Summary  
In this study acoustic emission (AE) techniques were investigated to determine in situ rock stress from rock cores. The stresses were estimated from the AE behaviour and compared with the values calculated using conventional Hollow Inclusion (HI) cells. Stresses in three different directions such as normal to bedding and parallel to the strike and dip of bedding were determined from the rock cores. In almost all the tests the Kaiser effect was clearly observed, so the stress could be determined from the AE signature in the first loading. The deformation rate analysis (DRA) was also used to estimate the stresses. The results from DRA were consistent with those estimated from AE method. In general, the stresses calculated from core testing were within 10% of the values determined using the conventional HI cells.

1. INTRODUCTION

Reliable evaluation of in situ stress is an important step in the analysis and design of underground excavations, particularly for evaluating the stability of underground openings to prevent failures. Although a number of techniques have been proposed and developed to determine in situ stress, the actual measurement of the stresses is not an easy task and all suffer from deficiencies and limitations. The main deficiency of established techniques such as coring method or hydraulic fracturing method is that they are usually expensive and time consuming. Other shortcomings of the techniques are that they are deficient for measuring the in situ stress at depth in remote regions that are hard to access from mine workings.

As an alternative, several methods have been proposed for estimating in situ stresses from cored rock samples at depth and in remote regions. They include AE method, differential strain analysis (DSA) or differential strain curve analysis (DSCA), anelastic strain recovery method (ASR), and deformation rate analysis (DRA). AE and DRA methods are principally similar in terms of taking advantage of the Kaiser effect. This phenomenon suggests that previously applied maximum stress might be detected by stressing a rock specimen to the point where there is a substantial increase in AE activity. A number of researchers have studied the Kaiser effect in geomaterials since the 1970’s, and have discussed the factors that influence stress memory recollection of rocks under uniaxial and triaxial conditions. This technique has been developed and tried by various researchers in the past with the aim of providing a practical technique for retrieving the Kaiser effect (Kanagawa et al., 1976; Kurita and Fujii, 1979; Houghton and Crawford, 1987; Seto et al., 1989 a, b, 1992 a, b, 1996; Holocomb, 1993; Utagawa et al., 1995). The Kaiser effect is a recollection of the maximum previous stress to which a rock had been subjected in its in situ environment. The technique is functionally workable technology, and is anticipated that a rapid and economical determination of the in situ stress in the rock is possible. It seems, however, that no satisfactory results have been obtained to date. The conclusions obtained are still contradictory, especially that regarding how long the stress memory can be retained. Yoshikawa and Mogi (1981) could see the Kaiser effect up to five days. Kurita and Fuji (1979) have reported that the Kaiser effect could be observed for a period of month. Yoshikawa and Mogi (1989) found out that the stress value estimated by the Kaiser effect is lowered as the delay time from drilling to testing is increased. Momeyez and Hassani (1992) reported that the memory of the previous stress is not lost after a period of two weeks in laboratory experiments.

Seto et al. (1989a,b; 1992a,b) and Utagawa et al. (1995) have reported on the basis of laboratory experiments using tuff, sandstone and granite in dry condition that the stress memory can be retained for a long time (more than one year). They have also shown that it is possible to estimate the previous stress by using the AE signature in the second and/or third reloadings, even when the Kaiser effect is not clear in the first reloading due to noise associated with crack closure or compaction. They
have also suggested the procedure to estimate the previous stress from the AE signatures in cyclic reloading of previously stressed rock (Seto et al., 1990, 1992b; Utagawa et al., 1995).

In this study the AE and DRA methods were applied to determine in situ rock stress, when a rock core specimen was uniaxially loaded repeatedly up to the certain stress level. The objective of this study is to explore the possibility of the AE and DRA techniques in the estimation of in situ rock stress using core from the McArthur River Mine. This core has been recovered from a site where conventional hollow inclusion stress measurements have been conducted.

