Correlations between the pressuremeter and the rigid dilatometer parameters in soils

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ABSTRACT

The Dilatometer Fondasol Test (DFT) is a unidirectional loading test in a borehole that provides an in-situ stress-strain curve. Two rigid shells are spread in the soil at a constant displacement rate by several small hydraulic jacks. First results using this probe in soils were obtained by Besson (2022) who also provided methods to compute from the stress-strain curve both a pseudo-elastic modulus and a limit stress. However, additional data were required to establish strong correlations between the dilatometer parameters and the pressuremeter parameters. This paper introduces new results obtained in various sites in France and synthetises all the results obtained so far. For each site, pressuremeter soundings and dilatometer soundings are carried out in pairs using the same drilling methods. DFT and PMT are performed at the same depths and at the same strain rate. For the computation of moduli and limit stresses, semi-automatic methods are employed to prevent subjective interpretations. Correlations are proposed between the dilatometer modulus and the pressuremeter modulus as well as between the dilatometer limit stress and the pressuremeter limit pressure. The established correlations, along with their limitations, are interpreted.

Keywords: rigid dilatometer test; pressuremeter test; in situ; modulus, limit pressure.

1. Introduction

Borehole expansion tests provide an in-situ stress-strain curve of the soil. Their principal advantage lies in the ability to derive two essential geotechnical parameters from this curve: a deformation modulus and a failure parameter. Among these tests, the Ménard pressuremeter test (PMT) is the most renowned. In the PMT, soil loading is achieved by inflating a tri-cellular rubber membrane probe with pressurized gas (Ménard, 1957). The test is traditionally carried out with incremental pressure steps until a predetermined deformation of the probe is reached or a set maximum pressure is attained.

The Fondasol rigid dilatometer test (DFT) is a novel borehole expansion test (Besson et al. 2020). In this method, two rigid semi-cylindrical shells are expanded within the soil at a constant strain rate driven by several small hydraulic jacks. Although rigid dilatometers have long been utilized in rock mechanics (Goodman et al. 1968, Fecker 2018), the Fondasol probe represents the inaugural adaptation of this concept specifically for soil applications. The equipment has been adapted to measure high deformations at low pressures in boreholes with a diameter of 64 mm. DFT is conducted at a constant displacement rate, in contrast to the pressure test increment of the PMT and the traditional rigid dilatometer test.

The DFT offers significant advantages over the PMT as it simplifies the testing procedure by removing the need of estimating the limit pressure. It enhances safety by avoiding compressed gas and minimizes the equipment's clutter, making transportation more convenient.

Given the DFT's recent introduction, it is essential to compare its results with those from the established PMT. Establishing correlations between the parameters derived from the two tests allows for a better understanding of both tests. Furthermore, this could provide a preliminary approach for using parameters from the DFT for foundation design.

First DFT results were obtained by Besson (2022) who also provided methods to compute from the stress-strain curve both a pseudo-elastic modulus and a limit stress. However, additional data were required to establish strong correlations between the DFT and the PMT parameters.

This paper introduces new results obtained in various sites in France and synthetises all the results obtained so far to offer correlations formulae.

2. Material and methods

This section depicts the sites investigated as well as the different materials used. All these characteristics are summarized in Table 1.

2.1. Sites description

The measurement campaigns took place between 2019 and 2023. Figure 1 displays the locations of these sites.

Table 1. Synthesis of the tests performed in the different sites.

