The Fundamentals of Stress Measurement in Rock

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ABSTRACT: The stresses that exist in a rock mass may be important for the design of any structure within it. Where the stress to strength ratio within the rock mass becomes high, the measurement of stress is particularly important, and the stress measurement becomes more difficult. The methods of measurement are divided into two fundamental groups – for those where the rock has or will fail around the borehole and those where the rock remains intact. There are a number of techniques that may be used, some more precise than others. Because of the variability of stress due to different rock stiffnesses and structure, the process of stress measurement should include both precise measurements and measurements that give a more continuous indication of stress. Finally, the paper discusses the concept of effective stress in rock and its determination.

KEYWORDS: Rock stress measurement, overcoring, hydrofracture, breakout, ovality.

1 INTRODUCTION.

Rock stress measurement must be divided into techniques that can be used in intact rock and those that are used in rock that has failed or will fail during the drilling of the borehole used to measure stress within it. All techniques have their limitations and most interpretations of rock stress require detailed analysis of the result itself and what it means in terms of the stress within the overall rock mass. The prime techniques that can be used are listed in Table 1 along with their applicability.

Hydrofracture and hydrojacking may, in the right circumstances, both deliver a minimum stress result directly from fluid pressure measurement without any knowledge of the rock type being required for the analysis process. Analysis of hydrofracture to obtain the major stress orthogonal to the borehole does however require the rock to be linearly elastic.

Overcoring requires both measurement of deformation and the rock's elastic behaviour, it can however yield a total local stress tensor under the right circumstances.

Core ovality can yield a major – minor stress difference orthogonal to the hole, but like overcoring analysis, requires the rock's elastic properties to be known.

The analysis of borehole breakout is based on elastic behaviour to failure around a borehole followed by compressive failure of the hole wall. This is a complex process and one that cannot be satisfactorily completed on the basis of breakout information alone.

These four measurement techniques are reasonably direct, being based on pressure, deformation and rock property determination.

While the last three techniques in Table 1 are shown as providing a source of stress measurement under all three situations considered methods in the process by which they accomplish this are much less direct than the first four as there is no direct link between the stress level and elastic deformation or fluid pressure. They might be considered very indirect and for this reason no attempt is made to present stress analysis based on them. The Kaiser Effect is one where a material begins to emit small level seismic noise when it is loaded beyond its previous stress level. Deformation Rate Analysis (DRA) involves the measurement of the incremental change in strain per incremental change in stress between steps in a sawtooth cyclic loading cycle. Anelastic strain recovery refers to the technique of measuring the deformation of a sample as soon as it reaches surface and relating this to the state of stress in the core via a viscous deformation model.

If the drilling of the hole does not lead to any form of rock failure that can be detected by such a device as an acoustic televiewer then it is possible to make the deduction that the stresses in the rock at the borehole wall are less than the strength of the rock. This is useful in itself and particularly if an opening of similar geometry to the borehole, such as a shaft, is going to be developed in the direction of the borehole. Where an opening is to be developed in a different direction or is of a more complex shape then the information obtained from examining the borehole wall alone is insufficient for design purposes. In this case the most useful method is usually overcoring.

Table 1. Some methods of rock stress determination

STRESS MEASUREMENT TECHNIQUE	No Borehole Wall Failure	Borehole Wall Failure	Fractured Rock Mass	Legend	
				Good	
Hydrofracture				OK	
Hydrojacking				Useful	
Overcoring				Indirect	
Borehole Breakout				Inapplicable	
Core Ovality					
Kaiser Effect					
Deformation Rate Analysis					
Anelastic Strain Recovery					

2 HYDROFRACTURING

Hydrofracturing is another method by which stress may be determined. It is essentially a biaxial stress measurement with significant limitations. Figure 1 shows hydrofracture in concept, along with one of the potential problems, in this case the possibility of the hydrofracture being captured by pre-existing joints.

