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Interpretation of pressuremeter tests in clays with non-linear elastic behaviour

Interprétation des essais pressiométriques dans les argiles tenant compte du comportement élastique non-linéaire

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ABSTRACT: Pressuremeter tests are an efficient tool to derive shear modulus of soils and its decay with shear strain. Non-linear behaviour of soils during cavity expansion, and its consequence on stress and shear modulus with the distance to the pressuremeter cavity have to be taken into account. This paper presents several methods based both on the monotonic loading and on subsequent unload-reload loops to derive shear modulus decay as a function of the shear strain for tests performed in saturated clays, where constant volume can be assumed, by means of several but distinct interpretation methods: i) retrofitting based on closed form solutions integrating the non-linear elastic behaviour, ii) comparisons to numerical modelling by finite difference analysis and iii) approaches integrating prior strains transformations. The different results are compared to each other and to other investigation tests providing the initial shear modulus G_0 associated with very small shear strain levels, in order to validate the different interpretation methods.

RÉSUMÉ: Les essais pressiométriques sont un outil efficace pour déterminer le module de cisaillement des sols et sa décroissance en fonction de la déformation de cisaillement (ou distorsion). Le comportement non linéaire des sols pendant l'expansion de la cavité, et ses conséquences sur la contrainte et le module de cisaillement en fonction de la distance à la cavité du pressiomètre, doivent être pris en compte. Pour les essais réalisés dans des argiles, pour lesquelles on peut supposer un volume constant pendant le test, cet article présente plusieurs méthodes pour déterminer la décroissance du module de cisaillement en fonction de la déformation de cisaillement, basées à la fois sur l'essai de chargement monotone et sur les boucles de déchargement-rechargement ultérieures, au moyen de plusieurs méthodes d'interprétation distinctes: i) adaptation basée sur des solutions analytiques intégrant le comportement élastique non linéaire, ii) comparaisons avec la modélisation numérique par analyse en différences finies et iii) approches intégrant les transformations de déformations préalables. Les différents résultats sont comparés les uns aux autres ainsi qu'à d'autres types d'essais fournissant le module de cisaillement initial G_0 associé à de très faibles niveaux de déformation de cisaillement, afin de valider les différentes méthodes d'interprétation.

Keywords: Pressuremeter tests; shear modulus; non-linear elasticity; clay.

1 INTRODUCTION

Pressuremeter tests (PMT) are cylindrical cavity expansion tests that can be performed either on a pre-bored cavity, in a cavity created by pushing the probe into the ground, or in a self-bored cavity. Several testing procedures exist, enabling the determination of both deformation and strength parameters of the ground. In France, the most known procedure is the Ménard one, which yields the Ménard pressuremeter modulus (E_M) and the pressuremeter creep and limit pressures (p_f, p_{lM}). In French practice, those parameters are used in semi-empirical and direct correlations, to determine the bearing capacity and stiffness of foundations and retaining walls. Since the beginning of the development of the pressuremeter, Ménard and other contemporary authors focussed on the semi-empirical approach due to its ease of use (Ménard and Rousseau, 1962): these approaches are still successful used in French practice (Frank, 2017), but is less frequently implemented in foreign practices.

Other approaches exist, based on an analytical background that confirms that it is possible to determine intrinsic ground properties from the pressuremeter. This theoretical background is remarkably strong and straightforward to use in saturated fine soils, where undrained conditions prevail and where one can assume that there are no volume variations during the test. In these cases, additional parameters can be determined: undrained shear strength, maximum shear modulus, or shear modulus decay. Whatever the aim is, it can be noted that the initial expansion curve is sensitive to disturbances due to probe insertion, that led to prefer the use of unload-reload loops.

