What are the benefits of a better interpretation of the pressuremeter test?

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ABSTRACT

This paper deals with the contribution of the realistic evaluation of the pressuremeter probe inflation mechanism and its technical and economic consequences for the project manager. This new approach allows to, within the framework of the Caderousse PCH studies, to significantly optimize the sheet pile modulus used by reassessing the soil characteristics in a more detailed way..

Keywords: pressuremeter; interpretation; gravel, sustaining well.

1. Introduction

The pressuremeter test has now acquired a worldwide reputation that no longer needs to be demonstrated. The principle of the test consists in considering a purely cylindrical expansion mechanism of a probe of negligible thickness inflated within a previously executed borehole. The performance of this test is governed by the (AFNOR 2015) standard (EN NF ISO 22476-4), which specifies the procedures for carrying out and interpreting the pressuremeter test. However, the interpretation of this test can still be improved, in light of the differences in behaviour observed between the theoretical and real expansion mechanisms of the pressuremeter probe (Monnet et al. 2022).

These discrepancies lead to an overestimation of the pressuremeter characteristics of the soil, especially when using a thick diaphragm probe or a split tube. This statement leads to question ourselves as project managers about the impact of these discrepancies on the design of our structures

In a tense economic context where the search to limit the human footprint on the environment is becoming essential, it is our responsibility to assess the real physical behaviour of the soil as accurately as possible, while of course maintaining the safety coefficients inherent in the uncertainties of the design of a structure, in order to assess the financial and environmental cost of our projects as accurately as possible.

2. State of the art

In the field of civil engineering, the design of structures is often carried out on the basis of pressuremeter tests:

- A first method of use is to make correlations between the quantities measured with the pressuremeter gauge and the quantities necessary for the design (Baguelin et al. 1978), (Mair and Wood 1987), (Clarke and Gambin 1998). These methods use the geotechnical characteristics of the soil related to the pressuremeter test, which are the Ménard limit pressure p_{LM} and the Ménard E_M pressuremeter module. This is why the pressuremeter gauge is widely used for the design of structures such as deep foundations with standard rules (AFNOR 2012) or the design and settlement of superficial foundations (AFNOR 2013). It is now known that these quantities are not intrinsic characteristics of the soil and cannot be introduced as data in a geotechnical calculation by Finite Elements or Finite Differences for the study of Civil Engineering works (retaining walls, tunnels, embankments, embankments, excavations, etc.). These modern calculation methods require, at a minimum, knowledge of the mechanical characteristics of the soil, in elasticity (with the Young's modulus E and the Poisson's ratio ν) and in resistance (with cohesion c and friction Φ).

- a second way of research is using the pressuremeter gauge to find the intrinsic characteristics of the soil, either from pressuremeter gauge measurements, to determine the angle of friction (Hughes et al. 1994), (Fahey and Carter 1992) (Silvestri 2001) or the undrained cohesion (Silvestri and Abou-Samra 2012) (Wroth and Windle 1977). These first promising approaches remain at the research level, but do not cross the technological barrier to move on to the sizing of real structures. Our approach is in line with this research, by proposing new corrections and interpretations in order to dispense with correlations, in order to find directly from the measurement, the geotechnical characteristics of the soil. This allows finding directly friction angle (Monnet 2012a) (Monnet 2012b) and Young modulus (Monnet et al. 2022) from pressuremeter test

3. The main areas for improvement in the interpretation of the pressuremeter test

The potential improvements relate to 3 essential points, which are not part of the current pressuremeter standard (AFNOR 2015) and which complements it:

- Taking into account the variable thickness of the membranes and eventually the slotted tube (Monnet et al. 2022); the pressuremeter test according to the standard (AFNOR 2015) does not take into account the thickness of the probe membranes. But the actual pressure applied to the soil is significantly different from the pressure exerted by the hydraulic device inside of the probe (Fig. 1)

