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Quality assurance of acoustic emission-based In-situ stress measurement data

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Abstract

In-situ stress measurements are critical for the safe design and operation of civil and mining engineering infrastructure. Among indirect methods, Acoustic Emission (AE)-based Kaiser point measurements offer a cost-effective alternative to overcoring and hydraulic fracturing, however, AE lacks standardised methods for assessing data quality. This study evaluates AE data from four mining sites, applying a weighted fuzzy logic-based system to assign certainty scores to reported Kaiser points. Factors such as curve type, confidence in the selected Kaiser point, statistical variance, and instrumentation suitability were used to calculate the scores. A blind test with ten participants was conducted to analyse the subjectivity of Kaiser point selection, showing statistical agreement with the certainty scores and revealing significant impacts of Kaiser point variations on principal stress estimates. Acceptable thresholds for Kaiser point variation were then established to enhance AE data reliability. The study also compares AE-based in-situ stress estimates with overcoring results from two mining sites, highlighting similarities, differences, and the situational reliability of the methods. Recommendations are provided to improve data quality and standardise AE-based in-situ stress measurements, promoting their broader and more consistent application in engineering practices.

Keywords

Acoustic emission, Kaiser point, In-situ stress measurement, data quality assurance, fuzzy logic

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1 Introduction

This study evaluates the quality and reliability of Acoustic Emission (AE) data for in-situ stress estimation, using data from four distinct mining sites in Australia. Several methods exist for estimating the stress states and mechanical properties of rocks (for example, Hudson et al. (2003),Serati et al. (2015)) , amongst them AE, a non-destructive testing (NDT) method, captures transient elastic stress waves that originate from localised sources within materials and thus is used widely in the context of rock mechanics and rock engineering. By conducting a systematic quality assurance and quality control (QA/QC) analysis, this study aims to quantify the certainty of AE data for stress estimation. The process of validation of the certainty scored for two of the mine sites was conducted with a subjectivity analysis with the use of ten participants and the AE data from the other two mine sites were compared with overcoring (OC) data. This comparative analysis contributes to the development of guidelines for AE testing service providers and for evaluating AE data for in-situ stress estimations.

AE technology is widely used in both laboratory and field rock mechanics, supported by guidelines from the International Society for Rock Mechanics (ISRM)(Feng et al., 2019; Ishida et al., 2017). AE data can be categorised as two measurement methods: parametric measurements, which focus on cumulative AE counts and other signal characteristics (Aggelis & Shiotani, 2022), and signal-based measurements, which involve waveform and quantitative analyses to extract information about fracture modes, stress histories, and source locations and have been used in the evaluation of rock and rock-like brittle material fracture evaluation (Kurz et al., 2022; Ohtsu, 2022; Schumacher et al., 2022).

The key technique in using AE for in-situ stress estimation is based on the Kaiser effect, which suggests that materials produce little to no AE signals when subjected to previously encountered stress levels. Deviations from this behaviour, known as the "Felicity effect," occur when AE events are generated at stresses below the previous maximum stress (Lavrov, 2003; Panteleev et al., 2020). The point at which significant AE activity is observed is called the Kaiser point. It should be noted that to estimate the Kaiser point AE parametric type measurements are considered. The Kaiser effect for stress estimation can be determined by various methods, including the tangential intersection method, statistical approaches, and Felicity ratio (Bai et al., 2018; Boyce et al., 1981; Hardy Jr, 1984; Hughson & Crawford, 1987; Jayanthu, 2019; Kharghani et al., 2021; Lehtonen et al., 2012; Yoshikawa & Mogi, 1981; Yoshikawa & Mogi, 1989). To compute the stress tensor, mini-core (sub-core) samples are drilled in six orientations for each depth and undergo cyclic loading to identify Kaiser stress points, which are then used to resolve the principal stresses and their directions for that particular depth.

AE offers a cost-effective alternative to traditional methods like OC and hydraulic fracturing for in-situ stress measurement, however, there are limitations such as the Kaiser effect may not fully align with the in-situ stress due to geological history, and identifying the Kaiser point can be subjective, particularly when AE data lack a clear inflexion (Jayanthu, 2019). Additional factors affecting AE accuracy include rock type, testing conditions, and sample heterogeneity, making the reliability of AE for stress estimation case-dependent and requiring initial assessments to determine applicability (Lavrov, 2003; Lehtonen et al., 2012; Yong & Wang, 1980).

While AE-based methods show significant potential for estimating in-situ stresses, their reliability and accuracy are highly case-dependent. Previous studies, such as those by Lehtonen et al. (2012), demonstrate AE's capability in stress estimation and also it should be noted that factors like sample conditions, geological history, and stress events impact the stress estimation (Holcomb, 1993; Hsieh et al., 2015). Therefore, this study explores a systematic evaluation of AE data quality and applicability, which can be used as a method for more consistent and reliable use of AE in mining and rock engineering practices.

