MEASUREMENT OF IN SITU DEFORMABILITY IN HARD ROCK

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ABSTRACT
The analysis of a set of 84 dilatometer measurements made in three deep mines in northern Quebec revealed a correlation between the in situ modulus of deformation (E_d) and the in situ stress, suggesting that dilatometer measurements could be used as to assess stress levels and integrity of mine structures (Labrie *et al.*, 1998). Since then more than a hundred measurements and three new sites have been added to the database, including a site less than 20 meters below surface. The database includes values for the intact rock modulus of deformation (E_l) determined in the laboratory using drill core samples recovered from the test sites, and estimates of the rock mass modulus of deformation (E_m) derived from E_l using the Rock Mass Rating (*RMR*). The enlarged database makes it possible to assess rigorously the correlation of E_d with in situ stress and to test the assumptions used to reduce the dilatometer measurements, in particular the use of the Lamé equation, which does not take in situ stress into account. Recent considerations to incorporate in situ stress in the computation are discussed.

RÉSUMÉ
L'analyse d'un ensemble de données résultant de 84 essais au dilatomètre effectués à l'intérieur de trois mines profondes du Nord québécois révélait une corrélation entre le module de déformation (E_d) et le niveau de contrainte des massifs rocheux en place, suggérant que les essais au dilatomètre pouvaient être utilisés pour évaluer le niveau de contrainte et vérifier l'intégrité des structures minières (Labrie *et al.*, 1998). Depuis, plus d'une centaine de résultats d'essai provenant de trois sites supplémentaires ont été ajoutés à l'ensemble, dont ceux provenant d'un site situé à proximité de la surface, à moins de 20 mètres de profondeur. L'ensemble de données inclut également les valeurs des modules de déformation déterminés en laboratoire sur le matériau intact (E_l) et les valeurs des modules de déformation des massifs rocheux correspondants (E_m), à l'intérieur desquels ont été réalisés les forages utilisés pour les essais. L'ensemble de données résultant permet aujourd'hui d'évaluer rigoureusement la corrélation existante entre le module de dilatomètre (E_d) et le niveau de contrainte des massifs rocheux en place, et d'examiner les hypothèses qui prévalent lors de l'interprétation des résultats, en particulier celles ayant trait à l'utilisation de l'équation de Lamé. Quelques considérations récentes pour tenir compte du niveau de contrainte lors de l'interprétation des résultats sont discutées.

1. INTRODUCTION

Strength and deformability are probably the two most important properties used to characterize the mechanical behavior of rock materials and to assess the stability of structures built in or founded on rock (Jaeger and Cook, 1969; Bieniawski, 1984; Brady and Brown, 1985; Yow, 1993). Goodman (1989) reviews many of the static and dynamic tests used to determine the deformability of rocks, describing the apparatus, field and laboratory techniques, and the interpretation of the results.

The dilatometer is one of the most versatile instruments used to determine the in situ modulus of deformation. The operating principle is quite simple: a known pressure is applied to the wall of a borehole and the displacement of the wall is measured. Depending on the particular instrument, dilatometers may be used in boreholes of various diameters with lengths of several hundred meters (Gill and Leite, 1995).

In this paper we describe a series of dilatometer tests that were carried out in six hard rock mines in northern Quebec, Canada, either to characterize rock structures (*eg.* mine galleries, crown and sill pillars, stope abutments), to estimate the level of damage occurring in rock masses in the vicinity of mine openings, or to provide data to support the interpretation of measurements made in boreholes. Field investigations were conducted to determine the geology, structure and stress regimes of the sites. Laboratory measurements of rock properties were made on core specimens. The significance of the dilatometer test results is assessed with respect to repeatability, correlation with deformability measurements of the rock mass and intact rock, and the influence of the in situ stress. Recently suggested methods to take stress effects into account are reviewed.

