The Probex: Over 25 years of Experience in Measurement of In-Situ Deformability of Rock

Le Probex : Plus de 25 ans d'expérience de mesure in situ de la déformabilité de la roche

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ABSTRACT: The Probex borehole dilatometer (or rock pressuremeter) is a radially-expandable, borehole probe used mainly to determine deformability of rock in situ. This equipment integrates elements of a pressuremeter, but is designed for testing rock. This paper gives an overview of various uses of this equipment over the last 25 years, as well as more detailed and recent experiences with this equipment. Advantages and limitations related to the use of the Probex are presented.

KEYWORDS: in-situ testing, rock pressuremeter, dilatometer, deformation modulus, back analysis.

RÉSUMÉ : Le dilatomètre de forage (ou pressiomètre haute capacité) Probex comprend une sonde cylindrique dilatable radialement utilisée in situ afin principalement de déterminer la déformabilité des massifs rocheux. Cet équipement a les caractéristiques d'un pressiomètre, mais est conçu pour utilisation dans la roche. Cet article donne un aperçu d'utilisations variées de cet équipement au cours des 25 dernières années, de même que des expériences récentes plus détaillées. On y présente finalement des avantages et limites propres à l'utilisation de cet appareil.

MOTS-CLÉS : essais in situ, pressiomètre haute capacité, dilatomètre, module de déformation, rétrocalcul.

1 INTRODUCTION

The pressuremeter test is not performed on a routine basis in North America. It will often be used in situations where undisturbed samples cannot be obtained, which is often the case in weathered or fractured rock or in weakly cemented material. This peculiar context brought Roctest Ltd to develop high capacity pressuremeters, including the Probex introduced in 1985. This equipment possesses characteristics of a pressuremeter, but is specifically designed for use in rock. Initially thought to be used as a dilatometer as defined in the ISRM *Suggested Method for Deformability Determination Using a Flexible Dilatometer* (ISRM 1987), the Probex became also commonly used like a rock pressuremeter i.e. according to testing sequences and interpretation methods associated to pressuremeters. Its versatility is probably one reason why the Probex is now used in various countries for various applications. But this versatility is accompanied by some limitations that must be well understood in order to ensure reliable use of this equipment.

2 DESCRIPTION AND TEST PROCEDURE

The Probex is designed for operating in 76-mm boreholes and has a maximum working pressure of 30 MPa. It is composed of an expandable probe, a dual-action hydraulic module, and a measuring module. A hydraulic pump together with hydraulic tubing and a digital readout unit complete the dilatometer system. The nominal diameter of the probe is 73.7 mm at rest and 85.5 mm when fully expanded, representing a maximum radial expansion of 16 % – equivalent to a volumetric increase of 675 cc. The membrane consists of polyurethane with fiberglass reinforcements at each end. Resistance of the fully-inflated membrane ranges typically from 2 to 2.5 MPa. The hydraulic module, incorporating a dual-action piston and two cylinders, is located on top of the probe. Displacement of this hydraulically-loaded piston forces water in or out of the flexible membrane. This configuration allows the use of the dilatometer at substantial depths. A linear potentiometer fixed to the piston allows to measure volumetric variations of the probe after a displacement.

No existing test standard specifically regulates the use of the Probex. The test procedure recommended by the manufacturer consists in loading the ground by constant stress control steps, typically in 10 steps of 3 MPa up to 30 MPa. At each step, pressure and volume are recorded after a one minute stabilization period. Like with a conventional pressuremeter, two calibrations must be performed: one in a steel tube for determining deformability of the probe, and one with the membrane unconfined in order to determine the inflation resistance of the membrane.

3 APPLICATIONS AND TEST RESULTS

Test results from the Probex can be used in various ways. Typical applications include estimating deformations of tunnel linings, concrete dam foundations, or bridge supports. Results can also be used for estimating end bearing capacity of deep foundations like caissons. Test data are interpreted using semi-empirical methods developed for pressuremeters, in elasticity analyses, or in finite elements analyses. A rather common application in North America consists in developing P-y curves for lateral deflection analysis of drilled shafts (Failmezger et al. 2005). Slope stability analyses, like the one presented in this paper, are sometime based on test results from the Probex.

