ARSCOP: a French national project to continue with the development of the pressuremeter

ARSCOP : un projet national français pour poursuivre le développement du pressiomètre

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ABSTRACT

The National Project ARSCOP aims to continue with the development of the pressuremeter. The objective is to provide a better testing procedure for ground investigation to obtain reliable soil and rock properties to be used in calculation methods for better geotechnical design. This paper describes the works carried out in this project by 46 industrial, academic, and project owner partners during the period 2015- 2024.

RESUME

Le Projet National ARSCOP a pour objectif de poursuivre le développement du pressiomètre pour fournir d'une part des protocoles d'essais et des outils permettant une meilleure reconnaissance des terrains et d'autre part des valeurs des propriétés des sols et des roches ainsi que des méthodes de calcul garantissant des calculs d'ouvrages géotechniques plus fiables. Les travaux menés de 2015 à 2024 par les 46 partenaires industriels, académiques, et maîtres d'ouvrages du projet avec ses différents axes sont présentés.

Keywords: artificial intelligence; finite elements; pressuremeter

1. Introduction

Over the past 40 years, the French civil engineering community has contributed to various developments in France and abroad. Some of these developments include mega-structures such as the Pont de Normandie (Bridge of Normandy), Millau Viaduct, Vasco da Gama Bridge and the Rion-Antirion Bridge. Other mega-structures include high-rise buildings such as Mohammed VI Tower (260 m) in Rabat and the Tower F (400 m) in Abidjan. Maritime infrastructure developments in Dubai in the UAE and in Morroco, large industrial facilities, public infrastructure for motorways, high speed railways, tramways lines and public underground infrastructure such as the Jubilee Line in the UK and the EOLE (East West Liaison Express) with Metro Lines L4, L11 and L14 in France are some notable examples. These achievements would not have been made possible without the input of geotechnical engineering knowledge into the design and the construction to take into account the complexity of the project and its environment and reduce the risks associated with their construction.

The invention of pressuremeter by Louis Menard in 1955 (Ménard, 1955, Ménard and Rousseau, 1961) paved the way for a more reliable geotechnical design. It is essentially a geotechnical investigation equipment which allows in a single test to evaluate both the deformation and failure properties for a wide range of ground mostly inaccessible to other usual techniques, from soft soils to rocks. It measures the pressuremeter modulus, creep pressure and limit pressure. In the more advanced equipment such as the self-boring pressuremeter, it also measures the initial state of stress in the ground and therefore the coefficient of earth pressure at rest can be obtained.

The work done in France and abroad especially by the Highways Research Laboratories and universities in USA, UK and Japan and also through past National Collaborative Projects have permitted the use of pressuremeter test results as valid design parameters for the design of retaining walls, shallow and deep foundations, soil reinforcement, etc.

However, many interesting points highlighting the challenges for future developments of pressuremeter especially about the limitations of the testing procedure, availability of equipment, difficulties in the interpretation and analysis of data derived from the test, etc. have put forward for discussion recently. The presentations of National and International States-of-the-Art Reports at the International Symposium on Pressuremeter in 2005 (ISP5, 2005; Burlon and Reiffsteck, 2013), the recent meetings of the Working Groups of the European Standards on Pressuremeter and the elaboration of the French Standards on shallow and deep foundations are some of the venues where such discussions were made.

This French National Project ARSCOP started in 2015 and had the objectives to continue with the development of pressuremeter. Three aspects of pressuremeter testing have been re-evaluated. They are (i) refined use of pressuremeter for ground investigation, (ii) the assessment of the bearing capacities of shallow and deep foundations (iii) the accuracy of displacement calculations for geotechnical structures. This paper describes the content of this research project regarding these three main issues.

2. A high performing equipment for ground investigation

2.1. General presentation

The objective of carrying out in-situ tests is to explore the ground conditions to obtain information about the presence of groundwater, the soil and rock types, their spatial distribution and their geotechnical properties. From these findings, it allows to identify any difficulties during construction in order to ensure the performances of the project.

The pressuremeter is a ground investigation equipment which provides information to achieve the above objective. It allows to:

- Measure the deformation moduli and the soil strength;
- Understand at least partly the stress state in the ground;
- Recognize partially or fully the ground conditions and soil types;
- Detect durig the drilling the possible presence of groundwater table.

2.2. The deformation moduli

Pressuremeter is one of the rare equipment that allows the derivation of a deformation modulus for the different geotechnical units of the ground model in an almost undisturbed state. From conventional modulus developed by Ménard (Briaud, 2013, Clarke and Gambin, 1998) to the development realized during the project on in situ lateral stress, pore pressure measurement during expansion or small strain modulus, a wide range of tools are now ready to be implemented in day to day practice.

Lopes et al. (2022) have proposed a new procedure for the interpretation of the pressuremeter test for the determination of the shear modulus at a targeted value of strain is presented. This procedure is illustrated on Figure 1 by a test carried out in Flanders sands in Dunkirk (France, 59). It has been shown that the results can be directly used for the evaluation of the settlement of a footing, as a function of its loading ratio (Lopes et al., 2022).