Location	Lithology	Number of pairs of tests	Drilling technique	Dilatometer prototype	Type of pressuremeter probe
Test chamber	Hostun sand HN31	20	No drilling	1 to 4	RC
Avignon	Silty clay	16	HA ϕ=63mm	3	RC
Le Thor	Silty clay	9	HA ϕ=63mm	3	RC
Messanges	Sand	12	OHD ϕ=64mm	3	RC
Pommiers	Marl	2	CFA ϕ=63mm	4	SST
Hyères	Sandy clay	4	RP ϕ=64mm	4	SST
Genas	Sandy gravel	3	CFA ϕ=63mm	4	SST
Guilherand-Granges	Clayey silt to sandy silt	3	CFA ϕ=63mm	4	SST
Nîmes	Gravelly silt	2	CFA ϕ=63mm	4	SST
Pennes-Mirabeau	Gravelly silt to sandy silt	21	RP ϕ=64mm	4	SST
Laudun-L'ardoise	Sandy silt	4	RP ϕ=64mm	4	RC

CFA = Continuous flight auger without mud
OHD = Open hole drilling (rotary)
RP = Rotary percussion
HA = hand auger
RC = 3mm thick pure rubber cover 58 mm
SST = Short cell + slotted tube 49/63 mm

Initial tests were conducted in a controlled environment using a cylindrical test chamber. Here, a pure and uniform sandy soil was reconstituted at varying density indices surrounding the probe. The number of these tests (20 tests) constitutes a small fraction of the overall data set.

Following the validation of the dilatometer probe concept within the test chamber, in-situ testing began. The first of these in-situ tests were performed under ideal drilling conditions, using a hand auger above the water table in Avignon and Le Thor.

Subsequent campaigns adapted to more typical drilling conditions encountered in the routine operations of a geotechnical design office like Fondasol. Techniques included the continuous flight auger, rotary, and rotary percussion drillings.

Figure 1. Sites' location.

2.2. Material

2.2.1. The Fondasol rigid dilatometers

Four different prototypes were successively developed between 2019 and 2023, each iteration being a refinement over the previous one. A comprehensive developmental history of this equipment can be found in Besson (2022). Notably, the majority of the tests in this study are performed using Prototypes 3 and 4.

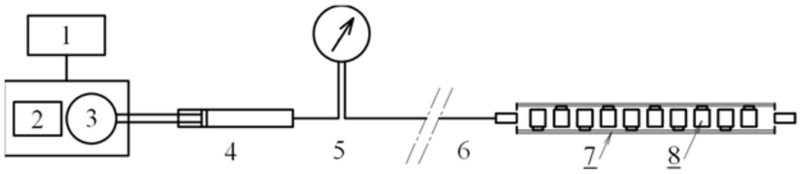
The operational principle is depicted in Figure 3 taking Prototype 4 in example. The probe is displayed in Figure 3 without its 3 mm thick protective rubber sheath. When outfitted with this cover, the probe has an initial diameter of 58 mm, which can extend up to 88 mm approximately. The shells, 360 mm in length, have a half-angle aperture of 90°. While Prototype 3 operates similarly to Prototype 4, its cylinders have only half the full displacement capability.

The shells' displacement occurs at a constant rate, managed by a control unit located at the surface. An electric motor rotates a screw within an oil tank injecting oil into the probe's cylinders. The oil pressure is measured by a pressure sensor near the oil tank. Testing is terminated when any of the subsequent conditions are met:

- An internal pressure reaching 20 MPa which approximately equates to a stress of 3.5 MPa exerted by the shells.
- The shells achieve their maximum displacement which corresponds to a 88 mm diameter.

2.2.2. The pressuremeter

Two different kind of tri-cell G type probes have been used throughout this study. The first one is a standard hollow probe body with a 3 mm thick protection membrane. The membrane is either a flexible rubber cover (RC) or a harder textile strips rubber cover (TRC). The probe has a 58 mm initial diameter. The second type of probe is a 44 mm diameter probe with a short central cell placed within a 58 mm slotted tube (SST). PMT are performed in accordance with the ISO standard 22476-4.



