Experience of Using the ANZI Strain Cell for Three-Dimensional, In-Situ Stress Determinations in Deep Exploration Boreholes

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ABSTRACT

This paper describes the Australia, New Zealand Inflatable (ANZI) strain cell, its operation, and recent development for overcoring in exploration boreholes. The ANZI strain cell is an instrument system that uses the overcoring method of stress relief to determine the three-dimensional, in-situ stresses in rock. The instrument has been used successfully for over three decades in numerous underground mining and civil projects, but technical advances over the last decade or so have allowed the system to be deployed in surface exploration boreholes to greater depths than was previously possible. Recent development of a downhole electronic data logger, a wireline-enabled drilling system, and an instrument deployment system has simplified the process of obtaining three-dimensional overcore measurements at depths approaching 1km to a single shift operation.

The capability to deploy ANZI strain cells in surface exploration boreholes represents a significant breakthrough for the design of underground mines and underground excavations generally. High-confidence characterisation of the in-situ stresses at the design stage provides the opportunity to design key infrastructure and mining systems to take advantage of the in-situ stress field from the outset before mining begins. Understanding the three-dimensional, in-situ stress field not only provides a measure of the magnitude and direction of loads acting within the rock mass, it also provides insight into the mechanics of all the various processes driving ground deformations, including which geological fault structures are at limiting equilibrium.

INTRODUCTION

The overcoring method of stress relief is one of the most direct methods for determining three-dimensional, in-situ stresses in rock. The Australia, New Zealand Inflatable (ANZI) strain cell combines overcoring with several other techniques to provide determinations of the three-dimensional, in-situ stress field and the properties of the rock and, importantly, provides an indication of how much confidence can be placed in the measurement. This paper describes the advances that have enabled overcoring of the ANZI strain cell in deep surface exploration boreholes and the development of various complementary techniques that build additional confidence in the determination of the in-situ stress.

An overview of the development of the overcoring method of stress relief and of the ANZI cell is provided for context. The operation of the instrument and the various stages of testing used to provide confidence in the integrity of each measurement are detailed. Recent developments in the overcore system include the following:

- wireline enabled drilling techniques to prepare the pilot hole
- a newly developed deployment and pressurisation system
- precision downhole strain, pressure, and temperature logging capability
- increase in the number of axial gauges to measure axial strain variations

Recent developments in the analysis include more robust methods for

- determining confinement dependent variation in elastic modulus
- compensating for axial strains caused by drilling
- recognising and compensating for water pressure effects
- measuring overcore out-of-roundness to provide an independent indication of major stress direction

Before describing any process of "in-situ stress measurement," the limitations of this terminology should be recognised. The concept of stress is a convenient engineering construct to link displacements and their derivative strain with forces through idealised models of material behaviour. Stresses do not actually exist as something that can be measured. Changes in stress can be calculated from changes in strain in a continuous, homogeneous, isotropic, linear elastic (CHILE) material. Six independent components of strain change are required to uniquely calculate the corresponding change in a three-dimensional stress tensor.

To conduct an "in-situ stress measurement" requires the following:

- a change in loading conditions, ideally from in-situ conditions to conditions of zero stresses
- the measurement of sufficient independent strain changes during this process
- an assumption about the material behaviour

To say that the stresses have been "measured" by this relatively involved process is somewhat misleading because the best that is possible is to "estimate" the in-situ stresses based on imperfect measurements of strain change and an idealised model of the behaviour of rock material. Nevertheless, the term "stress measurement" has gained widespread usage in the lexicon and is, at times, more convenient to use, but the limitations of the terminology should be recognised.

The overcoring process used with the ANZI strain cell allows a stress change in the rock, from the in-situ state of stress at the start of overcoring to a zero state of stress at the end of overcoring. The strain changes measured by the ANZI strain cell during this process allow the in-situ stresses to be determined. In practice, the approximation of the rock material as a CHILE material for the purposes of determining the in-situ stresses from strain changes measured during overcoring and then, more generally, for numerical modelling introduces a significant source of uncertainty. The additional characterisation of the material behaviour that is possible with the ANZI strain cell system provides insights into the rock behaviour and how well it can be approximated as a CHILE material.

BACKGROUND TO ANZI CELL DEVELOPMENT

This section describes the development of the overcoring method of stress relief, the development of the ANZI strain cell, and the design strategy behind these developments.