Tests results from various sites with various rock mass hardnesses are presented in figure 1.

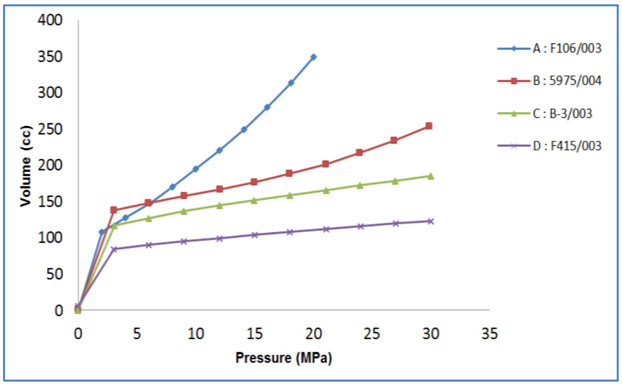

Figure 1. Probex test results from various sites (Source: Roctest Ltd)

Curve A was obtained from tests performed in Montreal (Canada) in 2006 for the Galipeault Bridge project in friable sandstone. The modulus measured on the linear portion of the curve, i.e. between 0.7 and 7 MPa, was 0.5 GPa (Courtesy: SNC-Lavalin).

Curve B was obtained from tests performed in Oakville (Ontario, Canada) in 2012 for a tunnel project. Rock consisted of sound sandstone and limestone with clayey joints. The modulus measured on the linear portion of the curve, i.e. between 2 and 14 MPa, was 2.3 GPa (Courtesy: Terraprobe Inc.).

Curve C was obtained from tests performed in West Virginia (USA) in 2004 during the Kings Creek Bridge project. Rock consisted of sandstone with moderate to slight weathering. The modulus measured between 15 and 30 MPa was 4.1 GPa (Kutschke et al, 2005).

Curve D was obtained from tests performed in Montreal (Canada) in 2008 for an A20 Highway Interchange project. Rock consisted of sound limestone. The modulus measured between 8 and 29 MPa was 21 GPa.

As described by Gill & Leite (1995), different phenomenon can explain the non-linearity of stress-strain curves often observed in rock, for instance the gradual closing or opening of microfissures in hard rock. Closing of a soft joint when the stress fields reach it during a test could explain a sudden strain (volume jump). Failure of the rock can occur during a test and would normally be due to radial cracking and/or formation of a crushed zone.

4 CASE HISTORIES

4.1 URS New Zealand

The Probex dilatometer has been used primarily for testing in very weak rocks (UCS = 1-4 MPa) in New Zealand. Two examples are presented.

4.1.1 *Testing in coal, Stockton Mine, New Zealand*

The Probex dilatometer played an important role in helping to solve a challenging slope stability problem at Solid Energy's Stockton Mine, where a weak, sheared coal seam formed a critical portion of a slope. It traditionally has been very difficult to obtain samples for laboratory testing and therefore shear strengths have usually been estimated via back analysis of existing slopes and previous slope failures. The shear strength values derived from back analyses were too conservative for this case – it was known that the coal strength was higher, but it was not known how much higher. Unless a higher coal strength could be demonstrated, it would have been necessary to undertake a more conservative and costly design.

Because of the weak nature of the coal (UCS = 1-3 MPa), the dilatometer tests could be carried out well into the range of plastic deformation, it was decided to attempt to back-analyse test curves in order to estimate the shear strength properties of the coal. The test curves were back-analysed using a FLAC model (Itasca, 2005) simulation of the dilatometer test in order to estimate shear strength parameters (cohesion, friction angle, dilation angle). A Mohr-Coulomb material model was used. Material properties in the model were varied to achieve a pressure-deformation curve which approximated the test results over the plastic portion of the curve. Estimates of the shear modulus and the average horizontal in-situ stress were made from the test and were used in the numerical simulation. The values for the three shear strength parameters were varied until the pressure-deformation curve from the numerical model gave a good fit with the test curve. Examples of numerical model fits for two test curves are presented in Figure 2.

