A Review of the In Situ Stress Database for Tunnel Design in the Hawkesbury Sandstone, Sydney, New South Wales

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ABSTRACT
The City of Sydney is currently investing in a number of infrastructure projects that require tunnel excavations within the Triassic Hawkesbury Sandstone. It is generally accepted that this formation has high residual stresses of ‘tectonic’ origin, so much so that these stresses have been implicated in a number of well-known failures and problems for tunnelling. These include failure of ‘roof beams’ comprising discrete beds in the crown of tunnel excavations; stress-induced spalling and ‘slabbing’ of tunnel walls; shear displacement between beds causing the failure of rock bolts; strain in adjacent infrastructure and, the necessity for re-grouting of high conductivity fractures due to stress relief dilation after excavation. Whilst there is an extensive published database of in situ stress measurements comprising ‘hydrofrac’; ‘over-coring’ and ‘slooter’ stress measurements, these data indicate a considerable spread of results. The traditional approach to interpreting this data has been to attempt to fit linear correlations to stress versus depth data, based on personal experience and ‘back-analysis’ of monitoring data during construction. However, there are a number of such correlations in the literature and there is divergence of opinion regarding the assessment of ‘background’ in situ stress and appropriate upper and lower bound values for design. This paper provides a brief review of the published data; suggestions on an alternative ‘risk-based approach’ to assigning in situ stresses for design; and, proposals on how in situ stress tests may be conducted in future to improve the quality of the database available to designers.

INTRODUCTION
It is well known that the Sydney Sandstone can carry high residual tectonic stresses and that these stresses have been implicated in a number of cases of ‘failure’ of the rock mass in deep excavations such as caverns, station boxes and basements. These include: collapse of discrete beds in the crown of tunnel excavations (eg de Ambrosis and Kotze, 2004); stress-induced spalling and ‘slabbing’ of tunnel excavation (eg Boomerang Creek tunnel, Pells, 1994) (Figure 1); ‘bulging’ of the floors of basement excavations such as at Martin Place and Kings Cross and explosive spalling of excavations such as for the Warragamba Dam (eg Branagan, 1985); shear displacement between beds (eg Chappell, Williams and Pollard, 1984); failure of rock bolts (eg de Ambrosis and Kotze, 2004); and, the necessity for re-grouting of high conductivity fractures due to stress relief dilation after excavation (Lees, Edwards and Grant, 2005).

Measurements of in situ stress may not be available for a new project because of program and cost constraints, or because designers may prefer to rely on personal experience and judgment and published data. Also, in the case of long linear structures such as tunnels, stress measurements at close intervals along the entire corridor are commonly impractical. While specific testing may be undertaken at critical locations, such as large span caverns or near significant geological structures, broader assessment is commonly undertaken on the basis of assumed regional conditions. This is often based on a number of upper and lower bound linear or bi-linear horizontal stress versus depth correlations that have been published in recent years.

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The Sydney Sandstone is a ‘stratified’ rock mass, comprising a range of bed thicknesses having ‘massive’, cross-bedded and ‘laminated’ fabrics. In addition, thin interbeds of laminated and argillaceous rocks and micaceous, clayey and carbonaceous coatings on bedding planes characterise the rock mass. Steep dipping and inclined joints with persistence often limited by bed thickness are also common.

Features that may influence the state of stress measured in the Sydney Sandstone will include: erosion and valley bulge due to uplift and Quaternary sea level variations; intrusive dykes and diatremes; gentle folding, faults and jointing; and, deep weathering in the Mio-Pliocene as indicated by re-mobilisation of iron oxides as liesegang banding and cementation in joints (Figure 2). All of these features of the rock mass will cause significant local variations in in situ stress; man-made features such as nearby basements, shafts and tunnel excavations can also modify the natural state of stress. Nonetheless, the dominant feature of the rock mass is the subhorizontal stratification and it is considered that this is the main influence on the general state of in situ stress at typical engineering scales.

