Phicometer borehole shear test improvement by continuous recording and automated pulling system

Essai de cisaillement en forage au phicomètre. Apport de l'enregistrement de l’essai en continu et d’une automatisation de la traction

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ABSTRACT

The phicometer invented by Gérard Philipponnat uses an adaptation of the pressuremeter split tube that allows it to perfectly fit the entire wall of a borehole with the same requirements as for prebored pressuremeter probe placement, unlike other techniques for measuring shear in drilling.

On the occasion of the ISO22476-4:2024 standard, it can however be noted that the regular use of the phicometer has not become sufficiently established, many geotechnical calculations are still carried out without measuring the friction angle φ, neither in situ nor on a sample. Geotechnical engineers are satisfied with an approximation of the value of φ based on the type of soil, possibly its grain size.

Drilling quality and the waiting time between drilling and testing are even more stringent than for pressuremeter testing, and conducting the test requires the coordination of two experienced operators.

For several years, the use of the Geopac, a Type C pressuremeter, has enabled pressure regulation and recording the force of the dynamometric pulling wedge in addition to pressure and volume data. The simultaneous recording of the three measurements, each with greater precision than manual readings and recorded continuously every second, allows for complete quality control.

Examples of tests are shown in two emblematic soil types: sand (Fontainebleau sand) and clay (Beauce decalcification clay). They demonstrate that the simultaneity and precision of the measurements provide a series of twin data (□ |□) over a wide range, whose alignment is close to a perfect straight line, a finding that validates the quality of the measurement. All that remains for the exegetes is to discuss what type of φ represents these experimental data.

Another improvement is in prototype form: the automation of the speed-controlled probe pulling, aiming at fully controlling the test on a site computer by a single operator.

RESUME

Le phicomètre inventé par Gérard Philipponnat utilise une adaptation du tube fendu pressiométrique qui lui permet d’épouser parfaitement toute la paroi d’un forage réalisé avec les mêmes exigences que pour le placement d'une sonde pressiométrique en forage préalable, contrairement à d’autres techniques de mesure du cisaillement en forage.

A l’occasion de la norme ISO22476-4:2024, on peut cependant remarquer que l’usage régulier du phicomètre ne s’est pas suffisamment imposé, nombre de calculs géotechniques étant encore réalisés sans mesure de l’angle de frottement φ, ni in situ, ni sur échantillon. Les géotechniciens se satisfont souvent d’une approximation de la valeur de φ basée sur le type de sol, éventuellement sa granulométrie.

La qualité du forage et le temps d’attente entre forage et essai sont encore plus draconiens que pour l’essai pressiométrique, et d’autre part la réalisation de l’essai nécessite la coordination de deux opérateurs expérimentés.

Depuis plusieurs années, l'utilisation du contrôleur pression-volume automatique Geopac, permet la régulation de pression, en ajoutant à l‘enregistrement des données de pression et volume, celle de la force de la cale dynamométrique de traction. La simultanéité des 3 mesures, chacune avec une précision accrue par rapport aux relevés manuels, et enregistrées en continu chaque seconde, permet un contrôle de qualité complet.

Des exemples d’essais sont montrés, dans deux types de terrain emblématiques, un sable (sable de Fontainebleau) et une argile (argile de décalcification de Beauce). Ils montrent que simultanéité et précision des mesures fournissent une série de couples (σ |τ) sur une plage étendue, dont l’alignement est proche de la droite parfaite, constatation qui valide la qualité de la mesure. Ne reste alors aux exégètes que discuter du type de φ que représentent ces données expérimentales.

Une autre amélioration est en prototype : l’automatisation de la traction de la sonde à vitesse régulée, visant le pilotage complet de l’essai sur ordinateur de chantier par un seul opérateur.

Keywords: Borehole shear test, Phicometer, Soil friction angle, Cohesion, Automation of a borehole shear test

