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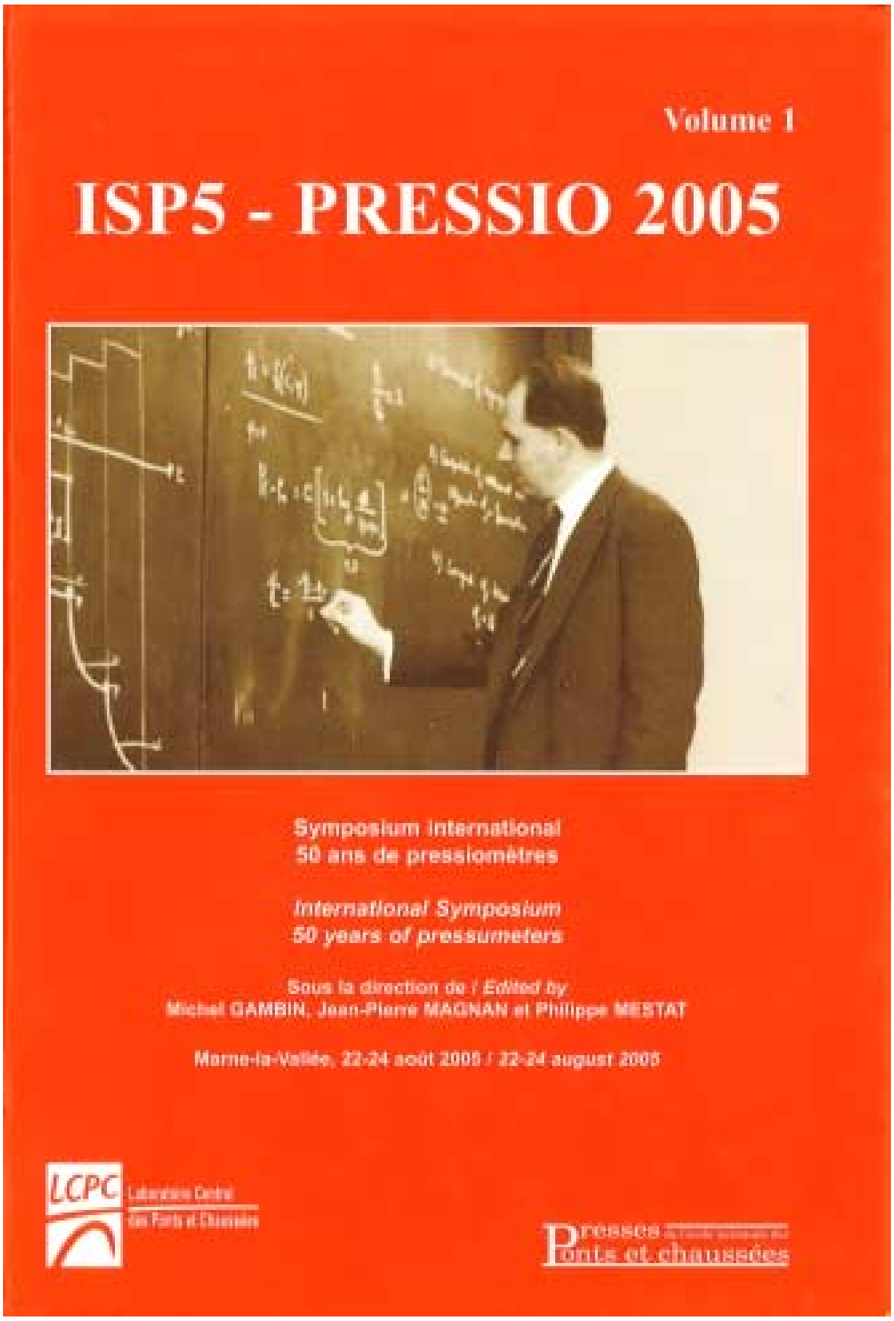

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Mr Ménard giving a lecture on the Pressuremeter in the offices of Kiso-Jiban Consultants Co, Tokyo, 1960
(Photograph from the obituary book of Dr Hiroshi Mori)

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RESUME – Dans la continuité des recherches et mises au point de Louis Ménard, plusieurs de ses collaborateurs, associés avec de plus jeunes géotechniciens ont cherché un moyen de réaliser la cavité où doit être introduite la sonde pressiométrique en mettant en jeu les techniques de forage les plus récentes, la procédure restant globalement économique. La cavité proposée est quasiment exempte de remaniement et le sol avoisinant exempt de relaxation. Des exemples comparatifs sont fournis dans un grand nombre de sols.

ABSTRACT – In continuation with the research and development work of Louis Ménard, several of his co-workers associated with younger geotechnical engineers tried and found an elaborated means to create the cavity in which the pressuremeter probe must be inserted. They used the most recent boring techniques available, the overall operation remaining still cost effective. The wall of this cavity is not subjected to remoulding and the surrounding soil does not exhibit stress relief. Various examples are given and compared with the conventional techniques.

1. Introduction

Right from the early days of the pressuremeter, Louis Ménard and his first co-workers were confronted by the criticism of sceptical geotechnical engineers on the meaning of the tests in some types of soil. Consequently the first users had to define boring and testing conditions, which would give the most reliable results for each type of soil. The stability of the borehole wall and the possibility of having a cylindrical cavity matching the diameter of the probe soon became essential (PLM, 1962).

The use of post-hole hand auger in clayey soil above the water table possibly completed by bentonite slurry circulation below water table became the archetype of a quality test drilling technique. The probe could be inserted immediately after boring into a properly cut borehole with a smooth wall, into which, right from the first pressure hold, the contact of the probe with the soil was obtained without any apparent remoulding (LCPC 1971).

The drilling rigs of the 60s had mechanical transmissions and were basically designed for core boring. Louis Ménard and his co-workers were the first to manufacture pressuremeter probes with diameters suitable for 2¼", 3'', 3½'', and 4'' core barrels. The hands-on time and the placing of the probe was too long and favoured stress relief of the ground surrounding a borehole created by core drilling. Thus, probes with smaller diameters were selected, 32mm (1¼''), 44mm (1¾''), 63mm (2½''), which enabled the use of this post-hole hand auger or the hammering of a push sampler. Pretty soon, Louis Ménard (1959) patented the slotted tube designed for direct hammering of the probe into submerged granular soil where it is difficult to prevent the caving in of unlined boreholes. Hydraulic vibratory driving machines were also designed and manufactured to implement the slotted tube for pressuremeter testing, especially in marine environment (Ménard and Gambin, 1965).

