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ISRM Suggested Methods for rock stress estimation—Part 2: overcoring methods

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Contents

1. Introduction

1. This is Part 2 of four new ISRM suggested methods (SMs) for rock stress estimation:

Part 1: Strategy for rock stress estimation.
Part 2: Overcoring methods.
Part 3: Hydraulic fracturing and/or hydraulic testing of pre-existing fractures (HTPF) methods.
Part 4: Quality control of rock stress estimation.

These SMs are published together in a Rock Stress Estimation Special Issue of the International Journal of Rock Mechanics and Mining Sciences, 2003, Vol. 40, Issue 7–8, together with a suite of supporting contributions describing various aspects of rock stress estimation. It is strongly recommended that the new SMs are studied in association with the supporting contributions in the 2003 Special Issue—because these contributions provide a wealth of further detail and measurement case examples.

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2. This Part 2 ISRM SM on rock stress estimation covers the technique of overcoring and is illustrated by the use of the Borre probe. The principles of overcoring are presented and the field instrumentation described. Methods for executing the fieldwork are recommended and summarized in an overcoring activity table. The five appendices cover, data and document management, protocols and checklists, primary and associated information, analysis and interpretation, and an example of an overcoring results table for presentation to the client. Because of the nature of in situ rock stress and the need for careful control of the field work, data recording and data reduction, there is strong emphasis on the quality control aspects of the measurements (see also Part 4 SM on quality control).

3. Three-dimensional overcoring stress measurement has been commercially established since its conception in the late 1960s (Leeman[2] and Hayes [1]; Leeman [2]) and a number of different incarnations of the measurement method currently exist worldwide. A comprehensive list of available methods as at 1997 is given by Amadei and Stephansson [3]. Earlier ISRM SMs on rock stress determination prepared by Kim and Franklin [4] in 1987 include SMs for the USBM-type gauge and the CSIR- or CSIRO-type gauge. The current new SM supersedes the latter 1987 SM. Note also that an SM on the specific Japanese CCBO overcoring device was also published in 1999 [5].

4. Quality assurance of rock stress measurement involves undertaking the correct work, and also carrying out that work correctly. The correct work is ensured by designing a suitable program and operating plan (see also Part 1 SM on strategy); carrying it out correctly is ensured by activity or procedure plans (see also Part 4 SM on quality control). An activity plan sets out how the activity is to be performed. It refers to a method description which, in turn, specifies general requirements with respect to the method of investigation concerned, the accuracy required, the actual method of working and data acquisition and processing.

2. Overview of the overcoring method

5. This SM method description concerning rock stress measurement with the overcoring method, possibly in water-filled boreholes, is illustrated by the Borre (SSPB) probe but the principles can be applied to any overcoring method. The purpose of the method is to determine the in situ rock stress from a borehole. Three-dimensional overcoring rock stress measurements are based on measuring strains when a sample of rock is released from the rock mass and the stresses acting upon it. The in situ stresses can be calculated from the measured strains and with knowledge of the elastic properties of the rock. The complete, three-dimensional, stress tensor is determined from a single set of measurements.

6. The measurement cell is installed in a pilot hole with strain gauges bonded to the borehole wall. The cell is then overcored using a larger coring bit, which effectively relieves the stress acting on the rock. The corresponding strains are measured before, during, and after overcoring. The strain difference (after vs. before overcoring) can be related to the in situ stress state assuming continuous, homogeneous, isotropic, and linear-elastic rock behavior. In addition to the measured strains, the elastic properties of the rock (Young's modulus and Poisson's ratio) must be known. These are determined on-site using biaxial testing.

7. The test results comprise the complete stress tensor, expressed as three principal stresses (magnitudes and orientations) which can be transformed to any preferable coordinate system. Normally, several sets of measurements are taken as close to each other as possible, typically 0.5–1.0 m spacing, and the results averaged using the stress tensor components of a common coordinate system (see Paragraph 27 in Part 1 SM). Thus, the mean principal stresses are presented for a test level in the borehole.

8. Evaluation of rock stress measurements by means of overcoring requires the assumption of ideal rock behavior (continuous, homogeneous, isotropic, and linear-elastic behavior). During field measurements, one strives to take measurements only when the above conditions are satisfied. However, because these conditions are seldom met completely in rock masses, errors are introduced. Also, even when seemingly ideal conditions apply, some scattering of the results always occurs. These errors may be quantified in terms of *accuracy*, i.e., how close a particular measurement result is to a true or accepted value, and *precision*, i.e., how close two or more measurements are to each other.

9. For similar three-dimensional overcoring methods, Leijon [6] concluded that non-systematic measurement errors had a standard deviation of 2 MPa or less. Depending on rock type, repeated measurement showed a standard deviation of up to 4 MPa. Amadei and Stephansson [3] reviewed several studies and found that the expected *imprecision* is at least 10–20%, even in ideal rock conditions. A recent study of Borre overcoring data [7] showed that there is an *absolute imprecision* of at least 1–2 MPa in the magnitude of overcoring stress measurement data, regardless of stress component or measured value. Furthermore, there is an additional *relative imprecision* of at least 10% for the stress magnitudes. Variation in orientation of measured stresses is large, particularly for cases when two of the principal

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[2] For further discussion of Leeman's contribution to rock stress measurement, see the paper by C Fairhurst "Stress estimation in rocks: a brief history and review" in the Rock Stress Estimation Special Issue of this Journal, Vol. 40, Nos. 7–8, 2003.