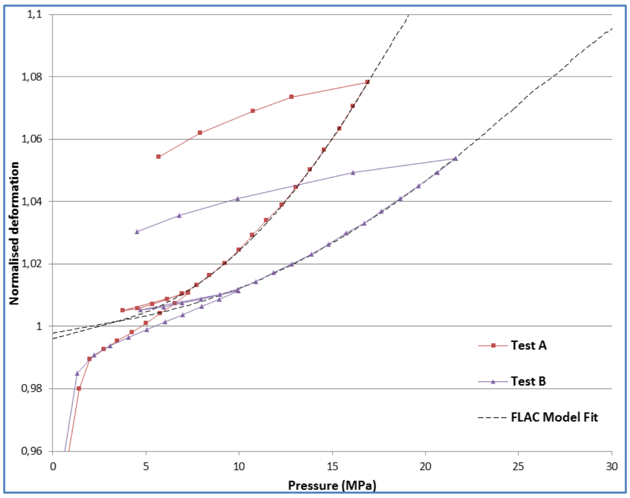

Figure 2. Selected results for two tests in coal, including numerical model fit to data

The back-analysed shear strength parameters are presented in Table 1, along with parameters estimated directly from the test curve.

Table 1. Summary of measured and back-analysed material parameters for dilatometer tests in coal

ID	Test A	Test B
(1) Modulus (GPa) based on reload cycle	0.8	1.2
(1) Avg Horiz. In-situ Stress (MPa)	2.0	2.0
(2) Cohesion (kPa)	750	1400
(2) Friction Angle (deg)	32	45
(2) Dilation Angle (deg)	26	23

(1) Estimated from test curve
(2) Back-analysed from numerical model fit to test data

No attempt was made to model the initial portion of the actual test curve, as this portion of the test tends to exhibit a softer response and is affected by borehole disturbance – especially in weaker rock.

One of the limitations of the back-analysis is that there is not a unique set of material properties that define the material behaviour; if the one of the parameters estimated from the actual test is not accurate, then it will affect the estimated parameters. This approach is still under development and results are considered preliminary. The shear strength parameters estimated for the coal are judged to be reasonable.

A special technique was used for selecting the testing zone. Typically the latter is carefully selected on the basis of recovered drill core. Core recovery in the coal was typically poor. A downhole caliper tool was used to measure the borehole diameter and select test zones where little variation in the borehole diameter was observed. This proved to be a useful method for selecting the test interval, however it is noted that the caliper only measures the diameter within a single plane.

4.1.2 *Testing in weak sandstone, Auckland, New Zealand*

Considerable testing has been undertaken in very weak sandstones and siltstones of the Waitemata Group (UCS = 1 to 4 MPa). These materials are traditionally difficult to sample and test in the laboratory, and therefore in-situ testing with the Probex has been valuable for estimating the deformation parameters of this very soft material. Testing has been carried out for a number of projects involving transportation and water tunnels in the Auckland region.

Due to the weak, erodible nature of the rock, testing was carried out immediately after drilling in order to minimise the potential for borehole wall disturbance.

Typical test curves for sandstones with varying degrees of cementing are presented in Figure 3. One unload/reload cycle was performed at the estimated onset of plastic deformation. The estimated deformation modulus (based on the reload cycle) ranges between about 0.7 and 1.5 GPa.

As with the coal, because the test can be extended well into the plastic deformation range, it may be possible to use a numerical model to back-analyse the test curves to estimate the shear strength of the sandstones. This work has not yet been undertaken.

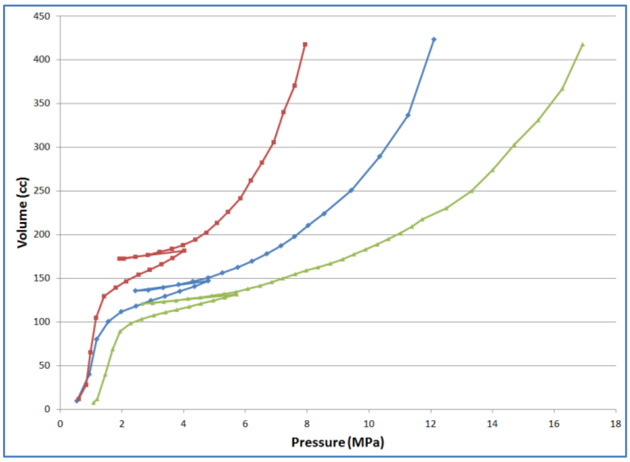

Figure 3. Typical test results for extremely weak sandstone (Source: NZTA, Waterview Project)

