# Borehole quality influence on expansion test results

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**ABSTRACT:** This paper presents a study of the preponderant influence of the mode of placement of the pressuremeter probe for borehole expansion tests. Several comparative field tests have been performed in sand, silt, chalk, marls to assess this influence. A presentation of the different sites and a detailed analysis of the results emphasize the role of the hole quality on load-deformation curve and determination of modulus and limit pressure.

**Keywords:** prebored pressuremeter, boring quality Ménard modulus, limit pressure

## 1. Introduction

It is worth mentioning that the pressuremeter modulus $E_M$ is very sensitive to the quality of the borehole in which the pressuremeter probe is inserted (as is, to a lesser extent, the limit pressure $p_{\ell M}$). Originally, boring conducted with a hand auger (in fine soils) with considerable precautions (for example, injecting slurry into the borehole if necessary in order to support its walls) was considered to be the technique that disturbed the soil the least. This boring procedure, which is unusable in many soils and very limiting in the case of deep investigations, has largely been abandoned in favour of faster equipment and therefore less costly execution, which is however considered by some to be "destructive" for the soil. The large range of boring tools and machines has encouraged studies of how the boring mode affects the characteristics obtained for the main types of soil and the development of recommendations, first of all incorporated in the LPC test procedures (see table 1) and then in the French standard NF P 94-110-1 (AFNOR, [1]) and international standard EN ISO 22476-4 (CEN, [2]).

However, good practice is not always followed, and it must be admitted that some of the values for the $E_M$ modulus (and the limit pressures $p_{\ell M}$) that are to be found in geotechnical investigation reports are completely unacceptable and underestimate the properties of the soil. This is a disservice to the pressuremeter method, which is of great value and whose usefulness in the context of calculating the settlement of deep or shallow foundations is well established [3,4].

Good quality boring, as it has already been stated, is essential for the quality of the standard pressuremeter test. A wide variety of factors determine the quality and reliability of the parameters measured by the pressuremeter: drilling tools, the drilling stage length between tests and drilling parameters all affect soil disturbance and influence the test results – i.e. the limit pressure $p_{\ell M}$ and the modulus $E_M$ (the latter being generally more affected than the former). These requirements stated since the seventies, it has therefore very early been asked to comply with the recommendations which are reproduced in table 1 in order to obtain results which are indicative of real soil behaviour and be able to use pressuremeter-based design methods.

**Table 1.** Guidelines for pressuremeter probe placement techniques (LCPC, 1971)

| | | Ground classification | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | fine soils | | | silts | | sand | | | gravel | | | rock | |
| | | 1 | 2 | 3 | 1 | 2 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 |
| open hole | hand auger | - | + | | - | + | - | + | | | | | | |
| | hand auger mud | + | + | | + | + | + | + | | | | | | |
| | continuous flight auger | - | o | + | - | + | - | + | + | | o | o | + | |
| | drag bit | - | o | + | o | o | o | + | + | | o | o | + | + |
| | sampler | - | - | + | - | - | - | | | | | | + | + |
| | rotary percussion | - | - | o | - | o | - | o | + | | o | o | + | + |
| | hammered thick tube | - | - | o | - | o | - | o | + | | o | | + | |
| | vibro driven sampler | - | - | o | - | o | - | o | + | | o | | + | |
| full disp. | driven slotted tube | - | - | - | o | - | - | o | o | o | o | o | | |
| | vibro driven slotted tube | - | - | - | o | - | - | o | o | o | o | + | | |
| tubing | self-boring probe | + | + | | + | o | + | | | | | | | |
| | slotted tube with inside drilling tool | - | - | o | o | o | o | + | + | + | + | + | + | |
| - not recommended<br>+ recommended<br>o Permitted | | 1 soft<br>2 medium<br>3 stiff | | | 1 below Water Table<br>2 dry | | 1 loose below Water Table<br>2 medium<br>3 dense | | | | | | 1 weathered<br>2 sound | |

## 2. Test sites

When drafting the French Public Works Laboratory (LCPC) procedure in 1971, for pressuremeter tests by the dedicated research Group of the French ministry of Public Works, a study devoted to the methods of setting up the probe according to the terrain made it possible to propose recommendations [5, 6, 7, 8, 9, 10]. The table summarizing the recommended, tolerated and unadvised implementation modes is the ancestor of Table C.2 extracted from the standard EN ISO 22476-4.

