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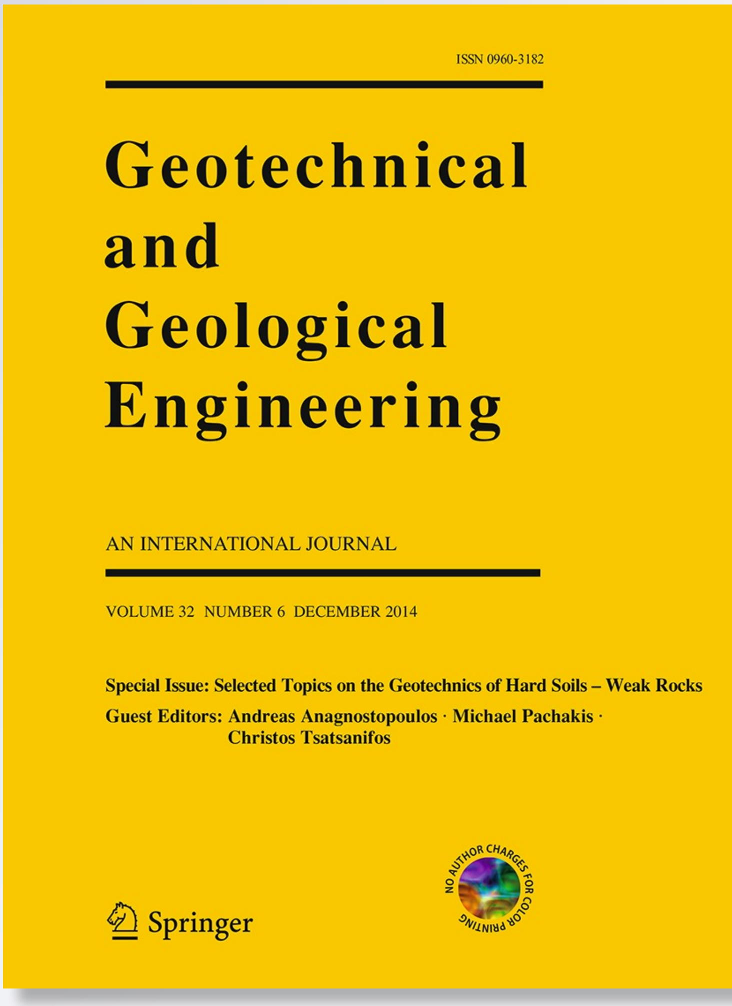

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ORIGINAL PAPER

Soil and Rock Classification from High Pressure Borehole Expansion Tests

Classification des Sols et des Roches à Partir d'Essais d'Expansion Cylindrique en Haute Pression

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Abstract Physical and mechanical properties used to characterize soil and rock are different according to the various approaches and targets of the different activities involved, namely soil mechanics, rock mechanics or engineering geology. The Authors suggest that the data obtained during a borehole expansion test, which can be summarized by a Ménard E-modulus and a limit pressure, be used in an overall classification ranging from loose soils to hard rock without any discontinuity based on the soil Pressiorama® as developed for soils these last 10 years.

Keywords Pressuremeter · Flexible dilatometer · Rock moduli · Rock limit pressure · Hard soils · Weak rocks · Weathered rocks

Résumé Les propriétés physiques et mécaniques utilisées pour caractériser les sols et les roches diffèrent selon les approches et les objectifs, ceux de la géotechnique, de la géologie de l'ingénieur ou de la mécanique des roches. Les auteurs suggèrent que les mesures faites lors de l'expansion de la cavité cylindrique d'un forage, et qui peuvent se ramener aux deux paramètres fondamentaux d'un module pressiométrique et d'une pression limite, soient utilisés pour une classification passant sans discontinuité des sols aux roches fondée sur le diagramme Pressiorama® mis au point pour les sols il y a quelques années.

Mots-clés Pressiomètre · Dilatomètre · Modules des roches · Pression limite des roches · Sols raides · Roches tendres · Roches altérées

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1 Introduction. Is There a Boundary Between Soil and Rock?

