In Situ Stress Determination: Recent experiences in acquisition and analysis

Deryk Forster[1]
Dr Richard Kelly[2]
[1]*Technical Principal – Engineering Geology, SMEC Australia Pty Ltd, Brisbane*
[2]*Chief Technical Principal – Geotechnics, SMEC Australia Pty Ltd, Brisbane*

As part of the development of some dams and hydroelectric power schemes, deep infrastructure is often required which requires and understanding of the in situ stresses of the rock mass. Recent works completed in southern Australia and Europe have led to improved methodologies for conducting effective, reliable, and repeatable measurements of in situ strain and/or deformation, as well as the subsequent estimation of in situ stress.

In situ stress testing is generally an item that is specified as part of a geotechnical investigation, however it is not commonly well understood in terms of reliability, repeatability, or, in fact, what the result actually means and its implications to project design. Commonly, a handful of tests are completed, with variable results, which often generates more confusion than answers.

This paper provides a discussion of recent in situ stress testing completed for two deep Australian projects. It summarises the aim of the investigations, test selection process, laboratory testing, data review and model development. This is to illustrate how complex the estimation of in situ stress can be and some of the pitfalls that may be avoided whilst acquiring and assessing the data. It also examines several different testing methods available in the Australian and International industry and some of the analysis techniques available to dam and tunnel projects. Finally, the paper provides an update on topical developments provided at recent workshops in Europe.

Introduction

In Situ Stress (ISS) determination is important in the design of underground openings and major surface excavations in rock in order to ensure appropriate support is provided. Common applications include nuclear waste repositories, nuclear power stations, tunnels, machine and transformer halls for hydroelectric power stations, railway stations, mines and gasification projects. To understand the stress conditions at specific locations within the proposed structures or openings, various techniques are available for acquiring data.

From the outset, it is important to note that the phrase 'stress measurement' is a misnomer, as the measurements acquired in situ are that of strain in a specific orientation. From these measurements, when combined with additional input from laboratory testing, an estimate of the in situ stress condition can be made, assuming the materials behave in a poro-elastic manner. As such, a stress measurement is more appropriately named a 'stress estimate'. In order to achieve a estimate of the in situ stress, three steps are required: 1) Data acquisition, 2) Geomechanical [laboratory] testing, and 3) Data analysis.

Implications for dams

In situ stress conditions require determination in situations where there is either a) existing evidence of high in situ stresses, such as rock bursts, spalling or well developed stress relief jointing, or b) in deep applications such as hydroelectric power stations and their associated tunnels. In some instances, rocks containing significant in situ stresses may be present at, or very near to the surface. An example of such a situation is within the foundations of the concrete gravity dam at Burdekin Falls in North Queensland. This case has been studied on several occasions since exploration began in the 1970s, with several in situ stress measurement techniques employed to understand the in situ conditions included the slot test (Otto, and overcoring using a United States Bureau of Mines style tool. Bock et al (1987) reported stresses ranging between 10 – 20 MPa within the river channel, where up to 50 m of material has been removed by erosion, to 30 – 35 MPa in the left abutment. Typically, these stresses strike north-northeast (Bock et al, 1987). The high stress conditions were identified due to a distinctive population of sheet joints, some of which developed during construction, as illustrated in **Figure 1**.

Determining and understanding the in situ stress conditions is essential in managing the foundation during the excavation and construction phase so as not to trigger the development of potential failure surfaces or seepage paths.

Figure 1 Example of stress relief joint at Burdekin Falls Dam in Fell et al (2015)

An example of bursting of a rock mass is provided as **Figure 2**.

Figure 2 Indication of highly stressed rock mass at a dam in Queensland.

Step 1: Data acquisition using in situ measurement methods

In situ strain measurement

The majority of in situ stress measurement techniques for civil applications use the process of overcoring. Other methods, such as hydraulic fracturing can provide in situ stress data, through are somewhat less commonly used during the investigation of civil structures. Overcoring involves the drilling of a hole using conventional coring techniques, such as HMLC (∅ 63.5 mm core) or NMLC (∅ 51.9 mm core) [or their wireline equivalents] to the target interval. At this point, a smaller diameter hole, referred to as the pilot hole, is advanced below the base of the original hole. The length and diameter of the pilot hole vary by service provider. A shallow countersink is often installed at the base of the original hole to facilitate the installation of the tool. The measurement tool is then installed into the pilot hole. Both the tool and the pilot hole are then over cored using the conventional coring equipment. As the coring bit passes over the tool, any change in deflection or strain at the wall of the pilot hole [from that prior to the commencement of overcoring] is measured, allowing an understanding of the local strain conditions to be determined.

There are several tools available for use in measuring the deformation of the pilot hole during the overcoring method. These tools utilise either a series of micrometers to measure the change in shape of the hole, or a series of strain gauges. The micrometer system relies on a series of pins pushing outward on the wall of the hole, and the strain gauge system involves directly bonding the instrument and strain gauges to the borehole wall.

Data is typically acquired by specialised contractors using conventional exploration or geotechnical drilling rigs and core barrels.

