STRESS MEASUREMENT IN ROCK

BACKGROUND

Stresses in rock and the rock material properties control how rocks will deform. This extends from elastic behaviour up to strength-based failure and the deformation thereafter. In some cases, such as tunnels, major deformation must be minimised, while in others such as block caves failure with large movement is essential or the mining process will not work.

Knowing the rock stresses and the material properties is extremely important in any rock mechanics design. This document describes the methods used by Sigra in rock stress measurement. The companion document 'Rock Property Testing' describes the methods used by Sigra in determining rock properties.

METHODS USED TO DETERMINE ROCK STRESS

Sigra uses multiple techniques to determine the stress in rocks. These are:

In hole testing using

Overcoring
Hydrofracture
Hydrojacking
Borehole breakout

Core measurements using

Core ovality measurement

Surface stress measurement

Surface overcoring

Overcoring

Overcoring is a technique that involves relieving the stress on surface, or at the bottom of a borehole, and measuring deformation or strain before and after stress relief. The deformation is related to stress using measurements of the rock's mechanical properties and the geometry of the test. The measurement of these rock properties is therefore just as important in arriving at stress values as the overcore operation itself.

In its most common form overcoring takes place at the bottom of a core hole. A pilot hole is drilled at the end of the core hole and a cell is inserted into it. This may be a device that measures the diameter of the pilot hole or one that measures the strain on the pilot hole wall. In modern systems this information is stored on board the cell rather than being transmitted out via a cable. This means that overcoring can be undertaken at significant distance from the hole collar. The cell may measure the diameter of the pilot hole or it may measure the surface strain on the pilot hole wall.

All overcore tests rely on the rock behaving in an elastic manner. This does not require the rock to be linearly elastic or isotropic, though the more complex the rock mechanical behaviour the more complex the overcore analysis. If the pilot hole wall breaks then the test process becomes invalid.

The types of analysis used for overcoring have the form shown in Table 1, depending on the rock properties.

Table 1. Overcore analysis processes.

Rock Properties	isotropic	axisymmetric anisotropic	non-axisymmetric anisotropic	In-homo genious
Linearly elastic	analytical	analytical	finite element	approximate analytical
non linear	finite element	finite element	finite element	practically impossible

Sigra IST2D

This is a two dimensional overcore stress measurement system. It is designed to work with variations of HQ, HQ-3 and HQ-U wireline coring systems. It can also be used with the PQ wireline coring system.

The IST2D system may be used in holes of any orientation, however as a two dimensional system, some estimate of the stress in the axial direction of the borehole will need to be arrived at to complete the measurements perpendicular to the hole axis. While theoretically three tests may be carried out at different orientations to arrive at a complete stress tensor drilling three boreholes is generally an expensive and inconvenient option. In addition, the variability of stress in rock frequently makes the calculation of a precise stress tensor difficult. Normally the IST2D test is conducted in near vertical holes and the vertical stress is assumed to be the overburden stress.

As the IST2D tool measures the diameter of the pilot hole through mechanical contacts it may be used for repeated tests quite rapidly. Tests at 50 m may take one hour, at 400 m two hours and at 800 m in four hours. The tool has been used to 1050 m depth and is capable of operation to 2000 m. The six pilot hole diameter measurements can provide 1 estimate of stress using six diameter changes, 6 measurements using five diameters, 15 measurements using four diameters and 20 measurements using three diameters. There is therefore a good degree of redundancy available in stress measurements.

As depth increases the component of pilot hole deformation associated with axial (vertical) loading and Poisson's ratio increases to the point where it may dominate over deformations brought about by lateral stresses. In this case the lateral stresses calculated become less certain.

The test method is ideal for near vertical holes to 800 m from the hole collar. As depth increases the measurement of Poisson's ratio becomes critical to obtaining precise answers.

The IST2D process is shown in Figure 1. Variants of the tool have been in use since 1996 in over 1300 stress measurements. Figure 2 shows the tool in use while Figure 3 shows the tool with the overcore it has just been extracted from.

