Stress measurements from oriented core

E. Villaescusa\textsuperscript{a,*}, M. Seto\textsuperscript{b}, G. Baird\textsuperscript{a}

\textsuperscript{a}Western Australian School of Mines, Curtin University of Technology, PMB 22, Kalgoorlie 6430, Australia
\textsuperscript{b}AIST Research Centre for Deep Geological Environment, Tsukuba Central; 7, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8567, Japan

Accepted 30 April 2002

Abstract

A low-cost methodology that allows the estimation of in situ and induced stress using oriented rock core specimens has been investigated. The technique can be used to determine the stresses either during the early stages of a project, even in undeveloped areas of a mine, or to measure in situ and induced stress within active mine workings, such as stopes and pillars. The research aim was to compare the experimental results estimated by the Acoustic Emission and Deformation Rate Analysis methods with those estimated by conventional HI cell measurements. Data was collected from a number of sites with different geological environments and in most cases the core was obtained from the same hole in which a conventional stress measurement had been carried out. The studies have focused on the determination of the full stress tensor from a single oriented cored rock. In all cases, the rock core specimens recollected similar in situ stress values to those estimated using conventional overcoring methods.

1. Introduction

Reliable evaluation of in situ stress is an important step in the analysis and design of excavations, particularly for evaluating the stability of openings to prevent failures. Although a number of techniques have been proposed and developed to determine in situ stress, the actual measurement is not an easy task, and all existing methods suffer from certain deficiencies and limitations. One of the deficiencies of conventional techniques such as overcoring and hydraulic fracturing is that they are usually time consuming and very expensive (requiring specialised personnel). In addition, overcoring techniques cannot be used to measure in situ stress where no underground access is available, as may be the case in feasibility studies of new orebodies or within the abutments of an existing orebody at depth.

In Western Australia a large number of mines are experiencing relatively high horizontal in situ stress fields, even at relatively shallow depths. Early signs of high stresses have been observed in several of the newly developed underground mines and this has stimulated a general interest in stress measurement techniques [1].

Currently, attention is focused on active extraction areas as well as the characterisation of in situ stresses at depth in remote regions that are difficult to access from current mine workings but where extensive geotechnical data from diamond drill coring is widely available. In particular, a low-cost methodology to carry out stress measurements at a number of locations over a short period of time has been investigated at the Western Australian School of Mines (WASM) over the last 3 years [2,3].

The stress measurement technique allows the estimation of the in situ stress field during the early stages of a project (such as mine feasibility studies), even in areas where development access is not yet available. Furthermore, in cases where access is available, the technique can be used to measure stress concentrations in isolated pillars, and within stope crowns. The information can be used as an input and calibration of numerical models and can lead to an optimisation of scheduled extraction sequences. As a result, safer and more economical mine design strategies are likely to be achieved.

2. Methodology

The acoustic emission (AE) and deformation rate analysis (DRA) methods used to estimate the in situ
stresses from cored rock samples are based on the principle of the Kaiser effect [4]. The analysis of this phenomenon supposes that a previously applied maximum stress may be detected by loading a rock specimen to a point where a substantial increase in AE activity is experienced. The Kaiser effect is the recollection of the immediate maximum previous stress to which a particular rock mass has been subjected by its environment. The principle behind both the techniques is that changes in the rate of AE and of axial strain with stress occur at the maximum stress level (along the axis of the sample) to which the sample had previously been subjected. The methodology has been developed by several researchers with the aim of providing a practical technique for retrieving the Kaiser effect [5–14].

2.1. Sample drilling

The methodology used at WASM consists of loading small cylindrical samples of rock (20 mm diameter) which are undercored from a single diamond drilled oriented core (minimum 51 mm diameter) recovered from the site for which stress data is sought. Undercore means re-drilling in the laboratory the oriented core obtained from the field in order to obtain the specimens for testing. Fig. 1 shows a typical stereographic projection in which the undercored laboratory drilling orientations with respect to the main oriented core axis are indicated. Six undercored directions are shown in the figure, as at least six independent undercore orientations are required in order to determine the six independent components of the stress tensor.

