STRESS MEASUREMENT: THE GRC PERSPECTIVE

*N. Bahrani[1] and S. Yong[1] and B. Valley[1&2] and S. Maloney[1]

[1]*Geomechanics Research Centre (GRC), MIRARCO – Mining Innovation*
Laurentian University, 935 Ramsey Lake Road
Sudbury, ON, Canada P3E 2C6
(Corresponding author: nbahrani@mirarco.org)*

[2]*Department of Earth Sciences, ETH Zürich, Zürich, Switzerland*

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ABSTRACT

Knowledge of the state of stress in the Earth's crust is very important to the safe and efficient development of underground excavations in mining and civil engineering projects. A number of methods have been developed over the past 40 years to assess the stress field in the rock mass. These range from local estimates derived from compilation of regional stress databases to back-analysis of field observations to dedicated in situ measurements. The Geomechanics Research Centre (GRC) at MIRARCO has a long history of undertaking in situ stress characterization and measurement. In this paper, the stress measurement techniques used by the GRC, including overcoring and undercoring in addition to borehole breakout back-analysis, are briefly reviewed. The limitations and application of each technique for different ground conditions and the challenges involved during the field work and in interpretation of the results are discussed. A successful stress measurement campaign is not limited to acquiring valid local measurement, but must include a careful interpretation and integration of the measurement with other geological and geotechnical context information. Based on our experience, it is suggested that all available stress indicators and data are combined and integrated with the local geological and geomechanical conditions to derive a consistent stress characterization for a given site.

KEYWORDS

Stress measurement, overcoring, borehole breakout, under excavation technique

INTRODUCTION

The in situ stress state, described by the magnitudes and orientations of the principal stresses, is a crucial design parameter for the construction of underground infrastructure such as tunnels, pillars and abutments. In highly stressed environments, the ratio of the strength of the rock mass to the in situ stress state is usually used as a simple index for stability analysis and support design. Incorrect estimation of this parameter can lead to costly errors at any of the various design stages of underground workings. Furthermore, the importance of the knowledge of this parameter becomes more critical with increasing excavation depth and corresponding in situ stress magnitudes.

Over that last two decades, the Geomechanics Research Centre (GRC) has been involved in determining the state of in situ stress using various methods for different mining and civil engineering projects. These methods range from small scale strain relief and back analysis techniques, such as overcoring and borehole breakout back-analysis, to large scale back-analyses, such as those employed in the under-excavation technique. In this paper, these methods are reviewed and the advantages and disadvantages of each under different conditions, based on the experience gained by the GRC, are discussed.

STRESS MEASUREMENT TECHNIQUES

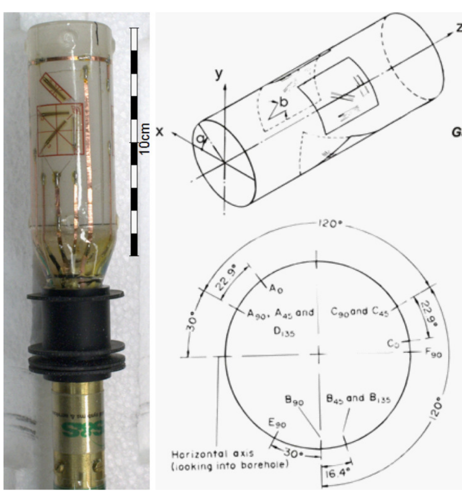
Overcoring Techniques

Overcoring is one of several relief methods that entail monitoring deformations or displacements as a volume of rock is partially or wholly isolated from the surrounding rock mass. There are a number of relief methods that can be applied at surface or in boreholes (e.g., see Chapter 5 in Amadei and Stephansson, 1997); in this paper, the focus is on the use of the thin-walled Commonwealth Scientific and Industrial Research Organisation (CSIRO) hollow inclusion (HI) cell in boreholes.

