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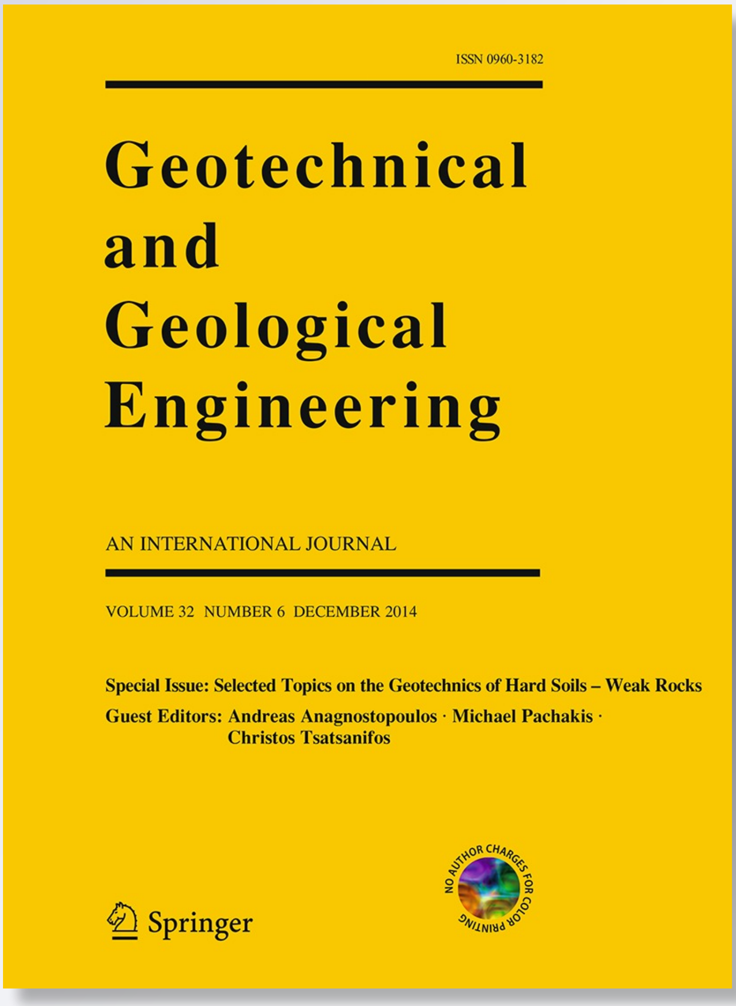

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Special Issue: Selected Topics on the Geotechnics of Hard Soils – Weak Rocks

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ORIGINAL PAPER

25 MPa HyperPac Fills the Gap Between the Ménard Pressuremeter and the Flexible Dilatometer

L'HyperPac 25 MPa Comble le Vide Entre le Pressiomètre Ménard et le Dilatomètre Flexible

Gérard Arsonnet · Jean-Pierre Baud · Michel Gambin · Robert Heintz

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Abstract The borehole expansion test can be used in any ground material, from the softer to the harder one, so as to obtain its stress–strain behaviour in situ. The authors submit their research work on equipment which permits to extend the use of the Ménard pressuremeter up to 25 MPa test pressure. They also give the first test diagrams up to this pressure in slightly fractured rocks.

Keywords Pressuremeter · Flexible dilatometer · Rock moduli · Rock limit pressure · Hard soils

Résumé L'essai d'expansion in situ d'une cavité cylindrique peut s'appliquer à tous les types de matériaux, des plus mous aux plus résistants, pour déterminer leurs propriétés mécaniques. Les auteurs présentent un appareil permettant d'étendre le domaine du pressiomètre Ménard jusqu'à des pressions d'essai de 25 MPa, ainsi que ses premières utilisations dans des roches peu fracturées.

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

1 Introduction

In situ geotechnical borehole expansion tests on soils and soft rock were initially developed by Louis Ménard from 1955 onwards using his own pressuremeter.[1] Thus, various techniques were created to drill the hole and carry out the test and subsequent methods were proposed to obtain the best parameters in order to design all types of foundations and earth works (Cassan 2006; Gambin 2005).

Similarly in situ equipment to measure deformation in hard, slightly weathered rocks were developed, such as the flexible dilatometer, also known as a rock dilatometer. However this equipment did not have the same impact on the history of rock mechanics as the pressuremeter had on geotechnical engineering.

