

Analytical Evaluation for the Design and Operation of a New Recoverable 3-D Stressmeter for Rock

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SUMMARY Numerous measurements performed by James Cook University's 2-D recoverable stressmeter ("borehole slotter") proved the feasibility of the new concept of borehole release slotting for stress measurements in rocks. The new technique enables numerous, continuous and very economical stress measurements to be made. It is a logical consequence to extend the principles of 2-D borehole slotting to a new recoverable stressmeter capable of measuring the general 3-D state of stress.

After a brief outline of the new 3-D stress measuring technique, this paper focuses on two specific theoretical problems. The first problem is related to strain measurements at borehole walls with a recoverable strain sensor. In practice, such measurements are carried out over a finite measuring length, whereas theory assumes point measurements.

A complete stress measurement requires at least three sidewall stress release slots in independent directions. Sequential slotting influences the stress distribution of the borehole. This is the second problem considered. Numerical models were used to simulate differently orientated sidewall slots within a parent borehole.

Detailed results are presented and conclusions are drawn with respect to the design and operation of a 3-D recoverable stressmeter.

1 INTRODUCTION

At the previous A.N.Z. Conference on Geomechanics in Perth, a paper was presented which introduced two new recoverable borehole stressmeters, the modified jack and the "borehole slotter" (Bock et al. 1984). At that time, particular expectations were placed on the "borehole slotter". These expectations were realised in the following years. Various in-situ tests demonstrated that borehole slotting

- * is a reliable stress measuring method with an accuracy at least comparable to that of overcoring (Armstrong, 1987) and hydraulic fracturing (Enever and Crawford, 1986);

- * is unequalled by any other known stress measuring technique with regard to speed of operation, measurement density and economy (Bock and Otto, 1986);

- * allows an internal check on the consistency of the stress measuring results with the degree of redundancy of the readings being adjustable to the particular geotechnical situation (Bock, 1986). This provision proved particularly useful when interpreting the stress measurements.

The "borehole slotter" is essentially an instrument for 2-D stress measurements. Its success suggests an extension of the underlying measuring principle to an intrinsically 3-D stressmeter. Research on this topic has been carried out at James Cook University since 1985. This paper introduces the 3-D borehole slotting concept. Against the background of requiring adequate guidelines for the design and operation of the new stressmeter, particular emphasis is placed on theoretical problems associated with 3-D borehole slotting.

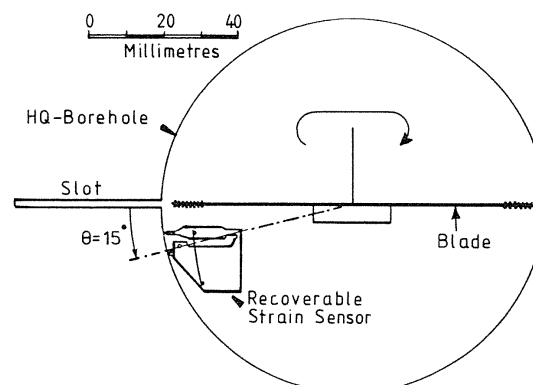


Figure 1 Principal configuration of 2-D Borehole Slotting

2 BRIEF REVIEW OF 2-D BOREHOLE SLOTTING

The borehole slotting technique is based on the principle of local stress relief. A radial slot is cut into the borehole wall by means of a small diamond-impregnated saw (Fig. 1). The slot is 0.8 mm wide and maximally 32 mm deep. The saw is pneumatically driven and is part of the borehole instrument. Before, during and after slotting, the change of tangential strain is measured at the borehole surface in the immediate vicinity (within a 15° arc) of the slot where, in practical terms, full stress relief occurs (Foruria, 1987). The strain change is measured by an innovative recoverable sensor (most recent version: Azzam and Bock, 1987) which is part of the borehole instrument.

At a particular test location, a number of successive slotting tests with cuts in different directions

is made (Fig. 2). Three cuts in independent directions is the minimum requirement for a single 2-D stress measurement. Normally however, more than 3 slotting tests are made per 2-D measurement for a redundant data base (Fig. 3). As the theory of linear elasticity is employed to transfer the strain readings into stresses, the elastic constants of the rock (E and ν) must be known. The timespan of a single slotting test is approximately 5 minutes, that of a complete, redundant 2-D measurement with 6 slots about 40 minutes.

