# IN SITU STRESS TESTING FOR TUNNEL DESIGN IN SYDNEY – HYDRAULIC FRACTURING AND OVERCORING

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## ABSTRACT

Over the last decade there have been several road and rail tunnels designed within the Sydney Metropolitan area that are now well into construction. For these tunnelling projects, a key design input has been an estimate of the magnitude and orientation of the *in situ* stress. Designers typically consider the measurement of *in situ* stress from boreholes located along the project alignment and also from published stress measurements and empirically derived relationships for the Sydney Basin. This is because there is often significant variability in the results obtained from limited stress measurements for a given project and a reasonable interpretation of these results needs to take into account a number of factors such as geological and topographical situation. Measurement technique is also a source of variation and practitioners need to be aware of the limitations and advantages of these to ensure that a stress measurement program has the opportunity to deliver the required project needs. This paper considers *in situ* measurements made within boreholes in Sydney using the commonly-used hydraulic fracturing method and the more recently used overcoring method by the Sigra IST tool. Results from two infrastructure projects, where these two methods were used, are presented and the possible reasons for differences obtained between the two methods are discussed. The process of overcoring is a focus including the factors that influence the determination of the elastic properties of the rock for the calculation of the *in situ* major horizontal stress. Numerical modelling is used to examine the potential for brittle microcracking in the porous Sydney sandstones, which can damage an overcored sample and invalidate elastic parameters obtained.

## 1. INTRODUCTION

Measurements of *in situ* stresses in the Sydney metropolitan have been collected for many decades and are well documented (Enever et al 1990; Enever 1999; McQueen, 2004). Subsequently there have been multiple linear correlations made between stress and depth data for deep excavations and tunnels (Pells, 1990; Enever, 1999; Bertuzzi, 2014). Even with the plethora of data available within the Sydney area, the influences on rock stress such as topography, geological structure and varying stiffness of sedimentary strata, *in situ* rock stress estimation is still a challenge. This is not just in Sydney, as John Hudson identified in his paper on what faces the International Society of Rock Mechanics (ISRM) in the next 50 years, 'rock stress is one of the major unsolved problems in rock mechanics' (Hudson, 2012). The ISRM Suggested Methods for Rock Stress Estimation, after discussing measurement techniques, puts *in situ* stress in the wholistic context of topography, soils, rock mass lithology, structural geology, hydrogeology and mechanical data (including rock stress) to arrive at a 3D Final Rock Stress Model (Stephansson and Zang, 2012).

This measurement of rock stress faces the key challenge, that stress cannot be measured directly, but requires us to measure some response that comes from the relief of stress or applied additional stress to the rock mass. Typically, this response measurement is undertaken in a stress-disturbed zone such as a borehole or wall of a tunnel. Therefore, we are changing the rock attribute we wish to measure. For this reason, calculated *in situ* stress from measurements of other rock properties are estimates at best. This paper aims to further the discussion on some of the key test measurement issues, to assist the practitioner in the interpretation of the stress measurements.

Elevated horizontal stress has been deduced from stress measurements in the Sydney area, and also from observations and measurements of displacements in deep excavations (Hewitt, 1999; Pells, 1990; Braybrooke, 1990) and failures in underground openings (Pells, 2004; McQueen, 2004). Spalling brittle failure of Hawkesbury Sandstone has been observed in the crown of the M5 East, Malabar Sewerage Outfall, Cataract, Pipehead to Potts Hill, Cross City and Northside Storage tunnels and Elgas Cavern, (Enever et al., 1990, Pells, 2002, De Ambrosis and Kotze 2004, McQueen, 2004, Bertuzzi, 2015). Spalling has also occurred in sandstones from other formations encountered in tunnels such as the Bringelly Shale and Newport Formation where these sandstones are interbedded with lower stiffness finer grained more jointed rocks. Certain conditions are required to elevate the stress to brittle failure levels (McQueen et al. 2017), such as stiffer beds in a stratified sequence, as recognised in Sydney stratified rocks by Enever et al. (1990) from CSIRO Hollow Inclusion Cell stress measurements in the Malabar Ocean Outfall Sewerage Tunnel. Another consequence of these elevated horizontal stress conditions is the potential for slip or shear between the varying stiffness layers. This has occurred in Sydney on a broad scale from folding in geological time, resulting in clay lined or sheared bedding partings.