2. AE AND DRA METHODS FOR DETERMINING IN-SITU ROCK STRESS

Figure 1 shows a typical example that indicates the existence of the Kaiser effect in a granite specimen. In this test, the previous stress was artificially applied to a specimen by a servo-controlled testing machine to understand the Kaiser effect of rock. The previous stress was nearly 11 MPa under the confining pressure of 5 MPa, which was kept for three hours to make a specimen memorise the previous stress. The rock specimen was tested under uniaxial compression 30 min. after the previous loading to look at the Kaiser effect. An arrow indicates the AE take-off point and the take-off point of AE activity coincides well with the axial maximum previous stress of 11 MPa. In all experiments conducted within a short delay time, the existence of Kaiser effect in rock specimens could be clearly observed and the assigned stress from the take-off point of AE signature was within 5%.

\[
\Delta \varepsilon_{ij} = \varepsilon_j(\sigma) - \varepsilon_i(\sigma) ; j>i
\]

Where \(\varepsilon_k\) is the strain in the k-th loading and \(\sigma\) is the applied stress. This function, called the strain difference function, represents mainly the difference of inelastic strain between two cycles. We assumed that the strain difference function bends at the stress close in value to that of a normal component of in situ stress along the loading axis by applying DRA to the core specimen.

Figure 2 represents the relation between differential strain and stress for a previously stressed granite specimen shown in Figure 1. A bending point can be recognised at nearly 10 MPa that is close to the previous stress along the loading axis. It can be also seen that there are not any bending points at the stress levels which corresponds to the differential stress (6 MPa) and confining pressure (5 MPa).

Figure 2. Differential strain vs stress for a granite core specimen.

Consequently, based on the results of the laboratory test, if the previously stressed rock specimen was re-loaded under uniaxial compression, the AE signatures in the reloadings and the DRA result can allow us to determine the maximum previous stress along the loading axis.

3. TESTING PROCEDURE

3.1 Rock Core Specimen

The rock cores were obtained from 2J4 borehole in the McArthur River Mine. Table 1 shows the features of cored rock, depth of the boreholes and time lag (delay time) between drilling and testing. A single block of rock core was under-cored into several 20mm diameter samples. Sample lengths were trimmed to about 50 mm and ground at each end. Rock core specimens were prepared in three
different directions: normal to bedding planes, parallel to the strike of bedding and down dip of bedding.

Table 1. Core details from the McArthur River Mine.

<table>
<thead>
<tr>
<th>Diam (mm)</th>
<th>Length (mm)</th>
<th>Depth (m)</th>
<th>Drill Date</th>
<th>Delay Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>560</td>
<td>245</td>
<td>Nov 97</td>
<td>60 days</td>
</tr>
</tbody>
</table>

In an adjacent site (along the same borehole), a CSIRO hollow inclusion (HI) cell was installed to measure the in situ rock stress. Based on the principal stresses evaluated by the HI cell, the stresses in the three different directions are 6.5 MPa normal to the bedding planes, 8.2 MPa parallel to the strike of bedding and 5.6 MPa along down dip.

3.2 Loading of The Rock Core Specimen

In the present study, the rock core specimens were repeatedly loaded five times up to a certain stress level under a constant loading rate (1.87 MPa/min) by means of a servo-controlled testing machine. The stress level was decided, taking into account the depth of the core and the uniaxial compressive strength of the rock. Rock core specimens were usually stressed up to the maximum stress level of nearly 15 to 20 MPa. The uniaxial compression tests of rock core specimens were carried out nearly 60 to 70 days after the drilling at the site. During the repeated loading, axial strains were measured by four strain gauges (gauge length: 10 mm) attached on the surface of the specimen. Using the results of the strains, a deformation rate analysis was carried out after the test.

3.3 AE Measurement Method

While the rock core specimens were repeatedly loaded, the AEs were also measured. The AE monitoring system used in the test consists of six NF-7661 AE modules capable of recording the full range of AE parameters as well as performing two-dimensional source location. In AE measurement, two AE sensors were attached on sides of the rock core specimen. The signals from the AE sensors were amplified 40 dB by the pre-amplifiers, then sent to the AE monitoring system and were amplified further by 40dB. Threshold level for AE counting was in the range of 150 to 200 mV that is slightly higher than environmental noise. After the test, the AE characteristic parameters were analysed using the recorded AE event data, and the relations between each characteristic parameter and stress were investigated.