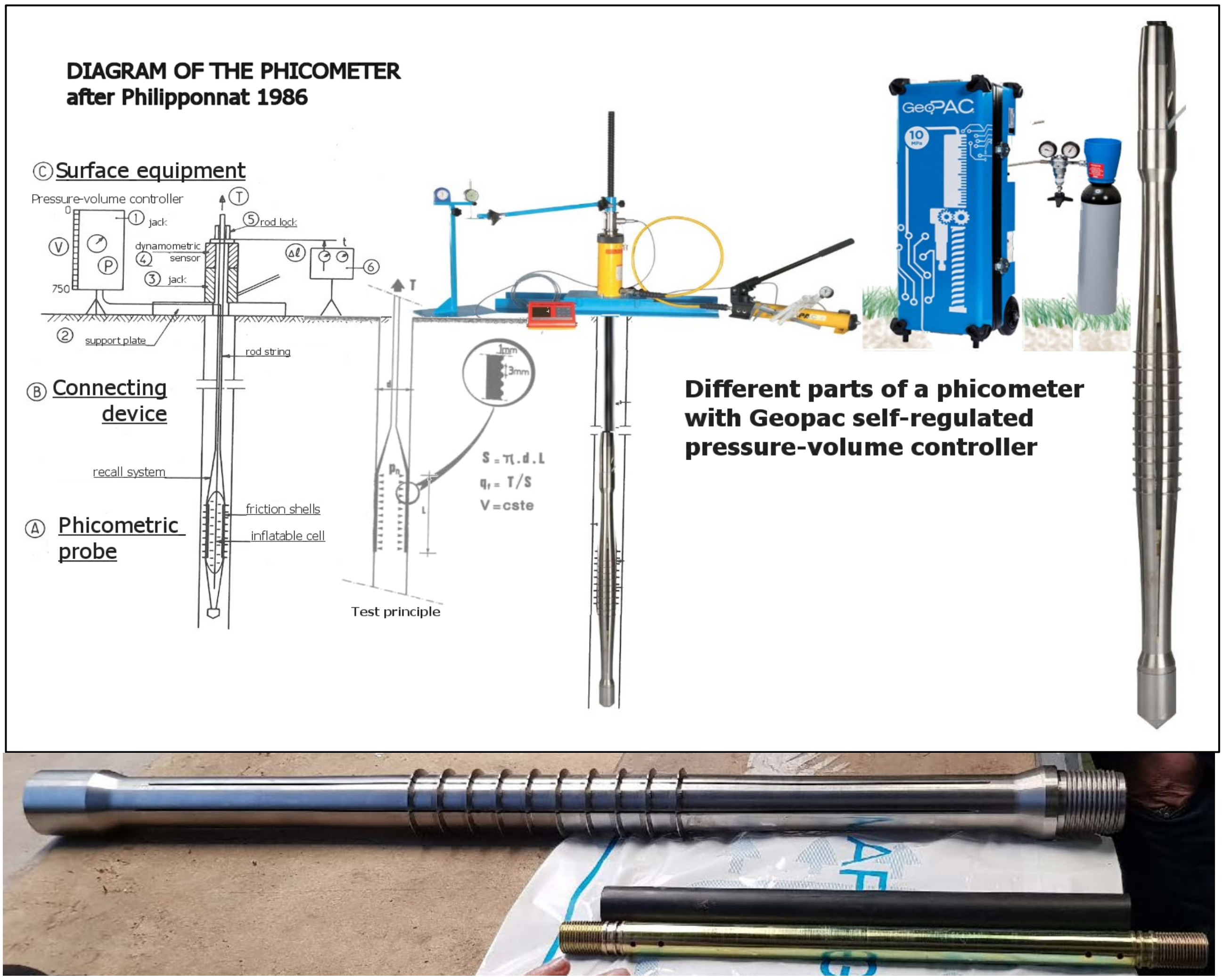

Figure 1. Implementation of the phicometer by a self-regulated Pressuremeter controller. Detail of the toothed split tube, the internal 32mm probe and its membrane.

1. Motivations

The phicometer borehole shear test has been used profitably by various geotechnical surveying and engineering firms in various locations across Europe and around the world since its invention in 1992 by Gérard Philipponnat and its initial development (Philipponnat 1987, Philipponnat and Zerhouni 1993, 2005). Similarly, other shearing devices in boreholes, such as Handy's device, are used by geotechnical engineers who derive maximum benefit from them (Handy & Fox 1967, Handy 2009, Lutenegger 1987). Some other have been reinvented and developed by geotechnical engineers in other countries.

It must however be recognized that despite the recent standardization of the phicometer by the ISO 22476-16 standard, well after the NF XP 94120 standard (1997), this test is not yet used commonly enough by geotechnicians, who nevertheless need daily the two fundamental parameters that are cohesion and friction angle (Coulomb 1773).

One reason could be the duration of the test and the need for two specialized operators, one operating a Pressuremeter for normal stress σ and radial displacement ε, the other a pulling device for vertical displacement with measurment of tangential stress τ .

The authors, three of whom are responsible for automating the test and commercializing the device (Apagéo and Cedarnet), have gradually improved the measurement procedure by automating pressure regulation and the simultaneous collection of pressure, volume, and pulling force data using an automatic pressure-volume controller, the Geopac (Arsonnet et al. 2013), type C according to ISO 22476-4. Such an equipment, which functions as a speed-regulated piston, can also be used to automatically provide speed-regulated pulling on the probe during the test. The result allows a saving in test acquisition time, and above all a quality of data collection which greatly improves the alignment of experimental points on the linear Coulomb law between normal stress σ and tangential stress τ in the soil concerned by the test.

2. Implementation Examples

A few examples demonstrate the gains in accuracy and traceability achieved by automatically regulating the parameters measured during the test and their continuous recording.