Overcoring Method of Stress Relief

The overcoring method of stress relief is a convenient method for changing the loading conditions on a rock specimen at the end of a borehole from in-situ stress conditions to conditions of zero stress. By measuring the strain changes during this process in six independent orientations, the full three-dimensional, in-situ stress tensor can be determined based on an assumption of CHILE material behaviour. In practice, there are a variety of influences that are found to complicate this process. These include drilling-induced effects described by Mills, Zoorabadi, and Puller (2016), material behaviours that are not captured by the CHILE model described by Mills and Gale (2016), and, for some types of instruments, the presence of the instrument itself influencing the final state of stress in the post-overcored rock.

The overcoring method of stress relief has beginnings in a technique where rock on a tunnel wall is isolated from the stress field by drilling a series of interconnected holes and the resulting displacements are measured. Lieurance (1933) reports using this technique during investigations for the construction of the Boulder Dam. Olsen (1949) reports using the same technique, but with the introduction of strain gauges for the purpose of measuring the displacements. The overcoring method of stress relief in boreholes progressed during the 1950s with the development of a variety of different instruments (Leeman, 1958; Hast, 1958; Obert, Merril, and Morgan, 1962).

In the 1960s, the technique developed further so that it became possible to measure in-situ stresses in three dimensions from one borehole. An analysis presented initially by Leeman and Hayes (1966) and refined for hollow inclusion devices by Duncan-Fama and Pender (1980) provides a method for estimating the in-situ stresses from elastic strains measured on the surface of a borehole. This method generally uses electrical resistance strain gauges bonded directly to the rock or included within a hollow inclusion bonded to the rock. The changes in strain that occur on the borehole wall during the overcoring are assumed to be caused entirely by the response to the change in stress of the rock material.

Hiltscher, Martna, and Strindell (1979) developed an overcoring method for use in deep boreholes, where the pilot hole can be drilled without the need to withdraw the rods. This method is reported by Hallbjorn (1986) to have been successfully used to measure in-situ stresses in exploration boreholes to depths of 500m.

ANZI Strain Cell Development History

The original Auckland New Zealand Soft Inclusion (ANZSI) strain cell (Mills and Pender, 1986) was developed from 1980 to 1983 at the University of Auckland for the purpose of being able to estimate the three-dimensional, in-situ stresses in coal. The primary goal was to reduce the tensile stresses generated at the borehole wall by the presence of the instrument. In soft rocks, such as coal, the tensile stresses generated at the borehole wall during overcoring of hollow inclusion instruments can be high enough to cause tensile failure of the rock itself, thereby compromising the test. A secondary goal was to develop an instrument where strain gauges bonded directly to the rock could be tested in situ prior to overcoring to confirm the behaviour of the rock material was consistent with a CHILE model.

From this start, the concepts of keeping the strain measurement system as unobtrusive as possible so that the presence of the instrument does not influence the strain measurements, coupled with providing as much redundancy of measurement of strains and material properties as is practical, have guided ongoing development of the instrument.

The ANZSI strain cell was 38mm in diameter and carried nine strain gauges. The instrument was successfully used to measure in-situ stresses in coal mines in New Zealand, Australia, and the United Kingdom, as well as at several hard rock civil sites in New Zealand. In 1990, the instrument underwent a significant upgrade and a name change. The diameter was increased to 56mm and was manufactured on a hollow, tubular body. The number of strain gauges on each instrument was increased to 18, and the name was changed to ANZI strain cell, reflecting the instruments combined development history and essential mode of operation.

A 29mm-diameter version of the instrument was developed in 1997 (Mills) for rapid deployment and used in specialist applications, such as determining bending stresses in concrete membranes. This development led to the introduction of bespoke epoxy cement with characteristics that suit deployment of the ANZI strain cell.

An ANZI strain cell was first overcored in a surface exploration hole in 2009 at a depth of 50m. The instrument is now routinely overcored at depths ranging to 750m with deeper measurements conducted from time to time as required. The 56mm-diameter version of the ANZI strain cell was used initially for overcore measurement, but this instrument required specialist core barrels because the standard HQ core size is only 61mm in diameter, and the annulus is too small to be effective. Several core barrel configurations were developed and trialled, but the requirement to swap out core barrels became a significant impediment to the ease of conducting measurements at depth.