A second problem still remained to be solved. That which relates to the idle time associated with the testing within the “authorized stroke” depth according to the Standard (AFNOR 1991 & 2000), that is the time taken to raise the drilling tool after each stroke plus the time taken to lower the pressuremeter probe, and, immediately after testing, the time to raise the probe and lower the drill bit again.

It is with the aim of reducing these series of idle times that a new research was initiated. These will result in the filing of a patent, which contains the rudiments of the method that will be presented (Ménard 1976). This patent submitted the concept of self-boring a tube by retro-jetting, possibly associated with the ramming of a slender drop hammer sliding in the lower part of a string of pipes and that of a pressuremeter probe either moved in and out in a wireline fashion, or more permanently placed at the level of the slotted part of the pipe string (figure 1).

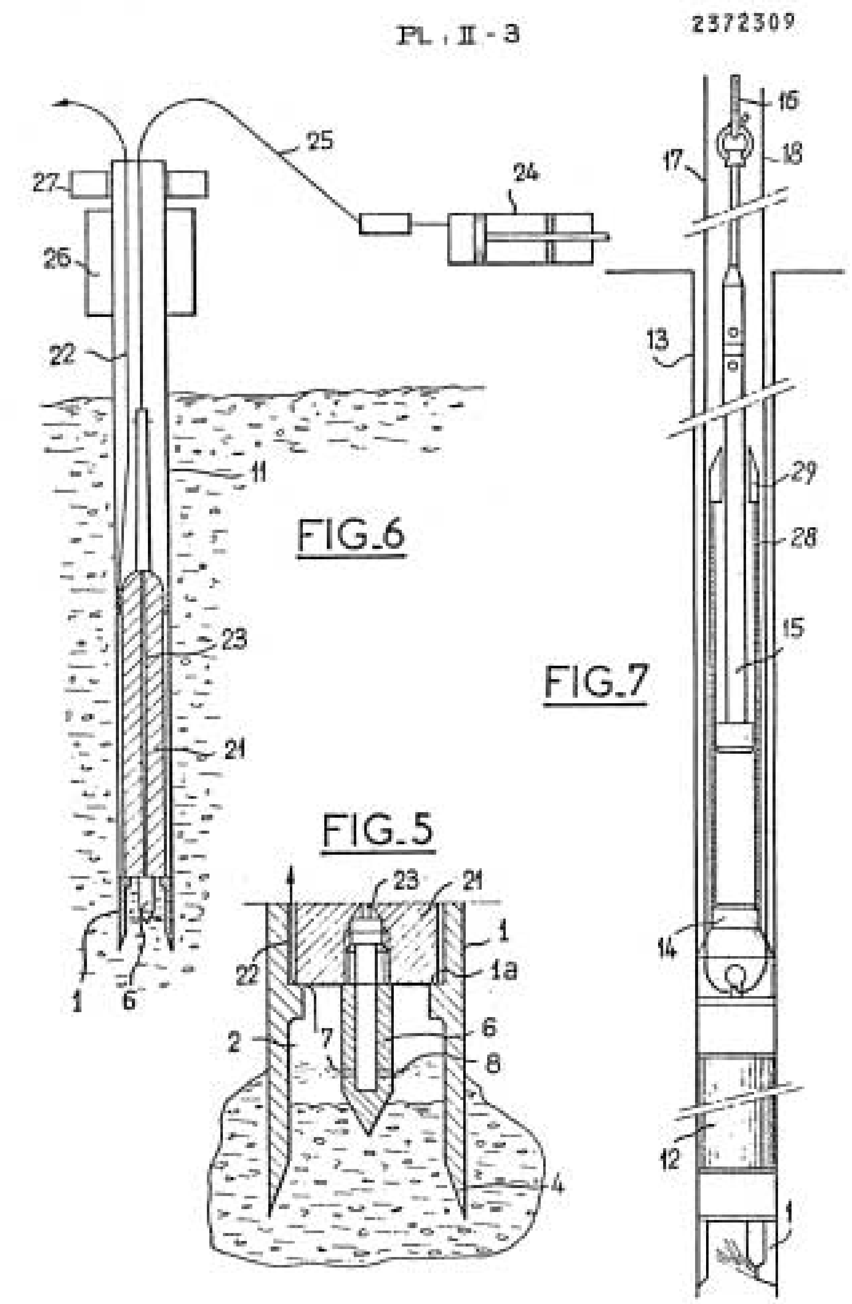


Figure 1. First example of a self-bored slotted tube (Ménard, 1976 – Fig. 5 - 7)

The method described in the patent helped do away with the concept of authorized drilling strokes since the borehole wall was always supported. Further the tests could be carried out during the final raising of the pipes string and no idle time was to be considered during the drilling operation. However, this technique was applicable only to loose to medium stiff soils, unless high-pressure "jet-cutting" equipment was available, which cannot be cost-effective for conventional geotechnical surveys at small job sites.

2. The slotted tube

The drilling methods, which help create a cavity compatible with the execution of a reliable pressuremeter test are varied, but generally associated with a type of well-defined soil (AFNOR, 2000). Among these, let us consider those which involve a "slotted" tube.

The slotted tube with outside diameters ranging from 63 mm (the most common) to 76 mm, bears at least 6 very thin slots generally parallel to its axis, much longer than the probe length. It is currently used in 3 ways that rest on completely different principles:

- As a "direct slotted tube": the slotted tube, 63mm O.D., closed at one end by a point (preferably at the end of a pipe extension) or a push sampler, is directly inserted into the ground by hammering, vibratory-driving or jacking. A pressuremeter probe 44 mm O.D. is fixed inside; that is the probe is emplaced at the same time the tool creates the test cavity. Further, the length of the stroke has no limit, the boring is simply limited by refusal to driving. It must be noted that the temporary densification of the soil near the point is reduced by the action of the subsequent vibrations created in the submerged sand at the depth of slots of the tube (TLM, 1966).
- As a "Chinese lantern": the slotted tube is introduced in a pre-bored hole: it is then used as a protection for a AX (44 mm) probe, the assembly acting as a BX (60 mm) probe in a borehole. This condition can occur when the borehole is either improperly supported or only partially supported by a column of mud slurry: since the slotted tube has a higher resistance to the ruggedness of a badly drilled cavity wall, generally non homogeneous – with pieces of rock badly protruding – than the rubber cover of the standard probe, its use helps create a tighter calibrated boring than for a probe with a simple rubber cover. It can also be used when the soil start squeezing the borehole, the diameter reduction can be such that the probe cannot penetrate. In between the actual pre-boring technique and the use of a direct slotted tube, there is the case where the technique known as pilot hole drilling is used (ASTM, 1987); Then, the length of a stroke is limited depending on the value spelled out in the Standard as a function of the type of soil tested.
- As an "open" slotted tube used as a push sampler at the end of a string of pipes, the "sample" being removed either subsequently after every driving phase by lowering a suitable drill bit or simultaneously by fixed retro-jet nozzles at the toe of the slotted tube, the cuttings being lifted either by the circulating mud or by the projected slurry; the length of the stroke has no limit, except when too much friction prevents the progression of the pipes string.

