Pressuremeter based methods to predict the behaviour of grouted micropiles and anchors

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ABSTRACT: Menard pressuremeter based calculation methods efficiently predict the behaviour of foundations and especially enable i) to estimate their (ultimate) resistance, and ii) to assess their load-displacement behaviour.
For grouted micropiles and anchors, although static load tests are always performed due to the sensitivity of their execution (and especially grouting stages), semi-empirical methods remain essential in preliminary stages of design.
To take into account evolution of contractors practice and development of new execution procedures, a database of static load tensile tests performed in France has been established, with more than 250 tensile static load tests. Their comparison to prediction of calculation approaches enables i) to evaluate and validate the existing pressuremeter based models, and ii) to determine a specific calculation model factor ensuring a predefined target of safety for resistances, following Eurocode 7 requirements.

Keywords: pressuremeter; Menard limit pressure; micropiles; grouted anchors; ultimate resistance; critical creep load

1. Introduction

The Menard Pressuremeter Test is an efficient tool to predict behaviour (both resistance and deformation) of piles, micropiles, anchors and soil nails, based on semi-empirical models.

For piles, current French national application documents of Eurocode 7 NF P94-262 ([1], 2012]) dedicated to the design of pile foundations provides details about the semi-empirical pressuremeter models to determine the bearing capacity and tensile resistance of pile foundations. The statistical analysis of the LCPC static load tests database has to assess the quality of the model, including its scatter, that can be quantified through a model factor directly usable in design procedures. (Burlon et al., [2] and [3]), and to

The present paper proposes to adopt a similar approach for grouted micropiles and anchors, for which the target post-grouting pressure is closely linked to the limit pressure of the ground.

2. Constitution of the database

2.1. Origin of the data

The database has been initiated with more than 300 faliure tests coming from SNCF (French National Railway Company) and Cerema (Centre For Studies and Expertise on Risks, Environment, Mobility, and Urban and Country planning) databases.

Over these 300 tests, only 40 tests have been maintained in the database: the other ones have ben discarded for different reasons (insufficient maximum load, grouting conditions insufficiently kwown, issue with the observed free length, etc.. However, the database has been then completed with additionnal data coming from LCPC database, established by Bustamante and Doix (1985, [4]).

2.2. Ground classification and execution conditions

2.2.1. Ground classification

As for French semi-empirical rules for predicting bearing capacity of both shallow and deep foundations, commonly encountered ground types are sorted in 4 conventionnal ground classes :

- Clays and silts,
- Sands and gravels (only siliceous sands are addressed here),
- Chalk,
- Marls and calcareous marls, for which the $CaCO_3$ content is between 35 and 95 %.

The Menard limit pressure p_{lM} (corresponding to the doubling of the initial volume of the pressuremeter probe, with a reference volume corresponding to the first contact pressure) is then systematically used.

2.2.2. Execution conditions

Two execution conditions have been kept for the present paper :

- A unique and globally post-grouting, with a grouting pressure p comprised between 0,5 p_{lM} and p_{lM},
- A selective and multi-stage post-grouting, with a grouting pessure p systematically superior to p_{lM}.

During the post-grouting phase, the grouting flow remains small, comprised between 5 and 10 l/s.

2.3. Content of the database

The database exclusively contains tensile failure tests, and its content is summarized in Table 1, for different execution conditions and ground types.

Table 1. *Constitution of the database – number of measurements*

Execution conditions → *Ground type* ↓	**Global grouting 0,5 p_{lM} < p < p_{lM}**	**Selecting and multistage grouting $p \geq p_{lM}$**	**Sub-total**
Clays and silts	38	57	*95*
Sands and gravels	40	114	*154*
Chalks	1	3	*4*
Marls, calcareous marls	5	18	*23*
Sub-total	*84*	*192*	***276***

3. Analysis of the tensile resistance and unit shaft friction

3.1. Evaluated rules

The rules to predict unit axial shaft friction q_s are based on the ground types given in Table 1, execution conditions, completed by the compacity of the ground, characterized by the net Menard limit pressure p_{lM}* (p_{lM}-σ_{h0}).