2 PRESENTATION OF THE INTERPRETATION METHODS

Several interpretation methods exist enabling the determination of ground moduli based on the measured cavity expansion curve. Historically, linear elasticity has been frequently used, supposing that ground response is linear, and that elasticity Young's modulus E (or shear modulus G) can be determined from the slope of the pressuremeter curve:

$$G = \frac{1}{2}\frac{dP}{d\epsilon_c} = \frac{E}{2(1+\nu)} \tag{1}$$

where dP is the variation in cavity pressure and $d\epsilon_c$ is the variation in cavity strain within a range of values assumed to be linear. Cavity strain is the ratio between the variation of cavity radius and the initial or current cavity radius, depending if analyses are in small strains or large strains, $\epsilon_c = \Delta r/r$.

Elasticity modulus determined in that manner, does not capture true ground behaviour that is not actually linear. If moduli determined in that manner are intended to be used for geotechnical modelling, correlations of many different types are required to adjust it for the appropriate level of shear strain associated with the soil-structure interaction problem being modelled.

In a pressuremeter test, the response measured at the cavity wall corresponds to an integration of the elementary ground behaviour around the cavity and is dependent on the non-homogeneous stress and strain variations with the distance to the cavity. If the hypothesis of linear elasticity could be verified, pressuremeter moduli would indeed correspond to ground moduli. However, this is not the case, because non-linear behaviour makes that the response at the cavity wall apparent to be stiffer than the elementary response and only "apparent" moduli may be derived from pressuremeter tests if no appropriate and further analysis is carried out.

Methods recognising and integrating the non-linear response of ground have been proposed by Briaud *et al.* (1983), Wood (1990), Jardine (1992), Ferreira et Robertson (1992), Bolton and Whittle (1999).

Briaud *et al.* (1983) observed that the ground response to a pressuremeter unload-reload loop can be considered to be hyperbolic, and that the inverse of the secant "apparent" modulus can be described by a linear relationship of the form:

$$\frac{1}{G_{s,app}} = a_0 + a_1\epsilon_c \tag{2}$$

where ϵ_c is the cavity strain and a_0 and a_1 can be determined from linear regression from the pressuremeter loop data.

From this assumption, the authors point to the possibility to derive the initial modulus of the ground from a pressuremeter unload-reload loop. Secant moduli calculated in that manner are, however, apparent, and do not integrate the ground behaviour around and with the distance to the cavity.

Wood (1990) presents the theoretical background linking secant "apparent" pressuremeter modulus with the elementary modulus (secant, or tangent) of the ground at different shear strain levels.

Based on a comparison of "apparent" pressuremeter modulus and modulus determined from laboratory tests for several types of soils, Jardine (1992) proposes the so-called strain transformation approach. It consists in a direct method enabling to transform the strains associated to an "apparent" pressuremeter modulus to the strains associated to the same modulus, obtained using elementary laboratory testing.

Ferreira and Robertson (1992) assume that the elementary behaviour of the ground is hyperbolic and that the modulus decay with shear strain can be described by a Hardin-Drnevich type function. The authors integrate this behaviour to the cavity expansion problem and obtain an analytical solution that enables to determine the maximum ground modulus from the pressuremeter curve. They state that it is preferable to use the method within an unload path, to avoid potential disturbance due to probe insertion.

Bolton and Whittle (1999) assume the elementary ground behaviour is associated with a secant shear modulus (G_s) decay following a power law function of the shear strain (γ), yielding an expression for the shear modulus that is parametrized by coefficients α and β that can be determined from pressuremeter unload-reload loops:

$$G_s = \alpha\gamma^{\beta-1} \tag{3}$$

According to the authors, this expression can be used to derive shear modulus decay from a strain range between 10^{-4} and 10^{-2}. As the method does not enable an assessment of G_0, it will not be further explored in this paper.

Habert and Burlon (2021) proposed an interpretation method for undrained cavity expansion that considers that ground behaviour is hyperbolic according to a Hardin-Drnevich function (4), following Ferreira and Robertson (1992). The following relationship is proposed:

$$\frac{G_s}{G_0} = \frac{1}{1+\frac{s_u}{G_0}\gamma} \tag{4}$$

$$p_c = p_0 + s_u \, ln\left(1 + \gamma_c \frac{G_0}{s_u}\right) \tag{5}$$

where p_c is the pressure at the cavity wall, p_0 is the initial horizontal pressure, s_u is the ground undrained cohesion, G_0 is the initial shear modulus of the ground, and γ_c is the shear strain at the cavity wall.