The research carried out in various soil types by the regional laboratories LRPC was organized as follows:

- Loire sand for Angers laboratory,
- stiff clay and marl for Bordeaux laboratory,
- silt for Lyon and Melun laboratories,
- stiff clay and weathered chalk for Rouen laboratory,
- soft marl-limestone for Melun laboratory,
- clays and weathered shales for from Saint Brieuc laboratory.

These results have been presented in part in Baguelin et al. [3].

For the tests described below, we therefore varied the boring techniques, from the one we have termed the reference method (hand auger) to methods which are highly disruptive and obviously prohibited (table 2).

**Table 2.** Modes of placement used in this research

| Mode | Technique | Acronym | Diam |
|---|---|---|---|
| Mode 1 | Hand Auger, meter by meter | HA | 60 |
| Mode 2 | Continuous flight auger, meter by meter | CFA | 63 |
| Mode 3 | Continuous flight auger, in a single pass | CFA_u | 63 |
| Mode 4 | Rotary percussion, meter by meter | ROTOP | |
| Mode 5 | Desagregating tool, in a single pass | OHD_u | 63,5 |
| Mode 6 | Desagregating tool meter by meter | OHD | 63,5 |
| Mode 7 | Driven slotted tube | DST | 63 |
| Mode 8 | vibro-driven slotted tube | VDT | 63 |
| Mode 9 | Hammered thick tube | OS-TK/WH | 63 |
| Mode 10 | Core drilling | CD | |

For each site, ground investigation had been supplemented with laboratory identification tests and as far as possible, compressibility and shear tests. Other in-situ measurements have been associated with pressuremeter sounding, such as static penetrometers, field vane tests.

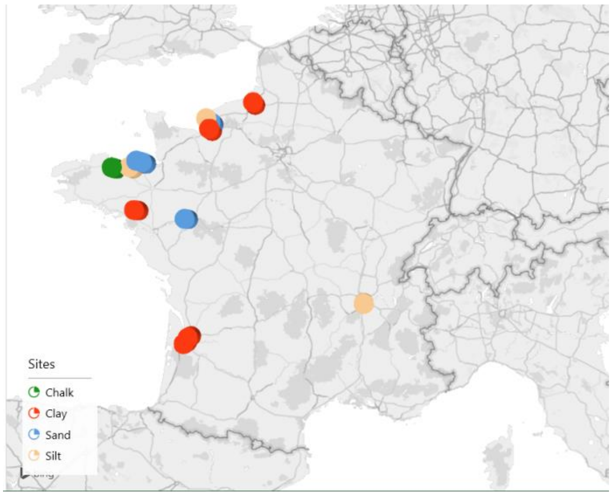



**Figure 1.** Experimental test sites location

These campaigns have been complemented by studies by Rouen laboratory in 1997, Bordeaux laboratory in 2010 and IFSTTAR and Saint-Brieuc laboratory in 2018 and Ginger in 2019 [11, 12, 13, 14]. These tests have been conducted in three soils (silt, very plastic clay, sand).

## 2.1. Clayey test sites

The first site is located close to Bordeaux, five borehole 7 to 10 m deep have been drilled in a 5 m square zone [6].

The minimal distance between borehole is 1 m. The upper layer of the ground, 2m thick, is a marly clay very plastic (Stampien) lying on a layer of stiff marl of low plasticity (Sannoisien inférieur). The site is quite homogeneous. The water table is found at 1.1 m depth.

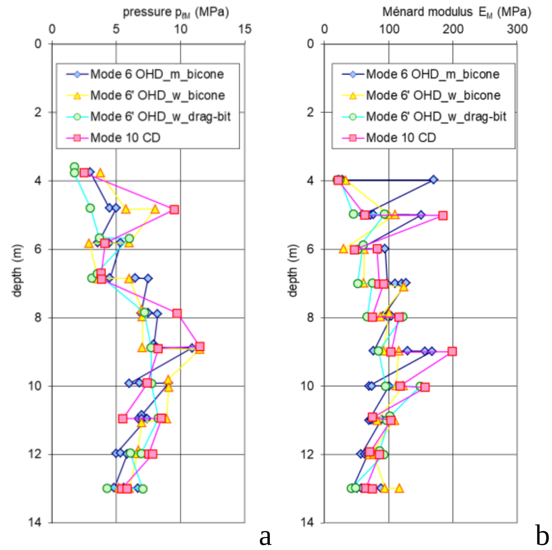



**Figure 2.** Influence of the mode of placement on the limit pressure and pressuremeter modulus for a stiff clay close to Bordeaux

If the drill bit with mud (mode 6) is taken as a reference, drilling with water in general (modes 6' and 6") and core drilling (mode 10) and drill bit give higher results (Fig. 2). But all these results stay in a range staying around 20% of the mean value.