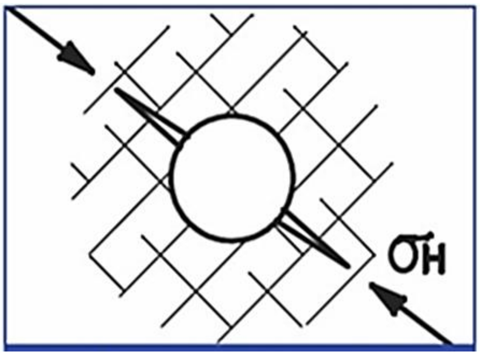

Figure 1. Hydrofracture stress measurement

In the form normally adopted hydrofracture involves sealing a section of borehole with inflatable packers and pressurising the zone in between until the rock fractures. Pumping is maintained for a period, then the test zone is shut in and the pressure is permitted to decline. Careful analysis of the pressure decline enables the fracture closure pressure to be determined (Barree, & Barree, 2007). The zone may then be repressured to re-open the fracture and the process repeated.

Figure 2 shows a pressure trace within the test zone of a hydrofracture operation. Pumping starts and the pressure rises to breakdown pressure when the fracture propagates. Pumping is then stopped and the test zone is shut in. The fluid leaks off into the rock mass and is accompanied by a pressure decline. The shape of this decline changes when the sides of the fracture touch. This is known as the fracture closure pressure and, in the right conditions, corresponds to the minor stress.

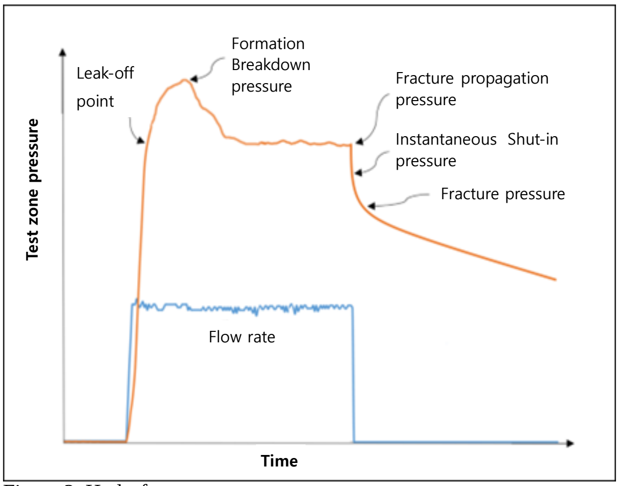

Figure 2. Hydrofracture pressure response

While ideally there is supposed to be a single closure pressure corresponding to the minimum stress in the rock, a rotating fracture or a fracture that is captured by multiple planes of weakness shows multiple closure pressures, making interpretation difficult.

The interpretation of the re-opening pressure to enable the calculation of the major stress requires that the fracture closes perfectly, that the minimum stress has been determined accurately from the closure pressure and that the rock behaves in a linear elastic manner. To these need to be added the condition that the axis of the borehole should be aligned perpendicular to the plane on which the major stress acts. Despite all of these significant limitations, hydrofracture is sometimes the only option, especially where borehole breakout has occurred. Its use in conjunction with borehole breakout information enables an indication of major and minor stresses and is the method most frequently used by the oil and gas industry to gain information on stress in the sedimentary sequences that they encounter.

The hydrofracture process has some other limitations. The first of these is that the packers must apply a higher pressure to the borehole wall than that of the test zone fluid or leakage would occur past them. This is the scaling pressure. This has the consequence that packers may, and frequently do, initiate the fracture. Keeping the pressure that the packer applies to the borehole wall just above test zone pressure is essential to minimise this potential problem. The second limitation is that there is no control over the direction of fracture propagation. The fluid pressure in the test zone will act on the wall of the hole and fracture initiation can be expected to be in a tensile mode approximately in the axis of the hole. It will however rotate to be perpendicular to the direction of minimum stress unless captured by pre-existing structures that require less pressure to open them than that required to overcome the tensile stress of the rock.

