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A REVIEW OF *IN SITU* STRESS MEASUREMENT TECHNIQUES

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ABSTRACT: Changes in stress orientations and magnitudes can have a significant adverse impact on mining conditions such as increasing the risk of violent failures. Knowledge of these changes can indicate the high-risk zones within a mine sites, which will enable mine operators to implement appropriate controls. At deep underground excavations, there are some difficulties in collecting reliable data at reasonable costs and majority of methods provide point measurement per test only. Thus, the utilisation of borehole techniques has received more attentions. In this paper, traditional stress measurement techniques are reviewed, including their pros and cons. Under specific geological conditions, some methods have significant advantages over others. Following the illustration of benefits and shortcomings of these techniques, the development potential of an i*n situ* stress measurement technique using borehole breakout is briefly addressed in conjunction with the future research plan.

INTRODUCTION

In situ stress magnitudes are always of great interest of mining and geotechnical engineering as they are essential to underground operations. With knowledge of the stress field, engineers can identify high risk zones and implement appropriate controls methods to prevent catastrophic failures. A series of *in situ* stress measurement techniques have been developed to interpret stress magnitudes in different geological conditions at a given point. However, a handful of point measurements sometimes might not be representative for the whole operation as stress field can vary significantly with various tectonic settings and overburden pressure at different depths. At deep underground operation, majority of techniques suffered from collecting reliable data at reasonable costs.

To effectively monitor ground conditions and make wise engineering decisions, it is crucial to obtain a clear understanding of applicability and limitations of each measurement technique. In this paper, various in-situ stress measurement techniques are reviewed with advantages and disadvantages, particularly emphasise on hydraulic fracturing, overcoring and borehole breakout due to their prevalence. Given the rapid advancement of borehole imaging technology, using borehole breakout to estimate stress magnitudes has received much more attention (Gaines et al., 2012). In general, breakout happens at different depths of a borehole and data can be collected with one measurement. This would considerably save time and cost compare with other techniques. It is also clear that breakout dimensions are stress dependent (Zoback et al., 1985; Barton et al., 1988) and some methods have been proposed to constrain stress magnitudes (Zoback et al., 2003; Chang et al., 2010). Therefore, borehole breakout has a great potential to be developed as a primitive stress estimation technique.

In addition, this paper provides a brief discussion about the future research plan of authors in borehole breakout area. Experimental studies have been undertaken; it is expected to be combined with field and numerical data for further analysis.

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HYDRAULIC METHODS

Hydraulic fracturing is one of the commonly used methods for stress measurement, especially in petroleum engineering. Currently, there are two major categories, which included conventional hydraulic fracturing and Hydraulic Tests on Pre-existing Fractures (HTPF).

Conventional hydraulic fracturing

Conventional hydraulic fracturing utilises the hydraulic pressure created by fluid injection to form tensile fractures around the borehole to estimate the in situ stress. It was initially used for the reservoir productivity stimulation and was applied to stress measurement in early 1960s.

A sealed section of the borehole is isolated by a straddle packer. Fluid is then slowly injected into this interval to apply pressure on borehole sidewall. When the pressure induced tangential tensile stress surpasses the tensile strength of the surrounding rock, two fractures occur in opposite directions and penetrate along the plane perpendicular to the minimum principal stress direction, which has the least resistance. This pressure is recorded as breakdown pressure, P_b. After two fractures are initiated, there is a pressure required to hold the fractures open and allow fluid flow into them. As postulated by Hubbert and Willis (1957), if the borehole is drilled vertically, the vertical principal stress is the maximum principal stress; then this pressure is equal to the minimum horizontal principal stress magnitude, which can be measured by turning off the injection system, namely, Instantaneous Shut In Pressure (ISIP).

$$S_h = S_{ISIP} \tag{1}$$

where S_h = minimum horizontal principal stress and S_{ISIP} = instantaneous shut in pressure. Thereby, based on the Kirsch solution (Kirsch, 1898), the maximum horizontal principal stress, S_H, can be obtained from Equation 2.

$$S_H = 3S_h + T - P_0 \tag{2}$$

in which T = tensile strength of rock and P_0 = pore pressure. The illustration of hydraulic fracturing is displayed in Figure 1. To conduct the stress measurement where tensile strength data is unavailable, Bredehoeft, *et al.* (1976) modified the conventional equation:

$$S_H = 3S_h - \mathrm{P_r} \tag{3}$$

where $\mathrm{P_r}$ = re-open pressure. This is measured by turning on the pumping system cyclically, which enables the fluid to re-open fractures multiple times at the borehole wall. However, due to some uncertainties, such as plastic behaviours of the surrounding rock (Rutqvist, *et al.,* 2000) and remaining apertures at the start of each cycle (Cornet, 1993), the measurement of re-opening pressure may not be accurate. For this reason, the application of this modified equation is limited.