2. DILATOMETER TESTING

Dilatometers with a range of probe and membrane sizes and measuring devices are available (*eg.* Cambridge Insitu, 2003; Interfels, 2003; OYO, 2000). The PROBEX-1 model (Roctest, 2002) for N-size boreholes (75.7 mm) was used for this series of tests. The probe consists of a high-pressure flexible membrane that can be inflated up to 30 MPa, a hydraulic module comprising a dual piston and cylinder assembly to inflate and deflate the membrane, and a volume-change measuring device mounted inside the probe casing. A manual hydraulic pump is used to pressurize the system. The line pressure and the volume change are measured electronically with transducers mounted on the pump or built in the probe. A manually operated data acquisition module is mounted in the readout unit.

A standard testing procedure has been proposed for this type of dilatometer by the International Society of Rock Mechanics (IRSM, 1987), adapted by the manufacturer to respect the characteristics of its instrument (Roctest, 1992). A typical curve obtained for a dilatometer test done in hard rock is shown in Figure 1. All tests were conducted according to the procedure suggested by the manufacturer.

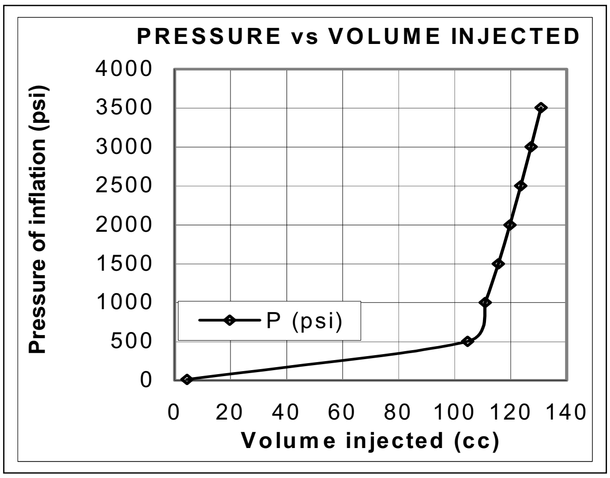

Figure 1. A typical curve obtained for a dilatometer test.

The interpretation of the results is based on the well-known Lamé equation (Goodman, 1989):

$$E_d = r [1 + v] [\Delta p / \Delta r] \quad [1a]$$

or in terms of volume, to respect the characteristics of the instrument used for the test program:

$$E_d = 2V [1 + v] / [(\Delta V / \Delta p) - c] \quad [1b]$$

In these equations, E_d represents the modulus of deformation determined in situ with the dilatometer, *v*, the Poisson's ratio, *r*, the borehole radius, *V*, the borehole volume, *p*, the pressure of inflation, and *c*, the constant of calibration of the probe.

3. MINE SITES INVESTIGATED

Six mines were involved in the testing program, with one to three sites of measurement investigated at each of these mines (Table 1). Tests were conducted in virgin ground, crown and sill pillars and stope abutments. Boreholes were drilled from the opening providing the best access to the structure to be investigated, usually haulage ways or mine galleries. The boreholes were usually drilled either vertically, or parallel to the main geological structures, or along the dip of ore bodies. If possible the boreholes were aligned parallel to a principal component of the general stress tensor. This is important when monitoring stresses in mine structures, as it limits the number of unknowns and facilitates the interpretation of results (Jaeger and Cook, 1969). Ground conditions and stress regimes determined or estimated for each test site are detailed in Table 1.

4. RESULTS

4.1 Induced stress levels

The magnitude and orientation of principal stresses at the test sites were determined for mine design purposes prior to the dilatometer test program (References are listed at the bottom of Table 1). The orientation of the major principal stress component (σ_1) was usually perpendicular to the ore body or structure investigated, in accord with the trends observed for the Abitibi area (Corthésy *et al.*, 1997).

4.2 Results of dilatometer tests

Dilatometer tests were conducted at twelve locations in six mines in the Abitibi and Saguenay areas of the Province of Quebec. All test sites were located underground, except for the Pierre-Beauchemin mine, where boreholes were drilled from the surface to investigate the quality of the bedrock in the area of the crown pillars. These crown pillars are permanent structures usually left in place to protect underground openings from intrusion of topsoil and to guarantee their stability at shallow depth.