3 HYDROJACKING

A variant of hydrofracture is hydrojacking. This is used to assess the stress in jointed rock. It involves straddling a joint with packers and pressurising it until the joint opens. After a flow period, the test zone is shut in and the joint is allowed to close and the closure pressure determined in a similar manner to that used in hydrofracture to provide information on the stress normal to the joint. Practically there are many limitations. The most usual being that it is not possible to isolate a single joint to be tested within the hole. Even if this is possible there is in most cases a high probability that the joint will connect to others so that during leak-off multiple closures occur. This gives an interpretational problem in determining the minimum stress.

4 OVERCORING

Overcoring is a process in which some form of smaller pilot hole or cone is drilled ahead of a core hole and a device to measure its diameter or the strain on the wall of the hole is installed. Coring then takes place over the top of this, thus relieving the stress in the pilot hole or cone. The change in strain or dimension of the pilot hole or cone is monitored during the overcore process. The analysis of stress is based upon this deformation and the elastic properties of the rock.

The USBM overcore device (Obert et al. 1962) enables the measurement of a change in pilot hole diameter during overcoring. Provided an assumption is made about the axial stress, the two dimensional stress field orthogonal to the borehole may be calculated. The next important development in this area was by Leeman (1969) who developed an end of hole device, known as a doorstopper, and more importantly a three dimensional device. The latter was particularly useful as it provided a good degree of redundancy in measurements. Both of these devices used strain gauges which were adhered to rock. Neither enabled the measurement of strain during the overcoring process. This was achieved by the CSIRO HI Cell (Wortoniki & Walton, 1976) which could be monitored via cable during overcoring. However, this instrument lacks direct contact between the strain gauges and the rock, and under high strains can suffer separation between its glued in place epoxy sleeve and the rock. This was addressed by Mills and Pender (1986) who used a device with strain gauges fixed to an expanding packer.

In 1996 Sigra developed its IST2D two dimensional stress measurement tool. This has some similarity to the USBM overcore device but can be deployed up to 2000 m depth as part of the Boart Longyear HQ coring system. Its limitation is the lack of axial stress measurement. This is not a problem if the hole is vertical and overburden stress can be assumed. It also has the advantage of speed as a measurement can be made at 400 m depth with about a 2 ½ hour interruption to coring.

As a development of the IST2D tool, the IST3D was developed and first deployed in 2022. Figures 3 to 6 show the process of overcoring using the Sigra IST3D tool. This tool is also designed to work with the HQ, HQ-3 and HQU coring systems. An NQ sized version has also been built. The overcore system could no doubt be made to work with other wireline coring methods.

Step 1 shows the breaking off of the core which is then withdrawn. The countersink tool is then pumped into place. Step 2 shows the countersink being drilled. The countersink tool is then removed on wireline and the pilot hole and cone drill is pumped into place in the core barrel. Step 3 shows the pilot and cone hole being drilled. Step 4 shows the stress measurement tool being pumped into the hole. Step 5 shows the IST3D stress tool being pumped into place with glue being exuded around the cone which is fitted with strain gauges. The glue is permitted to set and the setting tool is removed by the wireline. Step 6 shows the core barrel pulled back so that the magnetometers can work free of magnetic influence. Step 7 shows overcoring of the stress measurement tool. The core and tool are then withdrawn by the normal wireline process. The tool is then downloaded of its strain change information as shown in step 8. The core is kept so that its elastic properties may be determined in the laboratory.

The IST3D tool has 21 strain gauges on the cone. These provide redundancy as theoretically only six measurements are required to arrive at the stress tensor. Figure 7 shows the strain change of circumferential gauges with overcoring.