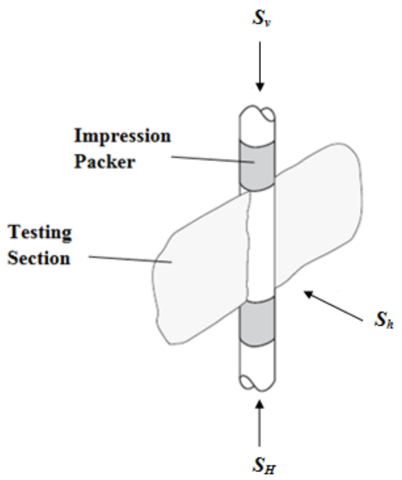

Figure 1: Conventional hydraulic fracturing (after Lakirouhani, *et al.,* 2016)

Conventional hydraulic fracturing provides a simple way to measure stress magnitudes, advance knowledge of rock properties is not essential, such as Young's modulus and Poisson's ratio. This method also offers a reliable and direct measurement of minimum horizontal principal stress at an accuracy of ± 5% (Ljunggren, *et al.*, 2003). Another advantage of hydraulic fracturing is its utilisation at deep location. Hung et al. (2009) successfully conducted this measurement below 1km depth. With conjunction of ancillary equipment, including impression packer, compass and borehole scanning technique, it is also possible to obtain the approximate stress orientations. This is because the direction of fractures' propagation is perpendicular to the minimum principal stress direction.

One inevitable shortcoming of this technique is the accuracy on maximum horizontal principal stress calculation. The variation of estimation can be over ± 20% (Ljunggren, *et al*., 2003). When there are pre-existing weaknesses around the testing section, the injected fluid would re-open and penetrate through pre-existing fractures instead of the plane parallel to the minimum principal stress direction since the resistance is much lower along pre-existing fractures. The disturbance of pre-existing weaknesses would lead to unreliable estimation of the horizontal stress field. Hence, this technique is not suitable with pre-existing weaknesses such as jointed rock and pre-exiting fractures. Hydraulic fracturing is also limited by the faulting mechanism. For instance, if the stress field is controlled by reverse faulting, where vertical stress is the minimum principal stress, fractures will be formed in the horizontal plane. In this case, horizontal stress magnitudes or orientations cannot be estimated in this case (Gaines, *et al*., 2012). Moreover, due to its stimulation on well production and favourable faulting condition, hydraulic fracturing is widely used in petroleum engineering.

Hydraulic tests on pre-existing fractures

HTPF was initially proposed by Cornet and Valette (1984), which was designed to overcome the shortcomings of conventional hydraulic fracturing method. Comparing with the conventional method, HTPF focuses on the re-opening of pre-existing fractures in the sealed section. This technique aims to determine normal stresses acting perpendicular to pre-existing fractures, which equal to the shut in pressure generated by fluid injection. Accordingly, it is important to gather precise locations and orientations of fractures prior to the commencement of the fluid injection. This is usually achieved by borehole imaging techniques, such as Mosnier tool (Cornet, et al., 2003). The sketch is shown below in Figure 2.

