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A New Stress Relief Concept for In-situ Stress Measurements in Rock and its Implementation in two Recoverable Stressmeters.

H. BOCK
Associate Professor, Department of Civil & Systems Engineering, James Cook University of North Queensland
V. FORURIA
Research Officer, James Cook University of North Queensland
and
R. LEQUERICA
Civil Engineer, Mining Research, Mount Isa Mines Ltd., Queensland

SUMMARY At James Cook University, research has been carried out for some time now on new in-situ stress measuring techniques. Ideally, these new techniques should overcome some of the major obstacles of the presently established overcoring and hydraulic fracturing techniques. Three essentials have been identified which must be met by any new stressmeter:

1. Reuseability
2. Use of standard boreholes, without relying on overcoring, and
3. Allowance for a large number of measurements over relatively short distances, even in jointed rock masses.

The stress relief concept adopted is to produce *local* relief by creating a radial crack or slot in the borehole wall. According to the Principle of St. Venant, practically full stress relief will occur in close proximity to such crack or slot. Initially, the aim was to produce a radial crack by applying very high directional loading within a borehole ("borehole jack fracturing"). Very severe technical and theoretical problems, however, were encountered with this approach. As a consequence, an alternative stress relieving technique was developed. Instead of fracturing boreholes with high-pressure hydraulic cylinders, the technique of slotting borehole walls with a diamond saw was developed. The new technique proved to be very successful in producing local stress relief at the desired points of the borehole wall.

Details of the two prototype stressmeters (borehole jack and borehole slotter), based on the principle of local stress relief, are presented. Their performance in both laboratory and field tests is delineated. It is concluded that, while the borehole jack is only of limited value for in-situ stress measurements in rocks, the borehole slotter has a great potential for carrying out quick and cheap 2-D tests. It is also useful for stress logging of boreholes.

1 INTRODUCTION

The measurement of rock stresses is an important engineering task when designing and controlling major rock structures. Failure to carry out such measurements, today comes close to violating the acknowledged rules of sound geotechnical engineering.

While the importance of rock stress measurements is well established, the adequacy of the present measuring techniques is still open to debate. One view is that "rock stresses can be measured reliably and accurately over a wide range of magnitudes" (KIRSTEN, 1976; p. 63). Their measurement is considered as "an established technology". The International Society for Rock Mechanics is in the process of preparing a number of "Suggested Methods" publications for measuring in-situ stress in rocks, "an indication of the growing view that no additional fundamental improvements in measurement instrumentation are needed" (U.S. Nat. Committee, 1981; p. 47).

The opposite view was expressed by the same U.S. Committee for Rock Mechanics only two years earlier (1979), despite the fact that no significant stress instrument developments took place in the years between releasing the two reports. It stated that there was "no consistently reliable, precise method of measuring the total stress field in-situ. The two methods most commonly used, hydrofracturing and overcoring, are expensive and limited in the settings in which they can be used" (p. 501). Occasionally, the problems involved in carrying out in-situ stress measurements (time and effort needed and the low degree of reliability achieved) have appeared to be so insurmountable that it has been argued that "the next breakthrough in rock mechanics" needs to be a "simple, rapid, and reliable in-situ stress gage" (POTHINI et al., 1977, p. 50).

Clearly, the methods by which rock stresses can be measured have not yet been exhausted. This is indicated by a continuous flow of publications on alternative stress measuring methods and instruments. The "philosophies" of these alternative attempts move in different directions; partly to reduce the sophistication of the in-situ measuring methods (RILEY et al., 1977; NOLTING and GOODMAN, 1979), and partly to increase the domain in which the stress measurement is carried out, up to the dimension of large underground excavations (BRADY et al., 1976; KIRSTEN, 1976). Another approach is to simplify the stress relief procedure by avoiding overcoring (de la CRUZ and GOODMAN, 1969; HOSKINS and OSHIER, 1973; de la CRUZ, 1977; STEPHANSSON, 1983).

In the authors' opinion the most serious disadvantage of the presently established rock stress measuring methods is that they discourage from making a high number of measurements, because of cost and time restrictions associated with each measurement. In almost all rock stress measuring operations, even those of prime commercial interest, a situation arises in which "the funding required exceeds by far the resources available"(LEIJON et al., 1980; p. 81). The authors believe that the practical limitations on the number of stress measurements are in contradiction with one fundamental

geotechnical principle (TERZAGHI and PECK, 1967). It is the principle that in complex materials such as soil and, in particular, rock, a set of numerous, reasonably accurate measurements is required rather than a few, very accurate measurements.

Against this background, three essentials for an adequate stressmeter have been identified by the authors. They are:

* Reuseability
* Use of standard-size boreholes, without relying on costly overcoring procedures, and
* Allowance for a large number of measurements over relatively short borehole distances even in jointed and fractured rock masses.

AMIRA[#]-sponsored research, carried out at James Cook University of North Queensland in the years 1978-1982, has led to two prototype stressmeters, which satisfy these three requirements. This paper presents a brief account of these developments.

2 STRESS RELIEF PRINCIPLE

As one of the above-stated essentials disallows overcoring, an alternative technique for stress relief was required. The general technique was to produce *local* stress relief by creating a radial crack or slot in the borehole wall. This is consistent with the Principle of St. Venant which implies that, in close proximity to such crack or slot, practically full stress relief will occur.

Stage 1 of the project was aimed at creating a radial crack by applying very high directional loading within a borehole, thus following an approach ("borehole jack fracturing") which had been attempted by de la CRUZ (1977). Section 3 accounts for this part of the project.

The main finding was that the Jack Fracturing Method is unable to create stress relief cracks in a controlled manner at the desired locations. This led to the implementation of an alternative local stress relief technique (Stage 2 of the project). Instead of fracturing boreholes with high-pressure hydraulic cylinders, the technique of slotting borehole walls with a diamond saw was developed. This new technique proved to be very successful in producing local stress relief at the desired locations around the borehole wall (Section 4).

For both the respective instrument developments and the interpretation of the test results, it was considered essential to study the stress relief mechanism due to radial cracking or slotting. Finite Element Analyses were undertaken (LEQUERICA, 1980; FORURIA, 1983), considering various load configurations on a borehole and varying crack or slot depths (Fig. 1a). One typical result is presented in Fig. 1b. It confirms that for points of the borehole surface in close proximity to the slot (say for $\theta < 15^{o}$), practically 100 % stress relief does occur.

3 BOREHOLE JACK

3.1 Scope

Although a NX-borehole jack has been previously developed for in-situ stress measurements by de la CRUZ (1977), there are still substantial questions left open. The principles, underlying this fracturing technique, have not yet been sufficiently investigated. Furthermore, inconsistencies in available field data exist, and a lack of suitable calibrations for the recoverable tangential sensors is obvious. This warrants a more detailed study on this method.