Site acquisition is somewhat complicated as the test interval is often selected by the Client's Engineer or Geologist, typically aimed at determining the in situ stress conditions within the proposed underground excavation. The location of the test is, at the time of selection and test preparation unknown, so the operators must use their judgement, based on the previous core run, to decide if the test should be attempted. Should the previous run indicate heavily broken ground, the test may be deferred until such time improved ground conditions are encountered. Appropriate test conditions are decided in direct consultation with the service provider. This is due to the effect of broken ground which may have relaxed during the drilling of the pilot hole or may also develop significant noise during overcoring, masking the true relaxation of the rock.

If the test proceeds, a pilot hole is drilled to a depth appropriate to install the tool, with the top countersunk to assist with insertion of the tool. The USBM style tools may then be installed directly into the pilot hole, with over coring commencing with little delay. Should CSIRO or ANZI cells be used, the tool is prepared [with the epoxy] and deployed to the base of the hole. Additional information about the variety of tools available is provided later in this paper.

The depth of testing is constrained by several factors including: a) water pressure, b) hole depth/length, and c) temperature. With each new generation of tool, issues with waterproofing of the electronics and protection against high [geothermal] temperatures have been reduced with improvement in solid state electronics and flash memory. Similarly, one of the major depth limiting factors, the epoxy, has also been improved, though provides a major limitation for investigations below 700 m [hole length]. Once mixed, the epoxy has a known working time at the ambient temperature.

The acquisition of in situ modulus, in addition to surface biaxial cell testing, is considered of significant value when selecting the input value for Young's Modulus.

Overcoring methods are, however, often more unreliable than reliable, as '*…the success rate with overcoring methods rarely exceeds 50 %.*' (Herget, 1993).

Two or three dimensions?

One of the major issues with the 'measurement' of in situ stress is that of an inclined stress field. Many tools were developed and used in coal mining applications, where stresses may be more horizontal or low angled, or nuclear facilities in massive, homogeneous igneous rocks, where stresses may be vertical and horizontal. The use of strain gauged tools allows inclined stress fields to be assessed, such as in folded and faulted rock of varying strength and elasticity.

Significant fracturing of the rock forming the borehole, or in the vicinity of the hole, can also influence the recorded change in strain during the overcoring process. In some cases, the use of a three-dimensional tool can assist in the interpretation of such datasets. Additionally, where the rock is not isotropic, multiple tests using USBM style tools, undertaken at different orientations, or strain gauged tools can assist in the analysis of stress conditions in these environments.

Some operators using the LVDT tool have countered this problem of measuring deformation normal to the axis of the tool, but using multiple, variably oriented and inclined boreholes, to determine the inclination of the stress field, therefore the maximum estimated stress.

The minimum horizontal stress (Sh_{min}) may also be estimated in the horizontal domain using in situ hydraulic testing methods, such as the hydraulic fracturing test. This, when coupled with acoustic or optical televiewer scans, can provide an indication of the minimum in situ stress and the orientation of the same. Where an in situ stress test can often provide an indication of stress and orientation, hydraulic testing requires televiewer data, showing breakout, to confirm the stress vectors.

Two dimensions

United States Bureau of Mines (USBM) tool

This tool comprises a series of six micrometers arranged about the instrument at 60° intervals relative to a single plane oriented normal to the axis of the tool (Figure 1), allowing deformation of the 'circular' pilot hole to be measured at regular intervals. This tool is designed to assess stress conditions near existing underground openings, hence the cable. USBM style tools used in applications where an inclined stress field may be present can, in our experience, significantly underestimate the maximum horizontal stress (Sh_{Max}). This device is reusable.

Figure 3 USBM style borehole deformation tool (arrow shows location of micrometers). (Source: https://www.geokon.com/5000)

Linearly Varying Displacement Transducer (LVDT) Cell

This tool is of a similar arrangement to the USBM however of much larger diameter so as to remove the effect of deformation and stress relief occurring in individual crystals grains (Figure 2). The larger hole diameter required also allows for greater relaxation of the rock mass, therefore more precise measurement when compared to the error of the micrometers. This tool may be used in overcoring or side coring applications, the latter being where a second hole is drilled immediately adjacent to the hole in which the tool is installed, typically near existing underground openings and voids to confirm stress conditions or monitor relaxation of the rock mass. This device is reusable.

