Soil and Rock Classification from Pressuremeter Data. Recent Developments and Applications.

Classification pressiométrique des sols et des roches. Développements récents et applications.

J.-P. Baud
Eurogéo, Avrainville, France, baud@eurogeo.fr

ABSTRACT: A chart classification of soils and rocks derived from classical Ménard Pressuremeter parameters p^*_{LM}, E_M and earth pressure at rest p_0, was previously proposed (Baud & Gambin, 2013), linked to the alpha (α) rheological coefficient defined by Ménard (1961).
The reliability of this (Pressiorama®) classification for describing soil layers was tried in various case histories, and checked by several authors in recent years (ref. in the paper).
In this paper we indicate development of the Pressiorama classification in four trends:
- Adaptation of coefficient k_E in the expression of α, taking into account some site conditions and drilling quality as experimented in these case histories.
- Correlation between this Pressiorama classification and the behaviour of soils and rocks in terms of auger-drilling (refusal level), drilling (drillability), driving (drivability) and even jetting. A graphical chart (E_M/p_o, α) is proposed.
- How to use Pressuremeter data sets {E_M, p^*_{LM}, p_o} on one site to determine seismic zoning according to Eurocode 8 (EN 1998) as a substitute to the parameters Cu (shear stress) and Vs (seismic velocity), the main criteria proposed by this Standard, but less easy to obtain during soils surveys than pressuremeter data. The proposal is based on two classic relations, Cu = f (p^*_{LM}, α) and Vs = f (E_M, α, γh, g), allowing to define soil seismic class only from E_M, p^*_{LM}, and PMT tests depths.
- Proposition of a new graph [$Ec1/E_M$; p^*_{LM}/p_0] by using one-cycle PMT.

Keywords: Pressuremeter, Ménard modulus, Drillability, Soil classification, Seismic zoning.

RÉSUMÉ : Un abaque de classification des sols et des roches, basé sur les paramètres classiques issus du Pressiomètre Ménard p*LM, EM et la pression des terres au repos p0 au niveau de l'essai, a été proposé (Baud & Gambin 2013), intégrant le coefficient rhéologique α (alpha) de L. Ménard (1961).
La fiabilité de cette classification (Pressiorama®) pour décrire la lithologie des sols a été testée sur différents chantiers par l'auteur, et également par différents auteurs publiés récemment (réf. dans l'article).
L'article montre le développement de cette classification dans différentes applications :
- Adaptation du coefficient k_E dans l'expression de α, prenant en compte les conditions de site ressortant de ces applications publiées ou non.
- Corrélation entre cette classification et le comportement des sols et roches en termes de refus à la tarière, de forabilité, de battage et vibrofonçage. Une expression graphique est proposée en surimposition sur le diagramme (E_M/po, α).
- Utilisation des données pressiométriques {E_M, p^*_{LM}, po} d'un site pour déterminer le zonage sismique en remplacement des paramètres proposés par l'Eurocode 8 (EN 1998), Cu (résistance au cisaillement) et Vs (vitesse sismique), données moins courantes sur site que les données pressiométriques. La proposition est basée sur deux relations classiques, Cu = f (p^*_{LM}, α) et Vs = f (E_M, α, γh, g), permettant de caractériser un site avec les seules valeurs de E_M, p^*_{LM}, et la profondeur des essais.
- Proposition d'un nouvel abaque [E_{c1}/E_M ; p^*_{LM}/p_0] utilisant les résultats de l'essai pressiométrique à un cycle.

Mots-clés : Pressiomètre, module Ménard, Forabilité, Classification des sols, Zonage sismique.

1. Introduction

The concept of sorting pressuremeter results by consolidating homogeneous subsets, before giving a statistical value to averages and dispersions of results, led to the creation of specific charts. Due to the characteristic typology of pressuremeter tests depending on the behaviour of ground subject to the test of cylindrical expansion, these charts become naturally soil and rocks classification modes. The interest is to furnish direct estimation for a lot of properties, more or less directly correlated to PMT measurements, such as elastic modulus hypothesis, refusal and drillability prediction, shear stress, seismic velocity, or estimation of liquefaction risk.

2. Use of PMT Pressiorama charts

2.1. An image of the spectrum of soil heterogeneity, and diversity of geotechnician's approach

The Pressiorama diagram as proposed originally (Baud, 2005) basically consists to report, from a series of PMT from one site survey, p^*_{LM} values versus E_M/p^*_{LM} ratio. Subsequently, various amendments have been added: extension to rocks domain, value for α rheological coefficient, replacement of p^*_{LM} by pressuremeter state parameter p^*_{LM}/p_0 (Baud & Gambin, 2011, 2013, 2016). The concept of pressuremeter state parameters was suggested by Dupla & Canou (2005). In the same time, several authors published case histories by using the diagram in various soils and rocks throughout different sites in the world:

