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# Cyclic Pressuremeter Tests – Shear Modulus Determination at Low Strain Rate

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## 1 Introduction

Pressuremeter test is a reference *in-situ* test for underground investigation in French geotechnical engineering practice. Performed according to current standards, these tests make it possible to obtain the so called Ménard pressuremeter module, the pressuremeter creep and limit pressure, for a soil behavior without cycle or with a single reloading cycle. For many geotechnical structures, such as foundations under repeated loads, the design cyclic parameters to be taken into account correspond to relatively low strain rates and cannot be accessed neither by the standard testing protocols, neither by the most common test equipment.

The Francis Cour® single cell probe offers new possibilities. It allows performing cylindrical cavity expansion tests in soils from the field of relatively small strains to that of large "pressuremeter" deformations, with direct measurement of the conventional limit pressure. Performing unload and reload loops with this probe can potentially allow the measurement of the soil shear modulus in a range of strains of  $10^{-4}$  to  $10^{-2}$ . The research work currently being carried out using this probe shows realistic estimation of deformation modulus for different types of soils.

A rigorous procedure must be followed to minimize the uncertainties associated with the testing material and the homogeneity of the soil layer to be tested. For the correct test implementation, some important aspects need to be considered.

This paper presents high resolution calibration studies of the Francis Cour® single cell probe and a simple way to account for uncertainty on its measurements. Examples of interpretation of *in-situ* tests with unload-reload loops are presented. The results obtained are compared to the ones given in the literature in the form of relationship curves between shear modulus and distortion and also to those obtained from laboratory tests performed in soil samples collected in the same site.

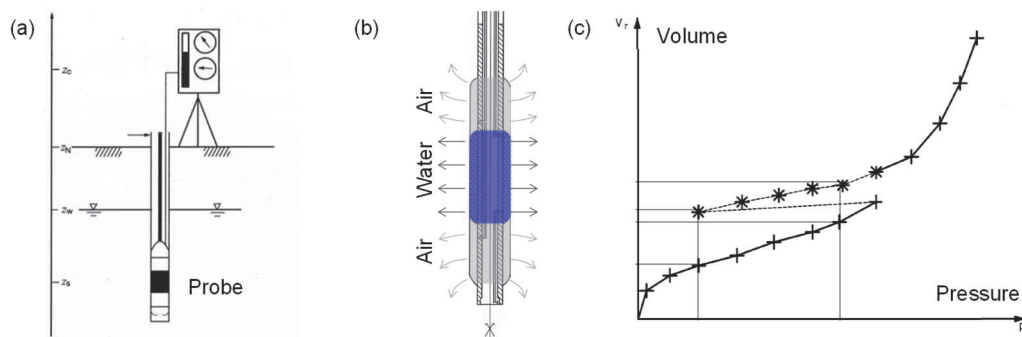
## 2 Brief review on pressuremeter practice

### 2.1 Principle of the test

Pressuremeter test is a cylindrical cavity expansion test used for measuring soil's strength and deformability properties. It basically consists on placing a probe on the ground, expanding it radially following a given test protocol and measuring soil's response in terms of radial stress / radial strain.

Probe insertion can be done in different manners: it can be pushed into the soil, placed in a pre-bored cavity, or self-bored. All insertion process will disturb soil's initial conditions. The last one is remarkably the one which will cause less disturbance, but also the most complicated to execute in practice. Push-in pressuremeter can only be pushed into relatively soft soils and probe penetration will first fail soil around the probe. Pre-bored pressuremeters can be performed in all types of soils and soft-rocks but care has to be taken so that the boring technique is properly adapted to reduce disturbance at most and that the probe is placed in a homogeneous soil layer. It is the most common technique used in France.

