Near Surface In-Situ Stress and Its Counterpart at Depth in the Sydney Metropolitan Area

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Summary
The nature of the horizontal stress field in the Sydney Metropolitan area is examined through the agency of an extensive data set obtained from hydraulic fracture stress measurements conducted in 18 surface drill holes. The data suggests a predominant stress field orientation in the northeast quadrant and a magnitude comprising a gravity and a tectonic component. The gravity component appears consistent with the concept of lithostatic stress, while the tectonic component appears approximately constant with depth within specific depth windows. The evidence suggests that the tectonic component is of lower magnitude closer to the surface.

1. INTRODUCTION
The measurement of rock stress in the Sydney Basin has become common practice in recent years, to the point where the Sydney Basin presents one of the densest concentrations of direct stress measurements over a range of depths anywhere in the world. Within the Sydney Metropolitan area, stress measurement associated with civil engineering projects has produced a database to depths around 200 metres in the Post Permian sediments. More recent activity associated with gas exploration has allowed the acquisition of deeper data from the underlying Permian rocks, providing a unique opportunity to gain an understanding of how rock stress varies from depth to near surface in the same general geographic area.

Other papers on the same general topic in recent times have dealt more broadly with the Sydney Basin (Enever et al., 1998, Enever and Clark, 1997) rather than focussing on the metropolitan area. These studies have sort to look at the nature of regional lateral variations in the horizontal stress field, in the context of the geological setting and tectonic activity. The current paper presents a more detailed look at vertical variations in the pattern of in-situ stress, within a geographic area that might broadly be described as having a uniform geological character.

Some implications of the stress field in the Sydney area for excavation performance were discussed in Enever et al. (1990).

2. DATA BASE
Figure 1 summarises the area covered by the database. The area in question constitutes a relatively constrained strip extending inland from the coast some 7 km and south to north some 14 km, from...
Botany Bay to the north shore of Port Jackson, including the C.B.D. Within this area, data was obtained from 18 different locations, generally over a significant depth range.

All the data reported here was obtained using the hydraulic fracturing technique (Enever, 1993) to make multiple measurements over a range of depths in surface drill holes. Although not representing all the data available, the database does include all hydraulic fracture data known to the author for this region. Given the intention to examine variations in the stress field with depth, hydraulic fracturing has the advantage of producing data over a depth range at any given location, not normally possible with other techniques. All measurements were conducted using the same general test procedure, in vertical holes, and predominantly in relatively uniform sandstone units.

The data discussed below can be reasonably considered to essentially reflect the impact of the structural geological environment on the stress field. All data points are free of any stress modifying effect due to proximity to existing excavations.

In the following sections, the orientation and magnitude of the horizontal secondary principal stress field is examined through a number of depth slices reflecting the major concentrations of data:

- 0–1200 metres, representing the full depth range of available data and encompassing both Permian and Post Permian rocks,
- 0–200 metres, representing the data obtained for various civil engineering projects in Post Permian rocks,
- 0–20 metres, focusing on relatively near surface civil engineering activity.

3. THE NATURE OF THE STRESS FIELD

3.1 Orientation

Figures 2a, 2b and 2c summarise the measured orientations of the major horizontal secondary principal stress for the three depth slices outlined above. In all cases the suggestion is of a strong clustering in the northeast quadrant, with some outliers scattered across the remaining orientation range. In each case it is possible to draw a tentative upper bound to the predominant cluster, with approximately the same proportions of outliers (26-29%).

The bandwidth suggested for the predominant clustering includes the impact of non-specific geological factors on stress field orientation. Such factors have not generally been obvious at the time.

Figure 2a. Summary of orientation of horizontal secondary principal stress field with respect to depth, (0-1200 metres). Note: Individual symbols represent separate holes.

Figure 2b. Summary of orientation of horizontal secondary principal stress field with respect to depth, (0-200 metres). Note: Individual symbols represent separate holes.