2.1. Equipment used

All the equipment used for the phicometer test was originally manufactured by Apagéo according to the inventor's specifications (Philipponnat, 1987). It is therefore always the same equipment regarding:

- the expandable probe, consisting of a special split tube with fine horizontal lamellae (or "teeth") on the upper surface of each section;
- the tubing for the liquid (water) used to pressurize the probe and measure its expansion volume;
- the pulling device, using an annular hydraulic cylinder, which moves the drill rods attached to the probe upwards at a set speed.

What is being replaced by up-to-date equipment are the devices for pressure control and numerical record of pressure P, volume V in the probe et pulling force F on the rod connexion. The automated pressure regulation by Geopac allows for the standardized steps of the Phicometer procedure, with a faster pressure build-up and then pressure maintenance for 6 to 8 30-second intervals at each level. The pressure and volume measurements are recorded every second.

Regarding pulling of the probe, the following examples will be used in this article:

- the conventional implementation of the pulling cylinder by an operator using a manually operated hydraulic pump to ensure the ascent speed required by the standard, by synchronizing the hands of a dial comparator and those of a special stopwatch at 1 revolution every 30 seconds;
- automated prototype implementation, ensuring movement at the speed imposed by a second Geopac (actually a Hyperpac) whose micro motorized piston allows very low-flow power to the pulling cylinder.

In both cases, the pulling force, pressure and volume measurement are synchronized and recorded every second.

2.2. Graphs of continuous recordings of the 3 test data (P, V, F) and calculation of the test parameters (apparent cohesion C_i and friction angle φ_i)

Synchronizing the recordings allows the evolution to be presented as a function of time (t in seconds), of pressure (P) and volume (V), as can be done for a full recorded pressuremeter test, plus pulling force (F) as additional data.

2.2.1. Sand.

Figure 2 is a test in Fontainebleau sand (Rupelian), at low depth (3 m), above water table. The recording shows the tooth penetration and pressure reduction phase, followed by the actual test, which here includes a larger number of stages (12) than required by the standard. The pulling force peaks already shows a fairly regular increase over time, with the pressure steps also remaining regular.

Each time a pressure step change is announced by operator A controlling the phicometer probe, operator B stops pumping for a while to reset his comparator and his stopwatch to zero, during which the pulling force is released. During each pressure stage, the pulling force is not strictly constant; it shows a tendency to increase, with oscillations related to the alternate pumping action on the cylinder. Figure 3 details the data for one stage (stage 7 of the test in Figure 2).

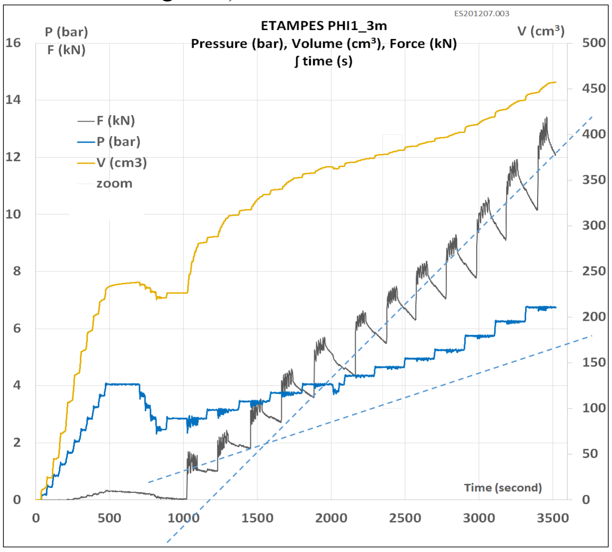

Figure 2. P, V & F data from a test, recorded every second. Fontainebleau Sand in Etampes (91, France).

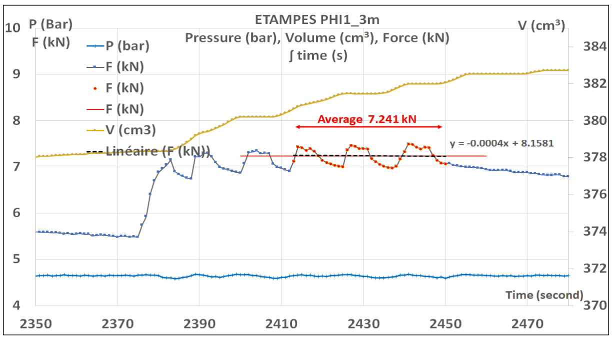

Figure 3. Details on recording one bearing step.

