Optimisation of Drilling Methods for Pressuremeter Tests - North American Experiments

Optimisation des Méthodes de Forage pour Essais Pressiométriques - Expériences Nord-Américaines

Louis Marcil[1#], *Simon-Pierre Gravel*[2]

[1]*Roctest Ltd, 580 Birch ave, Saint-Lambert,Québec, Canada*
[2]*Englobe, 505 Boul. du Parc-Technologique, Québec, Québec, Canada*
[#]*Corresponding author: louis.marcil@roctest.com*

ABSTRACT

This article describes techniques currently used in North America for the preparation of pressuremeter boreholes. The focus is on the predominant and strongly suggested method, i.e. rotary drilling with mud injection. Tools for validating drilling quality are also given, along with concrete examples of the effects that different drilling methods can have on test results. The aim of this article is to present, from a North American perspective, techniques for optimizing the quality of drilling and, consequently, of pressuremeter testing.

RESUME

Cet article décrit des techniques utilisées en Amérique de Nord pour la préparation de forages pressiométriques. Un focus est mis sur la méthode prédominante et fortement suggérée, soit par forage rotatif avec injection de boue. Des outils de validation de la qualité du forage sont également donnés, de même que des exemples concrets d'effets que peuvent avoir les différentes méthodes de forage sur les résultats d'essais. L'objectif de cet article est donc de présenter, d'un point de vue nord-américain, des techniques d'optimisation de la qualité du forage et par conséquent de l'essai pressiométrique.

Keywords: Pressuremeter test. Drilling method. Rotary drilling with mud injection.

1. Introduction

One of the special features of pressuremeter testing is the central role played by drilling and probe insertion. The quality of the information obtained from this test largely depends on good control of these elements. The primary goal is to carry out a loading test on soil that is as close as possible to its natural state.

Efforts have long been made to circumvent or mitigate this dependence. Selfboring and pushed-in pressuremeters have been developed, but with limited results insofar as such equipment entails other difficulties of a practical nature or in interpreting results. These difficulties have restricted the spread of such equipment. Even today, the vast majority of tests are still carried out using prebored pressuremeters. In our opinion, this situation justifies the importance of properly controlling drilling and probe installation techniques.

This paper aims to describe the North American experience in this field, intending to contribute to a better mastery of these elements. The techniques and case studies presented here are largely based on the observations and experience of the authors and the companies they work for.

2. Required qualities of a borehole

A proper pressuremeter borehole requires two qualities. The first one concerns the dimensions of the borehole, and the second one the level of soil disturbance.

Concerning size, the diameter of the borehole must exceed that of the probe by 3 to 10%. This means that using a 3" / 74 mm N probe (commonly used in North America) requires a borehole diameter ranging from 76 to 82 mm. In fact, this diameter may slightly exceed these values - the ASTM D4719-20 standard mentions 20% (Standard Test Methods for Pressuremeter Testing in Soils 2024) - but the risk of obtaining an incomplete test will then increase. These dimensions must remain uniform along the length of the borehole. The borehole must therefore remain linear and its walls as smooth as possible (without cavities).

The second quality requirement concerns soil disturbance, which must be kept to a minimum. The first condition is that the diameter of the borehole should not be too small, otherwise the probe would have to be pushed forcefully into place, risking remolding the soil and damaging the probe. Secondly, recommended drilling techniques must be followed, i.e. those that are the least aggressive or disruptive.

3. Drilling methods used in North America

The ASTM D4719-20 standard describes in details the drilling methods deemed acceptable for pressuremeter testing. It is strongly suggested to refer to it. These methods are associated with specific soil types. These include the use of a continuous flight auger, permitted in dense sand and weathered rock, and a thin-wall sampler pushed in stiff clays. The use of a hand auger with mud injection is theoretically very interesting, as it would be usable in several types of soil. However, because of its depth limitations and the large size of the probes in use in North America, forcing the use of a drill rig for their installation, this manual method is rarely used.

The use of the slotted tube (casing) is also fairly rare. It is mainly used for large-scale projects in soils and backfills containing a high percentage of gravel or boulders (20% or more).

