An innovative monocell pressuremeter probe to meet the recent needs of geotechnical engineering

F. Cour
Calyf, Maisons-Laffitte, France, courfrancis@gmail.com

A. Lopes
Fugro France, Nanterre, France, lopesa@fugro.com

ABSTRACT: A new generation of Francis Cour® tri-cellular pressuremeter probes has obtained great acceptance in French practice over the past years. This paper describes the new line of Francis Cour Monocell® probes. The geometry of the probes has been particularly studied to allow precise control of the radial expansion rate as a function of the volume of water injected on its single cell. This type of pressuremeter can cover an operation domain from that reserved for flexible dilatometers (small strains) to that of conventional pressuremeters (large strains). The main characteristics and new possibilities brought by this innovative probe are described. Applications are illustrated from tests carried out in the Parisian region.

Keywords: *In-situ* tests, pressuremeter test, dilatometer test, pressuremeter probe, cavity expansion

1. Introduction

A new generation of Francis Cour® pressuremeter probes has recently been developed by Calyf. These new probes use textile restraining sheaths for the control of the probe geometry during inflation. They have been in use by geotechnical engineers for more than seven years, as presented by [1]. These pressuremeters can reach a radial expansion ratio that is sufficient to double the volume of the cylindrical cavity and effectively measure the soil's conventional pressuremeter limit pressure.

This paper describes the new type of Francis Cour® (FC) Monocell probes, which was first presented by [2]. The pressure capacity of these probes allows their use in soils and soft rocks. The geometry of these probes has been particularly studied to enable precise control of the radial deformation as a function of the injected volume. By increasing measurement accuracy in a large expansion domain, they enable the possibility of extending the field of study of the cavity expansion of geomaterials, starting from deformation levels that are much smaller than those which can be measured with the conventional tri-cellular probes, and going up to the actual measurement of the conventional limit pressure. Nevertheless, the results of tests obtained with these probes can be expressed in a form equivalent to that of the conventional tri-cellular pressuremeters, which allows their direct use in the design of structures using well-established pressuremeter rules.

In the following text, a brief history of the development of the probe, as well as its technical specifications, operation and interpretation methods are presented. Applications will be illustrated from the results of tests recently carried out in France. Supplementary papers in this conference are allocated to the analysis of cavity expansion tests performed with this probe aiming at determining soil shear moduli at low strain levels. The use of a textile sheath favors the installation of special displacement transducers that have been recently patented.

2. Development – historical context

2.1. From packers to pressuremeters

Pressuremeter and flexible dilatometer probes are inflatable bodies used to perform *in situ* cylindrical cavity expansion tests. In these tests, pressure is applied against the walls of a cavity in the ground and the associated radial strain is measured. Inversely, it is also possible to impose a cavity radial deformation and to measure the associated pressure.

One should note that this working principle is identical to that of the inflatable packers, tools that are widely used in the field of drilling and high-pressure injection to seal cylindrical cavities. However, these tools do not allow measurements and have only one objective, which is to provide a mechanic seal to the cavity. Packers have undergone a technological development parallel to and often independent of that of pressuremeter / dilatometer probes: hence, the interest of referring to it.

In a similar way to measurement probes, packers have limitations in their expansion in diameter and pressure. A look at the history of packers with fixed heads shows that most of them did not exceed a dilation rate of 1.25 to 1.30 times their diameter at rest. In order to improve such expansion rates, manufacturers had to design and produce sliding-head packers, in which the length of the expandable cell varies during inflation and which were able to reach radial expansion ratios of 40 to 50%. However, the application of this type of technology to measurement probes, however, is not possible, because length variations during inflation disturb the assessment of probe radial expansion. To do this with a satisfying degree of accuracy, it is imperative to work with fixed head packers, which leads to the issue of limitation in radial expansion.

With various technological improvements (reinforced sheaths, superposed rubber layers, etc.), producers made it possible to push the inflation ratio to 1.4 times the initial diameter, for limited pressures, with a limited failure rate. The durability of this equipment, on the other hand, was of few tests (less than a dozen).

