Pre and Post Excavation Stress Measurements

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SUMMARY The results of pre and post excavation stress measurement programmes are presented for two sites (Malabar Ocean Outfall Tunnel and the King River Power Tunnel). The hydraulic fracturing technique was used at both sites for the pre excavation measurements. Borehole overcoring employing the CSIRO HF Cell was used for the post excavation measurements.

The results indicated good agreement between the two techniques in two vastly different geological environments. The two techniques have been shown to provide complementary information. Predictions made in advance by hydraulic fracturing were generally confirmed by overcoring.

1 INTRODUCTION

Knowledge of the in situ stress field is recognised as an important ingredient in planning engineering excavations in rock. A large number of stress measurement techniques have been developed over the past two decades in response to the growing awareness of the importance of in situ stress in mining and underground civil engineering projects. Until recently, application of these techniques has generally required that an excavation be available from which to conduct measurements. While providing vital information for updating planning, information gained at this stage of many projects may come too late to influence initial planning decisions. There is a demonstrable need for the development of reliable, simple, relatively cheap techniques to allow an initial understanding of the stress field to be obtained during the exploration/site investigation stage of projects.

At the pre excavation stage, it may not be necessary to have a detailed knowledge of the stress field. A general indication may often allow important decisions to be made on the best location and/or orientation of an excavation, the relative stability of alternative excavation layouts and possible reinforcement schemes. By contrast, detailed measurements made after the project has commenced (post excavation) can provide the specific information required to complete final design of uncommitted aspects of the project and to refine rock support practices. In any project there is a role for both pre excavation and post excavation stress measurements in the optimisation of planning to take account of the in situ stress field.

In Australia, the CSIRO Division of Geomechanics has been at the forefront of development and application of both pre and post excavation stress measurement techniques. This paper draws on two projects to illustrate the integration of pre and post excavation stress measurements. The two projects discussed are the Malabar Ocean Outfall Tunnel, and the King River Power Tunnel. In both instances the results of the pre excavations measurements were published prior to excavation commencing.

2 STRESS MEASUREMENT TECHNIQUES

2.1 General

Three methods for determining the in situ stress field in rock have received wide acceptance within the geomechanics community. These methods are the flatjack, overcoring and hydraulic fracturing techniques. Each is now a recognised and recommended method of the International Society for Rock Mechanics (ISRM, 1987). The flatjack method is rarely used within Australia, due in part to the successful introduction by the CSIRO Division of Geomechanics of the overcoring technique used in conjunction with the CSIRO Hollow Inclusion (HI) Cell, followed by the Divisions’ recent successes with the hydraulic fracturing technique.

The overcoring technique provides the complete stress tensor, with a statistical measure of confidence, in a single application. The technique is generally limited to operation in shallow holes (less than 20 m) and is ideally suited to post excavation measurements. Hydraulic fracturing provides more limited information (generally the stress components normal to the test hole axis) but is currently the only technique capable of measuring stresses to any appreciable depth from the surface at acceptable cost and reliability. Hydraulic fracturing is ideally suited to pre excavation measurements.

2.2 The Hydraulic Fracturing Technique

Hydraulic fracturing involves sealing-off part of a borehole, usually with an inflatable straddle packer, and then pressurising the isolated interval until the wall rock fractures. In the event that a fracture is developed in the axial plane of the borehole, analysis of the pressure and flow records obtained during pressurisation can be used to determine the magnitude of the stress field in the plane normal to the borehole axis.

If a vertical fracture is developed in a vertical hole, information recovered during testing may be used to determine the magnitude of the secondary principal stress components in the horizontal plane. The orientation of the horizontal stress field may be deduced from the orientation of the
induced crack.

When a vertical fracture is developed it will normally initiate in the direction of the major secondary principal stress in the horizontal plane \( (\sigma_{1''}) \). The shut-in pressure established in the crack when the test system is sealed can be used to directly estimate the magnitude of the minor secondary principal stress in the horizontal plane \( (\sigma_{2''}) \). The magnitude of \( \sigma_{1''} \) can be determined from either of the expressions:

\[
\sigma_{1''} = 3\sigma_{2''} + S - P_i - P_o \tag{1}
\]
\[
\sigma_{2''} = 3\sigma_{1''} - P_i - P_o \tag{2}
\]

where:

- \( S \) is the fracture strength of the rock (determined from laboratory fracture tests conducted on samples of the rock);
- \( P_i \) is the fracture initiation pressure, \( P_i \) is the ambient pore pressure, and
- \( P_o \) is the crack re-opening pressure obtained from cycles of re-pressurisation conducted subsequent to fracture initiation.