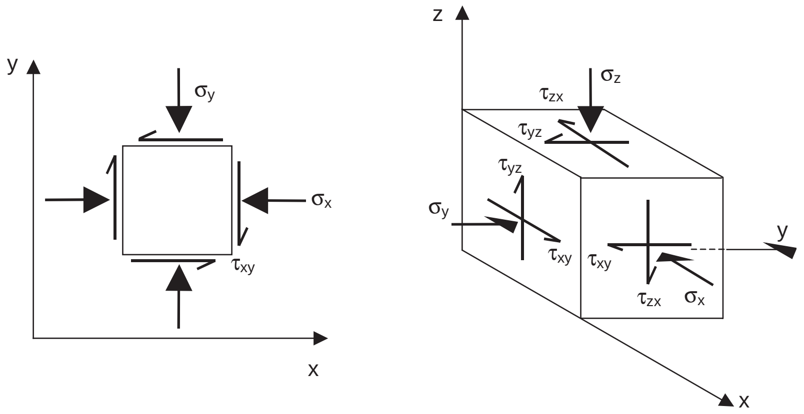

Fig. 1. Geomechanical sign convention used for presentation of measured stresses.

stresses are similar in magnitude. For the cases presented in [7], the best case gave an imprecision of $\pm 15^\circ$. All other cases showed larger imprecision for the principal stress orientations. As regards accuracy, this is not easily quantified since the true stress state is not known. Comparisons between different stress measurement methods may be used to assess accuracy, but this can only be accomplished in the later stages of a site investigation (see also Part 1 SM on the approach strategy).

10. Systematic errors may also arise, e.g., due to equipment errors or improper measurement procedure. Such errors can be minimized by careful control and adherence to the quality operating procedures for the method. In the final presentation of measured rock stresses, errors and uncertainties can be reduced by rejecting obviously erroneous measurements. Care must be taken when doing so, as it cannot be guaranteed that the rejected data are inaccurate. An assessment should be made of the experimental procedure and that all control procedures have been followed, including studying the recorded strain response during overcoring and biaxial testing, to assess the rock behavior and possible non-ideal conditions.

11. When presenting data from overcoring stress measurements, rock stress magnitudes are to be given in units of MPa with one decimal point, e.g. 4.1 MPa. The orientation of a stress component should be expressed as trend and plunge in whole degrees, e.g. 271°/81°. Furthermore, average values should be presented when more than one measurement is taken at a test level. The latter provides an opportunity to compare the deviation (i.e., the imprecision) of single measurements from the mean for that particular measurement level.

12. For presentation of measured stresses, a geomechanical sign convention is used in which compressive stresses are taken to be positive and shear stresses defined positive according to Fig. 1 (see also Fig. 1 in the SM Part 1).

3. Field equipment

13. The equipment for overcoring rock stress measurements using the Borre probe[3] comprises:

- pilot hole drilling equipment including both wireline and conventional pilot hole drilling equipment, planing tool and grinding bit;
- inspection tool (test probe) with built-in borehole cleaning brush;
- Borre probe with built-in data logger;
- set of strain gauges (to be mounted on the Borre probe);
- glue (for bonding strain gauges to the borehole wall);
- cell adapter (installation tool);
- glass fiber rods (for installation in sub-horizontal boreholes);
- biaxial test equipment including load cell, pressure gauge, hydraulic pump and strain indicator; and
- portable computer.

14. The most vital part of the equipment is the probe itself, which is shown in Fig. 2. The instrument carries nine electrical resistance strain gauges mounted in three rosettes. Each rosette comprises three strain gauges oriented (i) parallel (axial or longitudinal gauges), (ii) perpendicular (circumferential or tangential gauges), and (iii) at a 45° angle, to the borehole axis, respectively, see Fig. 3. Thus, the nine strain gauges of the Borre probe form an array representing seven spatially different directions. All strain gauges are mounted at a depth of 160 mm in the pilot hole.

15. The strain gauges are connected to a data logger inside the probe. The probe also measures the temperature in the borehole to assess the temperature effects on the readings during the overcoring phase. A description

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[3] If another device is being used, this SM should be amended according to the features of the device.

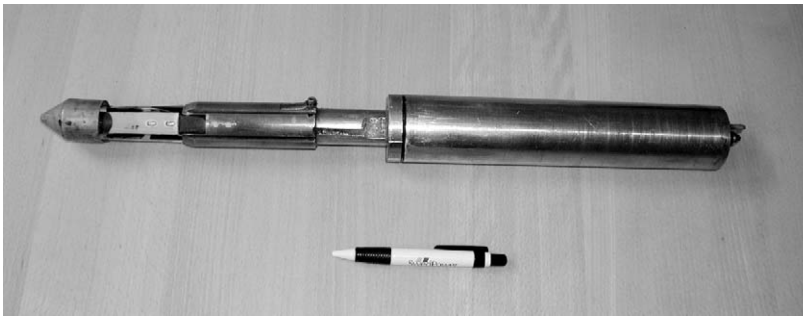


Fig. 2. Borre probe used in the overcoring method.