Pressuremeter probes are inflated with water and pressurized air (three-cellular probes) or only with water (single cell probes). In most systems the cavity's radial expansion is measured by measuring the injected volume of water on the probe and then correlating it to its radial expansion. The cavity pressure is measured by measuring the water pressure. As those measurements are made above ground level and the probe is placed underground, corrections must be made both for pressure (to account for hydrostatic water level and membrane inertia) and for volume (to account for system's compressibility). Some devices may implement local measurements of pressure and displacement, but it is generally reserved for special tests. A schematic representation of most usual test equipment is presented on **Fig. 1**.



**Fig. 1** Principle of a standard pressuremeter test. (a) Probe inserted on the soil and measurements at ground level, (b) dilatation scheme and (c) typical test with unload reload loop (adapted from AFNOR, 2015).

## 2.2 Commonly measured parameters

Three main parameters are obtained from standard Ménard pressuremeter tests (PMT) performed following the most commonly applied standards, the European one (AFNOR, 2015) and the American one (ASTM, 2007): the Ménard pressuremeter modulus, the pressuremeter “creep pressure” and the pressuremeter limit pressure. A standard PMT borehole log will present those parameters in function of depth. They can be used for the design of shallow and deep foundations, ground anchors, retaining walls and other geotechnical structures. Despite it is theoretically possible to derive intrinsic soil parameters from these tests, most of the present design rules based on pressuremeter tests pass through empirical correlations (Frank, 2017).

The cavity expansion solicitation is actually a shear test which consists on shearing the soil from a near-at-rest state to a near-failure state. Thus, it should be possible to derive intrinsic soil parameters from the test, such as its cohesion, internal angle of friction and others. Performing cyclic tests allows recovering soil's elastic state, measuring shear modulus at various strain rates and stress levels and its evolution in function of the number of cycles. Many methods for obtaining soil's intrinsic parameters from pressuremeter tests can be found in literature. However, they require more advanced data reduction techniques and there are currently no standardized protocols for this purpose.

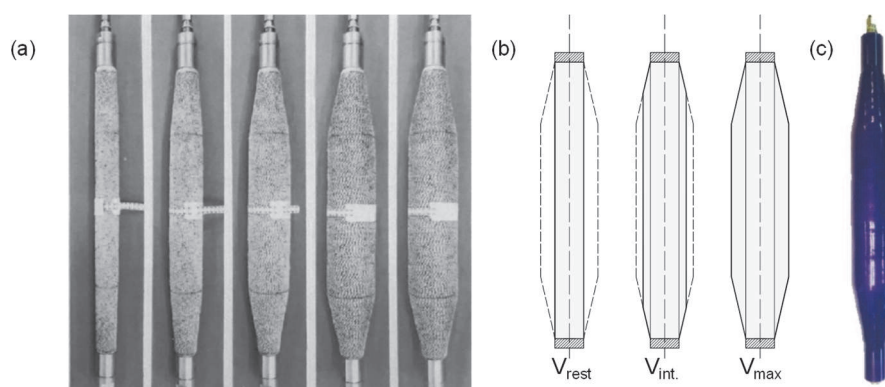
## 2.3 Limitations

Probes have limitations referring to its capacities in either maximum allowed volume or maximum pressure. Those limits may prevent it from measuring the desired soil parameters. For example, measuring the limit pressure in dense soils require the probe to expand to high volumes at high pressures, which is not always possible with most common rubber membranes.

Another limitation of conventional rubber-membrane probes is the fact that its actual radial expansion is calculated from a relation with the injected volume on its measuring cell. Probe inflation is frequently supposed to be cylindrical but it may not be true in some cases. In traditional three-cellular probes, if any variations occur between the gas and water pressure (differential pressure), the measuring cell will tend to deform longitudinally, differing from its supposed cylindrical shape. In the case of cyclic tests, where the probe is deflated and re-inflated several times, major uncertainty may be added to the test. In conventional mono-cellular probes, end-effects can be considerably high and also disturb the theoretically supposed cylinder-shape. The best way to assess the real probe volume to diameter relation is through calibration tests.