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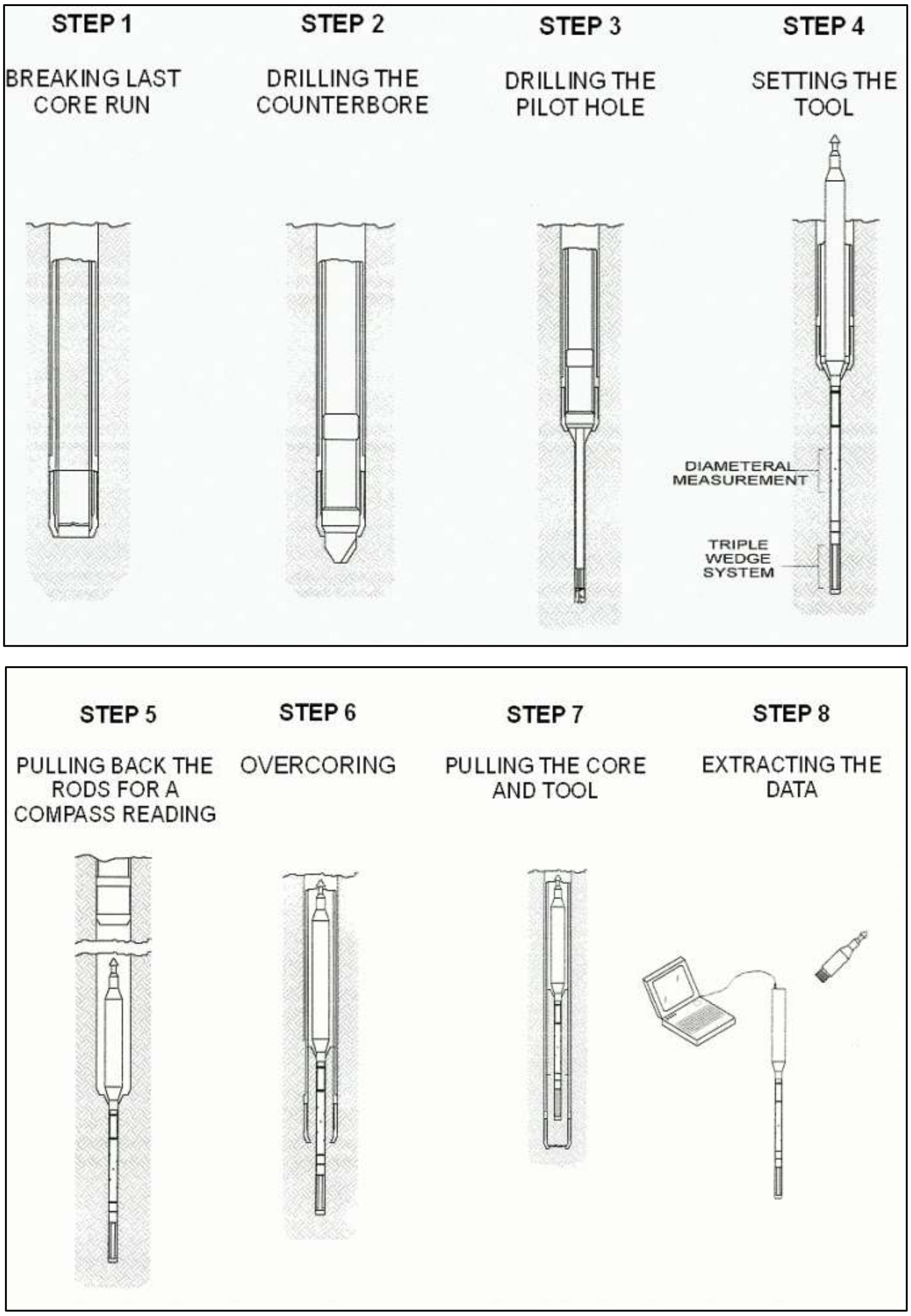

Figure 1. IST2D overcore procedure.

Figure 2. IST2D overcore tool about to go down the hole.

Figure 3. IST2D overcore tool and overcore from which it has just been extracted.

Sigra IST3D

This is a three dimensional overcore tool. It is a glue in cone cell that is locked at its end into a pilot hole. The cone is of very shallow angle and behaves fairly similarly to a normal pilot hole. Twenty strain gauges are at different orientations and locations on the cell wall and this provides a high degree of redundancy in the measurements.

The process is similar to that shown in Figure 1 except that the pilot hole is tapered and the cell is glued into the tapered section. The glue will work in clean water drilling fluid. The glue will take at least 8 hours to reliably set, depending on rock temperature. Practically this means leaving it in place for a 12 hour shift. As the cell is locked into a pilot hole and glued to the wall of the taper the system is very resistant to drilling vibration.

The tool can be used in any orientation with HQ, HQ-3 or HQ-U coring systems.

The tool may also be fitted with a cable for stress change monitoring.

Hydrofracture

Hydrofracture is in concept simple, though less so in practice.

It usually involves pumping fluid into a test zone, normally between two packers within a borehole in un-fractured rock. The pressure rises until the tensile stress exceeds the rock strength at the borehole wall whereupon a fracture opens and propagates. In un-fractured homogeneous rock the fracture can only start in the axis of the hole. If the borehole axis is not in the plane of the minimum principal stress the fracture will rotate to be perpendicular to it. When the fracture has extended, pumping is stopped and the fracture is allowed to close through fluid leak off into the rock mass. After closure the pressure will still decline, and this decline may be used to determine the permeability of the rock mass. The straddled zone in the hole may then be pressurised again to re-open the fracture.

A typical single hydrofracture cycle is shown in Figure 4. Figure 5 shows a graphical method used to determine fracture closure.

The two pressures that are used in the stress analysis of hydrofracture are the closure pressure of the fracture, which should equate to the minimum stress across it, and the fracture re-opening pressure.