Bed thicknesses vary from millimetre to metre scale. A recent review of over 100 discrete measurements of true bed thickness in borehole cores at depths greater than 15 to 20 m below rockhead was undertaken by the authors. For practical purposes, thicknesses of less than 0.2 m were not considered. For those data, the bed thicknesses tended to conform to a negative exponential distribution, with a mean thickness of approximately 1.9 m. For shallower depths this value reduced to approximately 1 m; weathering and stress relief effects were considered to be largely responsible for this reduction.

In the light of the distinct stratification of the Sydney Sandstone, it is considered that any attempt to define simple linear stress-depth correlations may not reflect the nature of the rock mass; such an approach would be more typically applied to soils, where in situ stress is largely related to the density state of the soil and the depth of overburden. For a strongly lithified, bedded and gently deformed rock mass such as the Sydney Sandstone, the depth of overburden would be expected to be of secondary importance and the general state of in situ stress much more dependent on larger scale plate tectonic effects, regional uplift and erosion and the geological structure in the rock mass.

![Image](image_url)

**FIG 2** – Typical exposure of the Sydney Sandstone, Sydney central business district (source: Steve Macklin).

**REVIEW OF PUBLISHED DATA**

The existence of a significant (and variable) horizontal stress field within the Triassic rocks of the Sydney Basin is well established, particularly within the Hawkesbury Sandstone, as described in Pells (1990), Enever (1999), Enever, Alton and Windsor (1990) and McQueen (2004) amongst others. The in situ horizontal stress is described in terms of a major horizontal stress ($\sigma_h$), a minor horizontal stress ($\sigma_m$) and a vertical stress ($\sigma_v$). Figure 3 (after McQueen, 2004) illustrates the locations of publically available stress orientation data and in-house data referred to by the authors; the key geological structures in the Sydney Basin are taken from Branagan (1985) and the New South Wales (NSW) government resources and energy website. McQueen's analysis suggested that there was a stress orientation predominantly trending NNE, roughly parallel to the dominant trend of the regional geological structures. Significant variation in this stress orientation does, however, occur, which we infer is associated with local features such as faults, dykes and valleys, etc. This variation in azimuth also appears to be more pronounced in data obtained above approximately 20 m depth.

A variety of equations have been published to describe the variation in the magnitude of stress at depths of civil engineering interest (up to 200 m) in the Sydney Basin. These have generally comprised a non-zero stress at the surface and a linear increase in stress with depth; the relationship between the major and minor horizontal stresses related by a ‘K’ ratio (lateral/vertical stress ratio). For example Enever (1999) and McQueen (2004), provides the following ‘stepped’ model of ‘upper bound’ tectonic stress in rocks down to 200 m depth:

$$\sigma_y = 0.025 \text{ MPa} \times \text{ depth in m (overburden pressure)}$$

$$\sigma_{hi} = 2.5 \text{ MPa} + \sigma_y \text{ down to 20 m depth}$$

$$\sigma_{hi} = 6.5 \text{ MPa} + \sigma_y \text{ down to 200 m depth}$$

$$\sigma_h = 2 \text{ MPa} + \sigma_y \text{ down to 20 m depth}$$

$$\sigma_h = 4.5 \text{ MPa} + \sigma_y \text{ down to 200 m depth}$$

Alternatively, Pells (2002) proposed the following equations to estimate the ‘natural total stress’ in sandstone to a depth of 150 m:

$$\sigma_y = 0.024 \text{ MPa} \times \text{ depth in metres}$$

$$\sigma_{hi} = 1.5 \sigma_y + 1.2 \sigma_y \text{ to 2.0 } \sigma_y$$

$$\sigma_h = 0.5 \sigma_y \text{ to 0.7 } \sigma_y$$

Testing for various projects in the Sydney region show that stress conditions are affected by rapid changes within and across the geological stratigraphy and that stresses may be concentrated in relatively stiff/strong massive beds, with correspondingly lower stresses in weaker interbeds. As such, simple linear correlations may mask more significant changes associated with stratification at the scale of engineering problems. Branagan (1985) reported earlier work by Blackwood (1983) that indicated that the elevated horizontal stresses in the rocks of the Sydney region could not be well explained by unloading due to erosion because measured stresses did not increase linearly with depth. The wide variation in stress measurements were considered to be more closely linked to
the regional structural deformations that formed regional geological structures such as the Lapstone monocline.

