In-situ stress measurement using non-destructive and relief methods

Zulfiqar Ali
The University of Adelaide, Adelaide, Australia

Murat Karakus
The University of Adelaide, Adelaide, Australia

Giang D. Nguyen
The University of Adelaide, Adelaide, Australia

Khalid Amrouch
Mohammed VI Polytechnic University, Benguerir, Morocco

Chris Chester
OZ Minerals, Adelaide, Australia

ABSTRACT: Over the past many decades, in-situ stress measurement using overcoring (OC) and hydraulic fracturing (HF) methods has been scientifically accepted and commercially adopted worldwide. However, with the mines getting deeper, their application has become more cumbersome and costlier. This paper presents the use of non-destructive techniques like the secant modulus method (SMM) and acoustic emission (AE) for in-situ stress measurement. Cyclic tests were performed on sub-cores extracted in six independent directions from the oriented main core having a trend and plunge of 285° and 75° respectively in the mine grid. The cores were retrieved from a mine site in South Australia where the OC method was applied. A minimum of two sub-cores were tested in each direction to get the complete stress tensor. The deformation was monitored using strain gauges and AE monitoring system. Results show a very good estimate of in-situ stresses that compares well with the OC method.

Keywords: Kaiser Effect; Stress Memory; Secant Modulus Method (SMM); Acoustic Emission (AE); Overcoring (OC).

1 INTRODUCTION

1.1 Background

The non-destructive methods of stress measurement based on the stress memory in rocks have been studied for the past many decades, which has great potential to be developed as an efficient, reliable, and cost-effective method of stress measurement (Karakus et al. 2014; Ali et al. 2021). The methods are best suited for situations where the conventional methods are not applicable and only the exploration cores are available. Numerous studies conducted by researchers have demonstrated a high correlation between the estimated stresses obtained through core-based methods and those obtained through conventional overcoring (OC) and hydraulic fracturing (HF) methods (Seto et al. 2001; Villaescusa et al. 2002; Tuncay & Ulusay 2008; Windsor et al. 2010; Lehtonen et al. 2012;

Wu et al. 2017; Bai et al. 2018). This correlation provides a solid foundation for further investigation of the core-based methods.

In this study the acoustic emission (AE) and Secant Modulus Method (SMM) methods are used to measure in-situ stress in an underground mine in South Australia. The objective of this study was to improve the existing core-based methods for accurate estimation of in-situ stress measurement and undertake a comparative exercise with the conventional OC method. An attempt is also made to understand the measurements in the context of regional stress patterns. For this reason, cyclic tests were performed on sub-cores extracted in six independent directions from the oriented main core having a trend and plunge of 285 degrees and 75 degrees respectively in the mine grid. The cores were retrieved from a mine site where the OC method was applied.

1.2 Principal of AE and SMM

When a rock specimen is subjected to cyclic loading, it can experience irreversible damage after the loading exceeds the previously applied maximum stress (Yamamoto et al. 1999; Ali et al. 2022). This damage can be detected by the substantially increased AE events occurring at the peak point. Using the AE method, the previously applied maximum stress is determined by plotting the cumulative AE counts against the stress. The point of inflexion in the curve (abrupt surge) indicates the previously applied maximum stress (Figure 1a).

The SMM is an efficient technique to recollect the previously applied stress memory using the inelastic strain in the rock samples (Ali et al. 2023). In this method the rock specimen is subjected to uniaxial compression to a desired stress level and a secant line is obtained from the secant modulus of stress-strain curve. The difference of the strains between the loading cycle and the secant line is calculated using a strain difference function, $\Delta\varepsilon_{ji}(\sigma)$ shown in Equation. 1 and plotted in a stress-strain difference graph.

$$\Delta\varepsilon_{ji}(\sigma) \;=\; \varepsilon_j(\sigma) - \varepsilon_i(\sigma); \quad j > i \tag{1}$$

In the equation above, σ is the applied axial stress, $\varepsilon_i(\sigma)$ is the axial or lateral strain, and $\varepsilon_i(\sigma)$ is the strain derived from the secant modulus. $\Delta\varepsilon_{j,i}(\sigma)$ is calculated from the gradient of line which is positive before the point of inflection and bends sharply to adopt a negative gradient after the peak (Figure 1b).