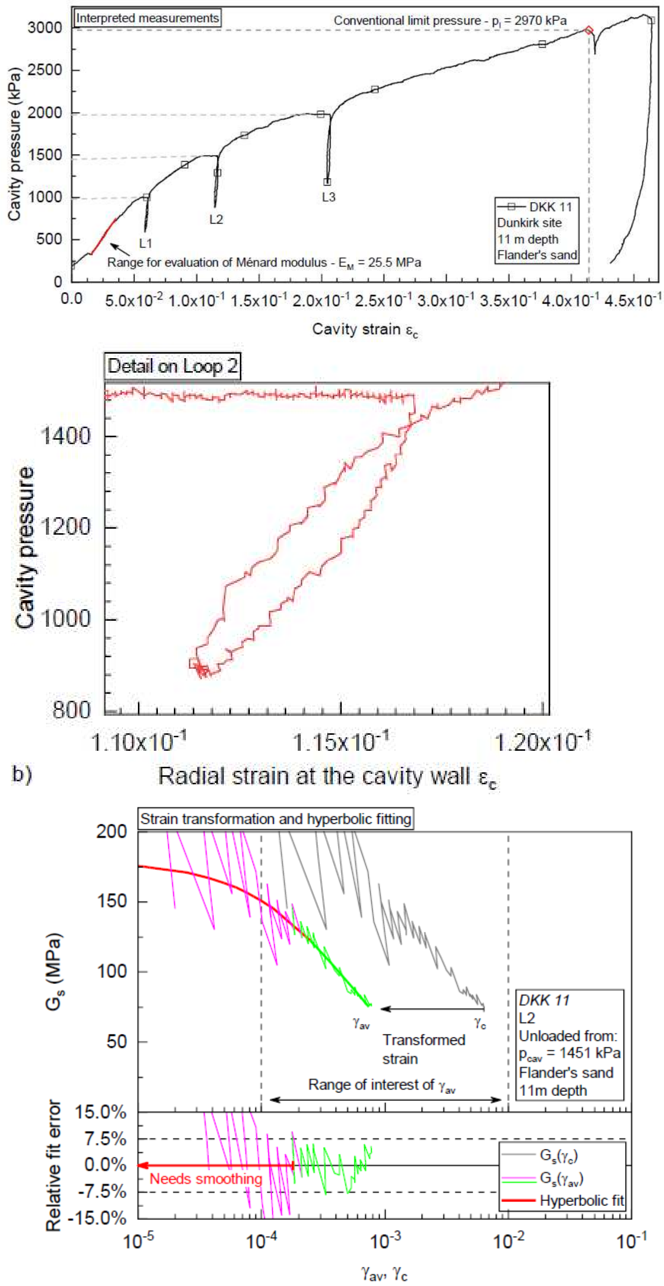


Figure 1. Interpretation of pressuremeter tests with unload-reload loops for the determination of shar modulus decay as a function of the strain level

Another approach enabling to derive small-strain stiffness and the stiffness degradation curve of soils with pressuremeter is the development of a new pressuremeter probe equipped with a Hall Effect sensor. For this purpose a specific probe was design and build. The main validation steps of the new pressuremeter probe and the results obtained from previous tests in a physical model have been developed in ARSCOP project. This approach allows drawing a degradation curve of the shear modulus; this would be useful in the practice of geotechnical engineering, and particularly for a better understanding of the nonlinear behaviour of soils subjected to cyclic, dynamic or seismic loads (Aissaoui et al., 2020a; 2020b).

2.3. The soil strength

The ARSCOP project was an opportunity to address a problem in field or interpretation practice. A study of the overwhelming influence of the way in which the pressuremeter probe is placed in test cavities. Historically, several comparative field tests were carried out in sand, silt, chalk and marl to assess this influence. Reports of the different sites and detailed analysis of the results emphasize the role of borehole quality on the load-deformation curve and the determination of modulus and yield pressure. Conclusions were used to draft the first field manuals.

A campaign of cross-check tests was carried out on several sites using the Ménard pressuremeter probe in clayey, silty and sandy soil below the water table. It is well known that the performance of pressuremeter tests in this type of soils is delicate and depends very much on the operator's know-how (Figure 2). The aim of this campaign, as part of the ARSCOP programme, was to compare current practice with the recommendations of the EN 22 476-4 standard.

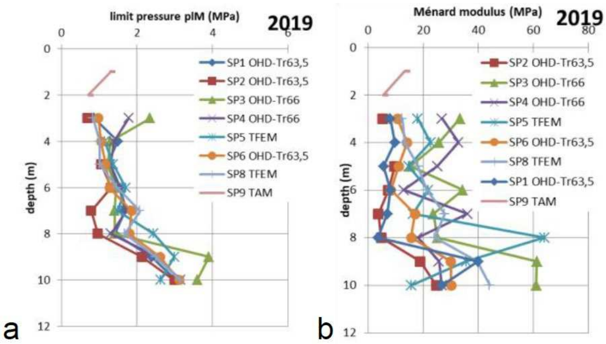


Figure 2. Influence of sand placement method on the limit pressure and pressuremeter modulus (Messange site).

These campaigns give good insight on the companies' practices and their influence on how the Ménard limit pressure p_{LM} and Ménard modulus are affected by the kind of probe and equipment chosen for tests realized in a prebored hole, and the type of drilling tools (OHD/vs DST).

A discussion of the relevance of the requirements of Table C.2 of the standard EN ISO 22476-4 standard for the soil concerned have been proposed (Rispal et al., 2022).

2.4. The ground model and the geotechnical design model

With this various sources of information provided by a set of pressuremeter tests, the geotechnical engineer can have an understanding of the geometry of different soil layers and build a geotechnical model for his design.