If the fracture is planar and passes through the axis of the borehole the determination of the fracture closure pressure is straightforward. If the fracture rotates then multiple apparent closure pressures are likely to exist. This is also the case if the hydrofracture extends into a natural fracture which captures it. This complicates analysis and causes uncertainty.

The determination of the major stress from hydrofracture is based on the assumption that the borehole passes through the intersection of the planes of major and minor stress in the rock mass. It also requires the assumption that the rock is linearly elastic. These assumptions are seldom justified and generally the major stress cannot be reliably determined by hydrofracturing.

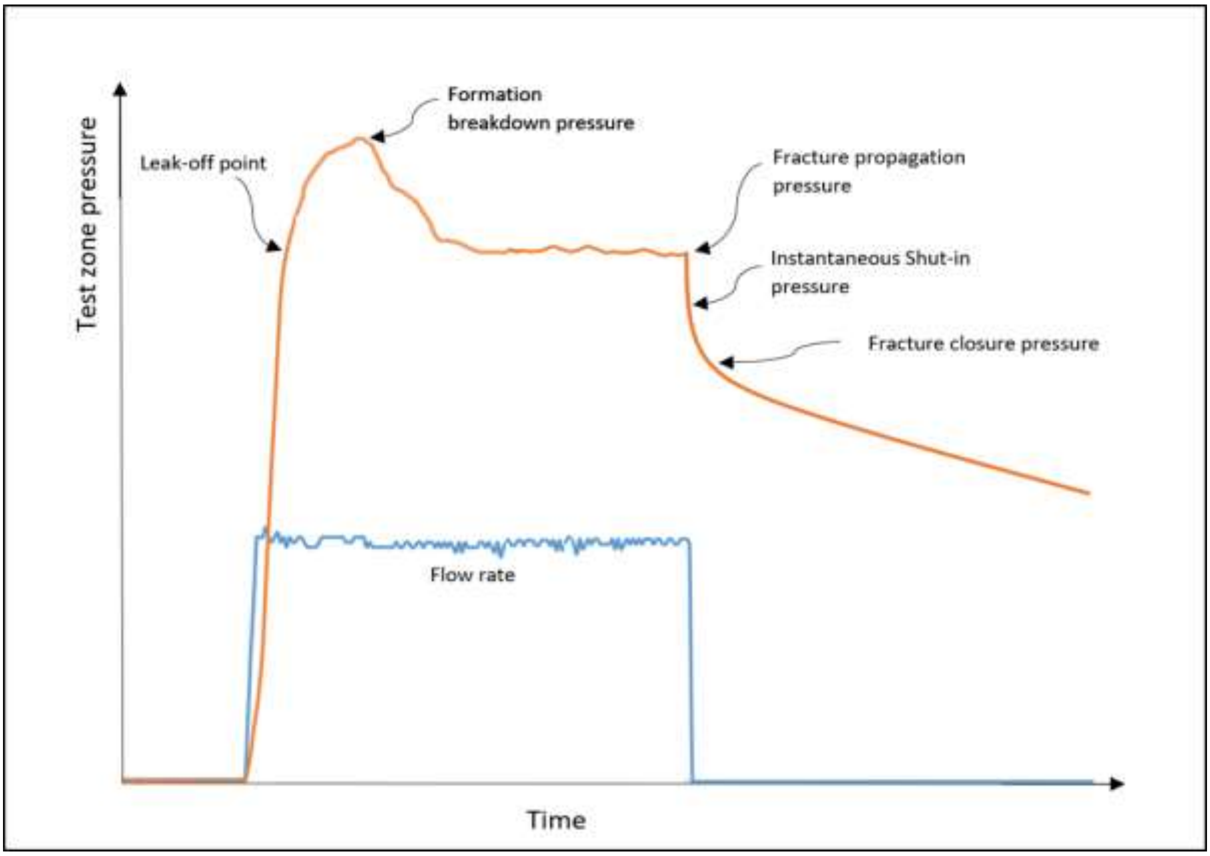

Figure 4. Typical hydrofracture flow and pressure plot.

