A practical method to derive shear modulus from pressuremeter tests in clay

Julien Habert[1], *Alexandre* Lopes[1]

[1]*Setec/Terrasol, Paris, France*
[#]*Corresponding author: julien.habert@setec.com*

ABSTRACT

Pressuremeter tests are an efficient tool to derive shear modulus of ground, and its decay with shear strain. Non-linear behaviour of ground during cavity expansion, and its consequence on shear modulus and stress with the distance to the pressuremeter cavity, have to be taken into account. For tests in fine soils, for which constant volume can be assumed during the test, retrofitting of unload-reload loops based on closed form solutions integrating the non-linear elastic behaviour can be implemented.
In a first phase, this paper presents a practical straightforward method to derive shear modulus decay with shear strain based on the cylindric cavity expansion theory including non-linear elasticity under undrained conditions and hyperbolic ground behaviour. In a second phase, the method is applied step by step to a pressuremeter test in clay with unload-reload loops. Finally, on a third and last phase, this paper compares the previous results from to i) other interpretation methods integrating prior strains transformations, but also to ii) other investigation tests providing the initial shear modulus G_0 associated with very small strain levels or the shear modulus decay with strain level.

Keywords: Shear modulus, small strain, shear modulus decay, pressuremeter, cavity expansion, unload-reload loops

1. Introduction

Pressuremeter tests 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 focused on the semi-empirical approach due to its ease of use (Ménard and Rousseau, 1962): these approaches are still successfully used in French practice (Frank, 2017), but are 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 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. Proposals

2.1. Theoretical developments

Several interpretation methods are available to determination of ground moduli based on the measured cylindric cavity expansion curve. Historically, linear elasticity has been frequently used, supposing that ground response is linear, that enables to determine shear modulus *G*) from the slope of the pseudo-linear part of the pressuremeter curve (corresponding to the relationship between the cavity volume *V* and the applied pressure *p* at the cavity walls), following Eq. (1).

$$G = V\frac{dp}{dV} \tag{1}$$

The previous Eq. (1) can also be written in terms of radial deformation $\varepsilon = \Delta R/R$, R being the cavity radius) or distortion (or shear strain) at the cavity walls γ ($=\Delta V/V$), following Eq. (2)

$$G = \frac{dp}{2d\varepsilon} = \frac{dp}{d\gamma} \tag{2}$$

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 different types are required to adjust it for the specific strain level corresponding to the soil-structure interaction problem that is 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 as non-linear behaviour leads to a response at the cavity walls stiffer than the elementary response: “apparent” moduli may only be derived from pressuremeter tests if non-linear elasticity is not considered during the interpretation process.

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

2.2. Proposals developed in this paper

The proposal developed in this paper is based on the method integrating cavity expansion proposed by Habert and Burlon (2021). It is applied under the following conditions:

- Shear modulus decay follows he formulation by Hardin and Drnevich (1972), that is now currently used in geotechnical engineering.
- The method is implemented on unload phases of unload-reload loops, to discard any detrimental effects linked to the use of the first loading (monotonic) of the test, disturbed by the probe placement and associated with significative strains, exacerbating perturbations linked to metrology and creep (or similar effects) during the test.

2.2.1. Shear modulus decay

It is assumed that the secant shear modulus decay G_{sec} is set-up by Eq. (3), that also corresponds to shear stress provided by Eq. (4), where the undrained shear strength s_u is strongly associated with the decay rate. These laws are plotted on Fig. 1.

$$\frac{G_{sec}}{G_0} = \frac{1}{1+\frac{G_0\gamma}{s_u}} \tag{3}$$

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

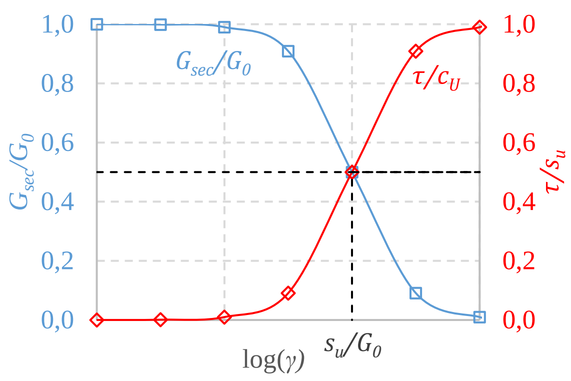

Figure 1. Assumed hyperbolic ground behaviour

2.2.2. Application to the cylindrical cavity expansion problem

On this basis, with the small strains hypothesis and undrained behaviour, translated by volume conservation, cavity expansion is determined by Eq. (5).