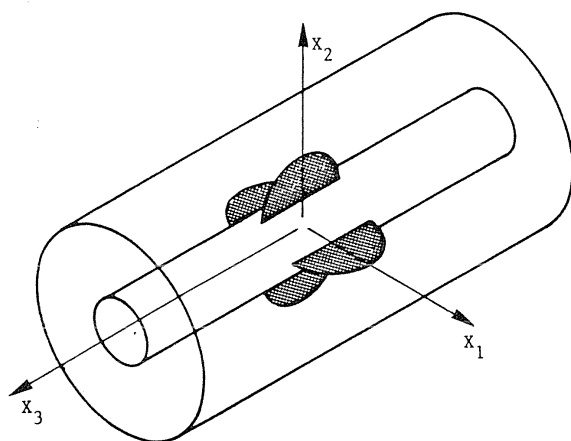


Figure 2 An isometric view of 2-D borehole slotting (out of Foruria, 1987)

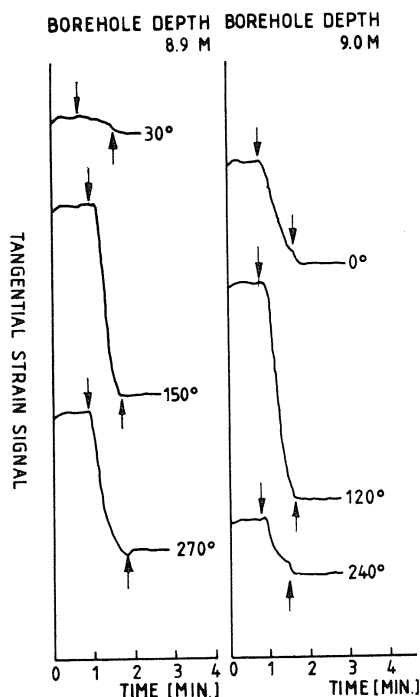


Figure 3 Field record of six slotting tests for a single 2-D stress measurement (Burdekin Falls Dam; Borehole S5). Arrows indicate beginning and end of slot cutting.

3 CONCEPTS OF 3-D BOREHOLE SLOTTING

The most obvious method of 3-D borehole slotting seems to be to supplement conventional 2-D slotting with additional axial slotting as indicated in Fig. 4. This configuration, however, is in fact insuff-

ficient for 3-D stress measurement. Slots which are oblique with regard to the borehole axis are also required in addition to both axial and radial slots (Yuen, 1988).

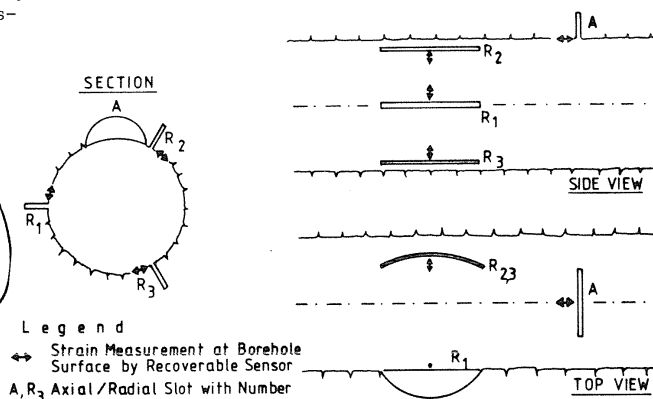


Figure 4 2-D borehole slotting R_1 - R_3 , supplemented by additional axial slot A. This configuration is insufficient for 3-D stress measurements

A more elegant solution is to increase the dimension of the stress release slot in line with the increase in dimension of the stress state to be determined (Table 1). Whilst, as mentioned before, the 2-D state of stress can be determined by some stress release slots which are straight, the determination of the 3-D state of stress will require some curved (circular) slots accordingly. Circular slotting of borehole walls is in fact nothing else than sidewall drilling. James Cook University's recoverable 3-D stressmeter development is based on such sidewall drilling.

TABLE I

2-D AND 3-D RECOVERABLE STRESSMETER DEVELOPMENT AT JAMES COOK UNIVERSITY

Stress State	Stress Relief by	Strain Sensors (Minimum)	Instrument	Reference
2-D	Linear Slot	1	"Borehole Slotter"	Bock, 1986
3-D	Circular Slot (Sidewall drilling)	3	3-D Recoverable Stressmeter	This paper

Sidewall drilling for stress measuring purposes is not entirely new. Brady et al. (1976) carried out such measurements in a 1.8 m diameter bored raise. A precondition for their tests was the direct access to the points of sidewall drilling. For some time now, the Seismological Laboratory of the California Institute of Technology has been experimenting with a recoverable 3-D stressmeter. Its operation is drilling a solid sidewall stress release hole whilst measuring the strain response of the parent borehole wall by means of laser interferometry (Bass et al. 1986).