This finding led the designer to completely review the structure of the inflatable body. The rubber sheath that seals and defines the expandable cell has been surrounded by a textile restraining sheath. This sheath, of patented design [3], has the capacity to expand freely to a limiting diametrical profile from which it opposes to any additional deformation (the sheath blocks the expansion when a limit profile is reached). A beveled shape (spindle) was chosen, since this geometry presents considerable advantage for reducing stress concentrations in the probe ends, and reducing the longitudinal stretches to less than 1%. These sheaths are made by cylindrical weaving.

In the restraining sheath, the warp yarns do not have any particular mechanical characteristics since they are subjected to very little elongation. The weft yarns are hybrid: a combination of elastic (elastomer) with very high strength (2evlar, high-density polyethylene) yarns. These hybrid wires have been patented [4]. They are able to stretch up to elongation factors of several hundred percent from their position at rest presenting a very weak resistance (a few hundred grams for a wire) and from a limit elongation state, to resist to several hundred kilos for additional elongations of a few percent. That is this characteristic that defines the behavior of the probe during its expansion.

2.2. From three-cells to monocell probe

The FC system was initially designed as a tri-cellular probe. Cavity strain measurement was made the same way as in the conventional Ménard type probes, from the volume injected into the central cell. It turned out that the central cell, which was indispensable in conventional pressuremeter probes, was no longer needed in the case of the new FC monocell probes, in which the membrane's radial expansion could be directly obtained from the volume injected into its single chamber. In fact, an adequate adjustment of the geometry of the restraining sheath made it possible to assess the radial expansion of the probe precisely and directly from the measurement of the volume, and particularly to obtain a proportional relation between the probe's outer diameter and the injected volume of water. This relation can be established via calibration tests.

3. Technical specifications

The expansion limits of the FC Monocell probes, in terms of pressure and maximum expansion, are given by the following formula:

$$\begin{aligned}&\text{Pressure [MPa]}\\ &\times\ \text{Maximum diameter after expansion [cm]}\\ &=\ \text{nominal value}\end{aligned}$$

The nominal value in the preceding formula is an intrinsic property of the restraining sheath employed. This value appears in the commercial name of the probe model. For example, a "FC60" probe has a nominal value of 60, which means that it enables a maximum pressure of 6 MPa for a maximum diameter of 10 cm after swelling. A FC160 probe (nominal value of 160), enables a maximum pressure of 16 MPa for a maximum diameter of 10 cm.

Due to this particularity of the membrane design, the probe's pressure capability is purely related to the mechanical strength of the peripheral wires of the restraining sheath. This great simplicity of the mechanical behavior of the probe means that probe pressure capacity does not rely on the rubber membranes, but only on the textile reinforcement. As a consequence, its resistance can be increased only by changing the type of wire of the restraining sheath or the wire density per centimeter of the sheath.

The probe's maximum expansion ratio is 1.65 times its diameter at rest. Inflation and pressurization are made exclusively by fluid injection, generally pure water, without the need of compressed air. The simplicity of the hydraulic circuit makes it suitable to be used with many types of pressure-volume controllers, from the advanced GDS-types to simple hand pumps. A device for controlling and measuring the probe pressure and volume has been recently patented [5], making it possible to control the probe inflation in increments of 0.2 cm^3 per injection cycle, and water flow-rates up to $10 cm^3/s$. This system allows expanding the probe up to its maximum diameter, corresponding to a volume of 2500 cm^3, and for pressures of up to 25 MPa.

The geometry of the probe during its inflation is presented in Figure 1. A photo of the inflated probe at its maximum volume is presented in Figure 2, along with the outer protective sheath.

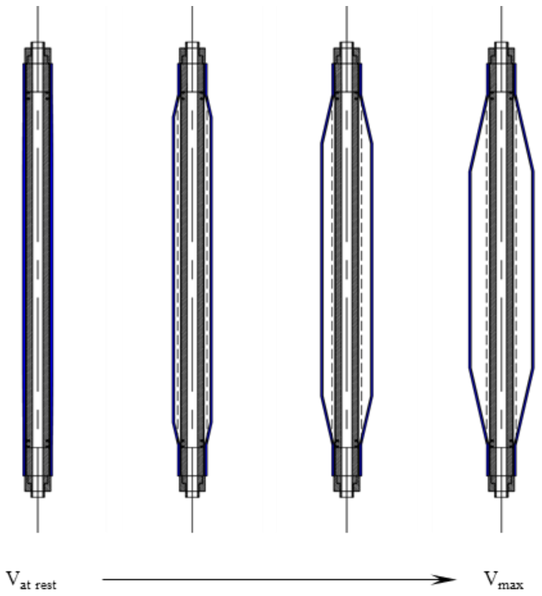


Figure 1. Detail on the probe geometry and the principle of the controlled inflation