The second site is located in Pont L'évèque in Normandy [8]. Fig. 3 shows a limit pressure overestimated, if hand auger (mode 1) is taken as the reference, when the probe is inserted by displacement of the soil (mode 7) and in a lower extend when drilling the hole using a destructive tool (mode 6). The Ménard modulus is under estimated when the borehole wall are not stabilized by mud or are displaced when driving the probe.

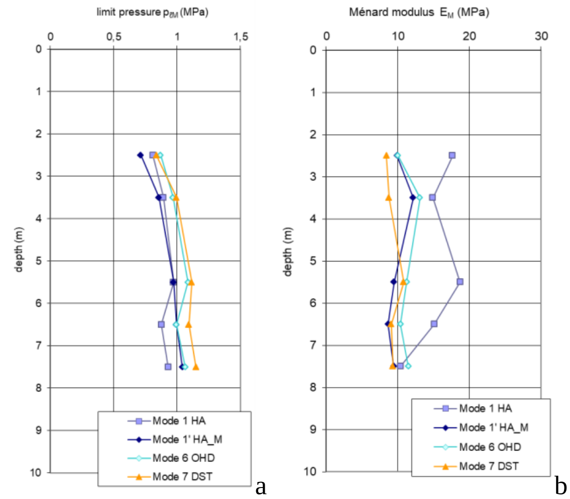



**Figure 3.** Influence of the mode of placement on the on the limit pressure and pressuremeter modulus for a soft clay at Pont L'évèque

The main conclusions were that for very soft cohesive soils to moderately consistent fine soils, the use of the hand auger with mud is the method that does not significantly disturb the borehole walls. For moderately consistent fine soils to overconsolidated compact clay when the hand auger can not penetrate this type of soil, the use of the continuous fligth auger or rotary drilling with mud is preferred.

The 1997 campaign was located at Callengeville, in the exhumed and eroded anticlinal fold of the Pays de Bray in the département of Seine Maritime [11]. The formation consisted of black Albian clay, known as Gault clay, located below the water table. The homogeneous zone of this geological horizon was tested by using seven very closely spaced boreholes, placed about 2 metres apart.

Seven boring modes were employed, ranging from the hand auger without soil “disturbance” and with 1 m stages (mode 1) to direct driving of the probe (mode 7), protected by a slotted tube, which is an absolutely prohibited method.

Fig. 4a and 4b show how the mode of placement affected the values of the Ménard pressuremeter modulus $E_M$.

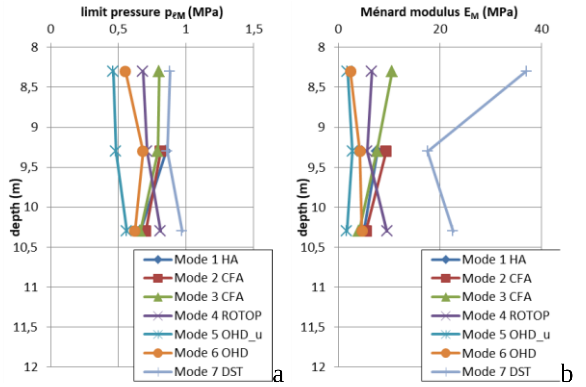



**Figure 4.** Influence of the mode of placement on the on the limit pressure and pressuremeter modulus for a firm clay at Callengeville

The highly destructive nature of modes 5 and 6 (desagregating tool without percussion) is apparent. This provides very low $E_M$ modulus values, with limit pressures also being considerably affected. Direct driving (mode 7) leads to very high $E_M$ modulus values in comparison with the hand auger mode. In reality, however, the considerable increase in pore pressures that occurs when the probe is driven is doubtless partly responsible for this result.

In the case of modes 2, 3, 4 and 1, the values of $E_M$ are relatively close together.