In 2014, a 48mm-diameter version of the instrument was developed for use in standard HQ exploration holes using double and triple tube wireline core recovery systems. This version of the instrument was initially monitored using a cable that ran to a logging system on the surface. Solid installation rods were replaced with a two-cable system deployed on a mechanised cable drum through the drill rods. The first cable was connected to the instrument and monitored at the surface for the duration of the overcoring. The second cable was used to pressurise the instrument during installation and the pressure test.

However, this approach becomes cumbersome at depths greater than a few tens of metres. These limitations were overcome with the development of

- a spline drive sub installed behind the core barrel that provides for a wireline deployable downhole drilling system similar to that used by Hiltscher, Martna, and Strindell (1979). This system does not require the HQ rod string to be withdrawn from the hole for drilling of the pilot hole.
- a downhole high precision data logging system
- a deployment system for the instrument and data logger
- an instrument pressurisation system that utilises the drill pipe

With this revised system, it is routine to conduct overcore measurements at depths of 750m in inclined holes in a single 12-hour shift.

Instrument Design Strategy

The ANZI strain cell has been developed with focus on simplicity of operation and providing high levels of redundancy to give a sense of the confidence that can be placed in each individual point measurement. Analysis techniques available for converting measured strains to stresses are limited by assumptions that the material is linear, elastic, isotropic, and homogeneous. However, many rocks in which overcore tests are conducted are not ideal materials. Sedimentary rocks are frequently inhomogeneous. Sandstone rocks are commonly non-linear because the elastic modulus varies with confinement, and rocks in high-stress environments are frequently damaged by drilling-related effects, causing permanent strain changes, particularly in an axial direction.

Recognising that the calculation of stresses from strains is imperfect, the key to obtaining value from the measurement is gaining a sense of the confidence that can be placed in each measurement and how well the rock properties can be approximated as an ideal material. In the authors' experience, not all measurements aimed at determining the in-situ stress field or changes in stress are reliable. However, having a basis to differentiate those that are high confidence from those that are not is invaluable when developing an overall understanding of the stress environment and the rock behaviour within that environment.

The design of the ANZI strain cell is focused on providing systems to allow the confidence in each point measurement to be assessed, as well as having sufficient duplication of measurement for rock behaviour to be characterised and departures from CHILE behaviour compensated for.

OPERATION OF THE ANZI STRAIN CELL

Figure 1 shows a photograph of the 48mm-diameter version of the ANZI strain cell with the data logger attached prior to installation and a second instrument after overcoring. The instrument has an inflatable membrane of soft, rubber-like material with 18 electrical resistance strain gauges exposed on its outer surface. When the membrane is covered in epoxy cement and inflated during installation, the electrical resistance strain gauges become directly bonded to the wall of the pilot hole allowing direct measurement of strain changes in the rock as it is overcored.

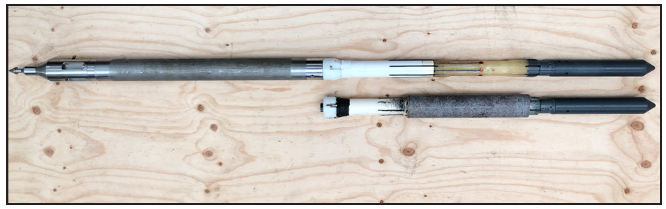

Figure 1. 48mm ANZI strain cell and downhole data logger prior to installation and recovered overcore, the results of which are used as examples throughout this report.

The wiring of the strain gauges is embedded in the membrane so that the instrument is waterproof. The gauge orientations are arranged so that there are six three-gauge rosettes distributed at 60° intervals around the circumference of the instrument on the same plane perpendicular to the axis of the instrument. On each rosette, there is a circumferential gauge, an axial gauge, and a gauge oriented at 45° to the axis of the borehole. The gauges are each 5mm long. The six rosettes improve statistical confidence in the in-situ stress measured (Gray and Toews, 1974).

Reference gauges on the instrument and in the logger housing that should not change are logged along with the 18 active gauges to observe environmental effects and the correct operation of the logging system. The instrument orientation, inflation pressure, downhole water pressure, and temperature are also logged.

There are seven stages in the standard ANZI strain cell test procedure: preparation of the hole, installation, in-situ pressure test, overcoring stress relief, biaxial pressure test, laboratory testing of the core recovered from the pilot hole, and out-of-roundness testing of the overcore.

Borehole Preparation

A borehole is drilled to the measurement location using standard drilling procedures. This borehole is now most commonly an HQ size (96mm diameter) borehole, but a range of other options are available and have been used. The end of the hole is prepared so that the core stub is removed, and a centralising conical indentation is formed. A smaller diameter pilot hole is then drilled concentrically from the end of the larger diameter hole, for a distance of 1m. The core from this pilot hole is inspected to determine an optimum horizon for instrument installation. The core from the pilot hole is retained for material testing in the laboratory.