On a smaller scale shear on these weaker bedding planes also occurs in tunnels walls on excavation, which can influence stability and tunnel support elements.

## 2. RECENT STRESS MEASUREMENTS IN SYDNEY

Variability in the magnitude of measurements of *in situ* stress between different techniques at the same site have been encountered elsewhere as well as in Sydney (Pells, 2004). Variations may be due to factors, as indicated by Hudson (1993), such as the theory used (assumes homogeneous, isotropic, linear elastic materials), presence of rock discontinuities, inhomogeneous rock, topography, anisotropic rock conditions and measurement error including temperature effects. Different measurement techniques also affect a different volume of rock and address a different rock property.

The variability in magnitudes of stress measurements is evident when reviewing recent data from two Sydney projects. The estimates of major horizontal principal stress from these two projects are presented in Figure 1. The data indicates a wide range in magnitudes and presents a challenge for interpretation without a detailed examination of individual tests, methods and the geological situation. A first pass differentiation of the data in Figure 1 can be made by grouping according to the test method used. Hydraulic fracturing and Sigra IST overcoring was used on both projects. The graph suggests two databases of measurements with hydraulic fracture results tending to be higher and Sigra IST results tending to be lower. Also shown in Figure 1 is the mean trend line from Bertuzzi (2014) for 0 to 50 m depth and the trend line of Pells (1990) representing the stress field for deep excavations in the Sydney CBD. The Pells (1990) stress trend is also supported by Oliveira and Wong (2012) from measured displacements for excavations in the upper 10 to 20 m in the Sydney CBD. Compared with these trend lines the Sigra overcoring results are generally low.

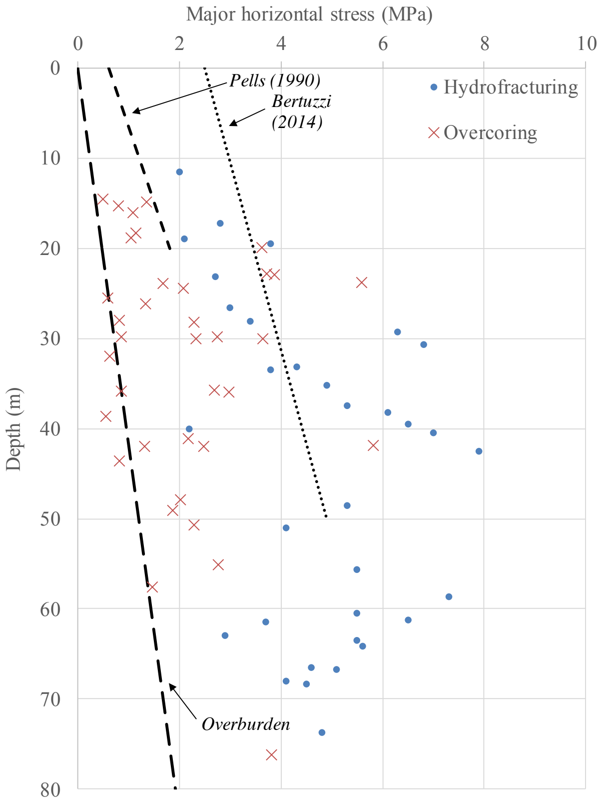

**Figure 1: Estimates of major principal horizontal stress versus depth from two Sydney projects**

Hydraulic fracturing has been the primary method of in situ stress testing in the Sydney area over the last few decades. Some overcoring has been carried out by the CSIRO Hollow Inclusion Cell and, predominately in the mining field, by the ANZI cell (Mills, 1997, Mills et al., 2016). Sigra IST overcoring has been a more recent addition. This overcoring technique, which can be carried out in boreholes to the depths required for Sydney tunnels, is a form of USBM apparatus (Hooker and Bickel, 1974). It measures the two dimensional strain response of a pilot hole during overcoring by the drilling of a larger diameter hole. Elastic parameters of the overcored rock are then required, from testing of the overcored sample, to calculate the in situ stress.