The CSIRO HI cell (Worotnicki and Walton, 1976) is a well known instrument that has been used in multiple rock types in both the mining and civil sectors since its introduction. The thin-walled version was developed to minimize separation of the cell from the rock caused by interface stresses or when good bond is difficult to achieve (Worotnicki, 1993). The cell typically used by GRC is the 12-gauge version with thermistor (Figure 1), which consists of three strain rosettes and three individual strain gauges fully embedded in an epoxy resin ensuring that performance is not affected by moisture or dust. Connected to the strain gauge leads is a shielded multi-strand cable, which allows for continuous recording during overcoring: an essential requirement for assessing the integrity of the cell's output.

Successful interpretation of the results depends greatly on the field execution of both the drilling and data acquisition. The overcoring procedure involves five basic steps: 1) drilling an HQ (nominal diameter of 96 mm) access hole to the requisite depth, 2) advancing and cleaning an EX (nominal diameter of 38 mm) pilot hole, 3) preparation and installation of the stress cell, 4) overcoring the pilot hole with a thin-walled HQ core-barrel while continuously recording the strain response, and 5) testing the recovered overcore in a biaxial pressure chamber. A more detailed description of the overcoring procedure can be found in the ISRM Suggested Methods (Sjoberg et al., 2003).

In addition to meeting specific project objectives, site selection for the underground measurements must consider the homogeneity of the rock mass (i.e., is volume of similar character being sampled?) and the distance of the specific measurement locations relative to existing openings and geological features. Measurements should be made at least one and one-half excavation diameter(s) away from opening boundaries to minimize excavation-induced effects. The test location should also be far from stress perturbing structures such as faults and dykes (unless this is part of the project objective). Lastly, the location must enable recovery of a sufficiently intact length of overcore. This last point is often a critical limitation as it depends greatly on the spacing and orientation of joints and/or the likelihood of disking in high stress environments.



Gauge No.	*Position*	*Gauge I.D.*	a°	b°
1	A (axial)	A_0	323	0
2	A (circ.)	A_{90}	300	90
3	A (diag.)	A_{45}	300	45
4	B (diag.)	B_{45}	163.5	45
5	B (diag.)	B_{135}	163.5	135
6	B (circ.)	B_{90}	180	90
7	C (axial)	C_0	83	0
8	C (circ.)	C_{90}	60	90
9	C (diag.)	C_{45}	60	45
10	D (diag.)	D_{135}	300	135
11	E (circ.)	E_{90}	210	90
12	F (circ.)	F_{90}	90	90

Figure 1 – CSIRO HI thin-walled 12-gauge cell.

Observation of core from drilling of the access hole allows for assessment of jointing in terms of spacing and orientation and homogeneity of the rock volume. Testing in a minimum of two boreholes, with two to three successful measurements in each borehole, constitutes sound practice due to the local stress variability that is inherent to any rock mass. The boreholes should be drilled at a maximum practicable angle to each other; this captures the greatest volume, allows for an internal cross check of the measurement reliability, in addition to improving and balancing measurement accuracy of all stress components (Worotnicki, 1993).

It is also important that the stress cell be positioned to avoid end effects from both the access and pilot holes (e.g., no closer than five respective radii from either end); inversion of the stress tensor is based on the assumption of an infinite hole. In addition, the cell should be located in a homogeneous section due to the assumption of a homogeneous and linearly elastic medium. Careful selection of the test interval also provides greater likelihood that recovery of a sufficiently intact length of overcore for testing in the biaxial chamber can be achieved (Figure 2). Elastic properties required for computation of the stress tensor can be ascertained from reloading and unloading the overcore in a biaxial pressure chamber immediately following recovery; later testing in the laboratory may be compromised by moisture effects on the epoxy resin, time-dependent processes and damage during transport. Biaxial testing can also be used to assess conformance with the assumptions of isotropy and linear elasticity.

An important advantage of this technique is the capability of determining the entire stress tensor in a single measurement. Use of the 12-gauge cell provides measurement redundancy (since only six unknowns require computation) and may compensate for fluctuations resulting from small scale, rock heterogeneity. Under preferred conditions, computation of the stress tensor is possible at three scales: 1) individual test, 2) all tests in a single borehole, and 3) all tests in all boreholes (Figure 3). This staged approach allows for an assessment of the data in terms of consistency and reliability.