When compared with the existing methods, the specific characteristics of James Cook University's

recoverable 3-D stressmeter can be identified as follows:-

- * Sidewall drilling in relatively small, inaccessible boreholes. As with the existing "borehole slotter" the prototype 3-D stressmeters are to be designed for standard HQ Boreholes of 96 mm diameter;
- * Measurement of the strain response to sidewall drilling by means of recoverable contact sensors. The strain can be measured in both digital and analogue modes thus enabling a continuous control of the testing procedures and instantaneous evaluation of the test results if required.

These two characteristics are considered indispensable should the 3-D stress measurements be cheap, quick, reliable and suitable for routine testing.

There are two principal configurations of sidewall drilling for 3-D stress measuring purposes; sidewall *undercoring* and sidewall *overcoring*. In sidewall undercoring (Fig. 5a) at least 3 recoverable strain sensors, identical to those of the "borehole slotter", are suitably grouped around the sidewall drilling hole. In sidewall overcoring (Fig. 5b) a reusable strain rosette is mounted at the borehole wall and radially overcored.

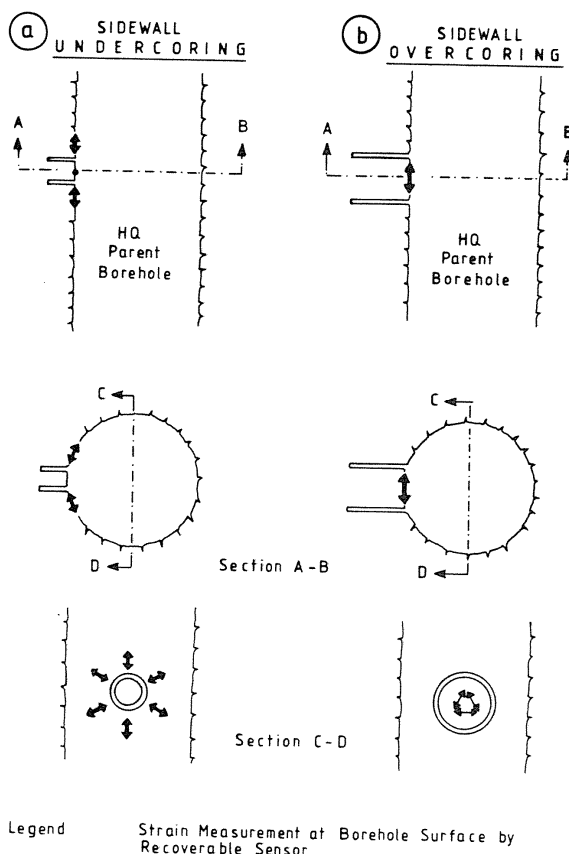


Figure 5 Sidewall stress release drilling for 3-D stress measurements. Left = sidewall undercoring; right = sidewall overcoring

The remainder of this paper is concerned with aspects of the theory of stress measurements by sidewall drilling. Points of interest are, amongst others, the theory of recoverable strain sensors at cylindrical surfaces (Section 4), the optimum diameter and depth of sidewall drilling and the spac-

ing of sidewall drill holes along both the borehole periphery and borehole axis (Section 5). The theoretical considerations are expected to provide guidelines for the design and operation of an appropriate recoverable stressmeter instrument (Section 6).

4 STRAIN MEASUREMENT BY REUSABLE SENSORS AT BOREHOLE SURFACES

4.1 Reusable Strain Sensors

The feasibility of sidewall drilling as a stress measuring technique relies, *inter alia*, on the ability to monitor normal strains at the borehole surface which develop in response to the stress release drilling. In the case of sidewall overcoring, the strain measurements are carried out right on top of the sidewall drill plug. Because of the recoverability required for the 3-D stressmeter, conventional gluing of electric-resistance strain gauges onto the borehole surface is not feasible. As with the 2-D borehole slotting technique, high-sensitive contact sensors are used (Fig. 6a; Azzam and Bock, 1987; Azzam and Yuen, 1987). For the sidewall overcoring option, a special recoverable strain rosette was developed (Fig. 6b; Azzam, 1987). The rosette was designed on the same measuring principles as the linear sensor.