4.2 *URS Corporation USA: Morro de Arica Project*

The Probex dilatometer was used to help characterize foundation deformation and predict performance of a proposed 220 meter high thin arch concrete dam at Morro de Arica, Peru. The rock mass at the Morro de Arica dam site was very strong and hard quartzite, with a high intact rock deformation modulus, estimated to be 35 to 50 GPa. The quartzite was closely to moderately fractured with 3 joint sets and steeply dipping bedding planes. Rock mass deformability for the proposed dam foundation was therefore expected to be approximately an order of magnitude less than the intact rock deformation modulus. The foundation was also thought to be anisotropic due to the orientation of joints and bedding planes with respect to the direction the proposed dam would load the foundation.

The Morro de Arica site was located within a steep walled and narrow V-shaped valley. Access to the rock forming the abutments of the dam was made possible by driving adits into the rock. Test holes were made with an NQ diamond core drill string, from within the adits, into the rock mass that would form the abutments. Test holes were oriented to be parallel to the planned surface of rock foundation so measurements of deformation moduli would be oriented in the same direction as the proposed dam would load the rock. Core samples obtained from the test holes were used to plan specific dilatometer test locations. A number of dilatometer tests were conducted in each of the test holes, in the range of rock mass conditions interpreted from the core samples. The dilatometer testing was used to measure deformation moduli in closely fractured rock that when cored, did not yield samples suitable for laboratory testing. The quartzite tended to break into small fragments during the coring process; however, the test hole walls remained in a condition suitable for the dilatometer testing.

Dilatometer tests were conducted with four load-unload cycles up to around 10 MPa in order to measure deformation moduli over the range of expected foundation loadings the dam would experience during planned operation of the reservoir, which was to be used as a water regulating reservoir.

Dilatometer tests were conducted using methods similar to those recommended for the pressuremeter in ASTM D-4719. A computer program was used to correct pressure and volume readings for deformability of the probe, resistance of the membrane and aid in making interpretations of rock mass in situ stress, deformation moduli, and shear strength of the rock mass. Results from the testing program indicated the fractured quartzite rock mass had deformation moduli of 10 to 20 GPa, about 25 to 40% of the intact rock modulus. In many areas moduli of the fractured rock mass was similar to that of the concrete that would be used to construct the dam, which was a favorable condition in the foundation to help mitigate stress concentrations that can occur in the concrete, especially along the rock-concrete contact. The dilatometer testing program at Morro de Arica was successful in measuring deformation moduli in the foundation of the dam to model performance of the dam and foundation during operation of the regulating reservoir. The Morro de Arica project was not built due to economic considerations and the ability to regulate water with other reservoirs.

4.3 *EN.OM.FRA sas - France*

Tests performed in 2012 by EN.OM.FRA in order to estimate deformation moduli of rock surrounding a railway tunnel in Chamborigaud (France) constitute another interesting use of the Probex. The rock mass consisted of schist with quartzite veins. Due the fractured nature of the rock mass (partially linked to its schistosity), the use of a standard dilatometer proved to be difficult without high risk of membrane burst. The Probex was then selected. The high reinforcement of its membrane allowed its use without problems. Testing was run alternately following the NF P94-110-1 Pressuremeter Standard (without cycle) and the XP P94-443-1 Flexible Dilatometer Standard (with progressive cycles). Two tests were conducted at the same depth (7.3 m) following these two French standards. They produced global moduli of similar magnitude: 1.5 and 1.1 GPa

(Table 2). Total loading time was about 15 minutes in the first case and exceeded 60 minutes in the second case.