The curve τ ∫ (σ) of the test (Figure 4,normal stress σ is given by pc for corrected pressure on x axis) based on the average stabilized values of the pulling force, the pressure being regulated with an extremely low oscillation, reflects this regularity: only the first two points after contact are to be eliminated, all the others present an almost perfect linear adjustment, according to an angle φ_i of 34.3° quite normal for a homometric fine sand whose properties are known to be very homogeneous. The question of the relevance of the figure after the decimal point can be asked, as to its geotechnical necessity, but the quality of the alignment of the points gives it a metrological representativeness: the value obtained varies very little whatever the points that one would like to eliminate among the 8 retained here. The control of the volumes shows that the test remained mostly in the pseudo-elastic phase, and that one could therefore have adopted a larger pressure step to achieve fewer points, while keeping the same result in φ_i; the apparent cohesion c_i is rather high, the sand at low depth can be little clayey.

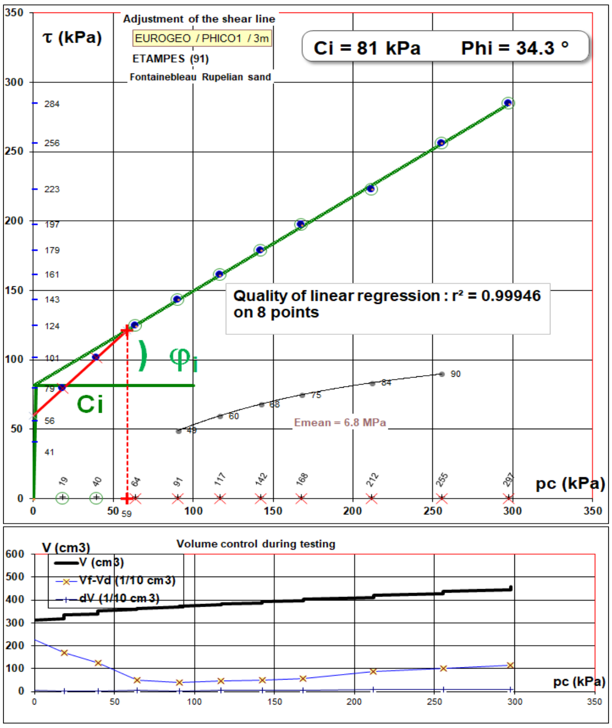

Figure 4. Interpretation of the test in figure 2.

2.2.2. Clay.

Figure 5 below is a test in Montmorency millstone clay, Quaternary decalcification clay on Beauce (Chattian) limestone.

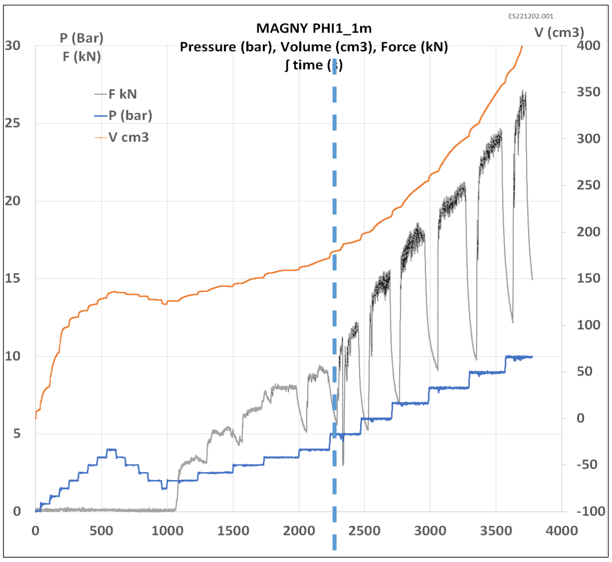

Figure 5. P, V & F data from a test, recorded every second. Beauce millstone clay in Magny-les-Hameaux (78, France)

A change in behavior is noted; the test appears to consist of two parts: one of a pseudo-elastic nature, with five stages, where stabilization of the increasing pulling peaks is achieved relatively well, followed by a second part where the more rapid growth in volume indicates plasticity. As a result, pulling force stabilization is increasingly difficult to achieve within the maximum planned 4 minutes. However, the test is stopped to move on to the next stage. In fact, the creep pressure has been exceeded.

Figure 6 shows the details of the variation in pulling force over stages corresponding to the two cases. In the first part, the pulling measurement oscillations, already more frequent than in sand, remain limited in amplitude, and an adjustment remains linear and almost horizontal; an overall average is significant. In the second part, the oscillations become more frequent and larger, and, above all, their linear trend remains increasing, requiring an average value to be taken only over the last third or quarter of the measurement range.