Figure 2 – Testing in the biaxial chamber.

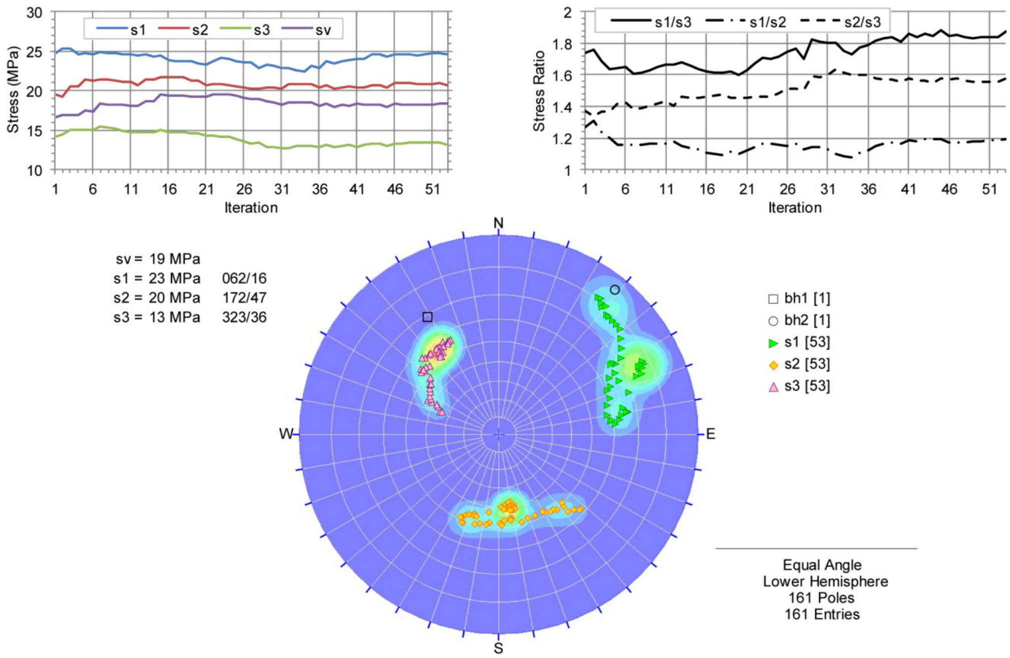


Figure 3 – Example of stress tensor computation from five individual tests completed in two boreholes.

In general, there is a need to resolve the issues associated with yielding of the resin at low rock temperatures and poor core recovery in jointed rock or under disking at high stress. Currently at GRC, work is underway to develop a method for ascertaining the full stress tensor from the strain recovery recorded during overcoring of a standard, mechanical USBM borehole deformation gauge, similar to that developed for the doorstopper by Corthésy et al. (1994) as well as to develop a triaxial, mechanical probe (similar in concept to the USBM gauge).

Borehole Wall Failure Observation

In greenfield operations, often the only available sense of the in situ stress state is provided from observations of wall damage in exploration drillholes. Borehole wall failure occurs when the local stress conditions exceed the strength of the rock. Since the stresses at the borehole wall are largely influenced by the in-situ far field stresses, failure can be used as an indicator of the in-situ stress conditions. Borehole wall stresses are the result of the superposition of three stress components: 1) the stress redistribution resulting from the void created by drilling; 2) the pressure that the fluid in the borehole applies on the wall; and 3) the stresses arising from the thermo-elastic response of the rock mass due to drilling induced temperature changes. For a vertical borehole in an isotropic rock the effective hoop stress is given by (e.g. Zoback et al., 2003):

$$\sigma_{\theta\theta} = S_{hmin} + S_{Hmax} - 2(S_{Hmax} - S_{hmin})\cos 2\theta - \alpha P_p - P_w - \sigma^{\Delta T} \quad (1)$$

where S_{hmin} and S_{Hmax} are the minimum and maximum horizontal principal stresses, respectively. The position around the borehole is given by the angle θ measured from the maximum horizontal principal stress direction. P_p is the pore pressure and α the coefficient of effective stress. The fluid in the borehole applies a pressure P_w to the borehole wall, and finally the stresses induced by the temperature differential ΔT between the formation and the drilling fluid are $\sigma^{\Delta T}$.