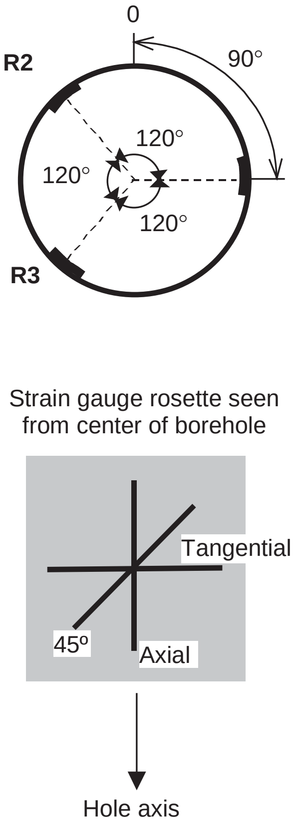


Fig. 3. Strain gauge configuration of the Borre probe. Axial strain gauges are denoted L1, L2 and L3 (gauge nos. 1, 4, 7), tangential gauges are denoted T1, T2 and T3 (gauge nos. 2, 5, 8), and inclined gauges are denoted 45-1, 45-2 and 45-3 (gauge nos. 3, 6, 9).

of the details of the Borre probe and other components of the equipment is presented in Sjöberg and Klasson [7].

4. Tools for analysis and interpretation

16. Adequate software for analysis of data shall be based on the theory presented by Leeman [2]. This software shall be specified by the Measurement Contractor in his Quality Plan for the current activity. Results include magnitudes and orientations of the three principal stresses, as well as magnitudes and orientation of the corresponding horizontal and vertical stress components. For the case of several measurements on one test level, the program should also calculate average stresses for all measurements combined.

5. Fieldwork

17. All fieldwork should be carried out with satisfactory safety and concern for the operators and the environment. The person performing the work should ensure that the necessary permissions are granted, and follow current regulations and laws, as well as the client's instructions. Since overcoring is performed as an integral part of the core drilling, it is covered by the activity plan for drilling. It follows that close co-operation with the drilling contractor is required regarding the practical aspects of pilot hole drilling and overcoring. Details are presented in the quality operating procedures of the Measurement Contractor.

5.1. *Preparations*

18. Before measurements start, preparations according to the quality operating procedures of the Measurement Contractor must be made and documented. At least the following aspects must be considered:

- functional checks,
- calibration,
- glue test,
- coordination with drilling contractor, and
- cleaning of down-hole tools; those parts of the equipment that are run into the borehole should be cleaned according to any procedures that apply.

5.2. *Measurements*

19. The procedure for a single stress measurement using the Borre probe is briefly summarized in Fig. 4.

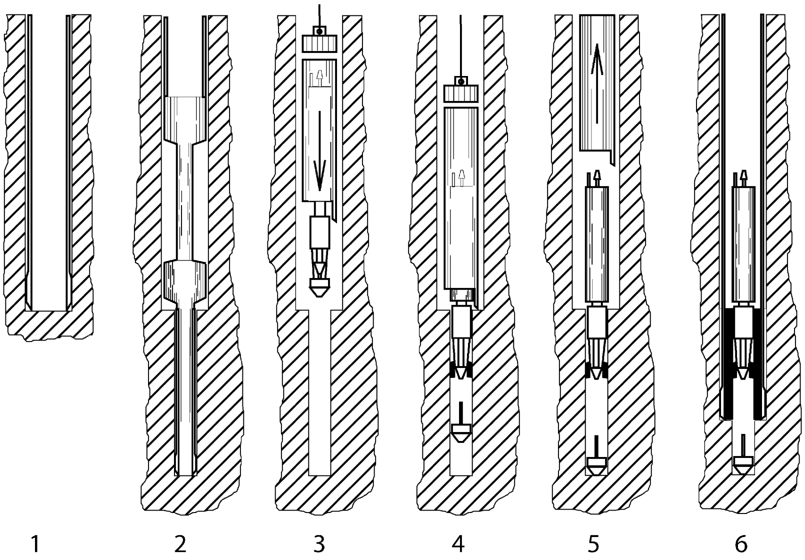


Fig. 4. Installation and measurement procedure for overcoring with the Borre probe. (1) Advance 76 mm diameter main borehole to measurement depth. Grind the hole bottom using the planing tool. (2) Drill 36 mm diameter pilot hole and recover core for appraisal. Flush the borehole to remove drill cuttings. (3) Prepare the probe for measurement and apply glue to strain gauges. Insert the probe in installation tool into hole. (4) Tip of probe with strain gauges enters the pilot hole. Probe releases from installation tool through a latch, which also fixes the compass, thus recording the installed probe orientation. Gauges bonded to pilot hole wall under pressure from the nose cone. (5) Pull out installation tool and retrieve to surface. The probe is bonded in place. (6) Allow glue to harden overnight. Overcore the probe and record strain data using the built-in data logger. Break the core after completed overcoring and recover in core barrel to surface.

20. The target test depth is normally specified in advance (in the activity plan or according to a predetermined scheme). Once at this depth, a decision as to whether to attempt the pilot hole drilling is made. The main criterion for attempting a pilot hole is that the 76 mm drill core shall contain homogeneous rock close to hole bottom. Discrete fractures may be accepted if the overall fracture frequency and/or orientation of discontinuities indicate that the pilot hole core shall be homogeneous and free of open fractures. If these requirements are not met, the 76 mm borehole is extended another 1–3 m.

21. Once a decision on pilot hole drilling is taken, drilling and examination of the core is conducted. The following aspects are of special importance:

- proper flushing of the pilot hole and inspection of return water cleanness;
- inspection of pilot core to determine whether the pilot hole is suitable for measurement;
- inspection of pilot hole regarding openness and free of debris.

