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A contribution to the improvement of ground investigation using the pressuremeter

Contribution à l'amélioration de la reconnaissance des sols avec le pressiomètre

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ABSTRACT: Pressuremeter test is the reference *in situ* test for underground investigation in French geotechnical engineering practice. Performed according to the current standards, it provides a deformation and a failure parameter of the soil, the so-called Ménard modulus and the limit pressure, respectively. These parameters can be used for the design of shallow and deep foundations under monotonic loads, relying on methods that are well established and included in the most renowned design standards, such as the Eurocode 7. However, for some geotechnical structures such as foundations under cyclic repeated loads, the design parameters to be considered correspond to a lower strain level, which cannot be assessed using the current standard pressuremeter procedures and equipment. In the context of a broader research project and aiming at developing a new methodology for the design of deep foundations under cyclic axial loadings using the pressuremeter test, this paper presents how the limitations of the current pressuremeter practice could be overcome. The innovative testing procedures and equipment proposed, as well as some of the results obtained are briefly presented and discussed.

RÉSUMÉ : L'essai pressiométrique est l'essai *in situ* de référence pour les investigations géotechniques dans la pratique française. Réalisé selon les normes en vigueur, il fournit un paramètre de déformation et de rupture du sol, respectivement le module Ménard et la pression limite. Ces paramètres peuvent être utilisés pour la conception de fondations superficielles et profondes sous chargements monotones statiques, en s'appuyant sur des méthodes bien établies et incluses dans les normes de conception les plus réputées, telles que l'Eurocode 7. Cependant, pour certaines structures telles que les fondations soumises à des charges cycliques répétées, les paramètres de conception à prendre en compte correspondent à un niveau de déformation plus faible, qui ne peut être évalué à l'aide des procédures et des équipements pressiométriques standard actuels. Dans le contexte d'un projet de recherche plus large et visant à développer une nouvelle méthodologie pour la conception de fondations profondes sous des charges axiales cycliques en utilisant l'essai pressiométrique, cet article présente comment les limitations de la pratique pressiométrique actuelle ont pu être surmontées. Les procédures et équipements d'essai innovants proposés, ainsi que certains des résultats obtenus sont présentés et discutés.

KEYWORDS: Pressuremeter test, shear modulus, small strains, ground characterization

1 INTRODUCTION

Design methods for foundations under monotonic loads are well established and included in the most renowned design standards, such as the Eurocode 7 CEN (2004), (2007). They are based either on *in situ* or on laboratory tests, for which the choice may vary country by country. In France, foundation design is mainly based on *in situ* tests, especially the Ménard pressuremeter test (Frank, 2017), for which the detailed calculation method is described in the national application standard (AFNOR, 2012, 2013a).

One of the main advantages frequently put forward regarding the use of the pressuremeter test for foundation design is that it gives both a deformation and failure parameter of the soil, the so-called Ménard pressuremeter modulus E_M and the pressuremeter limit pressure p_l , respectively. The testing standards (i.e. AFNOR, 2015) define the protocol for determining these parameters. The existing foundation calculation methods enable correlating the limit pressure of the soil to the ultimate limit capacity of the foundation, while the Ménard modulus can be correlated to soil-structure interaction parameters used to perform serviceability analyses. These correlations were established on a basis of full-scale load tests and are broadly accepted by practitioners. However, they cannot be extended to certain types of foundations, such as foundations under cyclic loading, for which the strain level involved is much lower. The design of piles under cyclic loading is currently widely developed through laboratory tests (Puech and Garnier, 2017) and there are no technical recommendations available regarding the use of pressuremeter tests on this subject.

The work presented in this paper was carried out in the context of the French National Project ARSCOP ("improvement

of the ground investigation and the design of geotechnical structures with the use of pressuremeter"), aiming at contributing to the development of a new methodology for the design of deep foundations under cyclic axial loadings using the pressuremeter. Focus was put on the determination of the shear modulus at small strain levels. This paper presents the roll-out of the research during three years of a Ph.D. thesis without getting into the details of the proposed procedures and methods. References are provided for the readers. The challenges faced at the beginning of the works due to limitations of the current practice are presented. It is shown how these limitations could be overcome by adopting an innovative testing equipment and modified testing procedures. These procedures were tested under controlled conditions in the laboratory and then validated under real operational conditions *in situ*. They enabled assessing the shear modulus of soil at small strain levels as well as its dependency on the stress state and on the strain level of the soil, confirming the potential of the pressuremeter test for this task. Results obtained are presented and discussed.