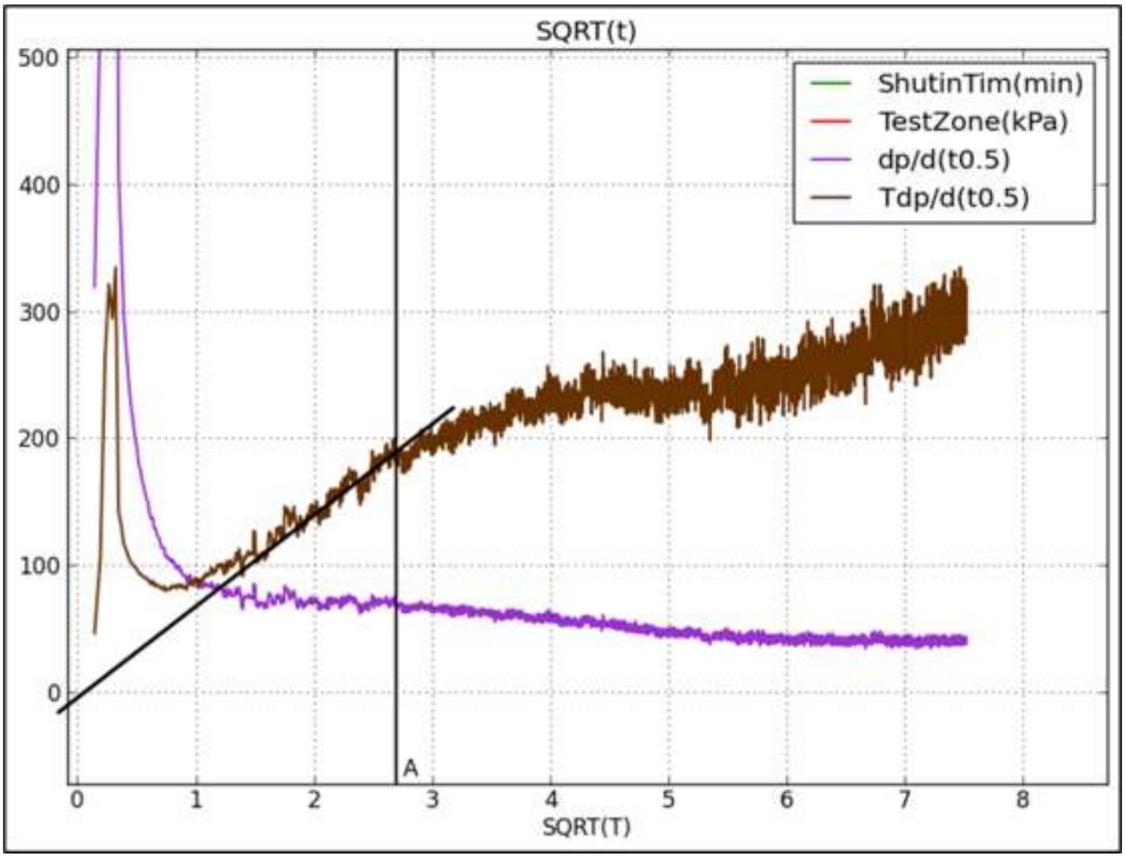

Figure 5. Square root plot of pressure after shut in – to determine closure pressure.

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The measurement of permeability from pressure decline after fracture closure is dependent on the time period being examined. In the short term the pressure decline is dominated by linear flow from the fracture. This is dependent on the fracture area, which is generally unknown, making definitive analysis of permeability impossible. In the longer term the pressure response is controlled more by radial flow and a permeability may be more reliably determined. This means that it is necessary to wait long enough after fracture closure if permeability measurement is required.

The use of inflatable packers to seal the hole has complications as it requires the sealing pressure of the packer on the borehole wall to exceed the fluid pressure in the test zone so as to avoid leakage around the packer. By definition the fracture will therefore be initiated by the packer. This effect can be minimised by keeping the packer scaling pressure just above the test zone pressure. This effect can be avoided by cementing a test pipe above a temporary seal in a borehole and fracturing through this. This however makes the subsequent measurement of fracture orientation practically impossible.

Another practical problem associated with hydrofracture is the pressure required to fracture it. Any system will, for hydrofracturing, need to have a pressure capability of 2.5 times the expected mean stress plus the tensile strength of the rock. If that stress is 60 MPa this means having about 170 MPa available. This is beyond the capacity of most packer systems and requires very high pressure pumps.

While most hydrofracture analysis is based on a constant rate injection this is seldom the case. Pressure builds up in the test zone and then the fracture opens with a sudden increase in flow. This flow increase is a better marker of fracture opening than a pressure rise rate change within the test zone.

If any stress orientation is required the fracture orientation at the borehole wall must be determined. It is usual practice to use an acoustic televiewer to check the test zone for the absence of fractures prior to testing and for fractures after testing. These are not always clearly visible. In the absence of an acoustic or optical televiewer the core can be examined so that pre-existing joints may be detected and avoided. An impression packer may be used after the test to detect the orientation of any fracture that is generated.

Hydrojacking

Hydrojacking is similar to hydrofracture except that a deliberate choice is made to open pre-existing joints within the rock mass. If a single joint set exists then these may be straddled by packers and opened in a similar manner to that used for hydrofracture. The fracture closure pressure deduced from the period after pumping ceases is an indication of the stress across the fracture plane.

If a multiple joint sets exist and if each of these could be individually straddled and tested, it would be theoretically possible to obtain the stress across each of these and thus build some elements of the stress tensor. This is practically impossible in most cases because it is seldom possible to straddle a single fracture or fracture set. In addition the hydrofracture fluid will propagate from one fracture set to another. This makes the analysis of the pressure decline for a unique fracture closure pressure difficult.