1 recording device
2 acquisition unit
3 electrical motor
4 hydraulic tank
5 pressure sensor
6 pressure line
7 shell
8 hydraulic cylinder

Figure 2. Operation principle of the Dilatometer Fondasol Test

Figure 3. On the left: The Fondasol rigid dilatometer (disassembled). On the right: Schematic cross-sectional view of the probe illustrating one shell spread apart while the other remains in its initial position

2.3. Testing procedure

The method followed is straightforward: for each site, pressuremeter soundings and dilatometer soundings are carried out in pairs using the same drilling methods. At least one pair of sounding is carried out. DFT and PMT are performed at the same depths and at the same strain rate.

2.4. Interpretation of tests results

2.4.1. Corrections

Before interpretation, both tests require measurement corrections. Open-air tests enable to determine the intrinsic resistance of the probe. Tests conducted in a rigid hollow cylinder measure the apparatus's self-dilatation under pressure and enable the calibration of the probes' diameter.

After subtracting the membrane's inherent resistance from the measured pressure and the equipment's self-dilatation from the measured probe's diameter, a stress-strain curve can be plotted (Figure 4). In this context, σ represents the corrected stress, ϕ is the corrected diameter of the probe, and ϕ_p denotes the borehole's initial diameter.

For both tests, a modulus is calculated based on the nearly linear initial portion of the curve. Additionally, the latter part of the curve is deemed nearly linear, and both segments are taken into account when determining the limit stress.

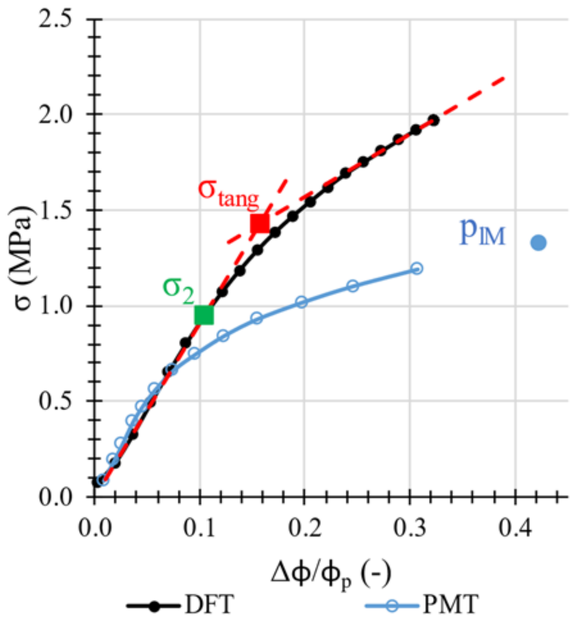


Figure 4. Typical dilatometer and pressuremeter test curves (Avignon site).

2.4.2. Modulus

Considering both tests, deformation moduli are extracted from the elastic theory, assuming an initially cylindrical borehole, homogeneous soil, and plane strains. In the pressuremeter theory, the probe exerts a purely radial stress on the entire borehole wall (Ménard 1957). In the rigid dilatometer theory, the shells expand in a singular direction, presuming full contact with the soil across their width (Goodman et al. 1968).

For both tests, it is crucial to adopt a consistent methodology when determining the range for modulus calculation. We have chosen to adhere to the ISO standard 22476-4 (2012) methodology for this purpose.

To begin with, the ($\Delta\phi/\phi_p$, σ) curves are transformed into (σ, V) curves. For the pressuremeter test, V is the injected volume of water in the measuring cell. For the rigid dilatometer tests, the volume V is inferred by treating the shell displacement as if it corresponds to the diameter of a hypothetical cylinder with a length of 210 mm. It is important to emphasize that this hypothetical volume V, is used to calculate a dilatometer modulus analogous to that of the pressuremeter. However, V does not directly correlate with the genuine volume of soil displaced during this test.