Table 2. Tests results (SC4 Bis) following pressuremeter and dilatometer standards (Courtesy: Hydrogeotechnique)

Depth (m)	Modulus (MPa)			
	1st Cycle	2nd Cycle	3rd Cycle	Global
5.3	-	-	-	545
6.3	1246	931	999	328
7.3	-	-	-	1497
7.3	3978	3301	2631	1121
12.0	-	-	-	145

The same year, EN.OM.FRA participated in two other projects related to tunnel structures. One of these consists in the modernization of a railway line located in Northern Slovakia in the Javorniky Mountains. The contractor responsible for the geological investigations conducted 77 tests at an average depth of 140 m in 13 working days. Tests were done in 6 boreholes essentially in claystone, siltstone, and sandstone (Source: CAD-ECO a. s. Slovakia).

5 ELASTIC VS INELASTIC STRAINS

As soon as a rock mass is loaded, elastic and inelastic strains can occur simultaneously. These behaviours can be difficult to distinguish. The effect of inelastic strains can be attenuated by waiting for a stabilization period when recording data. This method was followed during a testing campaign done by Roctest at Majun Elghidir, Tunisia, in 1991 for a dam project. Figure 4 presents a typical test result obtained at this site. Tested material was crystalline gypsum. At each pressure step, readings were taken every minute. If the volume variation of the last 2 minutes was less than 5% of the variation of the last 5 minutes, the volume would be considered stable and pressure could be increased to the next step. Minimum stabilization time at each step was then 5 minutes. At FG-17-1, stabilization took 33 minutes at the first pressure step and 5 minutes at the last pressure step. Total time of this test was 1h45min. The modulus obtained between 9 and 28 MPa was 10.5 GPa.

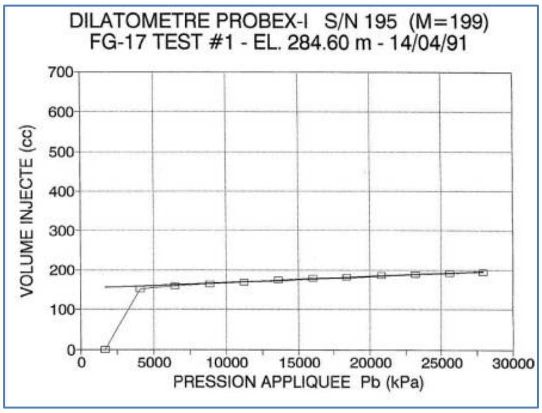

Figure 4. Test results recorded after a strains stabilization period (Source: Roctest Ltd)

A testing sequence including cyclic loadings allows better distinguishing and quantifying the effects of elastic and inelastic behaviours of the rock masses. Results obtained in 2012 by Fugro-Sial Ltd. from Turkey show these behaviours. For each test, three successive cycles were done in 3-MPa steps from 0 MPa up to 30 MPa. Results in BH-19010 show an elastic response of the rock mass (Figure 5). For each of the three cycles, modulus was stable around 23 GPa between 18 and 30 MPa. Results of BH-21001 (Figure 6) are quite different: the first cycle displays a lower modulus (1.4 GPa) whereas the two successive loadings display higher and stable moduli (around 2.7 GPa). It would appear that rock mass deformed in an inelastic way only during the first cycle and then essentially in an elastic way in the two successive loadings. This may lead us to believe that some cracks in the rock were squeezed closed during the first pressure cycle, and remained closed during the subsequent two pressure cycles. This shows the value of performing a cyclic test in that the rock mass properties changed significantly during the cyclic testing.

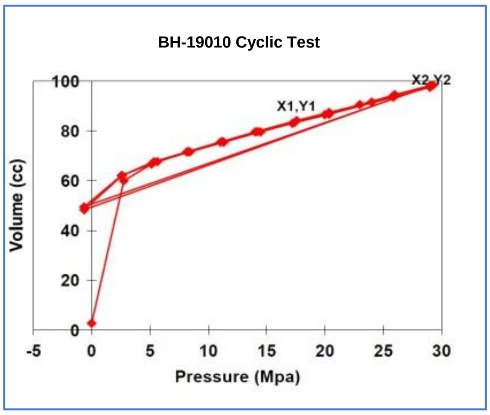

Figure 5. Test results showing elastic responses of rock masses (Courtesy: Fugro-Sial Ltd. from Turkey)