The probe can be equipped with an outer protective cover, such as metal stripes, for carrying out tests in very coarse terrains. In relatively homogeneous terrains, the probe can be inserted dressed just with a polyurethane sheath.

(a) (b)

Figure 2. Photo of the probe inflated to its maximum outer diameter. (a) only the restraining sheath; (b) polyurethane sheath

4. *Practical aspects*

4.1. *Calibration procedure*

The geometry of the probe's restraining sheath has been designed in such a way that its radial inflation is proportional to the volume injected into its measuring cell. The proportionality relationship is obtained from calibration tests in which the probe is placed in a thick steel tube of known diameter and then pressurized. This test is repeated with calibration tubes of several diameters and makes it possible to obtain, for a given pressure value, a relationship between the volume and the diameter. This relationship, linear, is used for the interpretation of the test, allowing analysis in terms of radial cavity expansion. A multi-diameter calibration test is shown in Figure 3a. The analysis of the relationship between volume and diameter is presented in Figure 3b.

In the example presented, a coefficient of proportionality of 0.016 between the diameter (in millimeters) and the volume (in cubic centimeters) is obtained. The ordinate at the origin for a zero volume is, in this case, 53 mm. This value is related to the outer diameter of the probe and varies according to its external protective coverage. The coefficient of proportionality varies very slightly with the pressure. Its variation with the probe dressing (in particular the metallic stripes) is negligible.

4.2. *Comparison with standard tests*

The multi-diameter calibration procedure previously presented enables correlating the volumes injected into a monocell probe with those of a conventional tri-cellular probe. This allows to compare the results of two different testing equipment, in any kind of soil, A mathematical relation can be established between the volume of water in the monocell probe and that in the tri-cellular probe for a given diameter. The basis of this analysis is shown in Figure 4. This principle can be used to transcribe the results obtained using a Monocell FC probe in an equivalent form to that of tri-cellular ones. This enables the application of test results obtained with the Monocell FC probe according to the well-established pressuremeter design rules. Examples are presented in chapter 5.

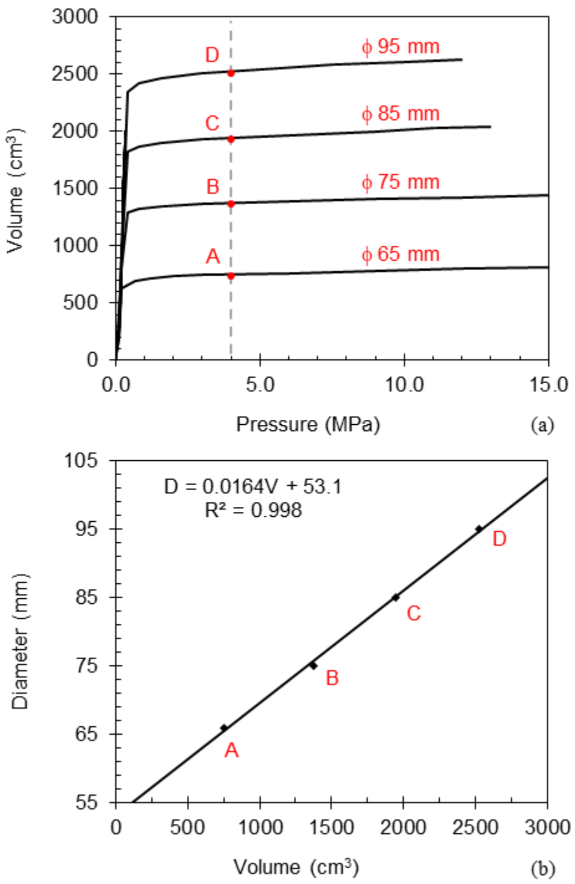


Figure 3. Monocell FC probe calibration test inside variable diameter calibration tubes (a), and the determination of the linear relation between probe volume and external diameter (b).