If multiple fractures are straddled and pressurised until an increase in flow rate indicates that fracture opening has occurred, then subsequent examination of the test zone by acoustic televiewer may sometimes reveal which fracture has opened. This is not always the case though.

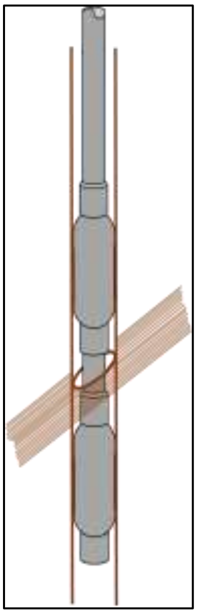

Figure 6. The concept of hydrojacking to open a fracture.

Sigra’s hydrofracture and hydrojacking tools

Sigra has a hydrofracture and hydrojacking system that maintains the packer pressure just above that required to prevent leakage around the packers. This minimises the likelihood of fracture initiation by the packers. This is a very important feature that is lacking in most hydrofracture systems. The Sigra system also uses flow change on hole pressurisation to detect the fracture opening pressure.

The current system is set up for operation with HRQ drill pipe for lower pressures (30 MPa with Sigra rod seals) or with CHD 76 drill pipe for pressures up to 40 MPa. Sigra have a diesel driven frac pump which will produce 40 MPa at a flow rate of 25 litres/minute.

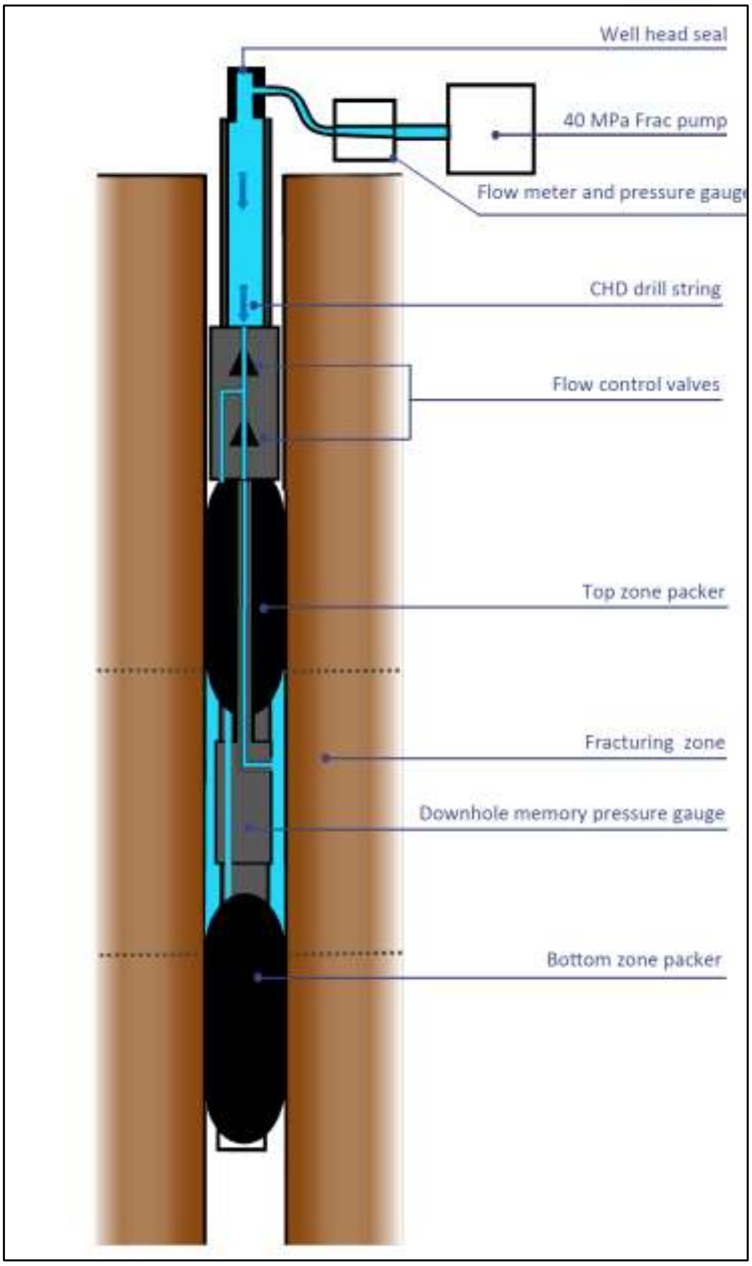

Figure 7. Diagrammatic indication of Sigra's hydrofracture tool.

Borehole Breakout

The process of drilling a hole creates a free face within the rock mass only confined by fluid pressure. It also causes a tangential stress concentration on the borehole wall.