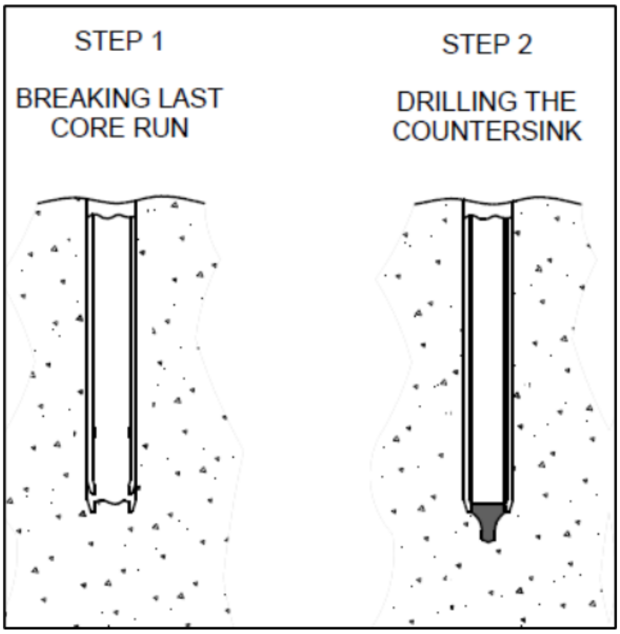

Figure 3. IST3D operation steps 1 and 2.

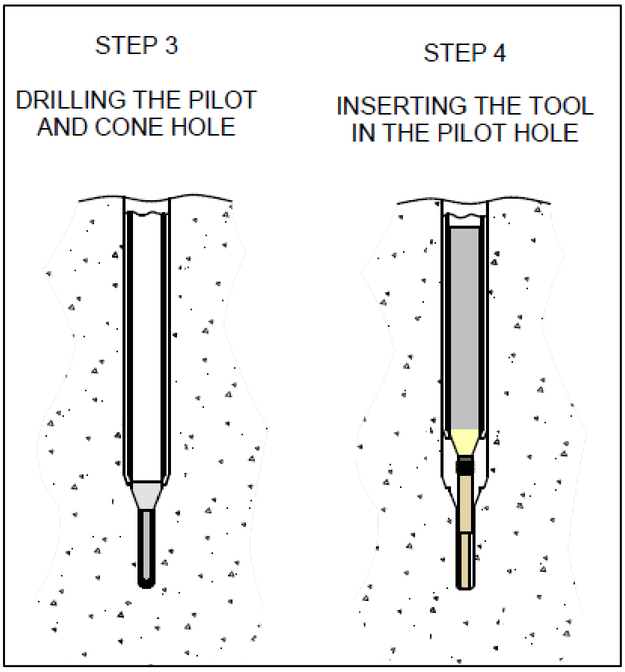

Figure 4. IST3D operation steps 3 and 4.

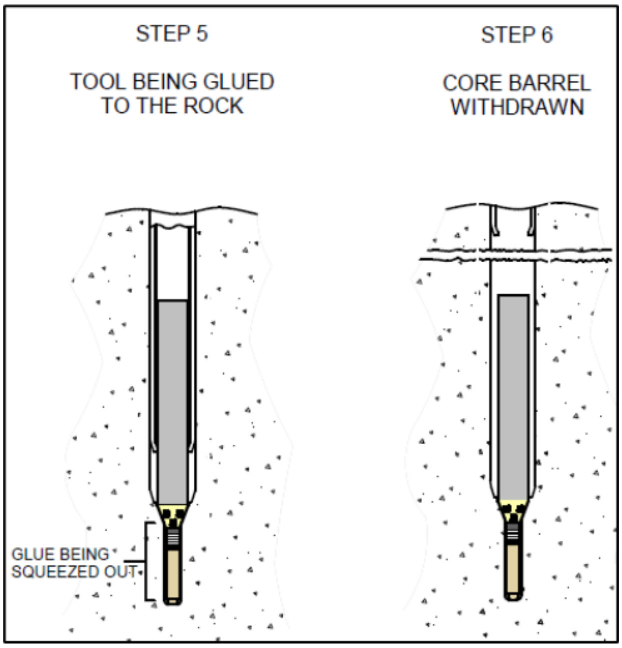

Figure 5. IST3D operation steps 5 and 6.