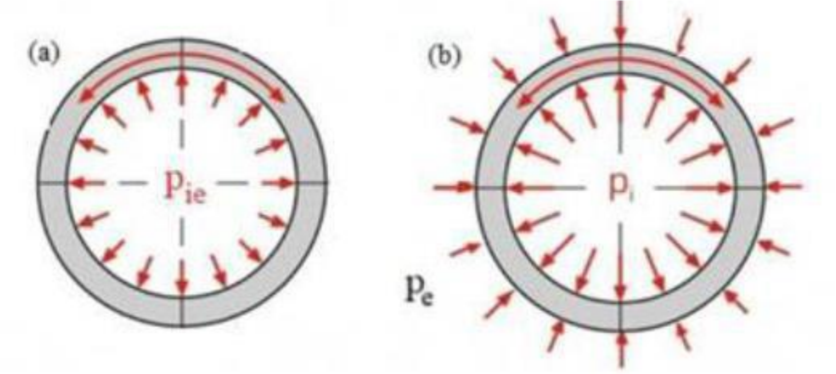

Figure 1: Difference between the pressure outside the pi probe and the pressure actually applied to the ground pe (Monnet et al.2022)

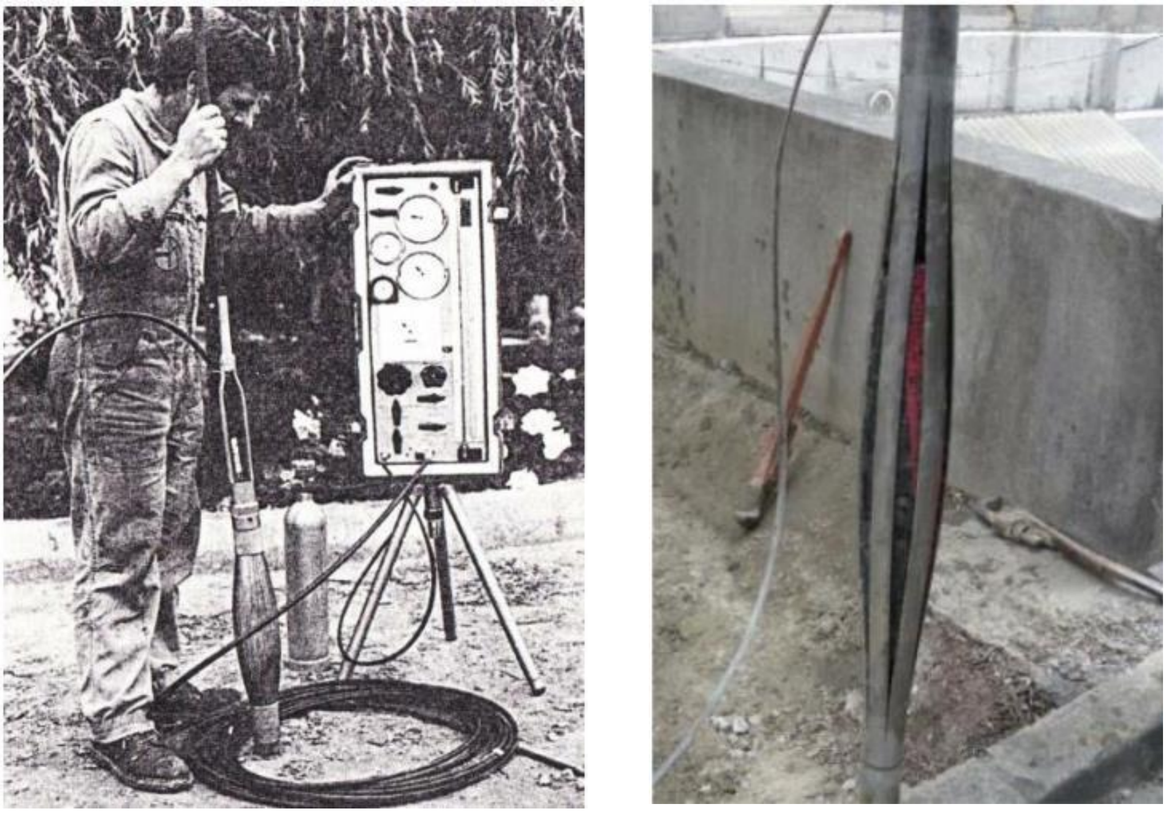

Figure 2:: Deformation of the bare probe (a) and lantern probe (b) in own resistance (Monnet et al. 2022)