The effective hoop stress is displayed in Figure 4a: a maximal compressive value is reached at 90° and 270° from the S_{Hmax} direction while a minimal compressive value or eventually a tensile value will be present at orientations aligned with the S_{Hmax} direction. These extrema will be the initiation point of breakouts and drilling-induced tension fractures (DITFs) respectively if failure conditions are met. It is evident from this figure that borehole failure provides a direct and reliable indication of the principal stress directions in the plane perpendicular to the borehole axis in the case where the rock is reasonably isotropic. When strong anisotropy occurs (e.g. parallel joint fabric), special care should be taken in interpreting the borehole failure since it will be influenced by both the stress and the strength anisotropy (e.g. Kaiser and Maloney, 1987).

If historically, borehole breakouts were identified on the basis of oriented multi-arm (at least 4) caliper tools, the tool of predilection for the identification of borehole failure currently is the acoustic borehole televiewer (e.g. Luthi, 2001) as it provides a very detailed image of the borehole walls and of the borehole geometry. Examples of borehole breakouts and DITFs identified from acoustic televiewer data are presented in Figure 4b – d.

A closer examination of Equation 1 and Figure 4a shows that borehole cooling and borehole pressurization (e.g. by increasing the density of the borehole fluid) tend to inhibit the formation of breakouts. Also in the situation where the drilling fluid is cooler than the rock, cooling near the drill bit during drilling suppresses breakout formation however, they may develop later when the borehole recovers (heats up) to the formation temperature (solid curve in Figure 4a). On the other hand, DITF development is promoted by cooling and pressurization. In some situations, the cooling stresses are critical to the generation of the additional tensile stresses (dashed curve in Figure 4a) needed for the formation of DITFs. The control of the borehole pressurization to inhibit breakout formation while preventing fluid losses through tensile failure of the borehole is critical in deep well drilling operations (e.g. Charlez, 1999).

The estimation of stress magnitude using breakout shape has been proposed, based on either the breakout width (Barton and Zoback, 1988) or depth (Martin et al., 1999). However, neither is recommended since both are highly dependent on the assumptions made concerning the estimation of the borehole wall strength and the failure development mechanisms for which there is not a consensus within the rock mechanics community (e.g. Zhang et al., 2010). In addition, if the strength is measured by testing core samples, sample damage can affect the estimated strength (Valley et al., 2010; Bahrani et al., 2011).