22. The probe is prepared and installed in the pilot borehole according to the Measurement Contractor's procedures. After a predetermined time for glue hardening, overcoring of the probe is carried out. A detailed checklist is followed to control drilling rate, rotational speeds, flushing, etc. Flushing is recommended to start 10–15 min before the commencement of overcoring, and continue for at least 5–10 min after completed overcoring. The borehole should then be left with no ongoing activity for at least another 5–10 min before the core is broken loose from the hole. This procedure ensures that sufficient strain data are recorded to assess temperature effects, possible non-ideal rock behavior, etc., which may affect strain readings and measurement results adversely. After overcoring, the probe is recovered with the overcore sample inside the core barrel. Before removal of the sample and disconnection of the strain gauges, the data recorded are retrieved according to the Measurement Contractor's procedures.

23. Whether the measurement has been successful or not, the overcore sample is mapped and described regarding:

- Length of the overcore sample.
- Concentricity (uniform wall thickness).
- Reference line for "down" (also on the core specimen) and reference orientation of the core, determined from the compass reading.
- Gauge positions (also on the core specimen), to check that strain gauge rosettes are 120° apart.
- Lithological description.
- Structures and rock fabric: schistosity and bedding. Orientation of features in terms of the strike and dip (for the influence of anisotropy see [8]).
- Microcracks: the location, spacing and orientation.
- If the core has fractured, the position, the orientation and properties of the break or breaks.

24. After the cell has been removed from the sample, biaxial testing should be carried out as soon as possible. An attempt should be made to test the overcore sample under conditions that are as similar as possible to those in the borehole. Practical constraints may hinder this,

but extreme temperature changes, etc., should be avoided. Furthermore, the overcore sample must be at least 24 cm long, without fractures, for biaxial testing to be possible (for the sample to fit into the biaxial test chamber used for the *Borre* probe). The biaxial testing is conducted on-site and according to the Measurement Contractor's procedures.

5.3. Handling, processing and storage of primary data

25. While the work is being carried out, i.e., before data is supplied to the client, all forms and data media shall be handled in such a way as to guarantee the integrity of their information. In general, all deliverances of data to the client should include the "original" raw data body, which has not been subjected to any subjective process, such as removal of spikes, corrections for drift or other collation of data.

26. After the completed measurement, the original test results (measurement data and other documentation) are delivered to the designated recipient for the activity. Before delivery, the Measurement Contractor should check that all results are quality-assured. The recipient signs the receipt and checks that all documentation of results is obtained, and arranges for storage of the data in databases and document archives, in accordance with any required procedures.

27. The following procedure, included as an example, applies to the use of the Borre probe and can be amended for other devices and programs used. Routine data processing of measurement data involves importing the strain data file (**.esd*) from overcoring into the *Microsoft Excel* application for presenting the overcoring strain response, see Appendix D. Graphing of the strain response is performed automatically by the software application. Recorded information on start and stop of overcoring is input and strain differences calculated automatically. The calculated strain differences are written to file (**.str*) for input into stress calculation. Similarly, the strain data file from biaxial testing (**.esd*) is imported into the corresponding *Excel* application for presentation of biaxial test response and automatic calculation of elastic constants (Young's modulus and Poisson's ratio), see Appendix D. Calculation of stresses is carried out using a *Microsoft Excel* application, with input in the form of strain differences (**.str*), values on elastic constants, and borehole and strain gauge orientation, see Appendix D. Calculation is performed for a single measurement, or for several successive measurements on one test level, with automatic calculation of average stresses.

28. Documentation of which measurement data are used for the routine data processing, along with any calculation forms and the resulting data files, shall be delivered to the designated recipient for the activity. Before delivery of primary data, the Measurement Contractor should check that all results are quality-assured. The recipient signs the receipt and checks that all documentation of results is obtained, and arranges for storage of the data in databases and document archives, in accordance with any relevant procedures.

29. The primary data from the overcoring stress measurements are (example in Appendix E):

- magnitudes of the three principal stresses;
- orientations of the three principal stresses (trend and plunge); and
- values of elastic constants from biaxial testing.

The primary data to be included in the database are shown in Table 1.

In addition, the overcoring strain response diagram and the biaxial test response diagram are considered primary data.

30. The final report on measurement results should include:

- General information
    - borehole information,
    - technical aids (measurement equipment), and
    - implementation (measurement procedure).
- Results
    - reporting of overcoring test data,
    - reporting of biaxial test data, and
    - evaluated rock stress data (for each test as well as average values).
- Discussion
    - discussion of test results.

Definite specifications for the primary data report may be given by the client.