Installation

Figure 2 shows a photograph of the instrument during preparation for installation. To install the ANZI strain cell, the outer surface of the instrument is coated with custom designed epoxy cement. Figure 3 shows the epoxy cement being applied immediately prior to installation. The instrument is then installed into the hole and floated down until it lands in the pilot hole at the target depth.

Pressure is applied internally to the membrane causing the strain gauges to be pressed directly against the borehole wall. Most of the epoxy cement coating is extruded away from the strain gauges and membrane leaving only a very thin (0.3–0.5mm) layer of cement

Figure 2. ANZI strain cell and data logger assembly being readied for installation in an inclined hole at a depth of 740m. The collar of the hole is approximately 1300m below the ground surface.

Figure 3. ANZI strain cell with epoxy cement applied to the surface of the instrument and data logger assembly being lowered into the hole prior to being released to float down the hole.

between the gauges and the rock. When the cement has cured, typically 3–4 hours depending on rock temperature, the strain gauges are bonded directly to the rock.

In-Situ Pressure Test

Once the cement has cured, the internal pressure is varied incrementally to conduct a pressure test using the instrument as a dilatometer or pressuremeter. This test is used to

- confirm that the strain gauges are well bonded to the rock
- provide an estimate of the in-situ elastic properties of the rock under plane strain conditions prior to any disturbance that can be caused by drilling during the overcoring process
- provide, under some circumstances, independent confirmation of the in-situ stress direction (Mills and Gale, 2016)

The pressure changes in the pressure test are kept relatively low to avoid disturbing the in-situ stress field. Maximum strain changes are typically maintained at less than 20–200 microstrain.

The pressurised length of the ANZI strain cell membrane is designed to be four times the diameter of the borehole to generate near-plane strain conditions during the in-situ pressure test (Laier, Schmertmann, and Schaub, 1975). The increased length of the instrument also improves the length of overcore recovered in low strength or highly jointed rock.

Figure 4 shows an example of a pressure test. The six circumferential gauges show the largest strain change. The six axial gauges show almost no change or a slight stretching consistent with the near-plane strain conditions at the centre of the pressurised length of borehole. The 45° gauges show a strain change midway between the circumferential gauges and axial gauges.

Overcoring

The ANZI strain cell overcoring operation is conducted in much the same way as other instruments that use the overcoring stress relief method. Direct bonding of the strain gauges onto the surface of the borehole means that the diameter of the overcore need only be slightly greater (10–20mm) than the diameter of the pilot hole and instrument for the result to be valid. The zero stress state of the final overcore means the overcore does not need to remain completely intact or maintain a regular geometry for the result to be valid. These characteristics significantly extend the range of rock types and drilling environments in which the instrument can be used.

Figure 5 shows an example of an overcoring result. The strain changes are plotted relative to the overcoring distance. The strains on all gauges are tensile going in nature consistent with the relief of the compressive in-situ stresses.