- Taking into account the actual deformation of the probe (Monnet et al. 2022) whereas according to the standard (AFNOR 2015), the probe is considered to be cylinder deforming, i.e. for standard the deformation is identical at any longitudinal point on the ground, the deformation at the ends of the probe being identical to the central deformation. This hypothesis is not confirm by experience, and we can observe a deformation in the shape of a rugby ball for the bare probe (Fig. 2, left), in the shape of a console for the lantern probe (Fig. 2, rigth). It is therefore appropriate to take into account the distribution of internal pressures brought by the water-inflated measuring cell and by the air-inflated guard cells, as well as the elastic reaction of the soil to the deformation of the membrane (Fig. 3). This correction was validated by a finite element calculation (Monnet et al. 2022).

- Determination of the accuracy related to pressuremeter measurements and quantities it for pressure, elastic modulus and limit pressure (Monnet 2021),

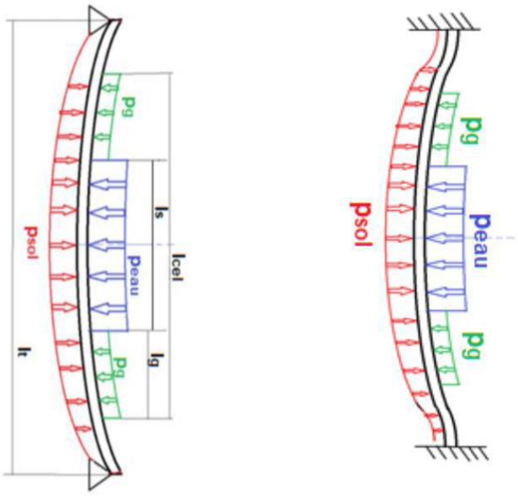

Figure 3: Principle of membrane correction for the bare probe G (a) and lantern probe (b) (Monnet et al. 2022)

4. Application to the Tèche retaining structure

4.1. Situation

The project (Fig. 4) is situated on the motorway A49 between Grenoble and Valence. This area has a slope of 30°, or even locally 40°, with a regular topography. The 10m to 20m upper excavated wall is stabilized by anchors and nails. The lower embankment wall, 6m to 15m, is made of reinforced earth. The 6m intermediate wall between the two levels of carriageways is also made of reinforced earth. A railway line runs up the slope and it is essential to have no displacements at that level; 900 anchors, 1100 nails and 14000m2 of reinforced earth surface were used in these retaining works for a total cost of 13.6 M€. It is precisely describe in (Monnet and Allagnat 2001)..

4.2. Geological context

The geology of the site is relatively simple; the molassic bedrock (Liocene), sub-outcropping in the gully zones, is covered by heterogeneous fluvio-glacial deposits of very variable thickness belonging to the "terrace of Saint Marcel les Valences". Downstream of the project, on the north side, an alluvial terrace floods the foot of the slope and borders the Isère river.

4.3. Usual approach

A traditional approach would have used a friction angle determined by inverse analysis on parts of the massif. In this type of approach, it is assumed that the slope is by default in limit equilibrium, which allows a friction angle of 33° to be recovered assuming zero cohesion. This value is then a lower bound for friction, but is not a realistic estimate of the state of the soil, which was overconsolidated under the weigth of 1000m of ice during the quaternary glaciation.