One drilling method has become increasingly popular in North America for pressuremeter testing, namely wet rotary drilling. There are several reasons for this method's success. Firstly, it is highly versatile; it can be used, with the necessary adjustments, in almost any type of soil. Secondly, the equipment required is not too expensive and is readily available locally. Thirdly, it is well suited to hydraulic probes requiring fluid in the borehole. Finally, when properly executed, this method maintains the soil disturbance low, thanks in particular to the use of drilling mud, which in a way replaces the evacuated soil.

The widespread use of this method may have contributed to the improvement of borehole quality (or at least to its standardization) and the (slow but sure) progress of pressuremeter testing in North America. The importance of this drilling method motivates the more detailed description given in the following section.

4. Wet Rotary drilling for PMT– Description

This method is carried out in two stages - see Fig. 1. First (1), a borehole of larger diameter (about 100 mm / 4’’) is made using a hollow auger, mud rotary with casing if necessary, or a solid auger if there is no risk of cave-ins. Then a 1.5-m (5-ft.) zone of smaller diameter is drilled to create a “test cavity” or ‘test pocket’. The probe is then inserted with a minimum delay into this cavity (2) and the test is carried out. This sequence is repeated for each test. Using this method, from 3 to 8 tests can be performed per day in a borehole, depending on depth, soil, and type of test. Preparing a longer test cavity in which several tests are performed in series does not give good results in general and should be avoided.

4.1. Cutting tool

The cutting tool must be adapted to the soil type. We suggest using a three-wing drag bit in clay and silty soils (carving the soil), and a tri-cone bit in sandy/gravelly soils and soft rock (breaking up the soil). The cutting tool should preferably be fitted with reinforced tips. It must allow for axial, rather than lateral, mud injection to avoid enlarging the borehole diameter. Examples of these tools are shown in Fig. 2.

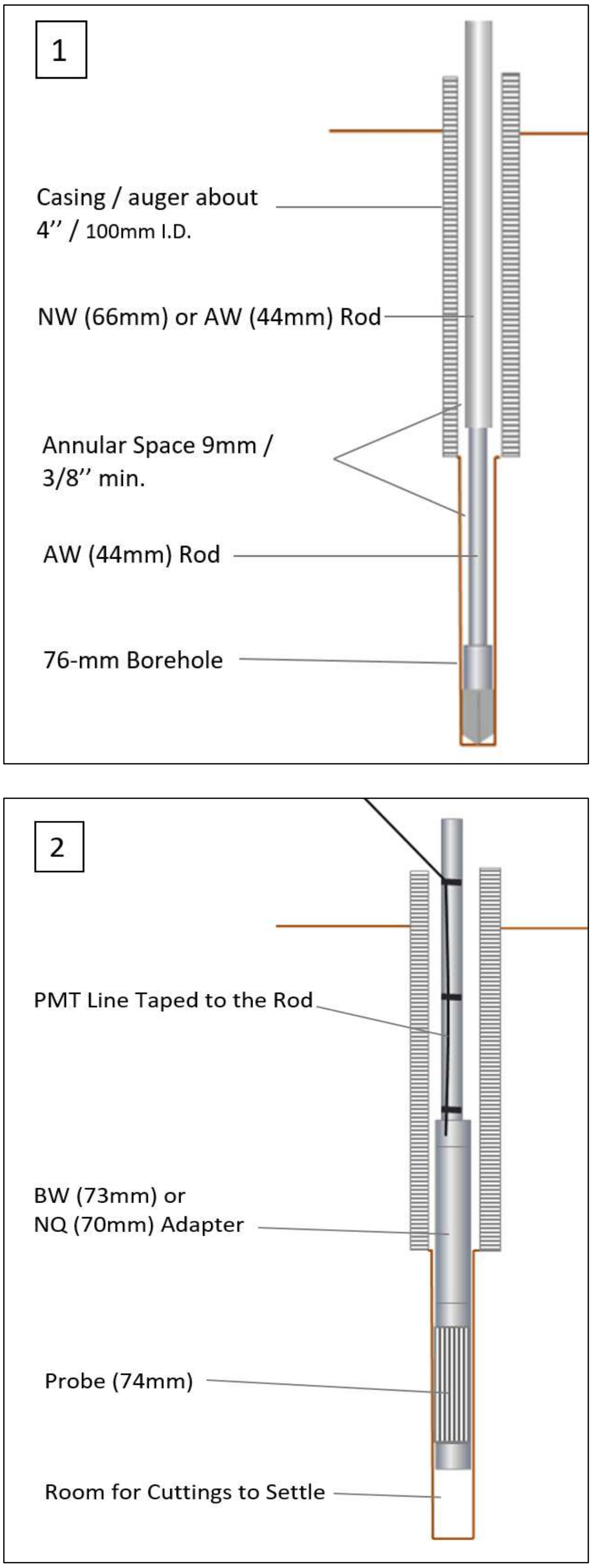

Figure 1. Recommended method for 1) test cavity preparation and 2) probe positioning