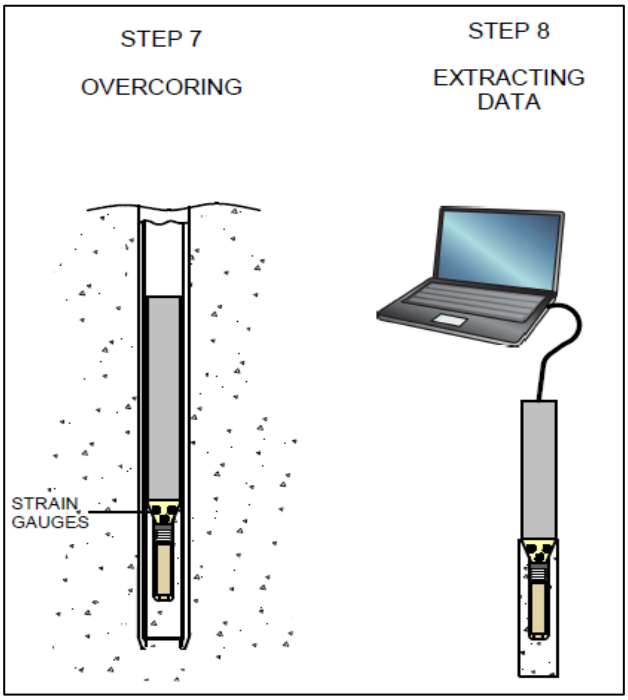

Figure 6. IST3D operation steps 6 and 7.

It is possible to analyse overcores that have been conducted in rocks that are non-linearly elastic or anisotropic provided they are reasonably homogeneous and do not behave in a plastic manner. Table 2 shows the types of analyses that are required for the various levels of elastic behaviour. Where finite element models are required the workload in analysing the test increases significantly. Whether this work is justified will depend on the situation. What is always justified though is proper testing to determine the rock properties. Simple uniaxial tests are not usually adequate and neither is biaxial reloading in the field. Rock properties are best determined by loading either the overcore itself or a similar piece of rock in a triaxial cell using multiple combinations of axial and confining stress to determine the rock's elastic properties (Gray et al. 2018a).

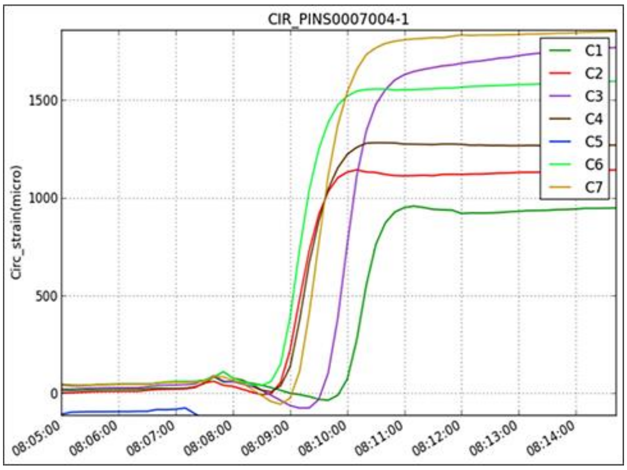

Figure 7. Strain changes in overcoring circumferential gauges on IST3D.

Table 2. Methods of overcore analysis.

Rock Properties	Isotropic	Axi-symmetric anisotropic	Non axi - symmetric anisotropic	Inhomo-geneous
Linearly Elastic	Analytical	Analytical	Finite Element	Approximate Analytical
Non-linear elastic	Finite Element	Finite Element	Finite Element	Practically Impossible
Inelastic	Practically Impossible			

5. BOREHOLE BREAKOUT

Borehole breakout involves examining an acoustic televiewer image for compressive failure of the borehole wall. This is an indication that the stress at the borehole wall is greater than the strength of the rock perpendicular to the hole axis. While this can be used to give a direction of the major stress, it does not enable the major and minor stresses to be determined. This is because the only information that is sometimes reliable is a measurement of the width of the breakout crush zone and this is inadequate to solve for the major and the minor stress perpendicular to the hole axis.

Measurement of breakout depth has been used as part of the breakout stress measurement process but is considered to be unreliable.