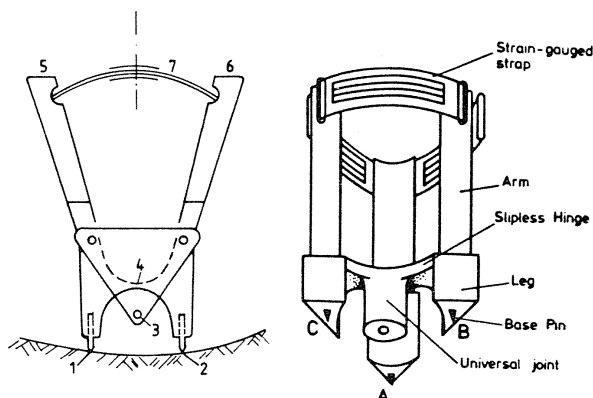


Figure 6 Linear recoverable strain sensor for sidewall undercoring (left; Azzam and Bock, 1987) and recoverable strain rosette for sidewall overcoring (right; Azzam, 1987)

The operating principle of the patented, recoverable linear sensor at borehole surfaces can be described as follows (refer to Fig. 6a):-

The base length over which the strain is to be measured at a section of a borehole wall, is defined by two points, coinciding with the tips of two needles (1) and (2), which are components of the sensor. The needles are pressed against the borehole wall by means of a sensor application device which could be an hydraulically operated piston. The application device is connected with the sensor via a joint (3). The joint is positioned between the two pins (1) and (2). Initially, the sensor is moved against the borehole wall by the application device and, once in contact with the wall, held there in position during the remaining measuring period. The relative displacement between the tips of the two needles is transmitted via a slipless hinge (4) proportionally to two pivoting arms (5) and (6), which are distant from the borehole wall. An electric or electronic measuring element (7) or part thereof is spanned between the two pivot points. In the sensors depicted in Fig. 6, this element con-

sists of a slightly curved, fully strain-gauged strip of spring steel. The change in curvature of the spring steel strip, as monitored by the strain gauges, is directly proportional to the normal strain between the base pins (1) and (2).

4.2 Errors of Strain Measurement at Borehole Surfaces

Normal strain in engineering context is a measure of the change in length per unit original length of an infinitesimal straight line. Strain measurements, however, are actually made over a finite base length. The normal strain, integrated over the base length, is considered to be the true normal strain at the centre of the measurement base. This assumption is only correct for the case of a linear, including a constant strain gradient. For non-linear gradients, as is generally the case with tangential strain at borehole surfaces, a certain error is committed. This error (Type 1 error) occurs with all existing 3-D strain cells such as the CSIRO-Soft Inclusion Cell. It is also of concern for the recoverable stressmeter.

A specific geometrical error (Type 2 error) is made when the recoverable strain sensors, as depicted in Fig. 6, are used at borehole surfaces. Whilst glued strain gauges integrate the normal strain over a certain segment of the borehole wall, the recoverable sensors measure along a chord of the borehole wall. This error might become significant at relatively great base length(s) to borehole diameter (2R) ratios. This ratio might be more conveniently expressed in terms of the angle 2ϕ , which is subtended by the chord at the centre of the borehole.

Table 2 summarizes the various types of error committed by the recoverable sensors, both in absolute terms and relative to conventional strain gauge measurements.

4.3 Parameter Analysis

Two types of tangential strain distributions at borehole surfaces were considered; a constant strain in response to an isotropic geologic stress field and a non-linearly varying strain field in response to a uniaxial geologic stress acting normal to the borehole axis.

The first case was considered with the purpose of isolating the geometric error from the strain gradient error. The latter is zero in such constant strain field. Elementary geometrical and analytical considerations reveal that the geometric error margins of 1% and 5% are at an angle 2ϕ of 20° and 44° , respectively. In a HQ Borehole of 96 mm diameter, for which all prototype instruments are designed, the respective base lengths of the recoverable strain sensor are thus 16.7 mm and 36 mm.

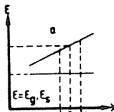
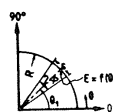
The case of a non-linear tangential strain gradient was subject to a more detailed error analysis. In the following, results are presented for an E to σ_1 ratio of 5000 and a Poisson's ratio of 0.25. These ratios represent relatively common geotechnical conditions, such as a rock with a Young's modulus of 50 GPa being geologically stressed by 10 MPa.