Some of the limitations of the hydraulic fracture and Sigra IST overcoring techniques in the Sydney sandstone, are discussed below, particularly overcoring since it is relatively recent. Detailed reviews on the advantages and disadvantages of in situ stress testing methods has been reviewed by others (e.g., Fairhurst, 2003; Ljunggren et al., 2003; Doe et al., 2006).

The hydraulic fracture technique has been the subject of discussion due to high results obtained for the horizontal major stress in Sydney tunnelling projects. Enever (2008) indicates that the validity of the framework behind the theory of the stress calculations has been established by laboratory studies. Pells (2004) discusses this and quotes from Fairhurst (1986) and others on the limitations of the hydraulic fracture test. Principle limitations peculiar to this test relate to the action of pore pressures during the test in the porous Sydney sandstone and the determination of the tensile strength, which is required to calculate the major horizontal stress. The Borehole Slotter was introduced as an alternative technique for two projects where high hydraulic fracture test results were obtained (Pells, 2004).

The IST overcoring tool is placed in a pilot hole approximately 26 mm in diameter and is overcored by a HQ core barrel which cuts approximately a 61 mm diameter core with a 96 mm borehole diameter. Mechanical gauges measure the 2D strain in the pilot hole. The overcored hollow cylinder core sample is recovered from the borehole and transported to the laboratory where strain gauges are fixed to the outside of the cylindrical sample and it is subjected to cyclical uniaxial loading to calculate the elastic parameters. Factors that could affect the determination of these elastic parameters and the calculation of the *in situ* stress normal to the borehole, include:

- Elastic parameters are obtained from the low end of the uniaxial stress-strain curve, which is considered to be the seating zone for closure of pore space in the sandstone. The cyclical loading and unloading of the hollow cylinder of relatively low strength sandstone may also aggravate this effect.
- Strain gauges are fixed to the outside of the cylindrical sample, whereas *in situ* strain measurements are made in the pilot hole, i.e., the inside of the hollow sample.
- The IST gauges measure pilot hole closure during horizontal unloading. The laboratory test is a vertical loading case.
- The IST gauge with mechanical pins are susceptible to inhomogeneities on the scale of a grain.
- Development of microcracks in the rock sample during the overcoring process

The authors consider that the above factors have contributed to low modulus determinations and hence to low *in situ* stress estimation.

ISRM Suggested methods (Sjoberg et al., 2007) specify that a biaxial test be carried out on site on the core sample with the overcored cell still bonded within, as soon as possible after it is recovered from the borehole. The elastic parameters are then determined from the same gauges that measured the *in situ* strains and in the same direction. The difference from the *in situ* test is that this is a loading situation not an unloading one.

The determination of the elastic parameters of the overcored rock has been scrutinised by the operators of the ANZI overcoring cell. The procedure for determining the elastic properties involves three tests: a pressuremeter test in the pilot hole prior to overcoring; a biaxial test on the overcored hollow cylindrical sample; and a uniaxial test on a solid core sample retrieved from drilling of the pilot hole (Mills, 1997 and Mills et al., 2016). The variability in the magnitude of Young's modulus from these tests in some cases have been reported to be up to 2 fold. Thus, further investigation is warranted to identify how the approach to obtaining elastic parameters from overcore samples can be improved.