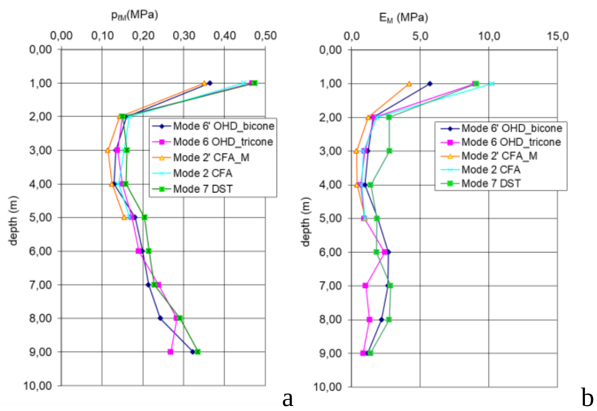



**Figure 5.** Influence of the mode of placement on the on the limit pressure and pressuremeter modulus for an organic clay et Cubzac (taken from Gardet et Leprêtre, [12])

A study by Gardet and Leprêtre [12] on the experimental site of Cubzac-les-Ponts shows, for the techniques currently used, that the conclusions of the previous work are not questioned (Fig. 5):

- the reference in quality remains for the compressible soil the continuous flight auger with injection,
- the dry continuous flight auger gives an overestimated value,
- the bi-cone rolling cutter drill bit with bentonite gives the best borehole,
- the tri-cone rolling cutter drill bit with bentonite probably implemented with an excessive advance rate and the pushed-in probe give an overestimation on full height.

During ARSCOP project, Désourtheau et Mourier [13] have investigated a thick layer of soft organic clay on Pont de Cran site.

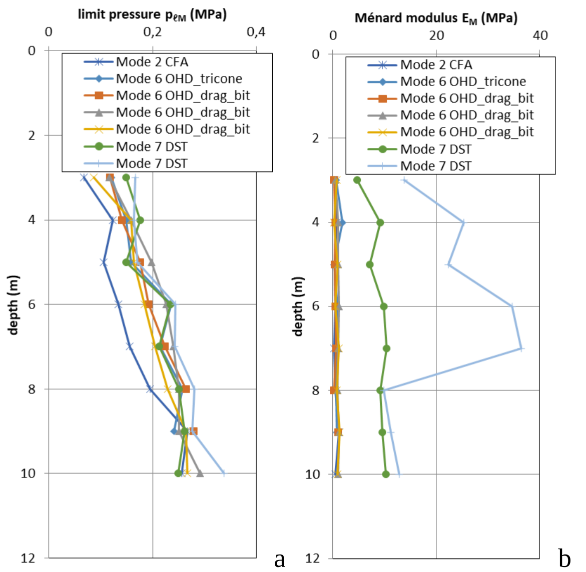



**Figure 6.** Influence of the mode of placement on the on the limit pressure and pressuremeter modulus for a soft organic clay (taken from Désourtheau et Mourier, [13])

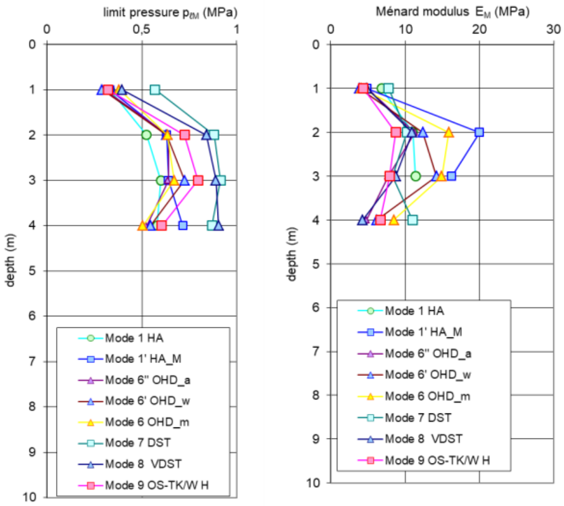
Fig. 6 confirms that driven slotted tube mode gives definetely overestimated values of Ménard modulus and should be prohibited in this type of soil. CFA (withour mud) mode in soft clay may create a succion when retrived and hence low values of limit pressure.

## 2.2. Silty test sites

The first silt site is located in les Minguettes [9]. The site is homogeneous constituted of overconsolidated silt of fragile structure called loess.

The cavity created with air give high initial volumes close to 250 $cm^3$. If the hand auger is taken as a reference, drilling with continuous flight auger and drill bit give slightly higher values of limit pressure (5 to 15%), this increase being more important with water (15 to 30 %) and even more with full displacement methods (50 to 100%) (Fig. 7). Injection of water and hammering of tube lead to an increase with depth (5% close to soil surface and 30 to 50 % deeper).