The overall tensile resistance of a micropile or grouted anchor is obtained by Equation (1).

$$R = \pi B \int \alpha q_s(x) dx \quad (1)$$

where B is the diameter of the drilling tool and α an expansion ratio, depending of the ground class and grouting conditions.

Under these conditions, the unit axial shaft friction q_s is obtained following Equation (2).

$$q_s = a p_{lM}^* + b \quad (2)$$

The parameters a, b and α are then provided in Table 2, for the different ground classes and execution conditions.

Table 2. *Semi-empirical rules*

Ground class	*Grouting conditions*	*a (-)*	*b (MPa)*	*α (-)*
Clays and silts	*Global*	0,06	0,1	1,1 to 1,4
	Selective and multistage	0,08	0,04	1,4 to 1,8
Sand and gravels	*Global*	0,1	0	1,1 to 1,2
	Selective and multistage	0,1	0,05	1,4 to 2,0
Chalks and marls	*Global*	0,05	0,1	1,1 to 1,2
	Selective and multistage	0,07	0,13	1,8

3.2. Conventional criterion to derive ultimate resistance

On a first step, an analysis of the failure criteria used to derive tensile resistance for anchors is conducted

In France, test Method 3 is used to test anchors ([5] to [7], 1999 to 2019), that corresponds to a maintained Load Test with monotnous increasing of the applied load during the loading phase.

Even if the loading procedure remains globally the same as before, it also introduces a new conventional failure criterion. Although failure has currently a simple definition, which is the load that can not be supported by the anchor, conventionnal failure critera are often introduced used to interpret static load tests performed on geotechnical structures. For anchors, EN 1537:1999 ([8]) first introduced the following failure criterion to derive the tensile resistance, corresponding to a creep value (slope of anchor head displacement versus logarithm of time) α_3 equals to 5 mm. This "new" criterion differs from the one previously used in France ([9], 1993), corresponding to the following conventionnal anchor head displacement w_u given by the Equation (3):

$$w_u = \frac{FL}{ES} + \Delta l_{es} \quad (3)$$

where F is the applied load, E the Young's modulus of the tendon, S its cross section, L its overall length and Δl_{es} a conventionnal displacement to fully mobilize the shaft friction at the tip of the bonded length of the micropile or the grouted anchor, equal to 1 cm.

The comparison of the obtained tensile resistance is provided on Figure 1.

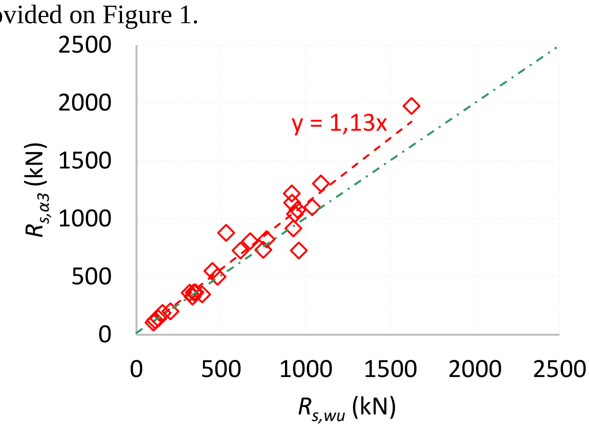


Figure 1. *Comparison of failure criteria*

It then appears that the "new" criterion leads to slightly higher tensile resistance (+13 %), but the difference remains acceptable, especially because both compared criteria remain conventional.

3.3. Obtained results

On a first step, the obtained raw data are given on Figures 2 and 3, representing the measured unit shaft friction $q_{s,mes}$ multiplied by α[1] versus the net Menard limit pressure p_{lM}*.

On a second step, the calculated unit shaft friction $q_{s,cal}$ is represented versus the measured one, on Figures 4 and 5.