4. RESULTS AND DISCUSSIONS

4.1 Examples of the AE Method

Figure 3 shows the AE signatures in the first loading of a core specimen that is normal to bedding planes. The maximum previous stress was recognised by the AE take-off point, which is indicated by the arrow in the figure. The estimated stress from the AE signatures was 9.74 MPa. It can be seen from the figure that AE started to generate from the stress level of nearly 3 MPa, however, the inclination of the AE curve significantly changed at the stress level of 9.74 MPa. Therefore, the stress of 9.74 MPa was determined as the previous stress.

Figure 4 shows another example of AE signature of a rock core specimen that is parallel to strike of the bedding planes. The take-off point of cumulative AE ring down counts was clear in the first loading. Using the AE signature, the previous stress could be estimated as 7.21 MPa. Figure 5 represents the relation between cumulative ring down counts and stress of a core specimen, which was loaded along down dip of bedding. The AE take-off point was clearly recognised at 5.86 MPa.

Figure 3. Cumulative AE counts normal to bedding, first loading cycle.

Figure 4. Cumulative AE counts parallel to strike of bedding, first loading cycle.
4.2 Examples of the DRA method

Figure 6 represents the strain difference functions between the second and the first loading on a core specimen that is normal to the bedding planes. The clear bending point was recognised at the stress level of 6.5 MPa, which is indicated by the arrow in the figure.

Figure 7 shows another example of strain difference function of a rock core specimen that is parallel to the strike of the bedding planes. The bending point was clearly observed at the stress level of 8.1 MPa.

4.3 Summary of the Estimation

Table 2 summarises the result of estimated stresses from AE and DRA methods. The average estimated stresses from the AE method are 8.4 MPa normal to the bedding planes, 7.3 MPa parallel to the strike of the bedding planes, and 5.6 MPa along down dip. In almost all the tests the Kaiser effect was clearly observed, and the stress could be estimated from the AE signature in the first loading. The estimated stresses from the DRA method are 6.9 MPa normal to the bedding planes, 7.9 MPa parallel to the strike of bedding, and 5.4 MPa along down dip. The estimated stresses from the AE and DRA methods were consistent with each other, particularly parallel to the strike and along down dip of the bedding planes.

The results from core testing have been compared with HI cell measurements carried out on the same borehole (Table 3). The results from core testing were within 10% of the HI cell values for the three different directions tested. Consequently, the AE and DRA have the potential to be used as an alternative for in-situ stress measurement techniques.
Table 3. Comparison of estimated stresses from core data with the results from CSIRO HI cell.

<table>
<thead>
<tr>
<th>Orientation of testing</th>
<th>AE (Mpa)</th>
<th>DRA (Mpa)</th>
<th>HI (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal to bedding</td>
<td>8.4</td>
<td>6.9</td>
<td>6.5</td>
</tr>
<tr>
<td>Along the strike of bedding</td>
<td>7.3</td>
<td>7.9</td>
<td>8.2</td>
</tr>
<tr>
<td>Down dip of bedding</td>
<td>5.6</td>
<td>5.4</td>
<td>5.6</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

In situ rock stress measurements were performed by using AE signatures and strain behaviours in repeated loading of rock core specimens from McArthur River Mine. The estimated stresses from AE and DRA methods were compared with the results from over coring method using CSIRO hollow inclusion (HI) cell. The main conclusions obtained here are as follows:

1. The estimated stress from the AE method normal and parallel to the strike of the bedding planes were 8.4 MPa and 7.3 MPa, respectively. The stress along down dip was 5.6 MPa.
2. The estimated stress from the DRA method normal and parallel to the strike of the bedding planes were 6.9 MPa and 7.9 MPa, respectively. The stress along down dip was 5.4 MPa.
3. A 10% difference was calculated between the stresses calculated from core testing and those calculated using conventional HI cells.
4. The time lag of up to 60 to 70 days did not deter the evaluation of the critical in situ stress condition. Rock core specimen recollected the in situ rock stress reasonably well.
5. The AE and DRA methods described in the paper should be applicable to the in situ stress measurement with reasonable accuracy.

6. ACKNOWLEDGMENTS

The authors wish to thank the management of the McArthur River Mine for the permission to publish the paper. The second author acknowledges the financial support from the Australian Centre for Geomechanics and Curtin University of Technology for his position as Professor of Mining geomechanics at the Western Australian School of Mines. The Australian Centre for Geomechanics has received funding for this position from the Government of Western Australia, Centres of Excellence Program.

7. REFERENCES