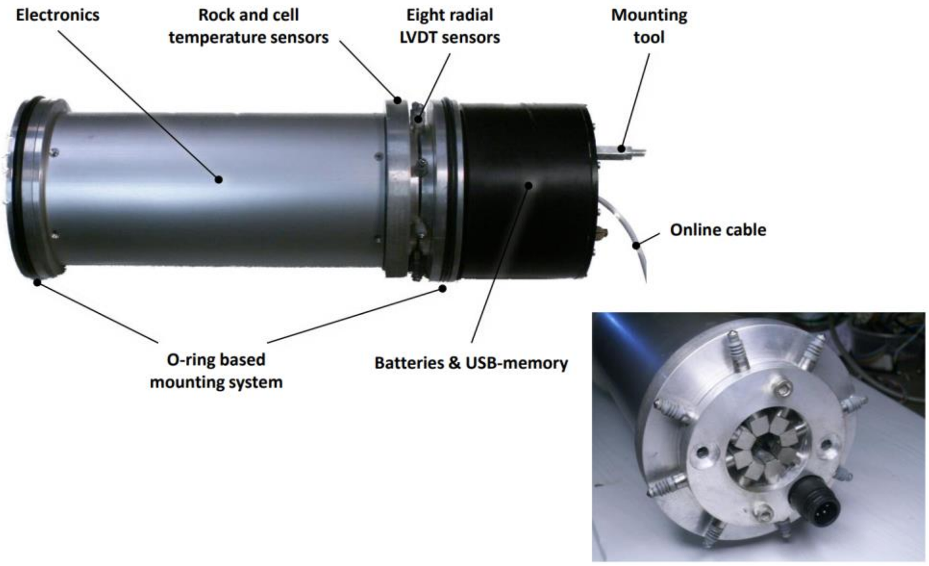


Figure 4 Stress Measurement Company Oy's LVDT Cell (Source: http://www.smcoy.fi/files/LVDT%20cell%20stress%20measurements.pdf)

Czech Cone Tool

The Cone Tool is designed for measurement of stress conditions close to existing underground openings or surfaces as the instrument has no onboard logging capability (Figure 3). The strain gauged instrument is glued into a countersink in the base of a borehole and is then overcored or side cored. Similar to the USBM or LVDT tool, it is commonly used close to existing openings or voids, such as coal mines. This tool is intended for single use only.

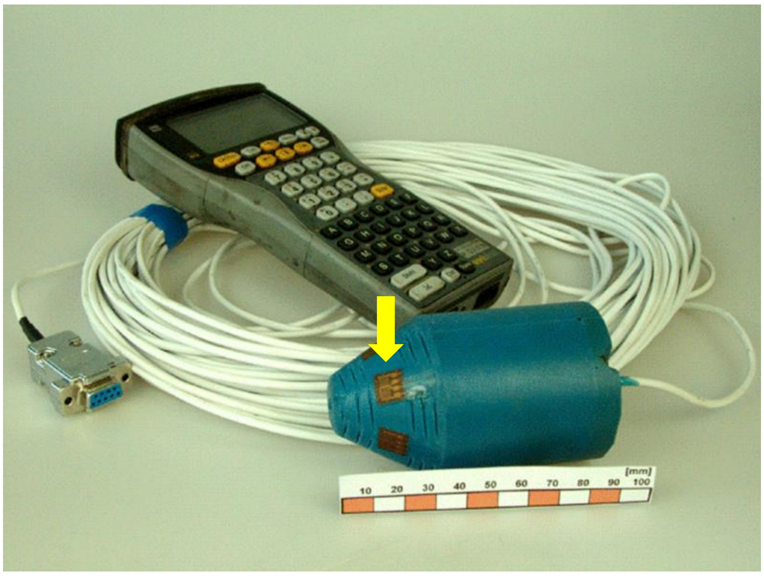


Figure 5 Cone Tool showing cable and readout unit. Strain gauges shown about the snout of the tool (arrowed).

Three dimensions

CSIRO Cell

The CSIRO Cell, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) comprises three sets of three strain gauges, placed about the instrument at 120° intervals (Figure 4). Each strain gauge set comprises one gauge oriented normal to the axis of the tool, one parallel to the axis of the tool, and the third at 45° to the tool axis.

This tool has been utilised extensively around the world, however operators anecdotally report success rates for measurement in the order of 50 %. This is partly attributed to the stiffness of the membrane, upon which the strain gauges are mounted, and the setting time of epoxy utilised to affix the strain gauges to the rock.

Users have indicated that, in some instances, the cell reports results consistent with the deformation in the membrane as opposed to deformation of the rock. This tool is intended for single use only.

Figure 6 Strain gauge arrangement about the CSIRO cell, showing parallel, normal and inclined strain gauges (arrowed).

ANZI Cell

The ANZI Cell, developed by Strata Control Technology (SCT) (Australia) is of similar design to the CSIRO Cell, however, with several distinct variations. The membrane upon which the strain gauges are mounted is significantly more flexible, similar in texture to a ballistics gel.

A different epoxy has been developed providing a greater travel time prior to setting, allowing much deeper tests to be attempted. In addition, this cell utilised additional strain gauges, with six sets of three gauges located about the tool, in a similar arrangement (parallel, 45°, and normal) to the CSIRO Cell (Figure 5). Operators suggest the success rate for this tool exceeds 75 %. This tool is intended for single use only.