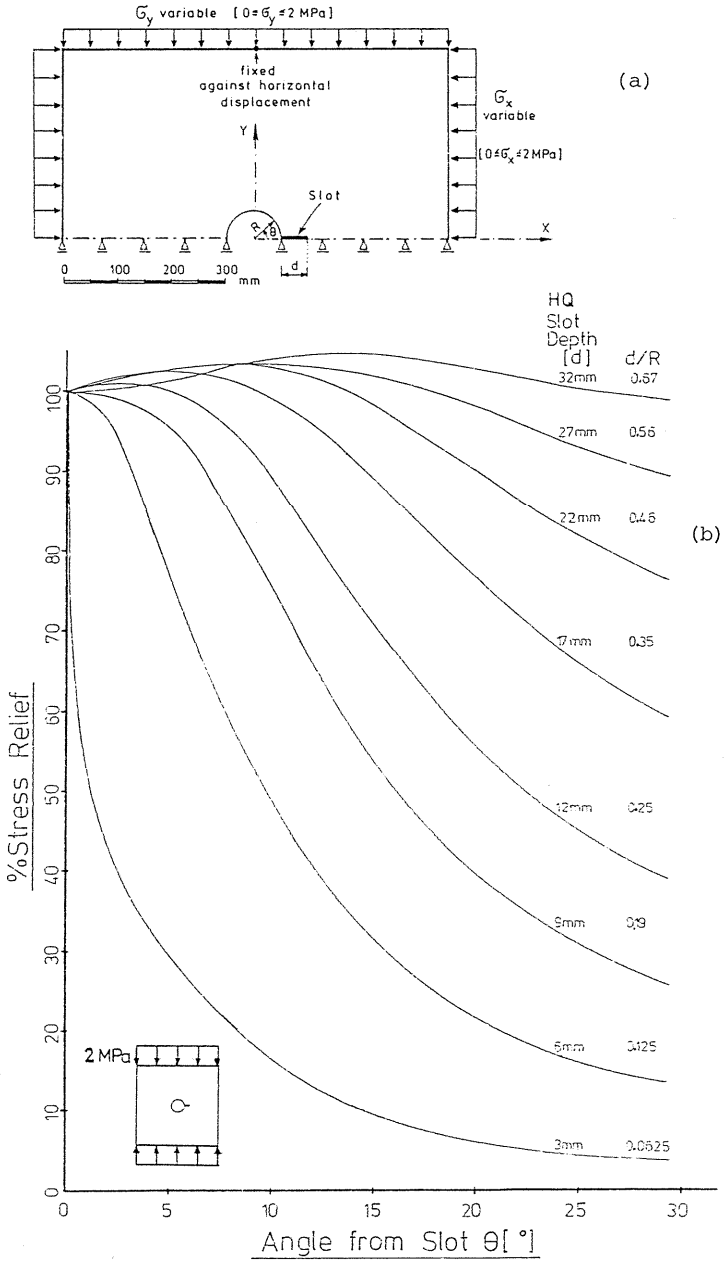

Figure 1. Tangential stress relief next to a tensile crack or slot at a borehole surface.
(a) Boundary Conditions;
(b) Results of FE analysis (example)

The fundamental theoretical problem encountered with the Jack Fracturing Method is the formulation of a relationship between tangential strain $\varepsilon_{\theta(R)}$, to be measured on the inner surface of a borehole wall, and basic units as described in the following two cases (Fig. 2):

Case (1) - The borehole remains unfractured, and the surrounding rock deforms linearly elastic. '$\varepsilon_{\theta(R)}$' must be related with the Young's modulus 'E' and the Poisson's ratio 'ν' of the rock in conjunction with the internal directional load 'F' applied by load platens onto the borehole wall.

Case (2) - When tensile fracturing of the rock eventuates, as indicated in Fig. 2, '$\varepsilon_{\theta(R)}$' as

[#]The Australian Mineral Industries Research Association Ltd., Melbourne. Research Project 77/P92.

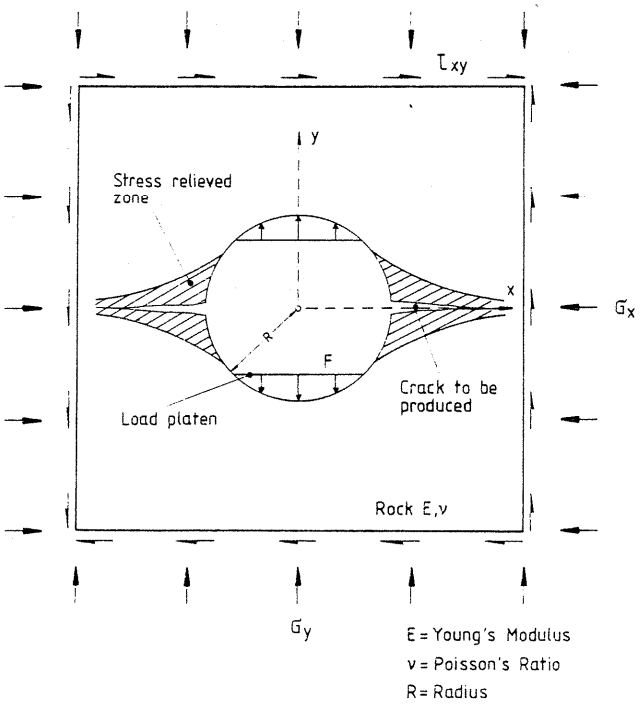

Figure 2. Definition sketch of generalised borehole jacking problem

measured close to the crack, must be related to the in-situ stresses 'σ_x, σ_y, τ_{xy}' and the elastic rock properties 'E^* and 'ν^*'.

Appropriate analytical investigations into these two cases have been carried out (e.g. GOODMAN et al., 1968; de la CRUZ, 1977 and 1978; LEQUERICA, 1980).

Two essentially independent sets of equipment had to be designed and thoroughly tested for implementation of the Jack Fracturing Method. They are:

1. Borehole loading equipment - A device that, ideally, applies a constant directional line load F along a borehole (Section 3.2);
2. Strain Sensors - Suitable recoverable sensors are required to measure tangential strain $\varepsilon_{\theta(R)}$ on unloaded parts of the borehole surface (Section 3.3).

3.2 Borehole Loading Equipment

The major objective in the construction of the high pressure load pistons was to provide the largest force possible to the borehole wall, but simultaneously, to restrict the size of the load pistons physically by the diameter of the borehole. For a 76 mm borehole, the maximum practical diameter of the load cylinders was 50 mm while the largest load piston for that cylinder had a diameter of 32 mm.

Each cylinder contained two load pistons, each 22 mm high, with a central passage allowing the flow of oil from cylinder to cylinder (Fig. 3). Two sets of neoprene O-rings sealed the cylinder. The maximum travel of each high pressure piston was restricted to 3 mm. The pistons were in direct contact with the load platens, and the platens were positioned exactly by locating pins. Retraction springs were attached between the platens and forced the pistons to return to their original position, once the hydraulic pressure had been released.

Two versions of the pressuremeter were developed simultaneously. A laboratory version (Fig. 4a) with