The cutting tool must have the same diameter as the probe, i.e. 74 mm (2-15/16") for 'N' boreholes. In some cases, it may be useful to have cutting tools of different sizes on hand (from 2-7/8" to 3-1/16").

Figure 2. Cutting tools generally used: Tri-cone Roller Bit and Drag Bit. An example of a modified tool is: Two-wing Drag Bit with a guide tube

4.2. Space for cuttings evacuation

It is important that the annular space between the equipment and the borehole walls is sufficient (9 mm – 3/8" minimum) to ensure proper cuttings evacuation. This objective will be achieved if the following measures are followed.

AW drill rods (44 mm) are often used successfully in 76 mm boreholes. However, as soil depth and hardness increase, these rods tend to oscillate laterally, which can affect the quality of the test cavity. To prevent this, we recommend using larger diameter rods (NW-66 mm) with a single 1.5-m (5 ft.) AW section positioned immediately upstream of the cutting tool, as shown in Fig. 1. Another option is to install a guide tube approximately 30 cm long upstream of the cutting tool. Ideally, this guide tube should remain inside the casing so as not to affect the walls of the test cavity. It must be designed in such a way as not to impede the return of drilling mud.

Secondly, the adapter between the cutting tool and the rods should be of small diameter, 60 mm or less in an N-size borehole.

Finally, some users modify the cutting tool they use (see Fig. 2). This may help, but is generally not essential.

4.3. Drilling fluid

The drilling fluid evacuates the cuttings and limits soil decompression and slumping by replacing, as it were, the soils evacuated from the borehole. In clay, water alone is often used, but as the grain size of the soil increases, the viscosity of the fluid will need to be increased as well. Although polymer-based slurries have been used successfully, those made from bentonite generally deliver better results and are to be preferred. This is because soil particles remain in suspension in bentonite-based slurries, unlike polymer-based slurries in general, enabling injection rates to be kept low without affecting the removal of cuttings. Using a polymer-based slurry will often mean increasing the injection rate to ensure good evacuation, especially at greater depths, which can affect the quality of the test cavity. Certain types of polymer are sometimes added to bentonite-based slurry to, for example, reduce the sticky effect of the clay or simply increase the viscosity of the mixture.

In some cases, it is useful to densify the mud, by adding baryte for example. Such cases include soils with very little cohesion (loose sand), very soft clays in which the borehole tends to cave in, and artesian situations. It should be noted, however, that increased densification and viscosity can have undesirable effects, such as requiring higher injection pressure for cuttings return, and increased suction when handling the drill rods. Larger-diameter casing may be required to counteract these effects.

4.4. General instructions

It is important to drill slowly to avoid excessive enlargement of the test cavity. This means:

- Keep cutting tool rotation speed low (aim for 60 rpm), especially in erodible soils.
- Do not apply excessive force to the rods: less than 100 kg (220 lbs) in an N borehole (much less in soft clay).
- Apply a low mud flow rate, less than 20 l/min (5 gallons/min).
- Maintain stable injection pressure. An increase in pressure will occur, for example, when clayey cuttings accumulate in clumps over the drill bit, blocking the mud return and risking over-pressurizing the test cavity. This may be due to the drill bit being lowered too quickly, or to the slurry being too viscous.

Drilling should go beyond the planned test depth (0.75 min) to allow cuttings to settle if necessary. Finally, the borehole should not be thoroughly cleaned. A second pass is possible except in loose sands. A final pass can also be made without injection or rotation, to check that the borehole remains open. When removing the cutting tool, make sure to maintain a high level of drilling fluid in the casing to avoid under-pressurizing the test cavity.

With these methods, 5 to 20 minutes will be required to prepare a 1.5-m test cavity.

