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An overview of rock stress measurement methods

C. Ljunggren[a,*], Yanting Chang[a], T. Janson[b], R. Christiansson[c]

[a] SwedPower AB, Sweden
[b] Golder Associates AB, Sweden
[c] Svensk Kärnbränslehantering AB, Sweden

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Abstract

This paper presents an overview of methods that have been used to estimate the state of stress in rock masses, with the emphasis on methods applicable to hard rocks and Scandinavia. Rock stress is a difficult quantity to estimate because the rock stress measuring techniques consist of perturbing the rock, measuring displacements or hydraulic parameters, and converting the measured quantities into rock stresses. There are two main types of method: those that disturb the in situ rock conditions, i.e. by inducing strains, deformations or crack opening pressures; and those that are based on observation of rock behaviour without any major influence from the measuring method. The most common methods are briefly described including their application areas and limiting factors.

1. Introduction

This paper focuses on the methods for rock stress measurement with the emphasis on hard rock. It is known that the reliability of rock stress measurements/estimations is partially dependent on the measuring technique and equipment, and partially dependent on the nature of rock masses; a large amount of literature exists on the subject of rock stress and these factors. One relatively recent compilation of information is the 1997 book by Amadei and Stephansson [1]. The so-called 'scale effects' have been studied intensively in recent years and a review of this aspect and a statistical study have been presented by Ljunggren et al. [2]. However, it is beyond the scope of this paper to discuss scale effects and other similar issues in detail; instead, the most common methods are highlighted and discussed in the context of the rock volume included in the measurement. Also included are the conditions for which the different methods are appropriate. Factors such as, inter alia, the purpose of the measurements, borehole locations, borehole orientations, geological circumstances and water conditions will have an impact on the decision on which method to apply. The paper discusses both direct measurement methods, e.g. hydraulic fracturing and overcoring, as well as indicative methods, such as core discing. The paper distinguishes between methods applicable from the ground surface and methods to be used when there is underground access, recognizing that some methods can be practised from both the ground surface and via underground access.

It must be emphasised that engineering and safety issues should govern the rock stress measurement process. The rock stress information may be required for the following engineering aspects, either directly or as input to numerical models:

- long- and short-term stability of underground structures (tunnels, caverns, shafts and other openings);
- determination of excavation methods (drill-and-blast or TBM and raise-boring);
- design of rock support systems;
- prediction of rock bursts;
- thermo-hydro-mechanical behaviour of the rock;
- design of grout methodology;
- fluid flow and contaminant transport;
- fracturing and fracture propagation.

Rock stress measurements are required as input information for the above engineering issues and design. Hence, for each measurement campaign, the aim of the

*Corresponding author. Tel.: +46-920-77-335; fax: +46-920-77-375.

E-mail address: christer.ljunggren@swedpower.com (C. Ljunggren).

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measurements must be fully understood in order to develop a suitable approach strategy to the estimation programme. The objective in determining rock stresses may in many cases be seen as an interactive process. The type of data needed may change, depending on at what stage an underground project is in. Furthermore, preliminary measurements may reveal information on the stress state that further advance of the project should be questioned.

For a given project, stresses can be determined using several (direct and/or indirect) methods at different locations. This approach is recommended since it will provide a measure of confidence through considerations of the consistency and reliability of the information. The data obtained from each method should be analysed separately and checked to see if the simplifying assumptions associated with each method are met. The data from different methods may also be combined in order to impose more rigorous constraints on the in situ stresses. The combination of data is also useful when a limited number of tests from each method is available. Also, stress measurements can be conducted in several stages with one or several methods. The idea is to use the best attributes of the different methods for a given project. Combining several methods (hybrid measurement) based on their respective attributes can help in obtaining a more reliable assessment of the in situ stresses. A more thorough discussion can be found in Brudy [3].

2. Methods

2.1. Types of stress measurement methods

Methods for the determination of in situ rock stress can be classified into two main categories. The first consists of methods that disturb the in situ rock conditions, i.e. by inducing strains, deformations or crack opening. The following methods may be included in this category:

- hydraulic methods, including hydraulic fracturing and hydraulic tests on pre-existing fractures (HTPF),
- borehole relief methods and
- surface relief methods.

The second consists of methods based on the observation of rock behaviour without any major influence from the measuring method. The following methods belong to this category:

- statistics of measured data (database),
- core-discing,
- borehole breakouts,
- relief of large rock volumes (back analysis),
- acoustic methods (Kaiser effect),
- strain recovery methods,
- geological observational methods and
- earthquake focal mechanisms.

The methods may also be classified by their operational type and an indication of the rock volume involved in their use provided, see Table 1.

The rock volumes presented in Table 1 above indicate the typical volumes involved in a test using the different methods. When conducting stress measurements, the procedure is to conduct a series of tests to obtain accurate and reliable results at a given location or within a predetermined depth interval. The details of the stress measurement programme will depend on what questions are to be solved in any specific project. For example, when the stress state at a location is to be determined using the overcoring technique, it is known from experience that at least five successful separate tests should be obtained close to each other in order to obtain adequate results on the stress state at that specific location. Further measurements, given that the geology does not change, may not alter the average results.

Table 1
Methods for rock stress measurement classified by operational type (the rock volume involved in each method is also given)

Category	Method	Rock volume (m^3)
Methods performed in boreholes	Hydraulic fracturing	0.5–50
	Overcoring	10^{-3}–10^{-2}
	HTPF	1–10
	Borehole breakouts	10^{-2}–100
Methods performed using drill cores	Strain recovery methods	10^{-3}
	Core-discing	10^{-3}
	Acoustic methods (Kaiser effect)	10^{-3}
Methods performed on rock surfaces	Jacking methods	0.5–2
	Surface relief methods	1–2
Analysis of large-scale geological structures	Earthquake focal mechanism	10^{9}
	Fault slip analysis	10^{8}
Other	Relief of large rock volumes (back analysis)	10^{2}–10^{3}

Fig. 1 shows the rock volumes that, from experience on rock stresses and geology, may be involved for some different stress measurement situations. The main factors limiting the volume for which the stress field may be judged to be representative are the vertical depth variation, the geological boundaries, and the presence of major faults.

If we study the commercial application of stress measurements, two methods dominate the others: hydraulic methods and borehole relief methods. Although both methods have undergone continuous development over the years, the basic principles have remained unchanged and both techniques have been practised now for several decades.

2.2. Hydraulic methods

There exist two stress measurement methods that use hydraulics as an active method to stimulate the rock surrounding a borehole and hence to determine the stress field. These methods are hydraulic fracturing and HTPF. Both methods use the same type of equipment, including straddle packers, impression packers and high-pressure pumps to generate high-pressure water during either the formation of new fractures or reopening of pre-existing fractures. Fig. 2 presents an example of equipment that is used for both hydraulic fracturing and HTPF measurements. The down-hole principle during testing is shown in Fig. 3.