Figure 2c. Summary of orientation of horizontal secondary principal stress field with respect to depth, (0-20 metres). Note: Individual symbols represent separate holes.
measurements were made. In the case of some of the outliers, there has been a more obvious reason for the different orientation. There is a suggestion in Figures 2a, 2b and 2c that the band defining the predominant clustering may become tighter (and/or possibly shift counter clockwise) as the impact of progressively shallower data becomes more significant. Within the predominant cluster for the 0–200 metre data in Figure 2b, there is a suggestion of a most common orientation around 20 degrees that is not as clear in the other plots. Overall, there is no evidence of a significant systematic change in predominant horizontal stress field orientation with depth.

3.2 Magnitude of Minor Horizontal Principal Stress

Figures 3a, 3b and 3c summarise the measured magnitudes of the minor horizontal secondary principal stress for the three depth slices. The data sets suggest a total horizontal stress magnitude made up of a depth (gravity) related component, and a superimposed (tectonic) component independent of depth and falling between reasonably well defined upper and lower bound trend lines. In general, the lower bound trend appears to be approximately defined by the nominal overburden pressure line, based on depth of cover and an assumed average S.G. of 2.5 for the sediments. The upper bound trend, however, appear to vary significantly from depth slice to depth slice:

- approximately 6 MPa above overburden for the 0–1200 metre slice,
- approximately 4.5 MPa above overburden for the 0–200 metre slice, and
- approximately 2 MPa above overburden for the 0–20 metre slice.

In each case the suggested band width covers the vast majority of data with very few outliers. The suggested band of tectonic related stress for the slice containing the deepest data is somewhat tenuous owing to the obvious lack of data at depth. As with the situation with respect to orientations, the band widths suggested in Figures 3a, 3b and 3c reflect the impact of non-specific geological factors, not necessarily obvious at the time of measurement.

3.3 Magnitude of Major Horizontal Principal Stress

Figures 4a, 4b and 4c summarise the measured magnitudes of the major horizontal secondary principal stresses for the respective depth slices. These show a similar pattern to the corresponding Figures 3a to 3c for the minor horizontal principal stress. In this case, the upper bound trend lines suggested are:

Figure 3a. Summary of magnitude of minor horizontal secondary principal stress with respect to depth, (0–1200 metres).

Figure 3b. Summary of magnitude of minor horizontal secondary principal stress with respect to depth, (0–200 metres).

Figure 3c. Summary of magnitude of minor horizontal secondary principal stress with respect to depth, (0–20 metres).
- approximately 15 MPa above overburden for the 0–1200 metre slice,
- approximately 6.5 MPa above overburden for the 0–200 metre slice, and
- approximately 2.5 MPa above overburden for the 0–20 metre slice.

The location of the upper bound trend lines in Figure 3 and Figure 4 is obviously somewhat subjective. The method applied was to draw the trend lines through (or close to) data points from three different holes, exclusive of data points from other depth slices, except in the case of the 0–1200 metre slice where lack of data necessitated a more flexible approach. This did not always produce the same outliers for the minor and major principal stresses. The proportion of outliers produced by this process was much less than for the corresponding orientation data, consistent with the orientation being more sensitive to perturbations than magnitude.

3.4 Magnitude vs Orientation

Figure 5 summarises the magnitude versus the orientation of the major stress, for the 0–200 metre depth slice. In this instance the magnitudes are those of the proposed tectonic component, after removal of the gravity component associated with depth of burial. To construct Figure 5, a notional gravity related component of the horizontal stress field equivalent to the corresponding vertical overburden pressure has been subtracted from each measured stress magnitude. Presented in this way, the data in Figure 5 can be viewed free of the impact of varying depth of burial. The 0–200 metre depth slice was chosen because this represented the zone of greatest data density.
Ignoring the obvious outliers (above the dashed line), Figure 5 suggests that a range of magnitudes can exist in a given orientation. Regression analysis of the data in Figure 5 is consistent with a non-linear relationship between magnitude and orientation, with periodic peaks in magnitude across the orientation range. This suggests that change of orientation may be accompanied by a systematic change in magnitude, although the statistics of the available data set are not conclusive.