- Ritsos *et al.* (2013) show on different geological formations in Greece a good correlation for cohesive and granular zones.
- Reiffsteck *et al.* (2013) point more dispersion, on the site of Grand Paris survey, by reporting pressuremeter surveys from a lot of drilling companies; they propose to modify the presentation of PMT parameters by using the axes [α | p^*_{LM}/p_0].
- Monnet (2013) resumes his theory of complete expression of p^*_{LM} as a function of friction angle φ', dilatancy ψ, horizontal pressure $K_0\gamma z$, shear modulus Ge (rather than E_M). He proposes to dispatch classification in 2 diagrams, [Ge/p0 | p^*_{LM}/p_0] for granular soils, [ln (Ge) | p^*_{LM}] for cohesive soils.
- Kanji M.A. (2014) cites Pressiorama chart in a general review on soft rocks. One of his diagram of case histories for natural rocks, reporting correlation for compression strength UCS versus E50 modulus, can be directly compared to Pressiorama chart.
- Tarnawski *et al.* (2015) report a lot of tests results in the same graph, from different formations in Poland, and find rather difficult to differentiate them, pointing also the influence of test quality on E_M/p^*_{LM} ratio.
- Elfatih *et al.* (2015) make a statistical study of PMT results in one single lithology, the Nubian sandstone formation in Sudan, and show the evolution of PMT values for this weak rock correlative with weathering.
- Hamdi & Holeyman (2016) apply their numerical modelling of cylindrical cavity expansion to a rock mass under different stages of weathering, and report this evolution in Pressiorama compared with PMT results on natural rocks.
- Marti, Perez & Devincenzi. (2019) study PMT surveys in Madingo, Cretaceous marly formation in Congo, and consider the ratio p^*_F/p^*_{LM} together with Pressiorama chart.

2.2. PMT State Parameters

Use of the limit pressure p^*_{LM} as main x-axis in the first Pressiorama is a natural way of thinking, as long as the concept of failing pressure in soils remains as one of the major contributions of Louis Ménard to geotechnical engineering. Unlike other parameters measured by different methods, for any soil-structure interaction, the failure criterion remains in direct proportion to the average limit pressure of the relevant area of soil. So, the range of values from 0 to 10 MPa for p^*_{LM} is by itself a classification of ground resistance from loose soils to soft rocks.

Nevertheless, for use as absolute soil classification, and for deducing intrinsic properties of soils, it is necessary to report PMT values to horizontal containment pressure p_0 created by test depth, and consider all charts in terms of the adimensional pressiometric state parameters: p^*_{LM}/p_0, E_M/p_0, E_M/p^*_{LM}.

2.3. Adaptation of the expression for α coefficient to site conditions

In the expression of α rheological coefficient, as given to draw parallel lines in Pressiorama chart (Baud & Gambin, 2013), we were brought to use a k_E "constant":

$$\alpha = \frac{\left(\frac{E_M}{p^*_{LM}}\right)^{\frac{1}{2}}}{k_E \cdot \left(\frac{p^*_{LM}}{p_0}\right)^{\frac{1}{4}}} \tag{1}$$

with a mean value of k_E=4, with lack of sufficient case histories experience at that moment.

Taking in consideration results from different authors cited above, and several recent case histories analysis (Baud et al., 2018), it seems necessary that k_E could be slightly variable, from around 5 for minimum value of E_M/p^*_{LM}, to 3 for higher existing values of this parameter. So k_E is given as

$$k_E = (\pi + 2)/(\ln E_M/p^*_{LM})^{1/3} \tag{2}$$

At the same time, the exponents of the two dimensionless parameters was slightly modified, their ratio remaining the same, and the expression was proposed for rather "perfect" tests, considered as selfbored. For the cases where a given amount of "remoulding", or more often simply decompression due to time between drilling and placing the probe, occurs, a correction is needed.

A more accurate expression for α is now given as:

$$\alpha = \frac{\left[\left(\frac{E_M}{p^*_{LM}}\right) \cdot ln\left(\frac{E_M}{p^*_{LM}}\right)\right]^{\frac{1}{3}}}{(1-d) \cdot (\pi+2) \cdot \left(\frac{p^*_{LM}}{p_0}\right)^{\frac{1}{6}}} \tag{3}$$

Where "*d*" < 1, is an estimation for decompression state of the soil before beginning of the test. This value can be either estimated by a knowledge of timing of drilling and testing sequences and drilling fluid used, or "measured" by the position of the point of contact between probe and borehole wall, in terms of volume (or radius) and pressure. So we can use to set an average value of "d" for a test or series of tests the relation in the graph below (Fig.1).

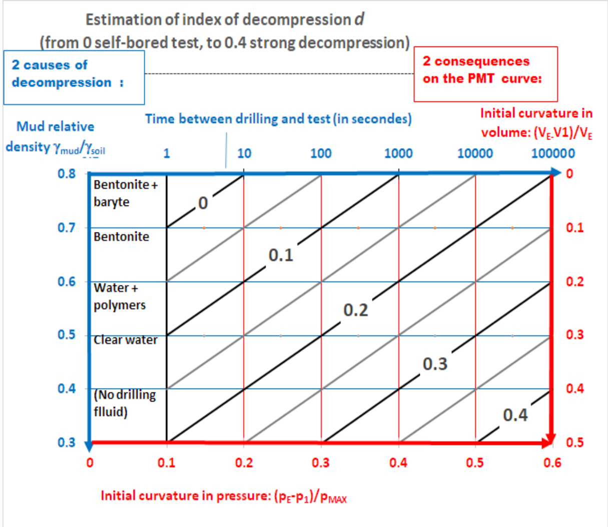

Figure 1. Estimation of the degree of decompression d, from 0 for a fully undecomprimed test (self-boring pressuremeter) to 0.4 for a test in highly decomprimed or remoulded soil.