2.2.1. Classical hydraulic fracturing

The term hydraulic fracturing is used for fluid injection operations in sealed-off borehole intervals to induce and propagate tensile fractures in borehole wall rock. It was first applied, during the 1940s, in the oil industry to stimulate productivity from low permeable oil-bearing formations. In the beginning of the 1960s it was proposed to derive the state of stress from such hydraulic fracturing operations. The classical concept for the interpretation of hydraulic fracturing pressure records was developed by Hubbert and Willis in 1957, see, for example, the 2002 paper by Rummel et al. [4].

Several authors, e.g. Bjarnason [5] and Ljunggren [6], have presented the hydraulic fracturing method.

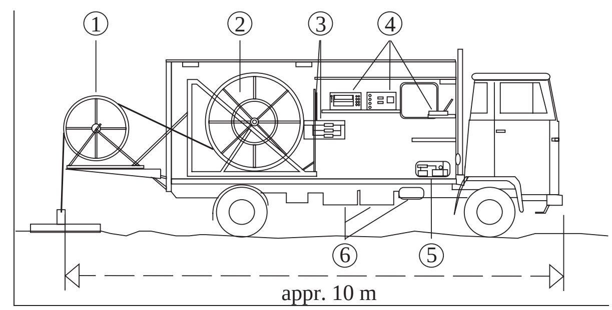

Fig. 2. Example of equipment for hydraulic fracturing and HTPF rock stress measurements: (1) guidewheel for multihose on adjustable working platform, (2) drum for 1000 m multihose, (3) flow meter manifold and manifold for control of fracturing flow and packer pressure, (4) data registration equipment, signal amplifier, chart recorder and portable PC, (5) high pressure water pump and (6) 400 l diesel fuel tanks, hydraulic pump and tank.

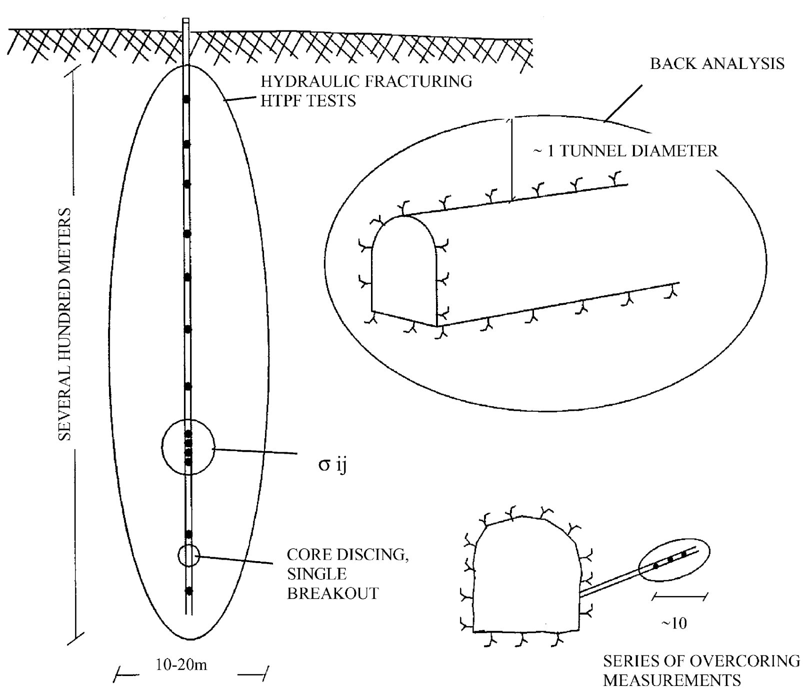

Fig. 1. Representative volumes involved in the stress measurement tests.

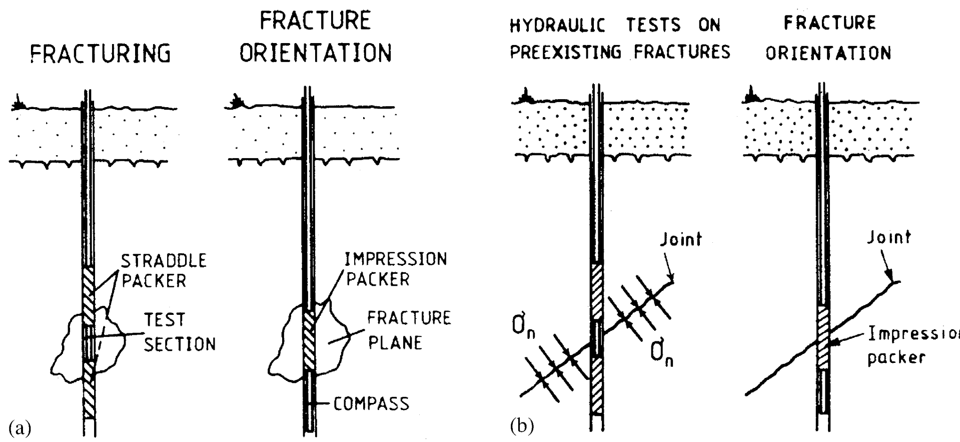

Fig. 3. Down-hole principle during (a) hydraulic fracturing and (b) HTPF measurements.

A section, normally less than 1 m in length, of a borehole is sealed off with a straddle packer. The sealed-off section is then slowly pressurised with a fluid, usually water. This generates tensile stresses at the borehole wall. Pressurisation continues until the borehole wall ruptures through tensile failure and a hydrofracture is initiated. Fig. 4 shows an example of a schematic view of a hydraulic fracturing system.

The fracture plane is normally parallel to the borehole axis, and two fractures are initiated simultaneously in diametrically opposite positions on the borehole periphery. The hydrofracture will initiate at the point, and propagate in the direction, offering the least resistance. The fracture will therefore develop in a direction perpendicular to the minimum principal stress. The orientation of the fracture is obtained from the fracture traces on the borehole wall. Thus, the orientation of initiated fractures coincides with the orientation of the maximum horizontal stress, in a vertical or sub-vertical hole where it is assumed that one principal stress is parallel to the borehole. The fracture orientation may be determined either by use of an impression packer and a compass or by use of geophysical methods such as a formation micro-scanner or a borehole televiewer.

In its conventional form, the method is 2D: only the maximum and minimum normal stresses in the plane perpendicular to the borehole axis are established. For a vertical borehole, these components are the maximum and minimum *horizontal* stresses. Since the principal stress directions in tectonically passive and topographically flat areas are usually close to horizontal and vertical, it can often be assumed that the components measured in a vertical borehole are two of the principal stresses.

