REVIEW OF OVERCORING TESTING TO MEASURE *IN SITU* STRESS FOR TUNNEL PROJECTS IN SYDNEY

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ABSTRACT

The magnitude and direction of *in situ* stress is important to the design and performance of an underground project. A number of techniques are available to estimate *in situ* stress in rock, with borehole deformation strain cells (a form of overcoring) and hydraulic fracturing being the most common used in investigative boreholes in civil projects in Australia. An assessment of recent stress measurements obtained from the overcoring technique for tunnels in Sydney indicates lower results for the magnitude of the horizontal stress, when compared to available published data on the Sydney horizontal stress field by hydraulic fracturing. Overcoring stress testing involves drilling a pilot hole in a borehole and measuring strains while overcoring. The calculation of the *in situ* stress further requires laboratory testing of the overcored rock sample to measure Young's modulus and Poisson's ratio. An iterative calculation is undertaken to determine the *in situ* stress in the rock. The intrinsic aspects of the overcoring testing method are discussed to assist in interpreting the stress field for tunnelling.

1 INTRODUCTION

The deformations and failures observed in underground openings in rock are governed by a number of factors; the key being rock mass strength, network of discontinuities, *in situ* stress, and shape of underground excavation, but also the construction sequencing and installed support measures. The first two are often assessed by using rock mass characterisation and classification systems along with rock mass failure criteria. The last three factors are somewhat controllable by prescription in the design. It is the middle one, *in situ* stress, that is 'not an easy task' and has been identified to be an unsolved problem of rock mechanics (Hudson, 2012). The magnitude and orientation of stress have been reported to be affected not only by weight of overlying materials and tectonic forces, but also by geological structure (both local and regional scale), residual stress and thermal stress (Kim, 1987). There is a complex interaction between each of these factors resulting in the state of stress varying spatially over short distances.

Measurements of *in situ* stress in the Sydney area have been undertaken for several decades and are well documented (Macklin et al, 2014; Enever, 1999). Subsequently there have been multiple linear correlations made between stress and depth data (McQueen, 2004; Enever, 1999; Bertuzzi, 2014) with more recent interpretations also considering stiffness of the rock mass (Oliveira, 2014). They have each recognised that the maximum horizontal stress is higher than the overburden stress, i.e., vertical stress. The presence of elevated horizontal stress in the Sydney metropolitan area has also been deduced from observations of displacements in deep excavations (Hewitt, 1999; Braybrooke, 1990; Pells, 1990) and failures in underground openings (McQueen, 2004).

Stress is not easy to measure as it is a tensor quantity, so it needs six independent components to be measured. These being three normal stress magnitudes that are orthogonal to each other, and three shear stress components. When the direction of the three orthogonal normal stresses are selected such that the shear stress components each equal zero, the normal stresses are then referred to as principal stresses. The *in situ* stress cannot be measured directly, but requires us to measure some response that comes about because of relief or additional stressing of the rock mass, whether it be a strain or deformation. Typically, this response measurement is undertaken in a stress-distributed zone such as a borehole or wall of a tunnel. Therefore, some interpretation needs to be made on how the borehole or tunnel would have already distributed the original *in situ* stress in the rock. For this reason, the currently reported *in situ* stresses calculated from measurements made *in situ* are estimates at best.

Historically, measurements of *in situ* stress for tunnelling projects in Sydney have been conducted primarily by hydraulic fracturing. There has been a significant number of stress measurements made in the last 5 years for multiple tunnelling projects currently under construction in the Sydney metropolitan area using the In-situ Stress Testing (IST) overcoring tool developed by Sigra Pty Ltd. Review of the results obtained from overcoring using the IST tool showed that estimates of *in situ* stress were on average less than those obtained using hydraulic fracturing and previously published data. The *in situ* stress testing results from two tunnelling projects are presented in this paper, together with details on how these estimates of *in situ* stress were calculated.