Fig. 2d shows a three-dimensional model of an actual oriented core showing the different undercored directions. However, in order to facilitate the procedure, undercored is carried out with the oriented core positioned horizontally or inclined at 45° under the laboratory radial drilling machine (Fig. 2e). The actual mine grid bearing and plunge of the undercored samples are obtained by rotating the nominal orientation of each undercored sample into the direction of the source (field-based) oriented core from which the undercore was drilled.

A rotation through an angle θ about the unit vector \( \mathbf{n} = n_1 \mathbf{i} + n_2 \mathbf{j} + n_3 \mathbf{k} \) can be represented by the orthogonal transformation

\[
A(\theta) = \cos(\theta)I + (1 - \cos(\theta))M + \sin(\theta)N,
\]

where

\[
M = \begin{pmatrix}
    n_1 n_1 & n_1 n_2 & n_1 n_3 \\
    n_2 n_1 & n_2 n_2 & n_2 n_3 \\
    n_3 n_1 & n_3 n_2 & n_3 n_3
\end{pmatrix},
\]

\[
N = \begin{pmatrix}
    -n_3 & 0 & n_1 \\
    0 & n_3 & -n_2 \\
    n_2 & n_1 & 0
\end{pmatrix}
\]

and \( I \) is the identity matrix.

We note that the unit vector \(-\mathbf{n}\) and the angle \((2\pi - \theta)\) determine the same rotation.

If the source oriented core is obtained from a subvertical hole of bearing and plunge \(x/\beta\) and that the undercored sample has a nominal bearing and plunge \(\psi/\xi\). Then letting \(\mathbf{n}(x, y)\) denote a unit vector with bearing and plunge \(x/y\), the true (mine grid) bearing and plunge of an undercored sample are the bearing and plunge of the unit vector \(A(\theta)\mathbf{n}(\psi + x, \xi)\), where the unit vector in the definition of the matrix \(A(\theta)\) is the unit vector \(\mathbf{n}(x, 0) \times \mathbf{k}\) (\(\mathbf{k}\) is the vertical unit vector and “\(\times\)” is the vector cross product).

2.2. Sample preparation

In this study, oriented (source) drill cores having a variety of sizes were used to estimate the stresses. The diameter ranged from 51 mm for exploration core to 141 mm for core recovered from HI cell stress measurements. In all the cases, each rock core was undercored into several 20 mm diameter samples. The sample lengths were trimmed to about 45–50 mm and ground square at each end. Parallelism between the top and bottom faces of each sample, to within 0.02 mm, was accomplished in all the cases. Usually, at least three specimens were prepared for each selected orientation of testing. Fig. 2 shows details of sample preparation including marking the undercored orientations, drilling and grinding the sample ends.

2.3. Sample loading

The specimens were instrumented with two axial strain gauges (gauge length: 20 mm) and a pair of AE transducers (Fig. 3). The strain gauges provide a measure of axial strain and the AE transducers provide a record of the number of internal acoustic emissions with increasing load (and hence stress). In the present study, the rock core specimens were repeatedly loaded five times up to a certain stress level under a constant loading rate (7.5 MPa/min) by means of a servo-controlled testing machine. The specimens were usually loaded up to a stress level that was determined by taking into account the depth of the core and the uniaxial compressive strength of the rock.
The AE monitoring system used in the test consisted of six NF-7661 AE modules capable of recording the full range of AE parameters as well as performing two-dimensional source location. The AE sensors used in this study were of the differential type (5 mm diameter, NF-AE-904DM model) and the resonance frequency was 500 kHz. They had high gains of between 200 and 550 kHz. The response frequency band of this system was between 50 kHz and 1 MHz.

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 40 dB. The threshold level for AE counting was in the range 150–200 mV, which was slightly higher than the 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. In addition, a DRA study was carried out using the results of the strains measured during the test.

2.4. AE technique

AE is a burst of high-frequency elastic waves caused by a localised failure such as microcracking within a material. The AE technique is based on the Kaiser effect, which is an AE phenomenon in which there is an
absence of detectable AE until the previously applied stress level is exceeded.