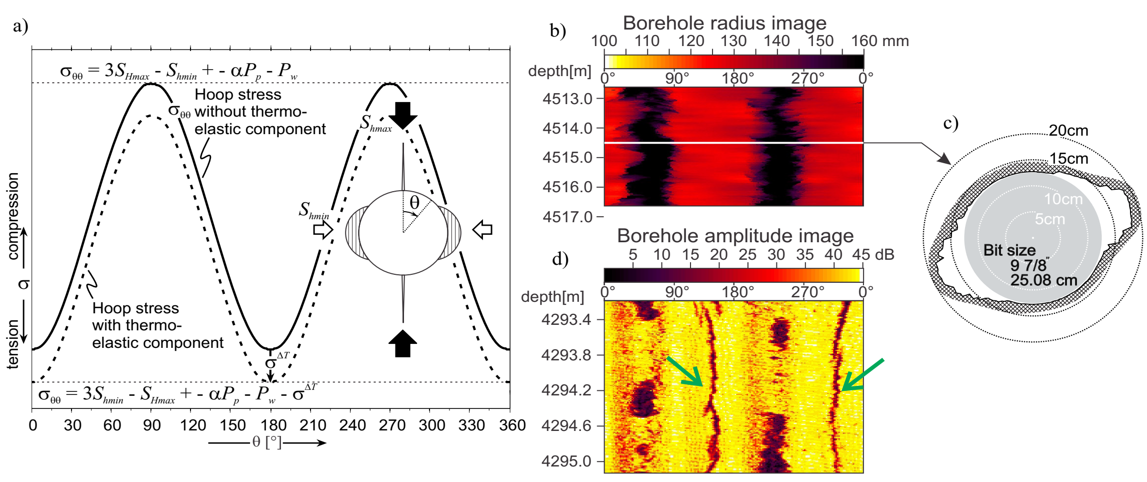


Figure 4 – a) Hoop stress at borehole wall. b) Borehole radii derived from an acoustic televiewer image of a section presenting breakouts. c) Borehole section showing clear breakout geometry. d) Acoustic amplitude borehole image showing axial fractures interpreted as drilling induced tensile fractures (green arrows). Examples presented in b), c) and d) are from Valley & Evans (2009).

The principal advantage of using observations of borehole failure, aside from its utility in greenfields, is that, contrary to most stress measurement methods that yield point measurements, it provides a continuous profile of stress orientation that allows the characterization of stress variability and heterogeneities, which are as important for mine design decisions and quantitative risk management as the mean stress trends. An example of the use of borehole failure for stress characterization is presented in Figure 5a – c. In this case, borehole failure indicates a local perturbation in the maximal horizontal principal stress orientation, which, on average, is about N-S to NNW-SSE at the site. These perturbations are often related to faults (see Figure 5c) either by the tendency of parallelizing the fault strike (indication of shear stress relief on the fault plane) or by showing very abnormal orientations close to fault tips, possibly indicating stress concentration. The study of this variability and its scaling is also of importance since it seems to be related to the scaling of structures (Valley and Evans, 2010) and seismicity (Day-Lewis et al., 2010).

One obvious limitation of borehole imaging and failure analyses for stress characterization is that, if the conditions for failure are not met, very limited information about stress can be provided. In this case one approach is to perform borehole shape analyses as presented in Figure 6 since, depending on the rock properties, it can highlight small (0.3% in Figure 6a) but consistently oriented hole ellipticity (Figure 6b – c). In this case ellipticity occurs for a section of the borehole in argillaceous limestone and is consistent with the expected stress orientation for the area.

An alternate approach, when borehole failure does not naturally occur, is to induce it by modifying the borehole wall stress state. While this is commonly performed in hydrofracturing stress measurements, it could be more generally applied by acting on the last term of Equation 1, i.e. by inducing excess thermo-elastic stress via heating or cooling the borehole as suggested by Hakami and Christiansson (2011).

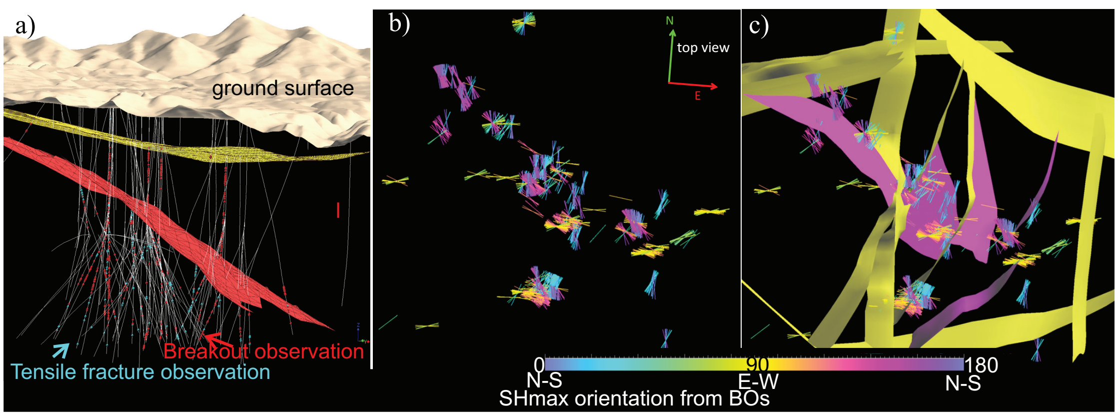


Figure 5 – Example of borehole failure database used for stress characterization at a deep mining project. a) View of the drillholes (white strings) and location of breakouts (red dots) and DITFs (cyan dots). b) Top view of SHmax orientation as indicated by interpretation of borehole failure. Locally, large variability is observed. c) Same data presented with interpreted faults (in yellow and purple) in order to highlights the relation between stress perturbations and faults.