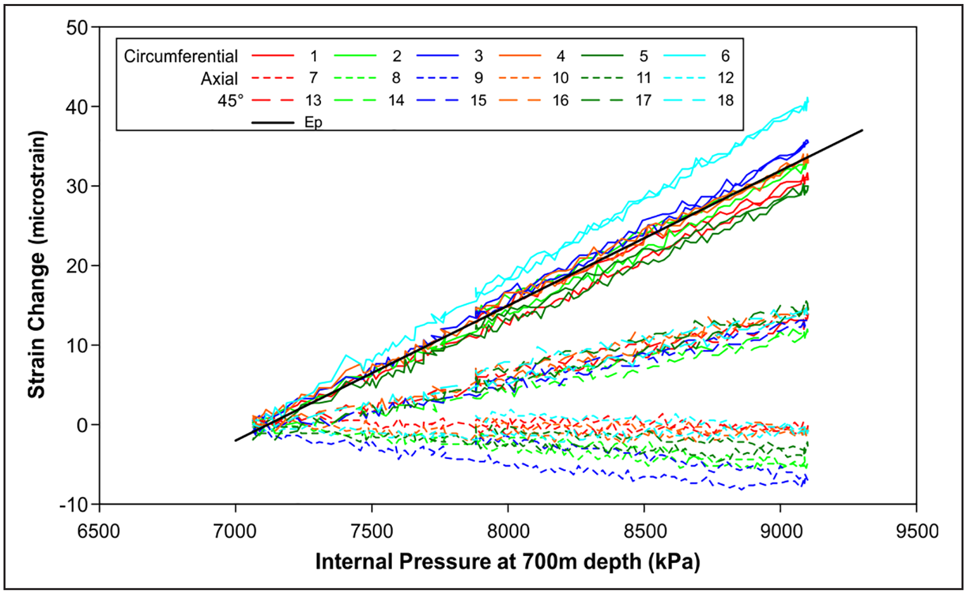

Figure 4. Example of in-situ pressure test result.

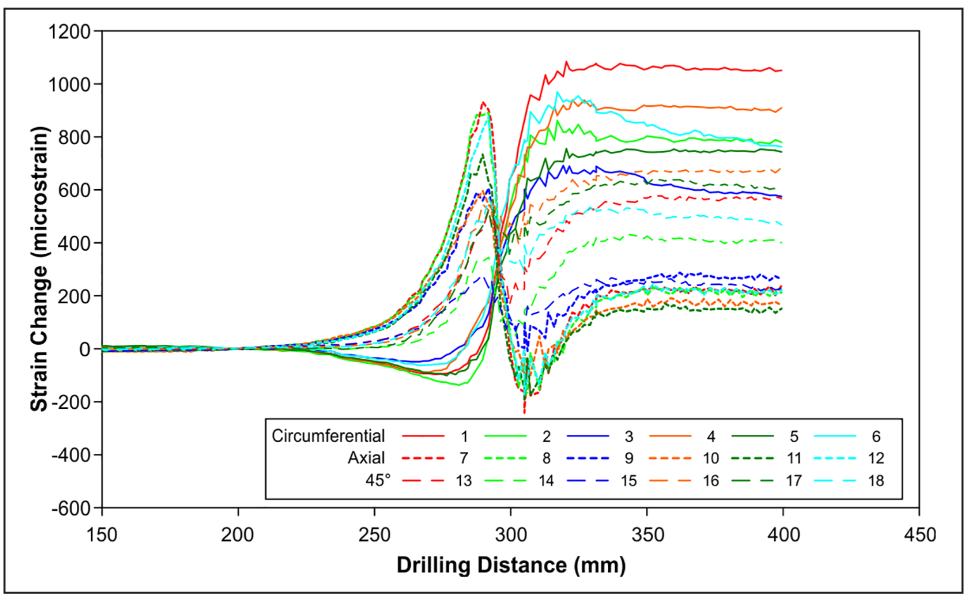

Figure 5. Example of strain changes observed during overcoring.

With the downhole logging system, strain, pressure, and temperature readings are recorded every few seconds commencing before the instrument is deployed until it is recovered, leading to a high data density. Figure 2 shows the strain changes associated with stress relief measured during overcoring for each of the 18 strain gauges. The general form of the overcoring strain changes can be used as a basis to identify rosettes of strain gauges that may be behaving irregularly and should be ignored in the final analysis.

In-situ stresses are calculated from the measured strains using the technique described by Leeman and Hayes (1966) and variously enhanced by others. A minor correction can be made during analysis to include the effect of the 0.3–0.5 mm thick epoxy cement layer formed between the membrane and the rock using the analysis described by Duncan-Fama and Pender (1980), but the effects of this correction are slight. For all practical purposes, the strain gauges can be considered bonded directly to the borehole wall.

The membrane material has a modulus of elasticity of only a few mega Pascals and is soft enough to be ignored in the analysis of strains and to keep the tensile stresses generated at the rock and instrument interface during overcoring low enough to avoid overloading the epoxy cement bond strength and the tensile strength of the rock. This means that successful overcore measurements are possible in a broad range of difficult drilling conditions and low strength materials such as coal.