To define a boundary between soil and rock is an approach which seems natural to many, from the Neolithic farmer to the twenty first century Builder, and yet this remains either a subjective or at least a variable concept. It is a function of the way each of them uses the natural material. For the geologist, since the emergence of this subject matter, all components of the Earth's crust are "rocks", from water to the material of the continental plates, therefore irrespective of their physical condition, a solid or a liquid or even a gas. All these rocks have their specific story and fate, essential to more or less sustainable global development, such as petroleum, the "oil-as-rock". For anyone involved in the Building Industry, this over-all classification is irrelevant, and rock in its solid state is distinguished from soil, which is all that is not rock, also characterized by a more or less marked lack of strength : soil is sensitive, workable, brittle, elastic, soft at its liquid limit.

Historically, K. Terzaghi, being both a geologist and a civil engineer, tried to establish the mechanical boundary between soil and rock: "Soil is a natural aggregate of mineral grains that can be separated by such gentle mechanical means as agitation in water. Rock, on the other hand is a natural aggregate of minerals connected by strong and cohesive forces. Since the terms "strong" and "permanent" are subject to different interpretations, the boundary between soil and rock is necessarily an arbitrary one. As a matter of fact, there are many natural aggregates of mineral particles that are difficult to classify, either as soil or as rock" (Terzaghi and Peck 1948).

One of the themes of the Athens European Conference of the ISSMGE on Hard Soils and Soft Rock in 2011 was about grounds which can be in either the field of soil mechanics or that one of rock mechanics. And although specialists in both disciplines are more often in cordial and fruitful relationships, and develop their expertise through universal physical laws, a claim of one group will sometimes challenge the relevance of his approach to the other: "A strong cohesion and many cracks are the two criteria often quoted for rocks, but this remains insufficient. The boundary between soils and rocks relies heavily on the school of thought and the field of experience. Congresses where stiff soils and soft rocks were treated together added to the confusion. Only geology shall facilitate clarification". (Comité Français de Mécanique des Roches 2000).

The diagram (Fig. 1) is therefore based on the distinction that conventional geologists would use, before the continental drift theory, between the factors which contribute to the formation for the rocks in the Earth's crust, or internal Geodynamics, and the factors of degradation of rocks and genesis of sedimentary rocks, or external Geodynamics. As a first approximation, this figure illustrates how the boundary between the fields of soil mechanics and rock mechanics can be visualized. For example, during its geologically very long cycle, a silica particle in a granitic magma may become a sand particle on a beach before consolidation inside a sedimentary rock, further into a metamorphized one, and then returning to the base of the Earth's crust. This mineral particle can successively be the component of rocks and soils of totally opposed mechanical resistance, as symbolized in the margin of the diagram by the shear modulus value of these formations. The essential genetic characteristic of rock is a stronger and stronger binding between the grains that make it, due to cementation during diagenesis of sedimentary rocks, crystallization or re-crystallization of metamorphic and magmatic rocks. Their fate at the surface of the Globe is by destruction of these strong structures, which progressively makes these grains without links. If you want to compare the mechanical characteristics of a very hard ground and a fairly weathered rock, even if they seem almost identical, you must keep in perspective the fact that they are diametrically opposite in this cycle.

2 Characterization of Soils and Rocks by the Conventional Pressuremeter Parameters

The behaviour of any material submitted to the expansion of a cylindrical cavity may be essentially reduced to a simple hyperbolic rule (Baud et al. 2012).

According to Ménard (1976) in soil the two fundamental parameters E_M and p^*_{LM} which are obtained from each test permit a soil classification. This is due to the close relationship between the ratio E_M/p^*_{LM}, and the type of soil behaviour, being itself a function of the soil gradation curve from typical sand to typical clay. This classification is shown for example in the diagram Pressiorama® (Baud 2005), and it is completely linked to the soil structure factor "α" defined by L. Ménard such as

$$\alpha = \left[\frac{E_M}{E_{ur}}\right]^{\left(\frac{1}{2}+\nu\right)}$$

where E_{ur} is an unload-reload value of pressuremeter modulus, and ν is of the second order of magnitude. Experience on soils is that E_{ur} could be an approximation of the so-called Young's modulus, in the same range of stress than E_M, so that $E_Y = E_M/\alpha^2$ (Ménard and Rousseau 1962; Baud and Gambin 2013).

The future of this classification, and the reliability of the soil structure coefficient α, is a question that arises when the pressuremeter test is applied to increasingly hard "soils", which can be either sedimentary formations in a condition of high geostatic consolidation, or rock in a condition of weathering and decompression more or less advanced, or, still, successively a less weathered rock, an extensively jointed rock, a slightly jointed rock and finally a solid rock.