2 OVERCORING STRESS TESTING

2.1 OVERVIEW

There have been numerous methods developed to estimate *in situ* stress, each with their advantages and limitations, which have been summarised by Kim and Franklin (1987) and by other authors (Doe et al, 2006; Fairhurst, 2003). The overcoring method requires preparation of the borehole, whether it be through drilling a pilot hole or shaping the end of the borehole, placement of a gauge, then overcoring over the gauge and recording the strain changes as a result of stress relief. Some forms of overcoring require strain gauges to adhere to the walls of the pilot hole and measure the three-dimensional response of the pilot hole while overcoring. Other forms measure closure of the pilot hole while overcoring and therefore only measure two-dimensional response of the pilot hole.

The Sigra In-situ Stress Testing (IST) tool is a mechanical borehole deformation strain cell that is based on the United States Bureau of Mines (USBM) tool and uses the principle of overcoring to estimate the *in situ* stress state in the ground. A USBM gauge is two-dimensional, so measures closure of the pilot hole as a result of overcoring. It measures the deformation over the scale of the pilot hole diameter, which is advantageous in coarse grained rocks that may provide a different result from a smaller scale strain-gauge rosette depending on the response of different mineral grains (Cai and Thomas, 1993). An advantage and efficiency of the USBM tool is that it does not require cementation to the pilot hole walls.

The methodology for testing using the IST tool (Sigra Pty Ltd, 2017) requires replacing the inner tube of an HQ coring system with an assembly to drill a countersink. This is followed by replacing the countersink assembly with the pilot hole tool and drilling a pilot hole. The pilot hole is 500mm long and 25.5 to 26.5mm in diameter. Finally, the stress measurement tool is locked into the pilot hole. The stress measurement tool contains triaxial magnetometers and accelerometers to measure its position in the pilot hole. The inner tube assembly is then re-inserted and coring continues over the stress measurement tool. Each assembly is positioned at the base of the borehole by wireline, which makes it an efficient process that results in the whole testing process taking approximately one hour, depending on the depth of the borehole.

The IST tool together with the recovered overcored sample is then extracted from the borehole. The displacements recorded over the length of the 26mm diameter pilot hole are recovered and analysed. The IST tool is then extracted from the overcored rock sample and the rock core is sent to a laboratory for uniaxial compression testing of elastic unloading properties from cyclical loading (Sigra Pty Ltd, 2017).

2.2 CALCULATION OF *IN SITU* STRESS

The equations used to calculate the estimated *in situ* stress from the measured strains are explained here. Since the IST tool only measures strains in the horizontal plane, the vertical stress is estimated assuming the overburden load in sedimentary rocks is equal to 0.025MPa/m depth. The horizontal stress is envisaged to comprise two components: a portion from overburden self-weight from Poisson's effect and the rest from tectonic strain.

$$\sigma_{h\_1} = \sigma_{h(sw)} + \sigma_{h(tec\_1)} \; and \; \sigma_{h\_2} = \sigma_{h(sw)} + \sigma_{h(tec\_2)} \qquad (1)$$

where σ_{h_1} and σ_{h_2} correspond to the two principal horizontal stresses that are orthogonal to each other.

The corresponding horizontal stress components due to the overburden self-weight is equal to:

$$\sigma_{h(sw)} = \sigma_v \left(\frac{v}{1-v}\right) \qquad (2)$$

where v is the Poisson's ratio.

The horizontal stress components arising from tectonic strains are equal to:

$$\sigma_{h(tec\_1)} = \frac{E}{1-v^2}\left(\varepsilon_{tec\_1} + v\varepsilon_{tec\_2}\right) \tag{3}$$

$$\sigma_{h(tec\_2)} = \frac{E}{1-v^2}\left(\varepsilon_{tec\_2} + v\varepsilon_{tec\_1}\right) \tag{4}$$

where ε_{tec_1} and ε_{tec_2} are principal tectonic strains, which are measured as pilot hole closure by the Sigra IST tool.

To be able to calculate the *in situ* stress using equations (3) and (4), it is necessary to measure the elastic properties of the rock; namely, unloading Young's modulus and Poisson's ratio. The elastic properties are sensitive to the state of stress, so Sigra selects the elastic properties corresponding to the *in situ* mean stress, which is the sum of the axial and double the mean lateral stress.