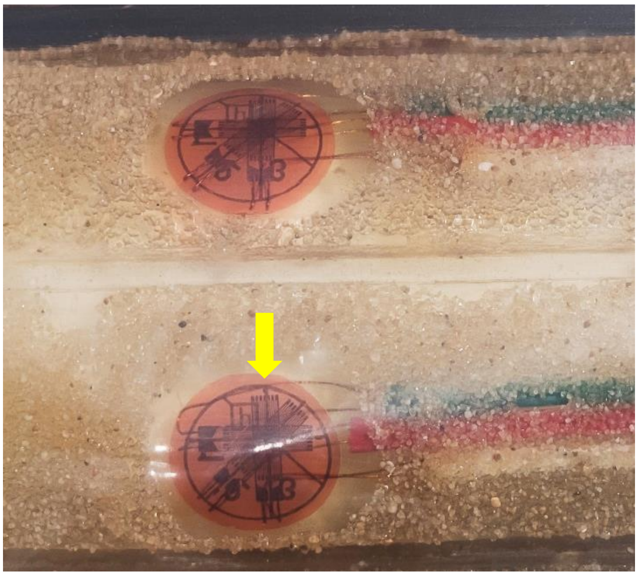


Figure 7 Arrangement of in situ strain gauges about ANZI cell, showing parallel, normal and inclined strain gauges (arrowed).

Other tools

Other operators have developed their own tools, being variants [to some extent] of the original USBM tool. Some tools utilise similar micrometer arrangements, or variations of the arrangement of the pins about the tool and in multiple horizontal planes along the axis of the tool. In most cases, however, only six pins, which may fall across several planes, are used to measure deformation.

Step 2: Geomechanical/laboratory testing

Once strain is measured, the estimation of the in situ stresses is completed using a series of equations which rely on rock mechanics input data including Young's Modulus, Poisson's Ratio, Biot's Coefficient and Uniaxial Compressive Strength (UCS). The calculations are very sensitive to Young's Modulus, with up to 50 % variation in calculated stress magnitude possible based on changes in modulus alone, with similar, though less sensitive responses, to changes in Poisson's Ratio and UCS. Variability in Biot's Coefficient may vary results by up to 7 % in some cases.

In hole Young's Modulus testing

To improve confidence in Young's Modulus, some operators using the strain gauged techniques, undertake an in situ Modulus estimate. Once the instrument has been installed in the hole and the epoxy has set, the hole is pressurised resulting in deformation of the rock. From this in situ test, an estimate of Young's Modulus may be determined. This is completed on the internal surface of the pilot hole, being confined by the rock mass in situ.

Biaxial testing

Following completion of the overcoring process, the sample is returned from the hole and prior to removal of the tool and de-bonding of the attached strain gauges, a further site test can be completed. The sample may be inserted in a portable biaxial cell and pressurised, allowing the sample to be 'deformed' and a second estimate of Young's Modulus to be made. The measurements of strain are completed on the internal surface of a hollow cylinder. This on site test, assists in increasing the confidence around the modulus.

Biot's coefficient

This test is somewhat rare in Australia and is generally completed only by Universities. It is typically used in the oil and gas industry, thus most laboratories undertaking this test are based in the United States or Europe. This test provides an indication of the change in primary porosity of the rock as a result of changes in confining pressure. Laboratory Young's Modulus & Poisson's Ratio Testing

Conventional laboratory testing is completed on a solid cylinder of rock core to determine Young's Modulus and Poisson's Ratio. For some operators, this [Young's Modulus] result is used to confirm the in situ and surface tests, providing good confidence around the input value with the greatest influence on the calculation.

Supporting data (In situ testing)

Density

In situ density of the rock mass is of importance for all holes to more accurately estimate the overburden stress (σ_v). In terrains where thick weathering profiles exist, the σ_v may be significantly overestimated if adopting a laboratory density for a fresh rock sample for example. Similarly, there may be significant variations in density with depth, such as volcanic terrains where basalts may overlie sedimentary rocks, or in coal basins where sandstones may be interbedded with dense siderite beds. In these instances, the use of wireline acquired density, ideally gamma-gamma, may greatly alter the estimated σ_v, which impacts some horizontal stress estimates.

Sonic velocity

Sonic velocity data, primarily P-wave velocity, although S-wave velocity is also utilised in some applications, can be manipulated to estimate the UCS of the rock, in addition to estimating Young’s Modulus and Poisson’s Ratio (Figure 6).

These data, which are acquired using wireline tools/sondes, are useful in cross checking laboratory results, especially in variable or fractured rock masses. When in agreement with laboratory testing, the velocity data can be used to develop predictive stress models along other intervals of the borehole.