The authors propose the following interpretation procedure to determine G_0 from a pressuremeter curve: use the cavity expansion curve to derive the undrained cohesion using the slope of $dp_c/dln(\Delta V_c/V_c)$ ratio for the last points of the virgin expansion curve, where V_c is the cavity volume. The authors argue that s_u is marginally sensible to variations in p_0 and thus, the method used for the determination of p_0 lead to minor impact on the value of S_u. The Ménard limit pressure can be assessed using conventional methods.

3 EXAMPLES OF APPLICATION

3.1 Tests without unload-reload loops

Ménard pressuremeter tests performed according to standard ISO 22476-4 (AFNOR, 2015), monotonic, can be interpreted taking the non-linear response of the ground into account using Eq. 5, provided ground response is undrained.

Figure 1 presents an example of interpretation of a pressuremeter test performed in the north of France in overconsolidated Flander's clays. The pressure and volume measurements are used. Values of radial strain at the cavity wall γ_c are calculated from the volumetric measurements as $\gamma_c = \Delta V_c/V_c$, where V_c is the current volume measured at the cavity wall and ΔV_c is the volume variation corresponding to the initial cavity volume, $\Delta V_c = V_c - V_c(p = p_0)$.

The interpretation procedure consists on:

(1) estimate the initial horizontal pressure at rest (p_0),

(2) calculate values of shear strain at the cavity wall,

(3) extrapolate the curve to determine the limit pressure and the undrained cohesion,

(4) use Eq. (5) to evaluate *G₀*.

(5) Hardin Drnevich relationship can be used to estimate the shear modulus decay curve.

The interpretation procedure presented above and illustrated in Figure 1 was applied to Ménard type tests in Flander's clays and further compared to the results of cross hole tests performed on the same site. Results and discussion are presented in paragraph 4.

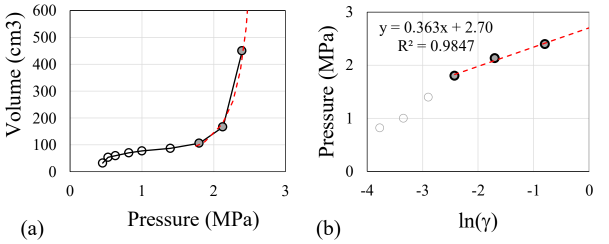

Figure 1. Example of interpretation of pressuremeter test to determine the initial shear modulus G_0 (undrained conditions). Overconsolidated Flander's clay at 37.5m depth.

Three cross hole profiles available on site enable a comparison between *G₀* from the PMT. Figure 2 shows an example for the test at 37.5m and compares the initial shear modulus to the ones obtained from 3 cross hole tests between 35 to 39 m depth. From this figure, it is also possible to see that the method enables an evaluation of the reference shear strain, $\gamma_{0.5} = s_u/G_0$, for which $G_s = G_0/2$.

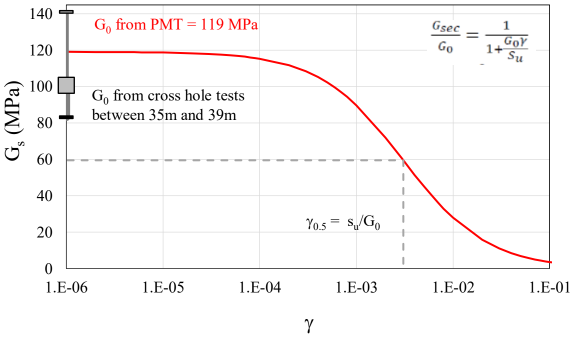

Figure 2. Shear stiffness decay curve derived from pressuremeter test showing the value of G0 compared to Cross Hole tests nearby.

3.2 Tests with unload-reload loops

Pressuremeter tests including unload-reload loops enable to enhance the reliability on the evaluation of the deformation modulus of the ground. Unload-reload loops are less susceptible to disturbance due to probe insertion; Furthermore, in undrained conditions, loops initiated at different cavity pressure levels should lead to similar results, which provides redundancy and easiness to verify and validate the test results. Yet, the interpretation procedure for monotonic tests can still be applied to these tests, providing another way to check its robustness.