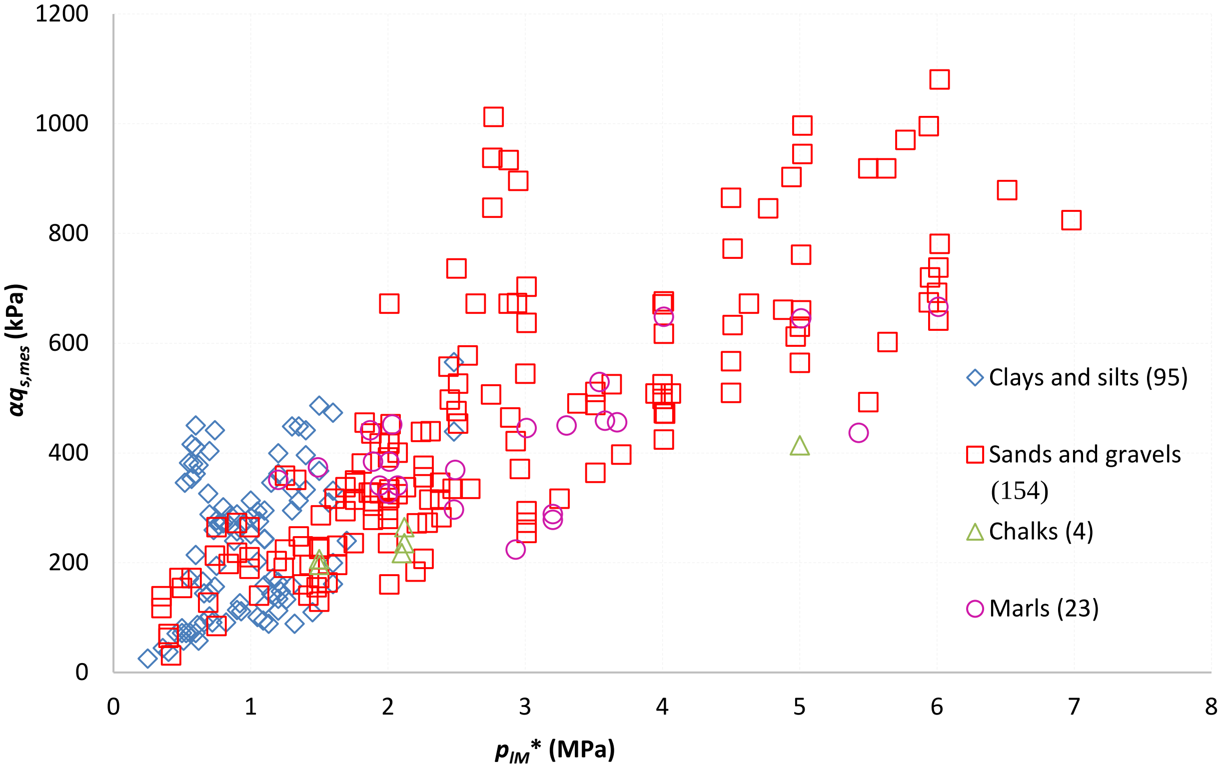


Figure 2. *Obtained results (by ground types – 276 q_s measurements)*

[1] When an interval is given for the expansion ratio α is available, the lowest value has been used for the present analysis.