3 ELASTIC PROPERTIES OF HAWKESBURY SANDSTONE

The elastic material properties of Hawkesbury Sandstone have been studied quite extensively (e.g. Pells, 2004; Pells et al, 1998). There have been many uniaxial tests conducted to measure the Young's modulus of Hawkesbury Sandstone, reporting both tangential modulus and secant modulus selected at 50% of the unconfined compressive strength (UCS). Correlations have been developed between UCS and Young's modulus (*E*). A typically reported ratio between the Young's modulus to UCS is in the order of 200, for both secant and tangent Young's modulus (Oliveira, 2014; Pells, 2004). Databases of laboratory test results have been used to develop tunnel design parameters in association with the Hawkesbury Sandstone classification system (Bertuzzi, 2014; Oliveira, 2014; Bertuzzi and Pells, 2002). The proposed ranges of intact Young's modulus for the better three classes of sandstone are given in Table 1.

Table 1: Summary of Young's modulus for Hawkesbury sandstone classes for intact rock

Class[1]	Bertuzzi and Pells (2002)	Bertuzzi (2014)	Oliveira (2014)
Class I Sandstone	8,000 - 14,000 MPa	8,000 MPa	6,000 MPa
Class II Sandstone		6,000 MPa	5,000 MPa
Class III Sandstone	6,000 - 10,000 MPa	4,000 MPa	3,000 MPa

Note: 1. Refer to Pells et al (1998)

For the purposes of calculating *in situ* stress from measured strains during overcoring, we ultimately need to obtain the rock parameters that apply to the relaxation experienced by the rock during overcoring. Presently this is usually not directly measured *in situ* by the IST tool, so assumptions are applied to laboratory tests that are carried out on the recovered rock core. Sigra Pty Ltd conduct uniaxial compression testing to obtain elastic unloading properties from cyclical loading.

The ISRM Suggested Method is to conduct a biaxial test for estimating the rock mass elastic properties (Sjoberg, 2007). The biaxial test measures the elastic rock properties of the overcored sample in the same plane as measurement of closure within the pilot hole during overcoring. The ISRM recommended procedure for conducting a biaxial test is to measure tangential strain (ε_T) using strain gauges that are bonded to the inner (pilot hole) surface of the overcored sample, which is effectively a thick-walled cylinder exposed to tangential stress (σ_T) at its inner surface. The Young's modulus is then defined as $E = \sigma_T/\Delta\varepsilon_T$ and the Poisson's ratio is calculated as $v= \varepsilon_T/\varepsilon_L$, where ε_T is the axial strain. Typically, the unloading secant values for biaxial pressures ranging between 3MPa to 8MPa are calculated and averaged for the three strain rosettes (Sjoberg, 2007).