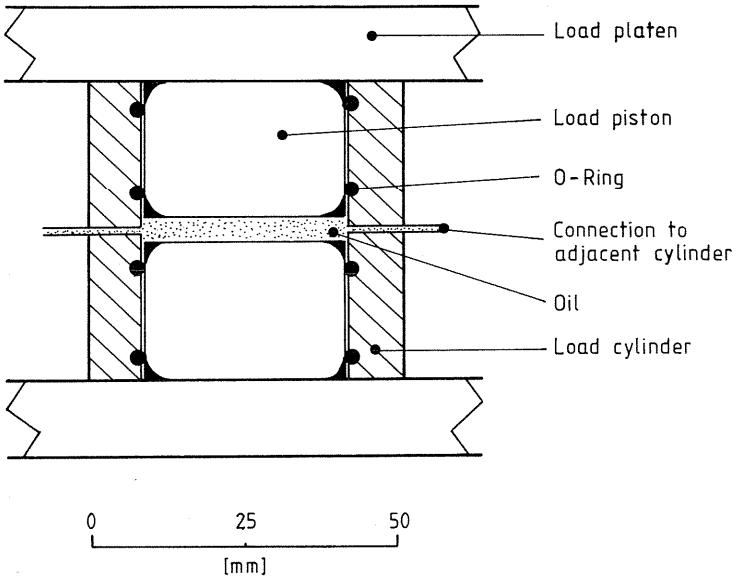

Figure 3. Section through high-pressure cylinder

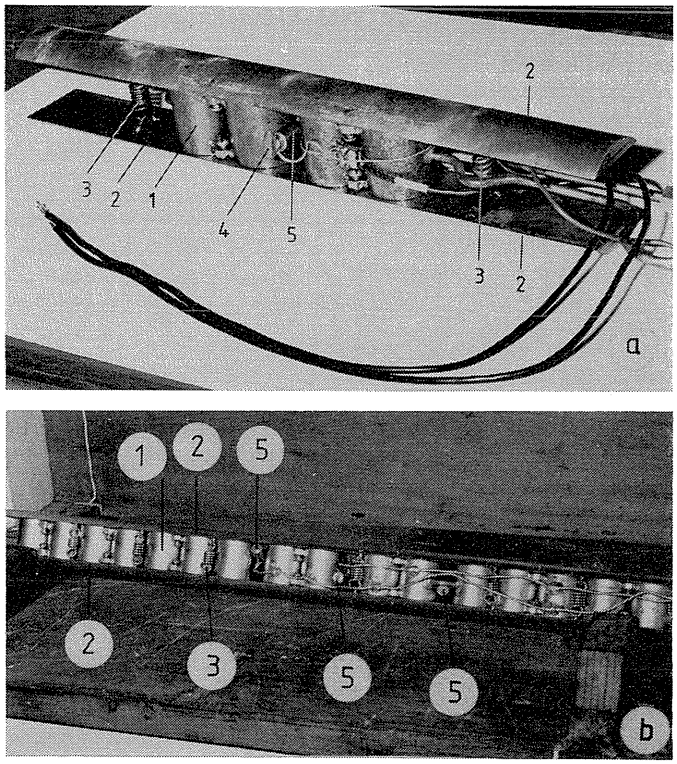

Figure 4. Borehole jacks
(a) Laboratory version
(b) Field version

(1) High-pressure cylinder
(2) Load platens
(3) Retraction springs
(4) Friction gauge
(5) Friction gauge application cylinder

400 mm long load platens and four hydraulic cylinders was tested and used in mortar blocks. The field version (Fig. 4b) is 1.0 m long and has 18 hydraulic cylinders. These are arranged in two sets of seven with the remaining four at the centre of the pressuremeter in groups of two. Spaces between the load pistons are provided for the positioning of the strain sensors (ref. Fig. 4). Two stainless steel feed lines supply oil to the two sets of cy-

linders. This configuration enables the load platens to be expanded at the same rate along their entire length. The load platens were constructed from steel and machined so that the curved surface would make even contact when placed in a 76 mm diameter hole. The chord length of the load platens was 55 mm while the central height was 12 mm, thus yielding an opening angle of the load platens of 47°.

In initial testing, hydraulic pressures up to 210 MPa (30 000 psi) did not lead to any leakages and could easily be maintained by the hydraulic hand pump. Retraction time was normally less than ten minutes. Under the piston pressure of 210 MPa, the borehole was subjected to a force of 3.0 MN over the 55 mm x 1000 mm area of load platen. With the laboratory version of the pressuremeter, a hydraulic pressure of 210 MPa produced a force of 0.7 MN along the length of the load platens.

3.3 Recoverable Tangential Strain Sensor

3.3.1 Friction gauge design

The idea of using recoverable sensors for strain or displacement measurements at borehole surfaces is not new. With respect to *radial* displacement, suitable sensors are readily available in the form of spring-loaded cantilevered arms, LVDTs and potentiometers. They are incorporated in commercially available systems such as the USBM deformation cell or the GOODMAN jack.

Recoverable sensors for displacement measurements in *axial* borehole direction have been developed for example by BONNECHÈRE (1969) and by GROB et al. (1975). In context with the instrument development, reported herein, such axial displacement measurements, however, are of no interest at this stage, as it is presently directed towards 2-D stress state determination. Once the single borehole slotting operation is extended to determine the full 3-D stress state, such axial strain measurements will of course become necessary.

It is the measurement of *tangential* strain at borehole surfaces which is difficult to achieve by recoverable sensors. Repeatedly, *friction gauges* were used for this purpose. Such gauges are electric wire resistance strain gauges, which are pressed by means of tiny hydraulic pistons against the borehole surface, negating the need for adhesives ("TALBOT strain cell" in DENKHAUS, 1976; de la CRUZ, 1977 and 1978). As no reliable data on the performance of friction gauges is available, a thorough investigation was necessary.

Curved friction gauges to fit borehole surfaces are not yet commercially available. Alternative forms of friction gauges with curved surfaces were designed, constructed and tested. In its simplest form, a friction gauge consists of a strain gauge, glued onto a backing material. One of the successful friction gauge versions consists of a commercially available waterproofed strain gauge (TML-WFLA-6), which is glued with its resin strip backing onto a curved steel saddle (Fig. 5). In some cases, a thin top layer of silicon carbide powder was added for protection of the gauge and for achieving a good frictional contact between gauge and borehole surface.

3.3.2 Calibration of friction gauges

The small laboratory version of the pressuremeter was placed in a simulated borehole drilled into a mortar block, 0.30 m x 0.35 m x 0.70 m. Friction

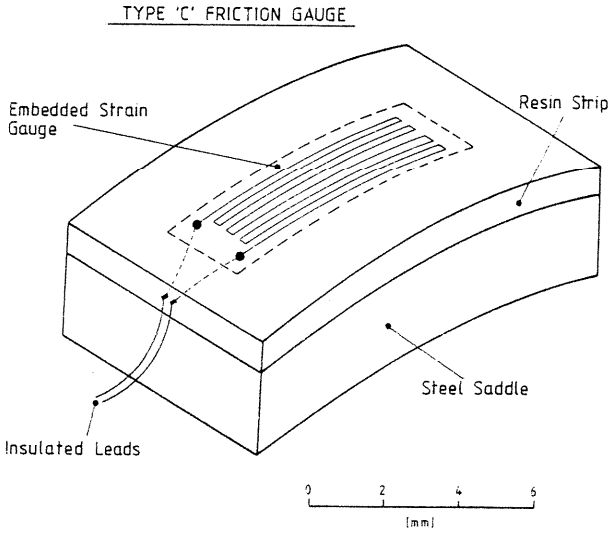

Figure 5. Friction gauge

gauge strain readings were successively taken at 15° intervals around the circumference of the borehole. In each gauge position, the mortar block was uniaxially loaded by 500 kN ($\sigma_1 \sim$ 4.8 MPa) in two cycles. This testing procedure was carried out for a set of 13 friction gauges.

Typical results are presented in Figs. 6 and 7. From Fig. 6 it can be gathered that the performance of

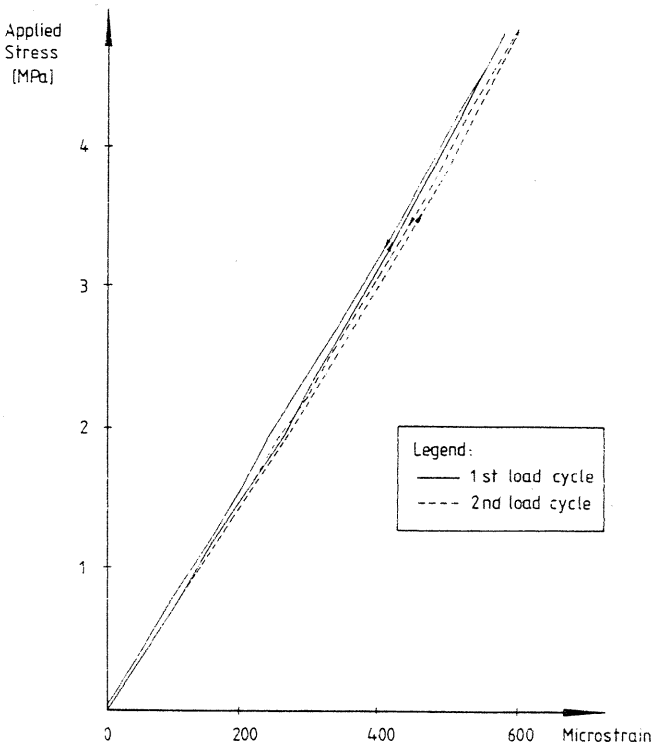

Figure 6. Friction gauge calibration test

friction gauges with respect to linearity and repeatability is quite satisfying. The polar plot of Fig. 7 indicates that also the accuracy of the friction gauges is generally acceptable. However, in Fig. 7 there are three areas of major discrepancies between the measured and theoretical tangential strain. The systematically lower strain readings on the left hand side was identified by LEQUERICA (1980)