In France, pressuremeter has become so important that it has become very often the only test that the engineers use for ground investigation instead of choosing any other investigation techniques such as core drilling, cone penetration tests or standard penetration tests. This situation also leads to a loss of reference for the same group of engineers (who have relied so much on pressuremeter tests) when no pressuremeter test results are available to them especially for works carried out overseas where pressuremeter test is not common.

In the past 20 years, pressuremeter testing has reduced partly due to a slower economy and smaller budget allocated to ground investigation so much so that the quality may be affected. Drilling with poor workmanship or test terminated prematurely are the main problems. One of the main advantages of the test has been lost due to poor workmanship.

In other countries, the use of pressuremeter is much less developed than in France. It is used for some large projects conducted by French companies or on sites where conventional SPT or CPT tests cannot be performed. In general, it seems that the pressuremeter has not been able to adapt to foreign geotechnical practice.

In any project, a geotechnical model is required to consider the natural scatter of ground conditions (spatial dispersion of data) and the soil volume variation induced by the strain and failure mechanisms. During pressuremeter investigation, the analysis of the measured data across the different test locations has to take into account both aspects in order to provide the geotechnical model. Currently, there is no specific reference method to do so. Attempts to take into account the spatial dispersion of the test data have been proposed, for example, from analyses based on statistics. This lack of reference methods often leads the geotechnical engineer to choose the value which seems to be the most realistic according to his own experience, which may not be the same value compared with others.

The Ménard modulus, the creep pressure and the limit pressure are typically some derived values in the sense of Eurocode 7. Their spatial variation can be analysed.

ARSCOP project was the opportunity to develop dedicated tools:

- Horizontal at rest pressure is a key parameter in geotechnical design, since it is directly linked to ground pressures applied to strutted retaining walls and tunnels. It also allows to assess the constitutive law of ground materials (evolution of the shear modulus with distortion level). Although correlations are mostly used, pressuremeter equipment can reliably measure this parameter. Several procedures are available or still under development: some of those may be applied during a standard Menard pressuremeter test with a specific interpretation, and other ones require to slightly adjust the loading procedure, for example in incorporating a contact procedure, and additional small cycles at the beginning of the test, or adding intermediary or final unloading phases. Based on different sites and ground types, and comparison with laboratory test results, a research has compared these different procedures and provide recommendations to assess the horizontal at rest pressure (Benoît et al., 2020).

- A chart classification tool for soils and rocks derived from classical Ménard Pressuremeter parameters p^*_{LM}, E_M and earth pressure at rest p_0, previously proposed (Baud & Gambin, 2013), linked to the alpha (α) rheological coefficient defined by Ménard

(1961) has been expanded and validated. The reliability of this (Pressiorama®, (Figure 3) classification for describing soil layers was tried in various case histories, and checked by several authors in recent years (Baud, 2005; Baud, 2021).

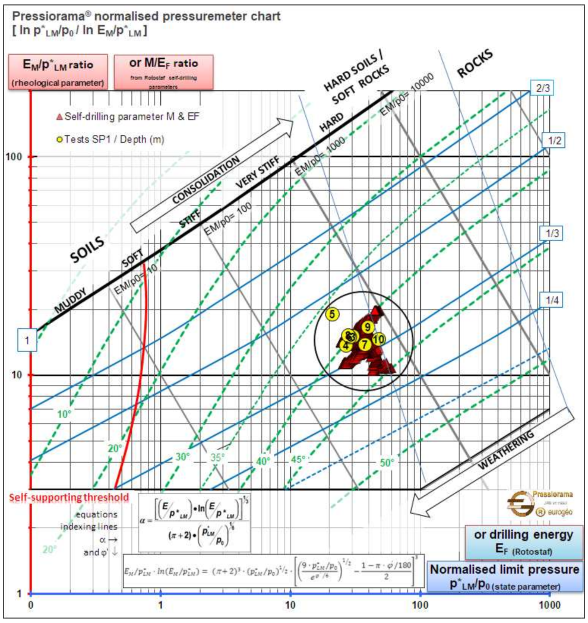


Figure 3. Dimensionless PMT chart based on state parameters E_M/p^*_{LM} and p^*_{LM}/p_0, comprising isolines of the values for α (Eq. 3) and the estimation for φ' (

- Web based solution developed by Soilcloud partner dedicated to the centralization of geotechnical data, has been used within the project to gather information from cross-check sites to begin digitizing its field data. It has shown the potential of these tools to modernize and streamline the daily work of the investigation teams (Fondasol and other partners) and the web based solution has been enriched and finalized to adapt the solution through feedback to pressuremeter use (Daktera et Janodet, 2024).

2.5. Liquefaction analysis

Liquefaction is of major concern in many countries subjected to seismic hazard. In practice, prediction of liquefaction is performed using simplified methods based on in situ tests such as the standard penetration test (SPT) or the cone penetration test (CPT). For some applications such as large projects (tunnels, high rise buildings), the Ménard pressuremeter is preferred as it provides a well-established method for foundation design. However, no simplified method to evaluate liquefaction potential has been fully developed for the pressuremeter. Based on pressuremeter calibration chamber and field tests on sands, a chart has been proposed for estimating the liquefaction susceptibility of saturated sands (Dang et al., 2019; Reiffsteck et al., 2022) (Figure 4). Other developments have been conducted in order to derive the relative density for hte pressuremeter tests (Figure 5).