## 2.4 Overcoming probe limitations: innovative probes

The Mono-cell Francis Cour® is an innovative single-cell pressuremeter probe that overcomes limitations related to membrane problems. It implements the so-called restraining sheath, which allows it to dilate following an imposed geometry (**Fig. 2**). This sheath's bevelled-end shape is designed in such a way to avoid end effects such as stress concentration. Two main advantages yield from this characteristic: (1) probe can reach very high pressures even at high volumes and (2) there is a precisely linear relation between the injected volume and the probe's diameter. This relation can be verified through calibration tests as described further in this text. Covering all the ranges of pressures and volumes reached by the test allows it to be interpreted in terms of radial strain.



**Fig. 2** Innovative probes and controlled geometry: (a) sequence of photos of a probe's inflation, (b) inflating scheme and (c) detail on the final bevelled-end shape.

## 3 Minimizing uncertainty

Uncertainty is present in any measurements. In pressuremeter tests, uncertainty comes from many different sources, but its influence on test's result is rarely addressed in literature.

The first and more evident source of uncertainty is related to the resolution of the pressure and volume measuring devices but other sources of uncertainty are related to all the testing equipment's measuring chain. For example, the tube carrying water between the measuring device and the probe may become add uncertainties related to temperature variations. Measuring the injected volume of water and then correlating it to the probe's radial expansion passes through the assumption that the membrane expands following a perfectly cylindrical geometry. Thus, membrane behaviour, if distinct from hypothesis, introduces another source of uncertainty. Furthermore, if there is any water flow on the tubing as during soil "creep", pressure losses will take place, making the real probe pressure lower than the measured water pressure at the controlling device.

The impact of some of those uncertainties on the test result can be minimized through a rigorous calibration protocol. However, other aleatory uncertainties, like temperature changes and gradients, are complex and cannot be calibrated.

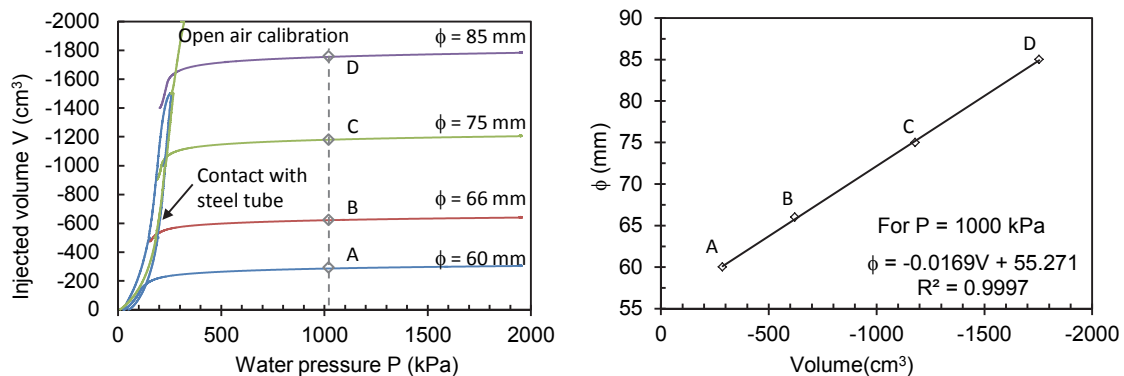
### 3.1 A rigorous calibration procedure

A rigorous calibration procedure as presented by Cour and Lopes (2018a) which consists to dilate the probe inside at least four different diameter steel tubes covering all the pressures and volumes reached by the probe during testing permits interpreting test results in terms of radial strain without making hypotheses on probe geometry. The particular case of the Mono-Cell FC® probe is that the relationship between the measured volume and the corresponding diameter is linear.