The last technique, which is very attractive in terms of concept, gradually became extinct due to the increase in multifunctional drill rigs, although the stroke length limit imposed by the Standard to reduce the stress relief occurrence was no longer applicable. Withdrawn from the list of methods in the governmental pressuremeter testing procedure (LCPC, 1971) and the first publication of the French Standard (AFNOR, 1991), it is referred to in the current version (AFNOR, 2000) under the name of "slotted tube with simultaneous removal of material" with the TFEM acronym.

This technique is also described and accepted in the American Standard (ASTM, 1987 and later) in § 7.4.2.9 under the title *Pilot Hole Drilling and Simultaneous Shaving*: “Drill a pilot hole smaller in diameter than the pressuremeter probe. Immediately behind the drill bit on the string of the drilling rods is a thin hollow cylinder that trims the cavity. Advance the drill bit and cylinder with high viscosity drilling fluid”.

Could we go beyond these techniques and increase the penetration of the tube without limit, and thus reduce both the stress relief and the idle times inherent to the various techniques, which occur between the testing periods?

3. Self-boring of the slotted tube or the STAF® technique

It is on the above mentioned bases that the authors of this paper used all their efforts to create a unique boring method suitable for any type of soil, enabling the execution of reliable pressuremeter tests, since the remoulding of the boring wall is reduced to a minimum and remains practically identical, whatever be the type of soil.

We have thus tried and reduced or more exactly optimised the two parameters influencing the shape of the origin of the pressuremeter curve:

- the remoulding of the boring wall as such, by looking for a soil cutting technique which would be rapid, typical and accurate in its calibration, yielding a perfectly cylindrical cavity and ensuring a speedy and complete removal of the cuttings
- the stress relief of the surrounding soil, a phenomenon which begins right from the drilling, whatever be its quality, by ensuring the immediate support of the boring wall using a string of pipe I.D. which would match the pressuremeter probe diameter to be formally used.

3.1. The equipment

The equipment required is selected in such a way that it can be implemented by all types of hydraulic drill rigs, as long as rotary-percussion is available coupled with the circulation of mud slurry. In the version used to obtain the results listed in chapter 4 below, this equipment includes the following elements:

- a coupling connecting the drill steel shank of the rotary-percussion head to cord type R32mm rods, this coupling being enlarged to press on a pile cap
- a sacrificial (that is: expandable) steel washer on the pile cap
- a pile cap 63 mm I.D., fitted with a discharge chute for the mud slurry loaded with cuttings
- a set of rod extensions 122 mm in length, 32 mm O.D., and rotary-percussion R32mm couplings, a standard equipment which nevertheless must be sturdy enough to sustain a heavy rotary-percussion
- a set of pipes 49 mm I.D., 63 mm O.D., in equal lengths of 122 mm, screwed flush with a thread designed for a better behaviour of the whole string during rotary-percussion
- a slotted tube 49 mm I.D., 63 mm O.D., positioned at the toe of the pipes string, fitted with an open cutting shoe at its lower end and a landing nut for the pressuremeter probe locking.
- an open hole type drilling bit for rotary-percussion guided by the casing shoe, unfolded for full face borehole drilling and retractable within the casing by folding when the drilling rods string must be pulled up; this is an improvement in the much larger Odex® type retractable tools, the diameter of the drag bit being designed so as to drill a borehole adjusted to the diameter of the pipes string used
- a pulling up system for the pipes string using hydraulic jacks and either a mechanical self-tightening collar or an annular hydraulic anvil

- an AX type pressuremeter probe 46 mm O.D., equipped with mobile locking dogs, which accurately guide its positioning at the centre of the slotted tube and can move inward to permit probe retrieval at the end of a test series
- lastly, the pressure-volume control unit of the pressuremeter, for recording readings on an electronic medium.

Fig. 2a

Fig. 2b

Figure 2. STAF® drilling bits :
2 a – Two types of STAF drag bits with either blades or buttons
2 b – The STAF blade type drag bit folded inside the pipe and unfolded below the pipe cutting shoe

Figure 3. STAF® drilling equipment :

3a - in front: a drilling rod fitted with a STAF drag bit, behind: the slotted tube (slots are less than 0.4mm wide).

3b – in front : drilling rod and STAF bit inside the slotted tube; behind the 44m pressuremeter probe with its clamping device

3c - detailed view of the STAF penetration system when knocked down.

3.2. Operation

The operating sequences of the STAF® technique are described in the diagram of Figure 4.

- the string of pipes, with the slotted tube at its toe, is lowered at the same speed as the drilling equipment, the drilling bit being unfolded below the pipe cutting shoe. This is typically carrying out an actual self-boring of the slotted tube. The unfolded drag bit protrudes from the base of the casing and can chip the ground in the full cross-section of the pipe. If, strictly speaking, this is slightly different from the "self-boring" principle, the minor change is widely compensated by the possibility of continuous drilling without the need to adapt the drilling bit to each type of geological formation met, from fine compressible soil to stiff clay with boulders and even some sorts of rocks or interbedded soil types.

It thus follows that the so-called "normalized" remoulding is reduced to a minimum, represented by a minimal stress relief of the ground during the elapsed time between soil disaggregation by the protruding drag bit and the next arrival of the pipe shoe.

Special attention must be paid to the upward transfer of the drilling cuttings. They are pushed inside the casing by the shape of the drag bit itself, since the direction of flow given by the nozzles to the mud slurry only permits to hit the ground axially (as required by the various Standards). Once inside the pipe shoe, cuttings are crushed to sufficiently fine grading to make the extraction easier. The circulating fluid may either be bentonite based or a polymer slurry which can be prepared almost instantly. This polymer based slurry is not used to coat the borehole wall, with which it is has practically no contact, except during the very small time this wall is not supported but mainly to obtain the viscosity required to coat the cuttings and permit to raise them to the ground surface. The whole slurry can be collected in a chute at the outlet of the driving cap, which enables the drilling foreman to check its continuous and regular outflow, and to have it settle immediately, permitting a correct sampling at the time of each rod and pipe extension, that is obtaining a proper log of the borehole. The job site around the borehole remains clean too and a double decantation helps the reuse of a clean slurry.