We understand that attention to the preparation of the test cavity is strongly suggested. Failmezger (Failmezger 2025) suggests :

- Measure the flow rate by writing down the time required to fill a 5-gallon bucket.
- Make a vertical chalk mark on the drill rods and record rpm.
- Make horizontal marks every 30 cm (1 foot) on the rods and time the penetration speed. This is important, among other things, to locate transition zones between very different soil layers, which should be avoided when positioning the probe.
- Roughly check soil composition by observing expelled cuttings.

The rods used to drill the test cavity will also be used to position the probe. The probe should not be pressed into position with excessive force. Two people can press on the rods using pipe wrenches. Do not use the hydraulic force of the drill rig. Excessive thrust can remold the soil, damage the probe and even cause cuttings to flow back around the probe. To this end, it is important to measure the lengths of the rods and adapters used, so as to know the exact elevation of the probe.

All of the above is frequently contrary to the drilling methods normally used by drillers. A learning curve is therefore required on their part.

5. Validation

Validation of the borehole quality is essential. It should be carried out after the first tests, and any necessary adjustments made to the drilling method. The two main tools for validation are : the shape of the curve and the ratio of Pressuremeter Modulus to Limit Pressure *Ep/Pl*.

5.1. Shape of curve

Fig. 3 and Table 1 describe the main forms that the pressuremeter curve can take. The ideal curve (3) is made up of three distinct zones (approach zone where the probe is not yet in contact with the ground, quasi-linear pseudo-elastic zone, and creep zone with increasing ground deformation).

In addition to being appropriately shaped, the curve must be smooth. Significant dispersion may indicate a problem with the drilling or testing method.

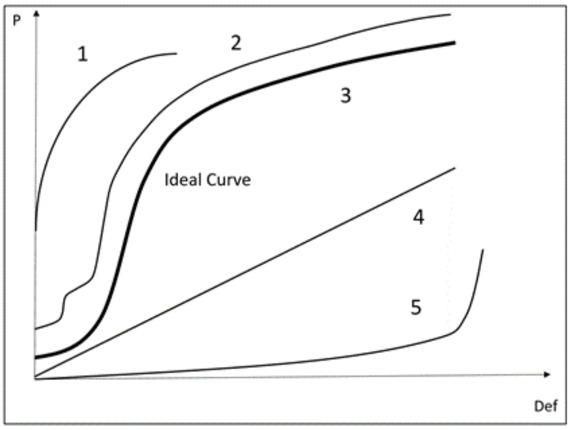

Figure 3. Possible test curve shapes (after Baguelin, 1978)

Table 1. Typical curve shapes and comments

Curve type	Comments
1 Borehole diameter too small	*Pl* usable, *Ep* possibly remolded
2 Some material between probe and borehole.	Mainly usable results
3 Ideal curve	Usable results
4 Borehole heavily remolded	Results not usable
5 Borehole diameter too large	*Ep* partially usable

Note that the shape of the ideal curve 3 will vary according to whether the soil is clay or sand. In the former case, the final yielding portion of the curve will be more pronounced, whereas in the latter, the soil will appear to fail more gradually.

A case not illustrated in Fig. 3 is when the quasi-linear zone of the curve has two distinct slopes. This situation may be due to the composition of the soil, for example those with alternating thin hard and soft layers, or those containing blocks embedded in fine, low-stiffness soils. In such cases, the pressuremeter probe might measure the reactions of the soil's softer and harder elements in turn. This type of curve can also be due to a handling error, i.e. if the operator positions the probe so that it straddles two layers of distinct rigidity. This situation can be avoided if the precautions outlined in section 4.4 are followed.

5.2. *Ep/Pl* Ratio

The *Ep/Pl* ratio is an essential tool for estimating the level of soil disturbance and therefore test quality. This ratio should be rather constant for any specific soil type and fall within certain ranges (see Table 2). Disturbance of the soil will generally affect *Ep* more than *Pl*, thus modifying the *Ep/Pl* ratio. If this ratio is too low (less than 5 in sand and less than 7 in clay), something is wrong and adjustments are required.

Table 2. Typical Menard *Ep/Pl* Values (Canadian Geotechnical Society, 1985)

Type of soil		*Ep/Pl*
Sand, silt, and gravel	Loose to dense	5 - 14
	Very dense	Over 14
Clay	Weathered or altered	7 - 9
	Normally consolidated	9 - 16
	Overconsolidated	Over 16

Other tools may help validate the tests, such as typical *Ep* and *Pl** (Net Limit Pressure) values for different soil types – see Table 3, the ratio of creep pressure (*Py*) to limit pressure, and correlations with other test parameters.