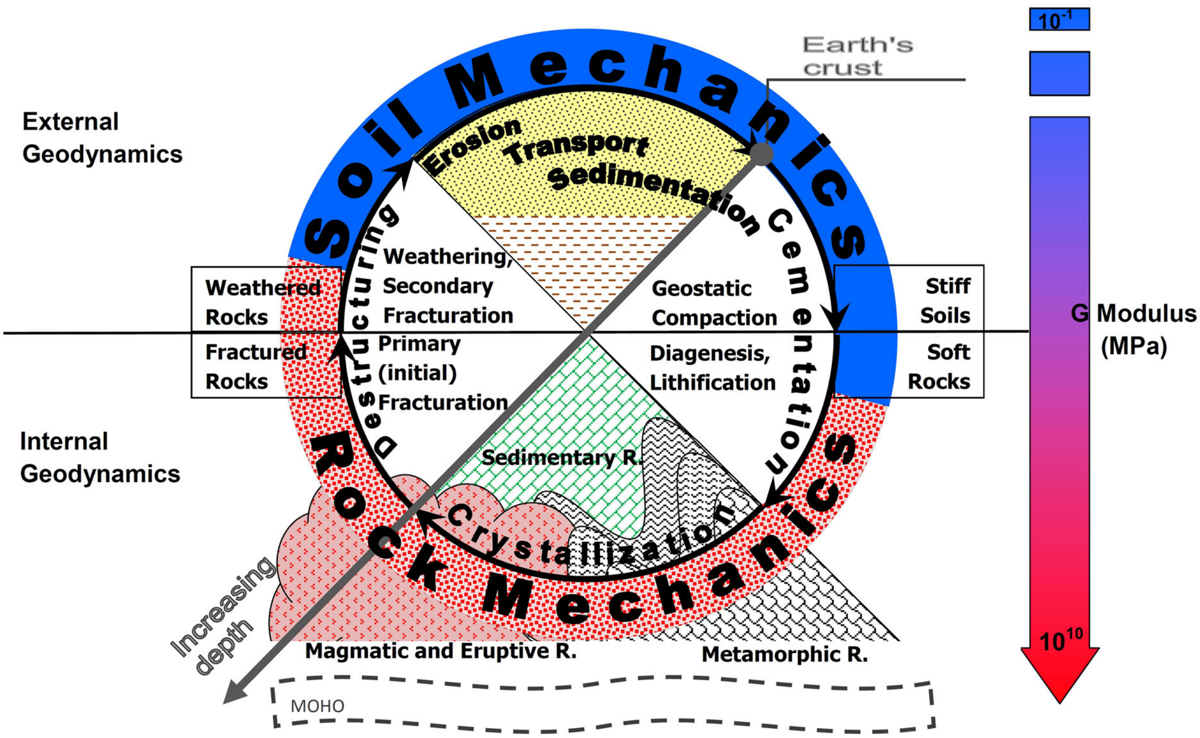

Fig. 1 Cycle of mineral and organic matter, from rock to soils and *vice versa*. Figure modified according to classical geological concepts, from a figure said to be « made so that geologists will roar » (*sic*), in a professional booklet by Hurtado (1988)

3 Behavior of Hard Soil, Soft Rock and Solid Rock Measured by Pressuremeter

The hyperbolic constitutive law of soil subjected to a cylindrical hole expansion test represents the overall measurement of the hole wall strain under the shear stresses applied to the soil. Displacements between soil grains during the test and the subsequent local failure is now well understood (Baud et al. 2012; Ménard and Rousseau 1962; Gambin 2005), even if details about their occurrence according to soil type will still be looked after by geotechnical research workers.

During the gradual transition from stiff soils to hard soils and then to weathered rocks, and further on to jointed rocks, the radial expansion behavior of the material does not suddenly changes in nature, but the scale of the associated stresses change gradually by one or two powers of 10. Limitation of tests up to 5 MPa due to available equipment until recently only permitted access to the initial phase of the borehole deformation. The test allows only the knowledge of an E or G-modulus along this restricted range of stresses, without the knowledge of either the change of the modulus under higher stresses or the limit pressure at test completion. Development of pressuremeter equipments making it possible to reach up to 50 MPa test pressure (Arsonnet et al. 2011; Baud et al. 2013), it is possible to start to observe if the mode of failure of the materials within the common range of pressures between soils and rocks remains comparable to that of soils.