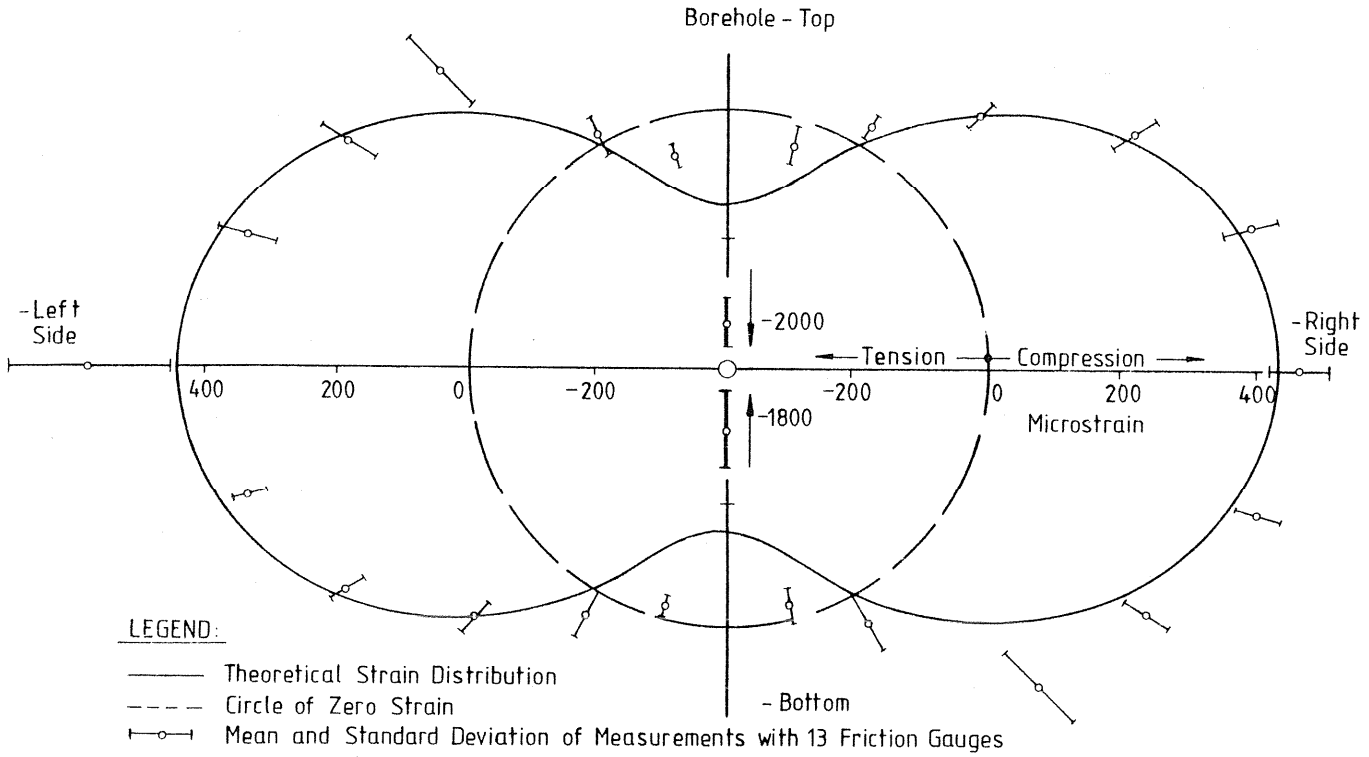

Figure 7. Polar plot of tangential strain distribution around a circular hole inside a uniaxially loaded mortar block

as being caused by the marginally lower loads on the LHS (compared to RHS) due to the non-perfect geometry of the test block. Rotating the block through 180° produced slightly higher strains on the LHS thus providing an answer to the discrepancy. The large and erratic strain recorded at the left-hand side of the borehole was due to the presence of a 4 mm ∅ clay-like inclusion in close vicinity to the point of contact of the friction gauge. The excessive strain readings at both the crown and invert of the borehole could be successfully attributed both theoretically and experimentally to the occurence of local tensile cracks, although it was impossible to detect them with the unaided eye.

From the calibration programme it was concluded that friction gauges are indeed suitable recoverable tangential strain sensors, at least in boreholes with clean, dry and smooth surfaces.

3.4 Laboratory Testing of Borehole Jack

Laboratory activities focused on two aspects:

(i) obtaining Young's modulus values of the mortar blocks by borehole jack measurements

(ii) fracturing mortar blocks containing simulated boreholes.

Within this contribution, reference is being made to the results of the fracturing tests only.

Of the eight mortar blocks fractured, three specific types of fractures were observed as illustrated in Fig. 8.

Fracture Type a - Fractures, initiated at the edge of the load platens. These were the most commonly occuring fractures.

Fracture Type b - Fractures, initiated from other parts of the load platens: less common.

Fracture Type c - Fractures in the theoretically "correct" position, initiated at about the centre of the unloaded part of the borehole surface: less common.

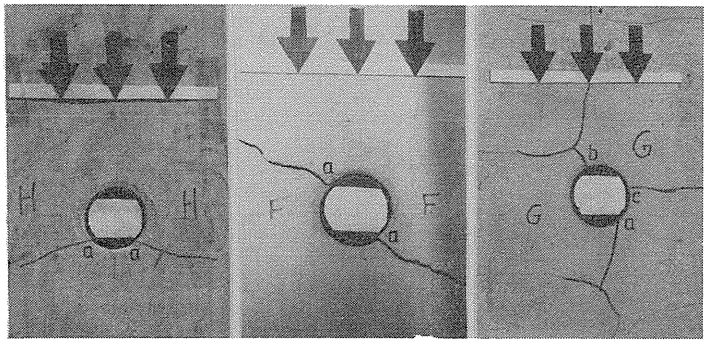

Figure 8. Three examples of laboratory fracturing experiments with borehole jack, indicating various fracture types

The results from these fracture tests on mortar blocks cannot necessarily be extrapolated and used with confidence to predict the likely failure modes in field situations. In the field, a very large volume of rock in addition to a long borehole without free ends and associated surface effects exists. Here only a comparatively small volume of rock is being subjected to a borehole jacking load. As the laboratroy and field situations are quite different, and since a total of only eight mortar blocks were fractured, conclusive results cannot be presented. However, different failure modes have been verified experimentally, and some doubt on the assumed relevance of fracture type c has been raised.

3.5 Field Testing

In-situ tests with the borehole jack were carried out at Mount Isa Mines Ltd. in dolomitic shales at 13-Level (610 m depth). The NX diamond-drilled borehole was parallel to the bedding planes, the spacing of which varied from 300 mm to 1000 mm. The bedding planes dipped towards the west at 65°, while striking N-S. From previous experimental programmes in

the region, the rock was considered to be quite homogeneous and isotropic despite the existence of bedding planes. The borehole was approximately horizontal. Only a minimal amount of water was present.

Initially, it was envisaged to obtain numerous Young's modulus values at a particular location along the borehole and subsequently to determine the in-situ stresses in the region by increasing the pressuremeter load until fracturing of the borehole. However, testing established that the rock mass was too competent for fracturing, and also that sustained high oil pressure (170 MPa) rapidly caused the deterioration of the O-rings, which sealed the pistons.