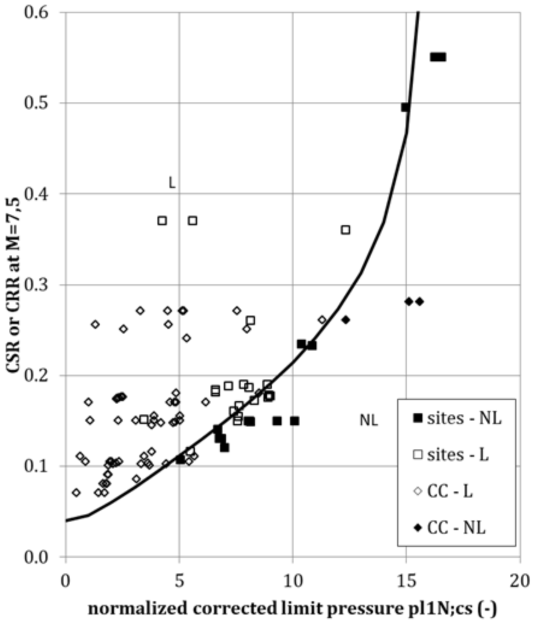


Figure 4. Comparison of the proposed cyclic resistance curve for clean sand with values from the literature.

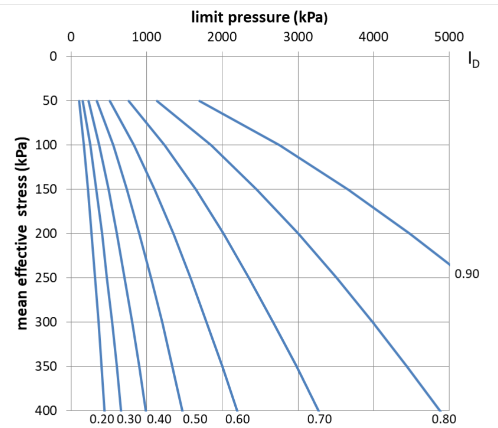


Figure 5. Diagram proposed for the determination of relative density with pressuremeter.

In addition, a method to correct the measured limit pressure from pressuremeter tests has been also proposed for tests in sands with fines content. The method was evaluated using extensive data obtained from tests performed in a calibration chamber using clean sand and sand with fines content against 45 pressuremeter tests performed in situ in various soil conditions. Based on these tests, a relationship was obtained between the field data and the chart developed from the calibration chamber tests. This research also provides suggestions to correct the limit pressure to account for the fines content.

Taking advantages of the last improvement of pressure volume controller, an application of multicyclic expansion tests carried out with a pressuremeter has been developed to evaluate soil susceptibility to this type of solicitation (Karagiannopoulos et al., 2020, 2022). These unique pressuremeter tests, interpreted in terms of deformation (volume change or radial strain) and number of cycles, offer relationships as a function of cyclic shear ratio

(Figure 6). New test procedures and probe enhancements were also implemented to develop additional data and to improve the quality of these tests.

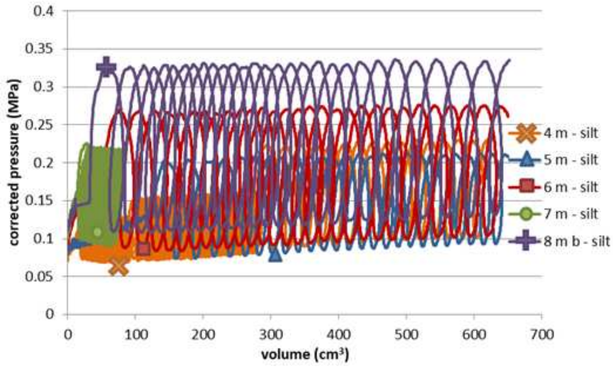


Figure 6. 2019 test campaign - Evolution of pressure with corrected pressure control for probe with (a) rubber membrane (borehole 4).

These cyclic tests were performed using a pre-bored Ménard pressuremeter as well as a new pressuremeter probe equipped with a miniature pore pressure transducer. Two sites were studied, one located in French Antilles and the second one located in Brittany (France), both consisting of normally consolidated sandy and silty soils profiles. An estimation of the relationship between cyclic stress ratio applied during the tests and the number of cycles to reach failure have been presented (Figure 7).

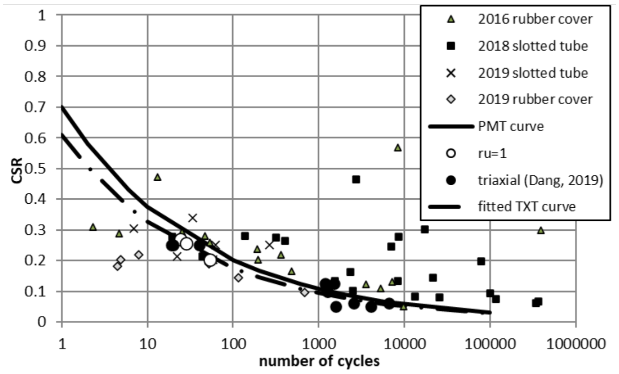


Figure 7. Comparison of the calculated and measured values for the bearing factor according to the LCPC database.

These results were compared to traditional cyclic laboratory test results and showed great potential for this in situ testing method. The results were used to develop preliminary charts for liquefaction prediction. This article presents a summary of the analysis and application of these cyclic pressuremeter tests.