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

Where p_0 is horizontal at rest pressure and γ is the distortion counted from this reference state.

Assumption of small strains introduces a small bias, that is limited but non negligible for the first loading (Ferreira and Robertson, 1994).

The previous Eq. (5) can be adapted for the unload part of the cavity expansion problem, leading to Eq. (6) (Ferreira and Robertson, 1992).

$$p = p_{0,i} + (\tau_{0,i}+s_u) ln\left(\frac{1}{1-\frac{G_0}{\tau_{0,i}+s_u}(\gamma-\gamma_{0,i})}\right) \tag{6}$$

where $p_{0,i}$, $\tau_{0,i}$ et $\gamma_{0,i}$ are respectively i) pressure, ii) shear stress and iii) distortion at the cavity walls at the beginning of the unload stage *i* (to consider tests with several loops *i* = 1 to *n*).

Shear stress $\tau_{0,i}$ is linked with *p*, G_0 and s_u following Eq. (4). For unload stage, it can be noted that assuming small strains keeps a negligible effect: this statement enforces the choice to work with unload-reload loops instead of the first loading.

3. Application

3.1. Practical implementation

The interpretation method proposed on this paper, through the fitting of Eq. (6) can be easily implemented, through the three following steps:

- Step 1: The unload part is analysed separately for each unload-reload loop *i*: the origin of each loop ($p_{0,i}$, $\gamma_{0,i}$) is first identified;
- Step 2: From this point, values $\Delta\gamma$ et $\Delta\gamma/\Delta p$ for each point of the unload stage for the loop *i*. It can be shown that the initial tangent of the curve is set up by two coefficients *a* et *b*, such as $\Delta\gamma/\Delta p = a\Delta\gamma + b$. *b* corresponds to $1/G_0$, allowing to determine G_0;
- Step 3: Iteration on undrained shear strength s_u is performed to fit by Eq. (6) and the experimental measurements. For each iteration, $\tau_{0,i}$ is incremented with Eq. (5).

3.2. Step by step example

An application example processed step by step is provided below. A pressuremeter test performed in Ypresian overconsolidated Flanders’ clays in Merville (France), performed at a 12.0 m depth; with results that have already been presented by Lopes (2020) and Lopes et al (2022) using empirical method requiring a strain transformation procedure to take into account the non-linear behaviour of the soil. The complete expansion curve is presented in Fig. 2. A focus on the third unload-reload loop is provided on Fig. 3 (using radial strain ε at the cavity wall and equal to $\gamma/2$).

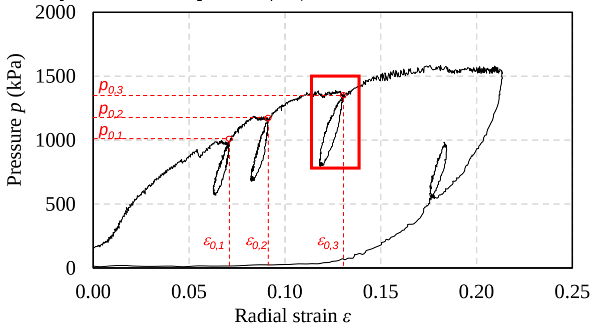

Figure 2. Pressuremeter test in Flanders clay at 12 m depth

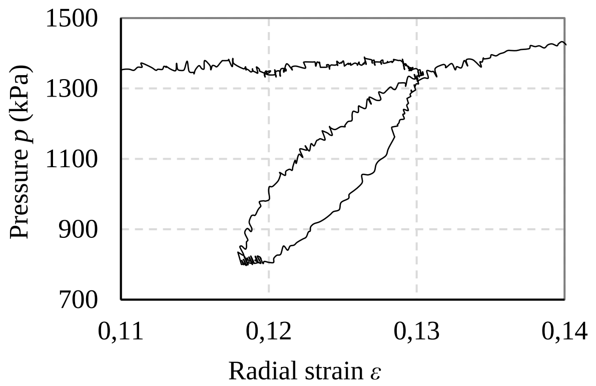

Figure 3. Third unload-reload loop Pressuremeter test in Flanders clay at 12 m depth

The different processing steps are the following:

- Step 1: Initial values for loop 3 are $p_{0,3}$ = 1350 kPa and $\gamma_{0,3}$ = 0.26;
- Step 2: curve $\Delta\gamma - \Delta\gamma/\Delta p$ is provided on Fig. 4. The initial tangent can be obtained by linear regression on the first part of the curve (with $\Delta\gamma/\Delta p = a\Delta\gamma + b$), yields b = 0.0186, corresponding to $G_0 = 1/b$ = 53.9 MPa;
- Step 3: different values of undrained shear strength s_u are computed to fit the $\Delta\gamma - \Delta p$ curve on Fig. 5.