The absolute error of the tangential strain at borehole surfaces under these conditions, as measured by the recoverable sensor, is presented in Fig. 7 for various sensor base lengths 2ϕ . For a given ϕ the error varies significantly over the circumference of the borehole. Figure 8 shows the information contained in Fig. 7 in a modified form by graphing the absolute error of the tangential strain measurement versus the base length ϕ .

From Figs. 7 and 8 it is obvious that an increased base length 2ϕ of the recoverable sensor is associated with an over-proportionally increased error.

TABLE II

TYPES OF ERROR OF GLUED AND REUSABLE STRAIN SENSORS AT PLANAR AND CYLINDRICAL SURFACES

Strain Gradient	Mathematical expression of true normal strain ϵ	Normal strain measured by glued strain gauge ϵ_G	Normal strain measured by reusable sensor ϵ_s	Error of ϵ_s relative to ϵ_G $e_r = \frac{\epsilon_G - \epsilon_s}{\epsilon_G}$	True error $e = \epsilon - \epsilon_s$	Remarks
Planar surface						
Constant	$\epsilon = c$	$\epsilon_G = \frac{1}{s} \int_d^{d+s} c dx$ $\epsilon_G = c$	$\epsilon_s = \frac{1}{s} \int_d^{d+s} c dx$ $\epsilon_s = c$	$e_r = 0.00$	$e = 0.00$	$a, b, c = \text{constants}$ $d = \text{arbitrary constant}$ $s = \text{measuring base length}$ 
Linear	$\epsilon = ax + b$	$\epsilon_G = \frac{1}{s} \int_d^{d+s} (ax+b) dx$ $\epsilon_G = ad + \frac{as}{2} + b$	$\epsilon_s = \frac{1}{s} \int_d^{d+s} (ax+b) dx$ $\epsilon_s = ad + \frac{as}{2} + b$	$e_r = 0.00$	$e = 0.00$	
Higher Order	$\epsilon = f(x)$	$\epsilon_G = \frac{1}{s} \int_d^{d+s} f(x) dx$ $F = \int f dx$ $\epsilon_G = \frac{F(d+s) - F(d)}{s}$	$\epsilon_s = \frac{1}{s} \int_d^{d+s} f(x) dx$ $F = \int f dx$ $\epsilon_s = \frac{F(d+s) - F(d)}{s}$	$e_r = 0.00$	$e = \epsilon - \epsilon_s$ $= f(d + \frac{s}{2}) - \frac{F(d+s) - F(d)}{s}$	
Cylindrical Surface						
Constant	$\epsilon = c$	$\epsilon_G = \frac{1}{2R\phi} \int_{\theta_1-\phi}^{\theta_1+\phi} CR d\theta$ $\epsilon_G = c$	$\epsilon_s = \frac{\cos\phi}{2R\sin\phi} \int_{\theta_1-\phi}^{\theta_1+\phi} CR d\theta$ $\epsilon_s = c\phi \cot\phi$	$e_r = 1-\phi \cot\phi$	$e = c - c\phi \cot\phi$	$R, \theta = \text{polar co-ordinates}$ $\phi = \text{half angle subtended by the measuring base at the centre of the cylindrical surface}$ 
Higher Order	$\epsilon = f(\theta)$	$\epsilon_G = \frac{1}{2R\phi} \int_{\theta_1-\phi}^{\theta_1+\phi} f(\theta) R d\theta$ $F = \int f R d\theta$ $\epsilon_G = \frac{F(\theta_1+\phi) - F(\theta_1-\phi)}{2R\phi}$	$\epsilon_s = \frac{\cos\phi}{2R\sin\phi} \int_{\theta_1-\phi}^{\theta_1+\phi} f(\theta) R d\theta$ $F = \int f R d\theta$ $\epsilon_s = \frac{F(\theta_1+\phi) - F(\theta_1-\phi)}{2R \tan\phi}$	$e_r = 1-\phi \cot\phi$	$e = f(\theta_1) - \epsilon_s$ $= f(\theta_1) - \frac{F(\theta_1+\phi) - F(\theta_1-\phi)}{2R \tan\phi}$	

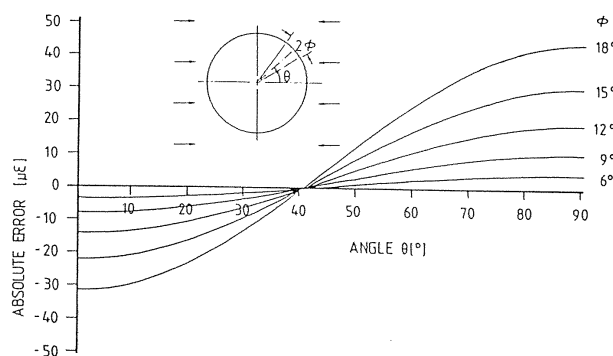


Figure 7 Absolute error of reusable strain sensor as a function of the location θ at the periphery of a parent borehole