2 LIMITATIONS OF THE CURRENT PRACTICE

The general principle of the pressuremeter test is to insert a cylindrical probe equipped with an expandable flexible membrane into a borehole and to expand the probe according to a predefined loading program. The soil responds to the applied load, resulting in a cavity pressure versus cavity volumetric strain curve, also called cavity expansion curve. This curve can be interpreted either through an analytical or empirical background, enabling the determination of soil properties.

In Ménard type pressuremeter tests, the loading program is standardized and consists in applying approximately ten load steps aiming at reaching the limit pressure of the soil. The typical soil response is presented in Figure 1, from which one can distinguish three phases: phase (P1) a recompression part on the beginning of the expansion curve, phase (P2) a quasi-linear portion usually called “pseudo-elastic” part, and phase (P3) a plastic phase, characterized by volumetric changes over the constant-load steps (time dependent). The increase in volume variations over time that can be observed by analyzing the usually called “creep curve” (2) defines the so-called pressuremeter creep pressure, p_f . The Ménard pressuremeter modulus E_M is calculated from the slope of the “pseudo-elastic” phase (phase P2 in curve (1), limited by pressure and volume values p_1 , V_1 and p_2 , V_2). The conventional pressuremeter limit pressure p_l is calculated as the pressure corresponding to doubling the initial cavity volume. The testing procedure can also include one unload-reload loop, to be performed according to AFNOR (1999).

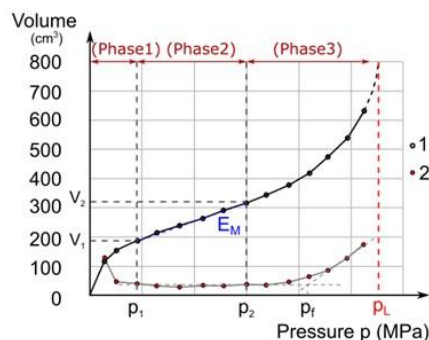


Figure 1. Typical cavity expansion curve obtained according to standard Ménard pressuremeter test

Ménard pressuremeter modulus is not an elementary modulus of elasticity of the soil and today it is generally accepted that Ménard modulus is actually closer to a modulus of the soil decayed to a shear strain level of approximately 10^{-2} . Figure 2 illustrates the domain of measurement of a standard pressuremeter test in a normalized shear modulus decay diagram. The green arrow shows the domain of measurement targeted by this research.

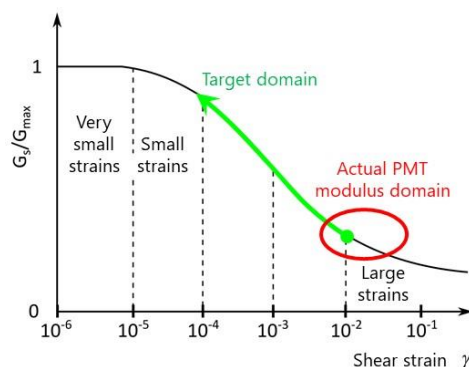


Figure 2. Actual measurement domain of PMT modulus and target domain for the research

While the very small strain domain is generally reserved to *in situ* geophysics tests (cross hole, down hole, seismic CPT, and others) or refined laboratory tests (resonant column, triaxial with local measuring, bender elements, and others), some recent works have confirmed the potential of the pressuremeter to assess the shear strain domain between 10^{-4} to 10^{-2} . Pressuremeter probes equipped with local punctual strain measurement devices, which enables a better measurement accuracy for the domain of

small strains, have been used. The presence of the local strain sensors, however, limits the maximum expansion capability of these probes, which makes them less appropriate to assess the limit pressure of the soil. For this reason, they are rarely used in French practice to perform Ménard type tests used for the design of foundations. The probes commonly used to perform Ménard type tests are tri-cellular, which provide a higher expansion capability, but a lower accuracy for the small strain domain.

The first challenge of this research consisted in evaluating the feasibility of the application of the standard testing equipment to the aimed application, which requires a probe that is able to assess, in a same test, soil properties associated to small strains and the limit pressure, associated to very high strains.