4.4. New pressuremeter approach

The proposed interpretation leads to the use of an internal friction angle corresponding to the average of the values found on the pressuremeter tests (44.2°) minus a standard deviation (6.1°) i.e. 38°. This methodology was adopted by default, despite the small number of tests, considering the evolution of friction as a function of depth as a curve for which the safest average value is to be determined. As a result, 86% of the angles are superior to the chosen value. The value of 35° takes into account the presence of more clayey or less compact layers, in the form of lenses, for which it is not possible to determine, a priori, a precise geometric extension..

4.5. Consequences for the design

Taking into account 35° instead of 33° by inverse stability leads to an economy of 10% of the cost of the retaining structure, and preserve security

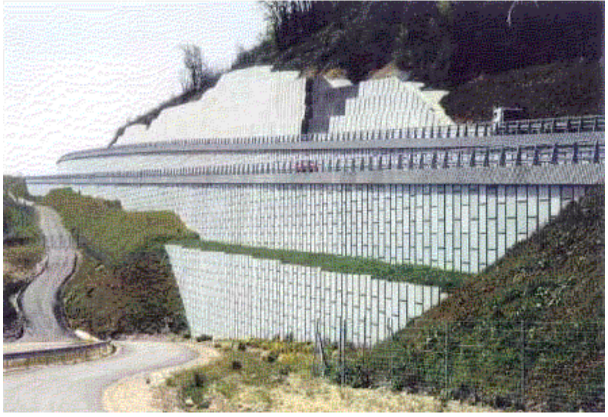

Figure 4: Tèche retaining structure ((Monnet and Allagnat 2001))

5. Application to a Small Hydraulic Power Unit (SHPU)

5.1. Pressuremeter tests performed

The Compagnie Nationale du Rhône (CNR) ordered a campaign of pressuremeter soundings to measure the compactness of the alluvial formations of the Rhône, dense sandy gravels. These gravels, located under a layer of silt 2 – 3 m thick, were covered during the development of the Rhône history (close to Caderousse) by several meters of backfill from the earthworks of the hydraulic channel leading to the main hydraulic unit. These alluvial deposits are underlined by the Pliocene marl bedrock, which is present to a large extent in the region. Seven pressuremeter boreholes were carried out, with tests every meter at a depth of 2 meters, up to 20 or 30 m depending on the borehole. A total of 54 pressuremeter tests were carried out, using a slotted tube due to the nature of the soil. The representative pressuremeter characteristics of a soil layer are only the estimated average of a variable that has significant dispersion and spatial variability, these values should be estimated with the best possible reliability.

-Two cyclic pressuremeter tests (Fig. 4; Fig. 5) were also carried out in the coarse alluvium of the Rhône, with the average ratio E/E_M ratio of 5.54 (Table 1).

On (Fig. 5 and 6) the experimental curve is corrected from the thickness of the membrane and from the deformed shape of the probe along the proposed method (Monnet et al., 2022); the theoretical curve is calculated from the proposed theory (Monnet, 2012).

Table 1: Cyclic pressuremeter tests carried out in the Rhone gravels

Test	Elastic modulus Ee (kPa)	Pressuremeter Modulus E_M (kPa)	E_e / E_M
SP3Bis_18	254047	32997	7.69
SP7Bis_16	130027	35295	3.4
Mean			5.54

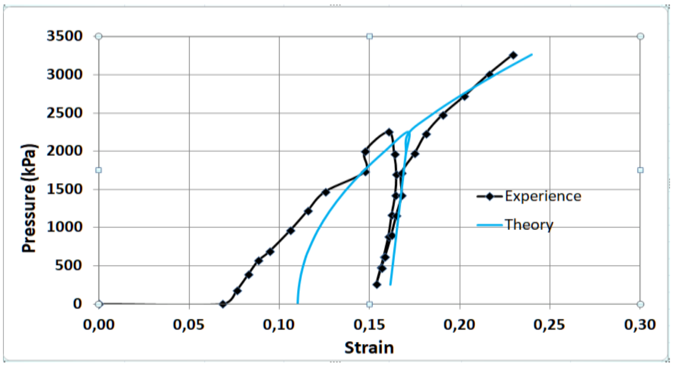

Figure 5:: Pressure curve corrected for membrane thickness - SP3Bis test - 18 m - Pressure module E_M = 33000 KPa - Elastic modulus E = 254000 KPa - Φ= 40°

