineers in North America to benefit from that experience.

One reason for the slow adoption of the PMT in North America is the lack of familiarity with the test and its interpretation and use. This can in part be traced to the education system. Benoît (2013), using a questionnaire distributed to members of the United States Universities Council on Geotechnical Education and Research (USUCGER), discussed the status of current pressuremeter activities in the United States of America. A questionnaire was widely distributed to academics to assess the level and type of activities in research and teaching. One of the questions asked how much lecture time was devoted to each *in situ* test in graduate courses. The results from this question are shown in Fig. 14. For the SPT and CPT, 25% of the programs spend less than 30 min while another 25% dedicate 1-2 h and about 13% cover the material in greater detail, using over 3 h. For the DMT, PMT and geophysical methods, approximately 40% of the programs spend only 10 to 30 min on these topics while about 15% of them use an hour or more. It was somewhat surprising that as much as 20% of the programs spend less than 10 min on the FVT, DMT, PMT and geophysical methods.

In this survey, the perception was that certain tools such as the pressuremeter are time consuming and too complex. However, if future and current geotechnical engineers are not taught the basic use and interpretation of the various test methods, opportunities to improve the efficiency and safety of our designs are likely to continue their slow progress and, of course, more sophisticated tests are unlikely. Proper training and understanding of more sophisticated test methods will lead to greater use of field methods such as the PMT.

6. Conclusions

While the PMT has been available in North America since the late 1950's, it has not achieved wide acceptance in geotechnical engineering practice. In sandy and finer soils which have not been subject to heavy overconsolidation or other processes of densification, the PM is slower and more expensive for routine use and cannot compete with more conventional tests such as the CPTu, DMT or SPT. It does find use in such soils for design problems where the consequences of poor geotechnical performance justify more extensive design and analysis. Examples of such uses would be in the derivation of p-y curves for the design of laterally loaded piles and the estimation of stiffness for detailed assessment of differential settlement. Where fundamental properties are derived from a Cambridge-style approach to PM testing, input parameters for detailed numerical analysis can be derived.

The PMT has been used extensively in areas of the US and Canada where hard or very dense soils are encountered such as in glacial tills and heavily overconsolidated clays, dense/hard residual soils, and very coarse granular soils. It has also been used in soft and fractured rock, frozen soils and ice and as a tool for quality control of ground improvement. Where the test has found favor, it has generally been where conventional approaches to site characterization yield uncertain or insensitive results (what is the difference in soil parameters between an SPT blow count of 50 for 1 inch and 100 for 1 inch?). As the methods of interpretation have a basis in theory, it is possible to derive meaningful strength and deformation parameters for all materials in which a PMT expansion curve can be obtained. It is also possible to relate the measured parameters to the extensive body of experience gained with the use of the PM for foundation design in Europe and elsewhere.

In order for the test to gain wider acceptance in engineering practice in North America, the following measures are required:

- the teaching of the theory and principles of PM testing at graduate schools must be improved. This will increase

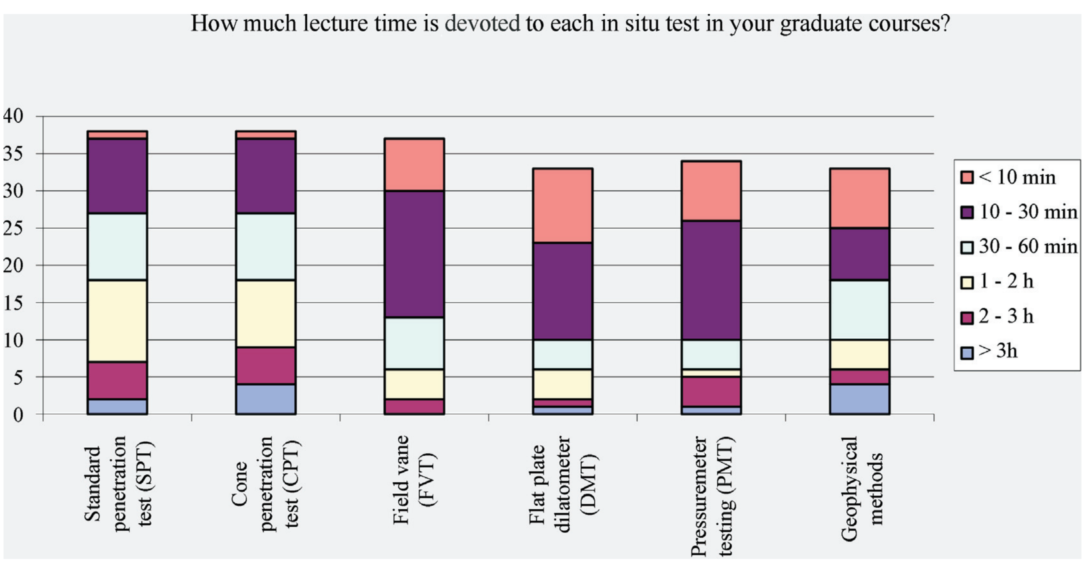


Figure 14 - *In Situ* tests lecture time in us graduate geotechnical courses (based on 40 respondents) (Benoît, 2013).

the likelihood that the PMT will be used appropriately and will result in a positive experience.