The slopes $m_i=(V_{i+1}-V_i)/(\sigma_{i+1}-\sigma_i)$ are computed for all data points. The minimum value among these slopes is termed m_E. The range along which the modulus is calculated includes all the consecutive segments which exhibit a slope less than or equal to λ times m_E. The coefficient λ is derived from the standard formula:

$$\lambda = 1 + \frac{1}{100}\frac{\sigma'_E+\sigma_E}{\sigma'_E-\sigma_E} + \frac{2\delta V}{V'_E-V_E} \quad (1)$$

With the coordinates of the origin (σ_E, V_E) and the end (σ'_E, V'_E) of the segment m_E. δV is a tolerance for V set as 3 cm3 initially. If the derived number of intervals is fewer than three, δV is incrementally increased by 1 cm^3 steps. It's worth noting that λ is a historically calibrated parameter, used specifically for the automated calculation of the modulus. It holds no direct physical significance and is dimensionless. This approach leads to the determination of the points P1 and P2 deliminting the pseudo-elastic phase.

The rigid dilatometer modulus, also called the borehole jack modulus and noted E_{BJ}, is given by

$$E_{BJ} = K(\upsilon,\beta)\Phi_p\frac{\sigma_2-\sigma_1}{\Phi_2-\Phi_1} \quad (2)$$

Where ϕ_p is the initial diameter of the borehole, (σ_1, ϕ_1) and (σ_2, ϕ_2) are the coordinates of the points P1 and P2 and

$$K(\upsilon,\beta) = \frac{720}{\pi^2}\frac{1}{\beta}(1-\upsilon^2)\sum_{m=1}^{\infty}\frac{1}{m^3}(1-(-1)^m)\sin^2(m\beta) \quad (3)$$

Where ν is the Poisson coefficient and β is the angle giving half the loading surface of the soil.

The pressuremeter modulus, traditionally called the Ménard modulus E_M, is computed using

$$E_M = 2(1+\upsilon)(V_c+\frac{V_1+V_2}{2})\frac{P_2-P_1}{V_2-V_1} \quad (4)$$

Where (P_1, V_1) and (P_2, V_2) are the coordinates of the points P1 and P2.
V_c is the initial volume of the probe.

2.4.3. Limit stress

Although approaches have been proposed to directly determine soil failure parameters from pressuremeter tests, they have often been found lacking in real-world applications. In practice, the reference criterion, the Ménard limit pressure p_{lM}, is arbitrarily defined as the pressure required to double the initial cavity volume (Baguelin et al. 1978). This level of deformation being rarely achieved, p_{lM} is extrapolated using the so-called double hyperbola method.

Considering the rigid dilatometer, the theory of failure has been minimally studied (Van and Goodman 1970, Hou et al. 2017) because rock mechanics experts show little interest in this phase. Besson (2022) proposed several approaches to determine a limit stress σ_{lim} based uniquely on the shape of the test curve in soils. In this paper, two approaches are considered (cf. Figure 4):

- σ_{lim} is the stress delimiting the end of the pseudo-elastic phase. This criterion denoted σ_2 matches the stress value at point P2.
- σ_{lim} is the stress denoted as σ_{tang} corresponding to the point where two lines intersect: the first being the pseudo-elastic line and the second fitted the latter part of the curve.

The first line is derived using the methodology described in §2.4.2. The second line is generated using the same method, but considering the maximum slope m_{max} instead of the minimal one, and taking λ_{max} = 1-(λ-1)/2 in place of λ. Then, the line is plotted between the two points that bound all successive segments exhibiting a slope greater than or equivalent to λ_{max} times m_{max}.

3. Results

Results are displayed on Figure 5. (A) and (B) focus on the moduli whereas (C) and (D) deal with limit stresses. Ordinary Least Squares (OLS) regressions (black dashed lines) are computed for all cases and select regression lines (gray lines, either dotted or dash-dotted) illustrate specific percentiles of the data spread. Two different colors are employed: pressuremeter data obtained using a 60 mm probe are represented in red, whereas pressuremeter measurements taken with a 44 mm probe inside a slotted tube are shown in green. The correlations formulae are gathered in Table 2 and in 0.