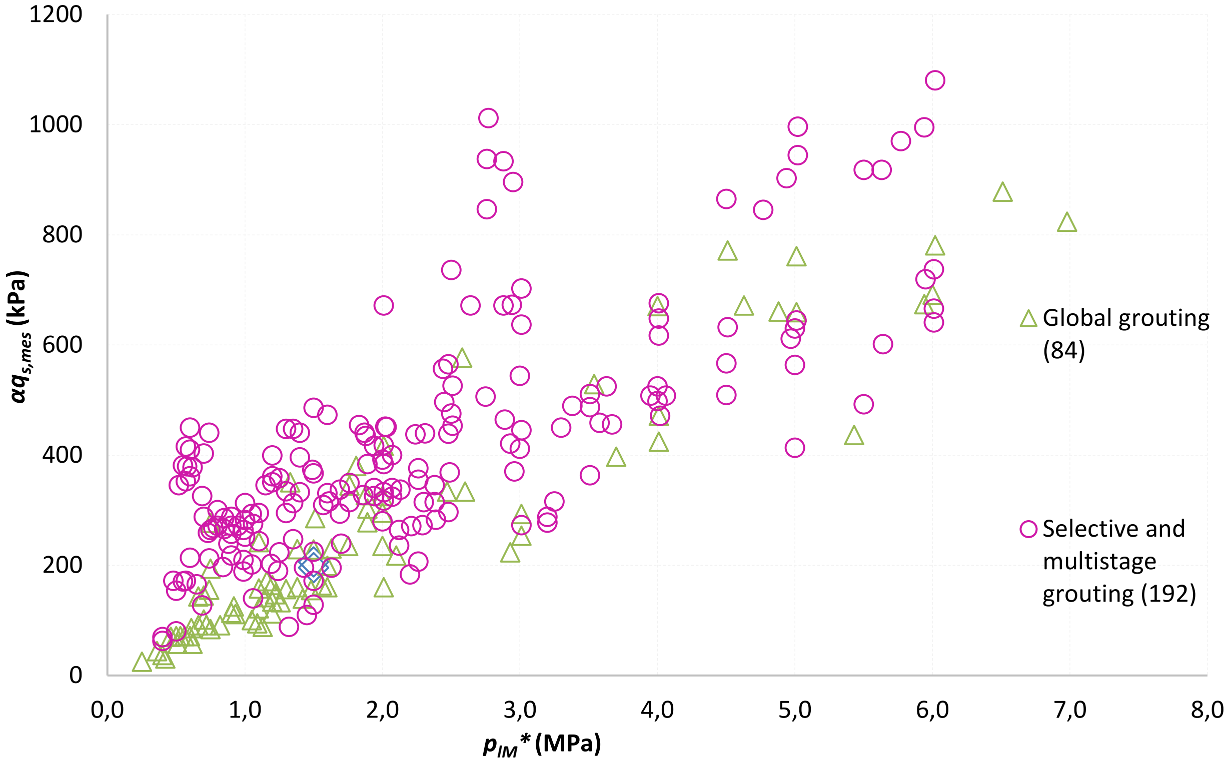


Figure 3. *Obtained results (by execution conditions – 276 q_s measurements)*

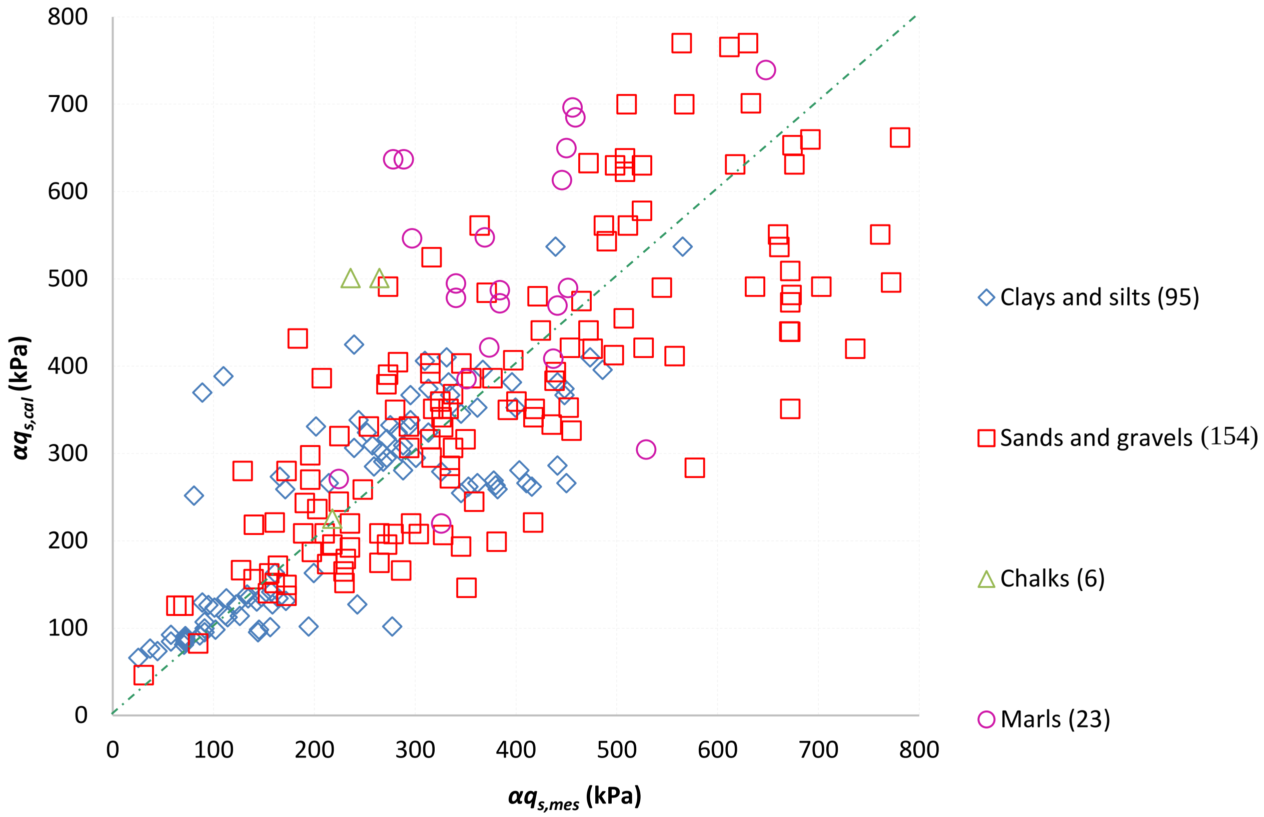


Figure 4. *Comparison of measured and calculated shaft friction, respectively $\alpha q_{s,mes}$ and $\alpha q_{s,cal}$ (by execution conditions – 276 q_s measurements)*