Table 1
Primary data for inclusion in the database

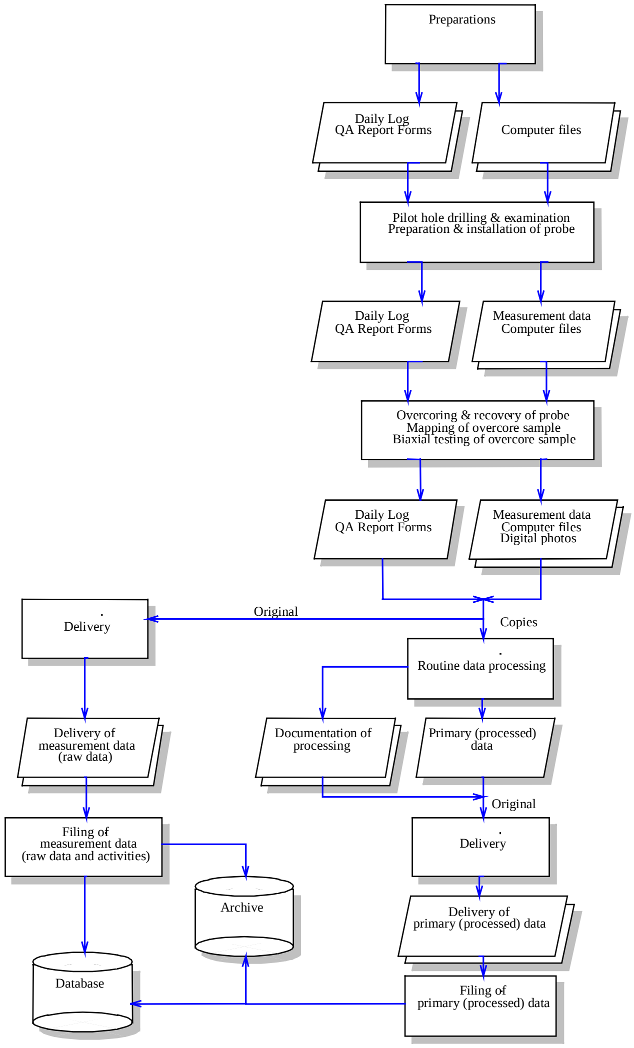
Parameter	Description
σ_1	Magnitude of major principal stress (MPa)
Plunge σ_1	Plunge of major principal stress (deg)
Trend σ_1	Trend of major principal stress (deg)
σ_2	Magnitude of intermediate principal stress (MPa)
Plunge σ_2	Plunge of intermediate principal stress (deg)
Trend σ_2	Trend of intermediate principal stress (deg)
σ_3	Magnitude of minor principal stress (MPa)
Plunge σ_3	Plunge of minor principal stress (deg)
Trend σ_3	Trend of minor principal stress (deg)
σ_H	Magnitude of maximum horizontal stress (MPa)
Trend σ_H	Trend of maximum horizontal stress (deg)
σ_h	Magnitude of minimum horizontal stress (MPa)
Trend σ_h	Trend of minimum horizontal stress (deg)
σ_v	Vertical stress (MPa)
E	Young's modulus (GPa)
ν	Poisson's ratio

6. Concluding summary of constituent steps

31. Table 2 summarizes the steps that constitute the method.

32. The primary and associated information generated by the method and which will be archived in the database are presented in Appendix C.

Appendix A. Example of flow chart of stress data and document management for overcoring rock stress measurements using the probe



Appendix B. List of protocols and checklists for overcoring rock stress measurements using the probe

(The latest version of each respective protocol/checklist is available from the client's computer network.)

- Client's Daily Log.

Furthermore, protocols and checklists of the Measurement Contractor will be used, e.g.,:

- Packing list.
- Overcoring test record.
- Overcore sample log.
- Biaxial test record.
- Tables to client.

Appendix C. List of primary and associated information for overcoring rock stress measurements using the probe (provided as an example)

The information generated by application of the method is shown in Table 3.

The associated information, for documentation and understanding of the measurement procedure, which will be archived in the database is shown in Table 4.

Appendix D. Example of analysis and interpretation

The analysis of the obtained test data comprise (i) analysis of overcoring strain data, (ii) analysis of biaxial test data, and (iii) stress calculation, using data from the first two tasks. For each task, quality control checks and data assessments are included, and described in the following.

D.1. Analysis of overcoring data

The overcoring data include the recorded strain gauge response and recorded temperature during overcoring. The recorded strains are plotted and studied by the measurement engineer. This is an important quality control procedure to check that gauges behave in an acceptable manner. An example of typical recorded strains during overcoring is shown in Fig. 5. Ideally, the recorded strains should show stable readings prior to the commencement of overcoring, often followed by a local maximum or minimum before passing the strain gauges. Another local maximum or minimum normally follows after the drill core bit has passed the strain gauge position, with final stable values developing after completed overcoring.

As shown in Fig. 5, minor variations are almost always recorded as this reflects the real behavior of the rock (which is not always as ideal as assumed). Larger deviations, e.g., steadily decreasing strains after completed overcoring, are a sign of either a malfunctioning logger or imperfect rock or strain gauge behavior. The latter can result from, e.g., core damage (microcracking), debonding of one or several of the strain gauges, a geological anomaly, time-dependent rock behavior, or temperature-induced strain changes.

Table 2
Summary of activities for overcoring stress measurements using the Borre probe

ID	Step	Input data	Controlling documents	Results/deliverables report documents	Comments
1	Preparations		Contractor's quality operating procedure	Daily Log, QA Report Forms (Appendix B)	
2	Pilot hole drilling and examination	Geological data, previous experience, 76 mm core at target depth; geological mapping, etc., pilot core	Activity plan, contractor's quality operating procedure	Daily Log, QA Report Forms	Decision on drilling and acceptance of pilot core taken jointly by Contractor and Client. Drilling conducted by drilling contractor, following checklists of Contractor
3	Preparation and installation of the probe		Contractor's quality operating procedure	Daily Log, QA Report Forms	
4	Overcoring and recovery of the probe		Contractor's quality operating procedure	Daily Log, QA Report Forms	Overcoring conducted by drilling contractor, following checklists of Contractor
5	Mapping of overcore sample		Contractor's quality operating procedure	Daily Log, Photos QA Report Forms	
6	Biaxial testing of overcore sample		Contractor's quality operating procedure	Daily Log, QA Report Forms	
7	Delivery and filing of measurement data	Original documents for output data from ID 1–6	As available	Delivery of field data material and raw data files	Check point in activity plan that all material for ID 1–6 is delivered
8	Routine data processing	Copies of output data from ID 7	Contractor's quality operating procedure, method description	Strain response diagram (digital), strain differences. Biaxial test response diagram (digital), elastic constants. Stress magnitudes and orientations	
9	Delivery and documentation of primary data	Original documents for output data from ID 8	Contractor's quality operating procedure, method description	Delivery of processed data	Check point in Activity Plan that all material of ID 8 is delivered

Such measurements are less reliable and may have to be rejected, or at least require additional analysis to possibly correct for errors—depending on the severity of these.