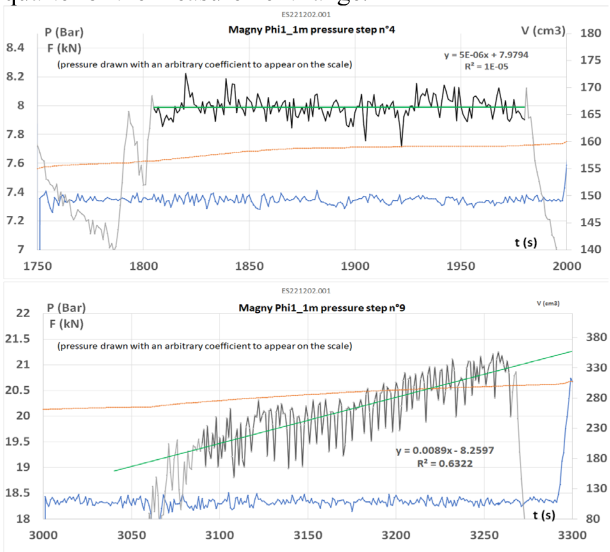

Figure 6. Detail of the recording of 2 bearing stages with different behavior.

The τ ∫ (σ) curve of this test (Figure 7, normal stress σ is given by pc for corrected pressure on x axis) based on these less stable average tensile values chosen towards the end of the measurement range, nevertheless remains interpretable as a linear regression over all the measurement points. Even the first and last points, eliminated from the calculation, remain close to the shear line, whose correlation coefficient r^2 is close to unity, as well as, if not better than, what was previously observed for sand. The control of the volumes during the test (classically reported under the τ ∫ (σ) diagram with the same abscissa scale) should normally encourage only stages 2 to 6, or even 2 to 5, to be retained for the interpretation of the test, the following stages clearly showing increasing creep. The shear line, however, remains practically the same, with an r^2 coefficient that is still excellent but slightly lower, for a result that is very little different (Ci= 13 kPa | φi= 11.8°). This seems to show that the shear law remains measurable, and above all remains the same, while a ring of soil around the probe has entered into plasticity. Other tests in other soils do not show the same thing, and sometimes a more marked change in the alignment angle.

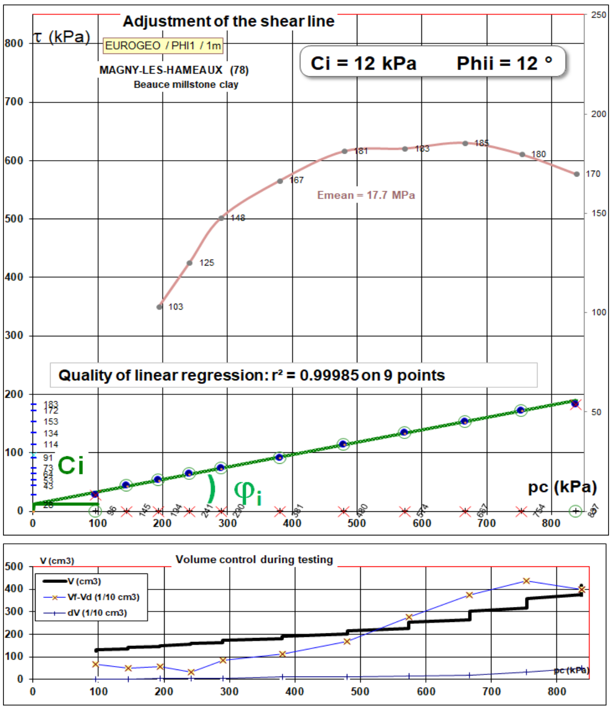

Figure 7. Interpretation of the test in figure 5.

2.3. Interest in pressure regulation associated with data recording.

Automatic pressure regulation by a Type C pressure-volume controller provides the same advantage to the pressure-deformation relationship of the probe during the test as in a Ménard pressuremeter test, namely the assurance that the pressure level remains constant all along the required duration. The corresponding volume variation is accurately recorded, and therefore the creep value during the pressure step, which is relatively low, is better appreciated.

It appears from the examples given that the second-by-second recording of the tensile force on the probe exhibits oscillations whose origin is difficult to determine, whether due to variations caused by the operator, the measurement system, or the ground itself. The recordings also confirm a fact already observed in the manual recording of the test: that tensile force stabilization takes a long time to achieve, and therefore is not always easy to distinguish from data recorded visually at 30-second intervals. The idea of automating the pulling action on the probe is not new, but has never been implemented to our knowledge.

3. Development of a mechanized pulling speed regulation

3.1. A pulling cylinder with a very slow regulated speed

The principle of a speed-controlled cylinder is not new and is used for various purposes in industrial components.

The need to apply such regulation to the Phicometer test was to find a device that was designed for site conditions and capable of regulating the very slow pulling speed required by the test, 2 mm/min according to ISO 22476-16.

A type C pressure meter such as the Geopac or Hyperpac is, by design, a highly accurate flow meter with a very low flow rate. Feasibility tests prior to on-site implementation were conducted using a Geopac measuring (P, V, F) in parallel, as in the previous examples, and a Hyperpac, whose usual flow rate is even lower, to create a constant flow rate as the pulling cylinder pump, capable of creating and regulating the desired displacement speed of 100/3 µm/s without drift of more than 3%, or 1 µm/s.