For pressuremeter modulus, the tendencies are less obvious: increase of the modulus for methods with use of bentonite (40 to 65%) and decrease for the other modes (10% for driven ou vibrodriven slotted tube).




a b

**Figure 7.** Influence of the mode of placement on the on the limit pressure and pressuremeter module for a silt of Minguettes site

For the 1997 campaign, the soil is an aeolian low plasticity silt. This is a very common geological formation in Normandy, as it covers all the plateaux [11]. The site which overlooks Le Havre (Le Mont Gaillard) has a layer of between 4 and 5 metres thick of this silt, whose density increases with depth, as we know from previous studies in the area. Below the silt the soil becomes very much more dense and structured and contains flint.

Three boring modes were tested, with one borehole for each mode; each was located at the summit of an equilateral triangle with sides of 2 m.

- Mode 1 (HA). Hand auger in dry conditions, with a diameter of 63 mm. The borehole, with a total length of 6 m, was bored by lengths of 1 m at a time, each metre requiring five or six auger passes. Silt was therefore extracted, with practically no “disturbance” of the wall of the cavity: This was the reference boring mode. A pressuremeter test was performed after each meter was bored.
- Mode 2 (CFA). Continuous flight auger in dry conditions with a diameter of 63 mm, according to the following procedure which minimized “reaming” of the cavity:
  - boring from 0 to 2,5 m with two pressuremeter tests performed at depths of 2 m and 1 m,
  - boring from 2,5 to 4,5 m with a pressuremeter test performed at a depth of 3 metres,
  - boring from 4,5 to 5,5 m, with a pressuremeter test performed at a depth of 5 metres.

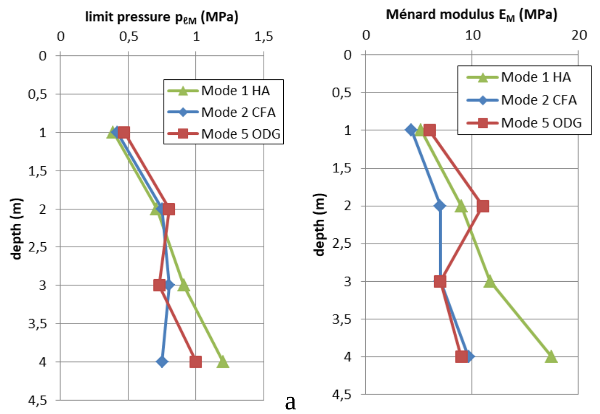
  This is the most frequently used boring mode in soil of this type.
- Mode 5 (OHD). “Three-blade” desagregating tool with a diameter of 64 mm in a single pass, from 0 to 5 m, followed by subsequent conduct of pressuremeter tests, from bottom to top.

Fig. 8a and 8b show the effect of the boring techniques on the values of the Ménard pressuremeter modulus $E_M$.

The Fig.8 elicit the following remarks:

- In general, the hand auger provides the highest modulus values. On average, the EM values from the continuous flight auger (mode 3 CFA) are 1,5 times lower than those from the hand auger (EM = 10,8 MPa, as opposed to EM = 7 MPa for the flight auger).
- The desagregating tool (DTS), with a single 5 m metre drilling stage leads to greater dispersion among results, which vary from being slightly higher to very much lower than those obtained with the hand auger.

It should also be noted that the number of tests conducted was very small and that the density of the silt increases considerably with depth, as illustrated by the limit pressure $p_{\ell M}$ profiles (Fig. 8a).




a

b

**Figure 8.** Influence of the mode of placement on the on the limit pressure and pressuremeter modulus for a silt of Mont Gaillard

## 2.3. Sandy test sites

The first site is a beach at Saint Jean de la Croix on the left bank of the Loire river [10]. The sand layer is slightly loose and considered as homogeneous.The watertable connected with the river is stable around 1.3 m depth (Fig. 9).

The values obtained for the limit pressures seems independant of the drilling mode. For the Ménard modulus, the hand auger method gives higher values than the vibro-driven slotted tube mode and driven slotted tube mode. In this soil, vibro driving of slotted tube gives results close to the hand auger ones.

For loose to compact coarse soils, the recommended method is therefore, in this kind of soil, the hand auger or by default the continuous fligth auger, any other process causing a thrust by pushing or vibration, should be discarded. When these soils are embedded, the driven slotted tube by threshing is not recommended and the method of vibro-driving the slotted tube can be a mode of implementation tolerated.