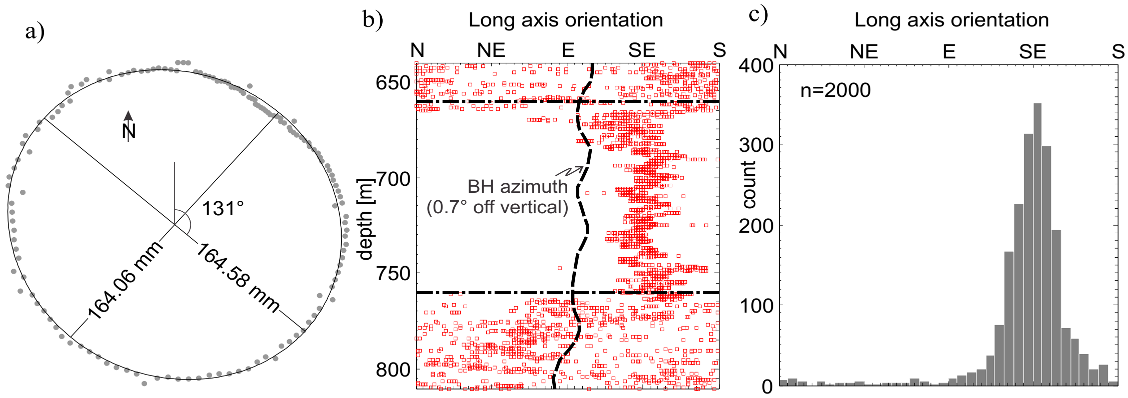


Figure 6 – Example of borehole shape analyses from Borehole DGR-2 on the Bruce Peninsula, Ontario, Canada. a) Determination of hole section ellipticity, i.e. length of axis and orientation of best fitted ellipse (extracted from acoustic televiewer image at 700 m depth). b) Direction of ellipse long axis with depth and borehole azimuth. Between the two horizontal dashed lines, the ellipse orientation is relatively stable. c) Histogram of ellipse long axis orientation for the depth interval 660 – 770 m (between dashed lines on b).

Under-excavation Technique

In the two preceding sections, pointwise measures of stress and indicators of its variability were highlighted. In this section, a measure of stress more appropriate to the excavation size is introduced. The Under-excavation Technique (UET), described in detail by Wiles and Kaiser (1994a&b), uses the response of strain measurement instruments (e.g., CSIRO hollow inclusion stress cells) or displacement measurement instruments (e.g., extensometers, inclinometers and tiltmeters) to the advance of a nearby excavation within the framework of elasticity theory to back calculate the far field stresses that existed in the rock mass. In the UET, instead of completely relieving the pre-existing stresses, as is the case in the overcoring, only a change in stress is induced in the rock mass as a result of excavation. The key difference with respect to overcoring is the volume of rock involved. As shown in Figure 7a, the UET can involve several hundred cubic meters and thus provides a stress state which is more relevant for the design of underground excavations.

The procedure in the UET analysis is described as follows: First, the instruments (e.g., strain cells) are installed around a future excavation with some known initial geometry. The instruments are allowed to stabilize and initial readings (zero measurement) are recorded. Excavation commences and the induced strain or deformation responses are recorded continuously or at a series of discrete excavation steps. Back analyses are conducted using a three-dimensional elastic numerical model for the initial geometry and all other chosen excavation steps to determine the pre-existing in situ stresses.