3.2. Feasibility tests

The Hyperpac dedicated to the experiment was filled with hydraulic oil and connected to the pulling cylinder. After verifying the linear relationship between the flow rate imposed by the Hyperpac and the cylinder's lifting speed with no charge, different load cases on the cylinder were tested to verify its ability to ensure movement at a constant speed regardless of the load, in particular by placing it in extreme conditions in a very slightly deformable frame, constituting a sort of calibration of the system (Figure 9).

The first "simulated test" was carried out by having the cylinder compress a powerful 5kN spring locked in a frame. The simulation confirmed the system's ability to ensure movement at a regulated speed while the strength can vary; in the case of the spring, strength increases directly with displacement since both are linearly correlated with pressure (Fig. 8).

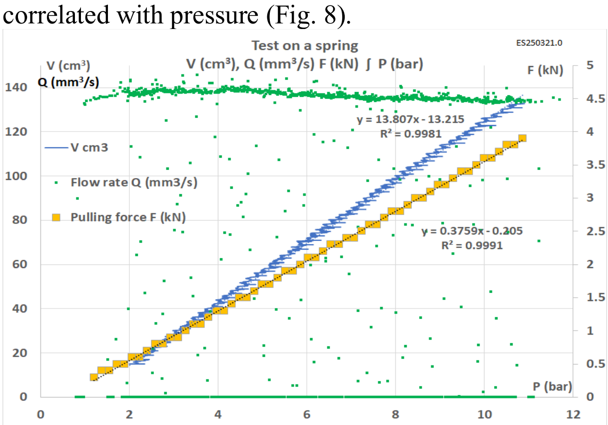

Figure 8. Recorded data from a test simulated by spring resistance.

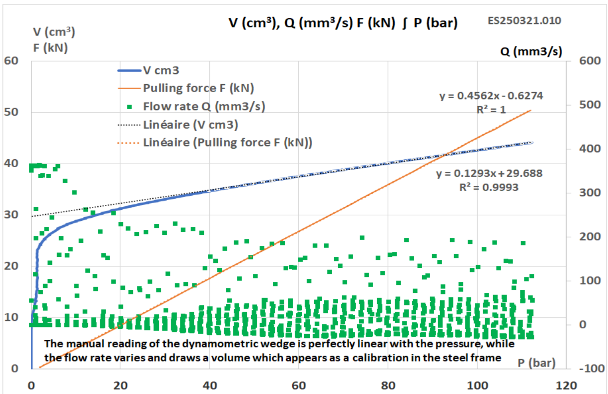

Figure 9. Recorded data from a simulated test by locking the cylinder in a frame (cylinder calibration)

Figure 10. Spring simulation of the rise speed regulation of the cylinder actuated by a Hyperpac (result Fig.8)

Figure 11. Pressurization of the cylinder blocked in a slightly deformable frame (result Fig.9)

3.3. First tests with the fully automated regulated Phicometer.

3.3.1. Clay.

The same Montmorency millstone clay, in a borehole a short distance from the test described in §2.2.2, was used to develop the prototype.

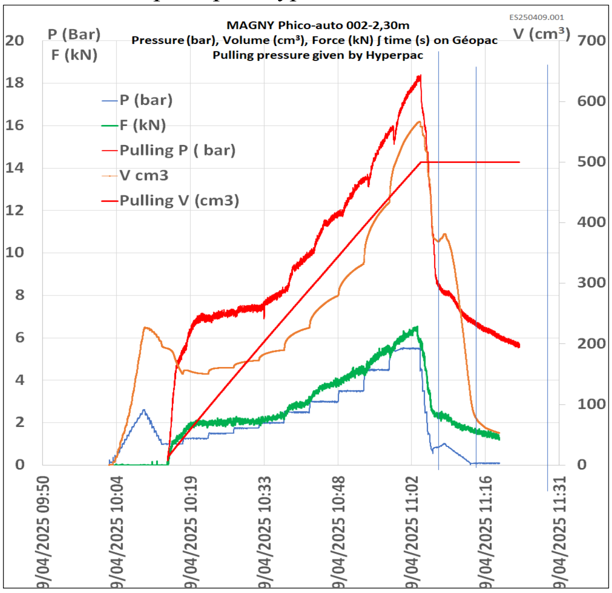

Figure 12. Data from one of the first "AutoPhico" tests, recorded every second. In addition to the P, V, F data from the phicometer, synchronous P and V data from the pulling cylinder (Hyperpac P-V unit)

The Pressure and Volume data of the cylinder are recorded synchronously with the P, V and F data of the phicometer (figure 12). The constant flow rate of the cylinder produces a V(t) flow line with absolutely no drift.

It can be seen that the pressure in the cylinder (red curve at the top) shows a homothetic growth of the recording of the tensile force in the wedge (green curve, similar, due to the scales, to the test pressure, the blue stepped curve).