Tests in River sand were conducted in 1997 at Honfleur on the southern bank of the Seine, and involved a thick layer (about 15 m) of fine sand which lies underneath silty alluvium [11]. This sand is below the water table and the tests were conducted at depths of 6, 7 and 8 metres (Fig. 10).

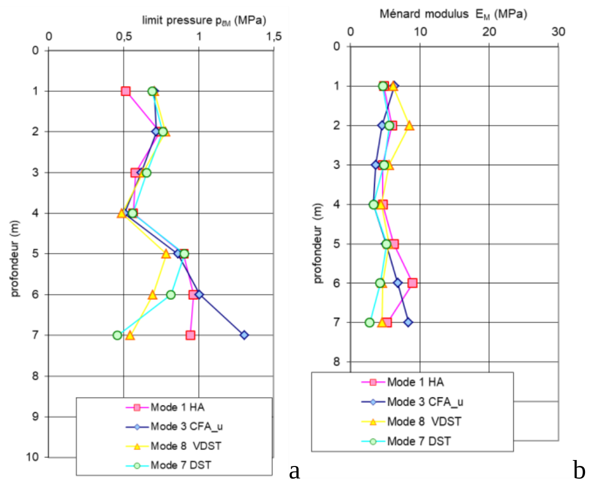



**Figure 9.** Influence of the mode of placement on the on the limit pressure and pressuremeter module for a sand at Saint Jean de la Croix

Four boring modes were tested, with two boreholes per mode:

- Mode 1 (HA): hand auger with injection of bentonite slurry, by means of successive passes of 1m with conduct of a pressuremeter test after each pass,
- Mode 2 (CFA): continuous flight auger with slurry circulation, by means of successive passes of 1 m with conduct of a pressuremeter test after each pass,
- Mode 3 (CFA): continuous flight auger with slurry circulation, by means of a single boring pass and with conduct of the pressuremeter tests from the bottom of the borehole to the top,
- Mode 4 (ROTOP): rotary percussion drilling; by means of successive 1 m passes and conduct of a pressuremeter test after each pass.

Of the twenty-four tests that were conducted, three were at a depth of eight metres and were not taken into account, in view of the very high limit pressures that were measured. These tests involved much more dense layers of sand in the lower part of the tested formation (1.35, 1.70 and 1.70 MPa).

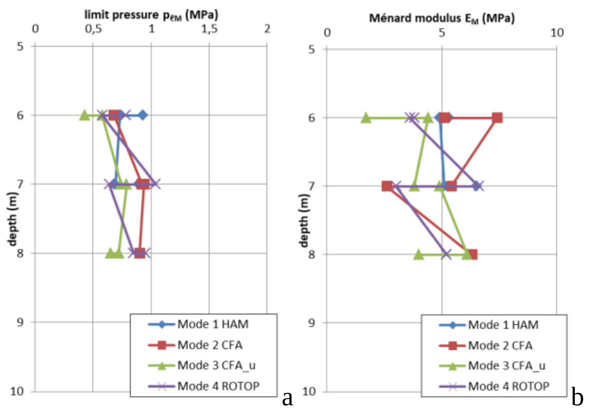



**Figure 10.** Influence of the mode of placement on the on the limit pressure and pressuremeter modulus for an alluvial sand at Honfleur

Although statistical analysis is made impossible by the small number of tests, we can nevertheless observe that in general the boring modes have a considerable influence on the $E_M$ and the limit pressure $p_{\ell M}$.

A recent study has been conducted in 2018 on the sea shore close to the dike protecting the city of Saint Malo [14]. The first drillings carried out on the beach below the dike were aimed at comparing drilling techniques and the influence on the measurements made with the Ménard pressuremeter (Fig. 11).

The graphs in Fig. 11 show the different profiles obtained. Although the expansion tests were not carried out in 1 minute increments according to the Ménard protocol, the loading speed being identical, there is no difference in the parameters measured.

Similar values are observed with the different modes of placement with a significant influence on the contact volume. For this site the slotted tube being placed after drilling a pilote hole the measured parameters don't show a major difference with the other techniques.