Table 3. Expected values of *Ep* and *Pl* (Briaud 2013)

Type of soil		*Pl** (kPa)	*Ep* (kPa)
Clay	Soft	0-200	0-2500
	Medium	200-400	2500-5000
	Stiff	400-800	5000-12,000
	Very stiff	800-1600	12,000-25,000
	Hard	Over 1600	Over 25,000
Sand	Loose	0-500	0-3500
	Compact	500-1500	3500-12,000
	Dense	1500-2500	12,000-22,500
	Very Dense	Over 2500	Over 22,500

6. Drilling in rock

Preparing a pressuremeter borehole is generally easier in rock, as the borehole diameter and disturbance level are easier to control. However, there are a number of peculiarities and challenges that need to be taken into account to ensure the quality of the measurements and the durability of the equipment:

- The borehole must be very well adjusted. Ideally, it should exceed that of the probe by 2 to 5%.
- The walls of the borehole must be smooth to ensure good contact of the membrane onto them.
- The membrane must be fully positioned in a rather uniform rock zone. Weathered or soft zones that are smaller than the length of the membrane should be avoided.
- Special care must be taken to avoid jamming the probe in place.

In sound rock, diamond core drilling generally allows to meet these requirements. This method is the most widely used in rock, since it not only produces a quality test cavity, but also samples that can be analyzed for probe positioning. A key criterion for this is the recovery rate, which should normally be around 100%.

If zones of lesser quality must be tested, the use of a less aggressive drilling method, like wet rotary drilling with tri-cone, must be considered.

It is also important to prevent rock fragments from falling onto the probe and jamming it in place. The borehole walls above the probe can therefore be supported using a casing, as shown in Fig. 1.2. A more common option is to use rods of the same diameter as the probe to core the test cavity and lower the probe in place (typically HQ or NQ rods). This option is all the more interesting as it makes it easier to carry out several tests in series by preparing a longer test cavity and starting the tests from the bottom upward. With this method, between five and ten tests can be carried out per day, depending on the test method used.

Further details about drilling in rock are available in ASTM D8359-21 (Standard Test Method for Determining the In Situ Rock Deformation Modulus and Other Associated Rock Properties Using a Flexible Volumetric Dilatometer, 2024).

7. Case Histories

The following are three examples of adverse effects linked to the drilling method in soil.

7.1. Disturbance due to the use of a thick wall sampler (split spoon)

Preparing the test cavity with a split spoon can significantly disturb the soil. The case illustrated here is a case in point.

Pressuremeter tests were carried out with a Texam single-cell probe in two adjacent boreholes at depths ranging from 16 to 22 m. The soil tested was uniform and consisted of very stiff clay with traces of sand, silt, and gravel, with N-SPT values around 30. The test cavities were prepared using the rotary drilling with bentonite mud injection method, using a 2-15/16" tri-cone.

Test results were repeatable and in line with expectations, except in the case where the test cavity was prepared with a driven split spoon. As can be seen in Fig. 4 and Table 4, the use of a split spoon had the effect of reducing the *Ep* value by half without significantly affecting *Pl*, thus lowering the *Ep/Pl* ratio value to non-compliant levels (from 7.64 to 3.39).

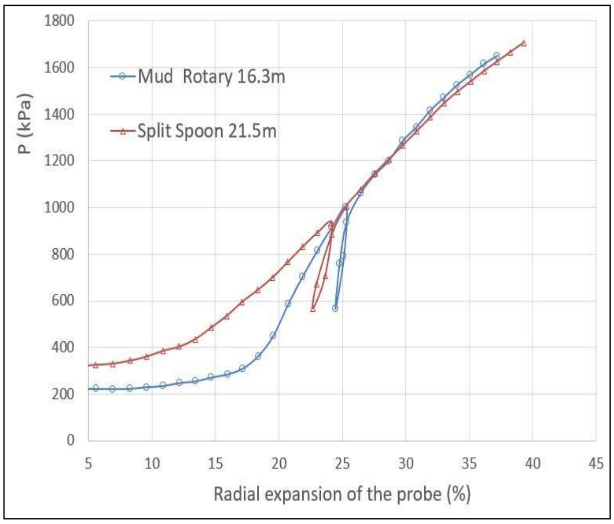

Figure 4. Effects of drilling methods (thick wall sampler vs mud rotary)