It is informative to note the paper by Anderson and Christiansson (2003) who compared hydraulic fracture and overcore stress measurements in the same borehole in a medium grained crystalline rock. Some of their conclusions are relevant to overcoring in our weaker sandstone, including the large scatter in the overcoring measurements due to the size of the strain gauges in relation to the crystals. They also questioned the validity of overcoring in high stress conditions compared to the rock strength and suggested that microcracking may be induced during overcoring resulting in a low Young's modulus during biaxial testing. Thus, they concluded that the determination of this elastic parameter using core samples may not be trivial.

# 3 TRANSIENT STRESS AND EXTENSIONAL STRAIN IN OVERCORED SAMPLE

### 3.1 THE POTENTIAL FOR MICROCRACKING

The variation of the measured strains throughout the overcoring process show that the rock core experiences a transient stress path due to stress concentration ahead of the drill bit and stress release when overcoring passes the measuring point (Mills et al., 2016). Some studies, utilising 3D modelling, have been conducted to better understand the transient stresses and strains and the nature of stress-induced microcracking in a core sample during the drilling and overcoring process (eg. Hakala, 1999; Hakala, 2006; Lundholm et al. 2000). The process of drilling the overcore can result in stress-induced microcracking that permanently alters the physical state of the rock (Eberhardt et al. 1999), which changes the elastic properties of the sample. Based on the critical extensional strain criterion (Stacey, 1981), microcracking of brittle rock will occur when the extension strain exceeds a critical limit that is characteristic of the rock. If these cracks propagate under higher strain levels in drill core then the ultimate result is a macro phenomenon of fracturing known such as core disking, or ring disking in the case of the overcored hollow cylinder core.

As indicated in the introduction, Hawkesbury Sandstone has been observed to behave in a brittle manner leading to spalling failure in Sydney tunnels. Pells (2002) indicates a critical extensional strain for Hawkesbury Sandstone of about 500 microstrains when considering stress-induced tunnel failures. A similar extensional strain is obtained on interrogating the back analysis model from McQueen et al. (2017) of the M5E tunnel spalling failure at a stress level of about 0.5xUnconfined Compressive Strength. The extensional strain in these cases results from a compressive stress situation in the walls of a tunnel, unlike a stress relief situation during overcoring.

In the case of overcoring that is being considered here, the release of stress in transient conditions during drilling a pilot hole and then overcoring to create an unconfined situation sets up a scenario for failure under axial extension. Extensional strain will also vary with position around the circumference of a borehole in an unbalanced stress field. This was investigated for the Sydney overcoring case, using numerical modelling using 3D and 2D axisymmetric methods, as reported in the next section.

### 3.2 NUMERICAL MODELLING

The tensile stress and the extensional strain during the transient overcoring process was considered in the wall of a hollow core sample with the borehole dimensions from the Sigra IST. The modelling was carried out as a parametric study of various *in situ* stress conditions using elastic stress analysis. The aim is to consider the *in situ* stress level that could generate a tensile stress that would exceed the tensile strength and critical extensional stain limit and thus the potential for microcracking in the overcored sample. This condition would result in the invalidation of the assumed linear elastic behaviour of the rock and the reliability of the calculated stress.

The two modelling approaches were employed, viz. a two-dimensional axisymmetric plane strain model using the RS2 software (Rocscience Inc.) and a three-dimensional model using the FLAC3D software (Itasca Consulting Group Inc.). The problem definition is presented in Figure 2. The parameters used in the models are listed in Table 1. The rock material was modelled as an elastic material. Both the 2D and 3D numerical models were staged to include an initial step where *in situ* stresses were applied, the borehole was then drilled followed by the pilot hole, and then subsequent incremental excavations of the rock to replicate the overcoring process. The size of the smallest incremental removal of rock in the overcoring process corresponded to 1 mm thickness, and this was applied around the nominated enquiry point for both models. The enquiry point was located on the edge of the pilot hole approximately 200 mm from the start of the pilot hole where a strain gauge would be located. The results present compression as positive values.