After failing to measure the in-situ stress state at Mount Isa Mines by means of the borehole jack, the tests concentrated on the question whether the jack is a suitable instrument for determination of the deformability of rock masses. It was found (LEQUERICA, 1980) that the borehole jack indeed is a suitable instrument for gaining quantitative information on Young's modulus of rock masses.

The significant findings from this part of the investigation are (ref. Table I):

Table I: Critical Appraisal of Borehole Jacking Technique

Aspect	Advantages	Disadvantages
FRICTION GAUGES	simple in construction rugged accurate voltage instability detected immediately	gauges placed on cracks and ridges will record only local deformations whole pressuremeter must be extracted in order to replace a single friction gauge
YOUNG'S MODULUS TESTS	many strain values can be obtained at any location all equipment can easily be transported to site only three men are required duration time is small (20 minutes) tests can be carried out at moderate pressures (70 MPa) numerical calculation of E from pressure-strain curve is easy	small tolerance necessary on borehole diameter and roughness sustained high oil pressure damaged O-rings possible jamming of pressuremeter in borehole if O-rings are damaged severely
In-SITU STRESS MEASUREMENT	fracture is theoretically possible (at right location) in rock which has favourable rock properties and suitable in-situ stresses	some rock masses are too strong small tolerance necessary on borehole distance of travel by the load pistons is limited (3 mm) jamming of pressuremeter possible especially at the very high oil pressures required for fracture position of crack cannot be controlled friction gauges may not be close enough to record complete stress relief

1. The recoverable strain gauge technique, involving friction gauges, has been successfully developed, and the concept appears to be very promising for further application in geomechanics.
2. The pressuremeter is a suitable instrument for gaining quantitative information on Young's modulus of the rock mass by performing in-situ deformation tests in boreholes.
3. For the range of rock strengths encountered (U.C.S. ≈ 150 MPa), the pressuremeter in its present form is not suitable for creating a localized stress-relieved zone by fracturing the borehole wall. In particular, doubts must be raised on the concept of creating tensile cracks at the "theoretically correct" location of the unloaded part of the borehole wall by means of a borehole jack.

4. BOREHOLE SLOTTER

4.1 Scope

The failure of the Jack Fracturing Method to create, a stress relief crack at a well-defined location in a controlled manner led to the implementation of an alternative technique. Instead of fracturing boreholes with high-pressure hydraulic cylinders, the technique of slotting borehole walls with a diamond saw was developed (Fig. 9). This new technique proved to be very successful in producing localised stress relief at the desired locations of the borehole wall (Fig. 10).

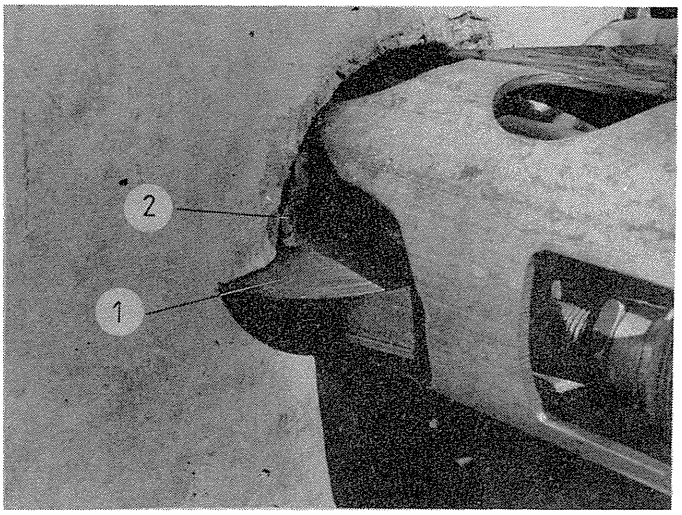

Figure 9. Slotting a HQ borehole with a diamond saw (1) for local stress relief.
Note: Tangential strain sensor (2) pressed against the borehole surface in close proximity to blade.

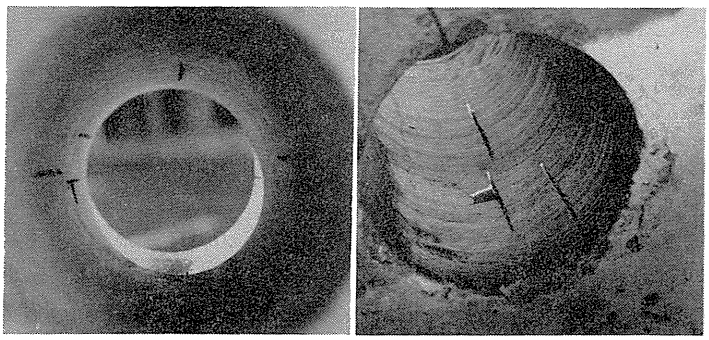

Figure 10. Saw cut slots in borehole walls

4.2 Slotting Instrument

Fig. 11 shows a cross-sectional view of the slotter, which, on the request of the majority of the sponsoring companies, has been designed for use in HQ (96 mm ø) boreholes. It is enclosed within a 1.3 m long, 90 mm external diameter steel tube of 3 mm thickness (1 in Fig. 11). This tube constitutes a rigid shell to provide a mounting platform for all components. Towards either end of the tube there is a pair of hydraulically operated platens (2), which, when expanded, clamps the slotter within the borehole.

(3) is a commercially available pneumatic angle grinder (BIAX SWKH14) to drive the diamond impregnated blade (4), which is 90 mm in diameter and 0.8 mm thick with a central bore of 10 mm and with a continuous run of diamond matrix. The grinder is mounted on a pivot (5).

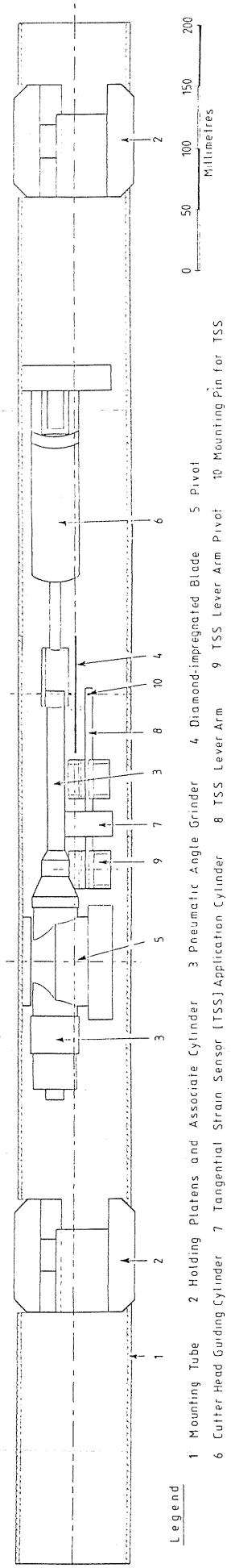

Figure 11. Elevation of the HQ borehole slotter (simplified)

Attached to the grinder head and slightly eccentrically aligned with the pneumatic grinder is a single-acting hydraulic cylinder (6). Its purpose is to push the blade towards the borehole wall during the slotting operation, and to return the blade clear of the borehole walls whilst not in use.

The purpose of the hydraulic unit (7), together with a lever arm (8) and a pivot (9), is to bring a tangential strain sensor (10) into contact with a borehole wall. As indicated in Fig. 9, the strain sensor is located very close to the slot to meet the analytical requirements (ref. Section 2).