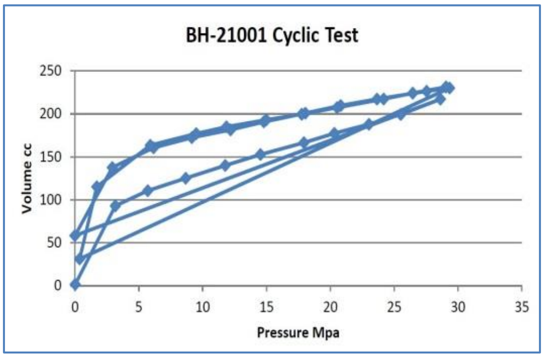

Figure 6. Test results showing elastic and inelastic responses of rock masses (Courtesy: Fugro-Sial Ltd. from Turkey)

6 USE OF THE PROBEX IN HARD ROCK

The use of conventional pressuremeters can be extended to soft rock only (Galera et al, 2005). The use of the Probex is possible in harder rock (Kaneshiro et al, 1987; Labrie et al, 1998) due to the special characteristics of this equipment, and as long as specific precautions relating to the test techniques are taken. These characteristics and precautions are listed below.

a) The working capacity of the Probex is high: 30 MPa.
b) Measurement of the probe's expansion is done with a sensitive linear potentiometer, which enables to detect small diametric variations (0.001 mm).
c) The pressurization of the Probex membrane is done by the movement of a piston located immediately upstream of the membrane. This configuration eliminates the 'parasitic' deformation of the tubing and pumping system.

d) The length-diameter ratio of the measuring membrane exceeds 6 (457/73.7 mm) in order to reduce the end effects of the Probex mono-cellular probe.
e) A thick-wall (12.5 mm) calibration steel tube must be used. Though extremely rigid, the deformability of this tube must be considered in data reductions.
f) De-aired water can be used for reducing the deformation of the probe.
g) Five successive volume calibrations in the steel tube must be completed just before running tests with the Probex. These calibrations will knead the membrane ensuring a better repeatability of the deformability of the probe (typical values are around 1 cc/MPa).
h) Tests must be conducted in boreholes with diameter values as close as possible to the inner diameter of the calibration tube. The calibration tube provided by the manufacturer has an inner diameter of about 76.2 mm. Calibration tubes of various inner diameters can be used if necessary.
i) Though more delicate to carry out, the rock mass modulus and the deformability of the probe can be calculated over equivalent loading sequences within pressure ranges having the same order of magnitude.

The harder the tested rock is, the more rigorous the execution of points e) to i) will need to be for ensuring reliability of results. Most of these precautions are also applicable to other mono-cellular pressuremeters based on the volumetric measurement principle.

7 LIMITATIONS AND ADVANTAGES

Precautions enumerated in the previous section constitute important limitations to the use of the Probex. Additional limitations include precautions that must be taken to prevent the probe from getting stuck in the borehole – consisting essentially in lowering the probe to testing depths with rods/casing having diameter identical or close to the one of the probe itself – and precautions necessary to limit bursting rate of the membranes. Also, the Probex does not measure the anisotropic response of the rock. Finally, it must be kept in mind that each day of testing must begin with a series of five calibrations which takes up to two hours.

Advantages of the Probex can be listed as follows. Using the proper test techniques, the Probex can be used in very soft, weathered and/or fractured rock up to hard rock for various applications. The Probex can be used as a supplement to a standard pressuremeter where the rock becomes too strong for the loading capacity of the standard pressuremeters. Conducting tests with the Probex is easy and quick. Around eight tests per day can typically be done in a single borehole. One user reported doing up to 25 tests in a single long day (reference Peter Brown, Kanada Teknik). The Probex membrane is rugged. Almost 300 tests have been done with a single membrane in sound rock (reference Peter Brown, Kanada Teknik). Also, the Probex can be used at great depth. Roctest performed tests down to 286 m in Tunisia. Tests at greater depths can likely be done. Finally, the Probex is especially well adapted for the design of laterally loaded foundations – like drilled shafts in rock – due to the close analogy between the Probex test and how these types of foundations behave in reality.

8 CONCLUSION

The Probex has been used for over 25 years for various applications according to testing sequences and interpretation methods associated with either flexible dilatometers or pressuremeters. Case histories have been presented in an effort to give an overview of these various applications. Advantages and limitations of the Probex have been presented to contribute towards ensuring its proper use.

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