The hydraulic fracture technique was used to conduct pre-excitation strain measurements. The specific theoretical considerations pertinent to both sites have been published previously (Enever et al. 1984, 1987).

In both instances work was conducted in 76 mm dia. vertical holes using a fracture tool featuring 1 metre long inflatable packers isolating a 1 metre long test interval. At both sites an impression packer was used to obtain the orientations of the cracks. At Malabar the tools were handled on CSIRO’s “endless tubing unit”. This is a trailer mounted coiled tubing unit specifically designed for fast and convenient operation in situations where site access is reasonable. The relatively more difficult access at the King River site necessitated the use of CSIRO’s “portable testing facility” which utilises specially modified drill rods to handle the tools.

At Malabar, interpretation was based primarily on the use of equation (2). Analysis of the King River data was based on the use of equation (1).

2.3 The Borehole Overcoring Technique

In the borehole overcoring method, a large diameter hole (generally 150mm diameter) is drilled to the desired location in the rock mass where a measurement is to be undertaken. A small diameter pilot hole (generally 38mm diameter) is drilled ahead of this hole for a distance of approximately 600mm. A strain or borehole deformation instrument is inserted into the pilot hole after which this hole is overcored at the larger diameter to relieve the stress in the hollow core so produced. The strains or deformations which occur on overcoring due to stress relief are measured by the instrument and converted to the pre overcoring stress field utilising the stress-strain relationships for the rock.

The overcoring technique was used to conduct post excavation stress measurements at both sites. The CSIRO HI Cell (Worotnicki and Walton, 1976) was used to measure the strains due to stress relief. This instrument enables the complete state of stress (i.e. all three principal stresses and their directions, or the six stress components in a chosen co-ordinate system) to be determined in one application. The CSIRO HI Cell consists of a thin-walled epoxy pipe containing 9 or 12 resistance strain gauges. The cell is glued into a pilot hole with epoxy cement. The stress relief strains sensed by the cell are monitored during overcoring. This provides data to assess whether the test has been successful.

After retrieval from the borehole, core containing an HI Cell is tested in a cylindrical pressure chamber (biaxial cell) allowing radial reloading of the core. Strain changes detected by the HI Cell during reloading are used to determine values of deformation modulus and Poisson’s ratio of the core.

3 SITES

3.1 Malabar Ocean Outfall Tunnel

The Malabar tunnel forms part of an environmental engineering scheme designed to service the waste water requirements of metropolitan Sydney. Construction work on the scheme started in 1984, and is due for completion in 1991. The scheme includes three outfalls situated at Malabar, Bondi and North Head. Each outfall will extend approximately 4km offshore and consist of a Decline Tunnel, a Submarine Tunnel and a number of offshore Diffuser Shafts. A location plan of the outfall tunnels is shown in Figure 1(a).

Each outfall tunnel is planned to penetrate a gently dipping sedimentary sequence composed of Hawkesbury Sandstone and the upper three units of the Narrabeen Group, namely, Newport Formation, Bald Hill Claystone and Bulgo Sandstone. The Narrabeen Group is situated beneath the Hawkesbury Sandstone, and generally below the depth of previous engineering activity in the Sydney area.

The general lack of information on the lower stratigraphic units prompted the conduct of an extensive geotechnical site investigation along the tunnel alignments. This included a stress measurement programme using the hydraulic

![Figure 1(a) Location Plan - Sydney Ocean Outfalls Project](image)
fracturing technique. The aim was to provide information for decisions on tunnel alignments, tunnel profile shapes as well as temporary and permanent support strategies.

The measurements were conducted in existing off-shore exploration holes. Successful tests were achieved in a total of four holes, two at Malabar (M1 and M2) and one each at Bondi and North Head. The results obtained from Hole M1 at Malabar are drawn on for this paper. A total of 7 tests were conducted in this hole, from 70 to 120 meter depth, in the Hawkesbury sandstone and sandstone units of the Newport Formation. A discussion of the results of the programme is given in Enever et al. (1984).

To extend the information base and obtain more detailed information on the stress-strain response of the formation to excavation, a second phase geotechnical investigation was initiated. This has included post-exavcation stress measurement using the overcoring technique from the partly completed Malabar tunnel.