Hydraulic fracturing is an efficient method for determining the 2D stress field, normally in the horizontal plane, and is therefore suitable at the early stages of projects when no underground access exists. Due to its efficiency, it is especially advantageous for

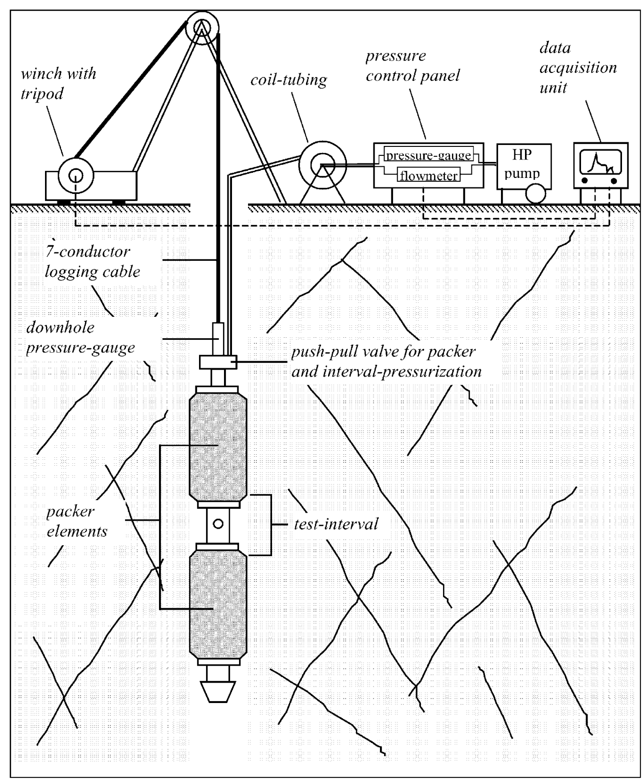

Fig. 4. A schematic view of a hydraulic fracturing system (from Rummel et al. [4]).

measurements at greater depth. The method is also not significantly affected by the drilling processes. Hydraulic fracturing normally includes large equipment, which requires space. Furthermore, the theoretical limitations normally imply that the measurements should be done in vertical holes. Hence, the method is most suited for surface measurements in vertical or sub-vertical boreholes.

The hydraulic fracturing method allows a direct measurement of the least stress in the plane perpendicular to the borehole axis, which is normally the least horizontal stress, σ_h and the accuracy is good ($\sim \pm 5\%$). The maximum horizontal stress is calculated from equations including a failure criteria and parameters evaluated from the field pressure data. The accuracy is less good for the maximum horizontal stress ($\sim \pm 10$–20% or more). In a study by Rutqvist et al. [7] it is shown that the general theory for calculating the major horizontal stress from the hydraulic fracturing suffers from uncertainties in the assumptions—a continuous, linearly elastic, homogenous, and isotropic rock together with the fracture reopening. It is probable that the major horizontal stress, determined from hydraulic fracturing, may be somewhat underestimated when the major principal stress divided by the minor principal stress is close to, or higher than, a factor of 3.

Classical hydraulic fracturing requires sections in the borehole free from fractures. These sections should be at least a few meters long so that the induced fractures do not interact with existing ones. Hydraulic fracturing may be difficult to apply with an acceptable success rate in rock domains with very high stresses, such as when core discing is indicated in the core from core drilling. Geological features, such as foliation planes in gneissic rock, may also affect the possibilities of success as they act as weakness planes and thereby may control the direction of the initiated fracture.

2.2.2. Hydraulic tests on pre-existing fractures (HTPF)

Cornet and Valette [8] first presented the theoretical basis and practical use for the HTPF method. The method is a development of the hydraulic fracturing technique because it uses the same equipment and is based on measurement of the same parameters. The HTPF method has been practised for some 15 years. The method has been applied in four projects in the Nordic countries, Ljunggren [6,9], Bjarnason and Raillard [10], Ljunggren and Raillard [11].

Instead of inducing new fractures in intact rock, the HTPF method is based on the re-opening of existing fractures found in the borehole wall and thereby determining the normal stress across the fracture plane. Depending on assumptions made regarding the stress field, the HTPF method allows either a 3D or 2D determination of the stress state. A 3D determination requires a larger number of fractures to be tested.

When conducting HTPF tests, it is of importance that the fracture tested is of a size at which the normal stress can be assumed to be uniform and the geometry of the fracture must be planar. The HTPF method relies only on four field parameters; test depth, shut-in pressure, dip and strike of the tested fracture. The shut-in pressure is equivalent to the normal stress acting across the fracture plane. Given these parameters for a sufficiently large number of fractures with different strike and dips, either the 2D or 3D stress state can be determined.

Theoretically the 2D solution requires at least six different fractures to solve the problem. In practise some redundancy, however, is required. For successful measurements, it is suggested that at least 10–12 isolated, pre-existing fractures with different strikes and dips are found and tested in the borehole wall within the depth interval of interest. The 3D alternative of the HTPF method includes less assumptions on the stress field but requires a larger number of fractures to be tested. In the 3D alternative the vertical stress does not have to be a principal stress. Theoretically, 12 unknowns exist in the system of equations. In practise, it is suggested that at least 18–20 successful tests are obtained to resolve the 3D stress field.

As compared to classical hydraulic fracturing, the method has the advantages of less limitations as regards geological features. Nor does the method require determination of the tensile strength of the rock and it is independent of pore pressure effects. As long as a variation in strike and dip of the existing fractures exists in the rock mass, neither weakness planes such as foliation planes nor core discing should cause any problems in obtaining successful measurements. The method is more time consuming than hydraulic fracturing as the down-hole equipment must be positioned at the exact location of each discrete fracture to be tested. This requires good accuracy in the depth calibration. A drawback, compared to hydraulic fracturing, is also that no preliminary results can be obtained until all field-testing has been completed, field data evaluated and those data processed using computer codes.

2.3. Borehole relief methods

The family of borehole relief methods can be divided into the following sub-groups:

- overcoring of cells in pilot holes,
- overcoring of borehole-bottom cells and
- borehole slotting.

2.3.1. Overcoring of measuring cells in pilot-holes

Overcoring based on the principle of overcoring a pilot hole in which the measuring cell is installed can be divided into further groups as follows:

- soft inclusion cells,
- deformation meters measuring displacements of the wall during overcoring and
- stiff/solid cells.

Stiff/solid cells are more unusual than the other two groups and have a general problem with the difference in material properties between the rock and inclusion material [1].

2.3.2. Soft inclusion cells

The principle of a soft cell is based on the theory of linear elasticity for continuous, homogenous and isotropic rocks. By measuring at least six strain components in different directions on the wall of a borehole, the complete stress tensor at the test location can be determined. Theories for stress measurements in anisotropic rocks have also been developed [12].

The most common instruments based on the above principle are:

- CSIR cell,
- CSIRO cell and
- Borre Probe cell.

Common to all these three instruments, and a major advantage, is that they allow the 3D state of stress to be determined from one single measurement point. The method is well known and has much testing against, for example, temperature changes and calibration against known boundary stresses. The method is considered to be reliable, given acceptable field conditions (discussed later). Table 2 summarises the characteristics and differences between the instruments. A description of the CSIR and CSIRO cell may be found in Amadei and Stephansson [1].

The Borre Probe cell includes a built-in datalogger, which runs on batteries and permits a continuous logging of the strain gauges before, during and after the overcoring process, which enhances the evaluation process. In Fig. 5, the principle of the Borre Probe cell is presented.