3. Calculation models for bearing capacity of shallow and deep foundations

The limit pressure obtained during pressuremeter test is the most important parameter for the assessment of the bearing capacity of shallow and deep foundations. In the case of shallow foundations, this calculation is carried out by means of correlations between the limit pressure and the ultimate resistance of the soil. In the case of deep foundations, the calculation is carried out by means of a correlation between the limit pressure and the bearing resistance at the toe of the pile and the unit axial friction along the pile shaft. These correlations are obtained through statistical analysis of full scale static loading tests on shallow and deep foundations. The comparison between the values estimated by different calculation models and the measured resistance values allow to fix the partial factors (or safety factors) defined in the French standards.

For shallow foundations, these tests were conducted during the 1960s and 1970s on different experimental sites and they were collected by IFSTTAR (in a similar manner to the one performed by NGES in USA). There were 15 load tests in silty soils,11 in clayey soils, 29 in sandy soils and 5 in chalk. The results (Figure 8) allow to propose a comparison between the measured ultimate bearing pressure $q_{ult,mes}=k_{p,mes}.p_{le}^*$ and the calculate ultimate bearing pressure $q_{ult,cal}=k_{p,cal}.p_{le}^*$ where p_{le}^* corresponds to geometric mean of the net values of limit pressure p_l^* on a depth equal to 1.5B below the base of the foundation.

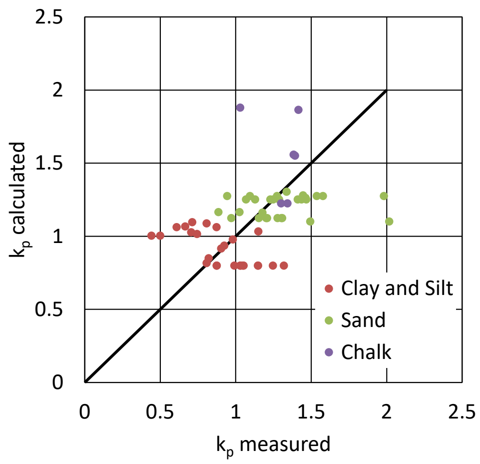


Figure 8. Comparison of the calculated and measured values for the bearing factor according to the LCPC database.

For deep foundations, compression load tests were carried out and kept for nearly 40 years by LCPC, IFSTTAR and UGE. They have recently calibrated new calculation models based on pressuremeter tests and cone penetration tests. These new models are included in the French National Standards NF P 94-262 related to the design of deep foundations and it is compatible with Eurocode 7 (Burlon et al., 2014).

The tip resistance R_b is determined by the relation:

$$R_b = k_p A_b p_{le}^*$$

where the values k_p are presented in Table 1.

Table 1. Bearing pressure coefficient

Ground / Class of pile	Clays % CaCO3 < 30 % Silts Intermediate soils	Intermediate soils Sands Gravels	Chalks	Marls and marly limestones	Weathered and fragmented rocks (a)
1	1.15	1.10	1.45	1.45	1.45
2	1.30	1.65	1.60	1.60	2.00
3	1.55	3.20	2.35	2.10	2.10
4	1.35	3.10	2.30	2.30	2.30

5	1.00	1.90	1.40	1.40	1.20
6	1.20	3.10	1.70	2.20	1.50
7	1.00	1.00	1.00	1.00	1.20
8	1.15	1.10	1.45	1.45	1.45
For piles of classes 5, 6 and 7 executed with vibrodriving instead of driving, it is appropriate to reduce the factor k_p by 50%. (a) Rock mechanics approaches have also to be applied, if relevant.					

The shaft friction q_s is determined with the following relation:

$$q_s = \min(\alpha_{pile-soil} f_{soil}; q_{smax})$$
$$\text{with } f_{soil} = (a.p_l^* + b)\left(1 - e^{-\frac{p_l^*}{c}}\right)$$

The parameters a, b, c and $\alpha_{pile-soil}$ are given the French standards NF P 94-262. The parameter $\alpha_{pile-soil}$ depends on both the soil types and the pile categories, whereas the function f_{soil}, defined by parameters a, b and c, depends only on the soil types. The function f_{soil} is also shown in Figure 9. This function is defined until a value of net limit pressure equals to 7 MPa, for which the maximum values of unit shaft friction q_{smax} can be calculated. When the net limit pressure is greater than 7 MPa, it is recommended to "cap" this value or to proceed to full scale static pile load test.

Figure 10 shows the ratio between the calculated value of the bearing capacity R and the measured value of the bearing capacity R_m. This ratio has been calculated for the three last calculation model used in France for the assessment of the bearing capacity. This type of analysis allows the determination of the model factor following Eurocode 7 recommendations.