To date, measurements have been conducted from within the Bottom Station of the Malabar Decline Tunnel. A total of eight measurements have been made in three holes normal to the tunnel axis. The profile of stresses from the tunnel boundary out to the far field (virgin) condition have been measured, including tests in sandstone and fine grained units of the Newport Formation. Of these, only one test (Test 3/4) was conducted sufficiently remote (14 m) from the tunnel wall to yield information on the virgin stress condition. This test was conducted in a sandstone unit.

A longitudinal section showing hydraulic fracturing and overcoring test locations is shown in Figure 1(b).

![Figure 1(b) Longitudinal section showing test locations at Malabar - in plane of tunnel](image)

3.2 King River Power Tunnel

The King River Project is a hydro-electric scheme designed as part of the continuing development of Tasmania's hydro-electric resources. Construction work commenced in early 1986 and is expected to be completed in 1992. The scheme includes two rock fill dams (Crotty and Darwin), a surface power station on the King River and a 7km long tunnel linking the two. A location plan of the scheme is shown in Figure 2(a).

![Figure 2(a) Location Plan - King River Scheme](image)

The tunnel comprises a 6 km headrace section, extending from the intake to a surge tunnel and pond, and a 1 km power tunnel section, extending from the surge tunnel to the power station. The tunnel is being constructed in a metamorphosed volcanic sequence. Three geological units (eastern, central and western) have been defined along the tunnel alignment. The Power Tunnel is located in the western sequence, comprising quartzfeldspar porphyry and bedded tuff with tuffaceous sandstones and silite. This sequence is characterised by a number of structural trends (joints, foliation, cleavage) with different orientations.

An advance knowledge of the in situ stress state in proximity to the Power Tunnel was considered important to the early choice of the length of steel pressure lining required.

Hydraulic fracture tests were conducted in three exploration holes drilled along the Power Tunnel alignment. Successful tests were achieved in two holes (DH6067, DH6121). A total of 30 tests were carried out in these holes at depths from 26m to 100m. Details of the results are given in Enever et al. (1987).

A subsequent, more detailed, investigation of the in situ stress state has been undertaken from the partly excavated power tunnel, using the overcoring technique, with the aim of refining decisions on pressure lining requirements.

Measurements have been conducted in two holes located in close proximity to one of the hydraulic fracture holes. Four successful tests have been achieved, two in each hole. Both holes were sub-horizontal and drilled at approximately 45° to the tunnel axis. All tests were conducted sufficiently remote from the tunnel to be substantially unaffected by it.

A longitudinal section showing hydraulic fracturing and overcoring test location is shown in Figure 2(b).

4 RESULTS
The virgin principal stresses determined from overcoring at both locations are summarised in Figures 3 and 6. The hydraulic fracturing results from both locations are summarised in Figures 5 and 6. Also shown on these figures are the secondary principal stresses in the horizontal plane derived from overcoring.
5 DISCUSSION

5.1 Malabar

The results of the overcoring tests reveal a virgin stress field oriented approximately vertical and horizontal (Fig. 3) consistent with the gently dipping sedimentary sequence in which the measurements were made.

Figure 5(a) shows excellent agreement between the orientation of the horizontal stress field determined from the hydraulic fracture tests and the orientation of the secondary principal stress field in the horizontal plane resolved from the overcoring result.

The horizontal stress component magnitudes shown in Figure 5(b) suggest a systematic trend for increase of stress magnitude with depth, in accord with a predominantly "gravity" origin for the horizontal stress field as might be expected for the geological environment. The trend lines included on Figure 5(b) suggest consistency between the data for the two techniques. For $\sigma_1$, the overcoring result is consistent with the lower bound trend line through the hydraulic fracture data. The higher values of $\sigma_1$ measured by hydraulic fracturing in the Hawkesbury Sandstone may be attributable to local stress concentration from the adjacent notch formed by the intersection of the cliff line and wave cut platform (Fig. 1(b)).

The variation in the values of $\sigma_1$ and $\sigma_3$ determined by hydraulic fracturing in the Newport Formation may be attributable to a tendency for stress magnitude to vary within this layered unit. This type of behaviour was noticed in the overcoring campaign conducted at Malabar. It was not clear whether this tendency reflected a variation in virgin conditions, or was the result of stress redistribution occurring in response to excavation.