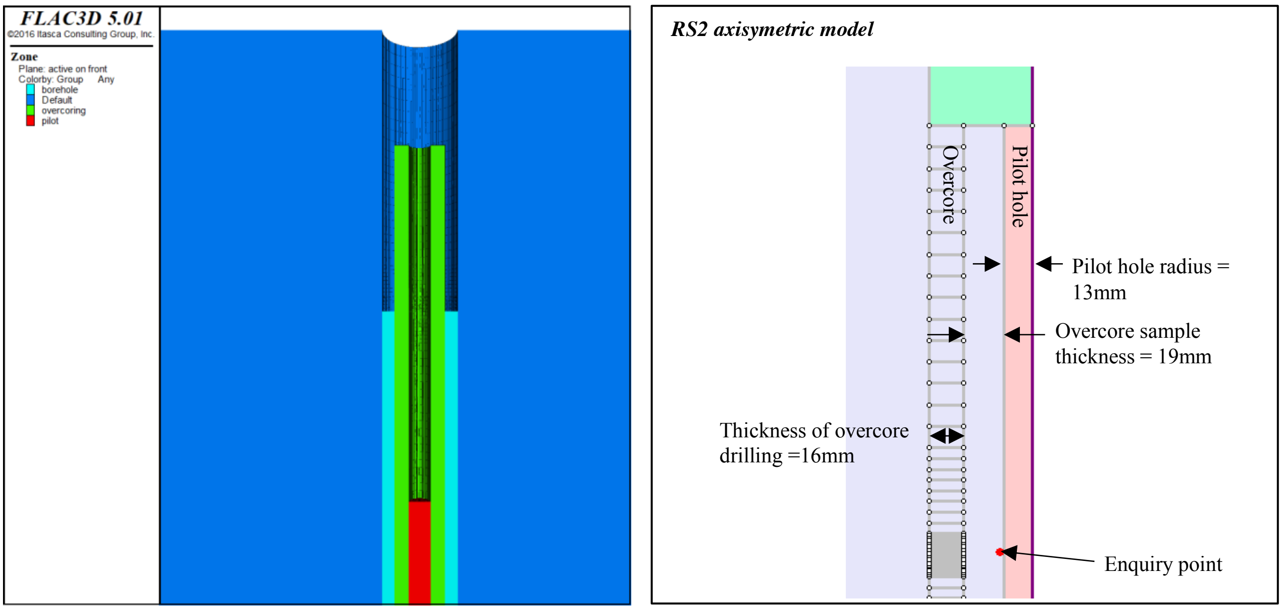

**Figure 2: Snapshots from FLAC3D and RS2 showing the model setup and geometry**

**Table 1: Summary of magnitudes of parameters used in both the FLAC3D and RS2 numerical models**

| **Parameter** | **Magnitude** |
|---|---|
| Depth of analysis ($z$) | 60 m |
| Major horizontal *in situ* stress ($\sigma_H$) | Varied from 2 to 8 MPa |
| Minor horizontal *in situ* stress ($\sigma_h$) | $= 0.625\sigma_H$ |
| Vertical *in situ* stress ($\sigma_v$) | = 0.024 x depth (MPa) |
| Poisson's ratio ($v$) | 0.2 |
| Young's modulus ($E$) | 8000 MPa |
| Diameter of pilot hole | 26 mm |
| Internal diameter of overcore | 64 mm |
| External diameter of overcore | 96 mm |

## 3.1 RESULTS OF 2D AXISSYMETRIC ANALYSIS

The axial stress and axial strain induced into a point in the 2D model throughout the overcoring process is presented in Figure 3. The results are presented as the overcoring proceeds from 250 mm prior to the enquiry point through to 100 mm past that point. These results are for the case of 60 m depth where vertical *in situ* stress was assumed to be 1.44 MPa.