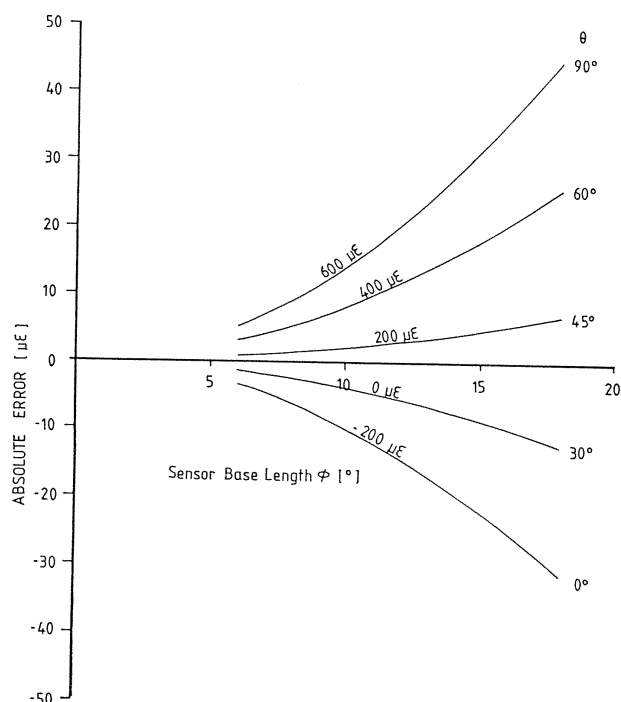


Figure 8 Absolute error of reusable strain sensor as a function of the sensor base length ϕ

James Cook's stressmeters aim at measuring at least 10 microstrain reliably with the recoverable sensors. Against this background, 2ϕ could maximally be 20° (Figs. 7 and 8). For an HQ Borehole of 96 mm diameter this means a maximum sensor base length s of 16.7 mm. In the instrument design for the sidewall overcoring option, an s of 15 mm was adopted. This was considered to be the most acceptable compromise between maximizing accuracy (s as small as possible) and minimizing the influence from the grains and other non-homogeneities of the borehole wall rock (s as long as possible).

The chosen sensor base length of 15 mm corresponds to 2ϕ of 18° which is actually greater than the length of the strain gauges incorporated in the CSIRO-SI cell (10 mm). However, as the SI cell is designed to be inserted into an EX Borehole of 38 mm diameter with a base length angle 2ϕ as high as 30° , the associated Type 1 error (influence from non-linear stress gradient) is generally significantly greater than with the recoverable stressmeter.

5 STRESS PERTURBATION OF THE BOREHOLE WALL DUE TO SIDEWALL DRILLING

5.1 Scope

The analysis focused on two main points:-

1. Minimum sidewall drilling depth required for a practically complete stress relief at the plug surface.
2. Amount and distribution of stress perturbation over the surface of the parent borehole due to sequential sidewall drilling.

The primary function of sidewall overcoring for stress measurements is to remove the boundary stresses of the plug. Drilling should be at least to such a depth that the plug's surface is practically completely stress relieved. The concept adopted has some similarities with conventional overcoring, except that the plug is not broken from the rock mass at the end of the drilling operation and that drilling is not in axial but in radial borehole direction. Of particular practical importance are the operational differences between the two overcoring techniques. Whilst conventional overcoring relies on the operation from an external drilling rig, sidewall drilling is done by a remote-controlled miniature drilling module which is to be part of the 3-D stressmeter. Unlike the conventional technique, which allows for great flexibility in the length of overcoring, the depth of sidewall drilling is technically very much restricted. Therefore the determination of a minimum overcoring depth for acquiring a sufficient degree of stress relief is of significance to the design of the recoverable 3-D stressmeter.

The technique utilized by the 3-D stressmeter requires at least three sequential radial sidewall drillings in independent directions. The formation of each of these sidewall holes disturbs the original stress distribution at the surface of the parent borehole. Subsequent measurements in the vicinity of existing sidewall drill holes are carried out in a somewhat disturbed stress environment. The degree of this disturbance controls the minimum spacing of sidewall drill holes in both tangential and axial directions of the parent borehole.