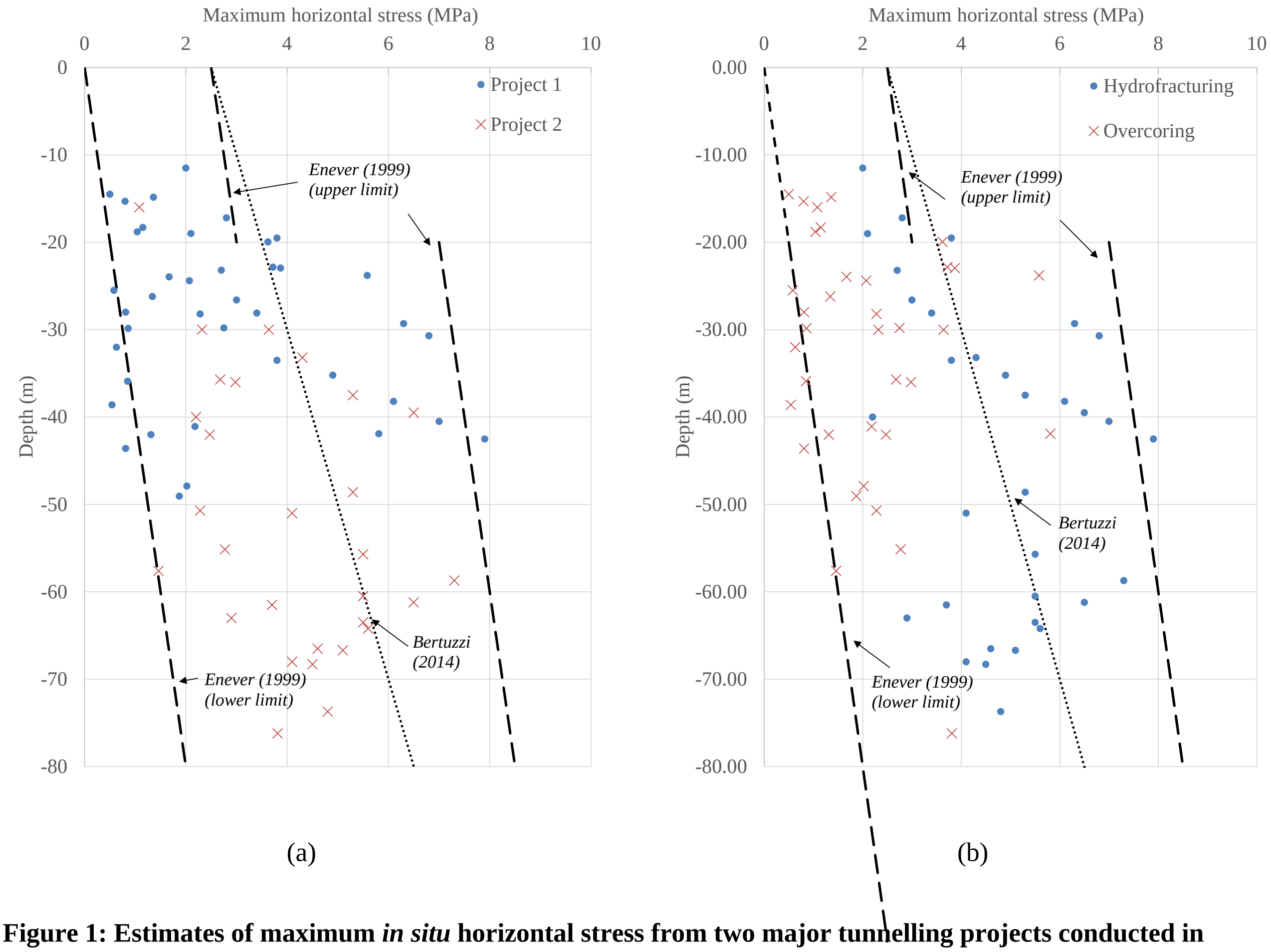
Another reason biaxial testing is recommended is that rocks can have elastic moduli that are not constant, rather, they increase with increasing minor or confining stress. This has been reported for porous or clastic rocks (Pells, 2004; Brown et al, 1989; Goodman, 1989) such as the Hawkesbury Sandstone.

4 *IN SITU* STRESS TEST RESULTS FROM RECENT TUNNELLING PROJECTS

4.1 OVERVIEW

Estimates of maximum horizontal *in situ* stress from two major tunnelling projects conducted in the Sydney area are presented in Figure 1. Figure 1(a) presents the estimated maximum horizontal *in situ* stress grouped according to the project, which typically fall between the upper and lower limit for maximum horizontal *in situ* stress reported by Enever (1999). The tests have been undertaken to a maximum depth of 50 m for Project 1, and 76m depth for Project 2.

Figure 1(b) presents the same data but grouped according to the test method used. It can be seen that the hydrofracturing method typically provided a higher estimated maximum horizontal stress compared with the IST overcored tool.



(a) (b)

Figure 1: Estimates of maximum *in situ* horizontal stress from two major tunnelling projects conducted in Sydney metropolitan area plotted against (a) project and (b) testing method

The trend mentioned above for Figure 1(b) is also evident in the statistical analysis presented in Table 2. The mean maximum horizontal *in situ* stress from overcoring is typically 1.0 MPa to 3.0 MPa lower than for the results obtained using hydraulic fracturing, down to a depth of 60 m. Such a variation in estimated *in situ* stress makes it difficult to interpret the stress field for tunnel design.