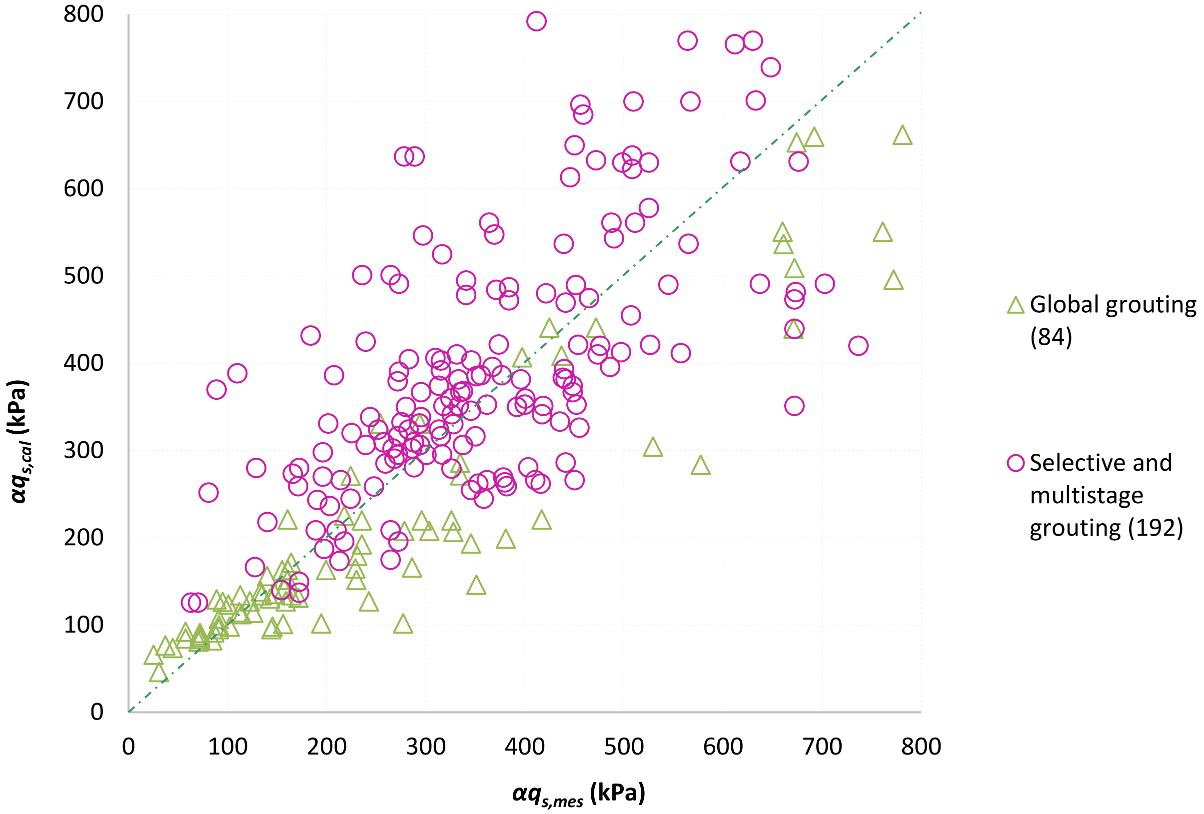


Figure 5. *Comparison of measured and calculated shaft friction, respectively $\alpha q_{s,mes}$ and $\alpha q_{s,cal}$ (by execution conditions – 276 q_s measurements)*

3.4. Statistical analysis

On a second step, a statistical analysis of the ratio between calculated and measured resistance is conducted. Figure 6 shows the global analysis. Figure 7 and 8 then focus on the two main ground classes, clays and silts then sands and gravels.