If the tangential stress at the borehole wall exceeds the tangential unconfined rock strength then the rock will fail in compression. In an even stress field this may cause total failure around the hole wall. More usually, the stress field around the borehole is not even, and if the stress is high enough, it will cause a localised line of spalling along the length of the hole wall. This spalling is readily detected by the use of an acoustic televiewer. The width of the spall zone may be detected with some accuracy in fine to medium grained sedimentary material and less so in coarser sedimentary or igneous or metamorphic materials, which tend to break in a more jagged manner. This is shown in Figure 8. The depth of spalling can be measured with much less precision. The orientation of the spalled zone is perpendicular to that of the major stress perpendicular to the hole.

In some cases where there is an extreme stress difference perpendicular to the borehole a tensile stress may be induced in the wall of the hole that exceeds the tensile strength of the rock. This leads to a tensile fracture on each side of the hole in the direction of the major stress.

The analysis of borehole breakout on its own is limited. In the first instance, the equations of stress around a hole cannot be completely solved for a linearly elastic rock using borehole breakout information alone. This applies even if the rock strength perpendicular to the borehole is known. Generally it is not.

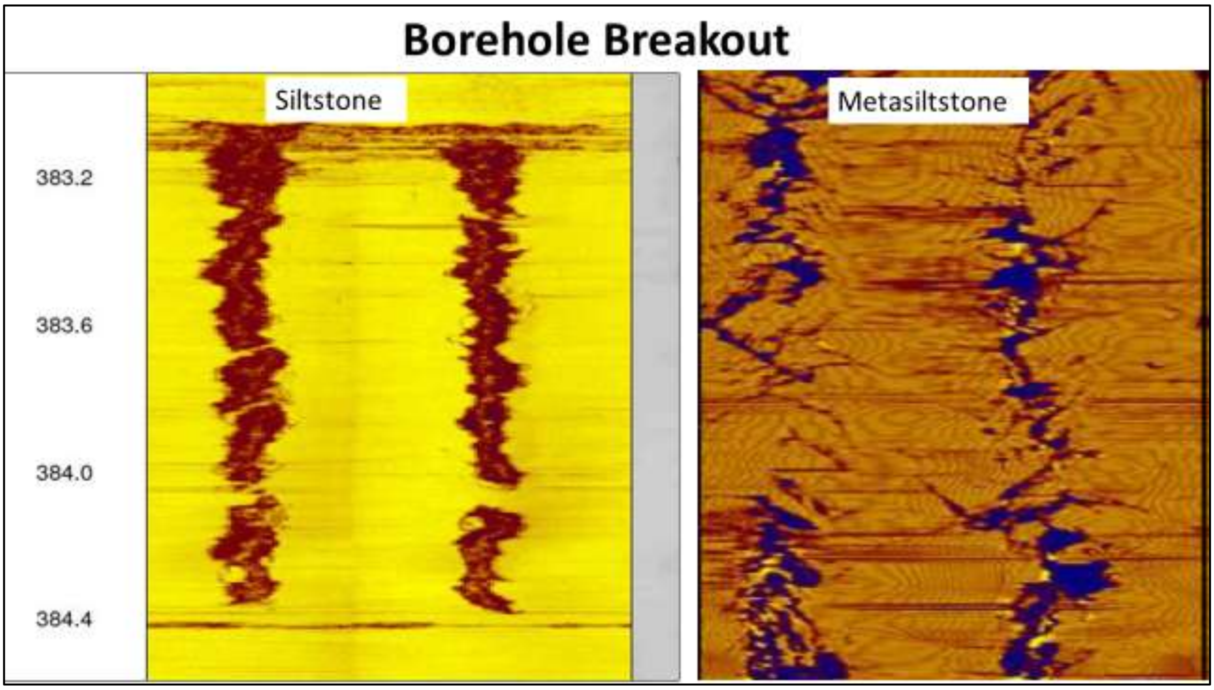

Figure 8. Acoustic televiewer images of borehole breakout in siltstone and in meta-siltstone.

Core Ovality

When core is cut it is relieved of stress and expands. In a normal coring operation core is reground by the inner gauge of the core bit causing it to lose some of this out of roundness. To avoid this Sigra provides core bits that expand internally. In addition they have created a tool to measure core ovality to two micron accuracy. In this the core is placed on rollers and rotated between two measuring arms. The major and minor diameters may be deduced from this measurement.

Simple elastic analysis can be used to determine the likely difference in the major and minor stresses perpendicular to the core.