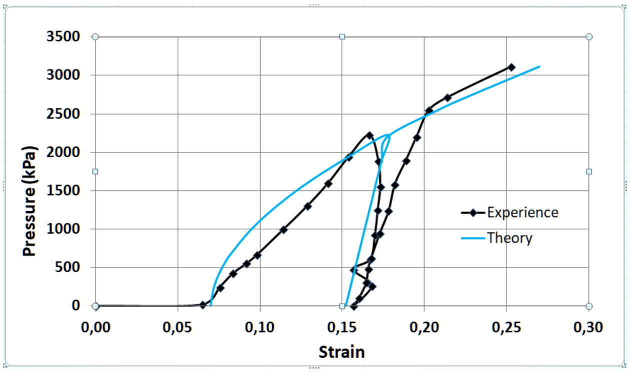

Figure 6:: Pressure curve corrected for membrane thickness - SP7Bis test - 16 m - Pressure module E_M = 35300 KPa - Elastic modulus E = 130000 KPa - Friction Φ= 43

5.2. Results related to the coarse alluvium of the Rhone river

More specifically, we are interested in the sandy-gravelly alluvium of the Rhône. The coarse alluvium of the Rhône is in the form of a complex formation in detail (more or less sandy gravel, with possible intercalations of sandy lenses), but accounts for a generally homogeneous and coarse formation. The figure below (Fig. 7) is an "average" representation of the average particle size zone of the alluvium in the central third of the Rhône

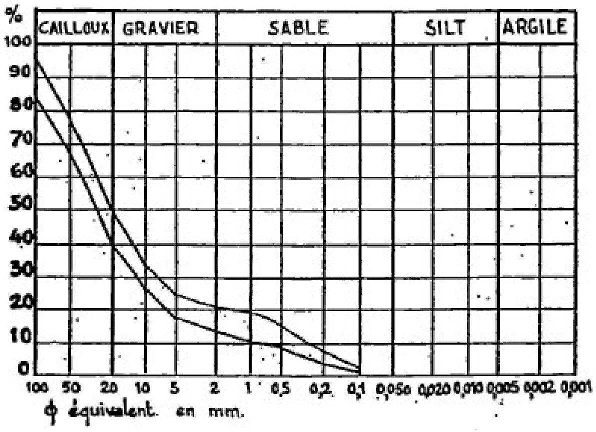

Figure 7: Average particle size zone of the coarse alluvium of the Central Third of the Rhône

5.2.1. Results related to coarse alluvium of the Rhone river

Pressuremeter measurements are carried out either by visual reading of the quantities, or by automatic entry by adapted devices (LIM, Geomatech, etc.); the accuracy of the pressuremeter results (pressuremeter module, limit pressure) depend on the accuracy of the measurements (Monnet 2021), (Monnet 2021). For example, the accuracy of the pressuremeter results on the site studied by CNR (SHPU of Caderousse) has allowed to give an acceptable accuracy of 14% on corrected modulus and of 4% on standardized modulus with an accuracy on the volume readings of 0.1 cm^3.

From a mechanical point of view, the various tests (large-diameter shear tests, etc.) carried out along the valley show materials with high friction angles, for zero cohesion, between 35° and 40°. The overall compactness of this formation is generally medium to strong. Given their granularity, geotechnical design offices rightly use the split-tube probe in such materials. The pressuremeter characteristics obtained are generally high, even very high, and it is not uncommon to not reach the creep of the test within this formation. The analysis of the pressuremeter tests analysed according to the AFNOR 2015 normative approach and the one taking into account the actual physical behaviour of the probe ("optimised" approach, (Monnet et al. 2022b)) leads to the observation of very significant differences in the various pressuremeter parameters.