Table 4. Examples of drilling method effects on results

Depth (m)	Drill method	*Ep* (MPa)	*Er* (MPa)	*Pl* (MPa)	*Ep/Pl*
16.3	Mud rotary	16.9	71.0	2.22	7.64
21.5	Split spoon	7.97	34.9	2.35	3.39

Interestingly, the divergence is more pronounced at the beginning than at the end of the curve. This is consistent with the fact that disturbance level generally decreases with the radial distance away from the borehole walls, explaining why *Ep* is more sensitive to soil disturbance than *Pl*.

We also note the significant effect of the change in drilling method on the Reload Modulus (*Er*), which may come as a surprise since this parameter is generally considered less sensitive to disturbance than the First-Load Modulus *Ep*. But this result is in line with the one observed by Combarieu (Combarieu 2001). A Reload Modulus measured at a higher strain level, would, like Pl, probably have been less affected by the soil disturbance. Still, the potential effect of remolding on *Er* reinforces, in our view, the importance of controlling the quality of the drilling method.

It should be kept in mind that driving a split spoon can have variable and even opposing effects, depending on the type of soil. Some soils are essentially densified and thus strengthened, while others are destructured, and thus weakened. This significant variability generally makes it difficult to estimate these effects. This phenomenon can be applied to any type of equipment that causes a significant displacement of the soil, such as the driven slotted tube (casing) or the pushed-in pressuremeter probe (Baguelin 1978, Briaud 1992).

7.2. Interposition of material between probe and ground

The second example illustrates the effects of interposing parasitic material between the probe and the ground. Fig. 5 and Table 5 show the results of three consecutive tests using a Menard pressuremeter in a borehole prepared using the mud rotary drilling method. The soil, consisting of sandy lean wet clay with a trace of gravel, is uniform and of medium stiffness.

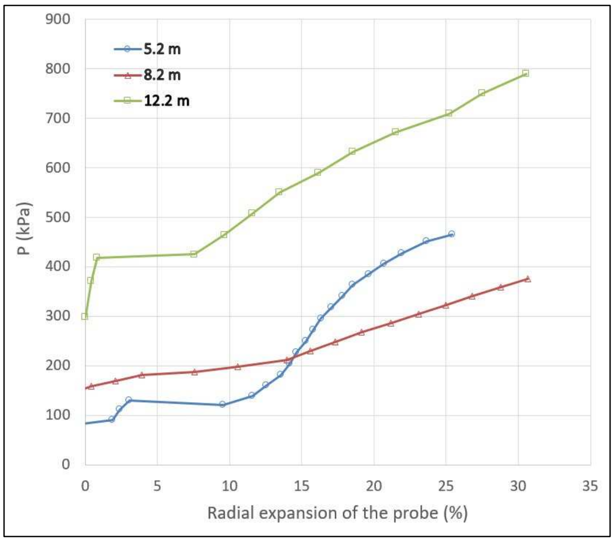

Figure 5. Effects of interposing parasitic material between probe and borehole

Table 5. Examples of the effect of parasitic material between probe and borehole on results

Depth (m)	***Ep* (kPa)**	***Pl* (kPa)**	***Ep/Pl***
5.2	6480	580	11.2
8.2	1590	418	3.80
12.2	3125	850	3.68

The first test at 5.2 m is successful. Except for a slight initial pressure spike, the shape of the curve is acceptable. It resembles curve 2 in Fig. 3, suggesting the presence of small amount of parasitic material between the probe and the borehole. The *Ep/Pl* value is also adequate. On the other hand, the following tests (at 8.2 and 12.2 m) are of poor quality, even though nothing has changed in the drilling method or soil type. The shape of the curves now resembles curve 4 in Fig. 3, and the *Ep/Pl* values are too low.