3. PMT drillability chart

A series of case histories from different sites were examined, based on the experience of contractors in sinking, piling, driving, earthworks, often with a pressuremeter survey motivated by drilling, piling, driving or excavation conditions more difficult than hoped. By reporting these experiences in the Pressiorama graph as proposed (Baud & Gambin, 2013) with E_M / p_0 on the ordinate (bottom positive) and on the abscissa α value obtained from the test by Eq. 3, we can approximate on the diagram a succession of boundaries linked to the increase in the resistance of the soil or the rock to the working tool used (Fig. 2). These limits can be qualified by the nature of the machines or techniques commonly used in earthworks (grader, ripper, dozer, rockbit/rock-tooth or explosives). The result is similar to the "Seismic Velocity Charts" for rippers (Caterpillar®), based on the values of seismic velocity Vs, the propotionality of which is well known with the modulus of the soil or the rock. The refusal to auger drilling, a fairly general concept whatever the drilling rig, corresponds well enough to the border between soils, even very hardened, where a ripper can be used, and weathered or soft rocks where use of bulldozer is economically preferable.

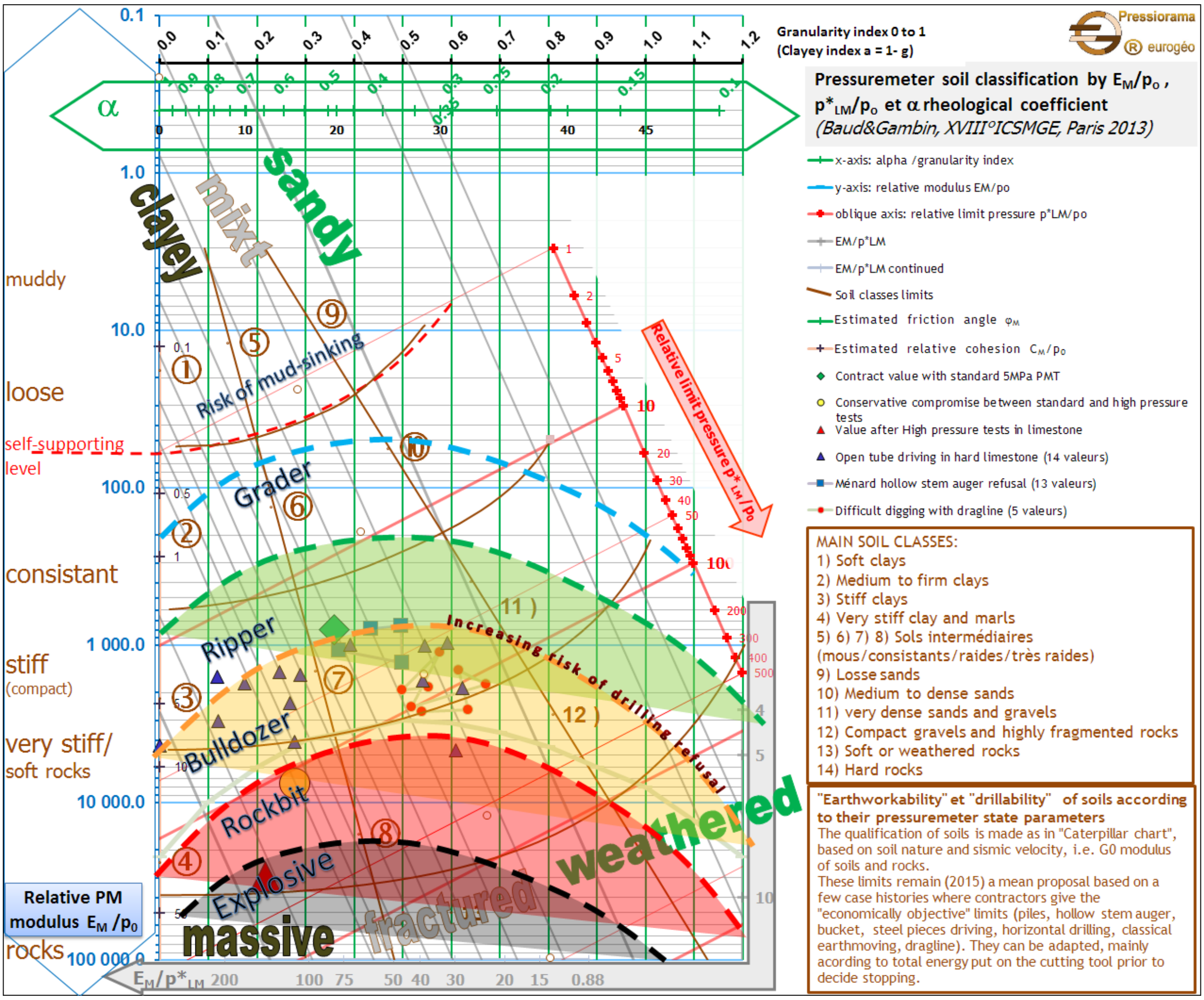

Figure 2. Drillability chart from Pressuremeter tests.

4. Eurocode 8 seismic zoning with PMT

This Standard enjoins geotechnicians to furnish a classification of building sites, based on geomechanical properties of the soil on the first 30 m of a site. Three parameters only are retained in the present redaction of the standard: seismic velocity Vs,30 (m/s), NSPT, shearing resistance Cu (kPa). A table in Eurocode 8 indicates conventional limits for these parameters to define 5 seismic classes A to E, and 2 classes S1 S2. This table is an implicite correlation between Vs and Cu such as Vs (m/s) = 2 Cu (kPa) (Fig. 3).

More often than not, in Europe, geotechnical surveys don't measure any of these three parameters. Instead, it can be proposed that mean results of a pressuremeter survey can be used by improved correlations of strength parameters p^*_{LM} to Cu, and deformation parameter E_M to Vs, by the way of using α coefficient deduced from PMT by Eq. (3).