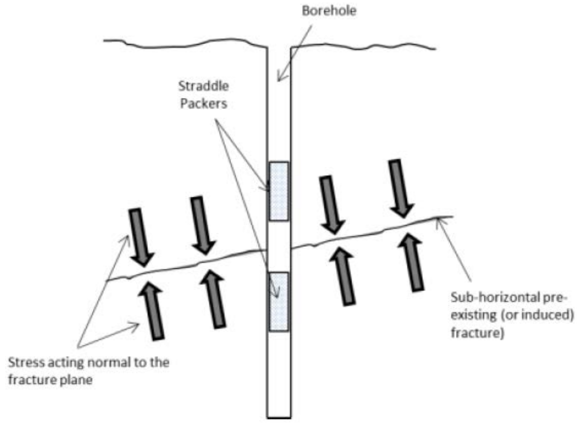

Figure 2: Schematic of HTPF (Gaines, *et al.* 2012)

Since there are no fractures induced by HTPF, it is less limited to the geological conditions. Comparing with the conventional method, tensile strength and pore pressure of the surrounding rock are not involved in the estimation, so that the measurement of rock properties is not mandatory. With sufficient tests conducted, 3D stress field can be computed using HTPF. However, due to strict requirements of fracture locations and large number of tests, HTPF is more time intensive than the conventional method. In general, 20 successful tests are necessary for a proper 3D stress interpretation (Ljunggren et al., 2003). Thereby, HTPF is based on the assumption that the fracture orientation is persistent. Distorted fractures can lead to overestimation of shut in pressure, which consequently results in inaccurate evaluation of principal stress magnitudes.

OVERCORING

Overcoring is also a widely used stress measurement technique, particularly in mining industries. The estimation is based on the strain deformation within a pilot hole. To overcome different limitations, a range of methods were developed with similar procedures and the same principal, i.e. linear elasticity. Depending on instrumentations and requirements of pilot holes, these methods can be divided into three types:

- Displacement Measurement
- Soft Stress Cells
- Overcoring without Pilot Holes

Displacement measurement

Deformation cells are common instruments used in overcoring. The change in borehole radial displacement is measured during overcoring using six cells, and converted to stress magnitudes in conjunction with rock properties such as Young's modulus and Poisson's ratio, which are measured from cored samples. The two prevalent displacement measurement instruments are US Bureau of Mine cell (USBM) and SIGRA IST. In Australia coal industry, the most used instrument is SIGRA IST.

A borehole is initially drilled to the desired measurement depth. By then, a pilot hole is advanced from the bottom of the borehole at the centre using a barrel. At the completion of drilling, equipment is retrieved together with cored rock samples. Cored samples are transported to laboratory for rock properties testings, usually biaxial tests. Afterwards, strain gauge is installed in the pilot hole and overcoring is commenced at the diameter of borehole. Subsequently, the radial displacement recording by the strain gauge is collected and used for stress estimation. A schematic diagram is shown in Figure 3. This technique provides stress measurements at high accuracy and can be applied to various geological conditions. For example, it is not constrained by faulting mechanisms. Besides, strain cells are recoverable which can later be used for multiple tests. This would reduce associated costs. Moreover, since cables are not connected from cells to the computer, theoretically, it is not limited by depth.

However, there are also a series of shortcomings related to the technique. Similar to other methods, the displacement cell is based on the assumptions of linear elasticity and rock homogeneity and isotropy. Clearly, rock mass doesn't satisfy these conditions, which infers it has inherent uncertainties as other techniques (Gaines, *et al*. 2012). Given the effect of water table and the continuity of cored sample under high stress conditions, this method is practically only suitable to shallow depth. Thereby, multiple tests are required to carry out for complete stress field estimation, which can be time consuming.

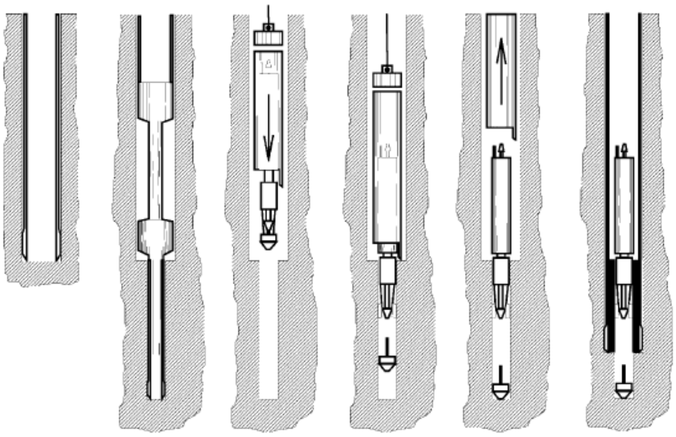

Figure 3: Overcoring procedures (Ljunggren, *et al.,* 2003)

Soft stress cells

The principal of soft stress cells is to stick highly sensitive strain gauges onto the rock around the borehole using temperature-specific gluing packs, so that gauges can rapidly become a part of the rock. As soon as overcoring is conducted, surrounding rock as well as gauges can experience similar deformation. Later, stress field can be estimated providing data obtained from strain gauges. In general, well-known soft stress cell instruments include CSIR, CSIRO HI Cell and Borre Probe.