Additional information is that of the completed QA Report Forms (Appendix B). Using this information, as well as the recorded strain response, an assessment is made whether the measurement can be considered experimentally correct. This also involves studying the strain response from biaxial testing. If the measurement is deemed acceptable, strain differences (after vs. before overcoring) are calculated for each strain gauge for later use as input to the stress calculation. Otherwise, the test is discarded.

D.2. Analysis of biaxial test data

Biaxial test data include the recorded strain gauge response and the noted pressures (QA Report Form, Appendix B). In addition to determining elastic constants, the biaxial test provides a direct check of the performance of the strain gauges. An example is shown in Fig. 6. The measurement engineer should study each of the strain gauge response curves with respect to linearity, possible hysteresis (which may be a sign of plastic deformation), etc. The three groups of strain gauge orientations should, in theory, respond identically within each group. Moreover, for isotropic conditions the strains measured with the 45° gauge should be [3]

$$\varepsilon_{45} = \tfrac{1}{2}(\varepsilon_{\mathrm{L}} + \varepsilon_{\mathrm{T}}). \tag{D.1}$$

A dashed line showing this equation has been included in Fig. 6. This criterion is seldom completely fulfilled. Deviations of up to ±20% can be expected without the rock being anisotropic [3]. Large deviations are, however, indicators of, e.g., poor bonding or anisotropic rock behavior, which may prompt additional investigations.

The primary objective of the biaxial testing is to determine the elastic constants of the rock. The theory for an infinitely long, thick-walled circular cylinder

Table 3

Primary information	Media
Preparations	
Checklists, QA Report Forms	Paper
Daily Logs	Paper/digital file
Pilot hole drilling and examination	
Checklists, QA Report Forms	Paper
Daily Logs	Paper/digital file
Preparation and installation of the probe	
Checklists, QA Report Forms	Paper
Daily Logs	Paper/digital file
Overcoring and recovery of the probe	
Checklists, QA Report Forms	Paper
Daily Logs	Paper/digital file
Mapping of overcore sample	
Checklists, QA Report forms	Paper
Digital photo (*.*jpg*)	Diskette/CD
Daily Logs	Paper/digital file
Biaxial testing of overcore sample	
Checklists, QA Report Forms	Paper
Daily Logs	Paper/digital file
Routine data processing	
Analysis of overcoring data:	
Checklists, QA Report Forms	Paper
Overcoring strain data file (ASCII-file, *.*esd*)	Diskette/CD
Strain response presentation (*.*xls*)	Diskette/CD
Strain response diagram (*.*tif*, *.*jpg*)	Diskette/CD
Strain differences (ASCII-file, *.*str*)	Diskette/CD
Biaxial testing:	
Checklists, QA Report Forms	Paper
Biaxial strain data file (ASCII-file, *.*esd*)	Diskette/CD
Results presentation file (*.*xls*)	Diskette/CD
Strain response diagram (*.*tif*, *.*jpg*)	Diskette/CD
Stress calculation:	
Checklists, QA Report forms	Paper
Stress calculation spreadsheet (*.*xls*)	Diskette/CD
Preliminary result report (stress magnitudes and stress orientations, elastic constants)	Paper
Final results (stress magnitudes and stress orientations, elastic constants) (*.*xls*)	Diskette/CD

Table 4

Activity	Associated information
Preparations	Name of company and persons who made the preparations ID-number for selected equipment details Date and validity of calibration
Measurements	Name of company and persons who conducted the measurements
Routine data processing	Name of company and persons who conducted the analysis and reporting of primary data
Measurement control	Designated delivery recipient and date of approval

subjected to uniform external pressure is considered. The tangential stress, σ_T, at the inner surface of the cylinder (where the strain gauges are bonded) is

$$\sigma_T = 2p\frac{D^2}{D^2 - d^2}, \tag{D.2}$$

where p is the applied radial pressure, D is the outer diameter of the hollow core, and d is the inner diameter of the core. Young's modulus, E, is usually calculated as the secant modulus, i.e.,

$$E = \frac{\sigma_T}{\Delta\varepsilon_T}, \tag{D.3}$$

where $\Delta\varepsilon_T$ is the strain in the tangential direction, measured by strain gauge nos. 2, 5 and 8 (T1, T2 and T3). Poisson's ratio, v, is calculated as

$$v = \frac{\varepsilon_T}{\varepsilon_L}. \tag{D.4}$$

Since the Borre probe incorporates three pairs of circumferential and axial strain gauges, three pairs of elastic property values are obtained from each biaxial test. The aim is to obtain rock parameters that apply to the relaxation experienced by the rock during overcoring. Therefore, the values of E and v are taken to be secant values, calculated from strain data obtained during unloading of the core specimen. Usually, the secant values between the pressures of 8 and 3 MPa are calculated and averaged for the three strain rosettes. It is important to note that loading should be limited to 10 MPa maximum load to minimize the risk of microcracking of the hollow cylinder, which, in turn, can result in unrealistical values on the elastic constants, in particular Poisson's ratio.