The 2 axes of the graph becomes :

- For y-axis, the relation $C_u = p^*_{LM} / \beta$ (Ménard, 1963, Amar et al. 1991) where $5<\beta<15$ according to soil nature, is generalised to any test with the assumption $\beta \approx 5/\alpha$, so:

$$C_u\ (S_u) = \frac{\propto . p^*_{LM}}{\pi+2} \qquad (4)$$

- For x-axis Vs, the classical relation $G_0 = \rho\ .Vs^2$ [ρ volumic mass deduced from estimation of γ (γh = ρ . g)], and $G_0 \approx 3\ .\ E_M / \alpha^2$ gives :

$$V_{s\,(m/s)} = \left[\frac{3.g_{(m/s^2)}.E_{M\,(kN/m^2)}}{\gamma_{h\,(kN/m^3)}.\alpha^2}\right]^{1/2} \qquad (5)$$

A set of PMT representative results from 30m depth boreholes, as recommanded by the standard, can be used in a (Vs, Su) graph as in Fig.3 to determine seismic class for a site.

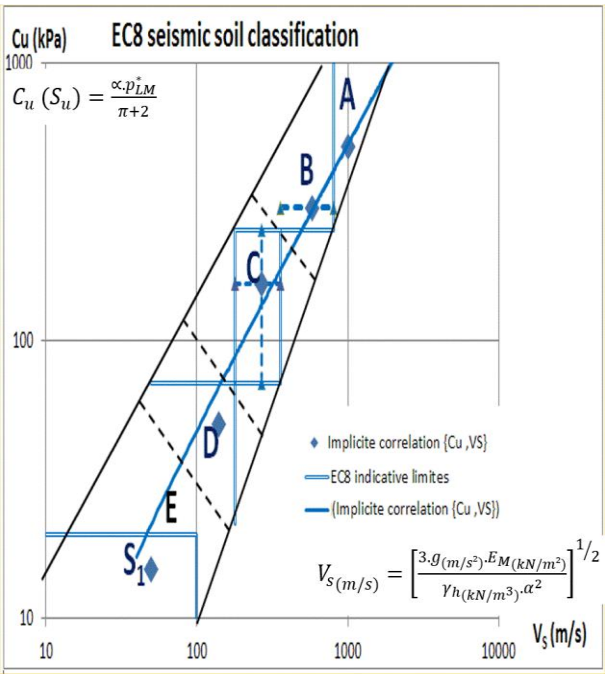

Figure 3. Use of Pressuremeter correlations for EC8 seismic soil classification [Vs | Su].

5. Adimensional Pressiorama Chart.

The use of pressuremeter state parameter p^*_{LM}/p_o instead of p^*_{LM} as abscissa leads to a slightly different clouding of points corresponding to each of pressuremeter tests. In this normalized chart [p^*_{LM}/p_0 | E_M/p^*_{LM}] in logarithmic axes, Eq. (3) is used to draw in the cartesian plane α values which appear as quasi linear (Fig. 5). The boundaries of the chart are: upwards (high values of E_M/p^*_{LM}) the line α = 1; downwards, the line E_M/p^*_{LM} = 3 below which no pressuremeter test is possible; to the right, the abscissa is limited to p^*_{LM}/p_0 = 1000 and could if necessary be opened further, in the case of tests in rocks with a very high rupture pressure. The chart covers the full range of pressuremeter tests in soils; the upper limit for α = 1 is used to graduate a third axis for E_M/p_0, and can be indexed in terms of soil softness or resistance, from mud to hard soils, and indicate transition to HSSR (Hard Soils and Soft Rocks) and beyond to hard rocks.

Pressuremeter state parameters used in this adimensionnal chart should in the same way allow estimations for friction angle φ' from PMT, which are included in the theoretical expressions given, among others, by Salençon (1966), Combarieu (1996) and Monnet (1997).

For now, we only propose to use the simplified expression of φ' given by Ménard (TLM 1963) and Gambin (1977):

$$p^*_{LM}\,(bar) = k \cdot 2^{(\varphi' - 24°)/4} \qquad (6)$$

with 2 < k < 3, or 2.5 as a mean.

We proposed a generalisation of this classical relation as follows (Baud, 2016):

$$\frac{p^*_{LM}}{p_0} = b \cdot \alpha^c \cdot e^{\varphi'/a} \qquad (7)$$

whose parameters have been set, based on published friction angle measurement data a=6, b=1/9 and c= 2:

$$\frac{p^*_{LM}}{p_0} = \frac{\alpha^2}{9} \cdot e^{\varphi'/6} \qquad (7bis)$$

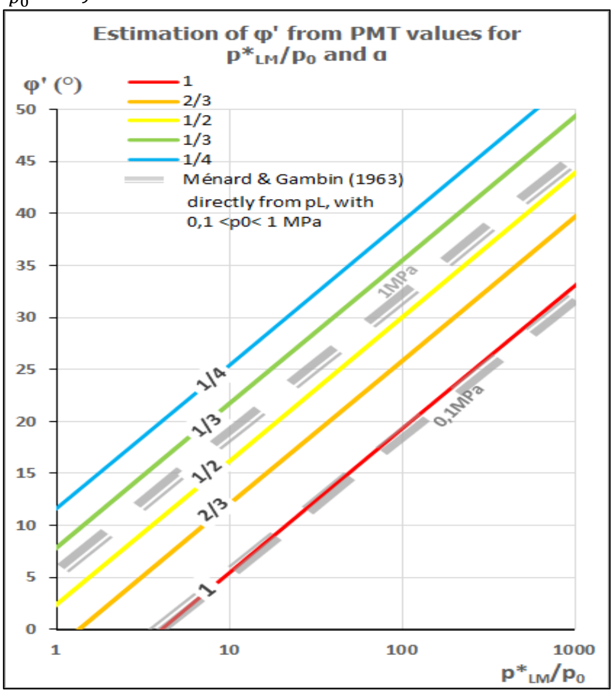

Figure 4. Estimation of φ' from Pressuremeter test.