Consider, for example, a simplified cyclic loading in which a rock specimen is subjected to two cycles of loading. In the first cycle of loading, stress is applied to the specimen at a constant rate up to a stress level ($\sigma_p$) and then returned to zero. In the second cycle, the stress is increased in a similar fashion, however, the previous maximum stress ($\sigma_p$) is exceeded. During each cycle, AE activity is monitored and recorded as a function of applied stress. In the first cycle, AE activity is generated at all stress levels. However, during the second cycle of loading no AE activity is generated until the stress level ($\sigma_p$) attained in the first loading cycle is exceeded.

The effect was first observed by Kaiser [4] in the experimental study of metals that were able to "memorise" the previous applied stress level. The Kaiser effect was also observed in rock by Kurita and Fujii [6] and it is believed that the Kaiser effect in rock is closely related to the extension of microcracks that had been formed in the previous stress state [15]. The extension of the microcracks induces the active AE and inelastic strain behaviour after the previous stress level is exceeded. In addition, the AE is generated by the irreversible movement of a discontinuity or a crack inside a rock core specimen such as shearing and closure, as well as microcracking.

Since a rock specimen inevitably includes microcracks, the first loading cycle often produces noise associated with crack closure or compaction that can sometimes obscure the Kaiser effect. This noise in the first cycle of loading, however, can be suppressed by subsequent unloading–reloading cycles at stress levels below the Kaiser effect, thereby making the take-off in AE associated with the Kaiser effect more pronounced. Most noise is reduced by the second cycle and the previous stress can be estimated by a clear AE take-off in the second cycle of loading [16]. Thus, in the present study the AE activity in the second loading cycle is usually used to estimate the in situ stress (Fig. 4).

2.5. Deformation rate analysis

The DRA method uses the behaviour of inelastic strain of the specimen under uniaxial compression to determine the previously applied stress. This method is similar to the AE method in that both utilise the inelastic properties of rocks under compression. Yamamoto et al. [17] experimentally demonstrated that the previous stress could be obtained from a change in the gradient of the stress–strain relation under cyclic uniaxial compression tests for a specimen, and then they named the procedure the DRA. The gradient change was not commonly determined in the stress–strain relations obtained by conventional techniques in
the case of small previous stresses, because the change was masked by the larger non-linearity of the stress–strain relation resulting from other sources, for example, crack or pore closure.

Yamamoto et al. [17] performed cyclic uniaxial loading tests and measured the strain difference values during loading between two cycles as a function of the applied stress

$$\Delta e_{ij} = e_j(s) - e_i(\sigma), \quad j > i,$$

(2)

where $e_k$ is the strain in the $k$th loading and $\sigma$, the applied stress. This function, called the strain difference function, represents mainly the difference of inelastic strain between the cycles.

The mechanical behaviour of pre-existing cracks in a rock specimen causes non-linear strains with respect to the applied axial stress. For instance, frictional sliding is expected to occur on a pre-existing shear crack when the shear stress exceeds a critical value. An isolated tensile crack may open or close elastically with the change in the axial stress. This type of non-linear behaviour in strain is considered to be mostly reversible during cyclic loading, as long as the pre-existing cracks do not change their size [13]. The reversible components of strain are cancelled by the operation in Eq. (2).

However, the axial stress may enlarge some of the pre-existing cracks and also create new cracks. This would be expected to occur, considering our interpretation of the Kaiser effect, when the applied stress exceeds the peak value of previous maximum stress. The resulting strain is irreversible for two successive cycles and is not cancelled in the strain difference function defined by Eq. (2). It is clear that the use of the strain difference function has the advantage of emphasising the irreversible component of the measured non-linear strain by eliminating the reversible component. Hence, the bending point of the stress–strain curve can be detected by using the strain difference function (see Section 2.6). The abscissa of the bending point is identified with the normal component of in situ stress along the loading axis (Fig. 5).

2.6. A criterion to establish the maximum previous stress

In order to estimate the maximum previous stress using the AE (or DRA) signatures, the “take-off” or “change” point on the cumulative AE (or the strain difference function) versus stress graph must be identified. In most cases, the “take-off” point is easy to pick from the AE (or DRA) signature obtained from a second loading cycle. However, a criterion has been developed to place the picking of the “take-off” point on a rational, consistent basis. It should be appreciated that this criterion is only required when the “take-off” point is not apparent. The criterion is based upon the slope of the cumulative AE (or the strain difference) versus stress graph. In what follows we explain in some detail the technique used to establish the criterion for the AE case. The criterion for the DRA case is the same as that for the AE case with the appropriate changes.