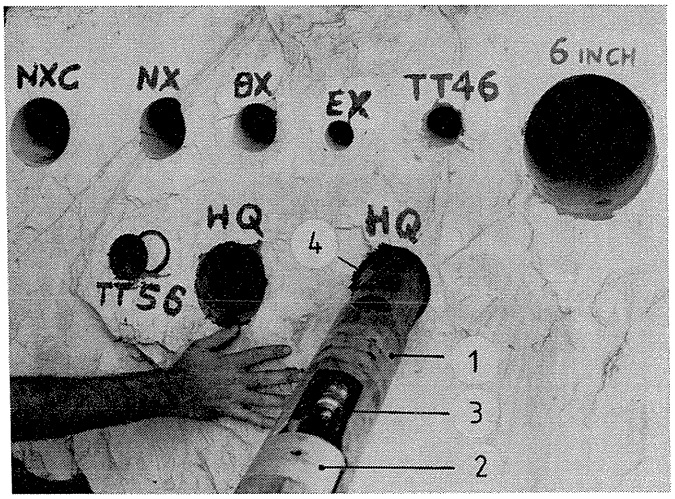

Figure 12. Demonstration of the borehole slotting technique at Mount Isa Mines. (1) Mounting tube; (2) Holding platen; (3) Rear of pneumatic angle grinder; (4) Blade.

In various tests under laboratory and field conditions, the mechanical, pneumatic and hydraulic components of the slotter proved to be both reliable and effective since the commencement of the first test (Fig. 12).

4.3 Tangential Strain Sensor for Slotter

With the first laboratory experiments it became immediately evident that, in contrast to jack fracturing, friction gauges are completely unsuitable for the borehole slotter. This has its reasons in two factors. First the friction gauges do not perform satisfactorily under the light vibrations which are created by a running slotter. Secondly, and more importantly, during slotting, some wet, fine-grained slurry is produced which partly settled on the borehole surface adjacent to the slot. As the borehole slotting technique requires slots being produced in different directions (at least 3) at the same borehole depth, a rotation of the slotter after each slotting process is required (e.g. in the case of 6 slots a rotation of 60°). This means that once the first slot has been produced, the friction gauge will settle on a wet, unclean borehole surface. In laboratory experiments it was clearly found that friction gauges do not perform satisfactorily under these borehole surface conditions.

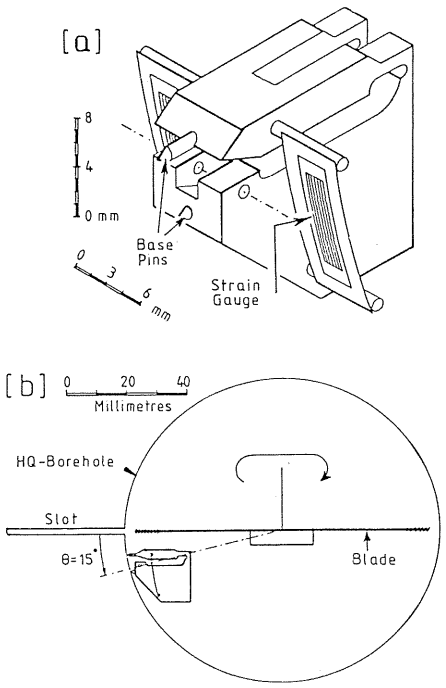

Figure 13. A-Beam tangential strain sensor with wings (a) and its position in HQ-Borehole (b)

Upon reflection of the difficulties associated with friction gauges, the idea of cantilevered elements was reviewed. This idea goes back to DRYSELIUS (1965) and LEAHY (1979). The main difficulty is associated with the apparently unsuitable low sensitivity of these elements. LEAHY has tried to overcome this problem by use of semiconductor strain gauges glued onto low modulus material (e. g. magnesium).

A total of four different types of strain measuring devices, utilising the cantilevered element principle, have been designed, manufactured and tested (BOCK and FORURIA, 1983). The most successful sensor is shown in Fig. 13. A change of its base length (defined by two pins) is directly reflected by a change in the opening of a gap between the two A-beam arms. This in turn changes the curvature of two external straps of thin flexible spring steel which can accommodate a set of four active strain gauges. The particular point in this design is to have only a minimal curve in the spring steel straps. By this construction a sensitivity is achieved, which is high enough to allow its application to the borehole slotting technique (ref. Appendix).

The sensor has excellent stability characteristics. It is rather insensitive to changes in the load with which the sensor is pressed against the borehole surface while being very sensitive to changes of the base length. Furthermore, it has the necessary ruggedness and waterproofness for "survival" in the field.

The results presented in Sections 4.4 and 4.5 are from applications of this type of sensor.

4.4 Calibration of Slotter

Extensive laboratory tests for the calibration of the borehole slotter and for identification of environmental influences on the strain readings were carried out. Mortar blocks, 0.50 m x 0.50 m x 0.60 m with a central borehole of 96 mm, were used to simulate a borehole in a homogeneous, isotropic rock. The mortar blocks were uniaxially loaded under a 5 MN testing machine.

Fig. 14 depicts a typical response of the strain readings towards stress changes and environmental

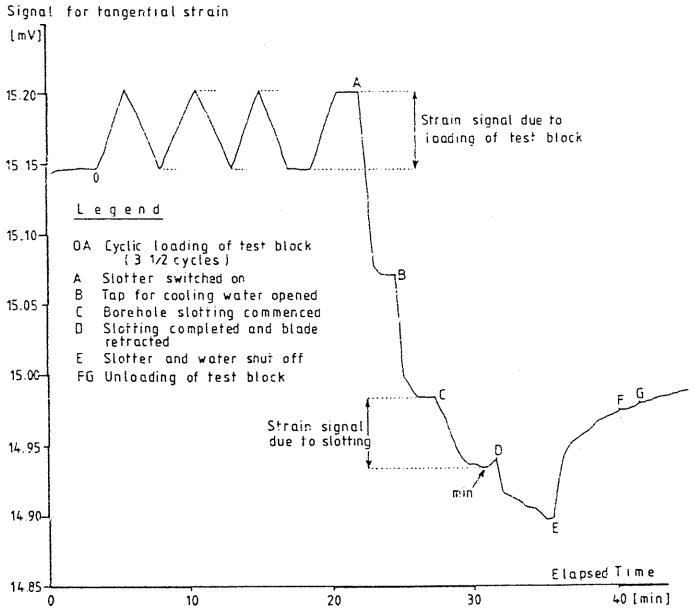

Figure 14. Strain readings of a calibration slotting test in the laboratory for identification of environmental influences by running slotter and cooling water

influences. First the mortar block was loaded and unloaded in 3 1/2 cycles with point A indicating a final level of applied stress of 2 MPa. At point A, the borehole slotter was switched on, resulting in a significant response in the readings. It took about 6 minutes, before the readings tended to settle down (point B). Following this, the cooling water tap was opened, again with recognisable effects on the readings (point B to C). After the signal stabilised with both the slotter running and the cooling water flowing (point C), the actual borehole slotting was done, resulting in a stress relief C-D. D-E and E-F mark the stages where the water tap was closed and the slotter switched off. Finally, unloading of the mortar block (phase F-G) showed only an insignificant effect on the strain readings, indicating that almost 100 % stress relief had been achieved. Note that the strain change readings (proportional to change of output signal) due to loading and unloading (prior to A) are approximately of the same magnitude as the strain change reading due to slotting (C-D), thus supporting the findings of practically full stress relief by the slotting action.