3.1 Mode of Shear of Hard Soils and Rocks up to Failure

The increase in the ratio E_M/p^*_{LM} when p^*_{LM} values increase is a common observation. On conventional Ménard pressuremeter plots this corresponds to an increase in the radius of curvature of the curve, and a trend for the soil structure factor α for very hard grounds to become closer to 1; in other words in solid not jointed rocks, it is customary to think that expansion tests lead to the direct measure of a Young's modulus:

- Cementation between their particles reduces the mutual displacement of these particles under high shear stress.

- Density, continuity, joints—their gap value and their inside faces condition, as well as their filling—have an impact on the deformation of the wall of a borehole in radial expansion.

3.2 Behavior of Jointed or Weathered Rock Under Pressuremeter Testing

Actual jointed rocks are very easily detected on a Ménard style pressuremeter plot due to a very long phase of decreasing gradient along the curve as pressure increases, since either open or filled-in joint gaps gradually contract, first those close to the borehole wall and, later during the test, those more remote in the rock.

Whatever the final pressure reached, between 5 and 50 MPa, three types of test curves can be obtained as for standard pressuremeter tests, regarding the way they are interrupted: for some of them, the phase of joint closing and dV/dp slope reduction is not completed, for others an inflection point is passed with some increase of dV/dp but without creep effect, and for the third type creep has started and larger strains occur.

These three types of curves permit a basic classification:

- Solid rock more or less slightly jointed
- Jointed and altered rock, but the rock material is not compressible
- Weathered and broken rock evolving toward a soil-like behavior.

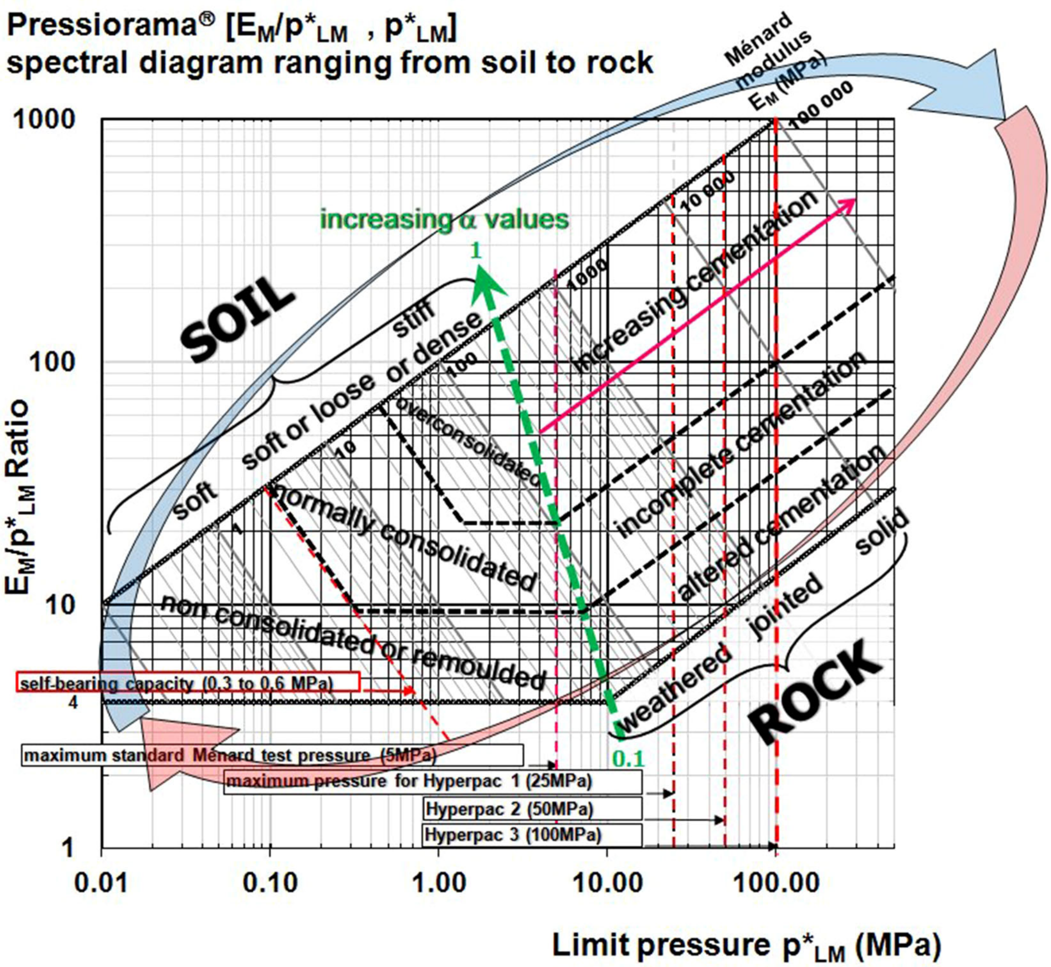

Fig. 2 Soil and Rock Pressiorama® classification based on their E_M and p^*_{LM} pressuremeter data. The genetic cycle shown is similar to that one of Fig. 1