3.5 Major Stress vs Minor Stress

Figures 6a and 6b show total major horizontal secondary principal stress magnitude versus corresponding total minor horizontal secondary principal stress magnitude, for the full (0-1200 metre) depth range and the 0-200 metre depth slice respectively. Figure 6a suggests an approximately constant ratio ($\sigma_H/\sigma_h$) of 1.66 across the full depth range. Figure 6b, however, clearly shows a range of ratios from just above one to approximately two when the relatively shallower depth is looked at in detail.

In Figures 6c, the proposed tectonic component of the respective major and minor stresses are plotted against each other for the 0-200 metre depth slice. The data in Figure 6c shows considerable scatter, with a fairly well defined lower limiting ratio ($\sigma_H(\text{tectonic})/\sigma_h(\text{tectonic})$) of approximately 1.54, encompassing much of the data.

4. DISCUSSION

4.1 The Model of the Stress Field

The horizontal stress field proposed in the above plots is based on a model where the total stress magnitude at any point is made up of a gravity component, equivalent to the corresponding vertical stress based on depth of cover, plus a tectonic component ranging between zero and an upper bound value. This upper bound value appears approximately constant over a given window of depth, but varies from one window to another. The band width of tectonic stress at any depth can be considered to accommodate potential variations in the tectonic stress component from point to point (both vertically and laterally) associated with non-specific geological factors.

Underlying the model is the concept of lithostatic gravity stress (McGarr, 1988) in which the stress field at a point deriving from gravity loading is considered to converge over time toward a condition where stresses are equal in all directions as a result of strain adjustments occurring on geological features.
An interesting feature of the proposed tectonic stress environment is the apparently changing limiting stress ratio (\(\sigma_T/\sigma_h\)) defined by the respective upper bounds:

- approximately 2.5 for the upper bounds based on the 0–1200 metre depth slice,
- approximately 1.45 for the upper bounds based on the 0–200 metre depth slice,
- approximately 1.25 for the upper bounds based on the 0–20 metre depth slice.

The relatively lower value for the near surface data is consistent with the notion of the near surface rock being relatively more mobile en mass, and approaching the condition of lithostatic stress in response to tectonic activity as well as with respect to gravity loading. The significantly higher value for the deeper data may reflect the converse of this situation, with the impact of tectonic activity relatively more ‘locked in’. The proposed ratio of 2.5 for this data would be consistent with the rock mass behaving as a continuum, with a Poisson’s Ratio of approximately 0.3. This implies significantly different response to tectonic activity compared to gravity loading at depth. The relatively more variable data at depth is suggestive of a potentially greater sensitivity to geological factors in the deeper, Permian rocks.

### 4.2 Outliers

As a general observation, outliers with regard to orientation do not necessarily correspond to magnitude outliers, and vice versa. This reflects the varied impact that non-specific geological factors can have on the stress field.

With respect to magnitude, most data points can be reasonably accommodated within the band widths set to encompass the variation attributed to non-specific geological factors, although this is of course to some degree subjective. The obvious outliers in Figures 3b and 4b were all attributable to the impact of surface topography, evident at the time the measurements were made. In all other cases, the impact of topography could be ruled out. This highlights the profound role that topography can have, over and above the impact of non-specific geological factors.

### 5. CONCLUSIONS

For the area defined in Figure 1, the horizontal stress field can be reasonably described as having:

- a uniform (non-directional) gravity related component of magnitude equivalent at any depth to the vertical stress attributable to depth of burial,
• a superimposed tectonic component of magnitude within upper and lower bounds as defined by Figure 7, such bounds encompassing the impact of non-specific geological factors,

• an orientation of the major horizontal secondary principal stress most likely to be in the northeast quadrant, resulting from the tectonic stress component,

• no clear relationship between horizontal stress field orientation and magnitude,

• a common ratio of major to minor horizontal tectonic stress component magnitudes of approximately 1.54.

Outside of the bounds of tectonic stress defined by Figure 7, topography can have a major effect locally, and must be addressed as a separate factor.

The band widths described in Figure 7 for tectonic stress are relatively large, and while they may be taken as a guide to thinking, more specific information may have to be obtained for detailed design purposes by conducting targeted measurements. The concept of an "average fit" to the data could be potentially misleading.

6. ACKNOWLEDGMENTS

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7. REFERENCES