Soft stress cells determine the stress field within one borehole measurement only, which is more favourable than displacement measurement. In terms of stress dimensions, soft stress cells offer an accurate 3D stress estimation rather than 2D through a rotational and continue logging, except CSIR. Furthermore, there is a major advantage which distinguishes Borre Probe with other overcoring techniques, which is its application in deep, water filled boreholes. (Gaines, *et al*., 2012).

In opposition, this technique also has a lot of disadvantages. Unlike USBM or SIGRA IST, soft stress cells are difficult to be recovered. Epoxy based glues is not applicable in humid and dusty environment, including coal mines (Coetzer, 1997). The thickness of glue and its associated temperature effect may influence the accuracy of the measurement. In line with USBM and SIGRA IST, unbroken long cores are required for successful measurements. It is usually difficult to be achieved due to pre-existing fractures, discing or joints. Under high stress conditions at deep locations, this problem is amplified for Borre Probe measurement.

Overcoring without pilot holes

Doorstopper is a special overcoring method which doesn't require a pilot hole. Instead, the borehole bottom has to be carefully polished to ensure it is flat so that the strain gauge can be glued and attached to the rock. It is principally the same as other overcoring techniques which records the deformation of rock induced by overcoring. Atomic Energy of Canada Ltd. modified this instrument for deep measurement, namely, Deep Doorstopper Gauge System (DDGS) (Thompson and Chandler, 2004).

Overcoring methods with pilot holes generally require more than 300 mm overcoring length, whereas doorstopper only needs 50 mm. As a result, doorstopper is less time consuming and can be conducted at deep locations, which can be up to 1000 m. It also provides a higher successful measurement rate in relatively weak or broken rock or even in high stress conditions, due to the un-essentialness of the pilot hole. With modifications, DDGS can also be implemented to deep, water filled boreholes. Therefore, in deep stress measurement, it is more favourable than Borre Probe.

Although the pilot hole is not necessary for doorstopper, polishing and preparation of the borehole bottom are essential. To obtain the stress field, the borehole has to be parallel to the vertical principal stress, indicating that doorstopper only permits 2D stress determination perpendicular to the borehole.

BOREHOLE BREAKOUT

Once a hole is drilled underground, the in-situ stress field is disturbed and the compressive stress is concentrated on the rock around the borehole. When the compressive stress overcomes the rock strength, the failure of rock occurs at opposite areas around the borehole wall. Induced void created by rock detachments or flakes is so-called ‘borehole breakout’, which initiates and propagates along the minimum principal stress direction, see Figure 4. To measure breakouts, logging systems are required to start from the surface of the borehole to the maximum depth. Most frequently used apparatus are borehole televiewer, formation scanner and calliper.

The classical concept of borehole breakout was initially proposed by Bell and Gough (1979), who interpreted the stress field around the borehole based on Kirsch solution. They suggested that the maximum compressive stress concentration is at the minimum principal stress direction, whereas the minimum compressive stress concentration is at the maximum principal stress direction. Thus, the maximum breakout depth should be aligned to the minimum principal stress direction. Based on this concept, borehole breakout has been developed as a reliable measurement technique for stress orientations.