The problem in this case was poor cuttings evacuation. The use of large NW drill rods (66 mm) along the entire length of the borehole, combined with a small internal diameter auger (82.5 mm or 3-1/4"), considerably reduced the annular space required for proper evacuation. And this problem became more acute with depth. The cuttings compressed on the borehole walls, creating a 'caking effect'. The curves illustrate less the reaction of the soil loaded by the pressuremeter probe than that of the cuttings compressed by it. To this may be added the effect on the soil of over-pressurization, which may have been necessary for mud circulation.

7.3. Using a thin-walled sampler

The last case presents the results of comparative tests between two drilling methods, using a thin-walled (Shelby) sampler and wet rotary drilling. The tests were carried out using a Texam single-cell probe in two adjacent boreholes. The soil tested consisted of sensitive clay of soft to firm consistency, with a shear strength ranging from 20 to 60 kPa.

The results presented in Table 6 show that the use of a thin-walled sampler reduced *Ep* by about half, without significantly affecting *Pl*. This had the effect of reducing the *Ep/Pl* ratio to unacceptable levels. The softness and sensitivity of the clay certainly made the D4719 recommendations to use a long sampler to create the test cavity in a single pass, and to remove the sampler very slowly to reduce suction, even more relevant.

This case is another example of the importance of using the *Ep/Pl* ratio to validate the drilling techniques.

Table 6. Comparative tests : thin-walled sampler vs wet rotary drilling

Drill method	**Depth (m)**	***Ep* (kPa)**	***Pl* (kPa)**	***Ep/Pl***
Mud rotary	3.05	2798	258	10.85
	6.25	3069	345	8.89
	9.15	4974	461	10.79
Shelby Tube	3.06	1333	299	4.46
	6.01	2237	342	6.54
	9.13	2242	451	4.97

8. Conclusion

A good knowledge of drilling techniques is essential to ensure the quality of pressuremeter tests. The selection of a drilling method should not be based primarily on its apparent ease or speed. The quality of the results must override these factors.

The rotary drilling method with axial mud injection has established itself in North America thanks to its efficiency and versatility. The widespread use of this method may have contributed to the improvement of borehole quality (or at least to its standardization) and to the (slow but sure) progress of pressuremeter testing in North America. This article presents this drilling method in detail. It illustrates the importance of using the shape of the curve and the *Ep/Pl* ratio as validation tools. Finally, it presents some examples of the impact of the drilling methods used.

This article may be viewed as a guide for best practices in borehole preparation and validation, using the mud rotary drilling method, to optimize the quality of pressuremeter testing.

Acknowledgements

The authors are grateful to Jason Mapes of Mapes Insitu LLC and Bill Villalpando of Roctest Inc. for their contribution to this paper.

References

ASTM. ‘Standard Test Methods for Pressuremeter Testing in Soils’ Annual Book of ASTM Standards, Section 4: Construction, Vol. 04.08: Soil and Rock (1) : D4719-20, 2024.

ASTM. ‘Standard Test Method for Determining the In Situ Rock Deformation Modulus and Other Associated Rock Properties Using a Flexible Volumetric Dilatometer, 2024’ Annual Book of ASTM Standards, Section 4: Construction, Vol. 04.09: Soil and Rock (ll) : D8359-21, 2024.

Baguelin F., Jezequel J. F., Shields D.H., ‘The Pressuremeter and Foundation Engineering’, Trans Tech publication, Clausthal, Germany, 1978. 617 p.

Briaud J. L., ‘The Pressuremeter’, Balkema, Rotterdam, The Netherlands, 1992. 322 p.

Briaud, J. L., ‘Geotechnical Engineering: Unsaturated and saturated Soils’, John Wiley & sons, 1000 P. 2013. http://doi.org/10.1002/9781118686195

Canadian Geotechnical Society, ‘Canadian Foundation Engineering Manual’ 2nd edition, Vancouver, BiTech Publishers Ltd, 1985, 456 p.

Combarieu O, Canépa Y. ‘L’essai cyclique au pressiomètre’ (Cyclic Testing with the Pressuremeter) Bulletin des LPC, 233 Réf 4381, pp. 37-65. 2001. (in French)

Failezger R. "Pressuremeter Test" Available at: https://insitusoil.com/soil-pressuremeter-test/#performing accessed : 01/27/2025

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 8th International Symposium on Pressuremeters (ISP2025) and was edited by Wissem Frikha and Alexandre Lopes dos Santos. The conference was held from September 2nd to September 5th 2025 in Esch-sur-Alzette, Luxembourg.