- the drag bit is folded and the string of rods is removed, as in the Odex® technique
- the pressuremeter probe is emplaced with the wireline technique at the depth of the slotted tube which forms a expandable protection of that probe
- the whole series of pressuremeter tests is carried out according to Standards, the string of pipes being pulled up by one depth interval between 2 consecutive tests
- in the event of any problem, the pressuremeter probe can be retrieved with the wireline technique, once the locking dogs have moved inward
- at the end of the full series of pressuremeter tests, the string of pipe has been entirely brought back to ground surface and the pressuremeter probe can be taken out of the slotted tube.

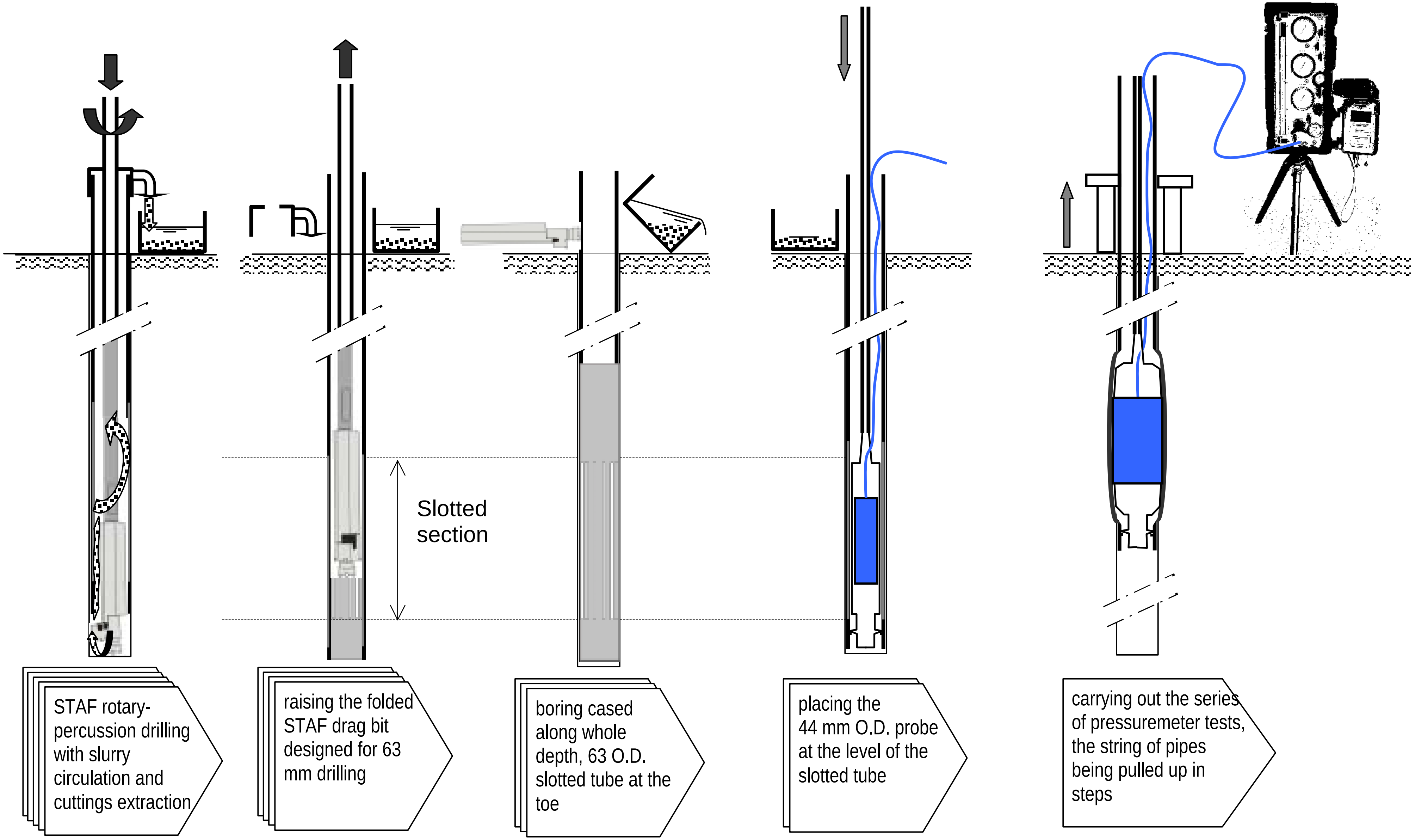


Figure 4. Sequences of the STAF® technique to perform Ménard pressuremeter tests by self-boring of a slotted tube

4. Submitting some test results

Below, we submit some test results obtained either when using an open slotted tube or by the STAF® technique. We analyse the qualities peculiar to the method and compare the pressuremeter results obtained either by these two methods or by other drilling methods.

4.1. Development

The first development of the retractable eccentric drag bit 63mm O.D. was carried out in year 2000 - 2003 and the first drillings with this tool were performed in 2003. First of all, the difficulties met during the penetration and the further raising of the string of pipes as a function of the drilling tool diameter had to be checked in various soils. It was proven that a drilling bit with a diameter exceeding that of the string of pipes by a few millimetres enabled a rapid and easy penetration of the whole string, but led to tests with a very highly remoulded borehole wall, because due to the annular extra space so created, whatever slight, the cuttings had a tendency to seep between the pipes and the ground, clogging the slotted tube. The Bruyères-le-Châtel pressuremeter tests in the FP3 boring of the Teratec project, with a button drag bit illustrate this problem: the tests can be interpreted, but the E_M/p_{LM} ratio seems overestimated in comparison with those obtained in pressuremeter tests in adjacent open holes drilled with mud slurry. Any of these ratios may represent the “real” value which is probably intermediate.

Tests complying with the expectations of the developers of the method were obtained quite quickly by fulfilling the following rules:

- Use of 65 mm diameter bits with tungsten blades
- Moderate slurry circulation pressure not exceeding an average of 2 MPa
- Moderate circulation flow rate also of 30 to 60 l/min
- Adaptation of the percussion frequency, which differs with the make of the hammer and the type of impact produced: this is a factor that the driller can adjust as a function of the ground type:
    - only few strokes (less than 30 strokes/min) in compressible soils, up to a limit pressure of the order of 1 MPa
    - a frequency up to 60 to 100 strokes/min in medium to stiff soils, up to p_{LM} equal to 2 to 3 MPa
    - a frequency reaching 300 to 500 strokes/min depending on the impactor type, in stiff to very stiff grounds, beyond 3 MPa
- Adaptation of the thrust on the drag bit to maintain a sufficient penetration speed.
- Monitoring the lifting flow rate of the slurry loaded with cuttings is essential for the driller, any tendency to lower the flow rate increases the risk of clogging, which must be compensated as soon possible with an controlled increase of the circulation flow rate, so as to restart the ascending movement of the whole fluid

Drilling carried out under these conditions leads fairly well to the achievement sought for a perfectly calibrated cylindrical vertical hole and a minimal stress relief: a properly guided drill bit carries out a full disintegration of the ground and the rigid edge of the cutting shoe wears down the borehole wall in the event where stiff fragments of soil would still remain, by mobilizing more friction to obtain the adjustment of the hole diameter.