4 Transition Between Hard Soil/Soft Rock and Weathered Rock/Residual Soil: Gradual or Abrupt?

4.1 Use of the Spectral Diagram [E_M/p^*_{LM}, p^*_{LM}] to View the Transition Soils–Rocks (Figs. 2, 3)

As a conceptual framework, we propose the extension of the spectral diagram [E_M/p^*_{LM}, p^*_{LM}] or Pressiorama®, that we permanently use in field pressuremeter surveys (Baud 2005), toward the area of test pressures greater than 10 MPa. This technique shall help and detect irregularities either in the test performance or in the soil itself, and also permits to classify ground types.

Actual cases of very hard soils and weathered rocks that we can locate in this diagram extension to the rock material are rather numerous for tests exhibiting pressures up to 15–18 MPa. Beyond this pressure range, the first tests with the Hyperpac control unit (Arsonnet et al. 2011) provide points up to 25 MPa and permit to consider possible extrapolation of limit

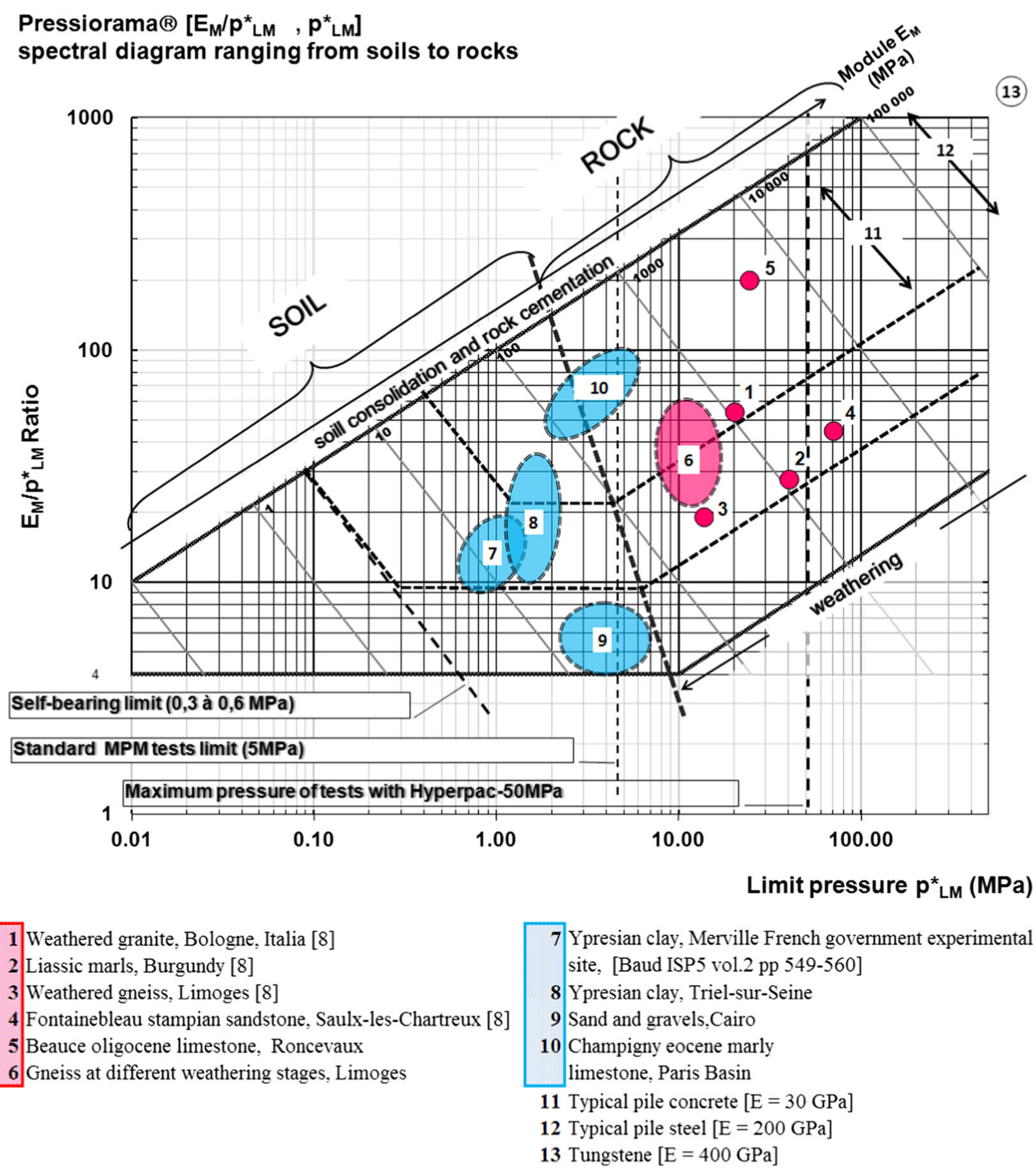

Fig. 3 Examples in Pressiorama pressuremeter classification for hard to weathered rocks, and overconsolidated to very stiff soils

pressure up to about 30–40 MPa, if at least the p_{CREEP}/p_{LM} soil correlation is validated in this pressure range. Beyond that range, dilatometer tests results can be reinterpreted according to the method of pressuremeter testing and give E_M values higher than 10^5 MPa, but in this type of test there is no way to estimate a limit pressure (Galera et al. 2005).

4.2 Brittle or Ductile Failure During In Situ Expansion Tests

The previous examples show that, where pressure can grow in pressuremeter type expansion tests, hard soils or soft rocks do not exhibit a behaviour quite different from that one of soil, with a phase of creep and later a phase of large deformations.

The significant difference is the trend for E_M/p^*_{LM} ratio to increase when the limit pressure increases. This ratio can quickly exceed the usual values for soft soils to reach $E_M/p^*_{LM} = 50$ or 100, and even 200. Pressuremeter curves corresponding to such values of E_M/p^*_{LM} have a fold or "kick" more and more striking between the no-creep phase and the creep phase.

As our investigation proceeds towards solid rock, it seems to appear that the behaviour of the material moves towards the "brittle" type of failure in which failure occurs without a definite plastic flow phase. This feeling is generally shared by research workers who always express concerns regarding tests at 25 MPa in concrete piles or columns, and Ménard himself considered that he would "pop" the rock (Ménard 1974). However, up to now, even in tests carried out to 25 MPa, this type of behavior was not observed, and all types of rock tested exhibited a gradual creep announcing the beginning of a failure phase.