So let be a direct expression of friction angle:

$$\varphi' = 6.\ln\left[\frac{9}{\alpha^2}\cdot\frac{p^*_{LM}}{p_0}\right] \qquad (8)$$

The result can be compared to original proposition of Ménard and Gambin (Eq.6), from only p^*_{LM} (Fig. 4).

$$\varphi' = 3.\ln\left(\frac{9}{\alpha^2}\cdot\frac{p^*_{LM}}{p_0}\right) + \frac{90.(1-\alpha)}{\pi} \qquad (9)$$

This allows us to draw lines of φ' values in the adimensionnal chart (Fig.5) as a function of p^*_{LM}/p_0 and α, the rheological coefficient, α being itself a function of E_M, p^*_{LM} and p_0 according to Eq.3.

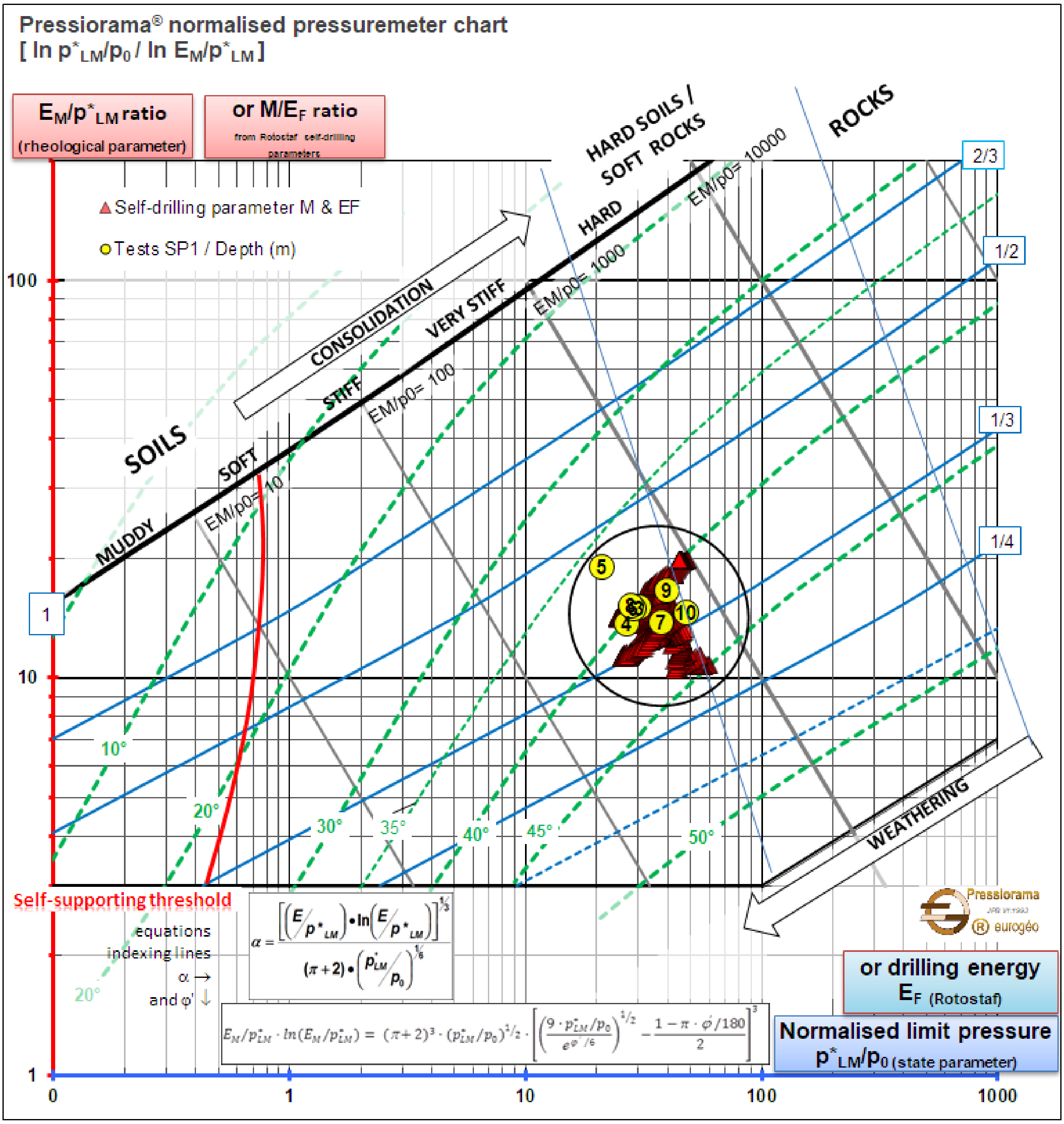

Figure 5. Dimensionless PMT chart based on state parameters E_M/p^*_{LM} and p^*_{LM}/p_0, comprising isolines of the values for α (Eq. 3) and the estimation for φ' (Eq. 9).