A total of 208 tests were done at these six mines during the last fifteen years: 128 were primary tests, being the first loading of the rock mass, and the remainder were secondary tests, *ie*. reloading experiments carried out at the same position within the boreholes, without moving the probe, to verify the accuracy and the repeatability of measurements and identify the presence of strain-hardening, if any. Most (69%) of the reloading tests differed from the primary test by less than 20%. Reloading tests were done systematically at Joe Mann, Sigma, Francoeur and Niobec mines, the latter having the largest variability with seven of sixteen secondary test results showing a difference greater than 20%.

The distance between tests carried out in boreholes varied between 0.4 and 2 m, depending on the objectives of the various test programs, *eg.* a 0.4 m test spacing was used at Mine Francoeur to map the depth of the damaged zone around a ventilation drift (Simon, 2002), a 2 m spacing was used at Mine Pierre-Beauchemin to determine the conditions of crown pillars (Cockburn and Désormeaux, 1988). Elsewhere, a 1 m interval was used, except where structural defects were detected. In this case, test was moved to the most proximate location, to avoid perforating the membrane.

Table 1. List of mines and characteristics of dilatometer test sites.

MINE SITE	SITE (no.)	BOREHOLE	DEPTH (m)	ROCK-TYPE	$E_{LABORATORY}$ (GPa)	POISSON'S RATIO	RQD [(1)]	RMR [(1)]	σ_1 [(2)] (MPa)	σ_{mean} [(2)] (MPa)	REFERENCE
Mine Pierre-	1	87-E1	7 – 20	Diorite (i)	88.60	0.295	65 – 88	50 – 61	0.5	0.5	Cockburn and
Beauchemin	1	87-E1	7 – 20	Diorite (a)	72.55	0.290	65 – 88	50 – 61	0.5	0.5	Désormeaux,
(former Eldrich)	2	87-E2	10 – 22	Diorite (a)	65.64	0.275	40 – 79	42 – 59	0.5	0.5	1988;
Evain	3	87-E3	8.5 – 21	Tonalite	66.63	0.290	63 – 79	48 – 52	0.5	0.5	Labrie, 1988
(Abitibi, Qc)											
Mine Niobec	1	600-F1	190 – 200	Carbonatite	52.52	0.337	86 – 89	76 – 78	11.5	8.0	Labrie and
Saint-Honoré	2	600-F3	185 – 200	Carbonatite	64.77	0.298	62 – 86	71 – 78	11.5	8.0	Conlon, 1997a
(Saguenay, Qc)											
Mine Joe Mann	1	20-O-9	565 – 575	Gabbro	81.36	0.247	82 – 96	77 – 81	52.9	39.3	Labrie and
Chibougamau	2	21-A-9	610 – 620	Rhyolite	68.24	0.250	87 – 94	78 – 80	64.6	45.8	Conlon, 1997b
(Saguenay, Qc)											
Mine Sigma	1	17018	1460 – 1465	Andesite	62.05	0.300	74 – 97	75 – 81	66.4	43.8	Labrie and
Val-d'Or	1	17018	1465 – 1470	Diorite	65.69	0.309	74 – 97	75 – 81	66.4	43.8	Conlon, 1997c
(Abitibi, Qc)	2	17020	1573 – 1578	Quartz (+To)	64.13	0.320	100	94	70.8	46.8	
Mine Francoeur	1	99.2	135 – 137	Andesite	62.00	0.230	59 – 66	53 – 54	5.0	3.4	Simon, 2002
Arntfield	1	99.2	135 – 137	Gabbro	59.30	0.250	60 – 74	58 – 61	5.0	3.4	
(Abitibi, Qc)	1	V1 – V4	135 – 137	Andesite	74.40	0.235	n/a	n/a	5.1	3.6	
	1	V5 – V8	135 – 137	Gabbro	72.90	0.238	n/a	n/a	5.1	3.6	
Mine Bell-Allard	1	520.1 – 520.3	965	Rhyolite	64.52	0.240	93 – 99	78 – 84	62.2	39.0	Labrie *et al.*,
Matagami	2	520.4 – 520.6	950	Rhyolite	63.86	0.237	85	79	34.8	23.0	2001
(Abitibi, Qc)	2	520.6	950	Rhyolite	63.86	0.237	85	79	34.8	23.0	

[(1)] References for description of rock masses and definition of quality indices. Rock Quality Designation (*RQD*) (Deere, 1964); Rock Mass Rating (*RMR*) (Bieniawski, 1984).