Both the pressuremeter and the dilatometer have the same goal, namely the measurement of E-moduli in soil and rock by radial deformations but for very

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[1] In French « Pressiomètre », registred trade mark of Louis Ménard.

different mean strain and stress levels, since with a pressuremeter one tries to obtain a limit pressure p_{LM} at failure of the ground whereas with a dilatometer one wants to produce precise readings of very small deformations of rocks (Galera et al. 2006). At last the pressuremeter is easier to handle than the dilatometer.

2 Specific Requirements for Soft and Weathered Rock Tests

There has always been a gap in the stress range of both equipment, i.e. there is neither an overlapping nor a continuous range for the two methods, between the readings obtained in soils from the pressuremeter and those taken in rocks from the dilatometer.

Although type A dilatometers are very precise, the extension of their displacement sensors is limited, which considerably hampers their use in rocks that are too fractured or weathered, so that the calibration of the borehole cannot always be performed at the place where the test should have been carried out.

Although a progressive increase of the Ménard pressuremeter maximum testing pressure was obtained throughout its history, it was not possible to match the range of pressures used in rocks by the dilatometer. With reference to the French Standard, and later the European and ISO Standards, its use is restricted to 5 MPa (NF P94-110-1 2000; EN-ISO 22476-4 2012), mainly because use of the tests results is devoted to soil mechanics. Nevertheless, needs for higher pressure have been expressed by users for years, although technical limitations of conventional pressuremeter devices stay more often under 10 MPa.

However, the increasing need to apply stresses both to very stiff soils and to the ground material ranging at the subjective borderline separating soils and rocks entails the application of pressuremeter probes and pressure–volume control units that can be used beyond 10 MPa. There is as yet little knowledge of the E_M moduli and limit pressures p_{LM} of weathered rocks or more generally of the behaviour of these ground materials under radial expansion. Yet knowledge of these parameters is more and more needed in civil engineering as shown by the topic chosen at the 2011 European Conference in Athens.

3 Beyond the Conventional Limits of the Pressuremeter

Since its origins and despite its name, in the Ménard "pressuremeter" the energy of a gas under pressure has systematically been used to apply equal stress increments to the borehole wall through a compressed water column permitting both the expansion of the probe and the record of the volumetric displacements. The present limitations are, on the one hand, the maximum pressure of the industrial gas cylinders, that is 20 MPa, and on the other hand the resistance of the probes designed to fit the standard fulfilment of 5 MPa. The design of the probe allows a safety margin well beyond 5 MPa, generally up to 10 MPa, which is twice as much, but the probe use in this pressure range is restricted to exceptional cases, since the probe cover bursting risk will systematically increases when the probe expansion increases.

3.1 Beyond 10 MPa Using a Ménard Type Pressuremeter with Compressed Gas

There are examples that illustrate the use of the standard pressuremeter, often at great depth, as soon as the end of the 60's still with the current control unit on which readings were copied manually. Ménard had then already worked out recommendations to use the pressuremeter in rock (Ménard 1966, 1967). Later, in the 90's, a new control unit was developed, called Geopress, which digitally registered readings, examples of its use are given here:

- Bologna, Italy, 1986, granite, from 80 to 190 m deep, 7 MPa test pressure
- Alise-Sainte-Reine, France, 1991, marl, less than 40 m deep, 10 MPa test pressure
- Limoges, France, 2004, gneiss, less than 20 m deep, 11 MPa test pressure

The tests mentioned above are represented in the following graphs. (Figs. 1, 2 and 3).

The plotted curves represent, on arithmetical scales:

- the pressuremeter curve, the volume being given on the vertical axis versus the pressure on the horizontal one,
- the creep curve, closer to the horizontal axis on the same graph, in terms of volume, the volume scale