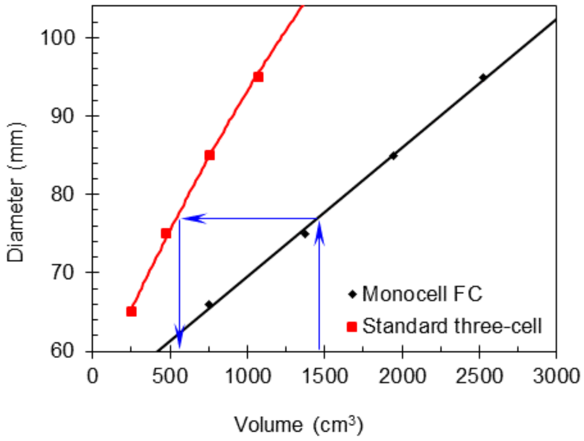


Figure 4. Procedure for transforming volumetric measurements with the monocell FC probe and standard three-cell probes.

4.3. *Testing and interpretation procedures*

The Monocell FC probe can be used to perform tests according to loading protocols proposed by the current standards (pressure, volume or water-flow control – i.e. strain rate control). The simplicity of the controlling device highlights the potential of its use for carrying out cyclic tests, ranging from tests with a few unload-reload loops to tests with a large number of cycles.

The conventional soil limit pressure (associated to doubling the cavity volume) can be directly measured during the test, with no extrapolations on the cavity expansion curve being necessary.

Regarding the evaluation of soil deformability moduli, standard interpretation procedures such as [6,7] can be used. Performing tests according to the loading protocol proposed by the French standard with one unload-reload loop [8] is also possible. Regarding tests with several cycles, whose loading protocol, and interpretation procedures are not standardized, several methods are proposed in the literature and can also be applied. The Monocell FC probe has been satisfactorily employed for the assessment of soil's shear stiffness degradation curve as a function of shear strain rate. The first results obtained in laboratory calibration chamber were presented by [9], underlining the effect of stress and strain dependence of shear modulus in drained sands. More examples of application for the determination of the *in situ* stiffness of sands and clays are presented in a companion paper by [10].

5. Examples of tests in soils and soft rocks

The Monocell FC probe has been used to carry out several pressuremeter tests in the Parisian region in different types of soils. Some test results are presented herein for illustrating the probe capabilities. A more detailed cross-validation program was performed in the context of the ARSCOP project. The parameters obtained in tests performed with the Monocell FC probe were compared to those obtained using other types of probes.

5.1. Sands

The results of a pressuremeter test performed with the Monocell FC probe in very dense Auteuil sands at 31.5 meters depth in the Parisian region is presented in Figure 5*a* (in terms of cavity pressure and cavity radial strain) and *b* (transformed into equivalent volume for standard three-cellular probes, according to the procedure shown in Figure 4). The test was stopped at 15.0 MPa and 40% radial strain. The derived Ménard pressuremeter modulus was 180 MPa.

5.2. Soft rocks

A pressuremeter test was performed with the Monocell FC probe in the chalk of the Parisian region at 59.0 meters depth. Two other pressuremeter tests were performed using the standard three cellular FC probe, one meter above and one meter below. Results are presented in Figure 6*a* (in terms of cavity pressure and cavity radial strain) and *b* (transformed into equivalent volume for standard three-cellular probes and compared with those tests).

The test with the Monocell FC probe was stopped at 27% radial strain and a pressure of 22.3 MPa. The derived Ménard modulus was 575 MPa. Tests performed one meter above and below yielded Ménard modulus of 1000 MPa and 630 MPa, respectively.

It can be seen from Figure 6*b* that the method for transforming monocell measurements into standard three-cell ones (presented in Figure 4) yields consistent values. There are two main advantages of this mixed approach: the first is that it enables plotting results into a format that is currently used by standard pressuremeter practitioners (probe volume versus cavity pressure). In that manner, the equivalent Ménard pressuremeter curve and the derived standard parameters can be used for geotechnical design using the current design codes.