- equipment and test procedures should be more strictly standardized so that they produce data that are consistent with the design methods being employed. If the Ménard rules are to be invoked, then the test should be carried out according to the Ménard rules, *i.e.* no unload-reload cycles. If the Cambridge-type approach is to be used, then the ASTM D4719 test procedures are inapplicable and alternative equipment and procedures should be followed.
- it should be recognized that the PMT is most applicable in difficult ground conditions provided a suitable test pocket can be prepared.
- more full scale load testing and monitoring of foundations of North American projects are required to verify and promote the applicability of PM based design methods.

As stated by Casagrande (1966) when dealing with projects and subsurface conditions in Richmond, Virginia, an effort had to be made to "collect and evaluate systematically information on the subsoil conditions, and on the design and performance of buildings, in Richmond. This would eventually lead to a set of relatively simple and reliable guide rules for the design of building foundations in this city." The Ménard rules have essentially been derived and improved following this philosophy. The pressuremeter is a tool that has been insufficiently used in North America and, at times, has been used inappropriately. A revival of the use of the pressuremeter is essential, especially as numerical tools require more sophisticated parameters for analysis.

References

AFNOR (2012) Justification des Ouvrages Géotechniques - Normes d'Application Nationale de l'Eurocode 7 - Fondations Profondes, norme NF P94-262.

ASTM D4719 (2007) Standard Test Methods for Prebored Pressuremeter Testing in Soils. Annual Book of ASTM Standards, Section 4, v. 04.08.

Baguelin, F.; Jézéquel, J.-F.; Le Mée, H. & Le Méhaute, A. (1972) Expansions of Cylindrical Probes in Soft Soils. Journal of Soil Mechanics and Foundation Design, ASCE, v. 98:SM11, p. 1129-1142.

Bandis, C. and Lacasse, S. (1986) Interpretation of Self-Boring and Push-In Pressuremeter Tests in Holmen Sand. NGI Report No. 40019-21, Oslo.

Baker, C.N. (2005) The use of the Menard Pressuremeter in innovative foundation design from Chicago to Kuala Lumpur. Proceedings of the International Symposium 50 Years of Pressuremeters, Gambin, Magnan and Mestat, Editors, Presses de l'ENPC/LCPC, 22-24 August, Paris, France, v. 2, p. 63-95.

Benoît, J. (2013) Current status of pressuremeter testing education in the USA. Parallel International Symposium on Pressuremeters, 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, France.

Benoît, J.; Atwood, M.J.; Findlay, R.C. & Hilliard, B.D. (1995) Evaluation of jetting insertion for the self-boring pressuremeter. Canadian Geotechnical Journal, v. 32, p. 22-39.

Briaud, J.-L. (2013) Ménard Lecture: The pressuremeter Test: Expanding its use. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, France, p. 107-126.

Briaud, J.-L. (2005) The pre-boring pressuremeter: some contributions. Proceedings of the International Symposium 50 Years of Pressuremeters, Gambin, Magnan and Mestat, Editors, Presses de l'ENPC/LCPC, 22-24 August, Paris, France, v. 2, p. 103-124.

Briaud, J.-L. (1992) The Pressuremeter. A.A. Balkema Publications, Rotterdam, 322 p.

Briaud, J.-L. & Shields, D.H. (1979) A special pressuremeter and pressuremeter test for pavement evaluation and design. Geotechnical Testing Journal, v. 2:3, p. 143-151.

Bustamante, M.; Gambin, M. & Gianeselli, L. (2009) Pile Design at Failure Using the Ménard Pressuremeter: An Up-Date. French contributions to International Foundation Congress & Equipment Expo '09 Contemporary Topics in In Situ Testing, Analysis, and Reliability of Foundations, ASCE Geotechnical Special Publication No. 186, Orlando, Florida, p. 127-134.

Casagrande, L. (1966) Subsoils and Foundation Design in Richmond, VA. Journal of the Soil Mechanics and Foundation Design, SM5, September, p. 109-126.

Cassan, M. (2005) Historique des Pressiomètres. Proceedings of the International Symposium 50 Years of Pressuremeters, Gambin, Magnan and Mestat, Editors, Presses de l'ENPC/LCPC, 22-24 August, 2005, Paris, France, v. 2, p. 125-200.