The initial axial compressive stress starts from the vertical *in situ* stress (Figure 3 at -250mm). The transient stress path dramatically changes to tensile stress within 40 mm of the enquiry point. The highest tensile stress is induced in the case of the highest major horizontal *in situ* stress. After the enquiry point axial compressive stresses are once again induced prior to the axial stress decaying to zero. These models indicate that axial strains in the rock are exposed to extensional strains with the overcore within 50 mm of the enquiry point. The higher the *in situ* horizontal stress the higher the induced extensional strain.

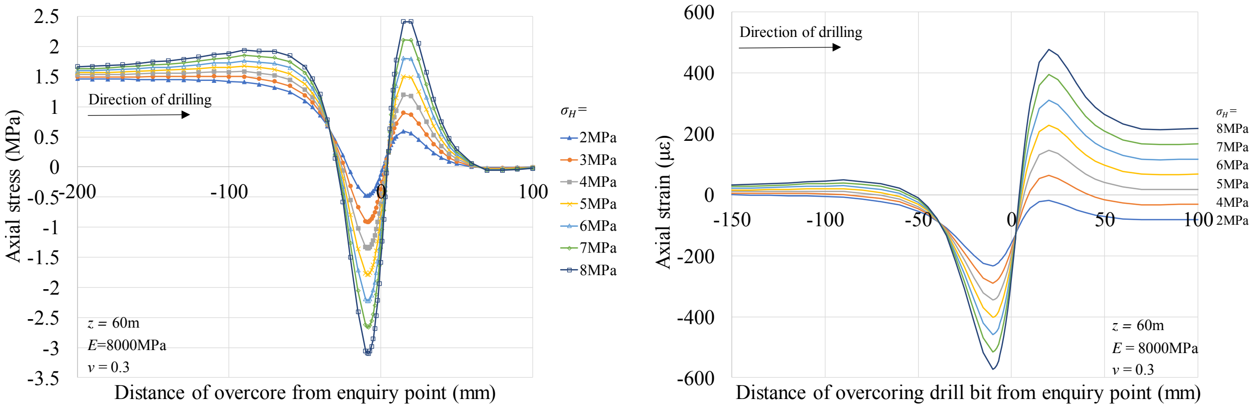

**Figure 3: 2D model results of axial stress and strain at the enquiry point during overcoring**

## 3.2 RESULTS OF 3D ANALYSIS

When the axial stress for enquiry points around the circumference of the pilot hole, at 200 mm from the start of the pilot hole, are plotted against distance around the borehole, they were found to vary roughly sinusoidally, being located 90 degrees from each other. Figure 4 presents the transient axial stress and axial strain path induced around the pilot hole. In contrast, the axial strain showed almost no variation in magnitude for the enquiry points located around the pilot hole. The 2D results for the same parameters are also shown for comparison. The results from the 3D and 2D analyses where further compared for three magnitudes of major *in situ* horizontal stress (Figure 5).