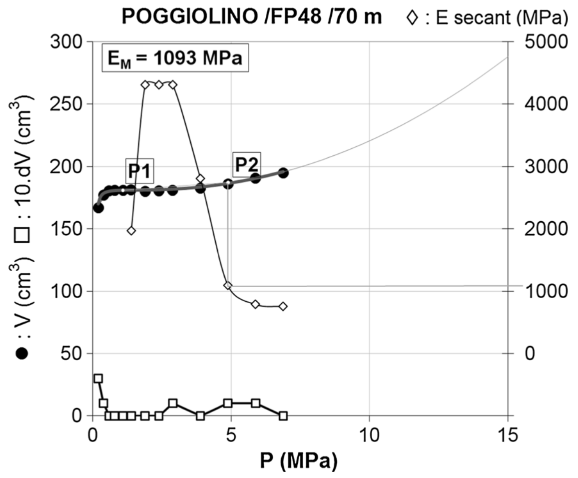


Fig. 1 A high pressure test in Flysch sandstone, Poggiolino, province of Bologna, 1986, Ménard pressuremeter type GA. *PMT curve*, *creep curve* and the *bell-shape secant E_M curve* are shown

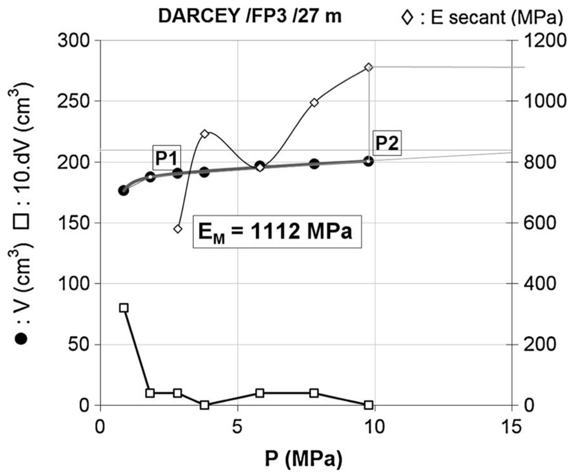


Fig. 2 A high pressure test in Lias marl, Alise-Sainte-Reine, 1991, Geopress pressuremeter. The secant *E_M curve* is rather irregular due to lack of volume readings precision for high pressure tests

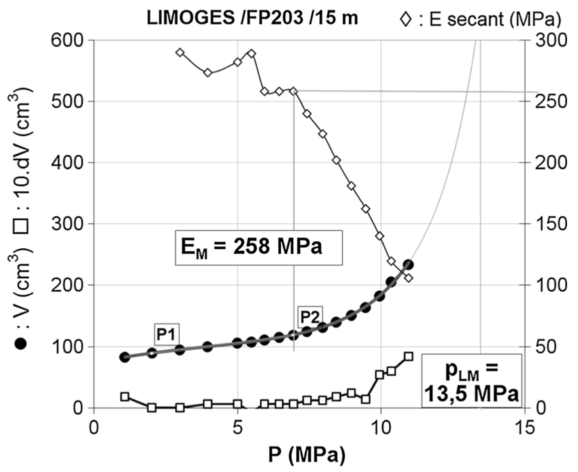


Fig. 3 A high pressure test beyond creep value in weathered gneiss, Limoges, 2004, Geopress pressuremeter

being increased by a factor of 10 on the vertical axis,

- the various secant moduli values for a pressure range starting from the point [P1] to any pressure up to the kick above the creep pressure; its value is read on a secondary vertical axis on the right; its form, bell-shaped or regularly sloping, being a function of the hyperbolic law followed by the pressuremeter curve (Baud and Gambin 2008).

E-Moduli given in any figure in this paper are pressuremeter moduli, computed, according to L. Ménard, from G modulus, or second Lamé coefficient, as measured during cylindrical expansion :

$$E_M = 2(1 + \nu)G_M = 2(1 + \nu)V.dP/dV$$

assuming a mean conventional $\nu = 1/3$, it comes

$$E_M = 8/3[Vp + (V1 + V2)/2](P2 - P1)/(V2 - V1)$$

where Vp = probe volume at rest.

As early as 1976 an internal report by the French Research Centre for Coal Mines—CERCHAR/Houillères du Bassin de Lorraine—described tests up to 90 MPa using the prototype of a Ménard pressuremeter control unit of 1,000 bars, connected to a probe that had retractable end-pieces (Ménard 1974; Arcamone et al. 1983). This pressuremeter probe, recently put back in use by Eurasol Geotechnical Consulting Engineers in Luxembourg, achieved a pressure of 36 MPa at which the original probe bursted (Heintz 2006). Its practical as well as its technical reliability has been recently studied at the French LCPC (Heintz and Reiffsteck 2003).