An example of this calibration procedure is presented in **Fig. 3**. Probe was inflated with water using a high resolution laboratory Pressure/Volume Controller (volume resolution of  $10^{-3}$  cm<sup>3</sup> and pressure resolution of 1 kPa). Four steel tubes with wall thickness equals to 8 mm (thus considered infinitely rigid compared to the pressuremeter system) and internal diameters equals to 60 mm, 66 mm, 75 mm and 85 mm were used. Despite probe can support pressures up to 20 MPa, pressure was limited to a maximum of 2 MPa due to limitation on the injection device. This allows writing the probe diameter  $\phi$  as a function of both its internal pressure  $P$  and the injected water volume  $V$ , as follows:

$$\phi_{(V,P)} = a_{(P)} \times V + D_{(P)} \quad (1)$$

For a given value of pressure, the relation between the injected volume and the outer probe diameter is linear and coefficients  $a$  and  $D$  can be obtained by the least square method. Due to system's compressibility, those coefficients may slightly vary with pressure, which can also be accessed through the proposed calibration procedure.



**Fig. 3** Example of probe calibration with multiple diameter steel tubes and correlation between probe outer diameter and injected volume using high resolution laboratory controller.

It is possible to derive the uncertainty  $\sigma_\phi$  on the calculated diameter in equation (1) using statistical error analysis formulation as proposed by Taylor (2000) and presented in Eq. (2):

$$\sigma_\phi = \sqrt{\frac{1}{N-2} \sum (\phi_i - D_{(P)} - a_{(P)} \times V_{i(P)})^2} \quad (2)$$

, where  $N$  is the number of calibration tubes (4, for instance),  $\phi_i$  is the steel tube internal diameter,  $V_{i(P)}$  is the injected volume in a given tube at a  $P$  pressure, and  $a_{(P)}$  and  $D_{(P)}$  are the coefficients calculated by linear regression at a given pressure as presented in **Fig. 3**.

Applying Eq. (2) for the calibration measurements interpreted according to eq. (1) leads to an uncertainty on diameter lower than 0.25 mm. Using a similar approach it is also possible to estimate the uncertainty in coefficients  $D_{(P)}$  and  $a_{(P)}$ , and thus derive uncertainty on diameter variation. This can be used further to estimate the probe's measuring resolution (which is its actual capacity to measure a radial displacement) and then use it to insert an estimation of uncertainty when interpreting a test result.

This calibration procedure permits automatically correcting device compressibility for all ranges of pressure and volume within its capabilities. Calibrating with different diameter calibration tubes has been previously suggested by Mair and Wood (1987) when testing rocks at high pressures, but this has not come to current practice and it is not required by the current standards. This procedure is only feasible if probe has a long durability and if it does not evolve with time / use. If this is the case, parameters of Eq. (1) can be established once and then be used for a series of soil tests. Probe should be recalibrated after a series of tests to verify if its properties have not evolved.

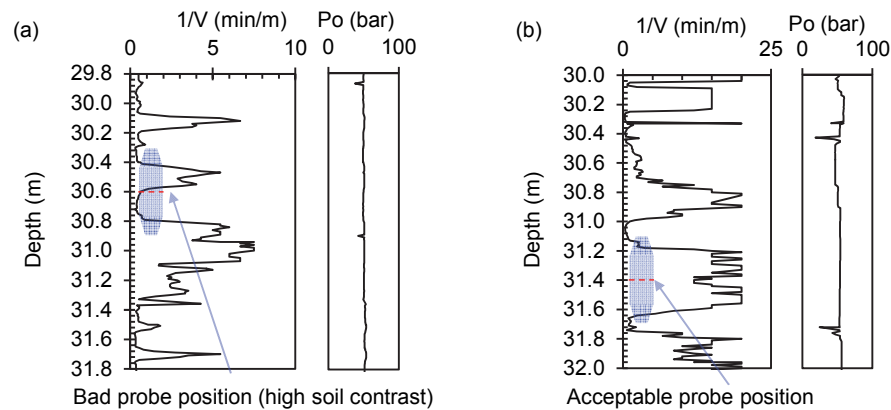
### 3.2 Wisely choosing probe position

Despite the rigorous calibration procedure described above, one hypothesis is still necessary to ensure its validity during soil test: the soil around the probe must be homogeneous so that the cavity expansion is cylindrical. Placing the probe between two soil layers of different stiffness will result in non-cylindrical strain field which cannot be interpreted by means of cylindrical cavity expansion methods. This will also lead to longitudinal deformations on the probe and possibly damage it.