Additional information from biaxial testing is recorded on the QA Report Form (Appendix B). Using this information, in conjunction with the biaxial test response and the analysis of overcoring data, a final assessment is made regarding the measurement quality. If the measurement is judged experimentally correct, stress calculations are conducted. Otherwise, the test is discarded.

D.3. Stress calculation

The Borre probe is a 'soft' stress cell in that only the strains induced by overcoring, in addition to the orientation of the probe in the borehole (including borehole orientation), and the elastic constants of the rock, are required to determine the complete stress tensor. Calculation of stresses from strain is done under the assumption of continuous, homogeneous, isotropic, and linear-elastic rock behavior [1,2]. The stress relief is identical in magnitude to that produced by the in situ stress field but opposite in sign.

Solving for the in situ stress involves expressing global coordinate stress components in the local borehole

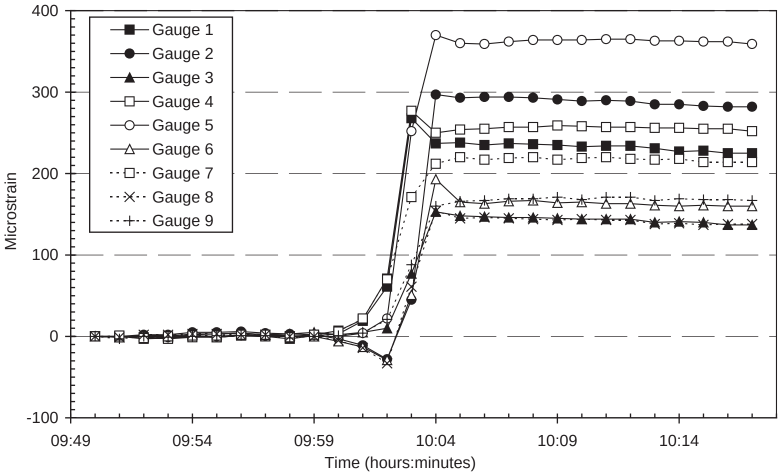


Fig. 5. Example of strains recorded during overcoring using the Borre probe.

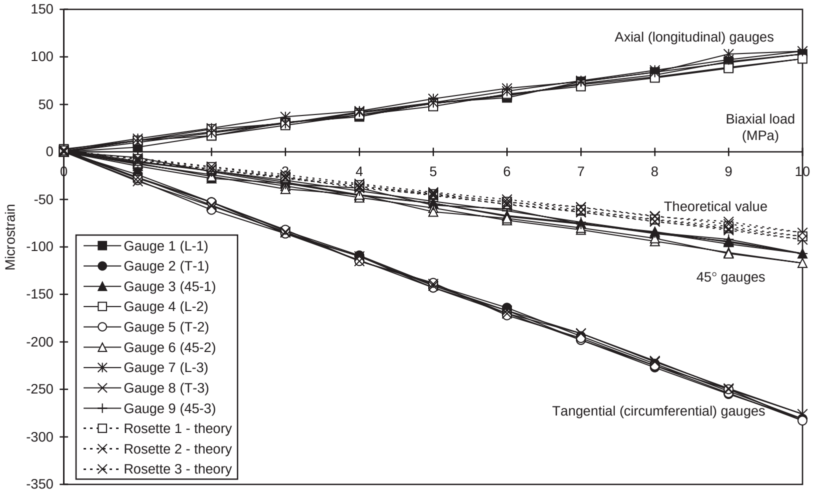


Fig. 6. Example of strains recorded during biaxial testing.

system and then accounting for the stress redistribution around the hole. From these secondary stresses, the strains at the borehole wall for each of the gauge orientations are determined, using Hooke's law. This can be expressed as

$$\sigma_{\text{local}} = [B]\sigma_{ij}, \tag{D.5}$$

$$\varepsilon_k = [F]\sigma_{\text{local}}, \tag{D.6}$$

where σ_{local} is the local (in situ) stress state tensor, σ_{ij} is the global (in situ) stress tensor $(\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx})$, $[B]$ is a transformation matrix, $[F]$ is a matrix accounting for stress redistribution around the borehole as well as Hooke's law (both E and v included), and ε_k are the strains for each of the strain gauges of the probe ($k = 1, 2, \ldots, 9$).

As these strains are measured (the strain differences due to overcoring), the in situ stresses can be calculated by combining Eqs. (D.5) and (D.6) and inverting the obtained matrix equation. The details of the formulation can be found in, e.g., Leeman [2] and Amadei and Stephansson [3] and are not repeated here.

As described above, measurements from at least six independent directions are required to determine the stress tensor (which has six components). When all nine gauges of the Borre probe function properly during a measurement, redundant strain data are obtained. A least squares regression procedure is used to find the solution best fitting all the strain data. From this solution, the stress tensor components σ_{ij} are calculated. The magnitude and orientation vector of each of the three principal stresses, σ is calculated as the eigenvalues (roots) of

$$\begin{vmatrix} \sigma_x - \sigma & \tau_{xy} & \tau_{zx} \\ \tau_{xy} & \sigma_y - \sigma & \tau_{yz} \\ \tau_{zx} & \tau_{yz} & \sigma_z - \sigma \end{vmatrix} = 0. \tag{D.7}$$

Table 5
Overcoring stress measurements

Project description: Example
Measurement level: 1
Date: 2003-01-10
Borehole Pl.: 89
Borehole Trend: 121