The data acquisition software captures the stress level $\sigma(i)$ during sample loading at discrete points. The difference in stress levels between adjacent readings, $\sigma(i + 1) - \sigma(i)$, is, of course, determined by the stress-loading rate. The slope of the cumulative AE versus stress graph $\Delta\sigma(i)$ at the stress level $\sigma(i)$ is defined to be

$$\Delta\sigma(i) = \frac{C_{AE}(\sigma(i + 5)) - C_{AE}(\sigma(i - 5))}{\sigma(i + 5) - \sigma(i - 5)},$$

(3)

where $C_{AE}(\sigma(j))$ is the value of the cumulative AE at the stress level $\sigma(j)$.

The normalised slope variation $N \Delta\sigma(i)$ at the stress level $\sigma(i)$ is defined to be

$$N\Delta\sigma(i) = \frac{\Delta\sigma(i) - \text{Min} \Delta\sigma(i)}{\text{Max} \Delta\sigma(i) - \text{Min} \Delta\sigma(i)},$$

(4)

where $\text{Min} \Delta\sigma(i)$ and $\text{Max} \Delta\sigma(i)$ are the maximum and minimum values taken by $\Delta\sigma(i)$, respectively. We note that $N \Delta\sigma(i)$ is always between 0 and 1.

A series of laboratory experiments using a truly triaxial loading machine was conducted in order to back analyse the “take-off” point within the AE signature. A number of samples recovered from different geological environment sites were prepared into 300 mm sided cubic blocks. The initial state of stress was determined by drilling samples in order to calculate the stress using AE and DRA methods normal to each cube side.

Once the initial stress was determined for each side, the rock cube was loaded by a known value of stress (finite stress change) along each of the cube sides. The cube was loaded until stress saturation (ranging from hours to several days) was experienced, and re-drilled normal to each cube side in order to recover suitable specimens. The specimens were prepared and tested as described above and a new stress was determined normal to each rock cube side. The known initial stress
value and the experimental finite stress change values were used to determine the criterion to “pick” the take-off point in the AE signature. A criterion of a 10% variation of $N(\Delta \sigma(i))$ with stress was established for the AE signature. Similarly, in order to detect a bending point of stress–strain curve in the DRA method a criterion of 1% was established for the DRA signatures. These criteria were chosen experimentally by considering the cases where the “take-off point” was clear.

Fig. 6 shows the cumulative AE counts and criterion prior to laboratory tri-axial loading for an andesite cube obtained from a shallow quarry site in Japan. The criterion indicates a maximum previous stress of 8 MPa. The sides of the cube were then loaded to 15, 10 and 5 MPa, respectively, and held for 3 h in a truly triaxial testing machine. Fig. 7 shows the cumulative AE counts and criterion indicating a maximum previous stress of 13 MPa for the side stressed to 15 MPa.

The sides of the andesite cube were then loaded to 25, 15 and 10 MPa and held under this constant load for another 3 h. Fig. 8 shows the AE results for the side stressed to 25 MPa. The criterion indicates a maximum previous stress of 24 MPa. It should be noted that in this case the criterion was not required since the “take-off point” from the AE cumulative count versus stress plot is very clear.

Fig. 9 shows the DRA results for the same specimen. The criterion indicates a maximum previous stress of 26 MPa. It is clear that the points in Fig. 9 exceeding the 1% threshold at low loads do not represent the maximum previous stress and were not considered in applying the criterion. It should also be noted that there is a clear bending point in the strain difference versus stress plot at approximately 25 MPa.