The string of pipes extraction is relatively difficult after a certain depth: it generally exceeds the pulling up strength of the current geotechnical drilling rigs and requires the use of hydraulic jacks. Assuming that no cuttings have penetrated between the pipes and the borehole wall, high pulling forces ensure that the aim of a perfect adjustment of the ground around the string of pipe is attained, without soil decompression but also without risk of soil displacement. From the point of view of organising the work, we have used either the well known jacking system of the annular hydraulic anvil taken and adapted from the D9000 Ménard drilling rig for extraction of the directly driven slotted tube, or an annular jack operated by the drill rig power.

But it is perfectly possible, and this is one of the advantages of the method, to distribute the work between a slotted tube self-boring crew who leaves the string of pipes in place before moving on, and a pressuremeter testing crew carrying out the pressuremeter tests in conjunction with the extraction of the pipes, immediately behind the first crew - or after a slight delay which may be set by the circumstances of the site (for example, road traffic with limited interruptions).

4 .2 Examples in different types of soil

In the following test curves we exemplify values of E_M modulus and p_{LM} limit pressures obtained from pressuremeter tests in various types of soil. Apart from the Avrainville tests, carried out during the development of STAF, and the Merville tests, on an experimental LCPC site, these are actual site tests, carried out during either G0 tasks followed by G1 and subsequent tasks, according to the French Standard on Geotechnical Site Investigations Classification.

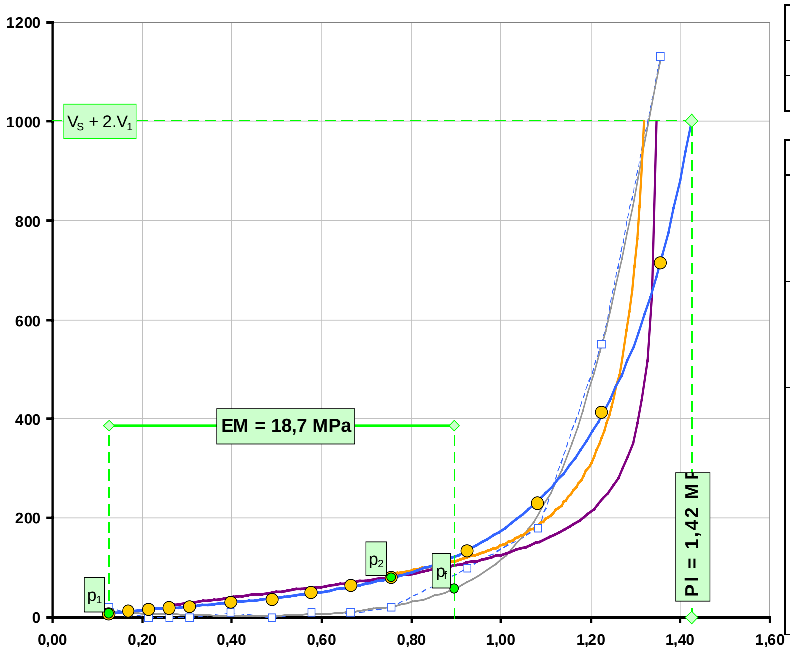


Figure 5. Grinding grit Brie clay.

Name of the site	**Avrainville**
Boring	**FP1**
Test depth	**12.50**

PARAMETER OF THE ADJUSTED CURVES		
Inverted volumes ▬	A	-1.06E-02
	B	2.81E-02
	Mean error (cm3)	7.30E+01
Hyperbole ▬	C	2.53E+00
	D	4.44E+03
	Mean error (cm3)	3.74E+01
Double hyperbole ▬	A1	5.32E+04
	A2	-2.78E+03
	A3	1.08E+06
	A4	3.49E+03
	A5	-2.00E+01
	A6	4.03E+00
	Mean error (cm3)	2.71E+00

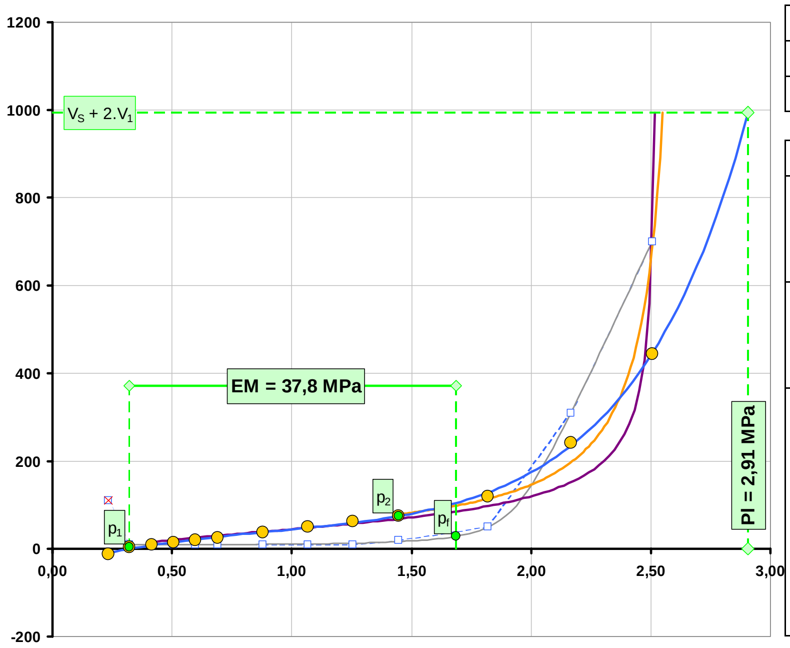
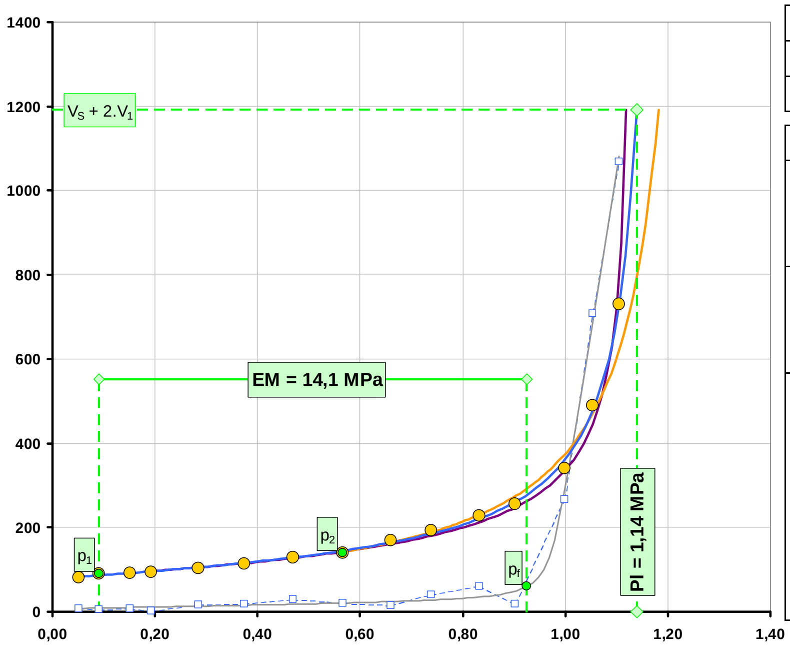