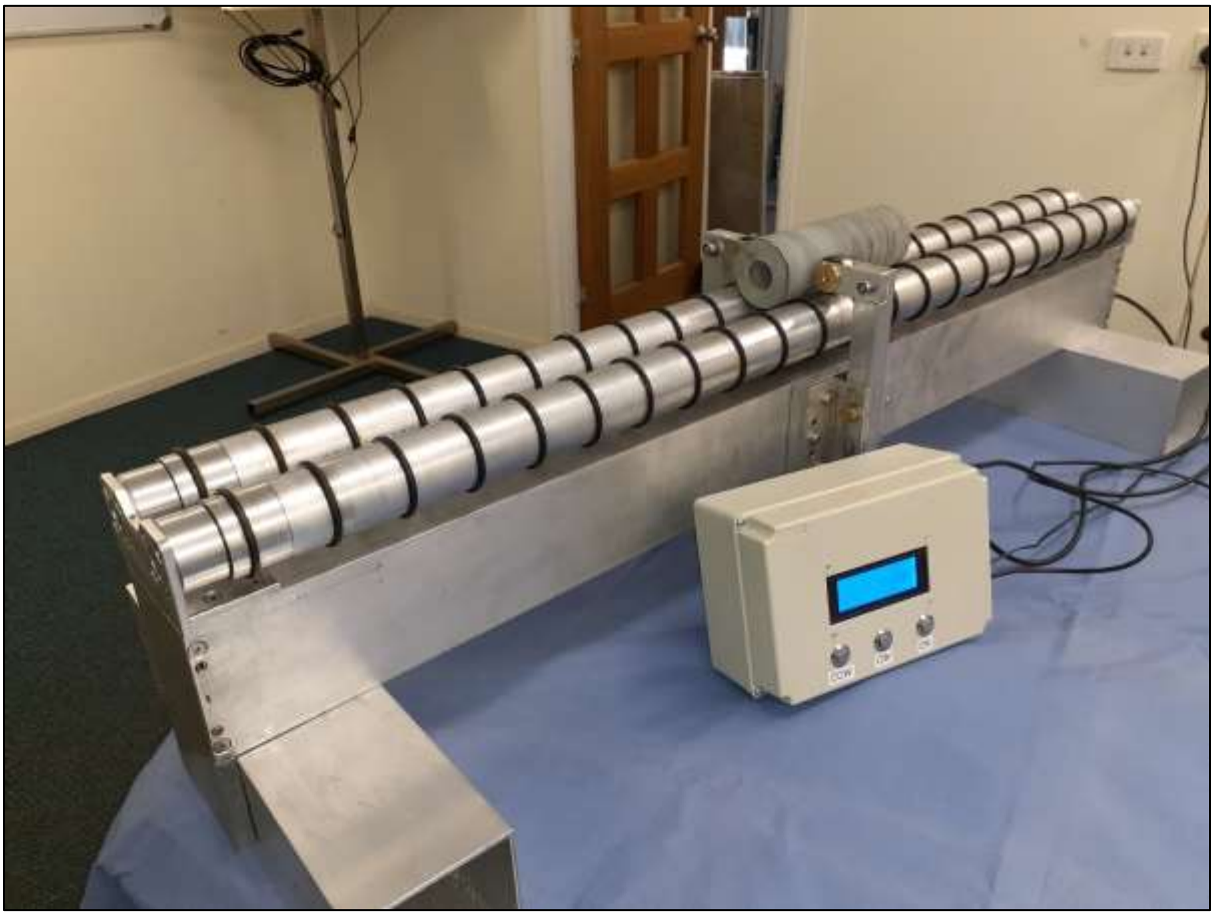

Figure 9. Core ovality test equipment.

Surface Overcoring

The measurement of stress at the surface of an opening in a rock mass, such as a tunnel wall, may be of considerable benefit. It will give an indication of what the stress is next to the opening. The method is more suitable for machine cut openings in rock than those cut by blasting, which probably suffer from blast induced fracturing.

Surface stress measurement is readily achieved by smoothing the rock surface with a diamond wheel and gluing a strain gauge rosette and temperature sensor to it. Once the temperature and strain readings have stabilised, the area is overcored to relieve the stress. This is conveniently done using a concrete core cutter. After overcoring the strain gauges and temperature sensors are re-connected and the temperature is allowed to stabilise. The strain difference between the pre-overcore and the overcore state is then measured and thermal effects subtracted. Using rock mechanical properties obtained from the core, the surface rock stress may be calculated.

COMMON FALLACIES IN THE MEASUREMENT OF ROCK STRESS

Rock stress distributions are complex. Different stiffness rocks will produce different stresses when strained by tectonic action, temperature change, diagenesis, metamorphism, faulting, folding or any of the multiple other changes that the rock mass is subject to. Because of all these effects the distribution of rock stress becomes more variable with complex geology.

Unfortunately, the days when geotechnical engineers thought of rock stress in terms of a unique far field stress for a site have not yet gone. Numerical modellers tend to like to believe in the concept of a unique far field stress because it simplifies their models. This approach is not appropriate.

Sigra still gets asked to undertake measurements outside potential mining areas so that the far field stress may be assessed away from workings or the ore body. This approach is less than ideal. While these measurements may be interesting, what is required are stress measurements in the zone where mining will take place.

WHICH ROCK STRESS MEASUREMENT SYSTEM TO USE?

The investment in the time and cost of rock stress measurement is frequently significant. Care needs to be taken to determine what is required and to maximise the amount of information that can acquired.