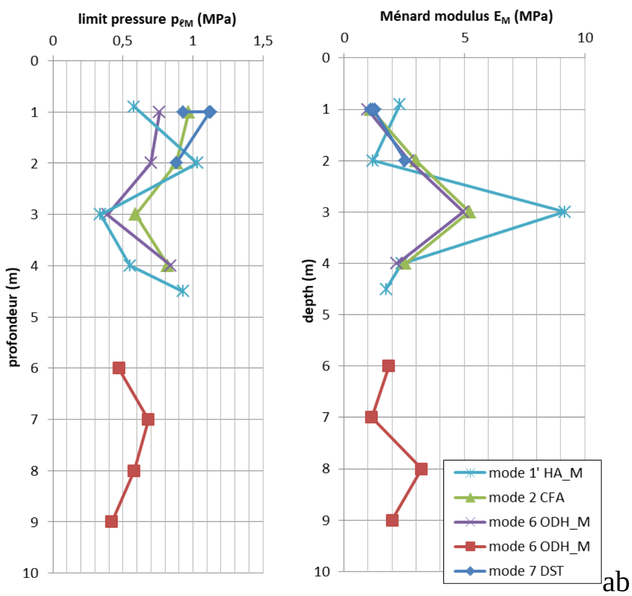



**Figure 11.** Module profiles and limit pressure for Ménard tests according to drilling techniques in a sand at Saint Malo

These tests show the difficulty of drilling in sand below the watertable. In accordance with the questions raised during the revision of the pressuremeter standard within ISO TC182/WG08, the national project ARSCOP and the French standardization committee, it seems that the technique of rotary drilling with mud is with the slotted tube technique with pre-drilling, adapted to the condition of controlling the centering of the tool (to limit wobbling).

## 2.4. Chalk

For weathered chalks and marl-limestones, it is not perfectly adapted to carry out tests to be considered as standards, therefore the methods by rotary percussion with moderate flow of flushing fluid and direct vibro-driving can only be tolerated any other method to be proscribed [8] (Fig. 12).

For sound chalk and stiff marl, core drilling with water as a flushing fluid is a delicate tool that can only be tolerated considering the fact that it requires a qualified staff having the concern of the quality of the drilling before that of the performance. The tool should be used by adopting for example a reamer to avoid the irregularities found and making it then a very competitive tool, given its speed of drilling. This conclusion is also true for rocks like sandstone.

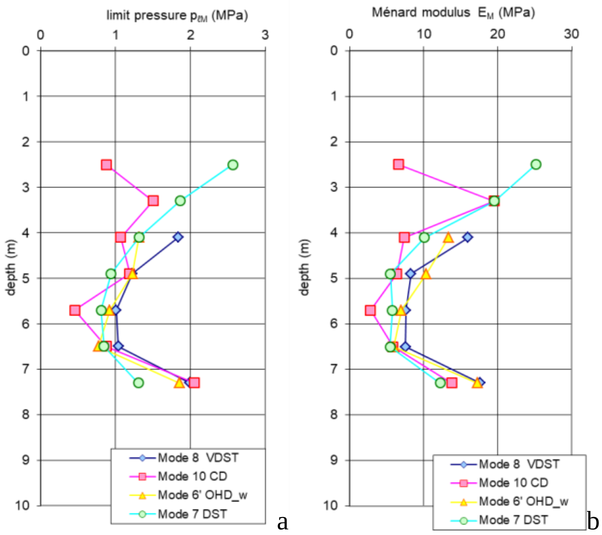



**Figure 12.** Influence of the mode of placement on the on the limit pressure and pressuremeter modulus for a chalk close to Rouen

## 3. Discussion

The main conclusion is the elimination of the coring method using a tube hammered (smooth tube frequently raised) in cohesive fine soils, silts and silts as well as compact sand or gravel.

The method of hand-auger drilling as much as possible remains the golden rule, although it does not combine the speed of drilling with the quality of drilling which must remain the main concern. However, due to the evolution of the trade and improvement of drilling machines, it has been completely replaced by the continuous fligth auger or better by drill bits (drag bits or rolling cutter bits) actuated by the hydraulic drilling machine. In soft fine soils, techniques causing succion when retrieving the tool (CFA and core drilling) should be eliminated.