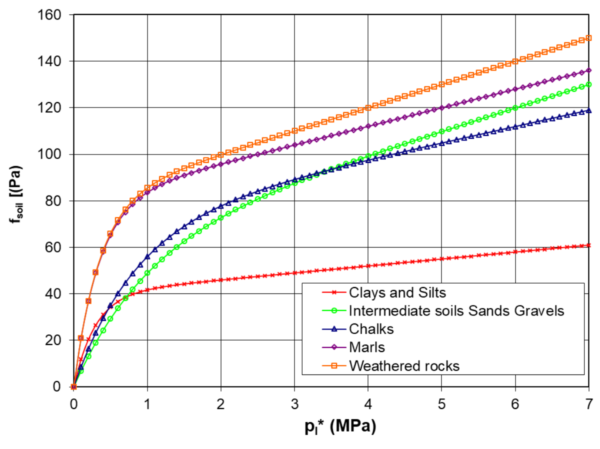


Figure 9. Function f_{soil} for the calculation shaft friction

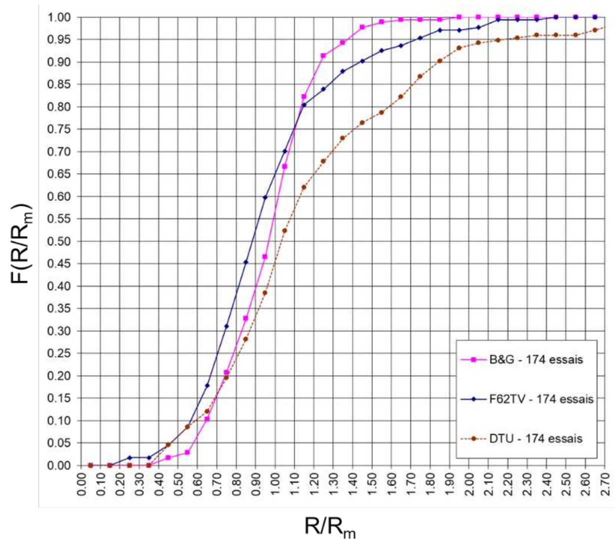


Figure 10. Distribution function of R/R_m for 174 piles 'PMT 2012' model (Burlon et al., 2014)

However, the relevance of this static load test database is becoming questionable since IFSTTAR (who is in-charge of this database) is getting less and less involved in conventional static load tests and that the piles considered for the calibration of the calculation models are old piles and they do not fully reflect the piling techniques currently used in the industries. If the database is not updated regularly, it would not be possible to update the calculation models and the prevailing safety factors. It would become necessary to use calculation models based on SPT and CPT. Also, it would be likely that the length of piles calculated with this direct design method will be longer and hence, a lack of optimization in design. Unless there is a continuous update of database using current piling techniques, companies will lose their competitiveness edge in terms of design of foundations given by the pressuremeter results and the associated calculation models. Nevertheless, during ARSCOP project, the database was clearly maintained and new issues can now be addressed such as the reuse of pile in line with the assessment of existing structures.

4. Calculation methods for displacements of geotechnical structures

When the pressuremeter modulus is evaluated according to current recommendations, it is an essential parameter to estimate the displacements and the deformations of geotechnical structures. For shallow foundations, from the relations proposed by Ménard, it allows the calculation of the settlement of the foundation according to the load applied. These rules are included in the Fascicule 62 Title V and in the French National Standard NF P 94-261related to the design of shallow foundations and it is compatible with Eurocode 7. For deep foundations, it is load transfer curves (t-z or p-y curves). For retaining walls, the pressuremeter modulus is also used to assess lateral displacements of sheet piles or diaphragm walls. Finally, it is also used for correlation by performing computations requiring Young's moduli.

The above examples distinguish three fields of application of the pressuremeter modulus:

- Direct calculation methods as in the case for shallow foundations;
- Calculation methods of soil-structure interaction based on the definition of curves representative of local interaction such as t-z or p-y curves;
- Methods based on modeling the ground as a continuous medium.

The use of pressuremeter modulus with a direct method of assessing soil displacements is restricted to shallow foundations. The method of settlement calculation from the Ménard pressuremeter, as proposed by standard NF P 94-261, is the method that was originally proposed by Ménard and Rousseau (1962). The pressuremeter modulus E_M is a deviatoric modulus that is well adapted to assess the settlement of foundations for which the deviatoric stress field is prominent, i.e., "narrow" foundations such as footings of buildings and bridges (unlike foundations having large dimensions relative to the compressible layer, such as embankments or rafts). In France, the alternative to this method remains undeveloped. In other countries, other methods exist including those based on the concept of stiffness where the ground is seen as a continuum medium whose properties can be defined by its Young's modulus or its shear modulus. The comparison of these last relationships with those of Ménard show that all these methods take into account in the same way the influence of foundation dimensions. However, the value of the settlement is not the same and requires some corrections on the Young's modulus or on the pressuremeter modulus.

The second application of pressuremeter modulus is related to the definition of local interaction laws. The t-z or p-y laws are widely used for the justification of the displacements of retaining walls and piles subjected to axial and transverse static or cyclic loads and seem to give satisfactory results. For shallow foundations or rafts, these local interaction laws raise a number of issues. However, developments are coming especially if experiments on real structures are performed.

The third application of the pressuremeter modulus is related to the soil modeling as a continuous medium and the use of numerical methods such as the finite element method or finite difference method. This type of application is of major importance. The correlations between the pressuremeter modulus and the Young's modulus are very diverse and no consensus seems to be emerging. Large differences in the results are thus obtained in terms of displacements or deformations. The basic problem here is to link the pressuremeter modulus with the elastic moduli depending on the stress state and the strain rate.

4.1. Example of direct calculations

The settlement over 10 years of a foundation having at least an embedment equal to one width B is given by the relation:

$$s(10\ \text{years}) = s_c + s_d$$

where:

$s_c = (q - \sigma_v)\lambda_c B\alpha/9E_c$ is the volumetric settlement;

$s_d = 2(q - \sigma_v)B_0(\lambda_d B/B_0)^\alpha/9E_d$ is the deviatoric settlement;

and where:

q is the vertical stress applied by the foundation;

s_v the total vertical stress before works at the base level of the foundation;

λ_c and λ_d the shape factors;

α is the rheological factor ($1/3 \leq \alpha \leq 1.0$), which depends on the nature of the soils (or of the rock);

B is the width (or diameter) of the foundation;

B_0 is the reference dimension, equal to 0.60 m; and

E_c and E_d are the pressuremeter moduli, in the volumetric zone and in the deviatoric zone respectively.