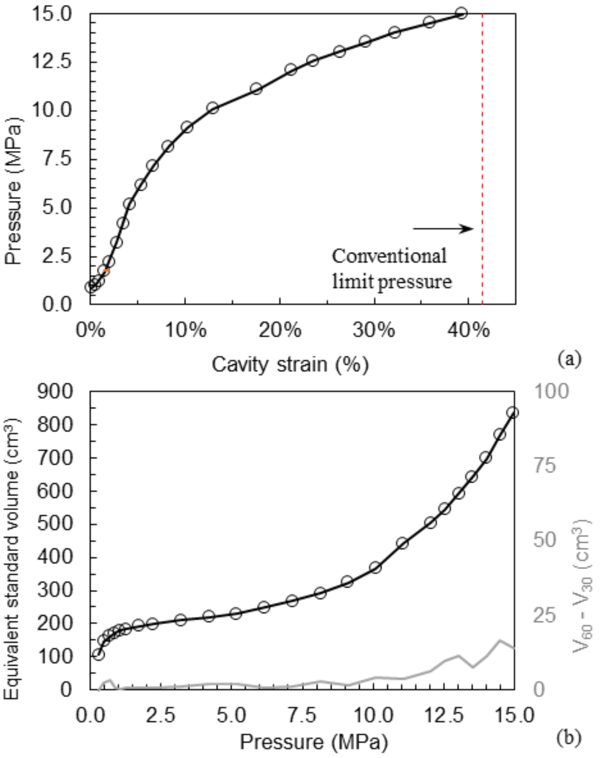
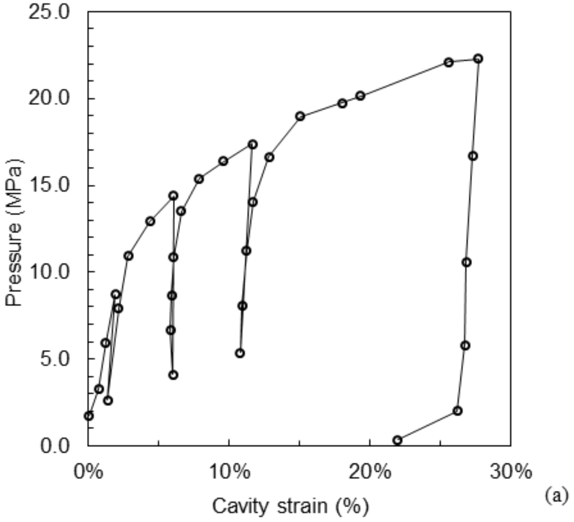


Figure 5. Example of a pressuremeter test in very dense sands at 31.5 meters depth in the Parisian region. Results presented in terms of cavity pressure versus cavity strain (a) and transformed into equivalent standard three-cell volumes (b).

The second advantage is that presenting results in terms of cavity pressure and radial strain (or diameter) is much easier to understand by engineers that are not familiar with pressuremeter tests. This makes the results independent of the type of probe, making it simpler to compare different approaches (pressuremeters and dilatometers, for example). This can provide a link between the international community interested in cavity expansion tests, helping bridge the gap that exists between practitioners.



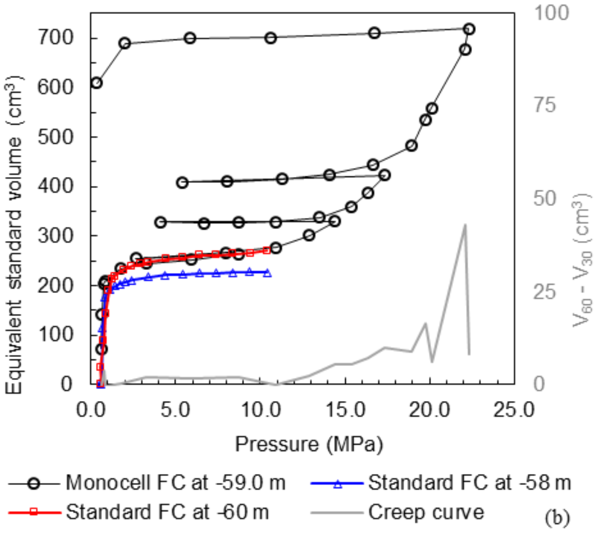


Figure 6. Example of a pressuremeter test in chalk at 59.0 meters depth in the Parisian region. Results presented in terms of cavity pressure and cavity strain (a) and transformed into equivalent standard three-cell volumes (b) and compared to standard test results.