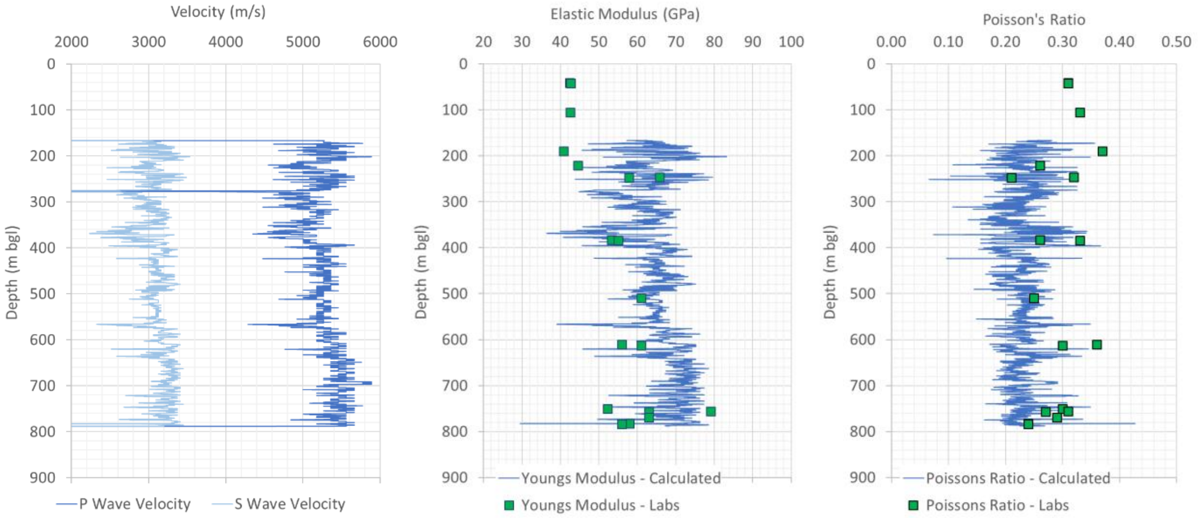


Figure 8 Left) Plot of P and S wave velocity, with Centre) calculated Young's Modulus, and Right) calculated Poisson's Ratio (blue trace) versus Laboratory results (green squares).

Acoustic televiewer

Acoustic televiewer data is used to confirm predictive modelling and the calculated stress orientation. Borehole breakout, which occurs with the in situ stress exceeds the UCS, the wall of the borehole is susceptible to breakout, which clearly shows in the televiewer image, confirming the orientation of Sh_{min} (Figure 7).

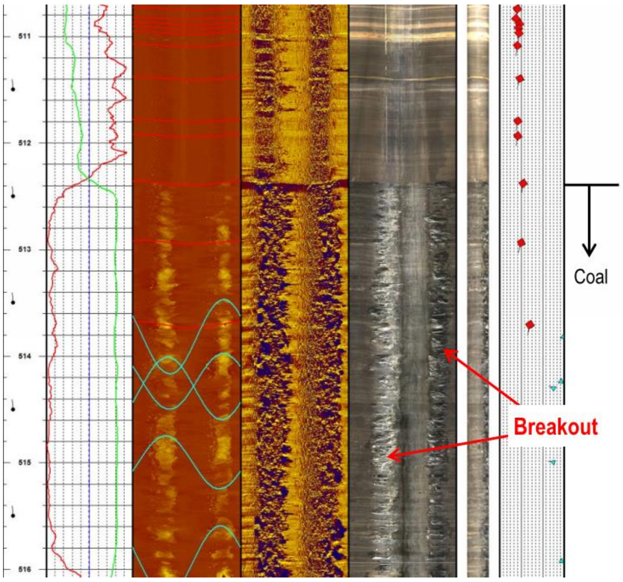


Figure 9 Acoustic image of borehole showing breakout relating to horizontal stresses exceeding rock mass strength.

Hydraulic fracturing test

The hydraulic fracturing test, also known as a Dynamic Formation Integrity Test, MiniFrac, and other company specific names and acronyms, utilise a double packer arrangement and can be located in a section of borehole either containing or devoid of fractures. Fluid volume and pressure is monitored during injection, with the pressure increased until such time that the existing fracture is reactivated (jacked open) or a new fracture is initiated and propagated. These data are utilised to assist in the determination of $\mathrm{Sh_{min}}$ orientation and, in some cases, magnitude.

Step 3: Data processing and use

Analysis of in situ strain measurements are commonly completed by the operator of the particular tool, with limited visibility to the end user as to the processing and algorithms applied to convert the measured strain to the estimated stress. This is because each tool differs in how it measures, records, compensates and calibrates.

Due to the numerous factors that influence the outcome of a test (e.g. rock condition, insipient fractures, grain size, stress orientation, water pressure, temperature, etc), the resultant dataset will often provide a significant spread of data. Similarly, the applied inputs to the stress calculation, such as density, Poisson's Ration and Young's Modulus, can significantly affect the result, as discussed later in this paper.

In more recent investigations, it has been the experience of the authors that submitting the data for critical review by independent parties has assisted in identifying which data are considered more reliable and robust, warranting inclusion in the dataset. Reviewing parties can analyse the original datasets to identify issues with vibration, temperature, and bond, to provide a second estimate of strain and stress. Where results are coincident, the dataset is adopted for use.

Three stresses are required in underground excavation design:

Vertical Stress (σ_v) $\sigma_v = \gamma z$ Hoek, 2007

Horizontal Stress ($\mathrm{Sh_{min}}$) $\sigma_h = \frac{\nu}{1-\nu}(\sigma_V - B \cdot P_P) + \frac{E}{1-\nu^2} \cdot \varepsilon_{hmin} + \frac{E\nu}{1-\nu^2} \cdot \varepsilon_{Hmax} + B \cdot P_P$ Reynolds et al, 2018

Horizontal Stress ($\mathrm{Sh_{Max}}$) $\sigma_H = \frac{\nu}{1-\nu}(\sigma_V - B \cdot P_P) + \frac{E}{1-\nu^2} \cdot \varepsilon_{Hmax} + \frac{E\nu}{1-\nu^2} \cdot \varepsilon_{hmin} + B \cdot P_P$ Reynolds et al, 2018

Ratio $k = \frac{Horizontal\ Stress}{Vertical\ Stress}$ Hoek, 2007

Where: γ = material density, z = depth (m), ν = Poisson's Ratio, E = Young's Modulus, ε = measured strain, B = Biot's Coefficient, and P_p = pore pressure.