5.2.2. Analysis of Limit pressures

It can be seen (Fig. 8) that the theoretical limit pressures (Monnet, 2012) are very close to the membrane-corrected limit pressures (Monnet et al., 2022).

5.2.3. . Analysis of Pressuremeter Modulus

In the case of the "optimized" approach of (Monnet et al. 2022b), the corrected results (Fig. 9) are almost identical to those obtained with a bare probe in the same soil. The differences in the values of the pressuremeter modulus between the NF approach and the so-called "optimized" approach are very significant, with a factor of about 2 separating the average results of the two methods (Table 2)

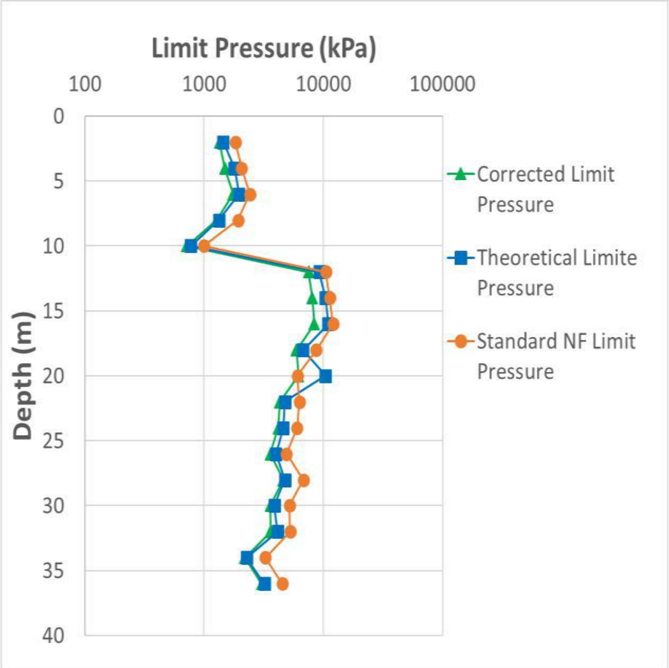

Figure 8. : SP2bis pressuremeter profile - significant proximity of the corrected limit pressures to the theoretical limit pressure, with regard to the approach recommended by the NF standard

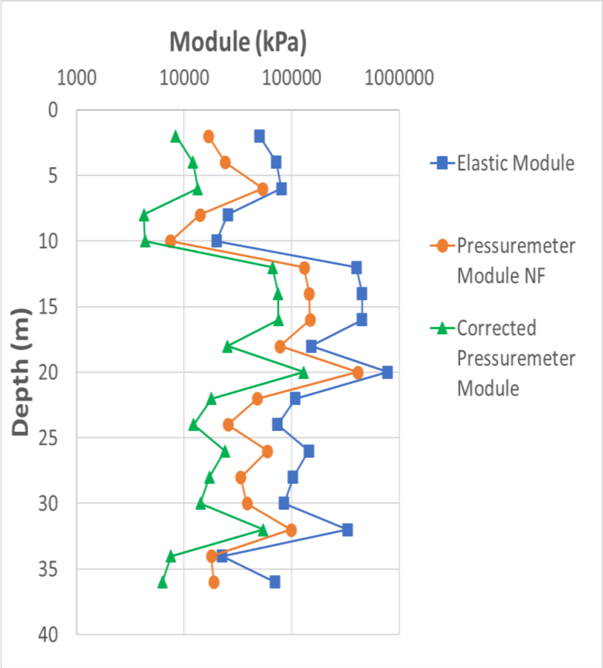

Figure 9. : SP2bis pressuremeter profile - illustration of the close proximity of the corrected pressure modulus to the elastic modulus with regard to the approach recommended by the NF standard