2 Methodology of evaluating AE data

The evaluation of AE data for in-situ stress estimation presents a unique challenge, as there is no established methodology to assess the quality of AE measurements, unlike OC, where the certainty of readings is determined based on the quality and quantity of strain gauges and their measurements. To address this gap, a fuzzy logic-based system was developed to evaluate the quality of AE data. Fuzzy logic has been shown in the literature to be used in engineering decision-making (Fayek, 2020; Fernando & Thivakar, 2007; Machacha & Bhattacharya, 2000; Ross, 2005). In this study, the authors used the fuzzy logic-based system to obtain uncertainties in AE measurements. This methodology provides a systematic way to assign a certainty score to AE based on the critical parameters.

The certainty score is calculated by assigning weights and scores to six key factors, identified as critical to producing high-quality AE data and averaging them. The maximum certainty score is 5, creating a scale where higher scores indicate greater certainty. Among these factors, curve certainty and the average coefficient of variation (CoV%) are assigned higher weights due to their significant impact on the reliability of AE measurements. Curve certainty is particularly influenced by the clarity of the Kaiser point and the type of curve generated during testing. Following the work of Jayanthu (2019), the curves were broadly categorised as Type 1 (sudden rise at the Kaiser point, reflecting a clear Kaiser effect), Type 2 (linear rise), and Type 3 (logarithmic rise). As the selection of the Kaiser point can be subjective, guidelines were developed to standardise the assignment of certainty scores for curves. The weighting, scoring, and certainty score requirements for each factor are detailed in Table 1, while Table 2 provides a detailed description of curve types and their associated certainty scores.

The average CoV%, represents the variability of Kaiser points across cycles. It is a critical factor in evaluating the consistency of AE measurements. Lower CoV% values suggest higher certainty and reliability. The number of sensors used is another important consideration, as greater sensor coverage allows for more comprehensive data collection, particularly in anisotropic rocks where stress distribution can vary. Operating frequency also plays a crucial role, as the literature indicates that sensors operating within the range of 50 kHz to 1000 kHz are most effective for capturing AE waves in rock mechanics applications (Cai et al., 2007; Feng et al., 2019; Ishida et al., 2017).

The number of curves provided in technical reports was also considered, as reports often include only selected samples of tested curves rather than the full dataset. Providing more comprehensive data enhances transparency and promotes confidence among stakeholders. Additionally, the number of cycles tested is a key factor, as AE measurements are sometimes limited to a single cycle of the uniaxial compressive strength (UCS) test. This practice restricts the quality of the data, and expanding the number of cycles tested is identified as an opportunity for improvement (Jayanthu, 2019; Seto et al., 1997).

This fuzzy logic-based approach was applied to AE data from four mining sites which were anonymised as Mine A, B, C, and D for confidentiality. The evaluation process highlighted significant variability in data quality and reporting practices across the sites, underscoring the need for standardised methodologies in AE-based stress estimation. By systematically addressing the critical components of AE data quality, this framework provides a practical and reliable method for assessing the certainty of AE measurements, identifying areas for improvement, and enhancing confidence in AE as a tool for in-situ stress estimation.

Table 1 Breakdown and parameters for assigning certainty scores based on the fuzzy logic scoring system

Description	**Weightage**	**Score**	**Score requirement**
Curve Certainty	2	5	High certainty about the selected point
		4	Certain about the selected point
		3	Moderately Certain about the selected point
		2	Uncertain about the selected point
		1	Highly uncertain about the selected point
Average Coefficient of Variation, CoV (%)	2	5	0-5%
		4	5-7.5%
		3	7.5-10%
		2	>10% or not sufficient data
Number of Sensors	1	3	4 sensors
		2	Minimum 2 or any other complementary measurement
		1	1 sensor
Operating Frequency	1	1	Between 50-1000kHz
		0	Other/not provided
Curves provided	1	3	All curves provided
		2	Some curves provided
		1	No curves provided

Tested cycles	1	3	All cycles tested
		2	Only 2nd Cycle

Table 2 Description and basis of assigning the curve certainty score for the Kaiser point selection