Figure 6. Supragypseous marl (Pantin marl).

Name of the site	**Avrainville**
Boring	**FP1**
Test depth	**3.50**

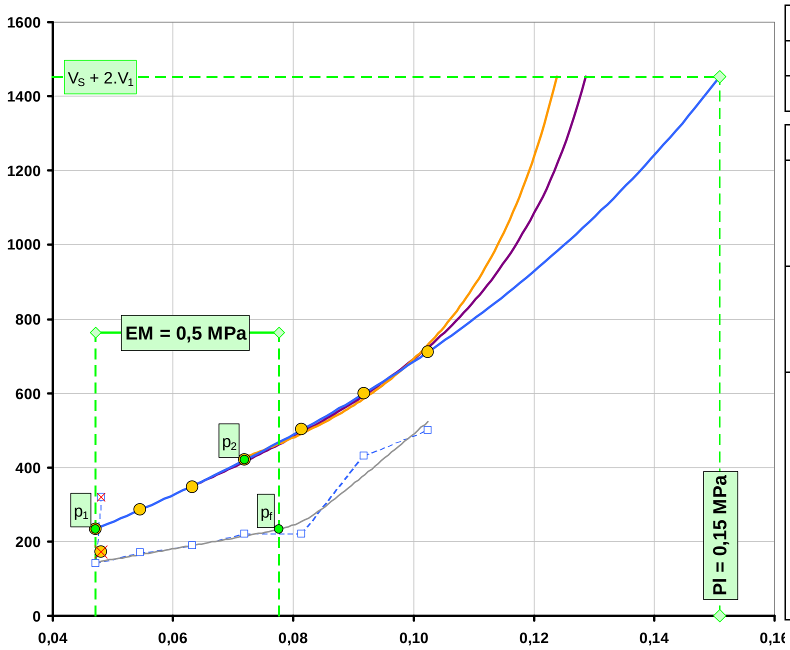
PARAMETER OF THE ADJUSTED CURVES		
Inverted volumes ▬	A	-1.84E-02
	B	2.53E-02
	Mean error (cm3)	4.50E+02
Hyperbole ▬	C	1.36E+00
	D	6.93E+03
	Mean error (cm3)	3.45E+02
Double hyperbole ▬	A1	7.75E+04
	A2	-3.99E+03
	A3	1.56E+06
	A4	5.96E+02
	A5	-2.00E+01
	A6	1.75E+00
	Mean error (cm3)	1.79E+00



Name of the site		**Merville**
Boring		**STAF1**
Test depth		**7.00**

PARAMETER OF THE ADJUSTED CURVES		
Inverted volumes —	A	-1.02E-02
	B	1.27E-02
	Mean error (cm3)	2.43E+01
Hyperbole —	C	1.13E+00
	D	7.30E+03
	Mean error (cm3)	1.44E+01
Double hyperbole —	A1	3.41E+01
	A2	4.54E+01
	A3	0.00E+00
	A4	5.27E+01
	A5	-2.00E+01
	A6	1.19E+00
	Mean error (cm3)	5.17E+00

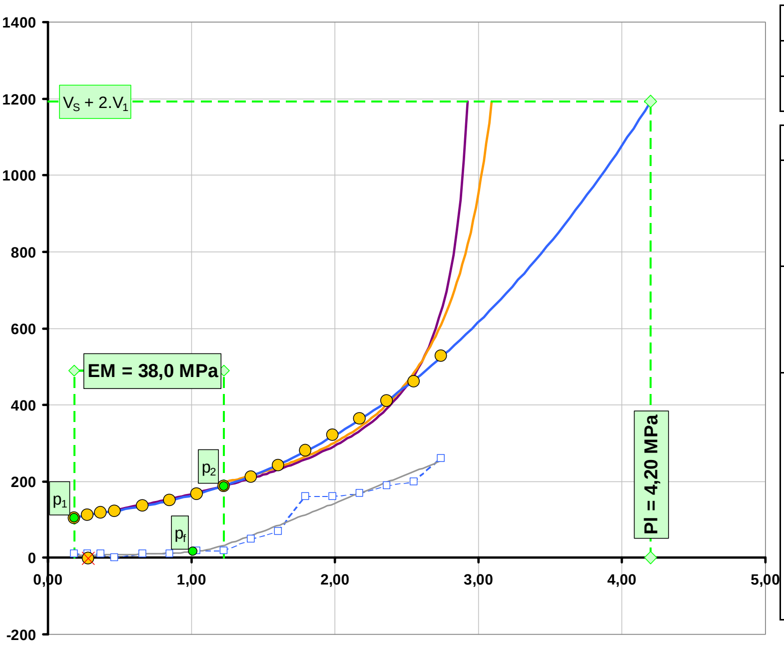
Figure 7. Merville (LCPC experimental site) – Grey clay



Name of the site		**19e rue Manin**
Boring		
Test depth		**8.00**

PARAMETER OF THE ADJUSTED CURVES		
Inverted volumes —	A	-3.18E-02
	B	4.62E-03
	Mean error (cm3)	1.30E+01
Hyperbole —	C	1.42E-01
	D	2.84E+05
	Mean error (cm3)	6.67E+00
Double hyperbole —	A1	-1.03E+03
	A2	1.26E+03
	A3	0.00E+00
	A4	2.64E+02
	A5	-2.00E+01
	A6	2.66E-01
	Mean error (cm3)	1.34E+00