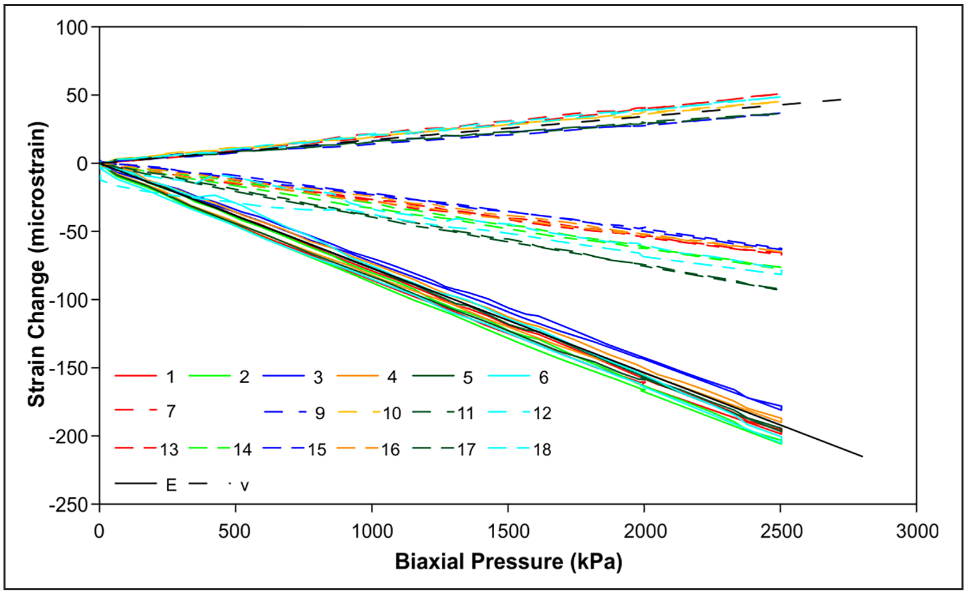

Figure 6. Example of biaxial test result.

Biaxial Pressure Test

A biaxial pressure test is conducted after the overcore is recovered. External pressure is applied incrementally to the outside of the rock annulus and is recovered when the pilot hole has been overcored with the instrument inside it. The elastic modulus and Poisson's ratio of the rock material can be estimated from this test at a range of different pressures. The strain changes measured provide not only an estimate of the CHILE rock properties but are also useful as an indicator of non-CHILE behaviour that may have been caused by deformation during the overcoring process.

Figure 6 shows an example of a biaxial test result. The circumferential gauges show compressive strain changes consistent with the application of external pressure to the outside of the overcored rock annulus. The axial gauges show tensile going strain changes due to the Poisson's ratio effect of the external pressure being applied to the rock annulus.

Laboratory Testing

Core recovered from the pilot hole at the location of the strain measurements is tested in a multi-stage uniaxial compression test to further confirm the elastic properties of the rock material. Axial and circumferential strain gauges and the load and displacement records of the compression test all the elastic properties of the rock to be estimated during three or more load and unload cycles up to failure in uniaxial compression.

Out-of-Roundness Testing

The out-of-roundness of the overcore is determined by measuring the diameter of the core at multiple orientations using a micrometer with a nominal precision of 1 micron. The direction of the largest diameter is indicative of the major stress perpendicular to the borehole. The concept is that, as the core enters the core barrel, it expands as the in-situ stresses are relieved. Strain measurements in the overcoring show this process occurs over a distance of 3–4cm. The rotating diamonds in the tip of the core barrel grind away the core to be circular during the early stages of this expansion, but the later stage occurs after the rotating diamonds have moved on. This later stage is captured as out-of-roundness in the core that can be measured. The overcore is oriented by the downhole compass system, so the direction of the largest diameter can also be oriented. Experience indicates that the largest diameter correlates closely with the direction of the major stress acting across the plane of the borehole when the out-of-roundness is greater than about 10 microns.

The out-of-roundness test is very useful to confirm the orientation of the major stress independent of the strain gauges bonded to the inside of the pilot hole.

Assessment of Elastic Properties

The elastic properties of the rock mass are determined in three separate tests:

- in situ pressure test conducted prior to overcoring
- biaxial pressure test conducted after overcoring
- laboratory tests on core recovered from the pilot hole

These three independent measurements are conducted on the rock at various stages of the measurement process and, therefore, at various levels of confining stress. The different conditions provide insight into the rock behaviour and the impact of drilling on the rock as it is unloaded and recovered from the hole. In a CHILE material, all three tests would indicate the same values of elastic properties.

Variations in elastic properties are commonly observed, and these variations have provided useful insights into the processes that occur at the tip of a borehole during drilling and a range of factors that affect the behaviour of rock materials. Figure 7 shows an example of the elastic modulus variation at different confining pressures, represented in this figure as the first stress invariant or sum of the three principal stresses. A refined estimate of the elastic modulus of the rock midway between the in-situ first stress invariant and zero can then be applied in the stress analyses.