The triaxial cells with strain gauges in a pilot-hole are quite sensitive to the isotropy, homogeneity and grain size of the rock. As a consequence, the results from the triaxial cells often show a certain scatter. It could also be argued that scale is a potential limitation here as small scale variations in the rock material composition may affect the results. Another general limitation for all three instruments are that relatively long unbroken (40–60 cm) overcores are required and hence similar lengths of the borehole free from fractures. High stresses may also put limitations on the method as these may initiate core discing.

2.3.3. Deformation meters measuring displacements of the wall during overcoring

The principle of deformation meters for measuring displacements is the same as for the soft inclusion cells. The instrument is installed in a pilot hole and later overcored. These instruments measure one or several change in pilothole diameter during the process of overcoring, instead of the strain. Two commercial instruments of deformation-type gages are the USBM gage and Sigra in situ stress tool (IST). The USBM gauge is extensively used and one of the most reliable and accurate instruments for determining in situ stresses in rock by overcoring [1]. The theory for the USBM is described in [1] and is in principle the same for the Sigra IST. Tables 2 and 3 summarises the characteristics and difference between the two instruments.

Some of the disadvantages of the gauges are that: it requires an unbroken core of at least 300 mm in length; the gauges can be damaged if the core breaks; three non-parallel holes are necessary to calculate the in situ stress field; and the gauge depends on the minerals in contact with the gauge pistons.

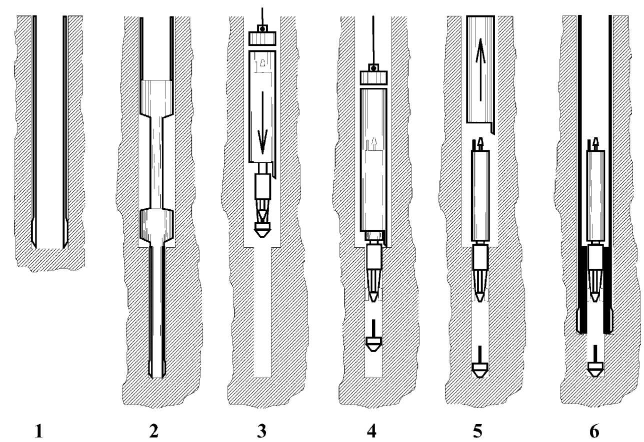

Fig. 5. Principle of soft, 3D pilot hole overcoring measurements: (1) advance ∅76 mm main borehole to measurement depth, (2) drill ∅36 mm pilot hole and recover core for appraisal, (3) lower probe in installation tool down hole, (4) probe releases from installation tool; gauges bonded to pilot-hole wall under pressure from the nose cone, (5) raise installation tool; probe bonded in place and (6) overcore the probe and recover to surface in core barrel.

Table 2
Characteristics of the most common soft overcoring cells

Instrument	No of active gauges	Measuring depths	Continuous logging	Borehole requirements
CSIR cell	12	Normally: 10–50 m, modified versions: up to 1000 m	No	38 mm pilot hole, usually 90 mm drillhole. Modified versions accept water
CSIRO cell	9/12	Normally: up to 30 m	Yes, via cable	38 mm pilot hole, usually 150 mm drill hole. Problems in waterfilled holes
Borre probe cell	9	Practised to 620 m. Tested for 1000 m	Yes, built in datalogger	36 mm pilot hole, 76 mm drillhole. Accepts water-filled holes

2.3.4. Overcoring of borehole-bottom cells

Methods for overcoring of borehole-bottom cells discussed in this paper include the following:

- Doorstoppers and
- spherical or conical strain cells.

The Doorstopper cell, Leeman [13,14], is attached at the polished flat bottom of a borehole, Fig. 6, while the hemi-spherical or conical strain cell is attached to the hemi-spherical or conical bottom of the borehole, Fig. 7. Hence, they do not require a pilot hole. After the cell has been positioned properly at the end of the borehole and readings of the strain gauges have been performed, the instrument is overcored. During overcoring, the changes in strain/deformation are recorded.

Leeman op.cit. developed a cell with strain gauges that could be cemented on the bottom of 60 mm boreholes and overcored. The cell is often referred to as CSIR (Council for Scientific and Industry Research) Doorstopper and has been used for measurements in 60 m deep boreholes. The CSIR Doorstopper is 35 mm in diameter and at the base of the gauge a strain rosette consisting of 3 or 4 strain gauges is cemented. The cell is pushed forward by compressed air and glued at the base of a drill hole. Reading of the strain gauges is taken before and after overcoring of the cell.

A modified doorstopper cell called the Deep Doorstopper Gauge System (DDGS) has been developed jointly by the Rock Mechanics Laboratory at École Polytechnique in Montréal and the Atomic Energy of Canada. The DDGS was designed to allow overcoring measurements at depths as great as 1000 m in sub-vertical boreholes [16]. The device utilises an Intelligent Acquisition Module, a remote battery-powered data

Table 3
Characteristics of two instruments of the deformation-type gauge

Instrument	No of active gauges	Measuring depths	Continuous logging	Borehole requirements
USBM	Normally 3; modified versions 4	Normally 10–50 m; modified versions up to 1000 m	No	38 mm pilot hole, usually 90 mm drillhole. Modified versions accept water
Sigra IST	3, in two or three levels	Used to 700 m. Designed for 1500 m	Yes, built in datalogger	25 mm pilot hole, 76 mm drillhole. Accepts water-filled holes

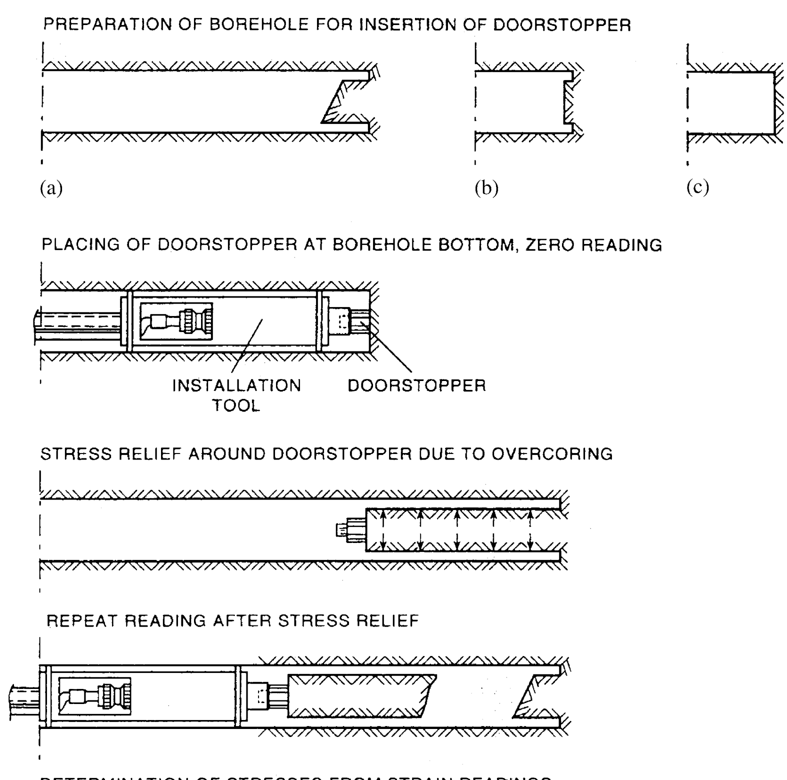

Fig. 6. Installation of Doorstopper (after INTERFELS): (a) cored borehole NW = 76 mm, (b) borehole bottom flattened and (c) polished.

logger that collects and stores strain data during stress measurement tests. The principle of the DDGS installation is shown in Fig. 8.