It is also noted that the test concerns both the pseudo-elastic phase and a significant part of the plastic phase, during which no stabilisation of the pulling force is achieved, in parallel with the same behaviour for the volume.

The correlation between the two independent measurements, pressure in the cylinder and dynamometric pulling wedge, is very strong (figure 13):

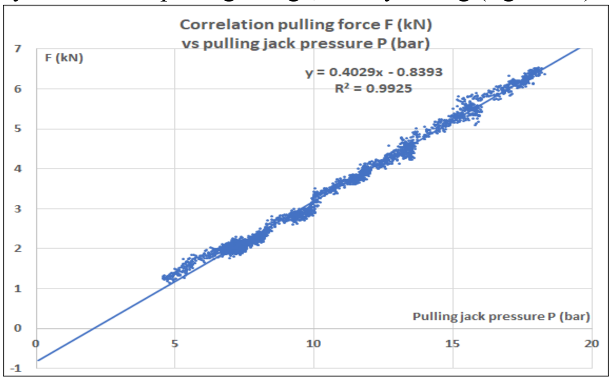

Figure 13. Correlation between pressure in the cylinder and measurement of pulling force during test steps.

This expected finding shows that factory calibration of the pressure in the cylinder to the pulling force would allow the latter to be directly determined by measuring the pressure in the cylinder's motorization system.

It is also noted that the regularity of the cylinder's rise had no effect on the micro-oscillations in the force value during each constant pressure stage; they exhibit, in detail, the same appearance as during the test in the same clay with manual pulling (Fig. 6).

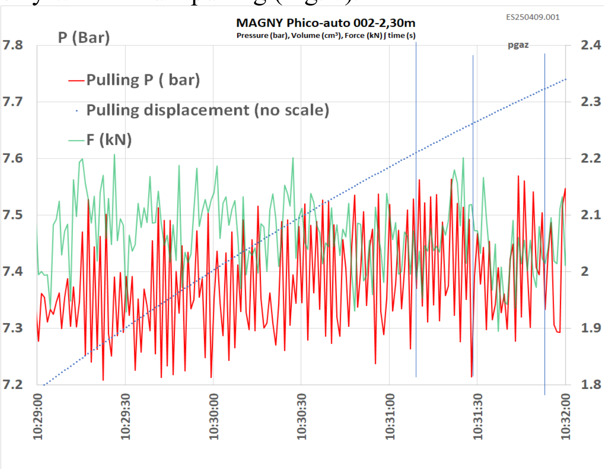

Figure 14. Examples of parallel F-wedge and P-cylinder variation over a few seconds.

One might wonder to what extent these micro-oscillations are related to the pulling system, or whether they come from micro-shears in the soil during pulling, since they are measured almost identically during manual pulling of the jack. The pressure in the jack, by constantly adapting to the soil's reaction to maintain an absolutely constant displacement speed, may reflect such micro-shears in clayey soil with a few grains of sand and pebbles. In the Fontainebleau Sand, the periodic oscillations (Fig. 5) are more clearly related to manual pumping and do not show the same micro-shear pattern. The interpretation of this test is given in the figure below (Figure 15). This is a very weak soil, with a limit pressure p^*_{LM} of around 0.35 MPa, in which a manual phicometer test is considered very difficult to perform. The linear relationship between τ and σ is nevertheless of very good quality, on 5 aligned points, for an angle φi of 6.5°, therefore smaller than the test in Figure 7, which is in similar soil but less deep.
As in the previous cases, the points in the plastic zone, which the standard recommends not to stress in order to favor shear in the pseudo-elastic zone, nevertheless remain in almost identical alignment.

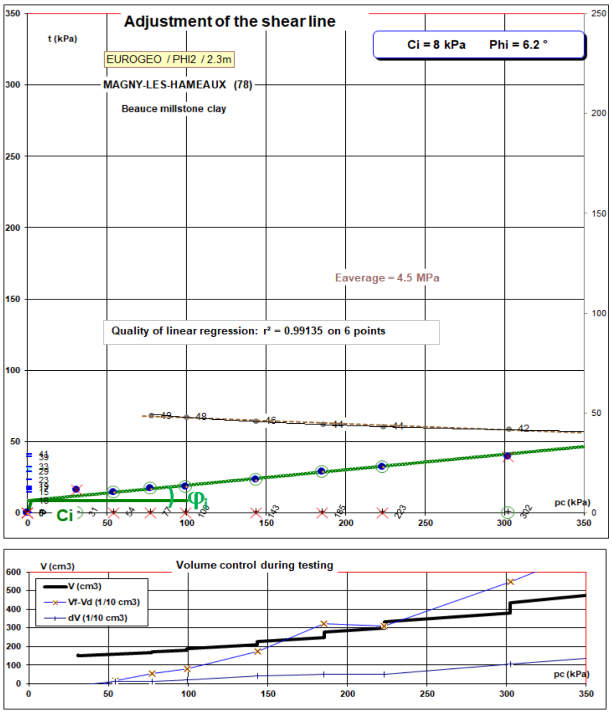

Figure 15. Interpretation of the test in figure 12.