Clarke, B.G. (1995) Pressuremeters in Geotechnical Design. Blackie Academic & Professional, city, 364 p.

Clarke, B. & Gambin, M.P. (1998) Pressuremeter testing in onshore ground investigations. A report by the ISSMGE Committee 16, International Conference on Site Characterization, Atlanta.

Clayton, C.R.I.; Matthews, M.C. & Simons, N.E. (1995) Site Investigation. Blackwell Science, city, 584 p.

Cosentino, P.; Kalajian, E.; Stansifer, R.; Anderson, J.B.; Kattamuri, K.; Sundaram, S.; Messaoud, F.; Misilo, T. & Cottingham, M. (2006) Standardizing the pressuremeter test for determining p-y curves for laterally loaded piles. FDOT Research Report, Contract BD 658.

Dafni, J. (2013) The Analysis of Weak Rock Using the Pressuremeter. M.Sc. Thesis, Department of Civil Engineering, University of Washington, Seattle.

Drahos, E.G. (2014) Personal communication.

Durkee, D.; Ackerman, F.; Smith, D. & Rucker, M. (2007) Borehole preparation technique for pressuremeter testing in sand gravel and cobbles. Geotechnical Special Publication No. 162, Geo-Denver 2007, February 18-21, 2007, Denver, Colorado.

Fahey, M. (1991) Measuring shear modulus in sand with the self-boring pressuremeter. deformation of soils and displacements of structures. Proc. X Eur. emif. SMFE, Florence,Italy, Balkema, Rotterdam, v. 1, p. 73-76.

Ferreira, R.S. & Robertson, P.K. (1992) Interpretation of undrained self-boring pressuremeter test results incorporating unloading. Canadian Geotechnical Journal, v. 29:6, p. 918-928.

Gambin, M.; Flavigny, E. & Boulon, M. (1996) Le module pressiométrique: Historique et modélisation. XI Colloque Franco-Polonais en Mécanique des Sols et des Roches Appliquée, Gdansk, Poland.

Gauthier, A.; Gonin, H. & Ménard, L. (1954) Travail de fin d'étude. Ecole Nationale des Ponts et Chaussées, Paris, France.

Hoopes, O. & Hughes, J. (2014) In Situ Lateral Stress Measurement in Glaciolacustrine Seattle Clay Using the Pressuremeter. Journal of Geotechnical and Geoenvironmental Engineering, 10.1061/(ASCE)GT.1943-5606.0001077, 04013054.

Houlsby, G.T. & Carter, J.P. (1993) The Effects of Pressuremeter Geometry on the Results of Tests in Clay. Géotechnique, v. 43, p. 567-576.

Houlsby, G.T. & Withers, N.J. (1988) Analysis of Cone Pressuremeter Test in Clay. Géotechnique, v. 38:4, p. 575-587.

Hughes, J. M. O. and Robertson, P. K. (1985). Full-Displacement Pressuremeter Testing in Sand. Canadian Geotechnical Journal, v. 22, p. 298-307.

ISO/FDIS 22476-4:2009(E) - ISO/TC 182/SC 1 (2009) Geotechnical Investigation and Testing - Field Testing - Part 4: Ménard Pressuremeter Test.

Jacobs, S.A. (2003) Insitu Measurement of Florida Limestone Modulus and Strength Properties, M. Eng. Thesis, University of Florida.

Jefferies, M.G. (1988) Determination of Horizontal Geostatic Stress in Clay with Self-Bored Pressuremeter. Canadian Geotechnical Journal, v. 25, p. 559-573.

Jefferies, M.G.; & Shuttle, D.A. (1995) Disturbance does not prevent obtaining reliable parameters from sbp tests, the pressuremeter and its new avenues. Proceedings of the Fourth International Symposium on Pressuremeters (ISP4), G. Ballivy (ed) Sherbrooke, Québec, Canada, May 17-19, A.A. Balkema, Publisher, p. 177-183.

Jefferies, M.G.; Crooks, J.H.A.; Becker, D.E. & Hill, P.R. (1987) Independence of geostatic stress from overconsolidation in some beaufort sea clays. Canadian Geotechnical Journal, v. 24:3, p. 342-356.

Kastman, K. (1978) In-Situ testing with the Ménard pressuremeter. Proceedings of a Symposium on Site Exploration in Soft Ground using In Situ Techniques, Alexandria, Virginia, Final Report, p. 206-223.

Ladanyi, B. (1995) A Brief History of Pressuremeter. Proceedings of the 4th International Symposium on the Pressuremeter and its New Avenues, Sherbrooke, Québec, Canada. Edited by G. Ballivy, A.A. Balkema, p. 5-23.