Successful measurements have been performed at the Underground Research Laboratory (URL), Canada [16]. The measurements were made at borehole depths as great as 518 m (943 m depth from surface), where both hydraulic fracturing and triaxial strain cells were not applicable at depths deeper than 360 m because of the high stress situation.

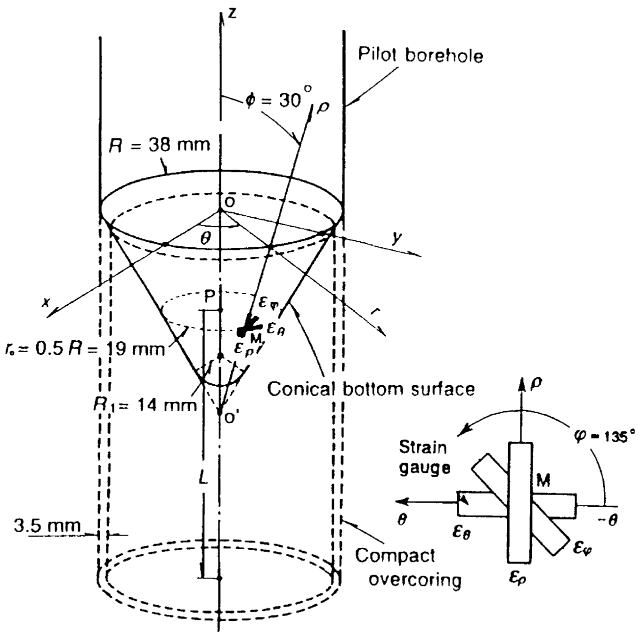

Fig. 7. Coordinate system and strains to be measured on a conical bottom surface (after Obara and Sugawara [15]).

An advantage for the Doorstopper, as well as the conical or spherical methods, is that they do not require long overcoring lengths, i.e. only some 5 cm, as compared to the pilot hole methods (at least 30 cm). As the methods do not require a pilot hole there are also better possibilities for successful measurements in relatively weak or broken rock, as well as in rocks under high stresses in which core discing is common. Compared to triaxial cells, a Dorrstopper measurement requires less time, and 2–3 tests can be conducted per day. Other advantages, valid only for the modified Doorstopper, include possibilities for continuous monitoring and the application in water-filled boreholes.

The disadvantage with the doorstopper is, however, that measurement at one point only enables the stresses in the plane perpendicular to the borehole to be determined. Furthermore, the end of the borehole must be flat which require polishing of the hole bottom.

For doorstopper cells, solutions for anisotropic rocks have also been developed. Corthesy et al. [18,19] developed a mathematical model to account for both non-linearity and transverse isotropy in the analysis of overcoring measurements with the CSIR Doorstopper.

Doorstopper methods have been developed and practised for more than 20 years worldwide.

Using a hemispherical or conical strain cell for measuring rock stresses, a borehole is first drilled. Its bottom surface is then reshaped into a hemispherical or conical shape using special drill bits. Thereafter, the strain cell is bonded to the rock surface at the bottom of the borehole. The latest version of the conical strain cell, equipped with 16 strain components, has been successfully tested by, e.g., Obara and Sugawara [15].

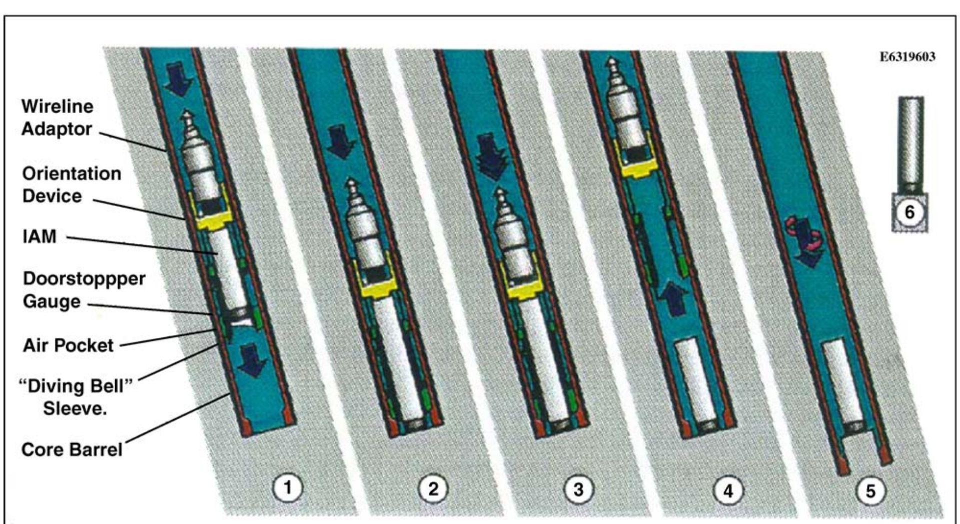

Fig. 8. Installation of the DDGS [17]: (1) After flattening and cleaning of the bottom, the instruments are lowered down the hole with the wire line cables. (2) When the DDGS is at the bottom the orientation of the measurement is noted in the orientation device and the strain sensor is glued. (3) The IAM and Doorstopper gauge are removed from the installation equipment. (4) The installation assembly is retrieved with the wire line system. (5) The monitoring and overdrilling start, the strain change in the bottom is measured by the time. (6) When overdrilling is completed, the core is taken up and a bi-axial pressure test done to estimate the Young's modulus.

Measurements with the conical borehole technique have been made mostly in Japan. This technique has been found to be a useful method for measuring rock stress in a single borehole and in various rock types.

Like the Doorstopper, a small length of the rock is required for overcoring. For the conical cell, the stress relief is achieved at an overcoring distance of 70 mm and then the strains remain at constant values [15]. Hemispherical or conical strain cells have mostly been used in Japan and successful applications have been reported in the literature (e.g. Matsui et al. [20]). Disadvantages with the conical or hemispherical cell are that they require preparation of the borehole bottom, either in the form of a cone or as a sphere. Another limitation is their poor success in water-filled boreholes.