Finally, to further verify the criterion, an ultramafic rock cube from the Mount Marion mine in Western Australia, was also tested. Initial testing indicated an in situ stress of 25 MPa normal to bedding (conditions as the block arrived in Japan). The block was then loaded in the truly triaxial testing machine to 35, 25 and 15 MPa normal to bedding, parallel and down dip of bedding, respectively. The load was held constant load for more than 3 days in order to achieve stress saturation. The block was then drilled normal to bedding and tested as previously described. Fig. 10 shows the cumulative AE count and criterion for the specimen, indicating a maximum previous stress of 36 MPa. Again in this case, the “take-off point” in the AE cumulative count versus stress plot is very clear.
2.7. Stress tensor calculation

The stress tensor \( \sigma_{xyz} \) may be represented, with respect to an XYZ (mine north, east, vertical) right-handed coordinate system, in matrix form as follows:

\[
\sigma_{xyz} = \begin{pmatrix}
\sigma_{xx} & \tau_{xy} & \tau_{xz} \\
\tau_{yx} & \sigma_{yy} & \tau_{yz} \\
\tau_{zx} & \tau_{zy} & \sigma_{zz}
\end{pmatrix}.
\] (5)

The normal stress \( \sigma_n \) acting on a surface normal to the unit vector \( \mathbf{n} = l_x \mathbf{i} + l_y \mathbf{j} + l_z \mathbf{k} \) is given by Eq. (2.14) of Brady and Brown [18]:

Fig. 8. Cumulative AE count and criterion following 3 h of loading for the side stressed to 25 MPa—andesite specimen.

Fig. 9. Strain difference and criterion for the side stressed to 25 MPa—andesite specimen.

Fig. 10. Cumulative AE count and criterion following 3 days of loading normal to bedding and loaded to 35 MPa—ultramafic specimen.
\[ \sigma_n = \sigma_{xx} + \sigma_{yy} + 2\tau_{xy} + 2\tau_{xz} \]

Thus, if six independent normal stresses are obtained from the undercored samples, six independent simultaneous equations may be established from which the components of the stress tensor can be computed. The principal stresses are then determined by a standard eigenvalue analysis of the stress tensor.

3. Case studies in Australian mines

In order to trial and test the methodology, the initial objectives of the research were to compare the experimental results estimated by the AE and DRA methods to those estimated by the HI cell measurements along a single drilling orientation. It is important to appreciate that conventional in situ stress measurement techniques do not, themselves, always provide absolute and reproducible determinations of the components of the in situ stress and their orientations. Indeed such measurements are influenced by local variations in rock material microstructure and rock mass structure and stiffness, by environmental conditions and by experimental error and uncertainty.

The results shown here include full stress tensor results for the Cannington mine in Queensland as well as the Junction, Mount Marion and Kundana gold mines in Western Australia.

3.1. Cannington Mine

The Cannington silver–lead–zinc deposit is located approximately 250 km south east of Mount Isa in Queensland, Australia. The mine processes approximately 1.5 million tonnes of ore per year to produce 24 million ounces of silver contained in 265,000 tonnes of lead concentrate and 110,000 ton of zinc concentrate [19].

Core obtained from an HI cell measurement hole was used to establish whether the complete stress tensor could be determined from AE and DRA test data. The conventional HI cell technique had been used at the Cannington Mine to determine the in situ stress, although this information was not used in any way during the experiment. Nevertheless, the rock mass at Cannington is geologically very complex and different stress magnitudes and orientations were calculated by the HI cell within adjacent locations along a hole axis. Two test sites were analysed for stress measurements using the oriented cored rock. The 520 Level site was drilled at approximately 521 m below surface with the hole oriented roughly horizontally north–south on the local mine co-ordinate system. The 605L site was also drilled horizontally, but bearing east–west and slightly deeper at 596 m below the surface.

The AE/DRA measurements were carried out to establish independent stress values to those determined by the HI cell. At least six independent orientations are required in order to determine the six independent components of the stress tensor. Table 1 shows the undercoring orientations chosen for the 520L measurement site.

The stress estimation from AE and DRA for the 520L site is shown in Table 2. In most cases, up to three stress measurements for each method and individual orientation were conducted. The input to the computer program used to calculate the full stress tensor was the average of the individual AE and DRA values for each orientation. Table 3 shows the full stress tensor for the...
520L measurement. The principal stresses obtained by an eigenvalue analysis are shown in Table 4.