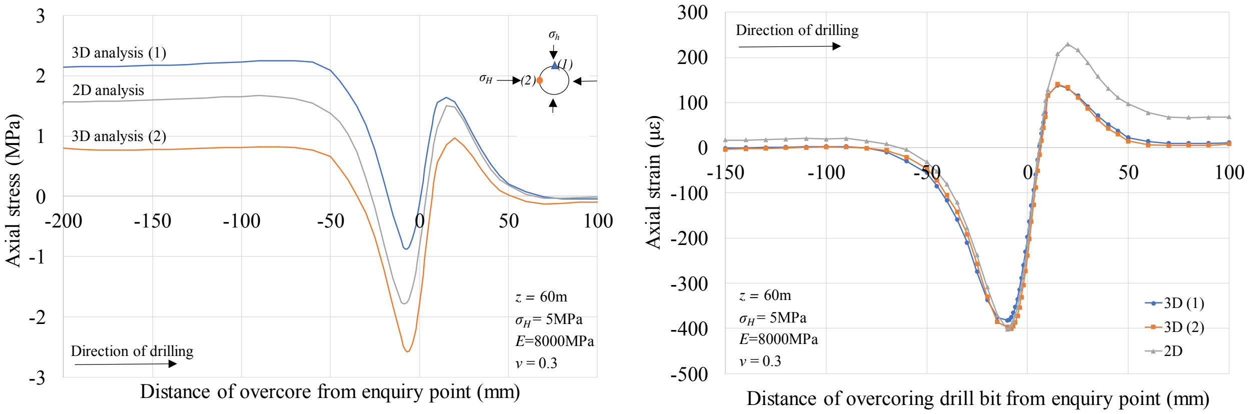

**Figure 4: 3D model results of axial stress and strain at the enquiry points around the pilot hole during overcoring for 60 m depth with 2D model results for comparison**

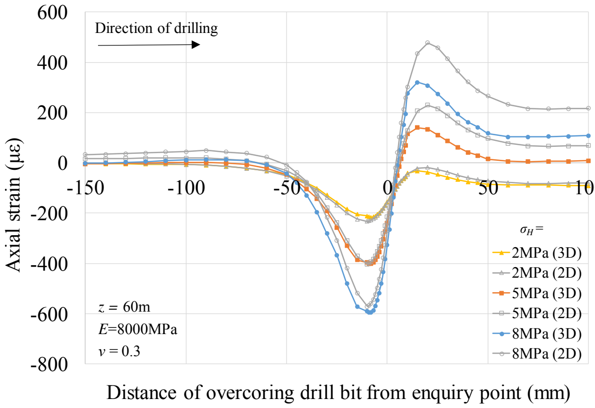

**Figure 5: Comparison of axial strain from 2D and 3D models for the enquiry point in the pilot hole for varying *in situ* horizontal stress levels**

# 3. DISCUSSION

The numerical modelling indicates that for a major horizontal stress ranging from 2 to 8 MPa and overburden stress for 60 m depth, the tensile stress is within the range of 0.5 to 4.5 MPa and extensional strain of 200 to 600 με, respectively (Figure 6). For a major horizontal stress ranging from 2 to 5 MPa and overburden stress for 30 m depth, the tensile stress is within the range of 1 to 3 MPa and an extensional strain of 150 to 350 με, respectively (Figure 6).

A direct tensile strength of about 1.5 to 2 MPa has been assumed, from Brazilian tensile strength of 2 to 3 MPa for the better classes of sandstone (Pells, 2002) and applying a factor of 0.7 (Perras and Diederichs, 2014) to estimate the direct tensile strength. The transient tensile stress that exceeds that limit occurs above about 3 to 4 MPa *in situ* major horizontal stress. Extensional strain at this *in situ* stress level is about 250 to 330 microstrain for the assumed Young's modulus of 8 GPa. Higher extension strains would be expected for lower modulus rocks.