3.1. Modulus

Figure 5 (A) displays a set of 96 data pairs (E_M, E_{BJ}). Pressuremeter moduli range between 1 and 94 MPa which represents the typical range for pressuremeter modulus measurements.

The data clearly shows that the pressuremeter modulus tends to be higher than the dilatometer modulus. This overarching trend is further highlighted by the OLS regression line which suggests an average relationship of $E_M=1.16 \cdot E_{BJ}$ with a rather strong correlation coefficient of $R^2=0.917$. Quantile regressions indicate that 50 % of the E_M data reside within the range of 0.83 to 1.49 times E_{BJ} while 80 % lie within the range of 0.71 to 1.66 times E_{BJ}. Upon splitting the dataset based on the type of pressuremeter probe, either RC or SST, we derive the following relationships:

- For the RC probe, $E_M=0.95 \cdot E_{BJ}$ with an R^2 value of 0.880, based on 56 data pairs.
- For the SST probe, $E_M=1.20 \cdot E_{BJ}$ with an R^2 value of 0.927, based on 40 data pairs.

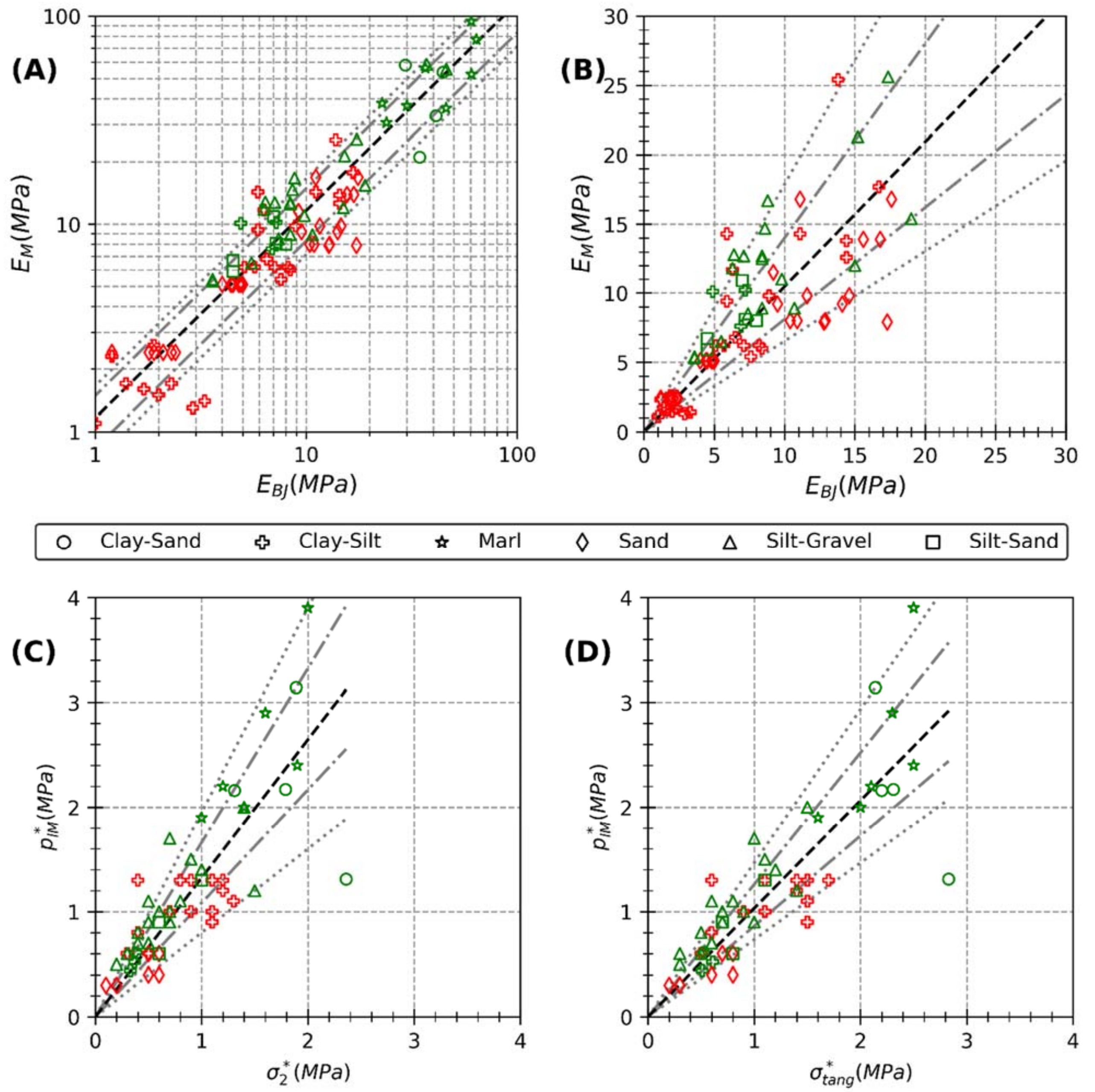


Figure 5. Correlations between the pressuremeter parameters and the Fondasol rigid dilatometer parameters. In red: PMT carried out with rubber cover (RC). In green: PMT conducted with slotted tube (SST).

Table 2. Modulus correlation formulae related to Figure 5.

Fig.	Condition	Regression type	Equation
(A)	All Data	OLS	y = 1.163x
(A)	All Data	10th quantile	y = 0.714x
(A)	All Data	25th quantile	y = 0.832x
(A)	All Data	75th quantile	y = 1.488x
(A)	All Data	90th quantile	y = 1.659x
(B)	E ≤ 30 MPa	OLS	y = 1.047x
(B)	E ≤ 30 MPa	10th quantile	y = 0.653x
(B)	E ≤ 30 MPa	25th quantile	y = 0.811x