At 520L the orientation of the estimated stresses appears to match the localised orebody orientation very well. The major principal stress was found to be parallel to the orebody strike. The intermediate principal stress was parallel to the dip, while the minor principal stress was normal to the orebody. At the 605 Level the orientation of the major principal stress was found normal to the orebody, while the intermediate stress was also parallel to the dip. The minor principal stress was found to be parallel to the strike of the orebody. The stress orientations estimated using cored rock for both sites are shown in Fig. 11.

The magnitudes and orientations for the principal stress directions obtained from the cored samples were then compared to those obtained using conventional HI cells installed within the same hole. The results for the 520L measurement site are shown in Fig. 12. The results from both methods are in close agreement.

3.2. Junction Mine

The Junction Mine is located 35 km south of Kambalda in Western Australia. Mining operations currently extend to 600 m below surface and the current production is 650,000 ton of ore at 5.6 g/ton [20]. The mineralisation at Junction is shear hosted within a 335 MPa UCS dolerite. The orebody extends over 1100 m in strike to a depth of 800 m below surface. The orientation of the Junction shear is 60°/052° (Dip/Dip Direction).

In this mine, a number of full stress tensor measurements using core have been carried out over the last 3 years. Some of the measurements were within crown pillars, some adjacent to HI cell measurements and some from deep exploration oriented core. The estimated principal stress orientations with depth are shown in Fig. 13, where the orientations are shown with respect to the local mine co-ordinate system. The orientation
results are consistent at depth, and the magnitudes have been compared to those established by the conventional HI cell measurements (Fig. 14).

3.3. Mount Marion Mine

The Mount Marion gold mine is located 70 km south east of Kalgoorlie in Western Australia. The mineralisation at Mount Marion occurs within a gneiss unit hosted by a sequence of talc chlorite ultramafic rock masses. Foliation is the dominant structural feature within the orebody and hangingwall rocks. Foliation is oriented 60°/027° and the compressive strength of the ultramafics is approximately 100 MPa.

In this mine, a number of stress measurements have been carried out over the last 3 years including full stress tensor comparisons between conventional HI cell and the AE method. In one case, core for the AE measurements has been recovered from the same hole where a conventional HI cell measurement had been carried out. The calculated principal stress magnitudes and orientations for both methods for the 363 m depth are shown in Fig. 15, where the orientations are indicated with respect to the local mine co-ordinate.
system. The results from both methods are comparable, and consequently an orientation average has been calculated suggesting that $s_1$ is approximately parallel to the strike of the orebody, while $s_2$ is normal and $s_3$ is down dip of the orebody.

3.4. Kundana Mine

The Kundana gold mine is located 50 km north east of Kalgoorlie in Western Australia. At this mine, the principal stress orientations were estimated by an external consultant using the HI cell. The estimated orientations between 200 and 600 m depths were (stress component: bearing/plunge) $s_1: 355/10$, $s_2: 260/20$, $s_3: 115/70$. These estimates are in excellent agreement with the estimated values determined from a single oriented core using the AE method as shown in Fig. 16.
4. Conclusions

A new methodology to undertake stress measurements using acoustic emission (AE) techniques and deformation rate analysis (DRA) has been developed and implemented in a number of geotechnical environments in Australia. The stress is determined using oriented core and the results are similar to those established by conventional overcoring techniques. The advantage of the new methodology is that the stress is obtained at very low cost and underground access is not required.

Acknowledgements

The authors acknowledge the sponsorship of the Minerals and Energy Research Institute of Western Australia (MERIWA), as well as the following mining companies; BHP Cannington, WMC St Yves Gold, Central Norseman Gold Corporation, Kanowna Belle Gold, Kundana Gold Mine and Sons of Gwalia all sponsors of the MERIWA M329 Research Project in Stress Measurements from Core. The management of the Mount Marion mine is acknowledged for their permission to publish. In addition, the facilities of the National Institute for Resources and the Environment (NIRE), Japan and the INSTRON laboratory of the Western Australian School of Mines were used to carry out the stress measurements. The contributions of Mr. Jianping Li, Mr. Takahiro Funatsu, and Mr. Fumiko Goto and Dr. Caigen Wang are greatly appreciated.

References