2.1 Equipment limitations

The most commonly used pressuremeter probes in French practice are of Ménard type, tri-cellular. In this type of probes, the volumetric strains at the cavity wall on the ground are determined by measuring the volume of water injected into the probe's central measuring cell. The central cell is surrounded by two “guard cells”, which are inflated with compressed air. The role of the guard cells is to provide a plane-strain stress-state around the measuring cell (avoid boundary effects) and also to ensure that the central cell inflates and deflates correctly (radial deformations only).

A series of qualification tests, aiming at confirming if this type of probe could be used to reach the goals of the research (measurement at small strains and cyclic tests) was performed as a first part of the research. Four types of tri-cellular probes, corresponding to those most frequently used amongst French practitioners, were tested (Ménard type AX 44 probes with slotted tube, BX 60, and FC 60, with and without slotted tube). The qualification tests (Lopes, 2020) consisted on several calibration tests to investigate the existing sources of uncertainty within the system's measurement chain: the pressure-volume controller, the tubing, the probe and its membrane, the fluid (water). Some points of vigilance arose from these tests, they are:

- The diameter and the length of the tubing. Small diameters (typically 3mm) and long lengths (greater than 50m) may lead to significant hydraulic head losses when the fluid flows through the line. This leads to a difference between the pressure at the CPV level and at the probe level, which is difficult to correct and that can be misleading for the operator.
- The shape of the central cell's membrane may be affected by variations in the differential pressure (difference between the pressure in the guard cells and in the central cell). If this happens, there will be an error in the relationship between the volume injected in the probe and the actual radial deformation at the cavity wall which cannot be corrected by calibrations.
- The qualification tests lead to the conclusion that tri-cellular probe design presents a major drawback for tests including unload-reload loops or several repeated cycles. It is complex to manually control two fluids (gas and water) simultaneously and ensure that the differential pressure at the probe level is constant during the test. Any errors generated by inadequate membrane behaviour are difficult to detect by the operator and can result in misleading test interpretation.
- Progressive dissolution of gas in the water (there is no separation between both circuits) leads to volumetric measurement errors.

Those limitations do not compromise measurements in standard Ménard type tests, for which the accuracy provided by these probes is sufficient. The huge success of the method and its great acceptance amongst practitioners are the best evidence for that. However, it was considered that these limitations would be problematic with regards to the research goals, especially regarding the small strain domain. The use of an alternative testing equipment was deemed necessary.

2.2 Procedure limitations

Ménard type procedures were developed in the late 50's in an engineering context where the description of the ground behaviour by the theory of linear elasticity was gaining acceptability. In that context, the determination of an "elasticity modulus" of the soil was considered good enough to characterise its stiffness. The pressuremeter test appeared as an original solution for assessing this parameter through *in situ* tests, which was one of the reasons of the test's success. Aligned with this engineering need at that time, the methods of interpretation of the pressuremeter test results were based on the theory of cylindrical cavity expansion in linear elastic perfectly plastic soil. That theory shows that the shear modulus of soil can be directly evaluated from the cavity expansion curve as the slope of the linear part of the curve. The strength parameters can be associated to the limit pressure. For this reason, during some time, Ménard modulus has been (mistakenly) associated to the elasticity modulus of the soil.

As research advanced, it was observed that the Ménard modulus is much lower than soil modulus assessed using dynamic methods (wave propagation methods), which Ménard called "micro-strain" modulus. At the 60's and the 70's the notion that the elasticity modulus of soil is related to the level of stress and strain commences to be developed.

Several are the reasons for which Ménard modulus does not correspond to the elasticity modulus of soil. This modulus is associated to the first expansion of the cavity, which means that it comprises a superposition of elastic and plastic behaviour of the soil. Yet, it is measured at a relatively high strain level associated to the testing protocol. Ménard modulus is also influenced by the probe insertion method and highly sensitive to disturbance.

The original pressuremeter test loading procedures have been developed aiming at the identification of the two main parameters: Ménard modulus and limit pressure. Originally, there were no unload-reload loops on the test. A pressuremeter procedure including one reloading loop was further developed, enabling the determination of a reload modulus E_R , generally higher than E_M .

Literature review confirms that moduli obtained using unload-reload loops in pressuremeter tests are closer to the elasticity modulus of soil and less susceptible to be affected by ground disturbance (i.e. Lunne *et al* (1989)). However, care has to be taken during the unloading stage to avoid soil failure by extension (Wroth, 1982).