6. *Future developments*

To ensure a satisfying performance of the restraining sheath to control the probe's geometry and provide a linear relationship between injected volume and outer diameter, it is necessary that the probe is placed into a homogeneous ground formation. In the case where it is mistakenly placed in a heterogeneous formation or in between two layers of significantly different soil types, two consequences can be expected: (1) the probe can be severely damaged or even burst, because it is not designed to resist to longitudinal stretches that can take place when it is inflated under differential stiffness/strength conditions, and (2), in the case it is not damaged, the obtained soil response curve will not correspond to a cylindrical cavity expansion. In this case, if an engineer is led to interpret the test even though, results may be misleading and not representative of ground properties. One should note that the "cylindrical cavity expansion theory", which is on the basis of the test interpretation, supposes that expansion occurs under plane strain condition (infinite cylinder).

Placing the probe into a homogeneous ground formation can be challenging in some geological contexts. Cour and Lopes [11] presented a simple method for evaluating the homogeneity of the test pocket before performing the test, based on the advancement rate of the drilling machine used to create the testing borehole. Despite this method has proven to be efficient in preventing probe burst, it is still susceptible to some operational errors, such as placing the probe mistakenly at the wrong depth.

One advantage brought by the implementation of the restraining sheath is that it enables using the textile sheath as a measuring device. A new type of measuring sensor has been recently developed and patented (Cour, 2019). Its working principle is based on measurements of the inductance of a hybrid elastic-conductor wire. The mechanical principle of the cable is similar to that used for the restraining sheath, which is composed of an association of elastomer and high strength yarns. For these particular sensors, the high strength yarns are replaced by a conductive one.

The hybrid elastic-conductor cable is installed through three or more turns around the probe. Several lines of sensors can be installed, as presented in Figure 7. A prototype probe equipped with four of those sensors is presented in Figure 8, in which one can see the two photos of the probe, fully deflated and inflated to 92 mm external diameter.

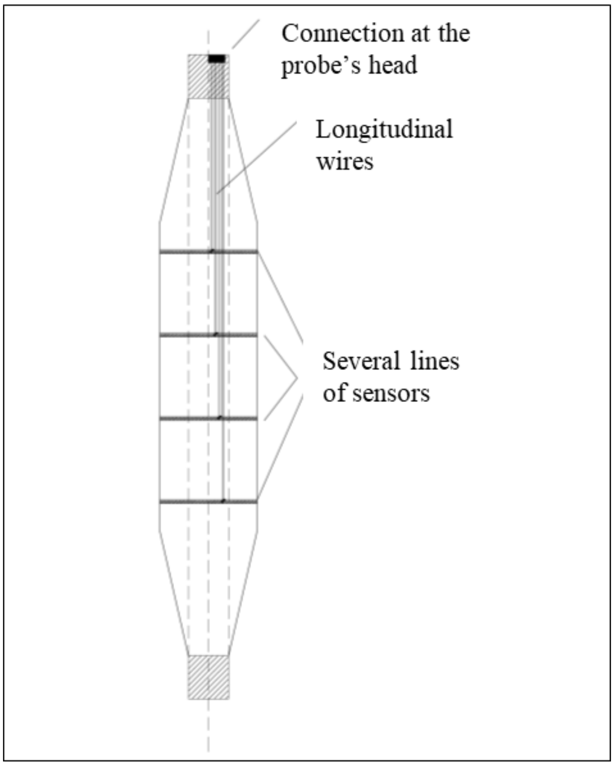


Figure 7. Schematics of the installation of the new type of sensors enabling assessing probe perimeter through inductance measurements

When solicited by an alternating current the cable will generate an electromagnetic field, and thus an inductance, which is related to the perimeter of the wire. By relating the measured values of inductance to the probe's perimeter it is possible to calculate its diameter. This principle has been used for medical/clinical applications in the past years for assessing patient's respiratory capacity, but the sensors employed for this application had two limitations: either they cannot expand to the required rates for pressuremeter application or they will present loss of linearity under high expansions. The use of the hybrid elastic-conductor wire enables overcoming this difficulty. The measured inductance is proportional to the cable's perimeter within all the probe expansion range. The sensors can be calibrated by performing simultaneous readings of probe perimeter and inductance, as it can be seen on Figure 9.