Enever and Clark (1997) published a review of the available stress measurement data to depths of up to 1 km (from over-coring and hydrofract tests) for the Sydney Basin. In addressing wide variations between the measured stresses and depth (at that scale), they proposed that an alternative way of looking at the data was to subtract the self-weight component of horizontal stress from the measured data and then plot the ‘residual tectonic’ stress results in the form of a frequency histogram. Their plot took a highly skewed form, suggestive of a log-normal or similar distribution. Due to uncertainty in the assumed value of Poisson’s ratio (they assumed a value of 0.5) and the potential for local features to modify the stress field, Enever and Clark (1997) considered that their statistical approach should be regarded as a qualitative guide to the magnitude of tectonic stress only.

Nemcik, Gale and Mills (2005) adopted the same approach when reviewing the results of 235 ANZI cell type over-coring tests in NSW and Queensland coalfields (premining). That is, they considered that for the highly stratified coal measures strata of the Bowen Basin, horizontal stresses were largely a reflection of tectonic effects and that the self-weight component of stress should be ‘removed’ from the data set before analysing the variation in the tectonic component of stress. The horizontal self-weight stresses were estimated by the equation:

$$\sigma_{h, \text{self-weight}} = \frac{\mu}{1-\mu} \cdot \sigma_v$$

Where they suggested that values of Poisson’s ratio ($\mu$) in the range of 0.2 to 0.3 would be appropriate. In addition, because the different beds had widely differing stiffness (eg weak coal versus strong sandstone) Nemcik, Gale and Mills (2005) also proposed that the stresses in individual beds may be estimated from a knowledge of the intact rock modulus around the test pocket and a ‘tectonic factor’ empirically derived from the available database.

For this paper, the concept of separating the self-weight from the tectonic components of stress for the general stress state has been adopted and applied to an analysis of published and in-house stress measurement data. Due to insufficient data on rock modulus obtained for each test, we have not attempted to derive a ‘tectonic factor’ for the Sydney Sandstone at the present time.

**ANALYSIS OF THE AVAILABLE DATABASE**

On the basis of published data (eg Prospect, Malabar, Warragamba) supplemented by an in-house database of in situ stress testing results obtained from hydrofrac, slotter and over-coring tests for a number of projects in Sydney (eg Epping to Chatswood Rail Link, Sydney Desalination Plant, central business district (CBD) Metro and West Metro, Cross City Tunnel, Molineux Point LPG Storage Caverns, Northside storage tunnel, North West Rail Link) the authors have undertaken an initial analysis adopting the approach of Enever and Clarke (1997) and Nemcik, Gale and Mills (2005).

Whilst the more unusual results have been ‘filtered’ from the data, the published data has been taken ‘as read’ because the actual test data is frequently not available. It is also acknowledged that an element of both systematic and ‘random error’ remains in the database due to assumptions within the analysis and sampling bias within the test methods. Notably, historical limitations in stress measurement techniques have resulted in testing being biased towards massive or competent beds which may be stiffer and reflect a higher level of stress than is present within adjacent strata.
Figures 4 and 5 (after McQueen, 2004) illustrate respectively, a plot of stress versus depth below ground level, as well as the ratio of maximum and minimum horizontal stress measured. Figure 4 shows that the scatter of measured stresses above approximately 20 to 25 m depth is very wide and fitting a simple linear correlation would not be a good representation of the data. Under these circumstances the selection of an appropriate design value of stress may be left to a somewhat subjective assessment, based on the experience and preferences of the designer.

As recognised by the ‘bi-linear’ equations proposed by some authors, we also have considered that a distinct change in the magnitudes (and consistency in orientation) of stress occurs at 20 m depth approximately and separated the data accordingly. The self-weight component of stress has then been deducted from the results assuming a Poisson’s ratio of 0.25 and a bulk unit weight of 0.024 MN/m³.