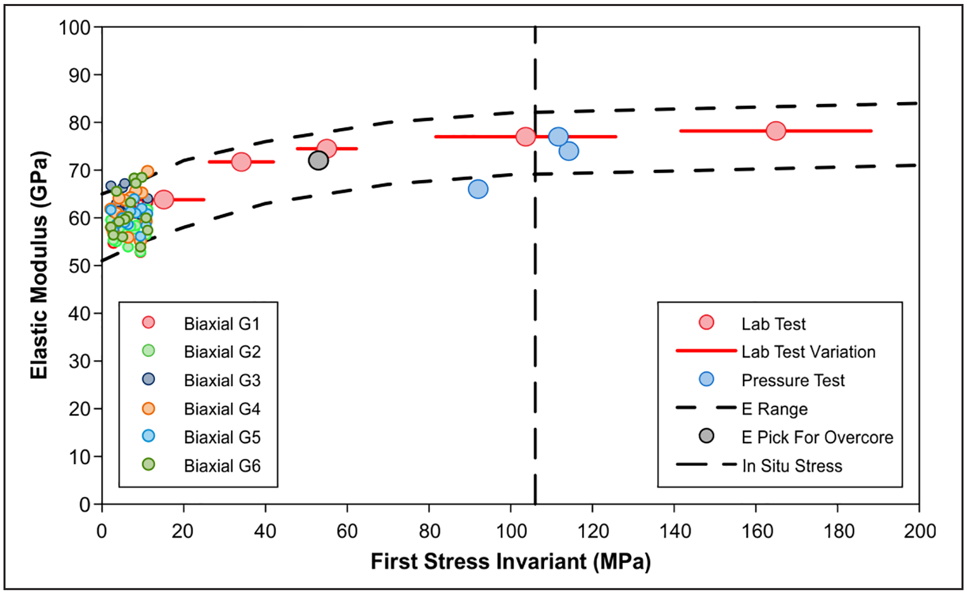

Figure 7. Variation of elastic modulus with first stress variant (sum of the three principal stresses).

OVERVIEW OF KEY DEVELOPMENTS

A number of key technical challenges were overcome to enable successful stress measurements at depths beyond a few hundred metres. These are described in more detail in this section.

Drilling Improvements

To streamline the drilling processes, a 48mm-diameter version of the ANZI strain cell was developed to allow overcoring with standard HQ2 and HQ3 coring equipment. A spline drive sub is installed behind the core barrel that provides for a wireline deployable downhole drilling system similar to that used by Hiltscher, Martna, and Strindell (1979). The driver sub can be installed at any time because it does not interfere with routine drilling operations.

The downhole drilling assembly is pumped down in a fashion similar to the inner tube, landing in the driver sub and protruding out through the HQ bit. The HQ rod string is raised off the bottom prior to deploying the downhole drilling assembly sufficiently that the protruding bit does not contact the end of the hole. The downhole drive drilling assembly rotates with the HQ drill string, and a series of seals and stabilisers direct drilling fluid to the bit face. Once drilling is completed, the downhole drilling assembly is retrieved on the overshot.

The end of the hole is first shaped with a special conical shaped diamond bit to remove any core stub and provide a smooth lead in to the pilot hole. A double tube LTK48 core barrel is then used to drill the 48mm-diameter pilot hole, avoiding the need to trip the rods and replace the HQ barrel. This wireline-deployed downhole drilling system was first used in 2014 to successfully prepare a 48mm-pilot hole for an overcore measurement at 160m depth.

Downhole Logging System

A self-contained downhole logger module and new deployment system were designed to eliminate connectivity from the instrument to the surface. This final piece of the system enables the ANZI strain cell to be deployed routinely to much greater depths than was previously possible. The downhole logger has the following benefits compared to logging at the surface via a cable:

- Increased accuracy, stability, and frequency of strain readings are achieved because the data cable that is sensitive to environmental effects is eliminated.
- Instrument internal pressure, downhole water pressure, and temperature can be recorded during the entire downhole duration.
- The need for a hydraulic cable winch system for deployment is eliminated.
- Less equipment is required, allowing faster deployment and airfreighting of equipment.
- Manual handling is reduced, and all significant hazards are eliminated.
- Drill rig downtime is reduced significantly while the measurements are made.

A prototype data logger housing was constructed in December 2015 for deployment to 1000m. Design, manufacture, and testing of the electronics in the logger were completed in June 2016.