Finally, Massonnet (2005), a French Consulting Engineer, submitted test results pushed up to 12 MPa, performed with a conventional Ménard pressuremeter control unit which was fitted with 16 MPa Bourdon gauges at full scale and which had reinforced cover sleeves with additional steel strips and fixing rings. The tests shown were performed in London's sands of

Thanetian age. The author drew attention to the fragility of the control unit burette which is prone to break beyond 10 MPa.

Conclusions from these examples of Ménard pressuremeter tests carried out at very high pressure are as follows:

- In hard soils and soft rocks which are weathered or slightly fractured but in which the creep pressure has not been reached during testing, assuming a pressuremeter equipment in perfect condition, it is possible to complete 12 MPa tests relatively safely and without leakage. The standard pressuremeter probes, when carefully fitted either with a rubber cover in direct contact with the soil or with a slotted tube, can stand the pressure without risk for the cover to slip off its fixing rings in a well calibrated borehole, the wall of which deforms only slightly.
- If the readings in the ground indicate creep pressures between 5 MPa and 12 MPa, it is more difficult to perform this type of test and there are fewer opportunities to complete them during a geotechnical investigation.

The few examples given above show that any weathered rock can have the same behaviour during borehole expansion as a soil, with a hyperbolic shaped curve that can be extrapolated towards pressure limits from 12 MPa up to 20 MPa.

Despite these successful yet sporadic attempts throughout the history of the Ménard pressuremeter, Engineers and Contractors have shown little interest, either because of a supposed lack of accuracy on the E_M modulus obtained by volumetric displacement readings during borehole deformations, or because of the more difficult task to reach a reliable p_{LM} limit pressure.

However more and more users of pressuremeter test results wish to extend the range of applications of the pressuremeter. This is due, in particular, to the difficulty of finding an equivalent to the Ménard limit pressure on core samples; for example, compressive strength values on intact rock samples are not significant to characterize a rock mass because the fracturing of the rock can be readily taken into account during a pressuremeter test.

Control units with automatic recording of readings without visible burette, such as Geospad2 at Apageo, are available to-day; they are limited to a pressure of 15 to 18 MPa, a pressure beyond which the rapid tearing of standard probe covers and the vast output of gas volumes leads to a certain limitation of use.

3.2 The Contribution of the Automated Pressuremeter (GeoPac) and Its Evolution into the 25 MPa Version (HyperPac)

In this new generation of pressuremeters (Arsonnet et al. 2013) an automatic Ménard pressuremeter loading programme is obtained through a volumetric system fitted with a motor-driven piston. The movement of this piston is self controlled by an electronic regulator which back-analyses the generation of the pressuremeter curve and stabilises the standard pressure holds without the action of the operator. The pressuremeter is remotely piloted from a distance by a ruggedly built site computer, the Geobox.

The necessary implementation of a micrometric piston advancement has at once permitted this device

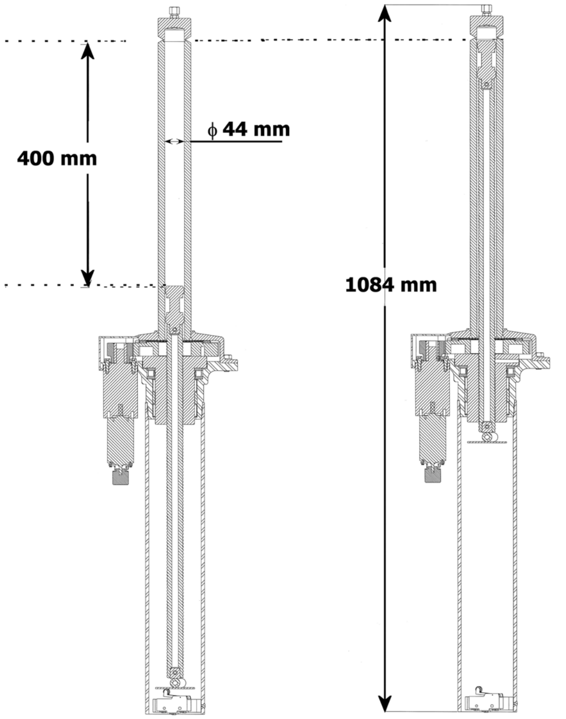
- to yield very precise volume readings during standard pressuremeter tests at 2×10^{-3} cm^3,
- to quickly reach precise pressure holds and maintain them stable for the required period of time (depending on the precision of the sensors used).