Figure 3 presents an example of pressuremeter test performed at 4.8m depth in the Whitby Mudstone in the UK. The test includes two unload-reload loops performed during the loading. An additional loop is performed while unloading the cavity and is not the scope of this paper. Initial horizontal stress at rest was evaluated using lift off method and p_0 = 76 kPa. Figure 4 presents a detail of the loop 1, showing the interpreted curves obtained using Eq. (2) fitted.

The interpretation procedure for Eq. (2) is:

(1) Define the origin of the unload loop
(2) Calculate secant shear modulus $G_{s,app}$ for all points measured in the unload loop
(3) Plot $1/G_{s,app} = f(\gamma_c)$, and determine a_0 and a_1 by linear regression
(4) G_0 is calculated as $1/a_0$
(5) Use strain transformation approach to determine shear modulus decay $G_s = f(\gamma)$

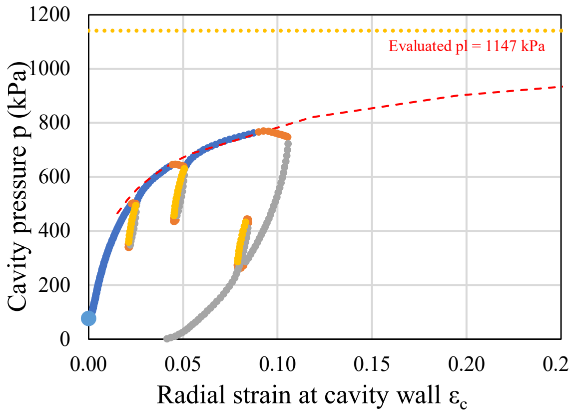

Figure 3. Pressuremeter test with unload-reload loops performed in the Whitby Mudstone at 4.8m depth.

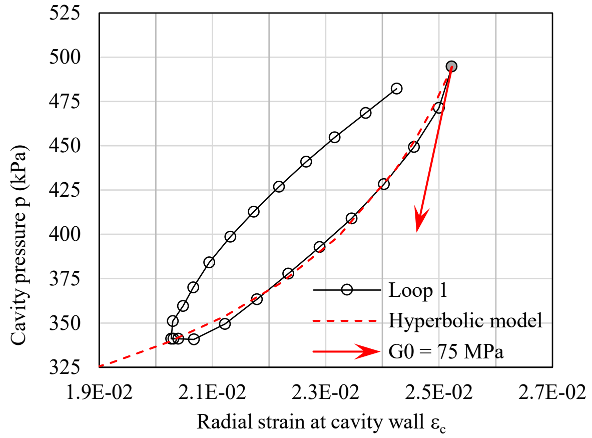

Figure 4. Detail of loop 1 showing the interpreted curves from Eq. (2) fitted.

3.3 Comparison of the methods

Figure 5 presents a comparison of the quoted interpretation methods: Eq. (2) applied to loop 1, and Eq. (5) applied to the plastic phase, both applied to the test shown on Figure 3. The following main differences can be underlined between the proposed interpretation methods:

- Both methods are based on a hyperbolic ground behaviour and enable the determination of the maximum shear modulus of the ground. The results obtained for G_0 should, in principle, be the same, which is not the case in this example. As will be explained in paragraph 4, this is due to the limited expansion of the probe, leading to an important amount of extrapolation (the evaluated limit pressure is about 40% higher than the maximum pressure measured during the test, which makes the method less reliable.
- This highlights the advantage of performing both analyses on a same test, providing redundancy and facilitating the verification of test results. As it can be seen here, the value obtained with the unload loop is close to what has been measure on site using seismic CPT.
- Regarding the shear modulus decay rate, there are two possibilities when hyperbolic ground behaviour is considered: (1) if strain transformation methods are adopted, the shear modulus decay rate will be a function of a_0 and a_1 and of the transformation function applied. There is some amount of empiricism on the determination of the transformation functions. (2) if Eq (5) is considered, the shear modulus decay rate is constrained and will be a function of the undrained cohesion, as per Hardin-Drnevich function.