2.3.5. Borehole slotting

The borehole slotter consists of a contact strain sensor, which is mounted against the wall of a large-diameter borehole, Bock [21]. Thereafter, three slots, 120° apart, are cut into the wall, see Fig. 9. A small, pneumatically driven saw cuts the slots. Each slot is typically 1.0 mm wide and up to 25 mm deep. Tangential strains induced by release of tangential stresses by the slots are measured on the borehole surface. It is based on the theory of linear elastic behaviour of the rock and uses the Kirsch solution for stresses and strains around a circular opening.

The most significant advantage with the method is that it does not require any overcoring. The method is also quick and between 10 and 15 measurements can be made during a day's work. The instrument is fully recoverable and provides continuous monitoring of strain as the slot is cut. The method also contains a number of limitations, such as that the borehole must be dry, it has only been applied in boreholes at shallow depths, and the stress parallel to the borehole axis must be known. The borehole slotter has been designed to work in boreholes with a diameter between 95 and 103 mm. In general, good agreement has been found between stress measurements with the borehole slotter and measurements with other techniques.

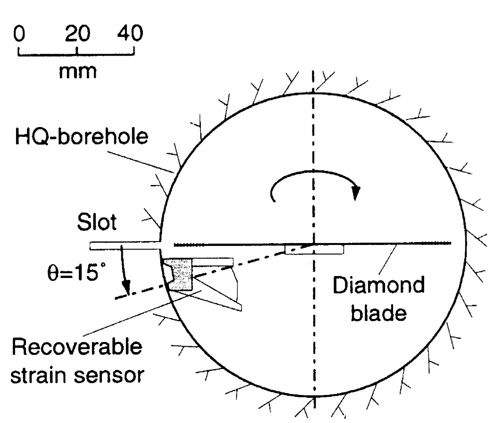

Fig. 9. Cross-section of the borehole slotter (INTERFELS).

2.3.6. Summary—borehole relief methods

There exists a variety of the so-called borehole relief methods. Some of them, however, are still in the development stage, and have not become commercially available. Today the pilot hole methods dominate and are used on a regular basis in many underground projects. As a consequence, their main application areas and limitations are fairly well known. Of the other methods, the doorstopper is the next most used technique, mainly to perform stress measurements in highly stressed rock volumes or when the fracturing is too intense to allow for pilot hole measurements. The other methods, although theoretically adequate, have only been used on a few occasions, due to their limitations. The conical or hemispherical cell has mainly been used in Asia.

2.4. Surface relief methods

This category of methods measures the rock response to stress relief (by cutting or drilling) by recording the distance between gauges or pins on a rock surface before and after the relief. Examples of the technique are the flat jack method and the curved jack method. The category is most suitable for measurement on tunnel surfaces For information the reader is referred to Amadei and Stephansson [1] and de Mello Franco [22].

2.5. Borehole breakouts

Borehole breakout is a phenomenon that occurs when the rock is unable to sustain the compressive stress concentrations around a borehole, see Fig. 10. This results in breakage of the wall on two diametrically opposed zones, called 'breakout'.

Leeman [13] first reported the use of borehole breakouts for the purpose of rock stress determination. Breakouts were found to occur along the direction of the least principal stress. Therefore, breakouts are generally used to determine the orientation of in situ stresses.

Attempts can be found in the literature where the authors use the depth and width of the borehole breakouts in order to estimate the magnitude of the rock stresses (e.g. Haimson and Lee [23]). It has been found that the shape and depth of breakouts in vertical holes depend on the magnitude of the major and the minor horizontal in situ stresses. This has led several authors to suggest that the geometry of the breakouts could be used for estimating the magnitude of the in situ stresses. However, this approach must be used with caution as breakouts can be enlarged because of various other factors, not directly the stress concentrations. Breakouts also provide a valuable link between

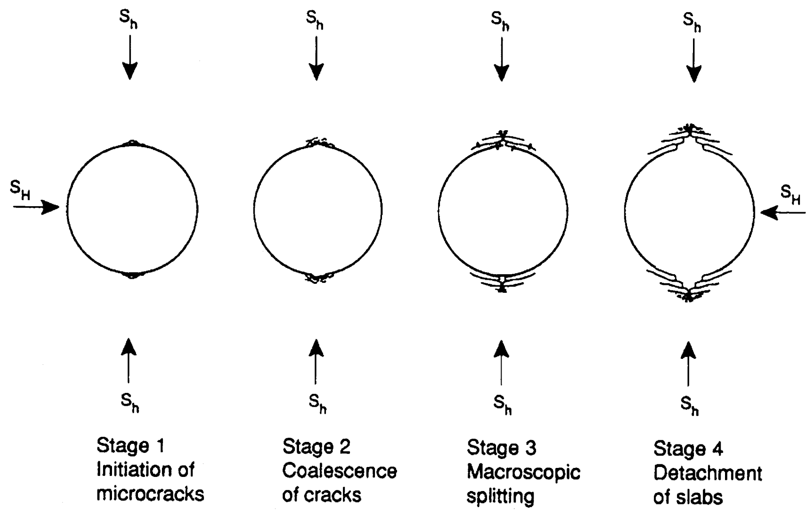

Fig. 10. Development of borehole breakouts.

overcoring, hydraulic fracturing and focal mechanism data [24].

To characterize breakouts, logging of the diametrical shape of the borehole is required. Such tools can be a caliper like a dipmeter, a televiewer, formation micro-scanner or a high resolution TV camera. The use of borehole breakouts as an indicator of the stress field has been used in some projects with deep drilling such as: the KTB hole in northeastern Bavaria, Te Kamp [25], the Cajon Pass hole in the vicinity of the San Andreas fault in southern California, Shamir et al. [26], and the borehole for deep earth gas in Precambrian rocks of Sweden, Stephansson et al. [27].

The method's major advantage is that it is quick to use and requires only measurement of the diametrical changes of the borehole wall to obtain information on the orientation of the stress field. Another advantage is that it may reveal information valid at great depth where other methods may be insufficient. The major limitation of the method is that it only works if breakouts exist. For example, breakouts do not normally exist in Swedish rocks above 1000 m, so the method cannot be used to obtain information above these depths. Also, the method cannot be used to determine the magnitudes of the stresses. Anisotropy of the rock may disturb the breakout locations and thereby also jeopardise the usefulness of the information.

2.6. Core discing

When boreholes are core drilled in highly stressed regions, the rock core often appears as an assemblage of discs. These discs sometimes exhibit parallel faces but are often shaped like a horse saddle. This phenomenon has been called 'core discing'. Attempts have been made to analyse this discing process in order to extract information on the local in situ stresses, Hakala [28] and Haimson [29].

Much experimental work has been carried out at the University of Wisconsin over the last decade in the area of core discing and borehole breakouts [29]. The studies show that high stresses bring about failure, not only at the borehole wall (resulting in breakouts), but also in the base of the core, giving rise to discing. Core tensile fractures initiated below the coring-bit extend toward the axis of the core with slight downward tilt in the direction of the least horizontal stress, σ_h. In the maximum horizontal stress, σ_H, direction the same cracks are practically horizontal. As drilling advances, these fractures open resulting in saddle-shaped discs having a trough axis oriented in the σ_H direction. This observation reinforces the idea that discs recovered from oriented cores could be used as indicators of the in situ σ_H orientation.