Examples of the UET analyses with different geometries and instruments are shown in Figure 7b to d. Figure 7b shows a 3D model of a circular and nearly vertical ventilation raise mechanically advanced from the 420 m level to the 240 m level at the Underground Research Laboratory (URL) in Manitoba, Canada. The initial geometry consisted of a 0.4 m diameter pilot hole followed by a 1.83 m diameter bore. As shown in Figure 7b, eight CSIRO cells were installed around the pilot hole and the stress change was monitored during raise boring. The UET was also used in an experimental drift located on the 240 m level of the URL. This drift was driven by standard drill and blast excavation method. Similar to the previous case, eight CSIRO cells were installed to monitor the stress changes during the excavation process (Figure 7c). Wiles and Kaiser (1994b) showed the consistency between the in situ stresses predicted by the UET analyses of vent raise and drift and those of other field measurements including overcoring, convergence, hydraulic fracturing and micro-seismic analyses.

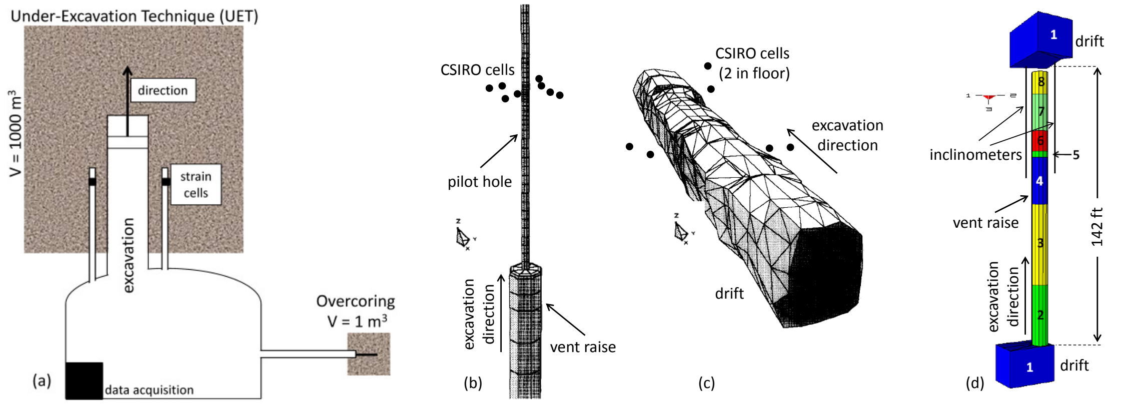


Figure 7 – a) UET compared to overcoring b) 3D view of the model of vent raise and the locations of CSIRO cells at the 420 m level of the URL, c) 3D view of the model of experimental drift at the 240 m level of the URL (a, b and c from Wiles and Kaiser, 1994), d) 3D view of the model of vent raise and the locations of inclinometers at a deep underground mine.

The UET was also utilized by the Geomechanics Research Centre at a deep underground mine, where conventional approaches have proven unsuccessful, to back analyze the maximum horizontal stress. As shown in Figure 7d, the displacements along two boreholes due to excavation of a ventilation raise were monitored using borehole inclinometers. The two boreholes were aligned such that the deformations measured by the inclinometers were oriented with the anticipated maximum radial deformation. The inclination readings along the boreholes taken in eight steps (Figure 7d) were then converted to displacements and the three-dimensional boundary element code Map3D used to back calculate the maximum horizontal stresses from each borehole. An example of the S_{Hmax} back analyzed from one of the boreholes is shown in Figure 8. In this case, the S_{Hmax} for a maximum radial deformation of 1.7 mm (Figure 8a) was back calculated to be 100 MPa. The results of back analyses from the two boreholes (Figure 8b) suggested a range for S_{Hmax}, which was consistent with the stress relationship employed by the mine extrapolated from past stress measurement campaigns.

One of the main advantages of the UET is the establishment of confidence in results via multiple predictions of stresses with a single instrument array (i.e., predictions for each excavation increments). Moreover, different types of instruments can be installed around a single excavation and used simultaneously to determine the state of in situ stresses. For example, a combination of CSIRO stress cells installed from the lower drift in the upward boreholes, and extensometers and inclinometers installed from the upper drift in the downward boreholes around a ventilation raise can be used. This allows for redundancy and reliability assessment of alternate forms of measurements. Another advantage of this technique is that strain gauge de-bonding in stress cells is less of an issue in the UET as undesirable nonlinear responses are minimized, since the stresses are only perturbed but not completely relieved.