(B)	E ≤ 30 MPa	75th quantile	y = 1.401x
(B)	E ≤ 30 MPa	90th quantile	y = 1.789x

Table 3. Limit stress correlation formulae related to Figure 5.

Fig.	σ_{lim}	Regression type	Equation
(C)	σ_2	OLS	y = 1.323x
(C)	σ_2	10th quantile	y = 0.800x
(C)	σ_2	25th quantile	y = 1.083x
(C)	σ_2	75th quantile	y = 1.661x
(C)	σ_2	90th quantile	y = 1.950x
(D)	σ_{tang}	OLS	y = 1.032x
(D)	σ_{tang}	10th quantile	y = 0.733x
(D)	σ_{tang}	25th quantile	y = 0.863x
(D)	σ_{tang}	75th quantile	y = 1.261x
(D)	σ_{tang}	90th quantile	y = 1.467x

Figure 5 (B) focuses on a subset of data points for which moduli are less than 30 MPa, corresponding to the intended application range for the Fondasol dilatometer probe. Based on this subset and regardless of the type of probe (82 data points in total), the OLS regression falls to $E_M=1.05 \cdot E_{BJ}$. This suggests that E_M is rather close to E_{BJ} for modulus values less than 30 MPa, while for higher values, E_M tends to be higher. Quantile regressions highlight that 50 % of the E_M values lie between 0.81 to 1.40 times E_{BJ} and 80 % are contained within the range of 0.68 to 1.79 times E_{BJ}. This suggests that considering the subset or the whole dataset has no significant impact on the data dispersion relative to the central trend.

3.2. Limit stress

Figure 5 (C) and (D) show all the 58 pairs (σ_{lim}*, p_{lM}*) data. Using OLS analysis, it is evident that the pressuremeter limit pressure substantially surpasses σ_2, being calculated as $p_{lM}=1.32 \cdot \sigma_2$. In contrast, it closely matches σ_{tang}, with the OLS regression indicating $p_{lM}=1.03 \cdot \sigma_{tang}$.