The influence of switching the slotter and changing the water flow on the strain readings has been eliminated in the test which is documented in Fig. 15. Here, the loading and unloading of the mortar block was done with the slotter already running and the cooling water flowing for more than 10 minutes. After

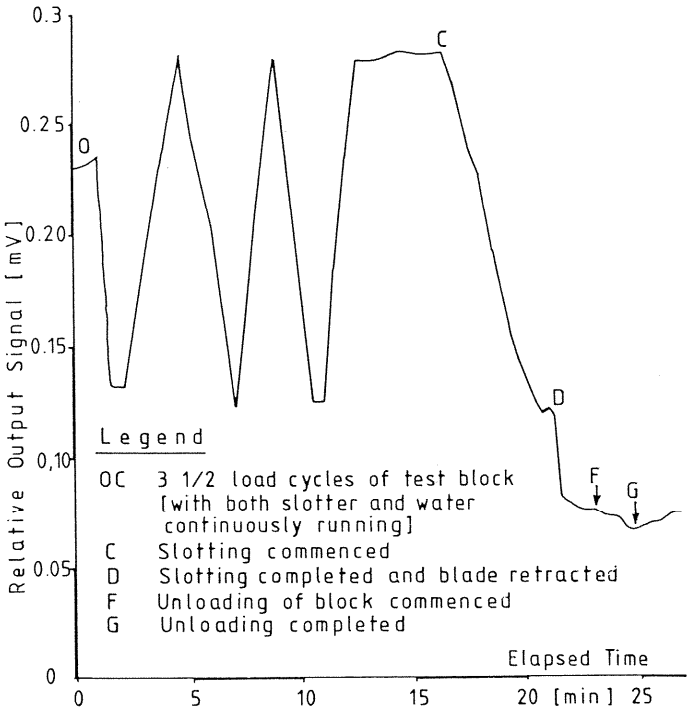

Figure 15. Strain readings of a laboratory slotting test with both slotter and cooling water continuously running throughout test

the usual load cycles, a slot was cut in one continuous slotting action, again bringing about 100 % stress relief (C-D in Fig. 15).

A typical feature of practically all stress relief curves is a small reversal ("hiccup") of the strain readings at cutting depths greater than 23 mm. This reversal was recognisable in almost all laboratory tests (e.g. at point D in Figs. 14 and 15) as well as in field testing (at point D in Fig. 16). From a total of 28 laboratory calibration tests it was found that the local stress relief minimum, occuring shortly before the characteristic "hiccup" in the strain readings (min. in Fig. 14) is identifiable as the point of full stress relief. The mechanical reasons for the occurrence of this "hiccup" are not fully understood at the moment, and some further studies are required on this particular aspect.

4.5 In-Situ Slotting Test

First in-situ field testing of the slotter was undertaken at the Mount Isa Mine in a subhorizontal HQ borehole at the same testing site at 13-Level as already described in Section 3.5.

The procedure for these tests was as follows:

- Flush the borehole with air or water; no special equipment for cleaning or drying is necessary;
- locate the slotter at the desired orientation and depth within the borehole using interconnecting rods as installation tools;
- clamp the slotter by activating the two holding cylinders (2 in Fig. 11);
- bring the tangential strain sensor into contact with the borehole surface;
- start the slotter motor and turn on water;
- wait for the output signal to stabilise (approximately 3 to 5 minutes);
- cut the slot to a maximum depth of 25 mm in one continuous motion (approximately 2 minutes);

* retract the blade and shut down the slotter when the output signal has stabilised.

Fig. 16 illustrates a typical result obtained from one in-situ slotting test. The actual slotting was done between the points C and D. As with the laboratory tests, a local minimum could clearly be identified (before the "hiccup" at D), which was taken as the point of 100 % stress relief.

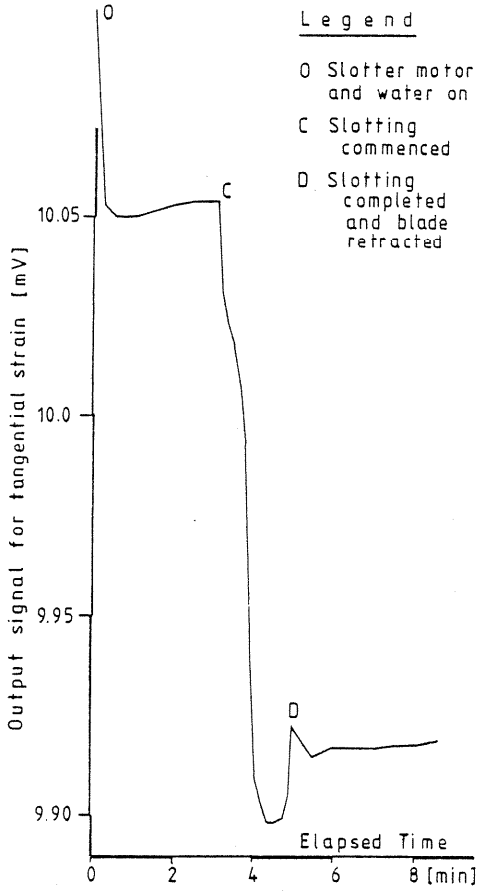

Figure 16. Typical strain reading during an in-situ slotting test at Mount Isa Mines

In order to determine the two-dimensional stress field in a plane perpendicular to the borehole axis, the results from a minimum of three such slotting tests at various orientations are required. During the test program the aim was to obtain up to eight such results at differing orientations (i.e. 45° intervals) for each location, in order to provide a high degree of redundancy.

By using a least squares approximation to match the closed-form solution for the tangential stress distribution around a circular hole in a two-dimensional stress field with the measured tangential strains, the orientation and magnitude of the principal stresses ($\bar{\sigma}_1$, $\bar{\sigma}_2$), acting in a plane normal to the borehole axis, were determined. Fig. 17 illustrates a radial plot of the measured strains, the calculated principal stresses (orientation and magnitude) and a plot of the tangential strain around the borehole produced by this principal stress configuration.

From the results obtained, the stress field for five separate locations was determined, yielding values for $\bar{\sigma}_1$ between 30 MPa and 57 MPa and for $\bar{\sigma}_2$ between 23 MPa and 36 MPa with the direction of σ_1 subnormal to bedding (Table II).

Earlier 3-D stress measurements with the CSIRO Soft Inclusion Cell (WOROTNICKI and WALTON, 1976), carried out by staff of Mount Isa Mines only a few metres

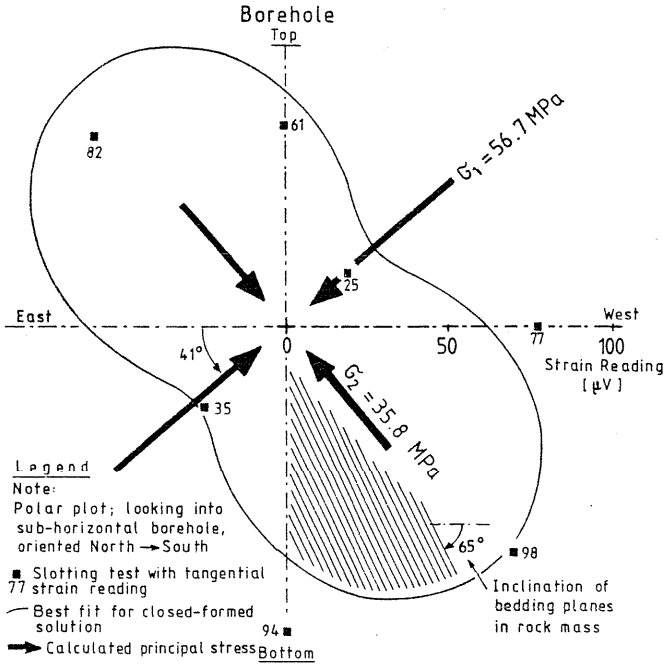

Figure 17. Least squares approximation of seven tangential strain readings from slotting test at 1.35 m depth to closed-form solution with resulting principal stresses

Table II: Summary of in-situ test results

Depth of Borehole [m]	$\bar{\sigma}_1$ [$\triangleq \sigma_1$] [MPa]	σ_2[$\triangleq \bar{\sigma}_2$] [MPa]	Angle between σ_1 and normal to bedding planes
0.55	47	34	- 11°
0.75	34	23	+ 60°
0.95	49	33	+ 37°
1.35	57	36	+ 16°
7.00	30	24	+ 17°

away, gave a σ_1 of 40.8 MPa and a σ_2 of 23.7 MPa with the direction of σ_1 normal to bedding. As in the case of the slotting experiment the borehole axis was aligned with the σ_3 direction, both σ_1 and σ_2 are directly comparable with $\bar{\sigma}_1$ and $\bar{\sigma}_2$, respectively. When comparing the results from the two stress measuring techniques, a reasonable agreement becomes evident.