[(2)] References for calculation or estimate of stress regimes at sites of measurement. Major principal stress (σ_1); and Mean stress [$\sigma_{mean} = (\sigma_1 + \sigma_2 + \sigma_3) / 3$]. Mine Pierre-Beauchemin: Estimated by the authors; Mine Niobec: Yu *et al.*, 1988; Mine Joe Mann: Yu *et al.*, 1995; Mine Sigma: Aubertin *et al.*, 1997; Mine Francoeur: Corthésy *et al.*, 1997; and Mine Bell-Allard: Corthésy *et al.*, 1999.

The probe was inflated to pressures up to 30 MPa at Mine Pierre-Beauchemin and 25 MPa at other sites, with increments of 3.45 MPa (500 psi). The pressure and volume of fluid injected to inflate the probe were recorded after each increment (Figure 1). Coefficients of linearity determined are mostly greater than 0.998, confirming the linear elastic behavior of all rock types investigated here.

Only the primary test results are discussed here. Secondary test results are detailed in Labrie *et al*. (1998). Twenty of the 128 primary tests were discarded: four (4) tests at Mine Pierre-Beauchemin were conducted in highly altered, soil-like material; four (4) were single results within locally contained rock units already covered by previous tests; eight (8) were discarded because tests were done in unspecified ground conditions, close to the excavation and inducing a high stress gradient at the location of measurements (Aubertin *et al*., 2002); and four (4) were rejected because their values exceeded the instrument limits (three (3) of these were replaced by secondary results). All dilatometer tests carried out over the last fifteen years and considered in this article are summarized in Table 2.

4.3 Results of laboratory tests

An extensive laboratory test program was carried out on samples recovered from the boreholes used for dilatometer testing. Tests were carried out under uniaxial and triaxial compression modes according to ASTM (2002) standards. Specimens were loaded until failure while recording loads and confining pressures. Axial and circumferential deformations were measured with electrical strain gages and linear and circumferential transducers during uniaxial compression tests, but only with transducers during triaxial tests. Young's modulus and Poisson's ratio were determined (Table 1). Poisson's ratio value is needed for the reduction of the dilatometer measurements (Equation 1b).

Table 2. Results of dilatometer tests and comparison with results obtained in laboratory and field.

MINE SITE (1) (2)	**BORE-HOLE**	**ROCK TYPE**	**RMR**	**$E_{DILATOMETER}$**		**$E_{LABORATORY}$ (GPa)**	**E_{MASS} (GPa)**	**RATIO**		
				Mean / N (GPa / n)	**StDv / CV (GPa / %)**			**E_D / E_L**	**E_M / E_L**	**E_M / E_D**
Mine Pierre-Beauchemin	87-E1	Diorite (i)	61	30.60 / 2	9.64 / 32	88.60	20.78	0.345	0.235	0.679
	87-E1	Diorite (a)	59	12.96 / 2	5.44 / 42	72.55	15.73	0.179	0.217	1.214
	87-E2	Diorite (a)	55	12.62 / 3	7.38 / 59	65.64	12.14	0.192	0.185	0.962
	87-E3	Tonalite (a)	50	18.47 / 4	3.76 / 20	66.63	10.03	0.277	0.151	0.543
Mine Niobec	600-F1	Carbonatite	77	26.72 / 8	4.57 / 17	52.52	22.52	0.509	0.429	0.843
	600-F3	Carbonatite	73	30.51 / 8	11.57 / 38	64.77	23.95	0.471	0.370	0.785
Mine Joe Mann	20-O-9	Gabbro	79	65.10 / 6	12.17 / 19	81.36	37.56	0.800	0.462	0.577
	21-A-9	Rhyolite	79	60.93 / 7	8.73 / 14	68.24	31.50	0.893	0.462	0.517
Mine Sigma	17018	Diorite	80	59.88 / 4	4.96 / 8	65.69	31.46	0.912	0.479	0.525
	17018	Andesite	81	71.65 / 5	9.68 / 14	62.05	30.83	1.155	0.497	0.430
	17020	Quartz+To	94	60.75 / 2	12.99 / 21	64.13	51.37	0.947	0.801	0.846
Mine Francoeur	99-2	Andesite	53	26.58 / 8	2.08 / 8	62.00	10.57	0.429	0.170	0.398
	99-2	Gabbro	59	32.77 / 2	0.50 / 2	59.30	12.86	0.553	0.217	0.392
	V1-V4	Andesite	53	35.31 / 10	7.53 / 21	74.40	12.94	0.475	0.174	0.367
	V5-V8	Gabbro	59	31.83 / 18	6.64 / 21	72.90	15.81	0.437	0.217	0.497
Mine Bell-Allard	520-1	Rhyolite	81	33.32 / 5	5.31 / 16	64.52	32.06	0.516	0.497	0.962
	520-5	Rhyolite	79	35.84 / 6	4.38 / 12	63.86	29.48	0.561	0.462	0.823
	520-6	Rhyolite	79	72.85 / 11	16.94 / 23	63.86	29.48	1.141	0.462	0.405