Table 2: Summary of maximum horizontal stress for the data in Figure 1(b)

Depth Range	**Overcoring (using IST tool)**			**Hydrofracturing**		
	Mean σ_H *(MPa)*	**Std. Dev. *(MPa)***	**Sample No.**	**Mean σ_H *(MPa)***	**Std. Dev. *(MPa)***	**Sample No.**
0 to 20m	1.36	1.03	7	2.68	0.83	4
20 to 40m	2.18	1.42	18	4.83	1.48	11
40 to 60m	2.30	1.36	10	5.61	2.00	7
60 to 80m	3.81	1.36	1	4.80	1.00	11

4.2 ELASTIC PARAMETERS USED IN CALCULATION OF *IN SITU* STRESS

A major factor in calculating the maximum *in situ* horizontal stress for overcoring using the IST tool is the derivation of the elastic parameters Young's modulus (E) and Poisson's ratio (v). These parameters are determined in the laboratory from tests on the thick-walled cylinder from the overcored sample. The equations used for these calculations are presented as Equations (1) to (4) above. A summary of the magnitudes of Young's modulus and Poisson's ratio from the two major projects considered in this paper is presented in Table 3.

Table 3: Summary of UCS, Young's modulus and Poisson's ratio from laboratory testing of overcored samples

		Unloading		**Tangent**		**Secant**	
	UCS (MPa)	**Young's modulus (MPa)**	**Poisson's ratio**	**Young's modulus (MPa)**	**Poisson's ratio**	**Young's modulus (MPa)**	**Poisson's ratio**
MEAN	31.0	4137.6	0.2	3916.5	0.2	4245.5	0.2
Maximum	56.8	9905.0	0.395	6583.0	0.346	9533.0	0.394
Minimum	15.5	1442.0	0.070	1310.0	0.003	1639.0	0.081
Standard Deviation	9.4	2056.1	0.064	1752.9	0.093	2143.0	0.100
Sample number	36	36	36	22	18	24	21
Mean UCS/*E*	-	136.9	-	128.7	-	135.5	-

Considering the results presented in Table 3, the mean ratio of unloading Young's modulus to UCS was 136.9, with a range of 53 to 312. These values are less than the previously reported ratio for Sydney Hawkesbury Sandstone of greater than 200 (refer to Section 3); however, this reported ratio usually considers either the tangent or secant Young's modulus, so for completeness they are also provided in Table 3. The laboratory test results from the two projects reported an average ratio of tangent and secant Young's modulus to UCS of 129 and 136, respectively, which is still less than 200.

For comparison, uniaxial compression testing conducted on ten solid core samples recovered from within 4m of the overcore stress testing depth were examined. The uniaxial testing provided elastic parameters, secant modulus and tangent modulus together with the unconfined compression strength (UCS). The UCS magnitudes measured for the thick-walled cylinder overcored samples are similar to those measured for the solid cores while the modulus values are considerably lower. Figure 2(a) presents the ratio of unloading Young's modulus obtained from the overcored samples to UCS plotted against the averaged ratio of tangent modulus to UCS for solid core samples. For completeness, the ratio of tangent modulus to UCS obtained from the overcored sample against the solid sample is presented in Figure 2(b). The tangent modulus to UCS ratio for the solid core samples tested ranged from 70 to 426. Overcored samples in the same stratigraphic horizon typically had a ratio that was half of the solid core sample, which can be related to low magnitudes of Young's modulus.