A series of attempts were made to correlate the stress magnitudes to breakout dimensions according to elastic conditions (Zoback, *et al.*, 1985; Barton, *et al.,* 1988; Chang, *et al.*, 2010). It is clear that both breakout width and depth are directly related to stress magnitudes, as stress magnitudes increase, the width and depth also increase. However, due to various reasons, the accuracy of stress field estimation is relatively low. The primary reason for this is the time dependent breakout deepening (Zoback, *et al.,* 1986). Stress re-distribution induced by rock failure and plastic deformation cause the change in compressive stress at breakout tip. As time goes, the rock at breakout tip may fail and advance forward due to accumulated stress concentration. The breakout measurement usually takes place at least after few hours of drilling, which means the depth measured is deeper than initially formed. In this case, the stress calculation based on elastic conditions yields unreliable results. Thereby, pre-existing fractures around the borehole can also result in the elongation of breakout, which further disrupts the estimation. In addition, current field equipment have drawback in measuring breakout depth. When fractures exist at the area of measurement, times for the equipment to receive emitted acoustic waves are considerably disrupted. Since there is no reference, the depth measurement cannot be verified and hence may not be used. Other than that, breakouts have to exist to allow the stress measurement take place and it rarely happens at depth above 100 m.

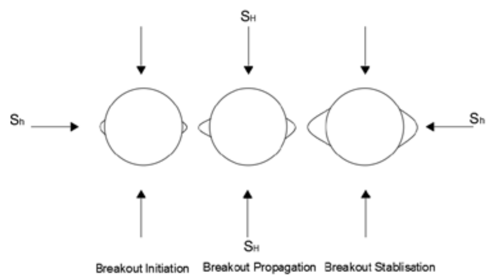

Figure 4: Borehole breakout formation

On the contrary, this method offers some advantages rather than other techniques. Firstly, it is simple and quick method for primitive stress estimation as only geometrical measurement is required. In Australia, every borehole drilled has to be logged. This means breakout data has already there, the estimation can be directly carried out. Secondly, it enables deep stress measurement which normal methods may not reach. Another advantage is that the shape and size of breakout can indicate the high stress concentration zone, which can be treated as a primary tool of coal burst detection and strata control. After the equipment scans existing breakouts within the borehole, stress profile at different depth can be interpreted in one measurement. This is cost effective and time saving.

FLAT JACK

Flat jack is another cost effective method conducted at the surface of the excavation. The concept is to calculate the stress based on the pressurisation of a flat jack in a slot. Two points A and B are selected and measured continuously by strain gauges which are followed by a nearby slot cutting. Afterwards, a flat jack is inserted into the slot and pressurised until the distance between A and B is back to the original distance. The pressure at this point, the cancellation pressure, is assumed to be the average normal stress across the slot and subsequently the stress field can be interpreted by multiple tests. This method is simple, cheap and easy to be carried out while the elastic modulus is not required for the calculation. Conversely, flat jack is only applicable at the surface of the excavation where the rock is closely to be overstressed. This may lead to unreliable estimation.

OTHER MEASUREMENT METHODS

There are also other stress measurement approaches which cannot be covered in this article, such as borehole slotting, core discing and acoustic emissions. Each method has its major advantages in particular conditions. For example, acoustic emissions are suitable for rock at shallow depth where principal stress magnitudes are lower than rock strength.

SUMMARY OF METHODS AND FUTURE RESEARCH PLAN

In previous sections, popular in-situ stress measurement techniques have been reviewed together with their advantages and disadvantages. It is clear that hydraulic fracturing is the most suitable method in normal faulting, whereas overcoring is widely used in mining industries providing reliable measurement. On the contrary, most methods only provide point measurement per test, the complete stress field profile over depth has to be obtained through a series of successful tests. Practically, it is economically unfavourable and time consuming to conduct multiple tests at different depths for ground controls.

Borehole breakout is a natural event which usually occurs different levels at depth below 100 m. With scanning or calliper measuring from surface to bottom of the hole, breakouts at various locations can be recorded in one scanning activities. In Australia, every borehole drilled has to be logged, which means breakout data is available already. Thus, borehole breakout presents a great potential for stress profile estimation over depth. To develop a primitive stress estimation technique based on borehole breakout on ground controls, it is essential to identify influential factors that affect breakout dimensions. To achieve this, a series of experiments have been carried out at China University of Mining and Technology

(CUMT) via a true triaxial test machine and undergone CT scanning after tests. CT scanning data is still under processing and influential parameters are to be recognised. A thorough parametric study is proposed to be performed using numerical software PFC. It aims to study the relationships between breakout dimensions and each influential parameter. Together with field data collected from mine sites, a primitive stress estimation method using borehole breakout is expected to be developed for ground control purpose.

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