With regards to the interpretation procedures, a bibliographical research showed that there exists a theoretical background that supports the test interpretation using non-linear elasticity (Briaud *et al* (1983), Wood (1990), Bolton and Whittle (1999), Jardine (1992)). These procedures, however, have been frequently reserved for tests performed using probes equipped with local punctual strain measurement.

Given these difficulties associated to the testing procedures and interpretation, it was proposed to apply modified loading procedures using an innovative probe and implementing the existing interpretation procedures for non-linear elasticity.

3 INNOVATIVE EQUIPMENT AND PROCEDURES

3.1 The choice of an innovative probe

Given the difficulties identified with the most common pressuremeter probes, the choice was made to test an innovative probe, the Monocell Francis Cour® probe, presented in Figure 3. As the standard probes, this one is volumetric measurement based: the deformations of the ground are evaluated by measuring the volume of water injected inside the probe's measuring cell. The main differences that made this probe

potentially better are: it is monocellular (it is operated using only water, without need for pressurized gas) and it implements an enhanced membrane technology (Cour, 2006, 2014), which enables longer durability and a better accuracy in the relationship between the volume of water injected and the actual external diameter of the probe. This probe was developed by a partner of the research project but had not been previously tested and validated. Preliminary *in situ* tests (Cour and Lopes, 2018) confirmed its potential for the targeted application, but a complete validation programme was required. This was done in the laboratory using devices developed exclusively with the purpose of calibrating and verifying that the probe works correctly, and further by its application for tests in soil, in the calibration chamber. Those devices are presented in the next section.

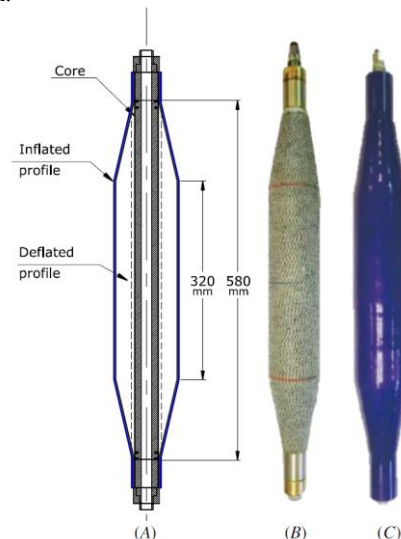


Figure 3. (a) Monocell FC probe scheme, (b) photo of the probe fully inflated showing the restraining sheath, and (c) photo of the probe fully inflated with the protective polyurethane external sheath.

3.2 Probe validation: calibration tests

The Monocell FC probe is a single cell probe for which a specific calibration procedure, comprising at least 4 calibration cylinders of variable diameter is necessary (Cour and Lopes (2018), Lopes *et al* (2020)). This calibration procedure enables determining the relationship between the volume injected into the probe and its external diameter. This calibration procedure is more complete than the standard procedures, where only one calibration cylinder is used. As it is not standardised, it was necessary to validate if the procedure was working correctly.

Two specific devices were developed to test the probe and the validity of the proposed calibration procedures under controlled limit conditions: the Instrumented Thick Cylinder (ITC) and the Hydrostatic Calibration Chamber (HCC), presented in Figure 4a and b, respectively. Further details are presented in Lopes (2020).

ITC consists on a thick polyurethane cylinder instrumented with 4 strain gages, 2 internals and 2 externals. The probe was placed inside the ITC and pressurised. The goal was to compare the measurements done with the probe with those done with the strain gages. If the probe is calibrated according to the procedure described in Lopes *et al* (2020), tests performed in ITC resulted successful.

HCC consists on a steel cylinder filled with water and closed at both extremities. The probe placed inside of the HCC and the chamber pressurised. The goal was to compare the pressure measured with the probe and the pressure of the water inside the chamber. Tests performed in the HCC confirmed that the standard pressure loss calibration procedure could be successfully applied to the proposed probe.