In the UET, the locations of instruments relative to the excavation geometry need to be accurately defined. While the instruments have to be installed within the zone of influence, it is important to perform preliminary analytical and numerical analyses to define and avoid the areas where non-linear borehole response is expected. Also, since the strain or displacement changes measured in the UET are relatively small, very accurate instrumentation is required. This limits the applicability of this technique to moderately to highly stressed ground. In such environments, where borehole breakouts are expected, stress cells, when employed, should be installed in small stable boreholes. The displacement measurement instruments such as extensometers and inclinometers can be used in boreholes where borehole breakouts are observed. It should be noted that the stress cells are best suited to up-hole placement to avoid ingress of water or other materials.

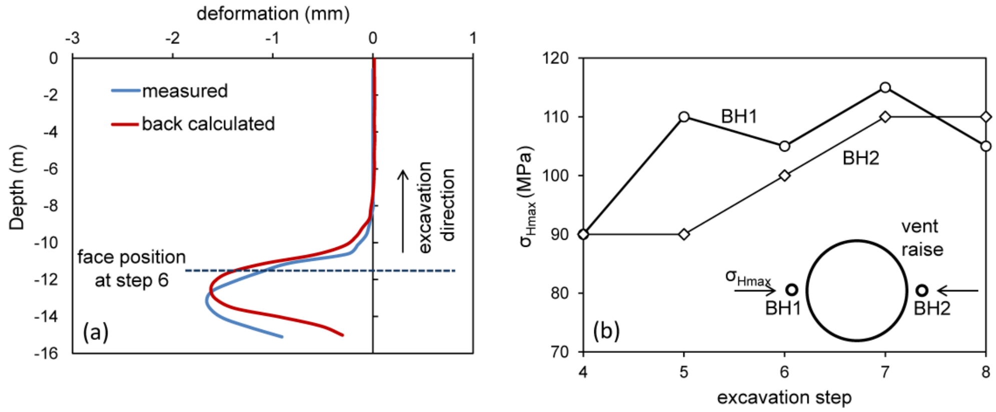


Figure 8 – a) Modelling radial deformation measured from one of the boreholes at step 6 to determine initial stress, b) Maximum horizontal stress back calculated from radial deformations along two boreholes for steps 4 to 8 using Map3D.

It is generally suggested that the UET be used in mechanically excavated openings such as those driven by raise bore or tunnel boring machines, as vibrations from blasting may cause some inelastic deformation within the ground by generating new cracks, propagating pre-existing cracks or allowing the joints to slip. Moreover, the better control of the excavation geometry in mechanized excavations allows for better results from the numerical analyses. It is worth noting that although the UET has limitations, just as all other in situ stress measurement methods, it represents an attractive alternative stress measurement method especially for moderately to highly stressed grounds. Advances in instrumentation and ground behaviour monitoring/characterizing techniques offer increased opportunities to employ this approach more systematically.

CONCLUSIONS

The goal of any stress measurement campaign is to come up with the best approximation for the stress state applicable to the rock volume of interest. As the natural environment can be quite complex, it can be resistant to simple quantification. The point values yielded by most techniques may be at substantial variance with respect to the mean and, in some circumstances, at odds with the client's expectations. Consequently, multiple and complementary measurements and inferences must be integrated to build confidence in a final determination. This approach has been formalized by the ISRM in Part 5 of their Suggested Methods for Rock Stress Estimation (Stephansson & Zang, 2012).

The variability in point measurements of stress and the cost of obtaining them is often used as an excuse for their avoidance. This variability is intrinsic and should be viewed as valuable information that, when compiled with complementary data, allows for a better understanding of the underground environment. It is only when taken in isolation that its value is diminished. That being said, it is the long term objective of the GRC, amongst others, to develop/enhance technologies/methodologies that promote more point measurements to be made with easier and at less cost.

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