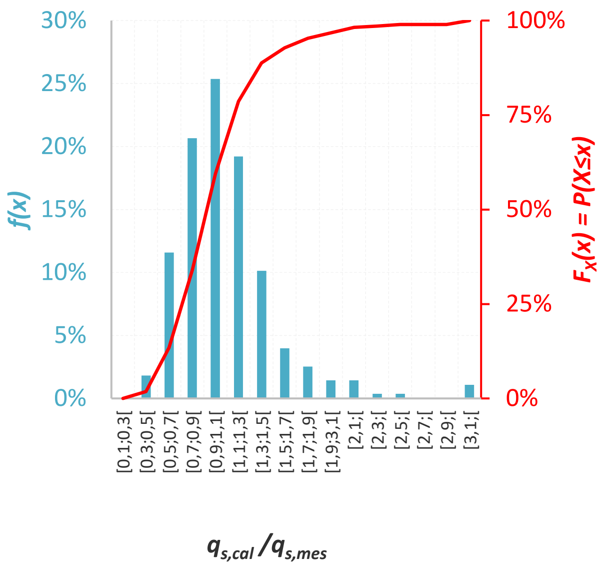


Figure 6. *Histogram and distribution functions of unit shaft friction ratio*

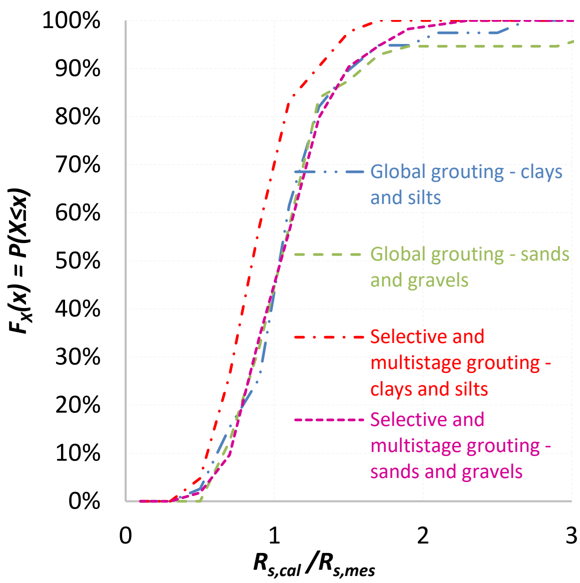


Figure 7. *Distribution function of global resistance ratio*

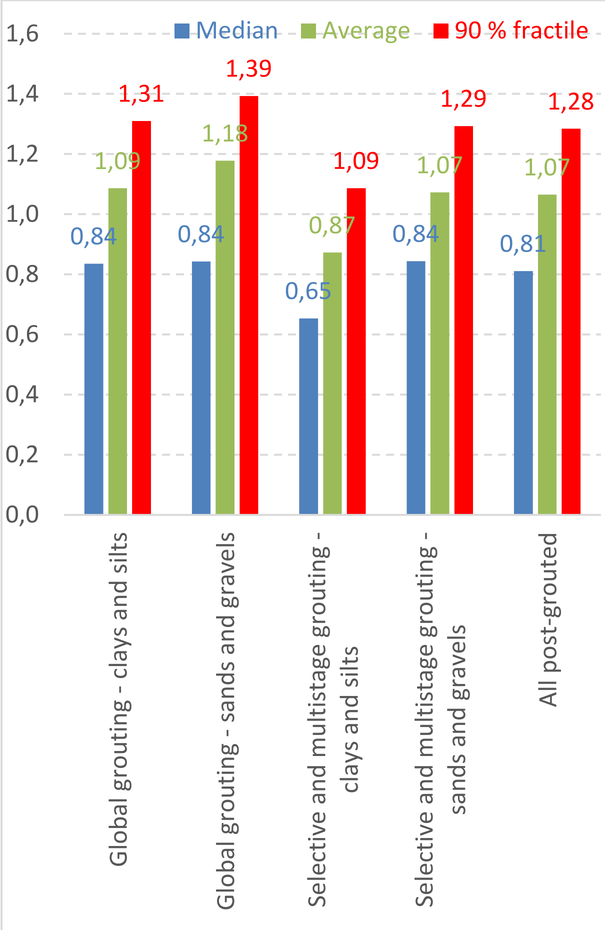
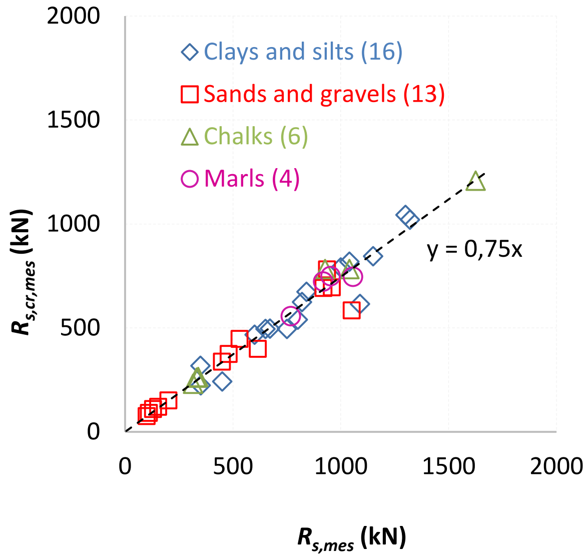


Figure 8. *Average, median and 90 % fractile for clays and silts then sands and gravels*

It then appears that the semi-empirical pressuremeter-based rules is quite well calibrated, as median and especially average values remain quite close from 1,0 value (apart from selective and multistage grouting in clays and silts). The 90 % fractile value highlights the low scatter, and can be directly used as model factor to derive characteristic tensile resistances in accordance with Eurocode 7 provisions.

3.5. Critical creep load

Finally, the ratio between the critical creep load $R_{s,cr}$ (applied load beyond which creep effects become significant, [9] and [10]) and the the tensile resistance R_s is analysed on Figure 9 and is equal to 0,75. It appears to be quite consistent with the commonly used value equals to 0,70, and does not seem to depend of the ground class.



4. Conclusion

The present paper shows the statistical analysis of a database of tensile tests and of the semi-empirical pressuremeter-base rules used in France to derive unit shaft friction and then global tensile resistance of post-grouted micropiles and anchors.

Under the specific groutig conditions given above, the commonly used French rules appear hence quite well calibrated, with a limited scatter, that has also been quantified.

Even if systematic tests remain mandatory for these sensitive geotechnical elements, the proposed analysis helps designer to setablish a preliminary design but also to efficiently prepare a campaign of tensile tests.

Acknowledgement

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