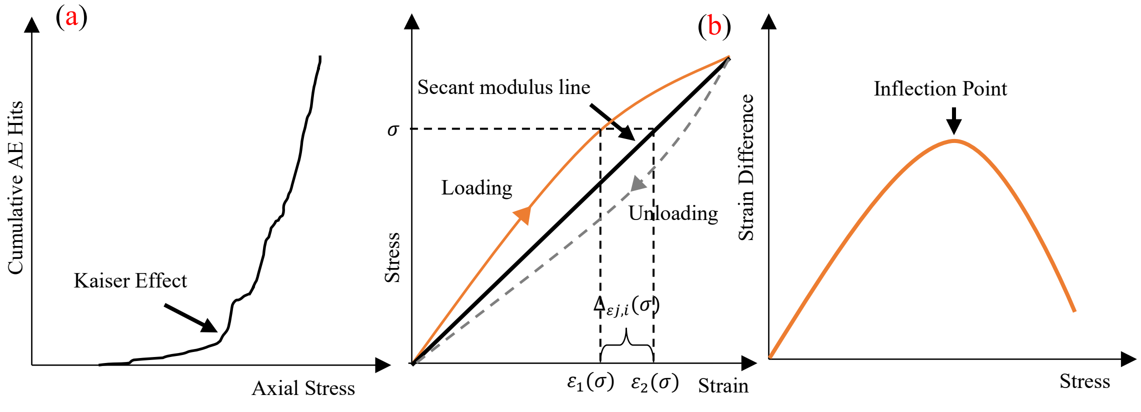

Figure 1. Schematic of the (a) AE Method & (b) Secant Modulus Method (SMM) showing the point of inflection.

2 SPECIMENPREPARATION AND EXPERIMENTAL METHODOLOGY

A minimum of six independent sub-cores are required to construct the six components of the stress tensor. The specimens are drilled using a 22 mm diamond drill bit from oriented main core recovered at the depth and location of interest. The actual mine grid of the sub-cores is obtained by rotating the nominal orientation of each sample using Equation 2.

$$Cos\ \theta_{uv} = [cos(\alpha_u - \alpha_v)\ cos\beta_u cos\beta_v] + [sin\beta_u sin\beta_v] \qquad (2)$$

Where θ_{uv} is the angle between main core trend/plunge $\alpha_u/\ \beta_u$and sub-core trend/plunge α_v/β_v. Figure 2 shows the sub-core orientations, sample preparation and loading process in the laboratory.

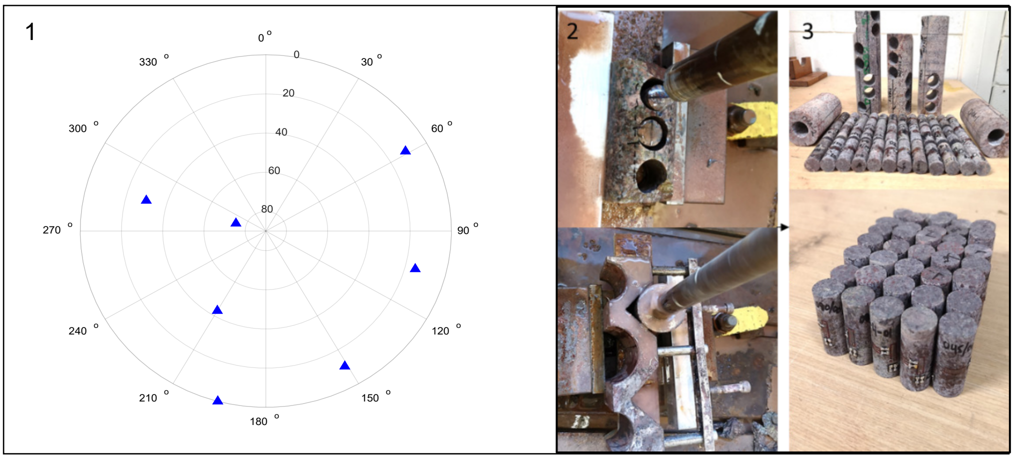

Figure 2. Orientation of subcores in mine grid and sub-core preparation process in laboratory.