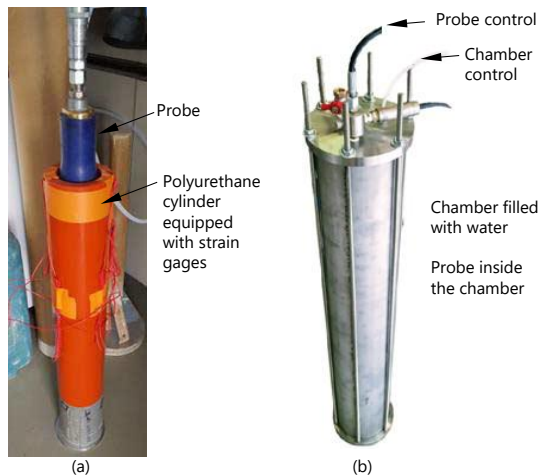


Figure 4. Specific calibration devices developed in the context of this research. (a) Instrumented Thick Cylinder. (b) Hydrostatic Calibration chamber.

3.3 Physical modelling: tests in calibration chamber

In order to validate the probe capabilities for tests in sands, a physical model in calibration chamber was proposed. The calibration chamber enables simulating conditions that are analogous to a real test on the ground, but with the advantage of keeping controlled conditions in the laboratory (fully controlled stress state, known soil). Fontainebleau sand, which is a reference silica sand frequently used in benchmark laboratory tests in France and for which the geotechnical properties are well known, was chosen.

Tests in calibration chamber required a first stage of testing, to understand which configuration best represents the *in situ* conditions. Several tests were carried out to define how to consolidate the soil specimen, how to simulate the geometry of a borehole in the ground and how to define the most adequate loading procedure. Some interesting insights were brought by these preliminary tests, such as regarding the requirement of a pressure-hold step before proceeding to unloading, which avoids superposition of time dependent phenomena and the elastic response during unloading. Figure 5 shows the difference between a loop performed immediately after loading, and the same loop performed after a 20 minutes hold period was performed. It can be observed that if there is no pressure-hold step, the initial slope of the loop is negative and it cannot be used to derive an elasticity modulus of the soil. Instead, after the hold period, the initial slope is much less affected by time-dependent phenomena: in this case the slope of the curve can be related to the shear modulus of the soil at the moment the loop was performed.

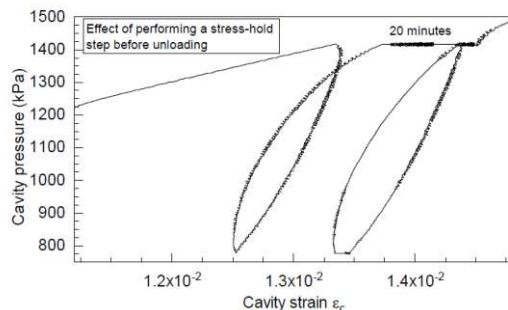


Figure 5. Two unload-reload loops performed at same stress level, one immediately after loading, and the second after 20 minutes pressure-hold

After the adequate loading procedure has been identified, a parametric study was carried out in sand specimens of variable density index. The same initial stress state was chosen for all

specimens, in order to enable evaluating the influence of the parameter density on the results. One repeatability test was performed to confirm if the test procedure is repeatable. Figure 6 presents the result of the repeatability test, performed in two different specimens of Fontainebleau sand of density index of 0.70, at an initial horizontal stress of 300 kPa. This same figure presents a detail of one of the unload-reload loops, where it can be observed that the soil response is non-linear. From each one of these loops, it was possible to derive one value of maximum shear modulus of the soil, associated to the stress state imposed to the specimen at the time the loop is performed, and a shear modulus decay curve.

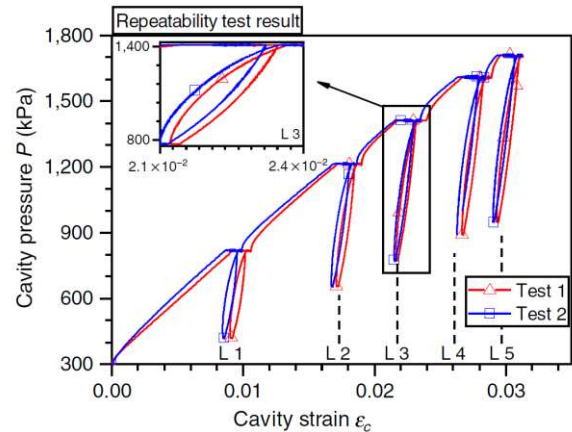


Figure 6. Comparison between repeatability tests performed in two different sand specimens at identical initial conditions in calibration chamber

The tests performed in the laboratory were interpreted using two different methods proposed in the literature (Briaud *et al*, 1983, Byrne *et al*, 1991). Both methods resulted in similar results. Figure 7 illustrates the principle of the derivation of moduli from an unload loop: the initial slope corresponds to the maximum shear modulus associated to the stress level around the cavity at the beginning of the unload. As the cavity is unloaded and it deforms, shear modulus decays, and it is possible to determine several values of secant shear modulus as a function of the cavity strain $G(\varepsilon_c)$ for all measurement points within the unload loop.