Most pre-bored pressuremeter tests are performed into pockets drilled by destructive methods. It is a common practice to monitor drilling parameters such as drilling advancement rate pushing force and injection pressure and to record it and use as a soil's diagraph. Despite they cannot be correlated to intrinsic soil properties, they reveal contrasts related to soil layer transition and they can be used

as a decision-aid tool by the operator to best choose the probe position before performing the test.

Cour and Lopes (2018b) presented the importance of this analysis. **Fig. 4** shows an example of a bad and an acceptable position for the probe regarding drilling parameters contrast.



**Fig. 4** Real examples of bad and adequate probe positioning regarding soil layer heterogeneity (two distinct boreholes).

### 3.3 Flow rate and tubing issues

Pressure losses on the tubing due to water flow may be very important and relatively difficult to take into account since it depends on many variables. Enlarging tubing diameter is the best solution, but it is limited due to practical reasons such as the borehole diameter.

The higher is the flow rate, the higher will be the pressure loss. Operating with constant pressure load steps means that flow rate may vary during a load step. On the other hand, operating with an imposed constant flow rate, which actually corresponds to a constant shearing rate, allows reducing uncertainty related to pressure losses. On this case, flow rate can be imposed as low as it can be neglected.

## 4 Modulus at low strain rate

### 4.1 Application example

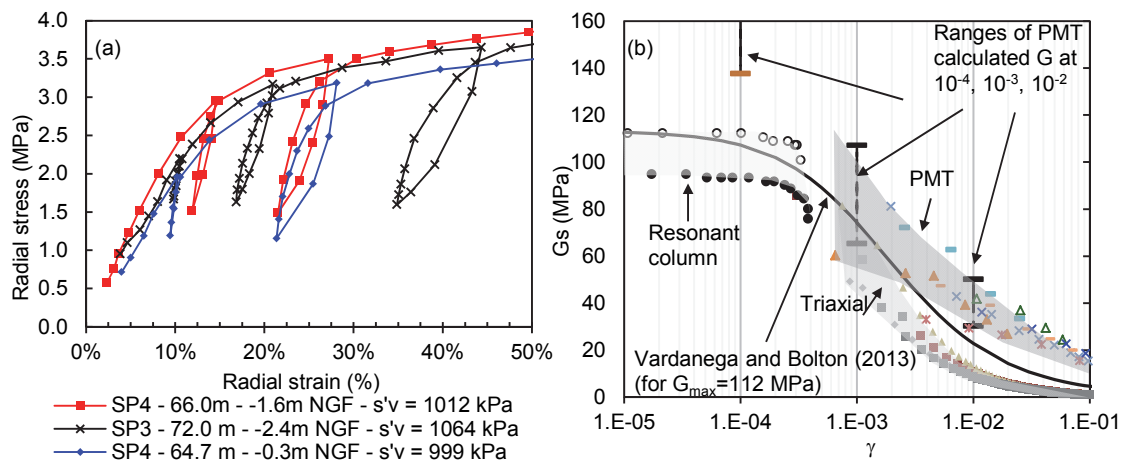
Lopes et al. (2018) presented two application examples of shear moduli measurements at relatively low strains using the mono-cell FC probe, one in dense sands and one in overconsolidated clays in the Parisian region. The analysis was

based on Whittle et al (2017) interpretation procedure which gives a shear stiffness decay curve taking into consideration stress levels at each unload-reload loop.