All the tests were conducted in MTS 300kN servo-controlled testing machine consisting of an axial dynamic loading frame and a data acquisition system. Two cycles of compression were applied to the rock specimen with stress levels set to 2.5 times the vertical stresses computed from the core depth and rock density. The deformation process was monitored using strain gauges; two in both axial and lateral directions, as well as AE monitoring system developed by Karakus (2014). To construct the stress tensor, six independent normal stress were measured, which can be given by instances of Brady and Brown (1994) equation shown in Equation 3.

$$\sigma_n = l_x^2\,\sigma_{xx} + l_v^2\sigma_{vv} + l_z^2\sigma_{zz} + 2l_x l_v\sigma_{xv} + 2l_v l_z\sigma_{vz} + 2l_z l_x\sigma_{zx} \qquad (3)$$

Where σ_n is the stress obtained in each direction from AE and SMM methods whose orientation is given by the unit vector $l_x\vec{\imath} + l_y\vec{\jmath}+l_z\vec{k}$ and used to form a system of equations that can be solved for the stress tensor σ_{ij}. The principal stresses and their orientation are then determined by a standard eigenvalue analysis of the tensor using the cubic equation described in Brady and Brown (1994).

3 RESULTS

A minimum of two specimens were tested in each sub-core direction, and the average values of the AE and SMM analysis were used to construct the stress tensor using the procedure described earlier. The principal stress magnitudes and their orientations based on the mean values of the AE and SMM are shown in Figure 3. The range shows the variation in the stress magnitudes based on the 10% margin of error applied to the measured values based on felicity ratio of 0.9 to 1.1 (Ali et al. 2022). The measured results show a thrust-faulting regime in the area with $S_H > S_h > S_v$ which is in good correlation with the OC and other similar measurements in the basin (Klee et al. 2011). The measurements of intermediate and minor principal stresses obtained through both methods are in reasonable agreement. However, the OC method tends to yield higher values for the major principal stress. This variation is acceptable, given the differences in measurement techniques and the algorithms used to solve the system of equations. When comparing the results of the first stress variants, it can be observed that the margin of error is quite low. This is because the solutions that result in higher maximum principal stress also tend to result in lower intermediate and minor principal stresses.