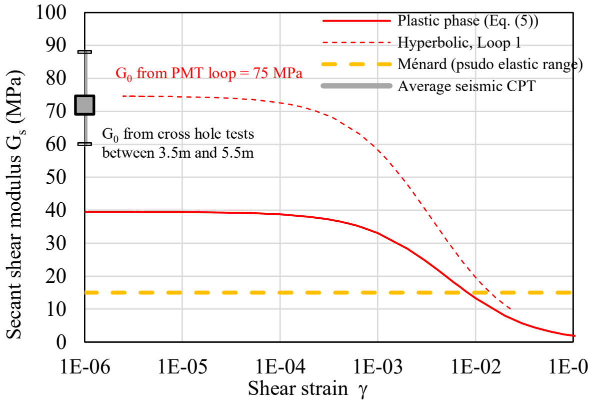

Figure 5. Comparison of the interpretation methods applied to the loop 1 and the plastic phase.

4 COMPARISON WITH OTHER MEASUREMENTS

Ménard pressuremeter tests were conducted as part of a quay project near Dunkirk, in the north of France. Other investigation campaigns, including cross-hole geophysical tests, were carried out on the same site and nearby. The encountered stratigraphy consists of an approximately 25m thick layer of sands, followed by the overconsolidated Flanders clay. This clay exhibits a plasticity index ranging from 40% to 70%.

The interpretation of the pressuremeter tests in this paper was limited to tests conducted in the clays, whose behaviour is assumed to be undrained. Tests with expansion curves considered to be disturbed (poor probe-soil contact, incomplete expansion) were excluded. The obtained values of G_0 from the studied tests (as per Eq. (5) as the tests are associated to monotonic loading) were compared to the shear modulus results determined by cross hole tests. The results are presented in Figure 6.

The G_0 values evaluated from the pressuremeter tests interpreted according to the proposed method are close to those measured by cross-hole tests. In the figure, two groups of results have been distinguished: for the pressuremeter tests where the limit pressure was obtained by extrapolation up to 15% of the measured maximum pressure value (Group 1), and the tests for which the extrapolation is less than 10% of the measured maximum pressure (Group 2). It is observed that, for this second group, the results are closer to the geophysical measurements.

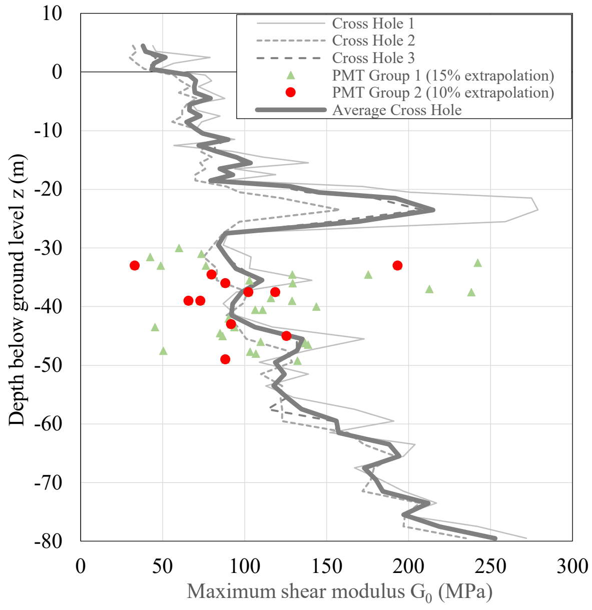

Figure 6. Comparison of the maximum shear modulus obtained through interpretation of the pressuremeter tests and measurements from cross hole tests in the Flanders clays.

The average ratio between the maximum shear modulus evaluated with the pressuremeter and the one measured from cross hole tests was calculated. For Group 1, this ratio is of ±25%. For Group 2, this ratio is of ±16%. This magnitude of error is considered to be sufficient for many types of projects. And this result points out to the interest of pushing the pressuremeter tests expansion level far enough to get the closest as possible to the conventional limit pressure, reducing the extrapolation levels and thus reducing errors.