It must be noted that at a higher pressure, rock failure by borehole expansion can be obtained in the Building Industry too by expansive foam under pressure (such as the patented DMX process used by Colas Rail). To tear down rock masses close to the ground surface in a quarry, a quick pressure increase up to 50–60 MPa is applied. It can be observed two distinct failure modes of the rock: the most common one is the immediate rock popping up in polyhedral blocks obtained by the opening of pre-existing thin joints; still, more rarely, in less fissured rocks, expansion causes a shift of the whole wall for a few seconds, before a fragmentation of the rock mass in elements exhibiting no flat faces. This seems to correspond to the opening of inter-granular joints (Delaporte 2009, and oral communication).

The State of the Art on the failure under triaxial stress of non-jointed rock samples, and the sliding resistance of rock joints is summarized by Parriaux (2009) and detailed in an abundant bibliography by Al Bied (2002). The breakdown of the matrix is obtained at the time shear bands appear in areas of stress concentration.

In a expansion test under very high pressure, the containment provided by the surrounding rock mass should therefore lead to failure by the combination of both slides along previous joints, and shear bands near the borehole wall, permitting to keep the concept of the pressuremeter creep pressure for rocks.

5 Provisional Conclusion and Future Developments

1. The recent development of equipment to carry out expansion tests in boreholes up to 25 MPa must still be checked by tests in more varied field conditions so that the back analysis can support the assumptions made here on the rock breakdown mechanism by shearing. We recently got means for reaching pressure tests up to 50 MPa (Baud et al. 2013). A prototype equipment is envisioned to work up to 100 MPa.
2. The proposed diagram for a single soil and rock classification using pressuremeter parameters helps us as a framework for this work, as well as the simultaneous development of the contour lines of the soil structure factor α compatible with the practice of the Ménard pressuremeter methods (Gambin 2005; Baud and Gambin 2013).

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