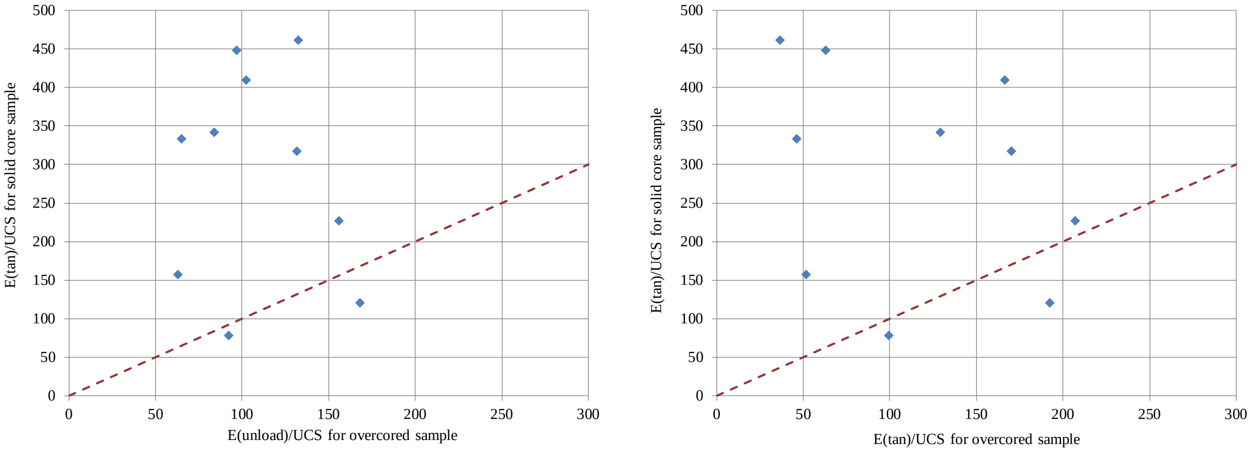
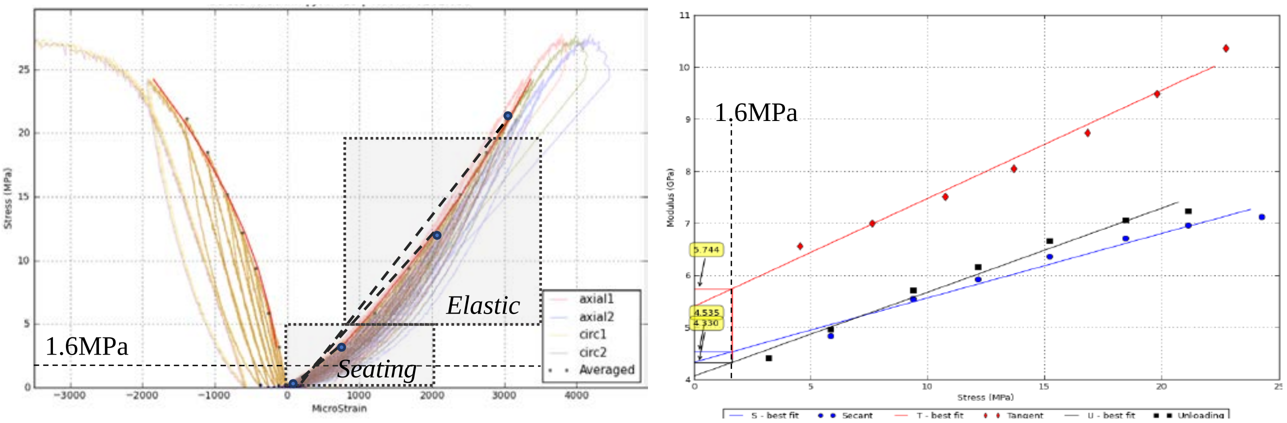


Figure 2: Comparison of (a) ratio of unloading Young's modulus to UCS for the overcored samples versus the tangent modulus for the solid core samples and (b) ratio of tangent Young's modulus to UCS for the overcored samples versus the solid core samples

An example of a stress versus strain curve of one of the overcored samples, is shown in Figure 3(a). There is initially a seating phase when deviatoric load is initially applied, which is an inelastic concave upwards stress-strain section. In this seating phase some fissures and pores close up (Goodman, 1989; Brady and Brown, 2005). Typically, unloading along the inelastic section of a stress-strain curve would result in the recorded strains not returning to zero when the uniaxial load is removed, which is not the case with this example. There are several loading and unloading cycles in the test, with the unloading modulus determined by the maximum strain achieved for an applied load. The strain that is measured when the sample is unloaded is denoted by the small blue dots presented in Figure 3(a). For cases where the strains in the seating phase are inelastic, the unloading path on the stress versus strain plot is approximately tangential to the curve or otherwise steeper than the tangent modulus. This section of low deviatoric stress should be treated with caution when using it to select elastic parameters as they may not reflect the true elastic response of the *in situ* rock at low stress.