Industrial compressed gas (nitrogen) is no longer needed for the measuring cell inflation. Still, compressed gas is used for the guard cells.

As soon as this equipment was put into practice in a standard control unit with electro-mechanical components and in particular with pressure sensors a little above the standard limit of 5 MPa, it appeared that the same design could be used at much higher pressures.

When constructing the HyperPac prototype, the aim was to achieve a pressure of 25 MPa, which is five times the limit of standard PMT's. This pressure has the advantage of corresponding to both the range of measurements that fill the gap between pressuremeter tests and dilatometer tests and the capacity of the mechanical and electro-mechanical industrial components that were tested and were proved reliable during the trials.

The use of a large-sized cylinder (Fig. 4), within which the piston moves, eliminates every risk of a blow-up in the event of a leak or the failure of one of



(a) **Starting the trip of the piston** **(b)** **Ending the trip of the piston**

Fig. 4 The self-controlled HyperPac pressuremeter. Diagram of the volumetric measurement device using a motor-driven self-controlled piston

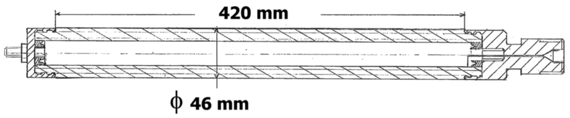


Fig. 5 Diagram of the THP probe 46 mm O.D. by Géomatech

the components of the hydraulic system including the connecting lines and the probe.

The resolution of the measure of the motor-driven piston travel is inferior to 1 µm, which corresponds to a theoretical measure of volume change of 1×10^{-3} cm^3, that is to say, for the probe described (Fig. 5), a mean displacement of the borehole wall of 3×10^{-2} µm.

Particular attention has to be paid to the measuring probe which is in close contact with the borehole wall and the calibration of the latter. We used a mono-cell probe, 46 mm in diameter, with different types of covers in accordance with a range of Shore hardness of 40–90, similar to that of the probes designed by Ménard for his '1,000 bars pressuremeter' (Ménard 1974).

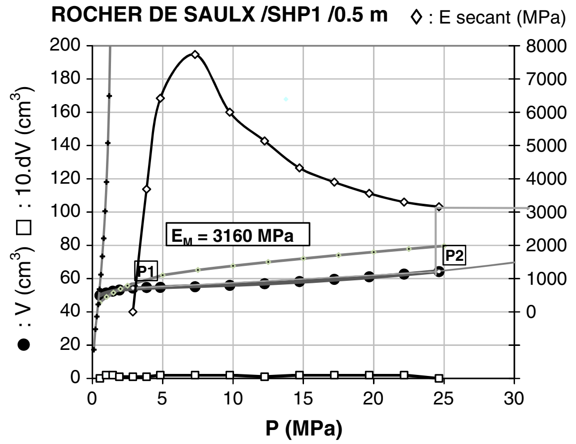


Fig. 6 Saulx sandstone test up to 25 MPa without creep; probe standard calibration *curves* are in grey. The *bell-shape curve* is the variation of the secant E_M along the *PMT curve*

3.3 Examples of Tests Done Using the Automatic HyperPac 25 MPa Pressuremeter

The readings and tests presented here seem like a 'simple' transposition of the usual operations carried out when performing a standard pressuremeter test, but following the appropriate steps for a type B dilatometer probe (EN-ISO 22476-5 2012).

- The calibration of a very high-pressure probe is done through increments of 2 to 5 MPa in a thick high elastic resistance steel pipe, the correction of its own deformation being either obtained by calculation or by the use of an equally pressurized double pipe (Ménard 1966).
- The expansion of a 46 mm O.D. very high pressure probe demonstrates that its rubber cover own resistance reaches between 0.6 and 1.2 MPa, depending on the Shore hardness and the thickness of the cover used.
- The capacity of volume deformation of these probes is presently limited to 350 cm^3, that is, for this measuring cell (Fig. 5), a relative deformation dV/V = 50 % or dr/r = 23 %

The two standard corrections on pressure and volume readings are given on the following graphs