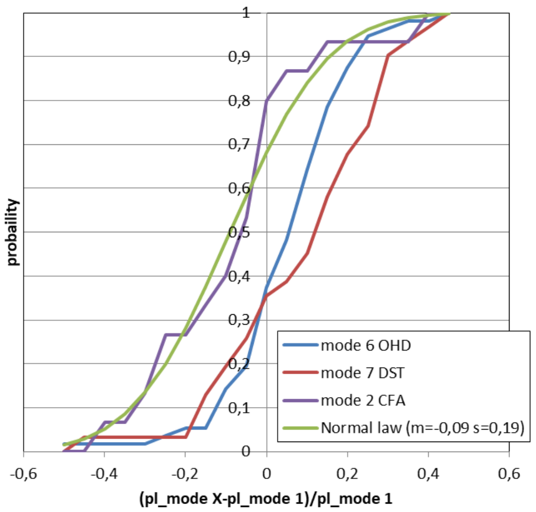



**Figure 13.** Cumulative distribution curve of the difference between limit pressure obtained using hand auger and other modes for drilling in all clay sites

Fig. 13 shows that for clay continuous fligth auger understimate limit pressure compared to hand auger in a proportion of 10% and the other techniques overestimated it by 5 to 15 % for desagregating tool and driven slotted tube repectively.

The methods by direct introduction of the slotted tube by hammering must leave the step to the method by vibrating which seems less disturbing the soil while being faster.

The limit pressure in the majority of cases is less sensitive to vibro-driving than hammering of the slotted tube as Ménard modulus but the study of mixed soils (wheathered chalk, flint clay, flysch or any other category of soils consisting of a weak matrix embedding hard elements) seems in this field to remain a local problem to be studied by each user according to the nature and the composition of these particular soils for which there is no standard drilling method.

With regard to tests carried out with a slotted tube in gravel or composite soils (tests after rest periods), the problem of the delay remains to be studied because too few tests have been carried out. The fact remains that this problem is important since for 2 hours of rest there was an increase of 50% of the modules.

Traditional core drilling methods may prove valuable in stiff grounds but require "fingering" for well-calibrated drilling.

Rotary percussion is well adapted in coarse and very coarse soils and hard rocky materials.

**Table 3.** Guidelines for pressuremeter probe placement techniques, EN ISO 22476-4 (CEN, 2012)

| soil displacement | | | without | | | | | | | | | with |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boring technique → | | | rotary | | | | Rotary-perc. | | Driven tube | | | |
| Soil and rock type ISO 14688-1&2 and ISO 14689 ↓ | | | OHD (M) | HA (M) | CFA | CD | RP (M) | ST DT (M) | OS T | OS Tk | VD | DST |
| fine | clay | soft ↓ firm | ++<br>+++ | +++<br>+++ | +<br>++ | +<br>++ | | +<br>++ | +++<br>++ | -<br>+ | | |
| fine | clay | stiff | +++ | + | +++ | +++ | -/+ | ++ | + | + | - | |
| fine | Silt above WT below WT | | +++<br>+++ | +++<br>++ | +++<br>- | ++<br>+ | -/+ | ++ | ++<br>- | -<br>- | +<br>- | -<br>+ |
| coarse | sand above WT below WT | | +++<br>+++ | +++<br>++ | ++<br>- | +<br>- | -/++ | ++ | - | -<br>- | -<br>- | -<br>+ |
| coarse | gravel | | ++ | - | - | + | -/+++ | +++ | | + | + | +++ |
| very coarse | cobbles, cobbles with gravels, boulder | | ++ | | | ++ | ++ / +++ | ++ | | - | - | ++ |
| intermediate | cohesive and non-cohesive non homoge-neous soils: tills, alluvial deposits, man-made, (un) treated fills | | ++ | -/+ | + | ++ | +/++ | ++ | | + | + | + |
| hard soil -soft rocks | chalk weathered rock, weak rock | | +++ | +/- | + | ++<br>+++ | ++ | +++<br>++ | | +<br>- | -<br>- | |
| rock | sound rock | | ++ | | - | +++ | +++ | + | | - | - | |

## 4. Conclusion

The pressuremeter tests conducted in a borehole drilled with the various techniques described above, whether accepted or prohibited, show more influence on the modulus values derived from the test than on limit pressure.

Although this conclusion is open to question in view of the small number of tests conducted at each depth and for each boring mode, given the current state of knowledge it nevertheless seems necessary when conducting pressuremeter tests to ensure the boring equipment is correctly selected and that boring is correctly performed. We therefore recommend to follow the rules laid down for borings in the case of standardized pressuremeter tests (table 3 taken from [2]) summarizing the conclusions of this communication.

Finally, experience shows that the limit pressure is generally insensitive to implementation, provided that the borehole is well calibrated. On the other hand, the pressuremeter module remains very sensitive to it, a defective implementation which can make fall this module of half or more.

The instructions in the table C.2 of EN ISO 22476-4 [2] must therefore be quite severe, leaving then a certain freedom of application specific to each particular case by users.

## 5. Acknowledgement

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