A complete redesign of the instrument deployment system was required for the downhole logger. The deployment system comprises two separate modules that are deployed together but recovered separately, one before overcoring and one after overcoring.

The full assembly consists of an upper landing module and a lower logger module that is connected to the ANZI strain cell and orientation module. These are connected together at the collar of the hole prior to deployment, the ANZI strain cell is coated with epoxy cement, and the assembly is released into the drill pipe and allowed to float down under its own weight. The assembly lands and seals on the landing ring in the core barrel. Cell inflation is achieved through pressurisation of the drill pipe at the surface through a series of valves and seals in the instrument and deployment assembly.

Cure time for the epoxy cement is temperature dependent. A testing program measured the relationships between temperature and gel time and between temperature and cure time. If necessary, the rate of descent of the installation assembly can be optimised depending on the rock temperature so that the instrument lands before the cement begins to gel. A dummy cell is typically run prior to cell installation to confirm the rate of descent, that the instrument will land successfully, and to measure the downhole rock temperature.

Once the epoxy cement has cured and the in-situ pressure test has been conducted, the upper module is detached from the lower module and is recovered on the overshot. The inner tube is then pumped in and seated with the downhole logger inside. The ANZI strain cell is then ready to be overcored.

In June 2016, after six months of laboratory and field trials, the downhole logger and deployment systems were used for the first time. Three successful overcore measurements were conducted at depths between 200m and 300m. In November 2016, successful overcore measurements in inclined holes at depths of 547m, 810m, and 850m were conducted in a single 10-hour shift with a return to normal drilling immediately after. In February 2018, several successful measurements were made at the bottom of a 740m-deep borehole collared from an underground mine roadway at 1340m depth.

OVERCORING IN EXPLORATION BOREHOLES

Conducting overcoring from surface exploration boreholes means it is now possible to routinely conduct measurements at mining horizons remote from underground excavations. This capability has several benefits. The potential to realise these benefits by being able to obtain high-confidence estimates of the three-dimensional, in-situ stresses has driven the development of the ANZI strain cell for use in exploration holes. This capability represents a significant breakthrough for the design of underground mines and underground excavations.

The benefits of understanding the in-situ stress field during exploration and the design phase of an underground excavation are significant. Once the in-situ stress orientations are known, underground excavations can be designed to minimise stress concentrations on key infrastructure, reduce the investment in reinforcement, yet still take advantage of elevated, in-situ stresses to fracture rock and induce caving.

The ability to conduct overcore measurements at large distance from mining excavations means that the extent of horizontal stress relief can be directly measured, characterised, and taken in to account in mine design. An example of this characterisation is presented in Coutts et al (2018). The effects of stress relief toward extracted longwall panels are now recognised and are routinely being measured by subsidence monitoring systems up to several kilometres in advance of longwall mining (Mills, 2014). Characterisation of the stress relief profile is seldom possible with measurements made from underground because the most advance development headings are usually still within the zone of stress relief. Variations in stress magnitudes are commonly and incorrectly ascribed to variation in strata conditions rather than stress relief effects.

Being able to obtain high-confidence measurements of the in-situ stresses at the planning stage provides the opportunity to take advantage of these stresses. Not only does it become possible to protect key infrastructure by locating this infrastructure away from areas of stress concentration, advantage can be taken of the major stresses to promote caving.

CONCLUSIONS

The capability to deploy ANZI strain cells in exploration boreholes represents a significant breakthrough for the design of underground mines and underground excavations. Being able to obtain high-confidence measurements of the three-dimensional, in-situ stresses at the planning stage of any underground construction activity provides the opportunity to take advantage of these stresses in design of underground structures. Not only does it become possible to protect key infrastructure by locating it away from areas of stress concentration, advantage can be taken of the major stresses to promote caving through appropriate design.

The ANZI strain cell has a range of operational features and analytical simplicities that have enabled in-situ stresses to be successfully determined in a wide range of rock types and applications over the last three decades.

The high levels of redundancy in both the instrument and the measurement technique are designed to provide an indication of the confidence that can be placed in each result and to enhance the understanding of material behaviour at the point of measurement and ground behaviour at the site more generally.

The development history of the instrument is described in this paper together with the key steps that enable high-confidence measurements in exploration boreholes at depths in excess of 800m. These measurements are able to be conducted within a single shift, allowing overcore measurements for the determination of the full three-dimensional, in-situ stress field to be made a routine component of exploration activities.

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