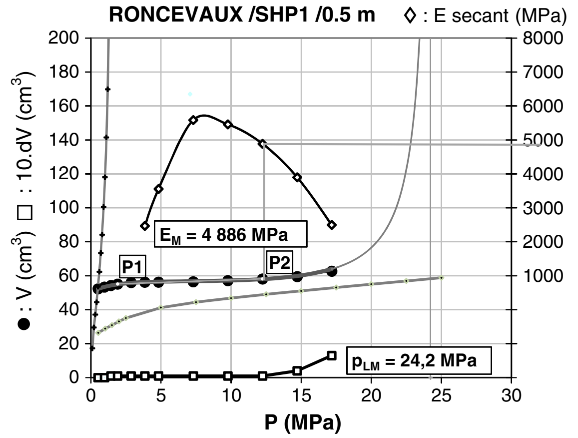


Fig. 7 Beauce limestone, creep beginning at 18 MPa; probe standard calibration *curves* are in grey. The *bell-shape curve* is the variation of the secant E_M along the *PMT curve*

(Figs. 6 and 7). They also show tests performed in a hole bored with a core barrel of 46 mm O.D. fitted with a diamond cutting tool in the following rocks:

- Fontainebleau sandstone, an old quarry of paving stones at Saulx-les-Chartreux (Essonne department, France) and
- Beauce limestone, the Roncevaux quarry (Loiret department, France).

Note the slope of the calibration curve quasi-rectilinear between the contact pressure in the calibration pipe and 25 MPa, the slope being here in the order of 1 cm3/MPa, using water as the transfer and measuring fluid. The quality of the best fit by either linear regression or by a hyperbole, gives an indirect degree of the precision obtained by the equipment when measuring volumes. For instance if water is replaced by an incompressible oil, calibration indicates an excellent reliability of the measurements and a drastic decrease in the slope of the curve.

3.4 Measurements of Moduli in the Range of 0–25 MPa and Creep of Very Hard Soils and Soft Rocks

The interpretation of the tests at very high pressure may result in estimates of E_M moduli that vary according to the span of pressure selected.

Among the examples submitted and considering the widest possible pressure span, the E_M moduli obtained are respectively 3,200 MPa in sandstone and 4,900 MPa in limestone (Figs. 6 and 7). For this last test, the shape of the PMT curve after creep allows to extrapolate a limit pressure of 24.2 MPa, that is an E_M/p_{LM} relationship of 200.

4 Conclusion. Future Developments

The equipment submitted here, the HyperPac 25 MPa, consists of a totally new control unit including a volumetric system made of a servo-controlled piston making possible standard pressure holds stable without the help of an operator. This device with a capacity of 600 cm^3 permitting to obtain 25 MPa contact pressure at the borehole wall is designed to test hard soils and soft rocks through borehole expansion that may present initial failure before reaching 25 MPa and in cemented rocks.

For the day to day use of pressuremeter tests up to 25 MPa by geotechnical firms, the development of the equipment actually rests on the following needs:

- expand the range of very high pressure probes to diameters of 63 or 76 mm according to the Ménard pressuremeter standards.
- scale down to a minimum value the calibration (pressure loss) correcting term, the probes still keeping a high value of cover resistance (volume loss correction), still not detrimental to the precision of the readings.
- provide a large range of calibrated drilling tools, core barrels and tools for wash boring suitable for working in the soils and rocks to be investigated.[2]

5 Note

High pressure tests in rock submitted in this paper are transcriptions of selected tests included in geotechnical surveys made with various pressuremeter devices. No other interpretation is proposed than a standard Ménard modulus E_M and when valid, extrapolation to a standard Ménard limit pressure p^*_{LM}. Such results

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[2] The authors consider that minimising the delay between drilling and testing is essential to achieve high-quality measurements of moduli; this applies to hard grounds and even rocks as well as to soils.

can take place in any conventional soil and/or rock classification. Use of E_M, p^*_{LM} together with earth pressure at rest at the level of the test is the basis of an original pressuremeter data classification submitted in a specific paper in this Special Issue (Baud and Gambin 2013).

6 Expression of Thanks

We would like to express our thanks to the technical team from Géomatech, Apagéo and Cedarnet, the companies which ensured that the HyperPac prototype became operational in 2010. The first public presentation of the functioning of the HyperPac 25 MPa was given during the 'Journées Techniques Apagéo' held from 23 to 24 September 2010.

Further developments occurred from that time and lead to double the maximum allowable test pressures up to 50 MPa (Baud et al. 2013).

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