Figure 6 shows the results of the analysis for the net component of stress after self-weight has been deducted. The stress axis has been plotted on a log scale – the same lack of trend with depth is seen if the data is plotted on a linear scale. Figure 7 is the same plot but for data below approximately 20 m depth. Both plots show that there is a lack of trend with depth apart from a distinct reduction in stress above 20 m depth. Furthermore, the data set above 20 m depth appears to show a distinct widening of the scatter between 15 and 20 m depth approximately, suggesting that further subdivision of this data set might be warranted. This is attributed to general effects of stress relief and redistribution associated with topography, weathering and erosion.

Comparison of the major to minor components of horizontal stress indicates that the σ₁/σ₃ ratios have a geometric mean of 1.4 above 20 m depth and 1.6 below for these data sets.

The results have been further analysed by considering that each test represents a ‘random sampling’ of the general in situ stress state and that a simple statistical approach can be adopted. Figure 8 represents a frequency histogram of the net maximum stress results below 20 m depth; two-thirds of the data fall between 2 MPa and 7 MPa, with a mean value of 5 MPa. Similarly, for the net stress data above 20 m depth, some two-thirds of the data fall between 1 MPa and 4 MPa, with a mean value of 2.5 MPa. In the data set below 20 m depth the data can be reasonably well fitted by a lognormal distribution with a geometric mean of 4.1 MPa (standard deviation 3.4 MPa). However given the wider variation in orientation and magnitude for the data set above 20 m depth, a well-defined distribution could not be achieved due to greater uncertainty in the data.

Whilst these statistics might be useful as a general guide on the variation of in situ stress in the sandstone, perhaps a more useful way of considering the data would be to consider the likelihood that the in situ stress would exceed a certain value – effectively a ‘risk-based’ approach could be adopted. That is, the in situ stresses that might be measured in a routine

**FIG 4** – Simple maximum horizontal stress versus depth plot, Sydney Sandstone.
investigation (i.e., without targeting a specific bed in the rock mass) may be estimated as the sum of the self-weight stress plus a tectonic component of stress at a particular cumulative percentile (Figure 9):

$$\sigma_{H,h} = \frac{\mu}{1-\mu} \cdot \sigma_v + \sigma_{\text{tectonic}}$$

This approach assumes that the occurrence of the general state of stress in the rock mass is entirely random and is unaffected by discrete local features, etc. However, as stated earlier, in situ stress is likely to be dependent on the stiffness of the bed in which the stress was measured. As such, these statistics, based on the database available, can still only provide a general guide on the potential magnitude of stress that may be encountered.

Figure 10 illustrates a comparison of one published ‘design line’ for maximum horizontal stress against our estimates based on self-weight plus a tectonic component at the 25th, 50th and 75th percentiles, below 20 m depth.

**CONCLUSIONS AND RECOMMENDATIONS**

On the basis of a review of an in-house database of in situ stress measurement data, this paper has considered an alternative ‘statistical’ way of estimating values of in situ stress for design
of deep excavations in the Sydney Sandstone, as suggested by Branagan (1985); Enever and Clark (1997) and Nemcik, Gale and Mills (2005). This approach has been considered because published linear trends with depth do not appear to adequately account for the very wide scatter in the general state of stress; it is feasible that an inappropriate level of confidence or reliability may be adopted when estimates are made from these correlations without consideration of their derivation.

For data obtained below approximately 20 m depth, it is proposed that by looking at the statistics of the net tectonic stresses and treating the results as a random sample of a population of feasible results, reasonable estimates of *in situ* stress can currently be made with an associated ‘likelihood’. This should only be applied in combination with a good geological model and consideration of the influence of local conditions on the general state of stress. An assessment of ‘likelihood’ associated with a chosen design value of stress, would provide a basis for assessing the consequences of deviations from the assumed stress state and could enable a rational basis for adopting particular material or load factors.
the data may enable a probabilistic approach to *in situ* stress to be successfully applied. The ‘tectonic factor’ as suggested by Nemcik, Gale and Mills (2005) may also enable initial estimates of *in situ* stress to be made, where only data on the rock modulus is available.

**REFERENCES**