Then, the transformed strain approach can be used to evaluate the elementary shear modulus decay of the sand. This enables transforming the strains measured at the cavity wall in equivalent elementary strains. The methods proposed by Bellotti *et al* (1989) and Jardine (1992) were applied. The results were finally compared to those given by empirical expressions determined for the Fontainebleau sand based on laboratory tests, leading to satisfying results.

4 PUTTING IN PRACTICE: *IN SITU* VALIDATION

To confirm the quoted capabilities of the probe and of the proposed procedures, *in situ* tests under real operational conditions were performed. Two reference testing sites were chosen, one mainly composed by dense sands (Dunkirk) and the other mainly by overconsolidated clays. Both sites had been previously characterised by complete ground characterisation campaigns, comprising standard pressuremeter tests, CPT, geophysics and laboratory tests.

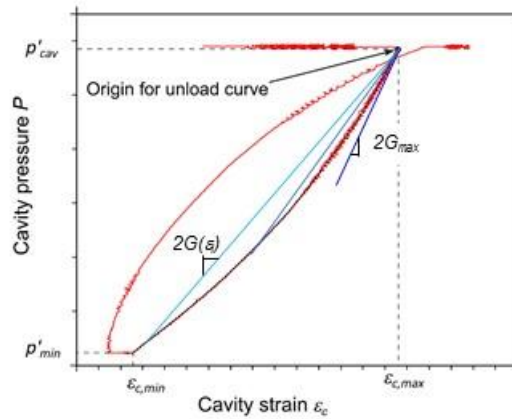


Figure 7. Derivation of moduli from a pressuremeter loop

The main challenge for the tests performed *in situ*, in comparison to those performed in the laboratory, is that they require heavy equipment to drill the hole and to place the probe in the ground and adequate shelter to protect the control unit from the weather. The goal of the *in situ* validation tests is to ensure that these additional difficulties do not compromise the capabilities of the proposed procedures.

The process of drilling was done by experienced operators according to the current standards. The whole probe calibrations and the test were carried out by the author. Figure 8a shows the FC probe on site, and Figure 8b shows the probe attached to the drill rig, ready to be placed into the borehole.



Figure 8. Preparation for *in situ* tests. (a) Probe assembled for the tests at Dunkirk site; (b) probe in the drill rig being positioned for the test

Several tests were performed on each site. Figure 9a presents one example of the proposed loading programme applied for one of the tests performed at the Dunkirk testing site at 11m depth. Figure 9b presents the cavity expansion curve obtained for this test. In this figure one can see that it is possible to derive an equivalent Ménard modulus from the quasi-linear portion of the curve and also measure the limit pressure of the soil. The test comprises three unload-reload loops that were interpreted according to the quoted procedures.

The results obtained *in situ* were consistent with the observations made in the laboratory calibration chamber. It was observed that moduli determined from unload loops performed at greater cavity pressure levels were higher than moduli determined at lower cavity pressures. It was also observed that within each unload loop, moduli decays as a function of the strain at the cavity wall. These results enabled confirming that it is

possible to assess both the stress and the strain dependency of shear modulus of sands using the proposed pressuremeter probe and procedures.