Two methods have been developed in framework of the ARSCOP project. These two methods are respectively based on the approaches A and B justified below. There are in line with the « S » shaped curves presented in 4.3.

For these two approaches (Hoang et al., 2018, El Khotry et al. , 2019), the settlement of a rigid spread foundation with a width B and a length L is calculated by considering 16 sub-layers with a width B/2:

- Approach A:

$$s = \frac{B}{2}\sum_{i=1}^{16} \frac{\eta_i \times a}{1 - \eta_i \times b} \quad with \quad \eta_i = \frac{q}{E_{M,i}} I(z)$$

where a and b are the two parameters provided previously (Family A)

and I(z) is given in the next table (Table 2).

- Approach B:

$$s = \frac{B}{2}\sum_{i=1}^{16} \frac{\mu_i \times a}{1 - \mu_i \times b} \quad with \quad \mu_i = \frac{q}{E_{M,i}} F(z)$$

where a and b are two parameters provided previously (Family B);

and F(z) is given in the next table (Table 2).

Comparisons with the Ménard solution are presented in Figure 11.

4.2. Example of t-z and p-y curves

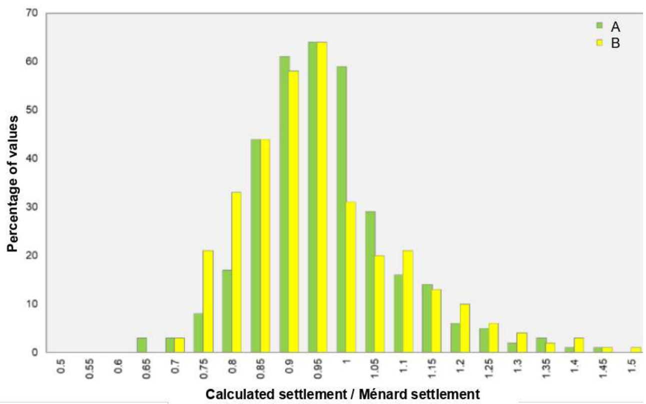
4.2.1. Axial behaviour

In addition to limit pressures that give a good assessment of shaft friction and bases resistance values for the design of piles, the Ménard modulus can be used to build t-z curves. Several correlations have been proposed: the most famous one is due to Frank and Zhao (1982) and more recently some attempts have been proposed to improve this model. Figure 12 show the distribution function of the ratio between the measured pile settlement « s_m » and the calculated pile settlement « s_{cal} » for 90 piles extracted from the LCPC database. The results show the good ability of these models to predict pile settlement. Nevertheless, it is important to have in mind that the results have a scatter between 30 and 50 % that the design should account for in its design.

Table 2. Values for the functions I and F

i	z_i/B	I(z_i)					
		L/B					
		1	2	3	4	5	20
1	0.0 – 0.5	0.353	0.354	0.355	0.363	0.370	0.395
2	0.5 – 1.0	0.265	0.309	0.319	0.325	0.330	0.351
3	1.0 – 1.5	0.148	0.212	0.233	0.241	0.246	0.261
4	1.5 – 2.0	0.088	0.142	0.169	0.181	0.187	0.200
5	2.0 – 2.5	0.057	0.099	0.124	0.138	0.146	0.160
6	2.5 – 3.0	0.039	0.071	0.094	0.108	0.117	0.132
7	3.0 – 3.5	0.029	0.054	0.073	0.086	0.095	0.112
8	3.5 – 4.0	0.022	0.042	0.058	0.070	0.078	0.097
9	4.0 – 4.5	0.017	0.033	0.046	0.057	0.065	0.084
10	4.5 – 5.0	0.014	0.027	0.038	0.048	0.055	0.074
11	5.0 – 5.5	0.011	0.022	0.032	0.040	0.047	0.066
12	5.5 – 6.0	0.010	0.019	0.027	0.034	0.040	0.059
13	6.0 – 6.5	0.008	0.016	0.023	0.030	0.035	0.052
14	6.5 – 7.0	0.007	0.014	0.020	0.026	0.031	0.047
15	7.0 – 7.5	0.006	0.012	0.017	0.023	0.027	0.043
16	7.5 – 8.0	0.005	0.010	0.015	0.020	0.024	0.039

i	z_i/B	F(z_i)					
		L/B					
		1	2	3	4	5	20
1	0.0 – 0.5	0.335	0.308	0.311	0.316	0.322	0.343
2	0.5 – 1.0	0.365	0.392	0.392	0.393	0.396	0.417
3	1.0 – 1.5	0.222	0.301	0.319	0.322	0.324	0.336
4	1.5 – 2.0	0.134	0.210	0.242	0.253	0.257	0.265
5	2.0 – 2.5	0.087	0.148	0.183	0.199	0.206	0.216
6	2.5 – 3.0	0.061	0.108	0.140	0.158	0.168	0.181
7	3.0 – 3.5	0.044	0.082	0.109	0.127	0.139	0.156
8	3.5 – 4.0	0.034	0.063	0.087	0.104	0.116	0.136
9	4.0 – 4.5	0.027	0.051	0.070	0.086	0.097	0.120
10	4.5 – 5.0	0.021	0.041	0.058	0.072	0.083	0.106
11	5.0 – 5.5	0.018	0.034	0.049	0.061	0.071	0.095
12	5.5 – 6.0	0.015	0.029	0.041	0.052	0.061	0.085
13	6.0 – 6.5	0.013	0.024	0.035	0.045	0.053	0.077
14	6.5 – 7.0	0.011	0.021	0.031	0.039	0.047	0.069
15	7.0 – 7.5	0.009	0.018	0.027	0.034	0.041	0.063
16	7.5 – 8.0	0.008	0.016	0.024	0.030	0.037	0.057