Two studies have been completed recently in Southern Australia, using similar equipment and at similar depths and both show significant variability in data, with quality affected by all of the factors described above. In all cases, it has been difficult, based on overcoring methods alone, to confidently verify the in situ stress conditions. It is common for projects to report datasets such as that provided as **Figure 10**, where estimated horizontal stresses vary about a predicted gradient, with multiple k (k = horizontal stress/vertical stress) values required to 'calibrate' the hole, especially at greater depths, as marked by the alternate dashed lines on **Figure 10**. Some of these variations are due to test failures, whilst others are a result of passing into different geological and stress domains.

As datasets often contain data of variable reliability, it has become part of our investigative program to utilise more than one input for understanding the in situ conditions, especially in deep applications or where significant [geological] structural disturbance has occurred.

The first phase involves the acquisition of the conventional in situ overcoring stress measurement, using strain gauged data acquisition methods as a first preference, coupled with the onsite modulus determination and laboratory testing compliant with accepted standards and procedures. In addition, and following completion of drilling, selected test locations where overcoring occurred, are selected for hydraulic fracture testing to determine the minimum horizontal stress and normal stress. In addition to acoustic televiewer logging of the borehole, to determine the geometry of defects within the hole and to identify defects directly affected (jacked open) during hydraulic testing, the sonic velocity (V_S and V_P) are acquired to allow theoretical estimation of rock properties including Young's Modulus, Poisson's Ratio and UCS.

Finally, and to provide confidence across the project results, one or more holes may be selected for geomechanical analysis using techniques most commonly applied to petroleum wells when assessing well stability. Whilst not commonly applied to civil applications, the use of reservoir engineers in the assessment of in situ stress conditions had provided significant improvement in confidence when selecting data for use in design. The theoretical modelling, using televiewer and sonic data, coupled with the in situ [overcoring] provides guidance to designers as to the reliability of individual tests, and which data can be filtered from the dataset for use.

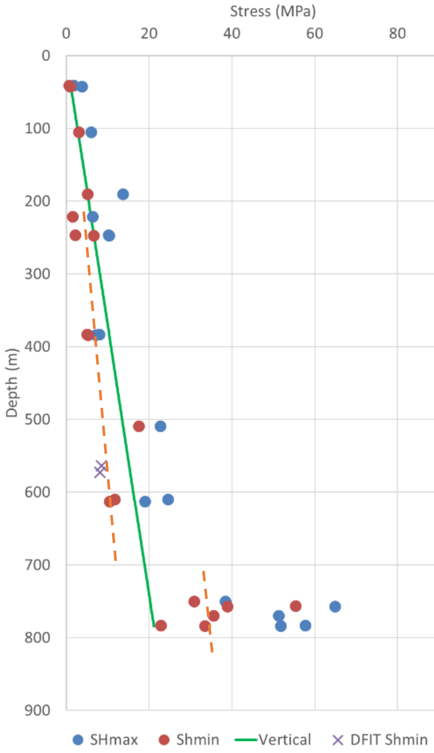


Figure 10 Example of deep project with significantly varying results with depth suggesting multiple stress domains, especially below 700 m.

This being said, it is common for such datasets to report an average reliability of approximately 50 %, with thorough technical review required to confirm those data which require exclusion from the dataset.

Data sensitivity

In addition to the data measured in the hole, the estimation of stress requires input of Young's Modulus, Poisson's Ratio, Biot's Coefficient and UCS. As with any data, there is an element of error associated with any test result. Should these errors be significant, the resultant estimation of stress can also contain significant error. For recent projects, rather than adopt a single stress value, a stress envelope has been applied, allowing Monte Carlo type analysis to determine likely in situ conditions based on the testing dataset. In this case, upper and lower bounds for each input value have been adopted to constrain the analyses.

The effects of thermal expansion [associated with the process of overcoring] must be considered and the strain gauge trace corrected to account for these artefacts.

To understand the effect of input data on the calculated maximum horizontal stress (σ_H), a single set of in situ strain measurements were utilised, whilst varying three of the four rock property input data: Young's Modulus, Poisson's Ratio and Biot's Coefficient. To illustrate the sensitivity, the following input data were applied to the calculations, with the change in estimated stress noted, as provided in **Table 1**.