(1) Definition of abbreviations. Rock type: Intact rock (*i*); Altered rock (*a*). Modulus of deformation: $E_{DILATOMETER}$ (E_D): Modulus determined with dilatometer (Roctest, 1992); $E_{LABORATORY}$ (E_L): Modulus determined in the laboratory (ASTM, 2002); and E_{MASS} (E_M): Modulus determined for the rock mass (Nicholson and Bieniawski, 1990). Statistical coefficients: Average value (*Mean*); Number of test values (*N*); Standard deviation (*StDv*); and Coefficient of variation (*CV*) [*CV* = *StDv* / *Mean*].

(2) References to original data sets and results. Mine Pierre-Beauchemin: Cockburn and Désormeaux, 1988; Mine Niobec: Labrie and Conlon, 1997a; Mine Joe Mann: Labrie and Conlon, 1997b; Mine Sigma: Labrie and Conlon, 1997c; Mine Francoeur: Labrie and Conlon, 2000; and Mine Bell-Allard: Labrie *et al*., 2002.

4.4 Deformability of rock masses

In order to analyze dilatometer test results objectively and to allow the comparison with results of laboratory tests done on intact rock specimens and values of deformability proposed for rock masses, consideration has to be given to scale effects (Bieniawski, 1984; Brady and Brown, 1985; Goodman, 1989; Jackson and Lau, 1990; Nicholson and Bieniawski, 1990; Pinto da Cunha, 1990; Pinto da Cunha and Muralha, 1990; Palmström and Singh, 2001; Asef and Reddish, 2002; Kayabasi *et al*., 2003).

Most practical formulations of scale effects are based on rock mass classifications. Indices are used to reduce values determined in the laboratory on intact rock specimens and to provide realistic values that take into account the inherent characteristics of rock masses (ISRM, 1978). The formulation proposed by Nicholson and Bieniawski (1990) was used to estimate the modulus of deformation of the rock mass, derived from the following equation:

$$E_m = [\ E_l / 100\ ]\ [\ 0.0028\ RMR^2 + 0.9\ e^{(RMR/22.82)}\ ] \qquad [2]$$

In this equation, E_m and E_l represent the modulus of deformation of the rock mass and the intact rock, respectively, and *RMR* is the Rock Mass Rating (Bieniawski, 1984). Derived values of E_m are listed in Table 2. Values of deformation moduli (E_l, E_d and E_m) are shown as a function of the in situ mean stress in Figure 2.

5. ANALYSIS OF RESULTS

The series of field and laboratory measurements produced some interesting observations regarding the deformation moduli:

(i) The intact rock modulus (E_l , or Young's modulus) was within quite a narrow range for all rock types tested, *ie*. 60 to 75 GPa with an average of 67.4 GPa and a standard variation of 8.2 GPa;

(ii) The rock mass modulus (E_m) ranged from 10 to 40 MPa. It was lower near the surface where the rock mass was more fractured and altered. The RMR value was between 50 and 60 near the surface and about 80 at depth;

(iii) The dilatometer modulus (E_d) is strongly correlated with the observed in situ stresses (Figure 3); and

(iv) The dilatometer modulus (E_d) is similar to the rock mass modulus (E_m) near the surface, at shallow depth and low stress, and close to the intact rock modulus (E_l) at depth and under high stress.