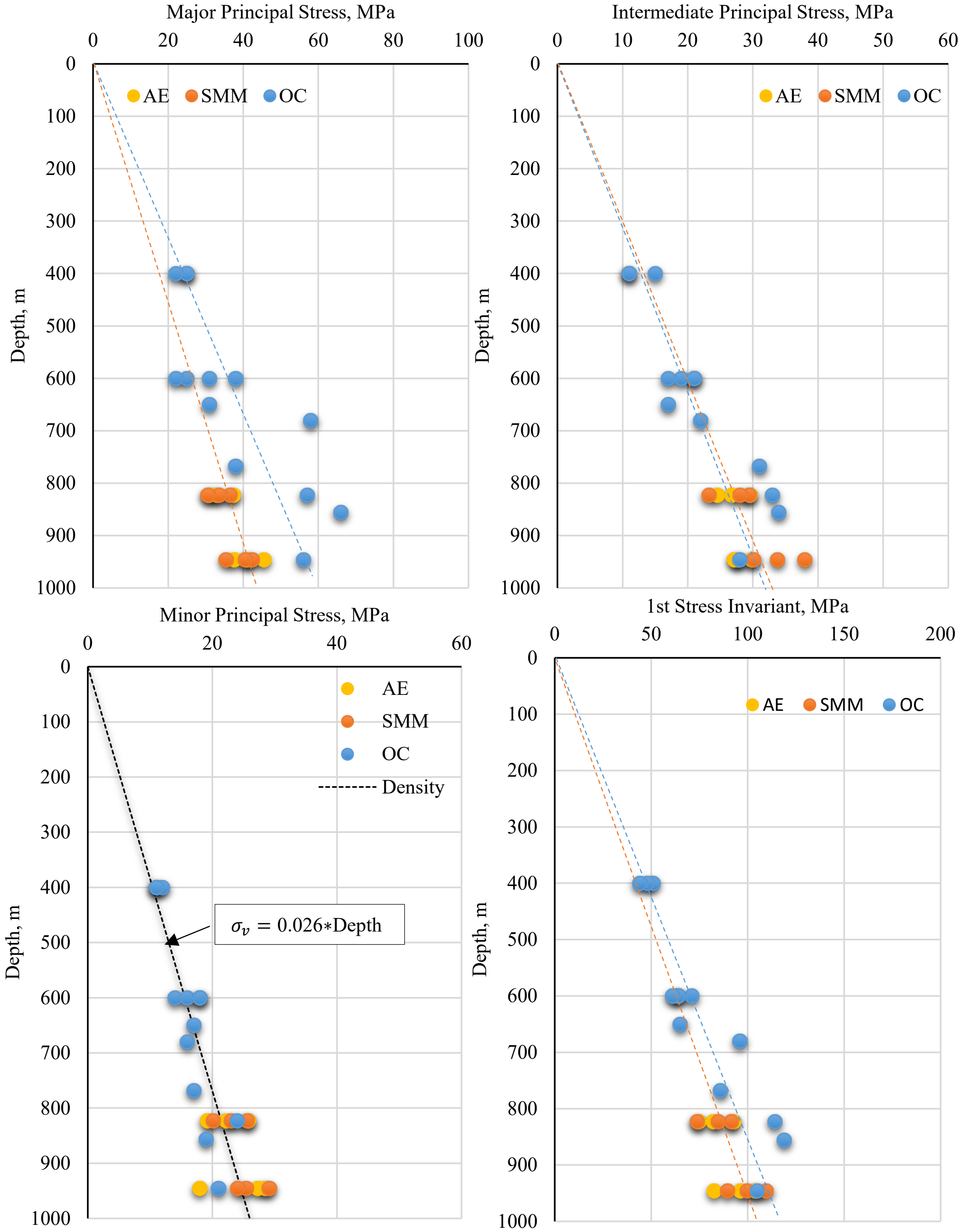

Figure 3. Comparison of Principal stresses measured using AE, SMM, and OC methods.

Our measurements indicate that the major principal stress is horizontal and oriented approximately 280º ± 10º which is similar to the tectonic regimes and other measurements in the basin suggesting East-West orientation (Klee et al. 2011; Rajabi et al. 2017) as shown in Figure 4b. The measurement from the OC shows a Northwest-Southeast orientation, which is also recorded in some other mines in the region (Klee et al. 2011). The orientations can vary with the locations and these variations in lateral stress direction are primarily caused by the in situ geological structures that can change directions of the stress flow in the mine. Additionally, variations or errors in the measured normal stresses can also significantly impact the direction of horizontal stresses.

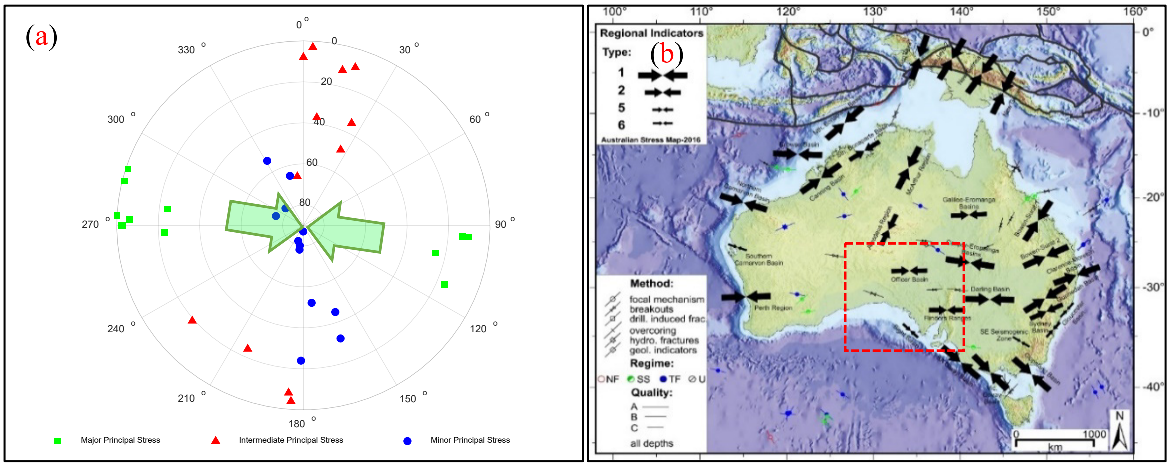

Figure 4. (a) Principal stress orientation from AE and SMM method (b) Principal Stress Orientation in Australia showing the region in question (Rajabi et al. 2017).

4 CONCLUSION

The AE and SMM techniques were used to measure in-situ stresses at a mine site in Australia. The cores were retrieved from a depth of 823m and 946m where the OC method was applied. The AE and SMM methods were found to be effective and reliable for measuring in-situ stresses, with good correlation with the OC method. The measurements revealed a horizontal major principal stress oriented in the East-West direction and a vertical or near vertical minor principal stress, consistent with the thrust faulting regime in the region. The OC measurements show higher magnitudes of major principal stress and suggest a Northwest-Southeast orientation slightly different from the AE and SMM results. These variations are natural and inherent to the method applied, which could stem from local geological structures and measurement errors. It is suggested that at least five specimens in each direction should be tested to achieve statistically reliable results. Despite slight variations in the magnitude and orientation of the major principal stresses, when analyzed collectively, the measurements obtained from non-destructive methods provide valuable insight into the stress conditions at a mine site. These measurements will aid in efficient mine layout design for safer mining operations.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Australian Coal Association Research Program (ACARP) for their generous financial support through project (C29010). The authors would also like to extend their appreciation to OZ Minerals for providing rock specimens necessary for the study. Their contribution was essential to accomplish this study.