Input data

Depth (m)	Bearing (ball)-X (deg)	Young's modulus (GPa)	Poisson's ratio	(values for gauge and resistance factor are always 2 and 1, respectively)	Overcoring time (hh:mm)	(hh:mm)
40.44	158	91	0.25		Start = 07:37	Stop = 08:02
41.53	100	91	0.25		Start = 07:38	Stop = 08:02

Strains

Depth (m)	ε_{L1} (gauge no. 1) (μstrain)	ε_{T1} (gauge no. 2) (μstrain)	$\varepsilon_{45\text{-}1}$ (gauge no. 3) (μstrain)	ε_{L2} (gauge no. 4) (μstrain)	ε_{T2} (gauge no. 5) (μstrain)	$\varepsilon_{45\text{-}2}$ (gauge no. 6) (μstrain)	ε_{L3} (gauge no. 7) (μstrain)	ε_{T3} (gauge no. 8) (μstrain)	$\varepsilon_{45\text{-}3}$ (gauge no. 9) (μstrain)
40.44	56	40	−1	77	872	639	35	1075	411
41.53	160	−20	60	16	651	303	88	1176	758

Calculated principal stresses

Depth (m)	σ_1 (MPa)	σ_1-dip (deg)	σ_1-bearing (deg)	σ_2 (MPa)	σ_2-dip (deg)	σ_2-bearing (deg)	σ_3 (MPa)	σ_3-dip (deg)	σ_3-bearing (deg)
40.44	49.6	13.7	13.7	20.7	57.6	261.0	16.1	28.7	111.4
41.53	48.3	8.5	143.7	23.7	80.1	355.6	14.0	5.2	234.5
Average	42.2	6.1	348.2	23.8	52.3	86.1	20.2	37.1	253.5

Calculated horizontal and vertical stresses

Depth (m)	Major stress		Minor stress		Vertical stress		
	σ_A (MPa)	σ_A-bearing (deg)	σ_B (MPa)	σ_B-bearing (deg)	σ_z (MPa)	Error (sum of squares)	Strains re-calculated?
40.44	47.9	14.6	17.2	104.6	21.3	1062.5	Yes
41.53	47.8	143.9	14.1	53.9	24.2	11992.5	No
Average	42	167.6	21.5	77.6	22.7		

Thus, all together, six components define the in situ stress state (three magnitudes and three vectors, or six tensor components). From the stress tensor components, σ_{ij}, the stresses acting in the horizontal and vertical planes are also found using the stress transformation equations. The results presented comprise (see also QA Report Form in Appendix E):

σ_1 = major principal stress: magnitude (MPa), trend (deg), plunge (deg);

σ_2 = intermediate principal stress: magnitude (MPa), trend (deg), plunge (deg);

σ_3 = minor principal stress: magnitude (MPa), trend (deg), plunge (deg);

σ_H = major horizontal stress: magnitude (MPa), trend (deg);

σ_h = minor horizontal stress: magnitude (MPa), trend (deg); and

σ_v = vertical stress: magnitude (MPa).

Since the Borre probe comprises strain gauges in seven spatially different directions, up to one non-parallel gauge and two parallel gauges may malfunction (or be rejected) during the overcoring procedure without impairing complete calculation of the stress tensor. Theory dictates that the axial (longitudinal) gauges should record the same value, i.e.,

$$\varepsilon_{L1} = \varepsilon_{L2} = \varepsilon_{L3} \qquad \text{(D.8)}$$

with notations according to Fig. 1. Hence, if one or two of these gauges (nos. 1, 4 and 7 in the probe) malfunction, the values of these can be set to the remaining gauge (or rejected from the calculations). Furthermore, it is possible to show that the following relation holds for all gauges of the probe

$$\varepsilon_{45-1} + \varepsilon_{45\text{-}2} + \varepsilon_{45\text{-}3} = \tfrac{1}{2}(\varepsilon_{L1} + \varepsilon_{L2} + \varepsilon_{L3} + \varepsilon_{T1} + \varepsilon_{T2} + \varepsilon_{T3}). \qquad \text{(D.9)}$$

Thus, it is also possible to re-calculate one of the circumferential (tangential) or 45° gauges in the stress calculation. It is important to note that no measurement values are blindly rejected based on the above equations—rather, this is done by the operator and based on experience, actual site conditions, and observed strain gauge performance during both overcoring and biaxial testing. It has been found difficult to establish stringent criteria regarding rejection for a single measurement point; hence, uncertainties regarding which gauge to re-calculate always exist. Re-calculation is thus only performed as a last resort to enable determination of at least approximate stress values, and always involves some amount of subjectivity. The above equations do, however, provide an additional quality check of the strain gauge function.

For the case of several measurements on one test level, the average stress state is calculated and reported (see example in Appendix E). This is conducted by first taking the global stress tensor components σ_{ij} for each of the measurements (defined in a common coordinate system, e.g., the site coordinate system). Each of the stress tensor components is then averaged, and from these mean values, the principal stresses are determined using Eq. (D.7). Average horizontal and vertical stresses are calculated directly from the mean stress tensor components using stress transformation.

There also exists an anisotropic solution for stress calculation derived by Amadei [8]. This solution is not employed for the probe. The reason for this is basically due to the difficulties in obtaining data on the elastic properties for anisotropic rocks in an easy and practical manner. However, there are no principal problems in using the probe also for such situations, should the need arise in the future.

Appendix E. Example of tables to client

See Table 5.

References

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