Regression lines fitted to the data (Figure 3) are described by the following equations:

$$E_m = 518.9\ \sigma_{mean} + 14{,}244 \text{ (in MPa) , with} \qquad [3a]$$

$$R^2 = 0.7762 \text{ , and} \qquad [3b]$$

$$E_d = 857.1\ \sigma_{mean} + 23{,}895 \text{ (in MPa) , with} \qquad [4a]$$

$$R^2 = 0.6767 \text{ ,} \qquad [4b]$$

where R^2 is the coefficient of correlation.

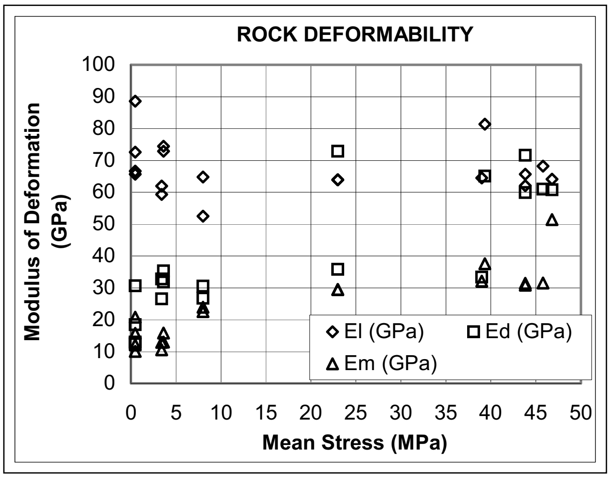

Figure 2. Modulus of deformation as a function of in situ mean stress.

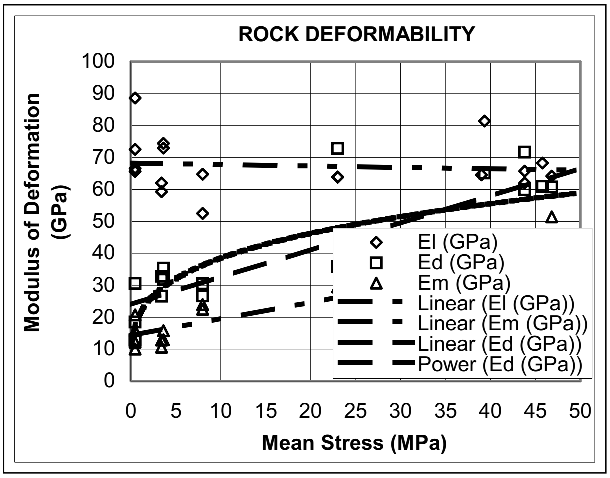

Figure 3. Correlation between modulus of deformation and in situ mean stress.

In an attempt to improve the quality of correlation of equations 3 and 4, the procedure was repeated with all results normalized by their Young's modulus (E_l), but no significant change was observed. In fact, the coefficients of correlation were slightly lower with values of 0.7424 and 0.6621 obtained for the rock mass (E_m) and the dilatometer (E_d) test results, respectively.

A last attempt was made to improve the quality of the correlation observed between dilatometer test results and the mean stress observed in situ, and therefore, propose an alternative interpretation of the data displayed in Figure 3. An exponent-type regression was fitted to the data, similar to the approach proposed by Santarelli *et al*. (1986) and Santarelli and Brown (1987) to model the behavior of confined boreholes. The new relation is then given by the following expression:

$$E_d = 20{,}904\ \sigma_{mean}^{0.2649} \quad \text{(in MPa)} \qquad [5a]$$

$$R^2 = 0.7389 \qquad [5b]$$

The coefficient of correlation of equation 5a shows a slight improvement compared to equation 4a. More interesting however are the boundary values displayed by equation 5a. At surface, unconfined, the modulus of deformation (E_d) is zero, and increases very rapidly to reach a value of 25 GPa under a stress level of 2 MPa, *ie*. the average value of the modulus of the rock mass (E_m) under the same conditions. Above 10 MPa, the modulus of deformation increases slowly and reaches 58.9 GPa under an average stress level of 50 MPa. Within the range of stresses considered, both relations, 4a and 5a, are consistent with all results reported in the present paper.