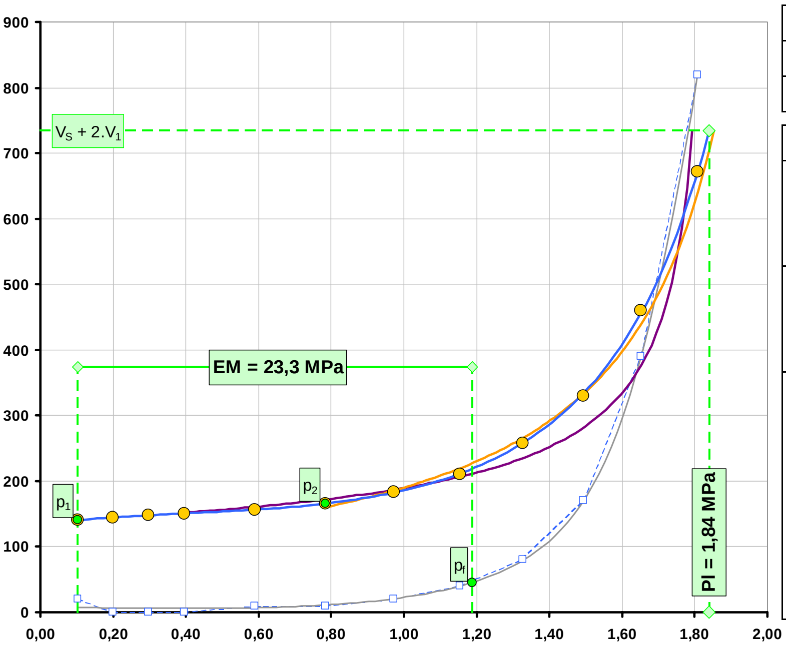
Figure 8. Mine rubble



Name of the site	**19e rue Manin**
Boring	
Test depth	**17.00**

PARAMETER OF THE ADJUSTED CURVES		
Inverted volumes ▬	A	-2.27E-03
	B	7.85E-03
	Mean error (cm3)	2.18E+01
Hyperbole ▬	C	3.00E+00
	D	3.07E+04
	Mean error (cm3)	2.04E+01
Double hyperbole ▬	A1	-2.03E+04
	A2	-1.04E+03
	A3	1.01E+01
	A4	4.08E+05
	A5	-1.38E-01
	A6	2.00E+01
	Mean error (cm3)	1.58E+00

Figure 9. Gypseous marl (Ludien)



Name of the site	**St-Germain-Co**
Boring	**FP3**
Test depth	**5.00**

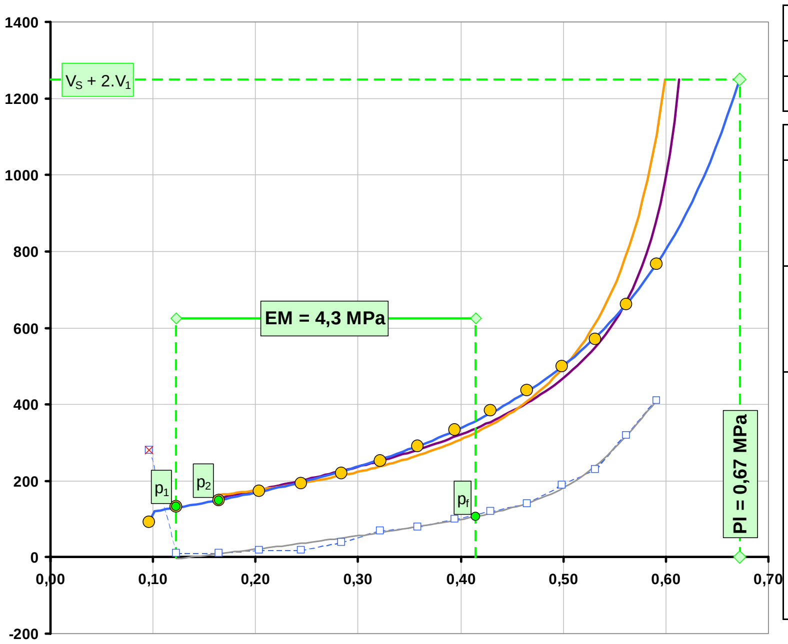
PARAMETER OF THE ADJUSTED CURVES		
Inverted volumes ▬	A	-4.57E-03
	B	9.83E-03
	Mean error (cm3)	1.14E+01
Hyperbole ▬	C	1.84E+00
	D	-5.23E+03
	Mean error (cm3)	4.43E+01
Double hyperbole ▬	A1	1.67E+02
	A2	-2.30E+02
	A3	3.00E+02
	A4	5.00E+02
	A5	-1.20E+00
	A6	2.30E+00
	Mean error (cm3)	1.03E+00

Figure 10. Brie marl-limestone

4.3 Comparison with pre-boring tests without casing

The site survey of Villeneuve-le-Roi is particularly interesting because it consists of 3 borings of 15 to 18 m for the construction of a warehouse on piles in an industrial park where two previous site investigations were already carried out with pre-bored pressuremeter testing, one for a storage buildings (Paprec company) and one for a stamping press.
The comparison of the results (figure 13) shows that in the recent rubble and alluvium of this site, up to 11 m approximately, the distribution of the E_M and p_{LM} values of the tests is statistically quite similar, if they differ in the details.

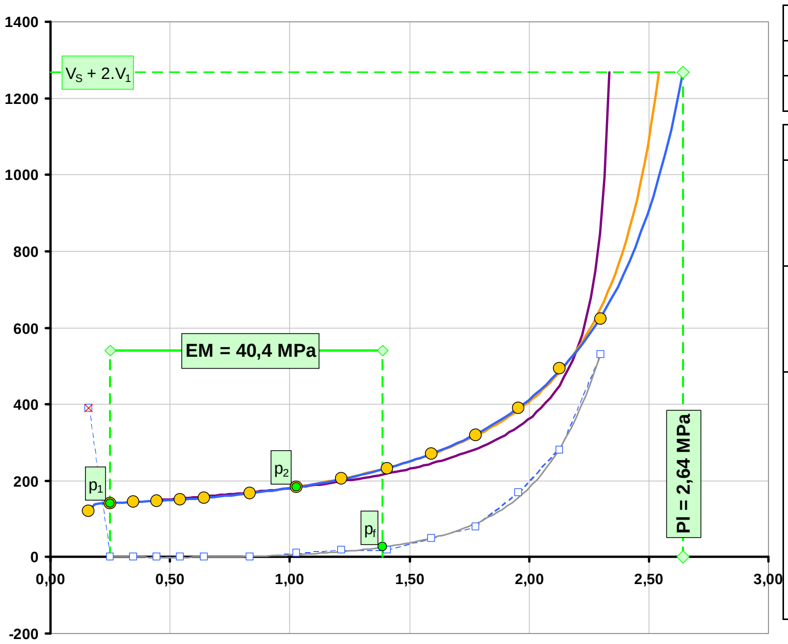
On the other hand, in the marly clay to marl-limestone substratum, the STAF tests show that for a comparable limit pressure, the E_M/p_{LM} ratios are greater and better grouped; in the present case, it is most probable that these modulus values are closer to the reality, and that the previous pre-boring values were slightly underestimating the modulus.