5.2 Numerical Model

A single sidewall drill hole with a core plug in its centre was considered. The drill hole is in a radial direction from the parent borehole. To achieve a maximum degree of stress disturbance, the sidewall drill hole was located at that particular point of the parent borehole where maximum tangential stresses occur. This means that the sidewall drill hole was in the geological σ_3 direction, the parent borehole in the σ_2 direction and σ_1 directed normal to the two boreholes. The problem is thus of rhombic symmetry with the necessity of discretization in the Boundary Element Model (BEM) of only a quarter of the borehole surfaces (Fig. 9). Four 3-D nine-nodal-point elements were used to model the half circumference of the parent borehole. The sidewall drill plug surface was modelled by three elements. The free end of the parent borehole surface was represented by four infinite boundary elements.

The study was accomplished using Beer's (1983) general purpose computer program code "BEFE". The input data were prepared via CSIRONET on the Cyber 845 system, while the actual calculations were performed on the Cyber 205.

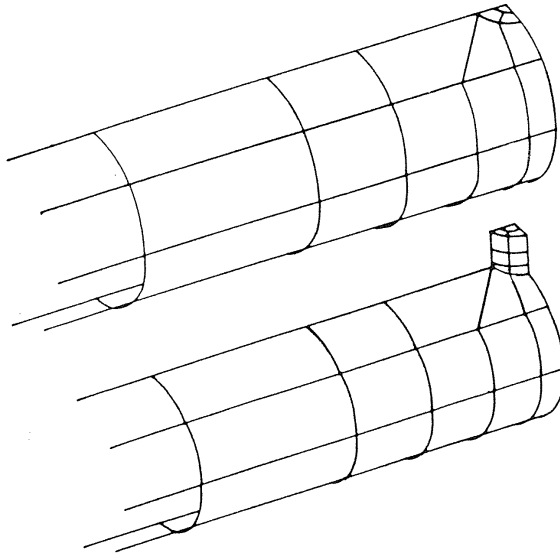


Figure 9 Boundary element mesh before (a) and after (b) sidewall drilling

5.3 Results

The calculated stresses were obtained at the four respective Gaussian points of each element. For the case of a parent borehole with no sidewall drillholes, the calculated stresses were compared with the exact solution of Kirsch (1898). The maximum deviations were of the order of 1 to 2%. Sensitivity tests with finer meshes also indicated that the chosen discretization was appropriate.

Figure 9b shows one of the meshes used to model sidewall excavation. The tangential stress changes at the drill plug surface, associated with such excavation, are illustrated in Fig. 10. As the plug surface was discretized into three elements, their individual responses to increased sidewall drilling depths are plotted simultaneously.

An example of stress perturbations over the circumference of the parent borehole due to sidewall drilling is portrayed in Fig. 11. The associated perturbations in axial borehole direction are shown in Fig. 12.

6 CONSEQUENCES FOR THE DESIGN AND OPERATION OF THE 3-D RECOVERABLE STRESSMETER

The results, depicted in Figs. 10 to 12, are for an R to R' ratio of 3.2, with R being the radius of the parent borehole and R' that of the sidewall drill hole. In a 96 mm diameter HQ parent borehole, this ratio represents a 30 mm diameter sidewall drill hole. From a technical point, such diameter was considered to be a minimum requirement for positioning and overcoring of the recoverable strain rosette as shown in Fig. 6b. It has been shown in Section 4.3 that the individual base lengths of the three sensors making up the rosette should be in the order of 15 mm. This plus the necessary tolerances from the rosette to the inside of the up to 2 mm thick sidewall drilling barrel exhaust very easily the 30 mm.

From Fig. 10 it is obvious that the tangential stress confinement at the top of the plug is prevailing only at relatively shallow drilling depths. The whole top of the sidewall drill plug reaches practically complete stress relief at a drilling depth of about 80% of the plug radius. The new re-

coverable 3-D stressmeter should therefore be designed for a drilling depth of about 15 mm.