Table 2: Comparison of Soil Modulus by the Two Methods

Soil	**E_M standard (MPa)**	**E_M optimized (MPa)**
Sandy gravel	123.9	60.8
Pliocene marl	44.4	21.4

Table 3: Relationship Between Pressuremeter Modulus and Support Processes

Pressuremeter modulus E_M (MPa)	**Percussion process**
E_M < 40 - 50 MPa	Sheet pile driving without any particular difficulties
50 MPa < E_M < 70 MPa	Sheet pile driving difficult, localized rejection possible
70 MPa< E_M <100 MPa	Very difficult piling, with extended rejection possibilities, widespread pre-drilling required
E_M > 100 MPa	Sheet pile driving Impossible

6. What are the consequences for the project manager

These very significant discrepancies lead to very different design choices for the supports in the study phase: if it is still possible to consider beating high inertia sheet piles in dense sandy gravels for 60 MPa pressuremeter modulus (at the cost of a certain difficulty and possibly prior pre-drilling), it seems illusory to consider a solution of this type with 123.9 MPa pressuremeter modulus.

As a guideline, without Sheet pile driving tests, CNR often uses the following empirical benchmarks for these Sheet pile driving operations in granular soils (Table 3).

According to this results and the analysis of the tests, we move from a total exclusion of a sheet pile-type retaining structure, to the possibility of building this same type of structure with a few additional pre-drilling!

It should also be noted that there is also a significant difference in cost between a sheet piling solution and a diaphragm wall solution that could be considered in a very compact soil. Excluding site installation (the price of wall installations quickly proving to be very expensive), the cost ratio (price per m²) between a diaphragm wall and a sheet pile wall is around 2.5 to 4 time more for construction and depth techniques and conventional depths.

The current high price of steel and the significant carbon impact associated with the manufacture of sheet pile curtains should prompt us to legitimize the relevance of the interpretation of the pressuremeter test. The weight of steel per ml of sheet pile varies significantly depending on the modulus chosen.

The differences in cost and complexity of construction are not the same between sheet piles and diaphragm walls. We cannot wait for the beginnings of the construction phase to have an expensive preliminary piling test carried out in order to change the solution of retaining design for the structure.

In the same way, we cannot be reasonably satisfied with knowing a parameter as important as the modulus of deformation of a soil with a precision of only 50%? If, for some common applications in civil engineering, such differences in estimations have no consequences, it is not the case for structures that are very heavily loaded and/or require very small deformation tolerances?

In today's challenges, it seems important to CNR that the interpretation of the pressuremeter test would be able to evolve in order to stick as closely as possible to the real behavior of the pressuremeter expansion test, which has greatly contributed to the development of modern geotechnics. The virtuous objectives of making a number of projects reliable in difficult geotechnical geological contexts impose us to construct "as accurately as possible" the needs necessary for the project, while minimizing our borrowing of resources from the earth.

The important points of this optimized pressuremeter interpretation are:

- High reliability of the interpretation validated by finite element calculation (Monnet et al. 2022b)
- Results (E_M, E_e, p_{LM}, Φ) for which accuracy is calculated and known (Monnet 2021)
- Direct determination of soil friction characteristics, without approximate correlations (Monnet 2012a) (Monnet 2012b)
- Taking into account the thickness of the membrane separating the loading fluid internal to the probe from the soil external to the probe (Monnet et al. 2022b)
- Taking into account the actual deformation of the probe (Monnet et al. 2022b)
- A better adaptation of the structure to the surrounding ground and a significant saving cost on the project
- Improvement in-service safety

7. Conclusions

We present new corrections and interpretations of the pressuremeter test for the Rhône river on the Small Hydraulic Power Unit of Caderousse. This analysis allows to justify soil characteristics that were more favourable to the construction and led to an extremely significant saving on the cost of the civil works, without compromising safety..

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