3.3.2. Sand.

Another implementation of the AutoPhico prototype was carried out in the same site (Etampes) as the test presented in 2.2.1 a few meters away. Figure 12 presents the data recorded every second of a test at 2m depth in Fontainebleau sand, above water table. Drilling by continuous flight auger.

The pressure recordings of the Hyperpac regulating the jack and of the force on the dynamometric wedge are much more regular than in the clay in § 3.3.1, and their correlation is almost perfect.

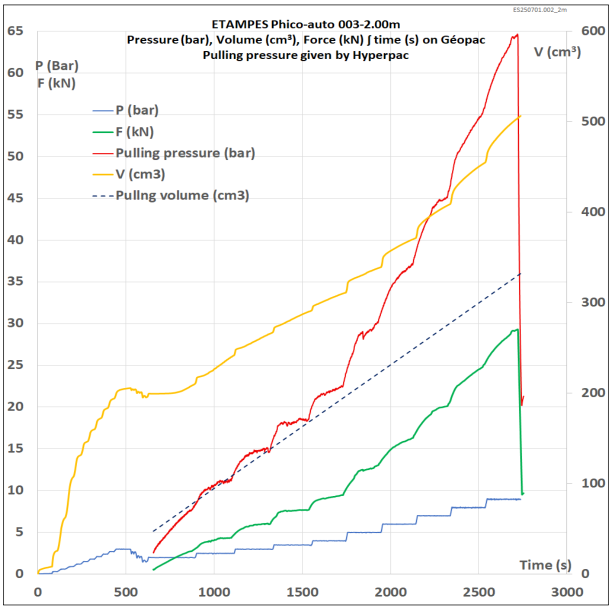

Figure 16. Data from one of the first "AutoPhico" tests, recorded every second. Fontainebleau Sands at Etampes, Joulin factory (78, France)

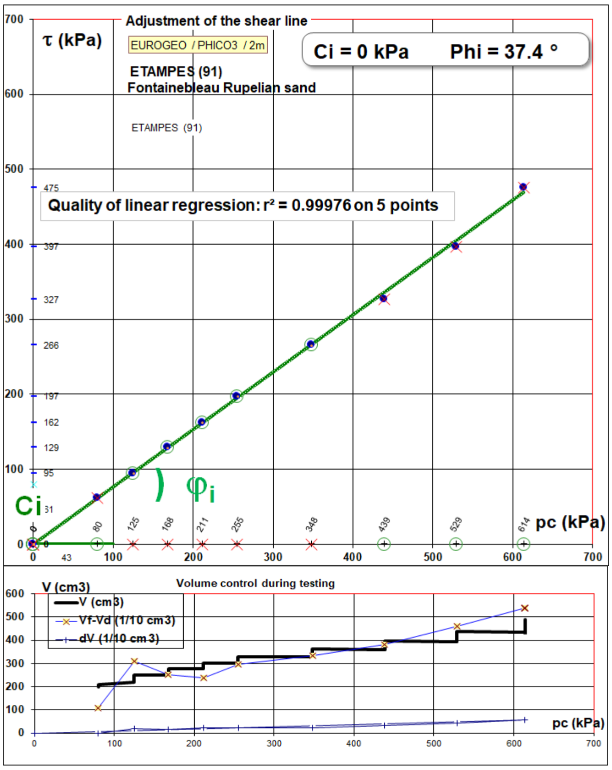

Figure 17. Interpretation of the test in figure 17.

The Coulomb line is fitted to 5 points of the pseudo-elastic phase, but we see that all the points of the test have an almost identical alignment.

4. Conclusions

Like other in situ tests, the Phicometer must be updated to become faster and fully automated, ensuring both complete test traceability and the ability to conduct more tests, as statistical representativeness is an essential element in geotechnical engineering given the natural heterogeneity of soils.

The automation presented in this article suggests that it will become possible to measure friction and cohesion in situ with a test set up more quickly (bringing the teeth into contact), followed by limited number and duration of test steps, as soon as the control computer demonstrates that the stabilization and alignment of 4 to 5 test points is perfectly ensured.

The guarantee of test representativeness is then primarily transferred to the preliminary drilling, for which self-drilling is also a possibility for the probe designed 40 years ago by Gérard Philipponnat.

Acknowledgements

The authors thank the management of the Joulin factory, at the foot of the sandy hill of Etampes. Many people from Apagéo, Géomatech, Cedarnet, and Eurogéo were mobilized for the equipment and time they provided to develop the prototypes, and for their perseverance in obtaining these initial in situ results from a fully automated phicometer. The prototype presented in this article did not receive any public funding.

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