Ten pressuremeter tests were carried out from 4.8m to 28m depth in the Whitby Mudstone, the UK. Tests at 4.8m and 10m depth were carried out using self-bored pressuremeter, with loops, and interpreted using both Eq. (2) and (5). Seismic CPT tests were performed from ground surface to approximately 10m depth, providing an estimate of the maximum shear modulus G_0. Plasticity index of the ground varies from an average of 33% to 28% as depth increases. The maximum shear modulus determined from the unload loops is compared to the values assessed from seismic CPT (Figure 7).

Three seismic tests performed on the formation lead to an average maximum shear modulus of 81 MPa and 56 MPa, respectively, at 4.8 and 10.0m depth.

Maximum shear modulus evaluated through unload loops using Eq. (2) is of 68 MPa and 49 MPa for these same depths, so an error of the magnitude of 15%.

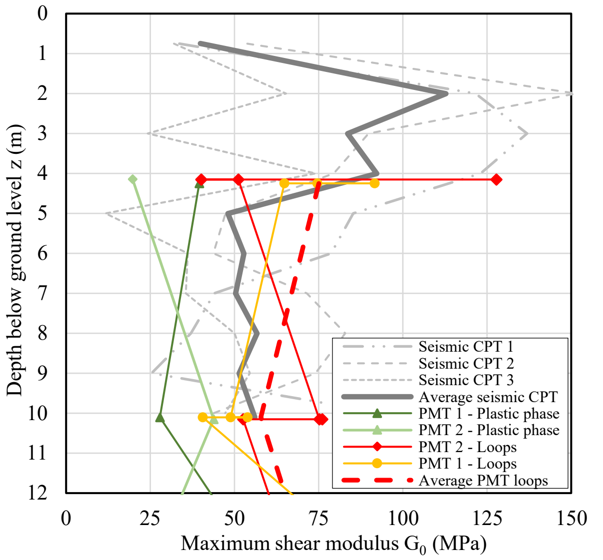

Figure 7. Comparison of the maximum shear modulus obtained through interpretation of the pressuremeter tests and seismic CPT tests in Whitby Mudstone.

Values of maximum shear modulus obtained using Eq. (5) for the plastic phase are of 40 MPa and 28 MPa, so 50% error in comparison to seismic CPT. As stated previously, this error can be explained by the excess of extrapolation required to evaluate the limit pressure: for the self-bored pressuremeter tests concerned, the cavity expansion has been limited to the magnitude of 10% radial strain. 42% radial strain is required to effectively measure the limit pressure. For these tests, the extrapolation ratio between the limit pressure extrapolated and the maximum pressure measured during the test is of approximately 40%.

While the unload loops yield a good estimate of the maximum shear modulus, an immediate recommendation that can be drawn from these results is to push the pressuremeter tests farther in expansion, to reduce the extrapolation ratio and enhance reliability.

5 SUMMARY AND CONCLUSION

Pressuremeter tests can be interpreted in considering the background of non-linear elasticity theory. In the case of undrained ground behaviour, the determination of the maximum shear modulus of the ground and the shear stiffness decay curve is straightforward.

Interpretation methods can be applied either in monotonic tests, such as tests performed using Ménard type procedures, or in tests including unload-reload loops, yielding two proposed methods. For high quality pressuremeter tests, both methods will lead to an evaluation of G_0 with an average error of the magnitude of 15%.

While both methods should be equivalent, methods based on unload reload loops enable to add redundancy and enhance reliability for the test interpretation. Loops are less susceptible to being disturbed due to probe insertion and its interpretation is less dependent on the assumption of the initial horizontal stress at rest.

Pressuremeter tests including several unload-reload loops and for which the cavity expansion is carried out sufficiently far (less than 10% extrapolation ratio) provide a reliable estimation of G_0. As different interpretation methods can be applied, all leading, in theory, to the same result, makes the test results to be easily verifiable and robust.

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