5.2 King River

The overcoring results summarised in Figure 4 reflect a virgin stress field approximately consistent with topography (Fig. 6(a)). The major principal stress ($\sigma_1$) is generally oriented parallel to the tunnel alignment and dipping approximately down the slope of the valley of the King River. The minor principal stress ($\sigma_3$) is also oriented approximately parallel to the tunnel alignment but dipping into the wall of the valley. The average bearing of $\sigma_3$ determined from overcoring is in reasonable agreement with the average bearing of $\sigma_3$, indicated by the hydraulic fracture tests conducted in Hole 6067. There was also reasonable agreement between the magnitudes of the major stress components determined from these hydraulic fracture tests (Enever et al. 1987) and the overcoring tests. This general agreement suggests the existence of a regional stress component, oriented approximately parallel to the tunnel alignment, changing from near horizontal under the flat terrain surrounding Hole 6067 to dip approximately parallel to the valley wall at the
Figure 5(a) Summary of secondary principal stress orientations in horizontal plane - Malabar

Figure 5(b) Summary of secondary principal stress magnitudes - Malabar

Figure 6(a) Summary of secondary principal stress orientations in horizontal plane - King River

Figure 6(b) Summary of secondary principal stress magnitudes - King River
location of the overcoring tests. The influence of
topography on the stress field in proximity to Hole
6121 is evidenced by the significantly different
orientation of the secondary principal stresses
(Fig. 6(a)) indicated by hydraulic fracturing and
by overcoring, compared to the primary stress
field.

Figure 6(a) indicates very good agreement between
the average orientation of $\sigma_1$ determined from the
hydraulic fracture tests conducted in Hole 6121,
and the orientation of $\sigma_1$ determined by two of the
overcoring tests (Tests 1/2 and 2/3) conducted in
close proximity. The horizontal stress component
magnitudes show very good agreement between
hydraulic fracturing and overcoring for these two
overcoring tests (Fig. 6(b)). It is of interest to
note that the hydraulic fracture estimates of $\sigma_2$
and $\sigma_3$ have been derived both from equation 2, and
from the direct use of shut-in pressure only. In
the latter case values of $\sigma_2$ and $\sigma_3$ were derived
from opening of sub-vertical structures oriented
approximately parallel and normal to the
orientation of $\sigma_1$ determined from those tests
amenable to “conventional” interpretation.

The other two overcoring tests (Tests 1/2 and 2/3)
yielded significantly different orientations of $\sigma_1$,
(Pig. 6(a)). This, with the gross variability in
the magnitudes of $\sigma_2$ and $\sigma_3$ for these tests (Fig.
6(b)) is symptomatic of a complex stress field.
This was supported by evidence from the hydraulic
fracture programme in which some tests (not
reported) yielded similar results.

The values of $\sigma_1$, and $\sigma_2$, in Figure 6(b) with
similar orientations imply a horizontal stress
field with approximately constant magnitude with
depth. This was also indicated by the hydraulic
fracture tests conducted in Hole 6067). A trend of
this type is indicative of a stress field of
tectonic origin which is consistent with the
geological environment. The tendency for $\sigma_1$ to
diminish in magnitude upward from approximately RL
70 m can be attributed to the influence of the
ground surface on a stress component oriented
approximately normal to the valley.

A feature of the hydraulic fracture tests conducted
in Hole 6121 were the tests yielding very low shut-
in pressures. These values were consistent with
the low minor principal stress component magnitude
determined from all overcoring tests (Fig. 4).

6 CONCLUSIONS

At both Malabar and King River, sites representing
distinctly different geological environments, there
was good agreement between results obtained from
overcoring and hydraulic fracture. General trends
predicted by hydraulic fracturing were confirmed by
overcoring.

At Malabar, variation in the magnitudes of the
horizontal stress components, particularly within
the Newport Formation, discernable from the
hydraulic fracture results were possibly consistent
with significant variations in the stress field
revealed during overcoring. At King River,
variability in the orientation and magnitude of the
stress field revealed by the hydraulic fracture
tests was reflected in the results obtained from
overcoring. Of particular concern was the
confirmation by overcoring of the existence of a
very low magnitude for one stress component, as
suggested by hydraulic fracturing.

In both instances, the measured stress fields
reflected the respective geological environments.
Combination of the information obtained from both
techniques enhanced the ability to identify the
nature of the respective stress fields more fully
than possible from either technique used in
isolation.

Integrated measurement programmes of the type
described in this paper will help to develop
confidence in the evidence obtained from pre
excavation measurement campaigns.

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