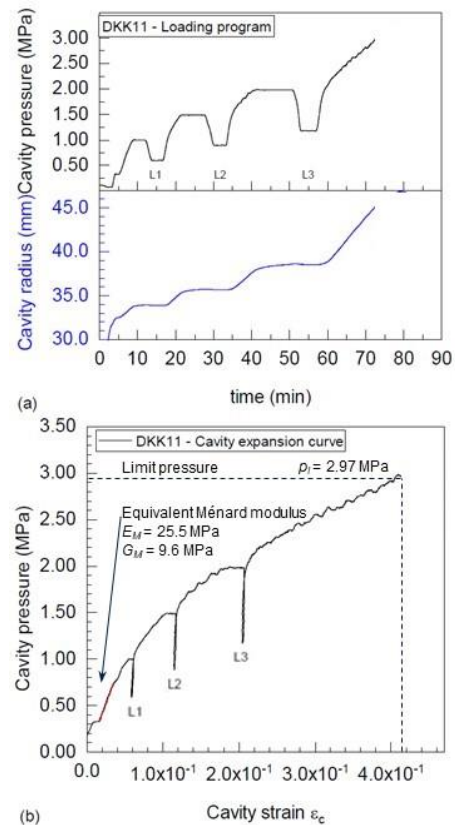


Figure 9. (a) Loading programme and (b) cavity expansion curve obtained at 11m depth at the Dunkirk testing site (dense sands)

Moduli determined from each unload-reload loop using the proposed procedures were compared to moduli evaluated using reference empirical expressions for Dunkirk sand, determined using other types of tests and available in the literature (Oztoprak and Bolton, 2013, Zdravković *et al.*, 2018). Results are presented in Figure 10. It can be seen that the shear moduli decay curves evaluated using the pressuremeter procedures are close to those determined using the reference elementary expressions for this sand. In this same figure the Ménard modulus evaluated from the expansion curve obtained according to the procedure proposed is compared to the range of Ménard modulus obtained on a near site (same sand, similar conditions). It can be seen that the values are close, pointing out that the proposed procedure is complementary to the standard Ménard procedures. Same is valid for the limit pressure.

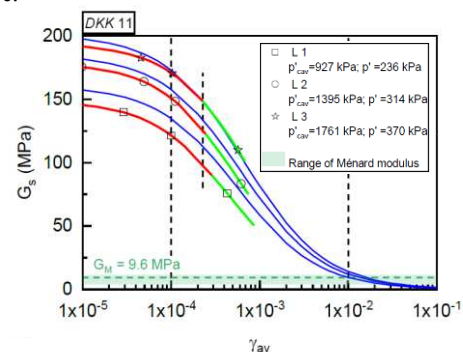


Figure 10. Comparison between the shear modulus decay curves for each unload loop determined using the pressuremeter procedure and the elementary shear modulus decay curve of the Dunkirk sand evaluated using reference empirical expressions based on laboratory tests

5 CONCLUSIONS

The work presented in this paper was carried out in the context of a broader research project aiming at developing new foundation design methods using the pressuremeter test. The particular requirement for assessing the shear modulus of soils in the small strain domain was identified as one recent and recurrent need of engineers.

In the early stages of the research it has been found that there were no available testing equipment able to assess, in a same test, soil properties in the small strain (moduli) and in the very large strain (strength) domains. Literature review showed that testing and interpretation procedures existed, but none of them was standardised nor had been tested using probes similar to those available for this research.

The choice was made to use an innovative pressuremeter probe that presents enhanced membrane characteristics that could potentially respond to the research goals. This probe has undergone a series of calibration and validation tests that enabled confirming its capabilities, initially under controlled conditions and further in real operation conditions (*in situ* tests). The validation procedure adopted in this work is simple and robust and it is encouraged that it be used as a framework for the validation of other pressuremeter equipment that might be developed in the future. A summary procedure is as follows:

- Establish a suitable calibration procedure for the quoted probe (in the present case, it comprised calibration tests using 4 different diameter cylinders, open air calibration and membrane compliance calibration);
- Test the probe under controlled boundary conditions (in the present case, ITC and HCC were developed and used as a reference for validating the calibration procedure);
- Test the probe in soil under well controlled conditions in calibration chamber (known state of stress, known soil properties);
- Validate the probe capabilities under real operation conditions in a reference testing site where the ground conditions have been characterised using other methods;

The loading protocol and the interpretation procedures adopted in this work were inspired from methods proposed in the literature, including some adaptations. For example, some aspects of the loading protocol were further investigated and addressed, such as the requirement of a pressure-hold step before unloading. The same is valid for the interpretation procedure, which results from a combination of other existing approaches (assumption of a hyperbolic response in combination with the strain transformed approach). The main contribution of this work in this respect is that it unifies both in French and Anglo-Saxon practices, based on semi-empirical correlations and on the determination of elementary soil parameters, respectively, which have been historically dissociated. The procedures proposed herein are complementary to the traditional Ménard type tests and enable a smooth transition towards and enhanced practice.

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