The other complication is that the compressive strength of the rock perpendicular to the hole wall is seldom known. If the minor stress is known from some other measurement, such as hydrofracture, or the difference between the major and minor stresses is known from core ovality measurement then a solution for the major stress may be approximated if the rock properties are adequately known.

Figure 8 shows an acoustic televiewer image of breakout in a siltstone. Figure 9 shows breakout in a metasiltstone. The breakout width in the siltstone can be approximated while that in the metasediment cannot. The former may therefore be used in the determination of stress values while the latter may not. Unless marginal, breakout occurs on opposite sides of, and in line with, the axis of the hole. It may sometimes merge with pre-existing joints within the rock mass making identification difficult. This is particularly the case where a joint passes through the centre of the borehole.

In some cases boreholes suffer tensile failure. These are caused by a combination of rock stresses, the poroelastic effects of fluid pressure within the rock mass and the drilling mud pressure within the borehole. These are in effect hydrofractures that occur during drilling. They are indicators of stress direction and may be used to provide a boundary on rock stress estimation.

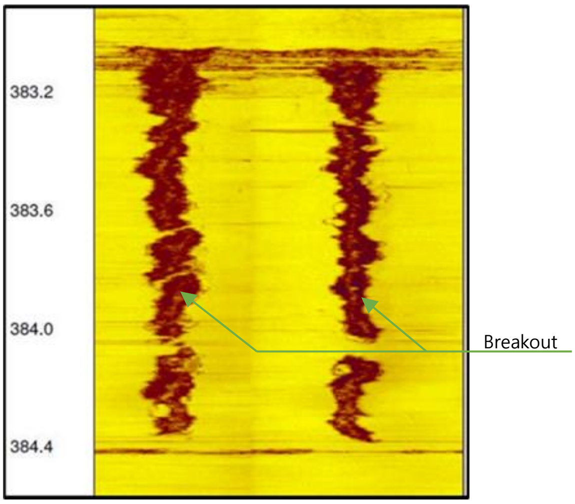

Figure 8. ATV view of breakout in a siltstone.

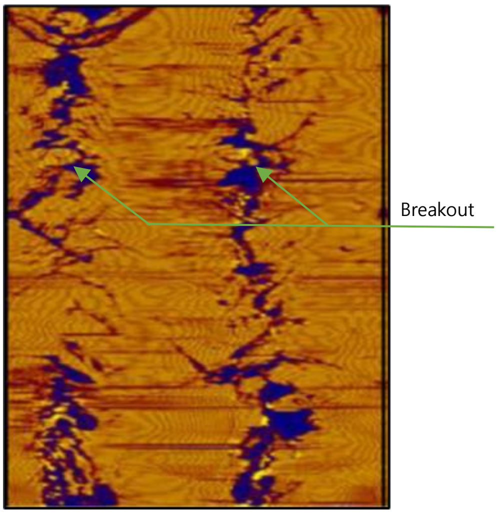

Figure 9. ATV view of breakout in a metasiltstone.

6 CORE OVALITY

A recent development, is the use of core ovality as a measurement. This works because the core expands elastically as it is cut. Proper core bit design with an internal expanding taper should be used to avoid core regrinding within the bit.

Core ovality is referred to as Diametrical Core Deformation Analysis (DCDA) in the seismology and geothermal power sectors. Following the publication of theory in Japan by Funato and Ito (2013), who named it DCDA, the concept was then applied in a seismological study relating to earthquake stress measurement in a 2,000 m borehole along the Japan Median Tectonic Line active fault zone where it was compared with established borehole breakout and hydraulic fracturing methods (Onishi et al. 2016). In South Korea, DCDA was compared with other methods in a 4,200 m deep hole in granodiorite as part of a geothermal power project. Kim et al (2020) reported that DCDA stress measurements were validated by the traditional methods but at a reduced cost.