A probe prototype equipped with several lines of sensors is currently under development. The development is co-funded by the French Project ARSCOP. A first series of calibration tests were performed by inflating the probe in open-air, inside a high-density polyethylene tube of internal diameter 61 mm, and inside a soil analog (polyurethane tube filled with a soft foam of internal diameter 72 mm). Using the relationship obtained between probe perimeter and the measured inductance (Figure 9) yields satisfactory results for the probe contact against the calibration tubes, as presented in Figure 10.

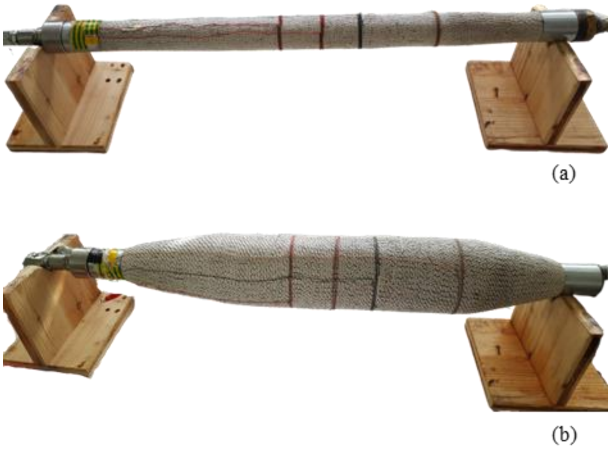


Figure 8. Probe prototype equipped with four inductance sensors. (a) deflated and (b) inflated

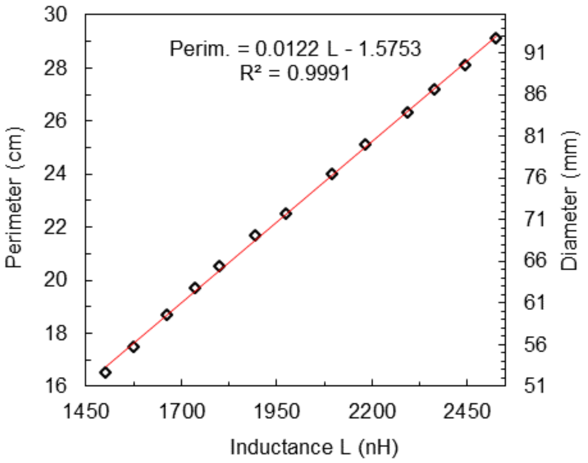


Figure 9. Readings of inductance for one sensor installed on the probe's center during its open-air inflation. A linear relation is obtained between the inductance and the perimeter.

The use of this new technology will also contribute to reducing the gap between pressuremeters and flexible dilatometers.

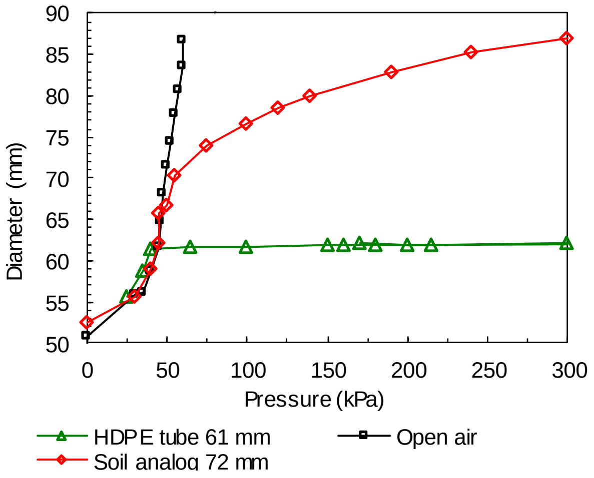


Figure 10. First calibration tests performed using a Monocell FC probe equipped with the innovative inductance sensors

7. Conclusions

The Monocell FC probe has significant advantages with regard to the simplification of the testing equipment (pressure-volume control system and tubing) and the possibility of applying various types of testing protocols and interpretation procedures, with a particular interest for performing cyclic tests. It makes it possible to cover the fields of application of different existing types of probes, such as dilatometers, Ménard-type pressuremeters, and mono-cellular pressuremeters. Its limit capacities in terms of diametric expansion and maximum pressure make this equipment suitable for a vast domain of application. It makes it possible to assess both the Ménard parameters, directly employed on geotechnical design in French practice, but also soil's intrinsic shear modulus, that can be used as an input for numerical simulations in soil mechanics.