In addition, the laboratory tests suggest that disc thickness is indicative of the level of the applied stresses. Careful measurements of core disc dimensions show that, for given magnitudes of σ_h and σ_v, the thickness of discs decreases monotonically with increasing σ_H, Fig. 11. The results indicate that the σ_H magnitude and orientation could be estimated from the average disc thickness and trough axis attitude, provided extracted oriented-core is disced and the relation between thickness and σ_H is established. Haimson op.cit., also pointed out that, together with borehole breakouts, core discing can provide upper limits on in situ stress levels and help assess the maximum horizontal stress from the measurements of characteristic dimensions.

Based on numerical analyses, Hakala [28] has suggested a methodology for interpretation of in situ

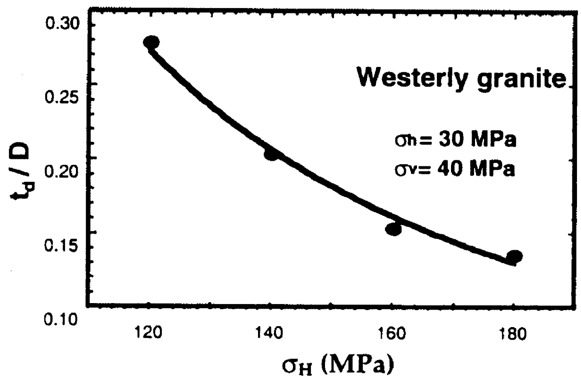

Fig. 11. Example of relation between disc thickness t_d (normalised by core diameter) and σH for given σ_h and σ_v [29].

stresses from core discing. The following minimum information is needed for the interpretation:

- the tensile strength of the rock,
- Poisson's ratio of the rock,
- the uniaxial compressive strength of the rock,
- the mean disc spacing,
- the shape of the fracture (morphology) and
- the extent of the fracture in the core.

According to Hakala, op. cit., the confidence of the interpretation can be increased considerably if the same information can be achieved from both normal coring and overcoring at the same depth level.

In practice, core discing can only be used as an indicator for estimation of rock stresses. When core discing occurs, one can of course also conclude that rock stress concentrations are higher than the rock strength. Such information, obtained already during the drilling stage, is of course valuable and a guide for further decisions.

2.7. *Relief of large rock volumes*

During excavation of underground openings, deformations/displacements of the rock mass will occur. These displacements may be measured using instrumented cross sections in the openings, Sakurai and Shimizu [30]. The displacements measured are related to the in situ stresses by use of numerical methods. More recently, Sakurai and Akutagawa [31] also presented material to account for non-elastic rock behaviour. Methods based on the above principle are often referred to as back-analysis methods.

The advantage of back analysis methods is that they are quick to use, require limited and simple measurement procedure and include large volumes. Other advantages are that they may be used to change support systems and excavation schemes on an almost real time basis. The limitations include that the technique can only be used on underground openings and only during the excavation process of underground openings. The method requires numerical analyses and does not allow unique solutions.

2.8. *Strain recovery methods*

Measurement of stress field parameters using the method of strain recovery is based on the principle that a core, after relief from the surrounding stress field, expands more in the direction of the maximum stress direction and less in the direction of the minimum stress. This relaxation consists of an instantaneous elastic component and a time-dependent anelastic component.

Methods that utilise the principle of strain recovery are:

- anelastic strain recovery (ASR) and
- differential strain curve analysis (DSCA)

Both methods are applied on drill cores from boreholes.

2.8.1. *Anelastic strain recovery (Asr)*

When a drill core is removed from the rock mass, it tends to relax and expand, due to that stresses are removed from the core. Field measurements show that the opening and propagation of preferential microcracks usually accompanies anelastic strain recovery. By measuring the strain recovery, see Fig. 12, the orientation of the principal strains can be determined. Thus the orientation of the principal stresses can also obtained. However, determination of the magnitude of the stresses is more difficult and a constitutive model for the rock must be used.

The ASR method requires that the core is orientated, which may be costly. The ASR method, which is not commonly used, has mainly been tested in very deep

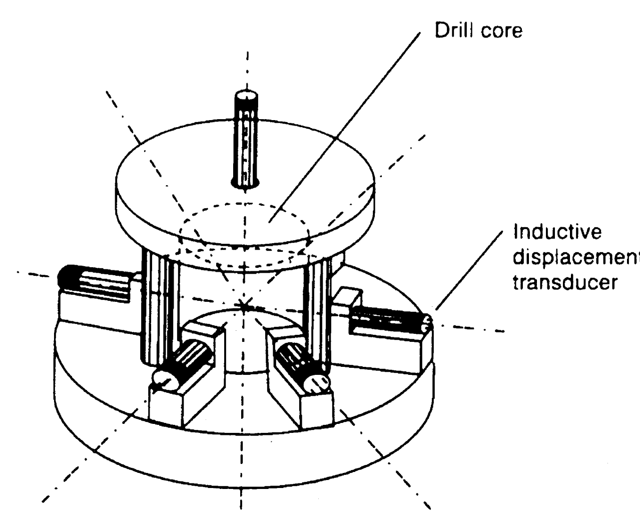

Fig. 12. Instrument for ASR measurements of a drill core. Three pairs of radial inductive displacement transducers and one axial transducer are used to measure the anelastic response of a core sample.

boreholes where methods such hydraulic fracturing have not been possible or too expensive to use.

The following nine parameters could significantly limit the application of the ASR method, Teufel [32]: (1) temperature variation yielding thermal strains, (2) dehydration of core samples, (3) pore fluid pressure diffusion, (4) non-homogeneous recovery deformation, (5) rock anisotropy, (6) drilling mud–rock interaction, (7) residual strains, (8) core recovery time and (9) accuracy of core orientation.

Studies show that the stress orientation obtained with the ASR method did not coincide well with that determined by overcoring. The difference was attributed to difficulties in measuring small strains, Matsuki and Takeuchi [33].

2.8.2. Differential strain curve analysis (DSCA)

This method is based on the concept that careful monitoring of the strain behaviour of a rock specimen upon re-loading can reflect its past stress history, Amadei and Stephansson [1]. After an oriented drill core is brought up to the surface, the micro-cracks have had time to develop and to align themselves in the direction of the original stresses. By subjecting the core to hydrostatic loading, the strain due to the closure of the micro-cracks can be obtained by the core with strain gauges.

To determine the in situ stresses, assumptions are made:

- The principal directions of the in situ stress field coincide with the principal directions of the strain due to the closure of the micro-cracks.
- The ratios between the three principal stresses are to be related to the ratios between the three principal strains due to the closure of the micro-cracks.