Figure 10 shows the Sigra system of core ovality equipment. A core sample is placed on the rollers and is rotated over 360° and the diameter measured to micron accuracy at 20° increments. Figure 11 shows five traces of core diameter measurement difference with an average sinusoid fitted to these using a least squares process. The difference in mean diameter can be used along with the Young's modulus and Poisson's ratio to arrive at a difference between the major and minor stress orthogonal to the axis of the core. Measurements may be made at metre intervals, each test taking about 2 minutes to conduct and record. The orientation of the measurements is obtained by comparison of structural features in the core with those determined from the ATV scan.

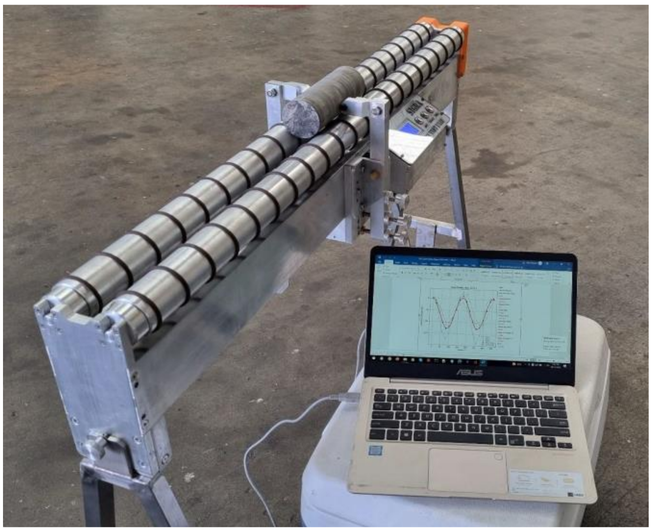

Figure 10. Core ovality measurement equipment.

This near continuous measurement allows the determination of where the stress regime changes, and it can be used as an indicator of where a more precise stress measurement may be made, such as an overcore. It may also be used in combination with the minimum stress from hydrofracture closure to determine the major stress, or more usefully with information on borehole breakout, to determine major and minor stresses orthogonal to the borehole. The system has given very similar values of stress difference to that obtained using the Sigra IST2D overcore tool in both a semi metamorphosed mudstone and in fine grained sandstone.

A key to the success of the core ovality process is that the core bit does not regrind the core behind the face of the drill bit. This can be achieved by having a bit with an internally expanding cone so this does not occur.

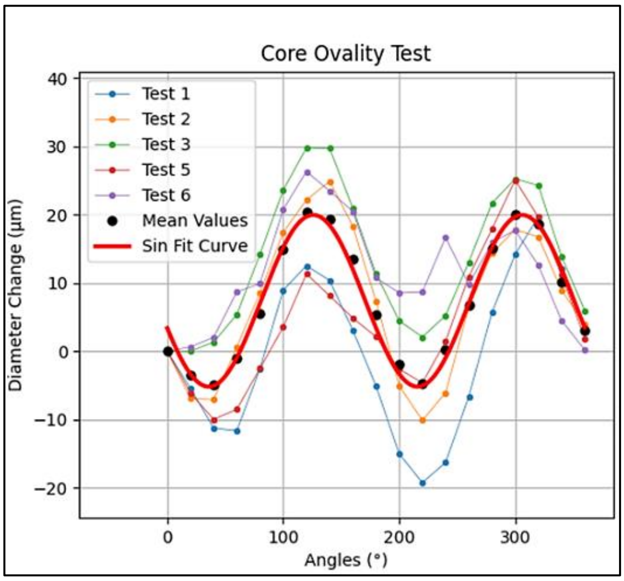

Figure 11. Traces in μm from core ovality testing.

7 EFFECTIVE STRESS

Effective stress in rock may be thought of in several ways. The most commonly taught is that of fluid pressure acting in a joint. To be able to analyse this, the area of the joint that is open to the effect of fluid pressure needs to be known, along with its orientation and pressure. Dealing with multiple joint sets can be quite problematic as a lot of information needs to be gathered. This approach might be used in the limit state analysis of a fractured rock mass.