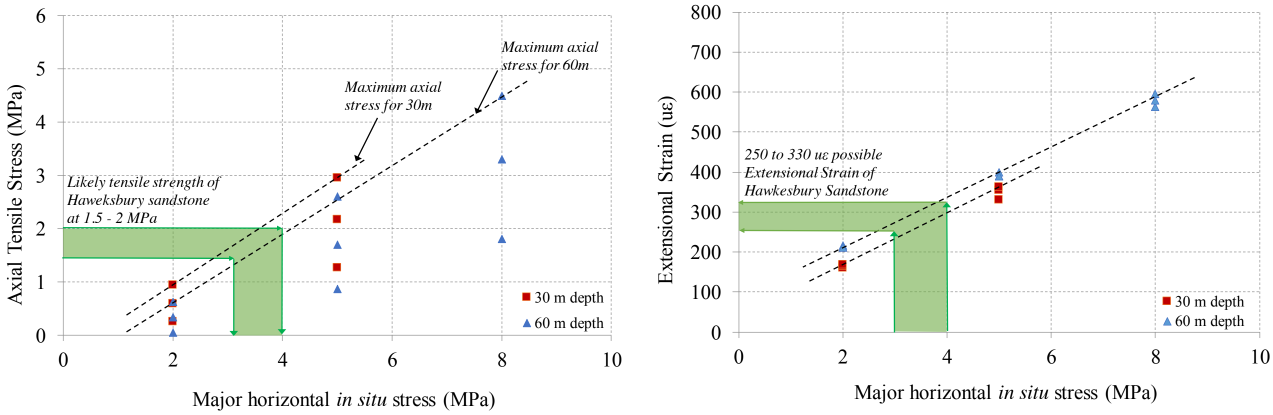

**Figure 6: Peak axial stress and extension strain obtained from the 3D model**

The 2D model cannot capture the variation in stress in an unbalanced horizontal stress field, however, the results trend midway between the axial stress results of the 3D model. There is good agreement between the peak extensional strain determined by the two numerical models. Thus given this comparative study of the overcoring process, a parametric analysis can be run with the quicker 2D model with confidence. The obtained extensional strains from the 2D analyses are shown in Figure 7. To assist in the interpretation of this graph, Bertuzzi's (2014) *in situ* stress trend line is shown. The peak extensional strain between 250 and 30 microstrain has been shaded to show the zone where there is a high likelihood that microcracking may start to take place during the overcoring process.

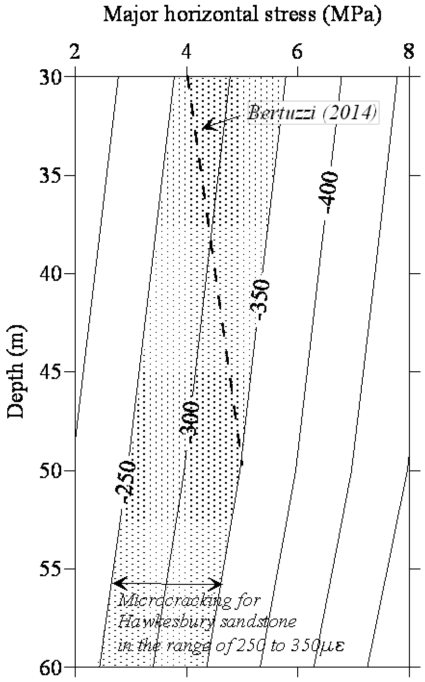

**Figure 7: Maximum extensional strain induced into the overcored rock sample obtained from the 2D analysis**

## 4. CONCLUSIONS

This paper has considered *in situ* major horizontal stress measurements made within boreholes in Sydney sandstone by the different techniques of hydraulic fracturing and overcoring. It was initially prompted by lower results obtained from Sigra IST overcoring than generally accepted in Sydney from the experience of stress-induced displacements and failure in deep excavations and tunnels. The process of overcoring was then examined along with experience elsewhere in the literature of overcoring in relatively high stress conditions compared with the strength of the rock.

Numerical modelling of the transient stress path at the measurement point during overcoring indicates the presence of a tensile stress level that can exceed the tensile strength of the rock and thus the potential for microcracking in the overcored sample. If this occurs, the measured elastic properties of the rock sample will be affected and thus the calculated *in situ* stress. The stress path and extensional strain was modelled for different *in situ* stress conditions to provide an indication of the conditions in which microcracking can occur.

Further work is required to model the influence of different *in situ* stress regimes and different rock conditions (anisotropic strength, presence of discontinuities adjacent to an overcore) on the stress path and the extensional strain, which can result in microcrack sample damage. Physical testing of the overcored hollow cylindrical samples, from which elastic parameters are obtained, could also be carried out to examine for the presence of microcracks.

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