The modulus of deformation determined with the dilatometer (E_d) is very close of the modulus of the rock mass (E_m) at a low stress level, and similar to the modulus determined in the laboratory (E_l) on intact rock samples, at a high stress level. Intermediate stress levels would logically lead to intermediate values of deformability as well. Unfortunately, very few results are available for intermediate depths and stress levels. This is discussed below.

6. DISCUSSION

The discussion is limited to the issues of interpolation of results to intermediate stress levels and the effect of in situ stresses on deformability measurements. Issues such as the comparison of results with similar results published in literature, the sensitivity of borehole dilatometers and limitations imposed by current instruments in practice, and the range and the meaning of rock properties determined with borehole dilatometers are addressed elsewhere (Kanishiro *et al*., 1987; Goodman, 1989; Labrie *et al*., 1998).

6.1 Interpolation of results

A fair estimate of the modulus of deformation at the scale of boreholes and for intermediate stress levels can be predicted by equations 4 or 5. However, the lack of experimental values at these stress levels remains a shortcoming. Additional measurements are needed to verify the proposed relationships. Nevertheless, our observations are consistent with those made by other researchers over the last twenty years (Koopmans and Hughes, 1986; Pinto da Cunha, 1990; Pinto da Cunha and Muralha, 1990).

6.2 Influence of in situ stresses

Results shown in Table 2 and Figure 3 clearly indicate that the stress level has a direct influence on the modulus of deformation determined in situ with dilatometer, until its value becomes close to the one determined in the laboratory on the intact rock material.

The efforts made by Santarelli *et al*. (1986) and Santarelli and Brown (1987) to model stresses and strains around boreholes and to explain their behavior at failure has many similarities with our measurements at the scale of the rock mass and our attempts to characterize the effect of in situ stresses on the deformability of rock structures. Tests and observations made by Santarelli *et al*. (1986) and Santarelli and Brown (1987) were conducted on non-linear porous materials that can only be modeled adequately through an intrinsic formulation that requires the definition of the appropriate constitutive law for the material, *eg*. the equivalent for porous non-linear materials of the well-known Hooke's law for elastic linear materials. Applied to the interpretation of dilatometer measurements, the implementation of a similar approach would mean a complete reformulation of the classic Lamé's solution, which was beyond the scope of the present article.

All rocks tested in the present program were hard rock materials, showing elastic linear behaviour, and therefore complying well with both Lamé's and Hooke's solutions (see Figure 1). Coefficients of linearity determined in the laboratory with compression tests and in the field with dilatometer tests are usually greater than 0.995 for stress levels discussed. Nevertheless, the results obtained show the importance of boundary conditions on the result of deformability measurements carried out with borehole dilatometers (Goodman, 1989).

7. CONCLUSION

Over two hundred dilatometer tests were done in six mines of northern Quebec, Canada, over the last fifteen years. Mines were hard rock mines, operating at different depths and stress conditions, from surface to depths exceeding 1,800 meters. Tests were done in boreholes drilled from surface and underground openings, at sites providing the best access possible to structures to investigate. Results show a good correlation between stress levels observed at the location of measurements and the deformability of structures investigated, in accordance with results published by other searchers over the last twenty years (Koopmans and Hughes, 1986; Pinto da Cunha, 1990; Pinto Cunha and Muralha, 1990).

The main outcome of the test program is a data set that offers a wide range of deformability values expected within rock structures under different stress conditions. Stress conditions are a critical factor to assess correctly the meaning of these values and decide on their application. Reasons for undertaking the test program and doing field measurements were detailed at the beginning of the article. These reasons cover most of the applications sought for dilatometer testing (Gill and Leite, 1995).

8. ACKNOWLEDGEMENTS

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