Another way to consider effective stress is to see how fluid pressure changes the dimensions of a block subject to internal pressure. This is the poroelastic approach described originally by Biot & Willis (1957). A measurement process to determine poroelastic behaviour is described by Gray et al. (2018a). It involves fitting a strain gauged rock core in a triaxial rig and measuring its axial and transverse Young's moduli and Poisson's ratios at multiple stress states. At each stress state gas is injected into the sample and then released. The change in strain of the core with this fluid pressure is measured and related through the established elastic parameters to a change in the effective stress. A second order tensor of components that are less than unity can be developed to describe the effect of fluid pressure on effective stress. This tensor only has components on the main diagonal.

The more detailed description of work on coals Gray et al. (2018b) suggests that its anisotropic poroelastic behaviour can be related to the microfracturing within the coal. Some of the fractures of the coal apparently close and seal to gas entry at high enough stress. The question may therefore be raised as to whether the behaviour of rock containing fluids at pressure is really dependent on scale. Does a large fractured rock mass show poroelastic, or even poroplastic behaviour when considered on a large enough scale?

8 STRESS DISTRIBUTIONS

The distribution of stress in a rock mass needs to be considered for any excavation design within that rock. The stress measurements that have been taken need to have some sort of model fitted to them to enable interpolation between measurements. This usually requires some understanding of the geology and sequential loading of the rock.

The tectonic strain model has been found to be particularly useful in sedimentary strata (Gray, 2000). In this the horizontal stress generated by vertical loading in a zero lateral strain environment is subtracted from the measured horizontal stresses. The remaining stresses are considered to be caused by tectonic strain. The tectonic strains have been found to be relatively even in many cases where the stresses vary widely because of the differing rock stiffnesses. Having relatively even or monotonically changing tectonic strains provides a first estimate of the distribution of stress in such rock masses. Where faults exist the tectonic strains change dramatically (Gray et al. 2013). Where faults do not daylight, stress concentrations can be expected at the fault tips. Disconformities also lead to changes in the tectonic strain.

Where complex igneous and metamorphic rock masses exist, the stresses can be expected to be more complex than a simple tectonic strain model can predict. Depending on the scale of the planned excavation, it may be necessary to build a historic model of deformation within the rock mass and to model it using a finite element or some similar approach so as to obtain fits with measured data and provide a basis for interpolation.

9 CONCLUSIONS

The measurement of stress in rock can be difficult. It requires the choice of the right methods for the rock and stress condition. The types of measurement are divided by whether a borehole in the rock will remain intact, whether it will fail by breakout or drilling induced tensile fracture and thirdly whether the rock mass has already failed and is therefore full of joints.

The only method that will deliver a full stress tensor is overcoring with a three dimensional overcore cell. This requires the rock to remain elastic through the process.

Hydrofracture can be used in this unfractured rock, but can only reliably return the minimum stress. In some cases an indication of the major stress may be found from fracture reopening. For this to be valid the rock must behave elastically and the fracture must close perfectly, something that seldom occurs. The minimum stress may be determined from hydrofracture in rock which does not behave elastically.

If the rock breaks around the borehole, then borehole breakout provides a direct indication of the stress to rock strength at the wall of the hole and a round tunnel of similar orientation. Breakout width information may be combined with the minimum stress determined by hydrofracture and an estimate of rock strength so that some approximate value of the major stress may be gained. Hydrofracturing in boreholes that show significant breakout is however difficult as leakage between the packer and the breakout zone is likely to occur. In addition, packer damage may take place.

Where the rock mass contains multiple joints, the only realistic measurement that may be conducted is hydrojacking, which will return some idea of the minimum stress on the joints that are intersected by the fracture fluid.

The core ovality method presented can provide near continuous measurement of the major-minor stress difference perpendicular to core. This is very useful and can be used to detect a change in stress regime at the drill site indicating that an overcore or other stress measurement should be undertaken. It may also be used with borehole breakout to provide a major and minor stress values orthogonal to the hole. However any measurement based on breakout requires knowledge of the rock strength perpendicular to the borehole. This is difficult to obtain.

In any serious excavation process it is necessary to interpret stress measurements with some model. This may be a simple tectonic strain model or a more complex one should that be required.

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