Rock stress information may be needed to determine elastic deformation around an opening, the interaction between a plastic and elastic zone, or to be sure that major failure will take place as in a goaf or block cave.

If we are considering a tunnel or shaft which should remain stable, then examining a borehole drilled in its alignment for breakout is a fairly good direct indicator of whether problems are likely to be encountered. This measurement is a direct assessment of the stress to strength ratio at the borehole wall, albeit for a circular opening. It avoids problems with trying to assess stress and rock properties separately.

From the acoustic televiewer image used to examine for breakout it would be normal to pick joints that intersect the hole. These may be used for stability analysis but may be chosen as locations for hydrojacking. In this case the hydrojacking results are directly applicable to the case where the hole is used to carry water at pressure, as in the headrace of a hydroelectric project. If the hydrojacking pressure is lower than the expected water pressure in the tunnel problems may be expected. Once again this is a direct assessment of whether a problem may exist in the constructed opening, without having to derive precise stresses or material properties.

Full stress measurement becomes more necessary where the opening is of complex shape or where rocks of varying properties exist. In this case the stress measurement needs to be associated with material properties so that it may be usefully used. This is the situation where numerical models are frequently used.

Stress measurement really falls into three categories. These are where the rock mass is highly jointed, where the rock mass is not jointed but breakout occurs at the borehole wall, and where the rock does not break within a borehole.

Jointed Rock

In the case where the rock is highly jointed, two practical options are to look for borehole breakout using an acoustic televiewer and to use hydrojacking. It is unlikely that any definitive stress value will be discerned from this but some approximate figures may be arrived at. The use of core ovality measurement in this situation may be useful but is as yet untried.

Unjointed Rock With Borehole Breakout

Where borehole breakout occurs and there is little jointing, the first approach would be to use an optical televiewer to determine the orientation and width of the breakout. It would be normal to augment this with hydrofracture to gain measurements of the minimum stress. If the minimum stress is known from hydrofracture, the borehole is in the same plane as this stress, and the uniaxial rock strength is known perpendicular to the hole, then with the benefit of breakout width it is possible to arrive at an approximate major stress. This is one of the approaches adopted by the petroleum industry to stress measurement. Usually rock strength is related to the sonic log velocity. This is a somewhat tenuous relationship. There are many other caveats related to the accuracy of stress measurement derived from this process, but some measurement is better than none.

In this case the only semi-continuous measurement comes from borehole breakout. It is possible to augment this with core ovality measurement.

Unjointed Rock Without Borehole Breakout

This situation is most suited to overcoring as a stress measurement system. Sigra provide two options, namely, the IST2D and IST3D overcore systems. While the IST3D may appear to be the best solution as it measures everything, it comes at a cost in time and money. It also places restrictions on the drilling fluid that may be used. Unless there is very good reason to believe that there are significant shear stresses in a plane between the vertical and horizontal, the IST2D system is probably the most useful. It certainly is where a number of measurements have to be made because of changing rock properties. Here its speed with which measurements are made is important.

The IST3D tool has particular use at great depth, where there is uncertainty in the product of vertical stress and Poisson’s ratio. Also, the tool has advantages in holes that are not vertical where the calculation of the stress in the axis of the borehole being a simple function of depth cannot be relied upon.

Point by point overcore measurements are just that. What is needed is some non-arbitrary basis for determining where the next overcore should be made. This can be chosen on changes in lithology. The core ovality measurement can be particularly useful in this instance. While it only enables the estimation of the difference in major and minor stresses that are perpendicular to the hole it does give an indication of where things change, and by inference where a new stress measurement should be made.

STRESS CHANGE MEASUREMENT

Frequently mining operations want to measure stress change as the mining process proceeds. This is generally required at the end of a borehole and may be in a pillar or above it. Ideally the stress at the location is measured first so that the stress change may be referenced to an initial stress.

If no borehole breakout is expected then an overcore can be undertaken to measure the initial stress level. The hole can be extended and another overcore cell (IST3D) can be glued in place with an attached cable. This can be used to monitor the changes in strain on the wall of the cone of rock in which the cell is installed. If the rock properties can be estimated this can be converted to stress changes. If the cone of rock into which the IST3D cell is attached starts to behave in-elastically the results will be erroneous. This occurs because the IST3D cell is inherently soft and will not support the hole wall.

In the case where breakout may occur, or where borehole breakout is present from the initial drilling of the hole, the only solution is to install a pressure cemented cell. This cell is stiff, comprising a strain gauged thick steel tube which is cemented into the borehole under pressure. The cement grout used is a portland cement that contains a post initial set expansion agent that makes the grout grow. This pre-loads the cell so permitting the measurement of stress reduction. It also pre-loads the borehole wall to resist wall failure. The pressure cementing is designed to penetrate the breakout fracture zone. The expansion of the cement grout takes about one month, during which time slow changes in stress may be lost against a background of cement growth.