The use of textile sheaths opens new perspectives regarding the local assessment of the cavity deformation. A new type of sensor recently developed on the basis of the measurement of the inductance of a hybrid elastic-conductor wire appears as a promising tool for increasing the accuracy of tests performed with this equipment. The use of this type of sensors enables at the same time ensuring that the cavity expansion deploys cylindrically (no differential deformations in the axial direction due to heterogeneities in the ground) and to obtain local measurements, simplifying the calibration procedures required for the current volumetric-measurement device, and increasing measurement resolution.

8. Acknowledgements

The authors acknowledge Fugro France for making the test results available and particularly Jean-François Barral and Michel Garnier for helping with the preparation and performance of the *in situ* tests.

9. References

[1] Jacquard C, Rispal M, Puech A, Geisler J, Durand F, Cour F, et al. Une nouvelle sonde permettant de mesurer sans extrapoler la pression limite pressiométrique des sols. Proc. 18th Int. Conf. Soil Mech. Geotech. Eng., Paris: 2013, p. 1–4.

[2] Cour F, Lopes A. Sonde monocellulaire innovante pour la réalisation d'essais d'expansion de cavité cylindrique (Innovative Monocell probe for performing cylindrical cavity expansion tests - in French). Journées Natl. Géotechnique Géologie l'Ingénieur, Champs-Sur-Marne: 2018.

[3] Cour F. Controllably-Deformable Inflatable Sleeve, production method thereof and use of same for pressuremetering applications. Manchon Gonflable à Déformation Controlée. Procédée de Fabrication et Application à la Pressiométrie. WO 2008/084162 A3, 2006.

[4] Cour F. Hybrid elastic cable and process for manufacturing such a cable. US patent US 2014/0373202, filled January 24, 2013, issued July 24, 2014, 2014.

[5] Cour F. Measurement device by pressurizing the subsoil and method for carrying out an associated pressurization test. US 2018/355715 A1, 2017.

[6] ASTM D 4719-07. Standard Test Methods for Prebored Pressuremeter Testing in Soils (Withdrawn 2016). ASTM International, West Conshohocken, PA, 2007, www.astm.org; 2007.

[7] AFNOR. Geotechnical investigation and testing — Field testing

— Part 4: Ménard pressuremeter test. French standard NF EN ISO 22476-4 2015:55 pages.

[8] AFNOR. Sols : Reconnaissance et Essais - Essai Pressiométrique Ménard. Partie 2: Essai Avec Cycle. French standard XP P 94-110-2 1999:8 pages.

[9] Lopes A, Dupla JC, Canou J, Droniuc N. Laboratory validation of an innovative mono-cell pressuremeter probe : test procedures and first results. 17th Eur. Conf. Soil Mech. Geotech. Eng., Reykjavik: 2019, p. 1–8. https://doi.org/10.32075/17ECSMGE-2019-0638.

[10] Lopes A, Puech A, Cour F, Dupla JC, Canou J. Assessment of shear stiffness at small strain rate using an innovative monocell pressuremeter probe. 6th Int. Conf. Geotech. Geophys. Site Charact., Budapest: 2020.

[11] Cour F, Lopes A. Paramètres de forage pour un positionnement judicieux de la sonde pressiometrique. (Using Borehole Drilling Parameters for Improving Probe Positioning and Results Interpretation - in French). Journées Natl. Géotechnique Géologie l'Ingénieur, Champs-Sur-Marne: 2018.

[12] Cour F. Détermination du diamètre d'une sonde pressiométrique. 19-09502. French patent demand deposited on August 19th 2019. Patent pending, 2019.