Thus, once one principal stress is known (e.g. assuming the vertical stress is equal to the weight of the overburden rock), the other two principal stresses can be determined. An advantage with the method is that it may be applied to estimate stresses at large depth as long as it is possible to recover a core. Major limitations include that it includes measurements on a micro-scale and involves very small volumes. The method is only 2D. Studies have found that the stress orientations determined with the DSCA method correlated poorly with those determined by the overcoring.

2.9. Geophysical methods

The following geophysical methods for estimation of in situ stresses have been reported in the literature:

- seismic and micro-seismic methods (i.e. Martin et al. [34]),
- sonic and ultrasonic methods [35],
- radio-isotope method [36],
- atomic magnetic method [37],
- electromagnetic methods [38]) and
- acoustic methods (Kaiser effects, 1950—now).

The techniques listed above have not gained much popularity in practice. Some remarks need to be made, however, about the last mentioned method (the Kaiser effect), which has been investigated over the past 15 years as a potential method to determine in situ rock stresses. Research originally conducted by Kaiser in 1950 on acoustic emission of rock revealed that when the stress on rock relaxed from a certain level and then increased, there is a significant increase in the rate of acoustic emission as the stress exceeds its previous higher value. It has been hypothesised that the stress experienced by a rock in situ could be inferred by monitoring the acoustic emission on core samples cut from different directions and loaded cyclically in uniaxial compression in the laboratory. The maximum stress that a rock specimen has been subjected to can be detected by stressing the specimen to the point where is a substantial increase in acoustic emission (AE).

An extensive review of the different studies conducted on the Kaiser effect was conducted by Holcomb in 1993. Despite encouraging results obtained by several authors showing a fairly good correlation between stresses determined with Kaiser effect and with other methods, the research carried out by Holcomb revealed that using the acoustic emission emitted during uniaxial compression laboratory tests to infer in situ stresses could not be justified.

Utagawa in 1997 concluded that the stresses determined by AE were consistent with the stresses from the overcoring method and hydraulic fracturing method. There was also significant correlation between the overburden pressure and estimated vertical stress from AE. It is not a directly commercially available method and there still exists a discussion on its justification as a method to determine stresses.

A method called RACOS is a relative new geophysical method to determination the in situ stress magnitudes and their orientations [39]. The principles of the method are the same as the DSCA except that the compression and shear wave propagations are measured instead of the strain. The method is based on the idea that the reloading on a sample can reflect it's past stress history. The measurements are made on a total of 5 cubic pieces, with a length of 25 mm. The pieces are placed in a pressure cell and subjected to a defined hydrostatic loading while the transmission times for the compression and shear waves are measured between opposing block face. The analysis is based on the change and different in velocity of the waves during the loading steps. The velocity change depends on the opening or closure of micro-cracks in the pieces. The method has

Table 4
Stress measurement methods and key issues related to their applicability

Method	2D/3D	Advantages	Limitations	Suitable for
Overcoring	2D/3D	Most developed technique in both theory and practice	Scattering due to small rock volume. Requires drill rig	Measurements, depth down to 1000 m
Doorstopper	2D	Works in jointed and high stressed rocks	Only 2D. Requires drill rig	For weak or high stressed rocks
Hydraulic fracturing	2D	Measurements in existing hole. Low scattering in the results. Involves a fairly large rock volume. Quick	Only 2D. The theoretical limitations in the evaluation of σ_H. Disturbs water chemistry	Shallow to deep measurements. To obtain stress profiles
HTPF	2D/3D	Measurements in existing hole. Can be applied when high stresses exist and overcoring and hydraulic fracturing fail	Time-consuming. Requires existing fractures in the hole with varying strikes and dips	Since the method is time consuming, it is of most interest in situations where both overcoring and hydraulic fracturing fail
Core discing	2D	Existing information, which is obtained already at the drilling stage	Only qualitative estimation	Estimation of stress at early stage
Borehole breakouts	2D	Existing information obtained at an early stage. Relatively quick	Restricted to information on orientation. Theory needs to be further developed to infer the stress magnitude	Occurs mostly in deep holes
Focal mechanisms	2D	For great depths	Information only from great depths	
Kaiser effects	2D/3D	Simple measurements	Relatively low reliability	Rough estimations
ASR/DSCA/RACOS	2D/3D	Usable for great depths	Complicated measurements on the micro-scale, sensitive to several factors	Estimation of stress state at great depth
Back calculation	2D	Quick and simple. High certainty due to large rock volume	Theoretically not unique solution	Can only be used during construction of the rock cavern
Analysis of geological data	2D/3D	Low cost	Very rough estimation, low reliability	At early stage of project

been applied to sedimentary rocks and metamorphic rock but the results have not been compared with any established stress measurement method.

2.10. Geological observational methods

From the literature there can be found numerous suggestions for estimating orientations and/or magnitudes of the stress field from geological structures, for example faults, dikes, volcanoes, lineaments. A discussion of the subject can be found in Amadei and Stephansson [1].

It should be pointed out, however, that most geological structures were formed a long time ago and the mechanism controlling the stress field at that time may have changed significantly since then. Plate tectonic driving forces may have had a different pattern than today, erosion may play a role, and a number of glacial periods have passed in some parts of the world. Hence, caution must be used if stress information is estimated from geological structures.

2.11. Earthquake focal mechanisms

Seismologists have studied the relation between the fault slip occurring during an event and the state of stress. Several attempts have been made to correlate stress magnitudes to data from earthquakes but these analyses have limitations. It is, however, possible to use the method to estimate the directions of the principal stresses. If a seismic acquisition network exists, the method allows monitoring of events on a continuous basis if earthquakes occur. As earthquakes normally occur at great depth, the method only gives information on the stress orientations at great depths, which may not be relevant for engineering at shallow depth, i.e. between 0 and 1000 m.

3. Summary of methods and conclusions

The previous sections have given a brief review of the most common methods to determine or estimate information about the in situ rock stresses. When studying the stress measurement methods available, the following can be concluded.

- A few methods dominate the others. These methods are commercially available; they have been applied world wide; many reference data exist; their accuracy given ideal conditions is well known; the methods have been benchmarked against each other; they have been practised for many years; and have been developed for the purpose of determining either the 2D or 3D stress field parameters. The methods in this category are hydraulic fracturing, overcoring, the doorstopper technique and back analysis.

- There exists a number of methods that are based on the interpretation of geological and/or stress related phenomena where no actual measurement of the stress field is performed. Normally these methods are less accurate, as compared to the true measurement method mentioned above, but the information may be obtained at a lesser price and they may also serve as a complement to the true measurement methods. For certain conditions, these methods may also be the ones to use to obtain stress field information. Typical methods that fall into this category are core discing, borehole breakouts, and analysis of geological structures.
- A category of methods includes those that do not have the general advantages of the most common true measurement methods but which under certain circumstances may be of great value. Mostly, these methods have not yet found their full commercial platform and are the ASR method, the DSCA method, the evaluation of focal mechanisms and most of the geophysical methods.

The methods are summarised in Table 4 with focus on some of the key parameters.

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