REFERENCES

Ali, Z., Karakus, M., Nguyen, G.D. & Amrouch, K. 2022. Effect of loading rate and time delay on the tangent modulus method in coal and coal measured rocks. *International Journal of Coal Science and Technology*, 9 (81).

Ali, Z., Karakus, M., Nguyen, G.D. & Amrouch, K. 2022. Application of full-field strain measurement to study Kaiser effect in granite under indirect tensile loading. In: *Proceedings of the 56th US Rock mechanics/ Geomechanics Symposium*. Santa Fe, American Rock Mechanics Association.

Ali, Z., Karakus, M., Nguyen, G.D. & Amrouch, K. 2021. Understanding the Kaiser effect in concrete using deformation rate analysis and acoustic emission. In: *Proceedings of the 10th Australasian Conference on Applied Mechanics*. Adelaide, Engineers Australia.

Ali, Z., Karakus, M., Nguyen, G.D. & Amrouch, K. 2023. Secant Modulus Method: A simplified technique for measuring applied and in-situ stresses in rocks. *International Journal of Mining Science and Technology*. [paper accepted]

Bai, X., Zhang, D., Wang, H., Li, S. & Rao, Z. 2018. A novel in situ stress measurement method based on acoustic emission Kaiser effect: a theoretical and experimental study. *Royal Society Open Science* 5, 181-263.

Brady, B.H.G. & Brown, E.T. 1994. *Rock mechanics for underground mining*. London, Boston, Allen & Unwin.

Klee, G., Bunger, A., Meyer, G., Rummel, F. & Shen, B. 2011. In Situ Stresses in Borehole Blanche-1/South Australia Derived from Breakouts, Core Discing and Hydraulic Fracturing to 2 km Depth. *Rock Mechanics and Rock Engineering* 44, pp.531–540.

Karakus, M. 2014. Quantifying the discrepancy in preloads estimated by acoustic emission and deformation rate analysis. In: *Proceedings of the European Rock Mechanics Symposium*. Vigo, ISRM.

Lehtonen, A., Cosgrove, J.W., Hudson, J.A. & Johansson, E. 2012. An examination of in situ rock stress estimation using the Kaiser effect. *Engineering Geology* 124, pp. 24–37.

Rajabi, M., Tingay, M., Heidbach, O., Hillis, R. & Reynolds, S. 2017. The present-day stress field of Australia. *Earth Science Reviews* 168, pp. 165-189.

Seto, M., Nag, D. & Vutukuri, V.S. 1999. In-situ rock stress measurement from rock cores using the acoustic emission method and deformation rate analysis. *Geotechnical and Geological Engineering* 17, pp. 41–266.

Shen, B. & Rinne, M. 2011. Estimate In Situ Stresses from Borehole Breakout at Blanche 1 Geothermal Well in Australia. *World Tunnel Congress*, Helsinki: ITA-AITES.

Tuncay, E. & Ulusay, R. 2008. Relation between Kaiser effect levels and pre-stresses applied in the laboratory, *International Journal of Rock Mechanics and Mining Sciences* 45(4), pp. 524–537.

Villaescusaa, E., Seto, M. & Bairda, G. 2002. Stress measurements from oriented core. *International Journal of Rock Mechanics & Mining Sciences* 39, pp.603–615.

Windsor, C.R., Villaescusa, E. & Machuca, L.A. 2010. A comparison of rock stresses measured by WASM AE with results from other techniques that measure the complete rock stress tensor. In: *Proceedings of the International Symposium on In-Situ Rock Stress*, ISRM.

Wu, J.H., Lin, H.M. & Chen, Y. 2017. Rock core-based pre-stress evaluation experimental validation: A case study on Yutengping Sandstone as CO2 storage reservoir rock. *Terrestrial, Atmospheric and Oceanic Sciences* 28, pp. 193-207.

Yamamoto, K. 2009. A theory of rock core-based methods for in-situ stress measurement. *Earth, Planets and Space* 61(10), pp. 1143–1161.