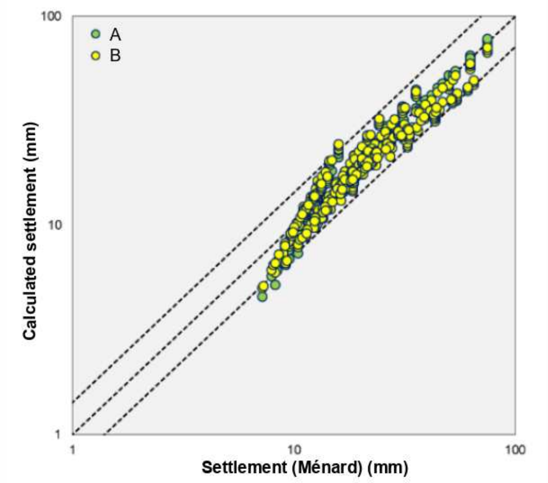


Figure 11. Comparison between Ménard model and ARSCOP models (approaches A and B)

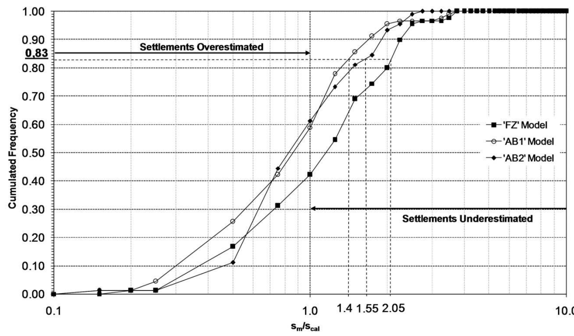


Figure 12. Distribution function s_m/s_{cal} for 90 piles (Abchir et al., 2016)

4.2.2. Lateral behaviour

The lateral behaviour of piles can be considered by p-y curves built in a similar way than t-z curves : the creep pressure or the limit pressure is considered as a strength parameter and the Ménard modulus is considered a deformation parameter. For laterally loaded piles, the relationship giving the slope of the p-y curve is deduced from the Ménard relationship used for the shallow foundation with a rotation of 90° and the consideration of a strip footing. The relationship is the following :

$$qB = s\frac{18E_M\, B/B_0}{2\lambda_c\, B/B_0\; \alpha + 4(\lambda_d\, B/B_0)^{\alpha}}$$

with λ_c=1.5 and λ_d=2.65 as it corresponds to a « strip footing ».

4.2.3. Retaining wall

For a retaining wall, p-y curves are also used and the slope of these curves can be determined with the Ménard modulus. The main idea is to establish a relation between the transfert length and the subgrade reaction modulus (Schmitt, 1995) :

$$k_h = \beta\frac{E_M}{l_0} \quad \text{and} \quad l_0 = \left(\frac{4EI}{k_h B}\right)^{1/4}$$

$$k_h = \frac{(\beta E_M)^{4/3}}{(4EI/B)^{1/3}}$$

where β is a scale factor taking into account the soil type for a strain range between 10^{-3} and 10^{-4} :

- β=2.5 for soft clay;
- β=3.3 for stiff clay, chalk, marls and loose sand;
- β=5.0 for dense sand.

B is equal to 1.0 for a retaining wall and to the pile diameter for a pile.

4.3. Pressuremeter data for continuous medium

Approaches A and B presented previously can be used to derive a representative value of the Young modulus taking into account the strain range (Figure 13). Several comparisons have been performed in order to show the ability of these two approaches for rafts and spread foundations. An important issue to highlight is the fact that the choice of the Young modulus is not just a matter a strain amplitude: the ability of the structure to transfer the loads is crucial and should be taken into account. The stress path is also important and can have a significant effect on the correlation.

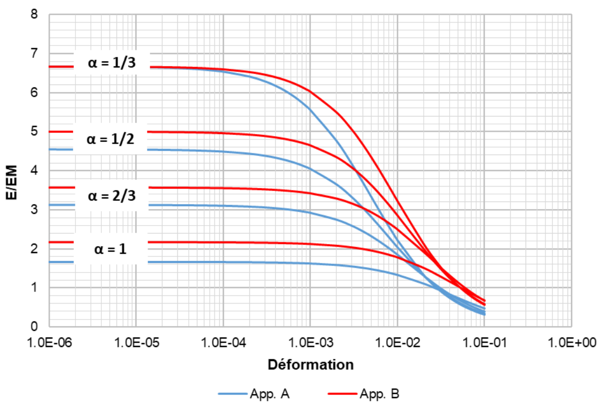


Figure 13. Assessment of the deformation modulus E from the approaches A and B

5. Conclusions

The National Project ARSCOP aims to continue with the development of pressuremeter to provide better and more relevant testing procedures for ground investigation to obtain reliable soil and rock properties to be used in calculation methods for better geotechnical design. This paper has described the objectives of this project together with well-defined work tasks.

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