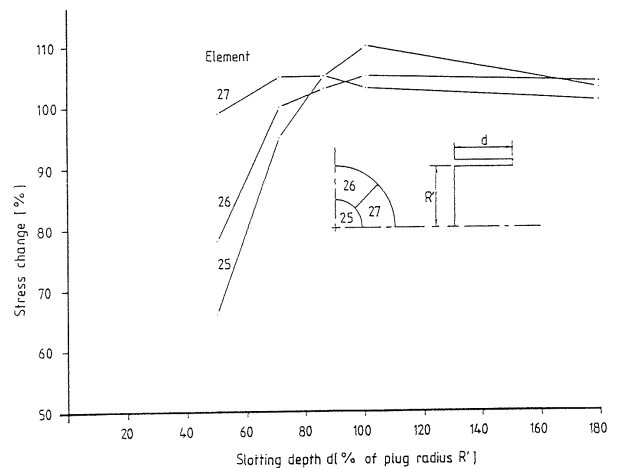


Figure 10 Stress changes at the surface of the sidewall drill plug

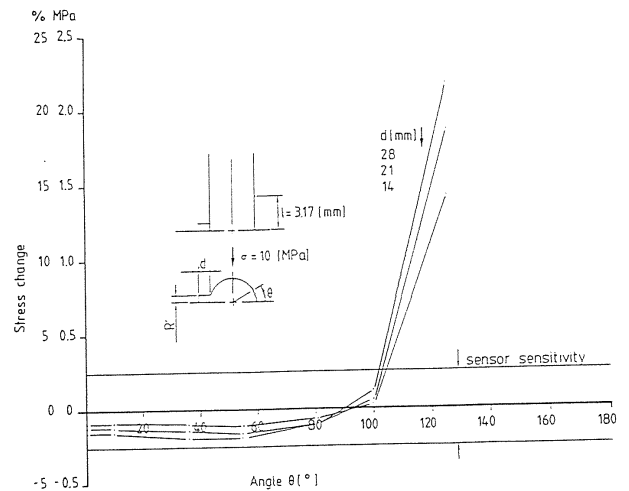


Figure 11 Stress changes over the circumference of a parent borehole due to sidewall drilling

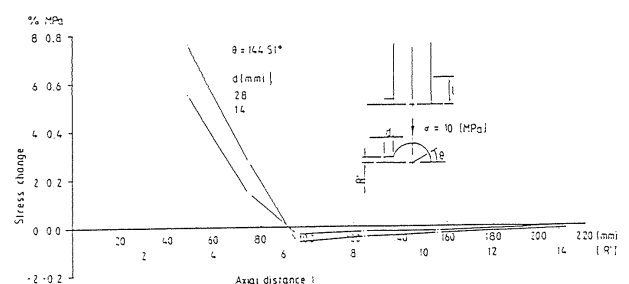


Figure 12 Stress changes in axial direction of parent borehole due to sidewall drilling

The results, contained in Fig. 11, indicate that, along the circumference of the parent borehole, significant stress changes exist close to the excavation. They attenuate rapidly with the distance from the sidewall drill hole. For example, at an angle of 60 degrees from the centre of the plug,

tangential stresses are influenced by about 15% of the ground stresses at a drilling depth of 100% of the plug radius. Beyond 80 degrees the change is negligible when considering the sensor's sensitivity and the usual geotechnical tolerances in stress measurements in rock. The analyses also indicate that additional drilling depths (up to 200% of the plug radius) have insignificant influence on the surface stresses of the parent borehole. With regard to the new recoverable stressmeter, it is the intention to drill at a particular location a total of 3 sidewall drill holes at 120° intervals. This should more than adequately prevent an interaction of the various sidewall drill holes.

The stress perturbation in axial borehole direction (Fig. 12) shows a similar pattern. The stress change is significant in the immediate vicinity of the sidewall drillhole but becomes negligible at a distance from the sidewall drill plug of about 5 times the plug's radius. For the proposed recoverable stressmeter with a 30 mm diameter external drilling barrel of 2 mm wall thickness, this amounts to about 75 mm. In line with the existing 2-D "Borehole Slotter", the minimum axial spacing of sidewall overcoring measurements might therefore be set as 100 mm.

7 CONCLUSION

The analytical and numerical investigations provide valuable guidelines for the design and operation of a new recoverable 3-D stressmeter for rocks. The base length of the contact strain sensors, the diameter and depth of sidewall overcoring holes, and their respective spacing in both circumferential and axial directions from the parent borehole have been optimized as to provide reliable, accurate, quick and high-density stress measurements. A prototype stressmeter for HQ Boreholes has recently been completed, adopting the principal dimensions presented in this paper. The prototype is currently being laboratory tested with the view of first field testing in 1988.

8 ACKNOWLEDGEMENT

This work was supported by the Australian Mineral Industries Research Association (AMIRA), Melbourne. Dr. Gernot Beer, CSIRO, Division of Geomechanics, Brisbane assisted in numerical modelling. All this support is gratefully acknowledged.

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