This result is consistent with the behaviour of sub-consolidated and normally consolidated soils, to get a reasonable approximation of phi' from a single standard Ménard pressuremeter test. However, the value of angle φ' thus established obviously quickly becomes too high as consolidation (E_M / p^*_{LM} or E_M / p_0) progresses, and would lead to values greater than 45° for any overconsolidated or cemented medium. To make it compatible with the behaviour of overconsolidated soils and soft rocks, we propose to make φ' tend towards a value of α so that α= 1-π·φ'/180, which amounts to express:

6. Correlation between PMT results and drilling parameters.

Several PMT surveys have been made using the method of self-boring slotted tube with the special drilling rig Rotostaf (Arsonnet et al. 2013) allowing simultaneous rotation and penetration of the open end slotted casing, and evacuation of sediments inside the casing.

Records of drilling parameters of the rig can be interpreted to furnish (Baud, 2018):

- A parameter of drilling energy E_F (joules):

$$E_{F\,(\mathrm{J})} = \left(1+\frac{1_{atm}}{(1_{atm}+P_I)}\right)^{1/2}\left(\frac{P_O.C_R^2\,.}{m.\,(V_A/t)}\right)^{1/2} \qquad (10)$$

whith drilling acceleration V_A/t (m/s²), torque C_R (N.m), tool thrust P_O (N), injection pressure P_I (atm), drilled ground mass m (kg).

- With adjunction of the ratio V_R/V_A of the rotation speed V_R versus drilling advancement speed, and a drill tool wear index based on a measurement of actual diameter of the Staf tool D_{mm}, a global parameter M (joules) is calculated, aiming a correlation with Ménard E_M modulus:

$$M_{Ménard} = \left\{[\pi.(\mathrm{D_{mm}} - 63_{\mathrm{mm}})].\frac{V_R}{V_A}.\left(1+\frac{1_{atm}}{(1_{atm}+P_I)}\right).\left(\frac{P_O.C_R^2\,.}{m.\,(V_A/t)}\right)\right\}^{1/2} \qquad (11)$$

In the drilling and testing log in Fig. 6 are reported the results of a PMT profile in dune sands at Messanges (Landes, France) made in the frame of ARSCOP (Arscop, 2019) by self-boring of slotted casing, with PMT tests between 3 and 10m depth, using a Rotostaf drilling rig. This log shows the fairly good correlation of E_F and $M_{Ménard}$ (in MJ, megajoule), respectively with p^*_{LM} and E_M (in MPa, megapascal).

The same set of results are reported in the adimensional diagram (Fig. 5):

- Drilling parameters, averaged each centimeter depth, by E_F as abscissa and M/E_F as ordinate.
- The 8 Pressumeter tests by p^*_{LM}/p_0 as abscissa and E_M/p^*_{LM} as ordinate.

In other words, $(V_R/V_A)^{1/2}$, known from long time as Somerton index, (Somerton, 1950) is more or less of the same nature, for soils in which is made drilling, than E_M/p^*_{LM} ratio.

Then, the α rheological coefficient of Ménard can be estimated by this other approach, by complete interpretation of drilling parameters. In this example, all results are included in the range α=1/3±15%, which is a classical α value representative for sands.

This underlines the need to systematically record the speed of rotation when drilling. The current recordings reduced to drilling speed V_A and only 3 pressures on the hydraulic and injection circuits of the rig furnish only partial data, not sufficient to anticipate soil behaviour and classification from drilling records.

It should be noted that this correlation has so far not been completely extended to drilling prior to PMT testing by conventional OHDM (open-hole drilling with mud) or RPM (rotopercussion with mud), two techniques commonly used for PMT drilling. Nevertheless, the continuous line drawn in such cases on the adimensional chart remains clearly representative of an evolution of the lithological profile crossed by the borehole ; more dispersion of PMT results are often related to decompression before time of testing.

Reiffsteck et al. (2016) demonstrated that it was possible to build a soil classification with basic drilling parameters expressed in terms of normalised friction Fr and normalised penetration rate Qr. The graphical report is more similar to Robertson than to Pressiorama charts, but is based on the same approach of combining a failure parameter and a deformation parameter with a range of behaviours from granular soils to coherent soils.