Figure 3(b) presents the unloading, tangent and secant modulus for each of the stresses from which the uniaxial test sample was unloaded, for the test results presented in Figure 3(a). The yellow boxes show the final mean stress at which the elastic parameters are selected for use in the calculation to obtain the *in situ* maximum and minimum horizontal stress from the measured pilot hole closure. In this case, the stress is less than the lowest unloading stress point in the stress-strain curve. As discussed in Section **Error! Reference source not found.**, the stress at which the unloading Young's modulus is selected is dependent on the mean stress in the ground which would govern the rock stiffness during overcoring. For the example presented in Figure 3(a) and Figure 3(b), the mean stress obtained through iterative calculations was 1.6MPa, which is in the seating range of the stress-strain curve. This was the case for many of the overcored samples in the stress testing conducted using the IST tool for the two tunnelling projects presented in this paper.



(a) (b)

Figure 3: Example of (a) stress versus strain result from uniaxial compression testing of overcored sample, and (b) associated results for three forms of modulus versus strain obtained from plot in Figure 3(a).

5 DISCUSSION

In situ stress is difficult to measure for the many reasons discussed in Section 2. It is a tensor that has a complex spatial distribution because of the many variables that influence it. To undertake stress measurement, it is necessary to disturb the natural *in situ* stress state in order to conduct the test (e.g., drill a borehole, or a pilot hole, or excavate a slot, or a tunnel). Furthermore, it is necessary to quantify the elastic properties of the rock that give rise to the strains or displacements measured during the load-relief stress tests. Given the anticipated variable influence of these factors on *in situ* stress, it might be prudent to report estimates of *in situ* stress as a range, rather than a single value.

The ISRM recommendation for measuring the elastic parameters of overcored samples is to conduct biaxial testing on site. This test method tests the elastic parameters in the sample plane as the primary stress relief that occurs during overcoring. Parameters obtained from the uniaxial loading of the thick-walled cylinder overcored sample may not yield values representative of the elastic behaviour of the rock during the overcoring process. The effect on the stress-strain response of an overcored sample of relatively low strength Sydney sandstone due to uniaxial compressive load testing requires further work. Further investigation of the appropriateness of using Young's modulus obtained from such an overcored sample is warranted. Other factors that may influence the derivation of elastic parameters, including induced microfracturing during overcoring and uniaxial laboratory testing, also require further investigation (Lundholm and Nordlund, 2000).

The difficulty in accurately measuring the elastic parameters at the test location appears to be common to many stress testing methods. Because of this expected area of uncertainty, the method being used by the operators of another form of overcoring tool, the ANZI cell, involves conducting three tests to measure the elastic properties: a pressure meter test in the pilot hole prior to overcoring, a biaxial test of the overcored sample and a uniaxial test of the cylinder retrieved from drilling of the pilot hole (Mills, 1997, and Mills and Gale, 2016). In some cases, the range of variability of Young's modulus results obtained from these tests has been reported to be as great as twice the lowest value. There is a strong case that further investigation is required into effectual measurement of unloading elastic parameters of the rock for use in the calculation of *in situ* stress estimates.

6 CONCLUSION

This paper presents an assessment of recent stress measurements obtained from various techniques for tunnels in Sydney. The calculated *in situ* stress from overcoring testing using the IST tool were on average less than estimates obtained from hydraulic fracturing testing and available published data on the Sydney horizontal stress field. The lower estimates of in situ stress magnitudes from overcoring testing arise due to factors such as lower measured elastic properties obtained from the uniaxial compression testing of thick-walled cylinder overcored samples. Understanding how stress is estimated is important in assisting the interpretation of results which can vary significantly between different measurement techniques.

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