Name of the site	**Villeneuve-le-Roi**
Boring	**FP3**
Test depth	**8.00**

PARAMETER OF THE ADJUSTED CURVES		
Inverted volumes	A	-1.23E-02
	B	8.15E-03
	Mean error (cm3)	5.22E+01
Hyperbole	C	6.36E-01
	D	5.51E+04
	Mean error (cm3)	2.20E+01
Double hyperbole	A1	-2.11E+02
	A2	-3.85E+01
	A3	2.53E-03
	A4	2.47E+02
	A5	9.58E-02
	A6	8.38E-01
	Mean error (cm3)	1.91E+00

Figure 11. Villeneuve-le-Roi. Backfill material of the old sand pit



Name of the site	**Villeneuve-le-Roi**
Boring	**FP3**
Test depth	**16.00**

PARAMETER OF THE ADJUSTED CURVES		
Inverted volumes	A	-3.08E-03
	B	8.63E-03
	Mean error (cm3)	5.42E+00
Hyperbole	C	2.36E+00
	D	3.27E+03
	Mean error (cm3)	3.49E+01
Double hyperbole	A1	-7.62E+01
	A2	-6.11E+01
	A3	3.73E-02
	A4	6.61E+02
	A5	1.57E-01
	A6	3.08E+00
	Mean error (cm3)	1.12E+00

Figure 12. Villeneuve-le-Roi. Marl-limestone substratum (Ludien).

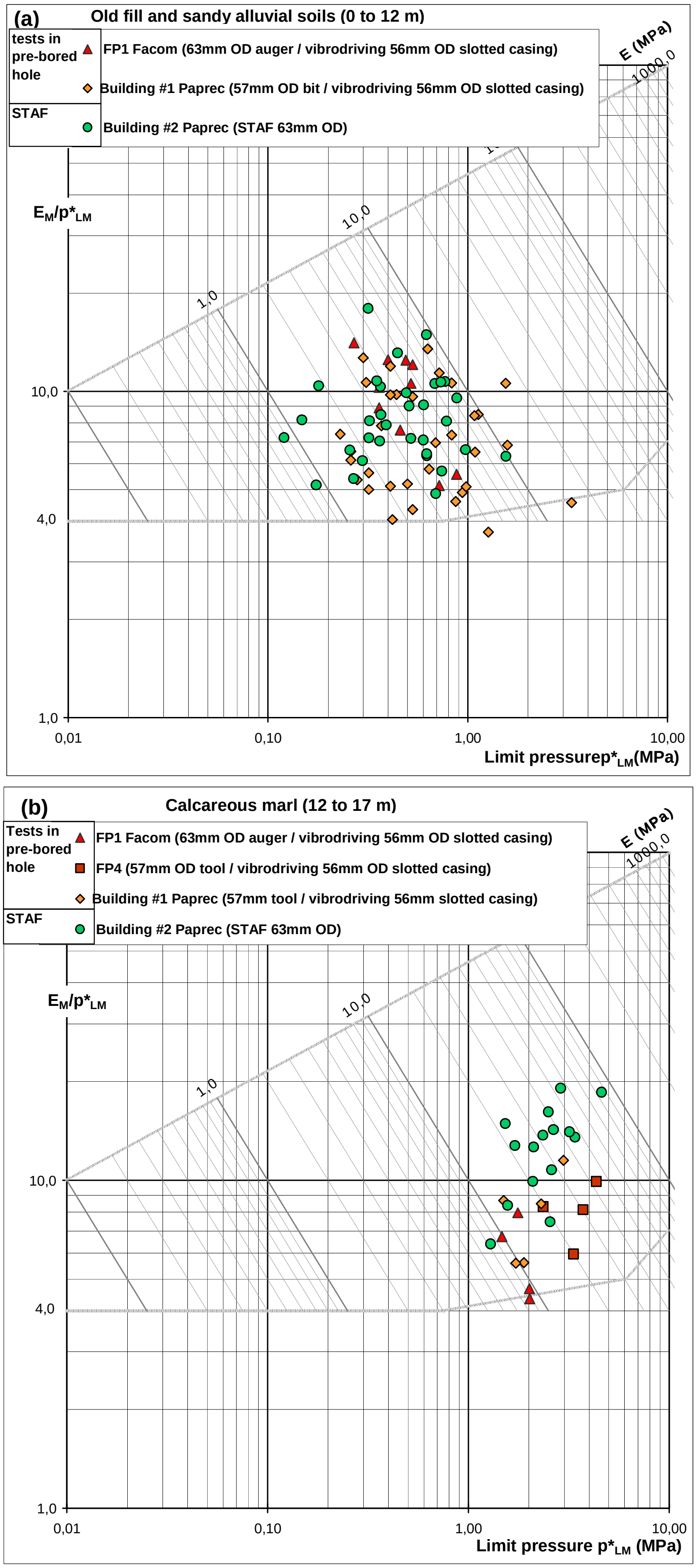


Figure 13. Villeneuve-le-Roi. STAF® test comparisons with pressuremeter tests in prebored holes, in the spectral pressuremeter diagram [log(EM), log(EM/p*LM)] (Baud, 2005)
(a) On the tests in the sand fills and the residual alluviums
(b) On the marl-limestone of the substratum

5. Conclusions and perspectives

The tests mentioned above (up to early 2005) correspond to about fifteen actual size sites, at different depths, up to 22 m at the moment – pressuremeter testing to 45 m depth are planned. The results are sufficiently encouraging so that we may have the certitude that the influence of the drilling technique on the initial phase of the test is greatly reduced. The development of drilling bits and the rotary-percussion continues with the aim of carrying out tests with negligible initial remoulding in all types of soil.

6. **Bibliography**

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