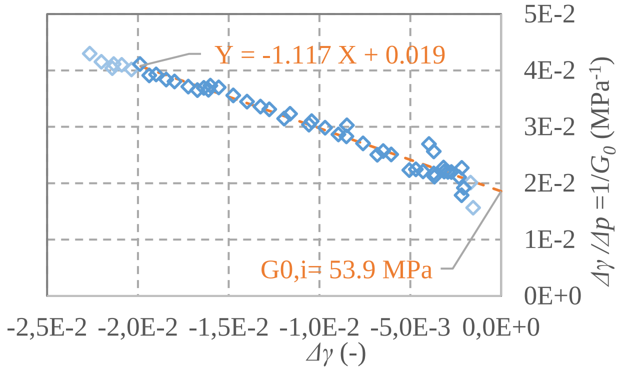

Figure 4. Determination of initial shear modulus G_0

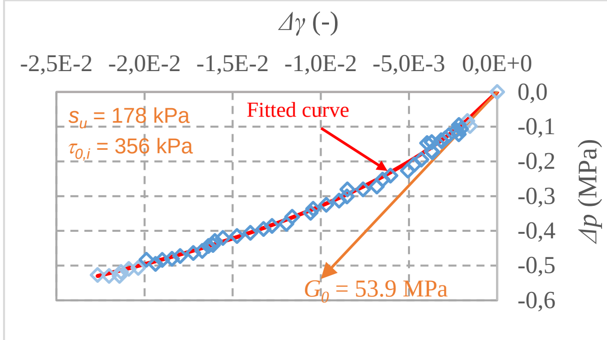

Figure 5. Determination of undrained shear strength s_u by retrofitting

With the hereby determined values G_0 and s_u previously determined, it is possible to plot the shear strain modulus decay using Eq. (3).

This curve is shown in Fig. 6, with the effective measurement range, between 3.10^{-4} à 1.10^{-2}, and the distortion reference value γ_{ref} equal to s_u/G_0 and for which $G_{sec} = 0.5\ G_0$.

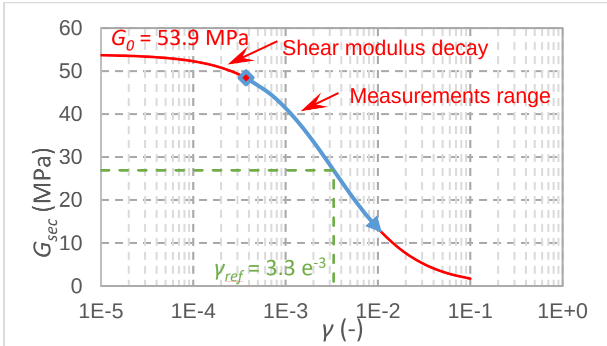

Figure 6. Shear modulus decay derived from loop 3

4. Comparison

4.1. Initial shear modulus G_0

Shear modulus associated with very small strains for Flander's clay has been obtained historically by geophysical tests, such as cross-hole and down-hole measurement of shear strain velocity.

At 12 m depth, initial shear moduli G_0 are estimated between 50 and 70 MPa. These values are compared with the initial moduli derived from the three loops of the pressuremeter test presented above, between 53 and 59 MPa, in Fig. 7.

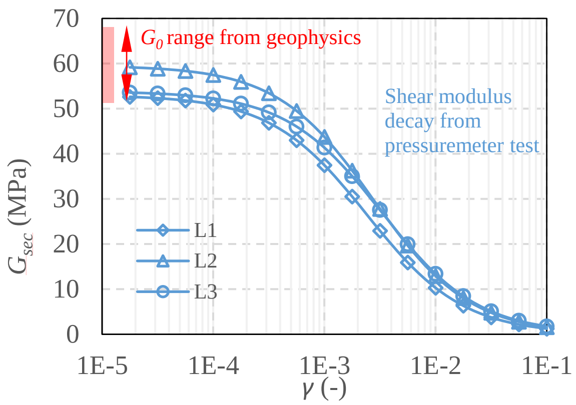

Figure 7. Shear modulus decay derived from each loop

4.2. Shear modulus decay

Normalized curve G_{sec}/G_0 can also be compared to proposals of Vucetic and Dobry (1991) based on the Plasticity Index *PI*, that lies between 40 and 50 for Flander's clay. The comparison is plotted in Fig. 8 for each loop.