Lopes et al. showed that for the clay tests there were no variations of the shear modulus with the stress level of the loops. On the basis of this assumption, two other tests performed on a near borehole, on the same soil layer and at near depths were interpreted. **Fig. 5** (a) shows the results of those three tests. The soil layer is described as stiff gray clay. Two undisturbed soil samples were collected at ground level -0.9 m NGF and -4.6 m NGF (70.5m and 74.2m below local ground level). Laboratory tests yielded in effective friction angles of  $12^\circ$  and  $6^\circ$ , effective cohesions of 20 kPa and 49 kPa respectively, and undrained cohesion of 120 kPa and 150 kPa. Overconsolidation ratio obtained by oedometer tests was 2.3. Plasticity index is 59% and 55% and liquidity limit is 88% and 81%. Two resonant column tests, performed at a confining pressure of 697 kPa, resulted in values of  $G_{\max,RC}$  of 112,2 and 94,8 MPa, for shearing strains of  $1,6 \cdot 10^{-5}$  and  $2,6 \cdot 10^{-5}$ , respectively. No geophysical tests were available, and the resonant column tests are here considered as reference values for the maximum shear stiffness of this clay.

One may notice that the soil resistance obtained by PMT tests is very near on the three tests, with an average conventional limit pressure measured of 3.6 MPa, showing that the soil layer is relatively homogeneous. One may also notice good similarity between the unload-reload loops, especially regarding its slope evolution against radial strain (slope and hysteresis loop). At the time those tests were realized, the testing protocol was still under experience, which justifies the fact that all the curves don't have the same number of measuring points.

All cycles were interpreted and compared to laboratory triaxial CUu and resonant column tests, as presented on **Fig. 5** (b). Literature data as proposed by Vardanega and Bolton (2013) on shear stiffness decay of clays were equally plotted on this graph adopting clay's plasticity index described above. From this figure one can see that pressuremeter and triaxial measurements of shear stiffness are equally distributed around literature proposition for strains between  $10^{-2}$  to  $10^{-3}$ . While PMT measurements tend to be higher than the literature proposed values, triaxial measurements tend to be lower than it by the same magnitude. When it comes to strains of  $10^{-4}$  the PMT model tends to highly overestimate shear modulus. On the present case, the measuring protocol was not optimized for this purpose as a continuous rate of shearing procedure was impossible for matters of data acquisition. Only a few measurements are available between  $10^{-3}$  and  $10^{-4}$ , which may justify the overestimation by the model. Laboratory tests with this probe in a calibration chamber are in progress in order to validate its capacity to perform measurements on this strain range. One should notice that the scatter obtained by the PMT measurements is of the same magnitude of the scatter obtained by triaxial tests and that the two resonant column tests resulted in 20% difference.



**Fig. 5** (a) Three pressuremeter tests on overconsolidated clays with unload-reload loops and (b) and comparison between shear modulus measured from pressuremeter, triaxial, resonant column tests and literature data.

## 5 Conclusions

Pressuremeter tests are one of the most used investigation tests for geotechnical design in French practice. If performed following current standards, they allow measuring a soil's deformation and a strength parameter, the so called Ménard pressuremeter modulus and the conventional limit pressure, respectively. Design rules based on those parameters are mainly empirical. Design based on low strain soil moduli, such as piles foundations submitted to cyclic loading, demands different testing protocols and devices.

The Francis Cour® mono-cell probe has shown advantages regarding its measuring capabilities. It can potentially lead to satisfactory measurements in the range of strains of  $10^{-4}$  to  $10^{-2}$  at the same time that it allows shearing the soil up to its failure even at high pressures. Its simplified controlling system permits conducting tests according to many different testing protocols, including constant rate of shear, which presents major practical interest.

This probe is currently passing through a series of laboratory calibration tests using high resolution controlling devices and reference soils. Those tests will be followed by a series of *in-situ* tests on sites where extensive geotechnical characterization has been carried out, including instrumented pile loading tests. This validation procedure should permit to validate this probe capability on measuring soil properties at relatively low strain and its use for the design of deep foundations under cyclic loads.

## 6 Acknowledgements

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