Long, M. (2008) Design Parameters from In Situ Tests in Soft Ground - Recent Developments. Proceedings of the Third International Conference on Geotechnical and Geophysical Site Characterization ISC-3, Taipei, Taiwan, p. 89-116.

Lukas, R.G. (2010) Pressuremeter Testing for Foundation Design. Art of Foundation Engineering Practice, ASCE Geotechnical Special Publication No. 198, Geo-Florida, p. 392-400.

Lukas, R.G. & De Bussy, B.L. (1976) Pressuremeter and Laboratory Test Correlations for Clays. ASCE Journal of Geotechnical Engineering, v. 102:9, p. 945-962.

Martin, R.E. & Drahos, E.G. (1986) Pressuremeter Correlations for Preconsolidated Clays. Proceedings of In Situ '86, ASCE, June, Blacksburg, Virginia, p. 206-220.

Ménard, L. (1957) An Apparatus for Measuring the Strength of Soils in Place. Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, University of Illinois, 50 p.

Messaoud, M.S.M.F. & Cosentino, P.J. (2011) PENCEL pressuremeter test evaluation for developing p-y curves for driven piles. ACEE International Journal on Transportation and Urban Development, v. 1:2, p. 14-18.

Messaoud, F. & Nouaouria, M.S. (2010) The use of PENCEL pressuremeter test for underground structures. International Journal of Civil Engineering, v. 8:1, p. 33-43.

Palmer, A.C. (1972) Undrained Plane-Strain Expansion of a Cylindrical Cavity in Clay: a Simple Interpretation of the Pressuremeter Test. Geotechnique, September, v. 22:3, p. 451-457.

Rabab'ah, S.R.; Niedzielski, J.C. & Durkee, D.B. (2012) Use of in-situ tests for design of drilled shafts in coarse granular deposits. GeoCongress 2012, p. 265-274.

Reid, W.M.; St. John, H.D.; Fyffe, S. & Rigden, W.J. (1982) The push-in pressuremeter. Proceedings of the Symposium on the Pressuremeter and its Marine Applications, Paris, France.

Reiffsteck, P. (2009) ISP5 Pile Prediction Revisited. French contributions to International Foundation Congress & Equipment Expo '09, Contemporary Topics in In Situ Testing, Analysis, and Reliability of Foundations, ASCE Geotechnical Special Publication No. 186, Orlando, Florida, p. 50-57.

Reiffsteck, P. & Burlon, S. (2012) Traitement des Incertitudes dans le Calcul Géotechnique avec la Nouvelle Norme Fondations Profondes NF P 94 262, Tunisia.

Roy, D.; Campanella, R.; Byrne, P.; & Hughes, J. (2002) Undrained Anisotropic Monotonic Behavior of Sand from In Situ Tests. Journal of Geotechnical and Geoenvironmental Engineering, v. 128:1, p. 85-91.

Schnaid, F.; Ortigao, J.A.R.; Mántaras, F.M.; Cunha, R.P. & MacGregor, I. (2000) Analysis of self-boring pressuremeter (SBPM) and Marchetti dilatometer (DMT) tests in granite saprolites. Canadian Geotechnical Journal, v. 37:4, p. 796-810,

Shuttle, D.A. & Jefferies, M.G. (1995) A practical Geometry Correction for Pressuremeter Tests in Clay. Géotechnique, v. 45:3, p. 549-553.

Withers, N.J.; Schaap, K.H.J. & Dalton, J.C.P. (1986) The Development of a Full Displacement Pressuremeter. Proceeding of the Symposium on Pressuremeter and its Marine Applications, ASTM STP 950, p. 38-56.

Wroth, C.P. (1984) The Interpretation of In-Situ Soil Tests. 24th Rankine Lecture, Géotechnique, v. 34:4, p. 449-489.

Wroth, C.P. & Hughes, J.M.O. (1972) An Instrument for the In Situ Measurement of the Properties of Soft Clays. Report of the Department of Engineering, University of Cambridge, CUED/C, Soils TR 13.

Yang. X.-L. & Zou, J.-F. (2011) Cavity Expansion Analysis with Non-linear Failure Criterion. Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, v. 164, p. 41-49.

Yeung, S.K. & Carter, J.P. (1990) Interpretation of the Pressuremeter Test in Clay Allowing for Membrane End Effects and Material Non-homogeneity. Pressuremeters, London, Thomas Telford Limited, p. 199-208.

Yu, H.S. (2004) James K. Mitchell Lecture: In Situ Soil Testing: from Mechanics to Interpretation. Proceedings ISC-2 on Geotechnical and Geophysical Site Characterization. Millpress, Rotterdam.