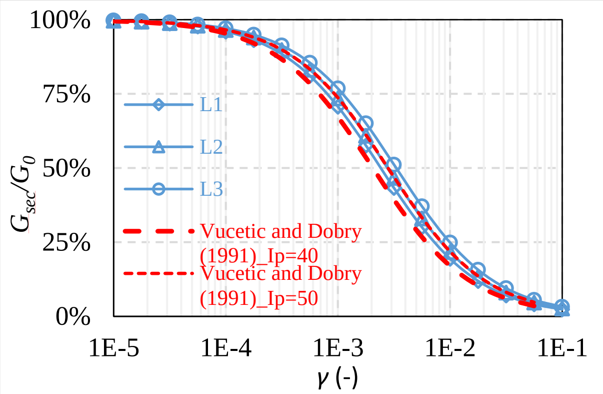

Figure 8. Shear modulus decay derived from each loop compared to Vucetic and Dobry (1991) curves for *IP* = 40 and *IP* = 50

It can be noted that both approaches yield close results. Especially, γ_{ref} values derived from the pressuremeter tests lies between 2.0 and 3.3 10^{-3}, whereas reference values lie between 2.0 and 2.8 10^{-3}.

These values can then be easily implemented in geotechnical modelling softwares requiring advanced constitutive laws, that often refer $\gamma_{0.7}$ corresponding to $G_{sec} = 0.72\ G_0$, and that can be obtained from Eq. (7).

$$\gamma_{0.7} = 0.385\gamma_{ref} = 0.385\frac{s_u}{G_0} \tag{7}$$

Using Eq. (7) leads to $\gamma_{0.7}$ similar to those determined by Lopes & *al.* (2022), empirical strain transformation method, calibrated on finite element analyses including non-linear elasticity. The present paper provides a theoretical and analytical approach, that enables to obtain similar results without the empirical assumption or simplifications underlying the previous works.

5. Conclusions

An analytical method is proposed to determine initial shear modulus and its decay with distortion based on a pressuremeter tests with unload phases, in undrained conditions. Its practical implementation has been developed step by step in the present paper on a pressuremeter test performed in Flander's clay. Comparisons to other methods demonstrate its efficiency. The proposed method enables to consolidate a theoretical and analytical approach to interpret pressuremeter tests in undrained conditions.

References

Bolton, M.D., Whittle, R.W., 1999. A non-linear elastic/perfectly plastic analysis for plane strain undrained expansion tests. Géotechnique 49, 133–141. https://doi.org/10.1680/geot.1999.49.1.133

Borel, S., and Reiffsteck, P. 2006. Caractérisation de la déformabilité des sols au moyen d'essais en place. Laboratoire Central des Ponts et Chaussées.

Ferreira, R., Robertson, P., 1992. Interpretation of undrained self-boring pressuremeter test results incorporating unloading. Canadian Geotechnical Journal 29, 918–928. https://doi.org/10.1139/t92-103

Ferreira, R., Robertson, P.K., 1994. Large-strain undrained pressuremeter interpretation based on loading and unloading data. Canadian Geotechnical Journal 31, 71–78. https://doi.org/10.1139/t94-008

Habert, J., Burlon, S., 2021. Taking into account inhomogeneous distortion around the pressuremeter probe to determine shear modulus, ISC'6, Budapest

Habert, J., Lopes, A., 2022. Elasticité non linéaire appliquée a l'essai pressiométrique, in: JNGGXI. Presented at the JNGGXI, Lyon.

Hardin, B., Drnevich, V., 1972. Shear Modulus and Damping in Soils: Design Equations and Curves. J. Soil Mech. Found. Div. 98, 667-692. https://doi.org/10.1061/JSFEAQ.0001760

Hughes, J., Whittle, R., 2022. High Resolution Pressuremeters and Geotechnical Engineering: The measurement of small things, 1st ed. CRC Press, London. https://doi.org/10.1201/9781003200680

Jardine, R.J., 1992. Nonlinear stiffness parameters from undrained pressuremeter tests. Can. Geotech. J. 29, 436–447. https://doi.org/10.1139/t92-048

Lopes, A., 2020. Determination of soil shear modulus at low strain level using an innovative pressuremeter probe. Application to cyclic pile design. Paris-Est.

Lopes A., Puech A., Dupla JC., Canou J. 2022. Determination of non-linear elasticity parameters from innovative pressuremeter tests. Strain transformed approach for hyperbolic undrained behaviour. 20th International Conference on Soil Mechanics and Geotechnical Engineering, Sydney. 2022.

Vucetic, M., and Dobry, R. 1991. Effect of soil plasticity on cyclic response. Journal of Geotechnical Engineering, 117(1): 89–107.