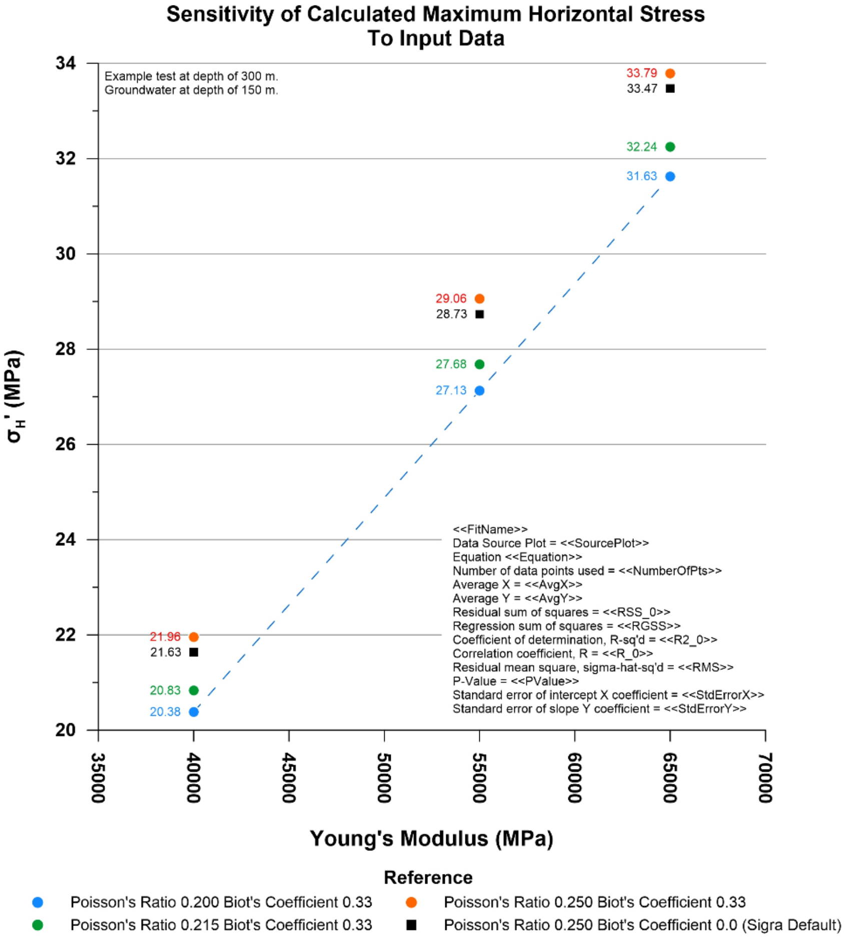
Table 1 Stress Calculation Input Data and Results showing sensitivity to data.

Young's Modulus (GPa)	Poisson's Ratio	Biot's Coefficient	σ_H (MPa)	Percentage difference from lowest result
40,000	0.200	0.33	20.38	0 %
	0.215	0.33	20.83	2 %
	0.250	0.33	21.96	8 %
	0.250	0.00	21.63	6 %
55,000	0.200	0.33	27.13	33 %
	0.215	0.33	27.68	36 %
	0.250	0.33	29.06	43 %
	0.250	0.00	28.73	41 %
65,000	0.200	0.33	31.63	55 %
	0.215	0.33	32.24	58 %
	0.250	0.33	33.79	66 %
	0.250	0.00	33.47	64 %

As shown in the table, by using the same input strain and σ_V, the estimated Maximum Horizontal Stress can vary significantly. In cases where no in situ modulus or surface biaxial testing is completed, the estimate relies entirely on a sample selected from core of similar [visual] appearance to that in the test zone.

In most cases, Biot's Coefficient is not measured in a laboratory and a number is drawn from experience or limited data available in the public domain or in-house databases. Typically, varying this value between the minimum and maximum allowable values may influence the estimated stress resulted by up to 7 %. Changing Poisson's Ratio from 0.15 to 0.35 increases the result significantly in rocks of lower modulus (30 GPa) by 35 %, to around 28 % in rocks of higher modulus (70 GPa). Modulus variability also affects the results in a similar, though slightly greater manner (refer **Figure 11**), with the magnitude of the effect reducing as modulus increases.

In some cases, the Young's Modulus has been determined on core containing the pilot hole used for installation of the tool. It was considered that this sample would report a differing Young's Modulus to a conventional, solid, core sample. To determine the likely impact this would have on the estimation of in situ stress, three samples were split into two equal intervals, with one cored centrally with a ∅ 25 mm pilot hole. Both were strain gauged as per standard practice and tested. These tests indicated the Young's modulus can be reduced significantly if a pilot hole is present as the rock is able to deform in two directions, as opposed to one in a solid sample. The results of this experiment are presented as **Figure 12**.



Note: Biot's Coefficient of 0.00 removes the influence of pore pressure.