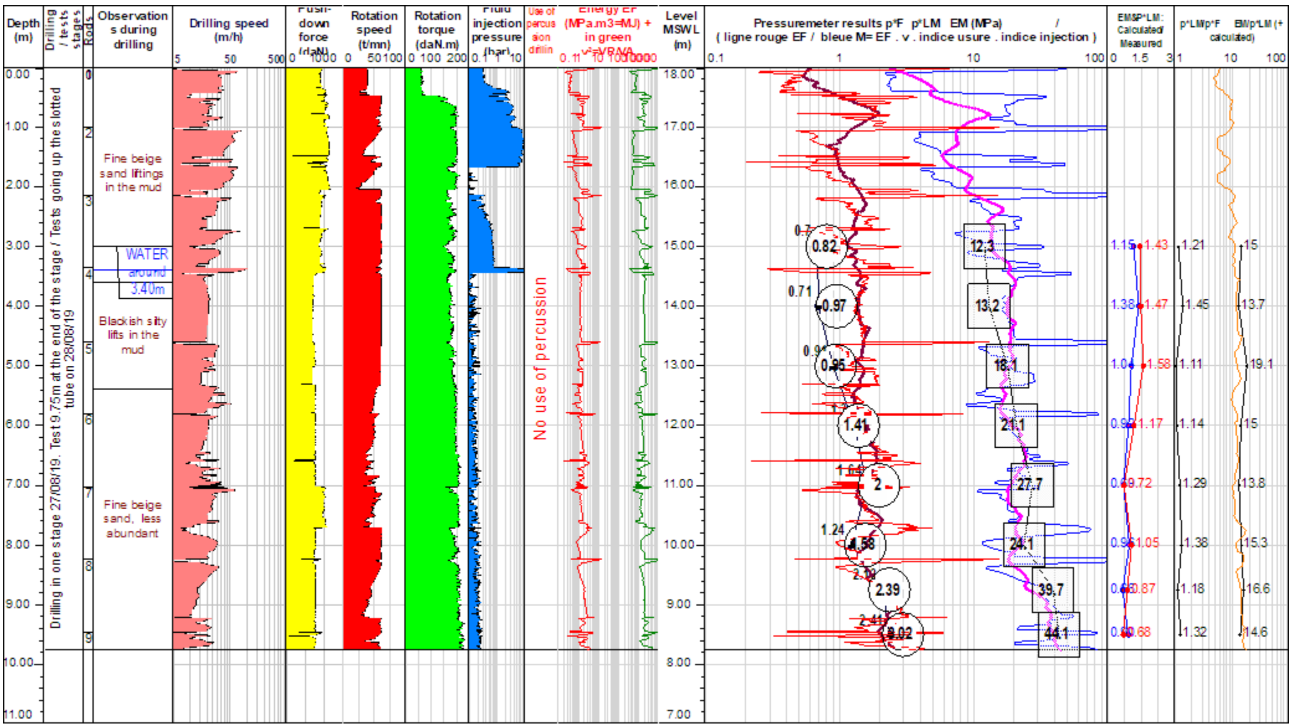

Figure 6. An example of interpretation of drilling parameters during self-boring of slotted casing together with the PMT tests made inside (Staf method).

7. Pressiorama® Chart based on one-cycle PMT

Determination of a value for α from only measurements linked to the test, p*LM, EM, and the earth pressure at rest p0 at test depth, brings extended possibilities to get more from each test. But a better way than calculation to get α is to measure it. The original definition (Ménard & Rousseau 1961, TLM 1963) derives α from E_a modulus of tests after 3 cycles:

$$\alpha \cong \left(\frac{E_M}{E_a}\right)^{1/2} \tag{12}$$

It can be simplified due to the fact that stabilised cyclic modulus is almost get from a single loop with the approximation $E_{c1} \cong 0.9\ E_a$, so:

$$\alpha = \left(0.9\ \frac{E_M}{E_{C1}}\right)^{1/2} \tag{13}$$

A new sketch of Pressuremeter classification can be made by drawing for PMT as x-axis the ratio E_{C1}/E_M and as y-axis the main pressiometric state parameter p^*_{LM}/p_o.This new Pressiorama® cyclic chart (Fig. 7) brings a better space for dispatching soil and rock classification from tests results. p^*_{LM}/p_o axis is down positive, so that rocks are at the base and soils overliesthem, up to loose soils at top of the graph, as an image of drilling logs in nature. Other axes can be drawn: α as secondary x-axis by Eq. (13), and consequently E_M/p_0 and E_M/p^*_{LM} from Eq. (3).

The relation given in Eq. (7bis) between p^*_{LM}/p_0 and φ' can be written using directly E_M and E_{c1}

$$\frac{p^*_{LM}}{p_0} = 0.1\frac{E_M}{E_{C1}}.e^{\frac{\phi'}{6}} \tag{14}$$

With the same assumptions than for Eq. (8) making asymptotic lines parallel to α abscissas for hard soils and soft rocks, we get a complete, rather no so simple, expression of φ' for tests with one unload-reload loop:

$$\varphi' = 3.\ln\left(10.\frac{E_{C1}}{E_M}.\frac{p^*_{LM}}{p_0}\right) + \frac{90}{\pi}\left(1-\left(0.9\ \frac{E_M}{E_{C1}}\right)^{1/2}\right) \tag{15}$$

In Fig. 7, cases of cyclic tests in soils whose φ' values can be measured or estimated by other ways had been checked to fix values of a, b and c in Eq.7 to obtain Eq.8. Similarly, we modified the expression of a ranking coefficient Ic proposed by Reiffsteck et al. (2013) to bring it to describe the space between 1 (minimum) for pure clay and 4 (maximum) for gravelly soils:

$$I_c = \left[\ln(p^*_{LM}/p_0) + (1+\ln(E_M/E_{c1}))^2\right]^{1/2} \tag{16}$$

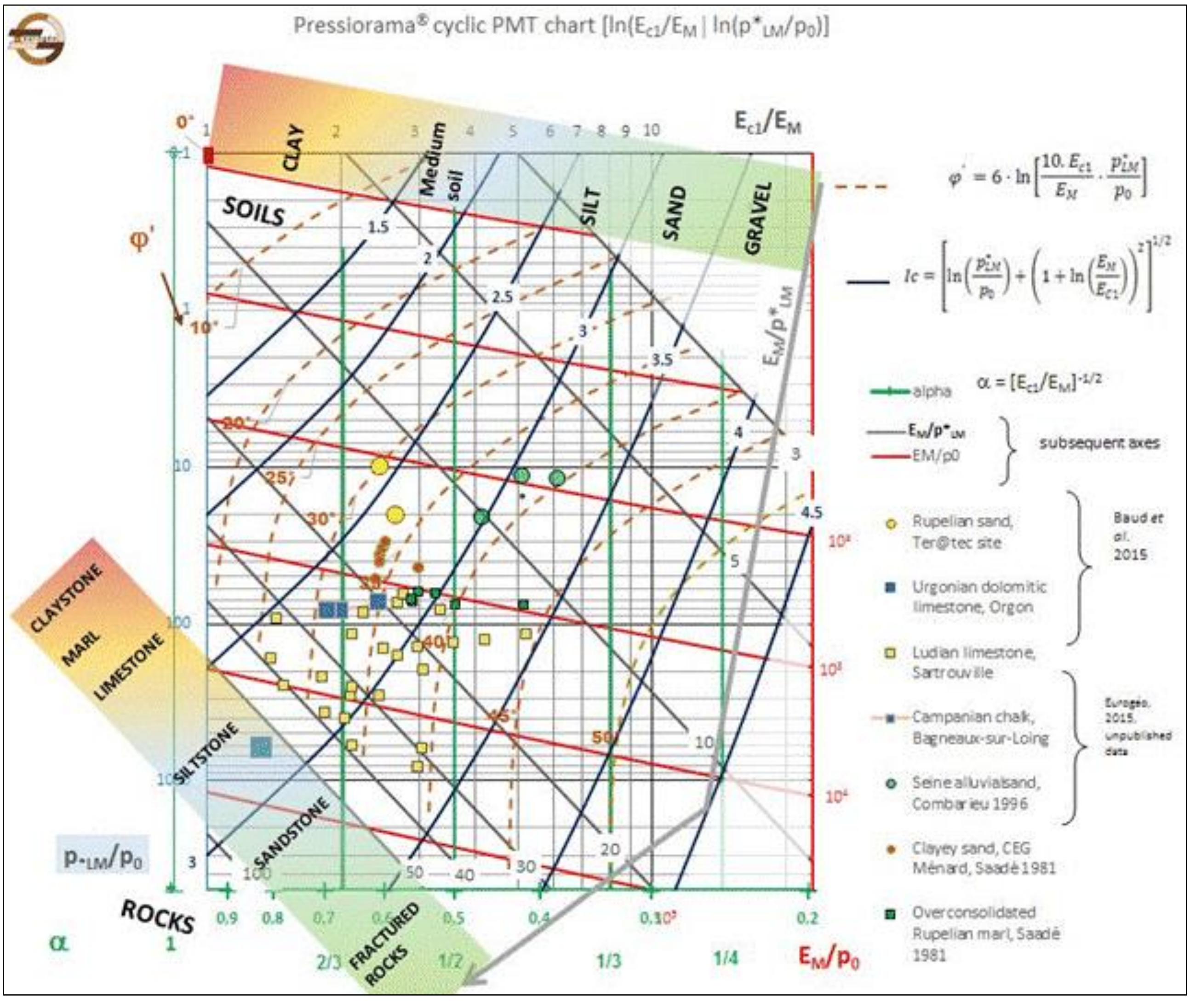

Figure 7. Soils and rocks classification from cyclic PMT

Ic values around 2.5 to 3 corresponding to the silts ensure the border, if any, between cohesive soils and granular soils. It is notable that, for low values of p^*_{LM}/p_0 i.e. soft soils, this index Ic is approximately equal to $1/\alpha$. As as the soil) consolidation progresses, that is to say the three state parameters (p^*_{LM}/p_0, E_M/p_0, E_M/p^*_{LM}) are simultaneously increasing, soil index Ic drifts to higher values of the rheological coefficient α. This index seems a good descriptor of the more cohesive nature of the soil, or more granular. Other observations trend to the adequacy of this index with soil lithology, among the case histories used in the chart, and others. Nevertheless, more cases must be checked to improve this chart, and for that Ménard PMT have to be performed more currently with one cycle (according to ISO 22476-5). Just as for initial [E_M/p^*_{LM} | p^*_{LM} or p^*_{LM}/p_0] diagrams, too remoulded tests, even with one cyclic loop, trend to give underestimation of E_M, so underestimation of E_M/p^*_{LM} and overestimation of E_{C1}/E_M, and consequently low value for α and high value for Ic : in other words, remoulded soil trends to appear as granular soil, and this is truly conform, the decompressed or disturbed soil is sheared in elements that make it appear falsely granular, and must be corrected by a decompression parameter as proposed in Fig.1.

8. Conclusions

The Pressiorama diagram was originally designed to quickly give a global view of the range of classical characteristics, E_M modulus and $p\ ^*_{LM}$ limit pressure, obtained in a series of pressuremeter profiles at a given site. It has led to successful applications in many areas of geotechnical works in soils and rocks. This diversity of applications only reflects the soil characterization power provided by Louis Ménard's invention of his Pressuremeter, and of design methods that he quickly founded between 1955 and 1970, for which the concept of rheological coefficient specific to each type of soil is a basic component.

Our current research is just another presentation of these dazzling intuitions. Applications have been exposed here in the fields of geomechanical classification of soils and rocks, of earthworks and drilling works, of the correlation with the classical mechanical characteristics of the ground, and of seismic zoning.

Nevertheless, for a systematic use of the charts presented here, it is recommended and essential to bear in mind that they should only be applied to tests perfectly executed in the rules of art, and for which it is certain that they are representative of the ground under test. This is obtained by controlling the degree of decompression of the soil before the test, and getting the most accurate knowledge possible of the nature and structure of the ground, by careful examination of drill cuttings, their identification and their place in the geological context of the surveyed site, for which a reliable geotechnical stratigraphic column must be established.

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