Quantile regressions for the 25th and 75th percentiles indicate that the middle 50% (i.e., IQR) of the p_{lM} data resides within the range of 1.08 to 1.66 times σ_2 and 0.86 to 1.26 times σ_{tang}. Meanwhile, 80% of the data spans from 0.80 to 1.95 times σ_2 and 0.73 to 1.47 times σ_{tang}. The data for σ_{tang} are generally less dispersed around the central trend compared to σ_2, with an interquartile range (IQR) of $0.46 \cdot \sigma_{tang}$ as opposed to $0.58 \cdot \sigma_2$.

4. Discussion

This study offers insights from an unprecedented campaign of in situ tests with both probes, marking the first instance of comparing pressuremeter tests with rigid dilatometer tests in soils with moduli below 60 MPa and limit stresses below 3 MPa.

The main result is the strong correlation observed between the dilatometer and pressuremeter parameters. Specifically, for moduli, the relation $E_M=1.16 \cdot E_{BJ}$ stands out. For limit stress the relationships to note are $p_{lM}=1.32 \cdot \sigma_2$ and $p_{lM}=1.03 \cdot \sigma_{tang}$.

The proximity between E_M and E_{BJ} was anticipated, given that both are rooted in elastic theory and are computed within a similar range of strain and stress. While the close relationship between p_{lM} and σ_{tang} is not immediately apparent given that neither of these parameters originates from plasticity theory, the observed correlations suggest that σ_{tang} serves as a reliable proxy for estimating the pressuremeter limit pressure. Even though the data dispersion with σ_2 is marginally higher, its utilization remains relevant. This is primarily because it means the rigid dilatometer test can be stopped as soon as the pseudo-elastic phase ends, which not only reduces the test's duration but also diminishes the risk of the probe bursting.

When differentiating pressuremeter data obtained with a standard 60 mm probe (RC) from that acquired with a 44 mm probe in a slotted tube (SST), notable differences in the correlation formulae emerge. Jacquard et al. (2021) previously observed that the use of SST probes could result in the calculation of higher pressuremeter moduli compared to the RC probe. Nevertheless, considering that most of tests from the RC probe measured moduli below 20 MPa, and most of tests with the SST probe measured moduli higher than 20 MPa, it's challenging to definitively ascertain whether the gap between moduli is a result of the pressuremeter probe or the real modulus range. To draw definitive conclusions, more measurements with the standard probe in soils with E_M>30 MPa are required.

The dataset contains fewer limit stress data points compared to modulus data. This discrepancy can be attributed to two main factors:

- Hard soils: In certain hard soil conditions, both pressuremeter and dilatometer curves tend to maintain linearity throughout the test. This linearity renders it impossible to determine failure parameters.
- Prototype constraints: Prototype 3 has a limited cylinder travel, which consequently reduces the probability of detecting soil failure. Consequently, most of the limit stress measurements were obtained using Prototype 4.

Thanks to these correlation formulae, geotechnical engineers, using results from a rigid dilatometer test, can deduce a pressuremeter modulus and a limit pressure. Following this, the pressuremeter methodology (NF P 94-261) can be applied to determine the bearing capacity beneath foundations and predict settlements.

5. Conclusion

The Fondasol rigid dilatometer test is a newly developed borehole expansion test that allows access to a deformation modulus and a limit stress. In order to validate this innovative test and to provide a preliminary approach for foundation design, an extensive comparative study with the widely acknowledged pressuremeter test was conducted.

This comparative study, carried out on soils of various lithological natures, resulted in the derivation of strong correlation formulae. These formulae relate the dilatometer modulus to the pressuremeter modulus, and the pressuremeter limit pressure to the dilatometer limit stress.

From now on, geotechnical engineers can use the formulae to apply the traditional methods for estimating soil settlement and bearing capacity beneath foundations. Currently, this represents the most direct application of rigid dilatometers. Moving forward, research on rigid dilatometer should develop methodologies that stand independent of the pressuremeter's one.

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