Figure 11 Effect of variation of rock mechanics properties on estimate of Sh_{Max}*.*

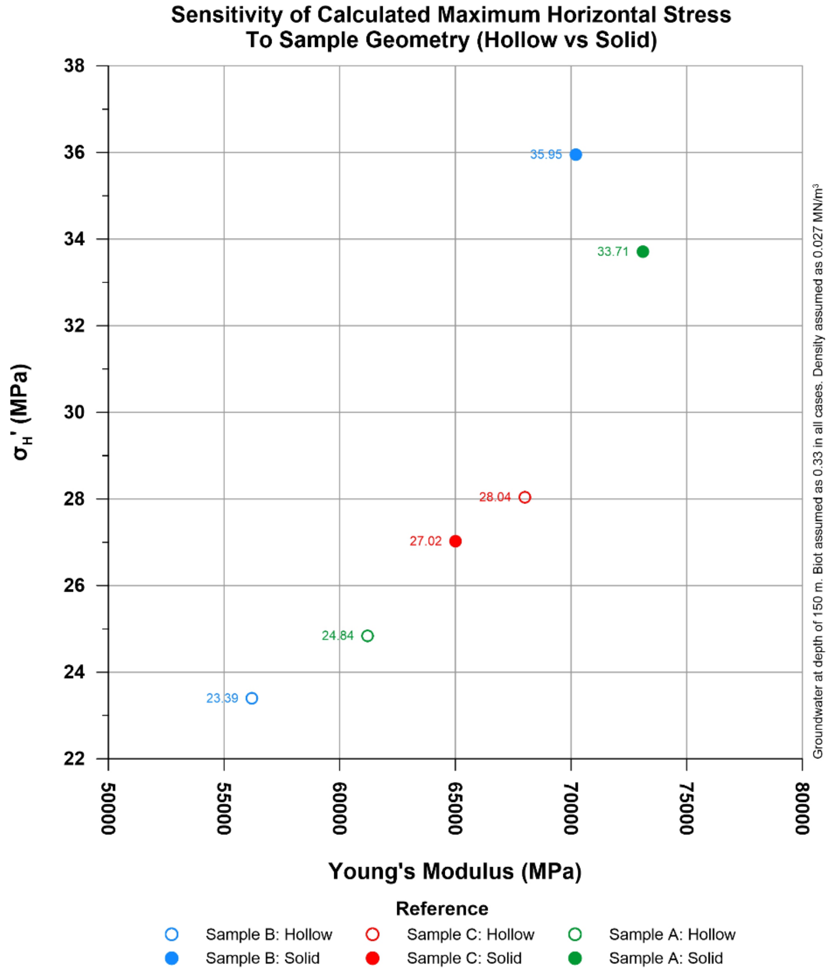


Figure 12 Young's Modulus, and calculated Sh_{Max} for Hollow and Solid core samples.

2018 Nancy (France) workshop

In November 2018, INERIS and GeoRessources conducted a two-day workshop in Nancy, France, entitled '*Technical Challenges of In Situ Stress Measurements',* which was attended by several of the leaders in in situ stress measurement from across the globe. Each of the different measurement techniques currently in use around the world, were discussed, with emphasis on both their successes [in application], but also on the failure of the tools, systems or techniques, to provide either a meaningful, reliable, or accurate result.

The majority of the methods available, and typically those with the greatest reliability and accuracy, are those related to measuring changes in stress in situations and environments adjacent to existing excavations and open voids, such as tunnels or mine workings. Where the frustration was generally concentrated was about the measurement of stress/strain in environments and locations distant to the user, where reliance was placed on remotely operating tools, drilling equipment and other remotely sensed data. The remote location also resulted in limitations in siting the tool to avoid defects in the rock mass, which may be [relatively] easier to achieve when testing within 5 – 10 m of the operator and visual guidance is available. In addition, the development of wedges in boreholes, or the drilling of completely new boreholes, is time consuming and, therefore, expensive, and accuracy of the test location is more constrained than in near excavation and void tests.

In situations of near excavation and void testing, the time and cost to advance boreholes is relatively inexpensive compared to targeting a potential underground excavation 1,000 m below a surface drilling position. Currently, only two or three tools, depending on geological environment, are suitable for such remote testing. Testing is constrained by limitations regarding water proofing of the electronics and epoxy, used to bond the strain gauges to the rock, and the composition of the rock itself. Whilst the location of a remote test may target a proposed excavation opening, the final test location is effectively selected blind. The test may be completed and only once the tool has been committed to the ground, can the user start to identify if the actual test location if suitable or not.

The workshop did confirm the approach recently adopted on several projects in Australia and overseas, where cross over between disciplines was starting to occur, although not by prior planning or design. Remote testing is an area where further development is required.

Summary

Through recent use of multiple in situ stress measurement techniques, in addition to industry discussion, there is no single method or procedure that will yield consistently high reliability rates in remote applications. This is primarily due to environmental factors that affect the test procedure, such as fracturing of the rock mass, water pressure, temperature, strain gauge bonding, micrometer seating and borehole geometry. Understanding inherent errors in laboratory tests, which provide key geomechanical inputs in the estimation of in situ stress, is also important for reliability.

Reliability issues are not uncommon and are an issue across the globe, affecting both mining and civil users attempting to determine in situ stresses at significant distances from the surface. Uncertainty surrounding results was raised by end users with those researchers present at the Nancy workshop in 2018.

Until such time that a new method is developed to improve confidence and repeatability of in situ stress measurements, it is becoming more common to apply multiple methods, some often borrowed from other industries (i.e. hydraulic fracturing from oil and gas), in order to provide a more robust data set for interpretation. Additionally, a statistically defensible dataset of laboratory derived geomechanical tests will greatly improve the estimated stress.

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