5 CONCLUSIONS

Two instruments have been developed for stress measurement in rock with the scope of producing local stress relief by cracking or slotting borehole walls.

The first instrument is a borehole jack, for use in NX (76 mm Ø) boreholes, which was equipped with friction gauges as recoverable tangential strain sensors. It was found that the success of the borehole fracturing method with respect to in-situ stress measurements is limited by rock strength in addition to borehole surface characteristics. Due to even the smallest irregularities in the contact between load platens and borehole surface, only a minimal control of the location of crack initiation is possible in practice. Major technical problems were encountered with the very-high pressures of the jacking system which led to accelerated wear of the neoprene O-rings to the extent that leakages or even permanent wedging of the jack down the borehole did eventuate. While the

borehole jack was of limited value for stress measurements, it proved to be a powerful instrument for logging boreholes with respect to in-situ deformability of rocks.

The second borehole instrument is a recoverable slotter for use in standard HQ (96 mm ø) boreholes. It avoids the major shortcomings of the borehole jacking technique, by eliminating the very-high pressure hydraulic system, by not depending on complex problems involved with the local load platen/borehole wall interaction and by ensuring that even the hardest rock will be locally stress-relieved. The borehole slotter has been developed to a stage where it has demonstrated its great potential for carrying out quick tests for the determination of in-situ stresses in 2-D. In its first in-situ test it provided results which are comparable with those determined by an already established stress measuring technique.

At James Cook University continuous research is being undertaken to validate the capability of the developed stressmeters. In addition to this, the application of the technique of borehole slotting in a recoverable 3-D stressmeter is being examined.

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APPENDIX

Sensitivity Analysis of Strain-Gauged Steel Straps as Displacement Sensors

Strain-gauged, curved spring steel elements are commercially available for the purpose of measuring relative displacements of their base points (e.g. TML Series PI transducers). None of these elements has the required sensitivity for application in conjunction with the borehole slotting technique. However, rather than discarding the use of curved spring steel straps from the onset, the following analysis was undertaken to investigate the possibility of improved sensitivity of such sensors.

Figure A 1 illustrates the basic configuration. Any change of the base length AB causes a change in bending of the spring steel straps. This in turn is associated with changes of the curvature $\frac{1}{r}$, of the opening angle α and of the lengths of both the outer and inner fibres of the spring steel elements.

Of particular interest is the sensitivity of the average strain at the extreme fibres of the measuring element in relation to the induced strain of the base AB:

$$Q = \frac{\frac{\varepsilon_i - \varepsilon_e}{2}}{\varepsilon_{AB}} \cdot 100\ [\%] \qquad (1)$$

with Q = sensitivity of strain measurement

ε_e, ε_i = strain at outer/inner fibre of measuring element

ε_{AB} = induced average strain of base AB

The strain of the outer fibre ε_e is as follows (extension positive);

$$\varepsilon_e = \frac{l'_e - l_e}{l_e} = \frac{(r' + t)\,\alpha'}{(r + t)\,\alpha} - 1 \qquad (2)$$

with l_e = initial length of outer fibre

l'_e = length of outer fibre after deformation

r, r' = radius, before and after deformation

α, α' = opening angle, before and after deformation

t = half thickness steel element

Similarly, the strain ε_i of the inner fibre is

$$\varepsilon_i = \frac{(r' - t)\,\alpha'}{(r - t)\,\alpha} - 1 \qquad (3)$$

Backsubstitution of (2) and (3) into (1) yields

$$Q = \frac{\left[\frac{r' - t}{r - t} - \frac{r' + t}{r + t}\right]\frac{\alpha'}{\alpha}}{\varepsilon_{AB}} \cdot 50 \qquad (1a)$$

r' and α' are i.a. function of ε_{AB}. Assuming that the length of the neutral axis remains unchanged and that the steel element bends like a circular arch at all deformation stages, it is

$$r\,\alpha = r'\alpha' \qquad (4)$$

Substitution of (4) into (1a) yields

$$Q = \left[\frac{1 - \frac{t}{r'}}{1 - \frac{t}{r}} - \frac{1 + \frac{t}{r'}}{1 + \frac{t}{r}}\right]\frac{50}{\varepsilon_{AB}} \qquad (1b)$$

For determining r', another equation, combining r' and α', in addition to (4) is required. From geometry it is

$$r' \sin\alpha' = a + \Delta a \qquad (5)$$

and by substituting (4) into (5):

$$\frac{\sin\alpha'}{\alpha'} = \frac{a + \Delta a}{r \cdot \alpha} \qquad (6)$$

After solving α' and backsubstitution into (4) or (5), all quantities on the right-hand side of equation (1b) are known for a given geometry of the spring steel element and a given strain of the base.

EXAMPLE

Given: $2\alpha = 18^o$; $\varepsilon_{AB} = -1.10^{-3}$ with $2a = 20$ mm

$t = 0.1$ mm.

From geometry, it is $r = 6.392\ a$. Equation (6) gives

$$\frac{\sin\alpha'}{\alpha} = \frac{(1 + \varepsilon_{AB})\ 20}{6.392\pi}$$

Solving by trial and error yields

$2\alpha' = 20.0669^o$ and

$r' = 5.734\ a$

Backsubstitution into equations (1b) gives

$Q = 17.9\ \%$

Figure A 2 is a sensitivity chart for curved spring steel elements. It clearly illustrates that their sensitivity Q depends on both the curvature of the measuring straps and the degree of strain imposed.

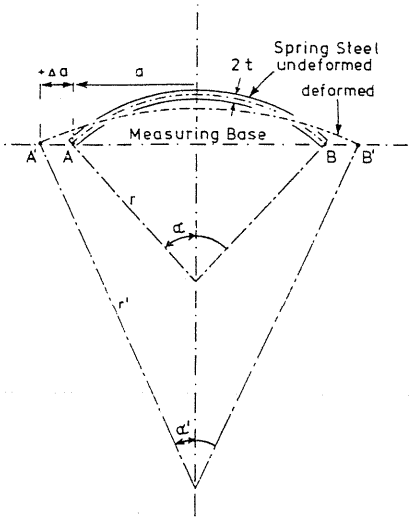

Figure A 1. Definition sketch (not to scale)

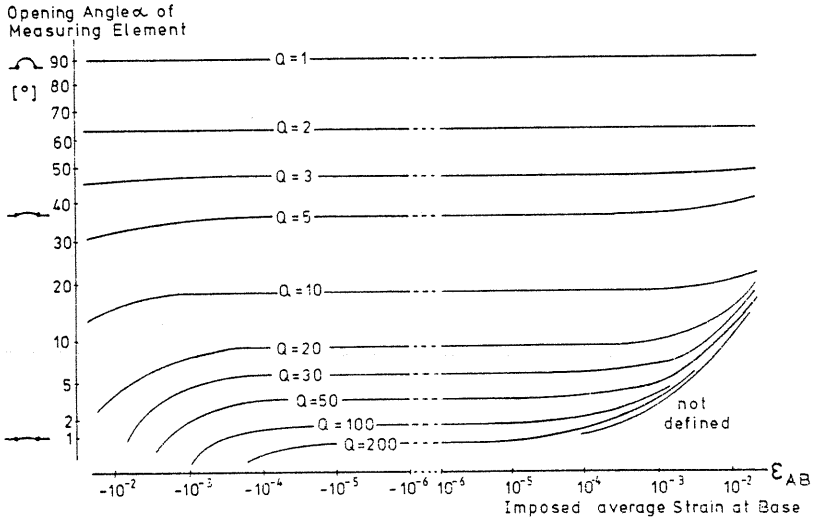

Figure A 2. Sensitivity Q of curved spring steel sensor