Score	Description	Remarks/ examples to assign the score
5	Highly certain about the selected point	Type 1 curves only. There is a clear point of rise where the rise is close to or equal to 90°. There is a clear rise, and the intersected points of the bilinear curves show the selected point clearly.
4	Certain about the selected point	Type 1 curves only. There is a clear point of rise where the rise is close to or equal to 90° but there are some localized points that show additional points of rise, but the selected point is the most appropriate point (possibly the first point) of rise or has the highest tangent. There is a clear rise but with some localized fluctuations, and the intersected points of the bilinear curves show the selected point clearly.
3	Moderately certain about the selected point	Type 1,2 and 3 curves. Localized points of rise from type 2 and 3 curves are selected to reflect the Kaiser points. For type 1; the selected point shows a reflection of a high rise in cumulative AE parameters or the bilinear regression, however, this is made apparent if a best-fit smooth curve is to be considered. For Type 1; the curve has a 90-degree rise at a separate point, but a first rise point has been selected that is less steep.
2	Uncertain about the selected point	Type 1, 2 and 3 curves. For Type 2 and 3; several localized inflections but one has been selected as the Kaiser point. For type 1; there are indications of a clear Kaiser point that reflects a different point from that which was indicated either by the linear regression method or by the point of inflexion.
1	Highly uncertain about the selected point	Type 2 and 3. There are no clear points of rise in the curve, but a point is selected to reflect the Kaiser point anyway. There are clearly higher localized rises that were generated but a different point is selected.

3 Results and discussion

3.1 Outcomes of the certainty scores

AE data from four mine sites—A, B, C, and D—were evaluated using the proposed certainty scoring system. Mine A provided data from two testing contractors, while Mine B, C, and D each had one testing contractor. Notably, the first testing contractor for Mine A was the same contractor responsible for AE data from Mines B, C, and D.

For Mine A, the certainty scores from the first testing contractor ranged between 3.5 and 3.7, indicating moderate certainty. However, the second testing contractor's scores were significantly lower, ranging from 2.0 to 3.6, with most values clustering around 2.5. The lower scores were attributed to several reasons: the data provided by the second contractor were limited to the first cycle, which lacks established literature to support its reliability, and the majority of the curves were classified as either Type 2 or Type 3. These curve types, as previously discussed, are less definitive in indicating a Kaiser point. Additionally, many selected points did not reflect the Kaiser point or lacked distinct curve features to justify the selection.

For Mine B, the certainty scores ranged from 3.3 to 4.1, suggesting a moderate to good level of data reliability. Similarly, Mine C's scores fell within a range of 3.2 to 3.9, with most data indicating moderate certainty. Mine D, which evaluated in-situ stress estimates at three different depths, achieved a certainty score range of 3.3 to 4.0. This also reflects a moderate to good level of certainty across the evaluated data.

To further validate the certainty scoring methodology, a subjectivity analysis was conducted, as described in section 3.2. This analysis involved a comparison of results from two mine sites to assess the potential variability in scoring due to subjective judgment. For two additional mine sites, the AE data were compared with OC data to examine the correlation between AE certainty scores and the reliability of stress estimation derived from a well-established method.

These findings highlight the variability in data quality among testing contractors and emphasize the need for standardised protocols to ensure consistency and reliability in AE-based stress estimation.

3.2 Subjectivity of AE Kaiser points in in-situ Stress measurements

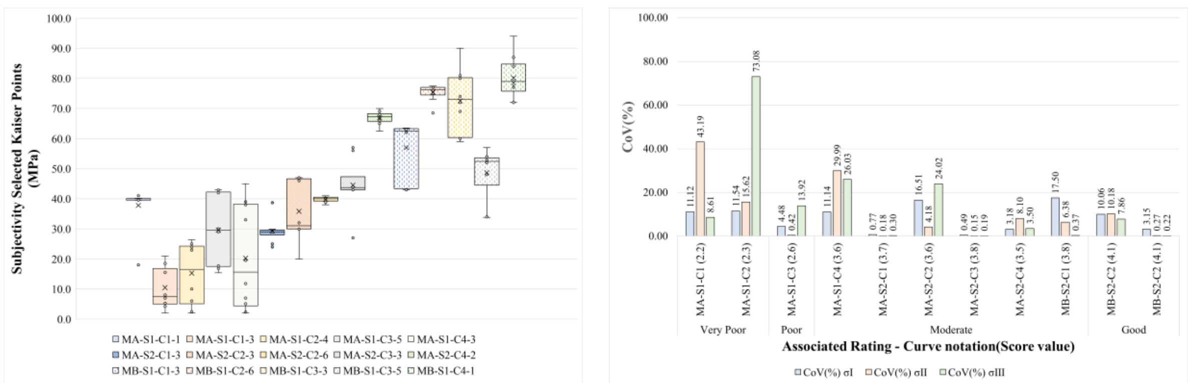
To assess the impact of subjectivity in selecting AE Kaiser points on in-situ stress measurements, a subjectivity analysis was conducted using 15 sub-curves - five from each supplier for Mine Sites A and B. The analysis aimed to validate the applicability of the fuzzy logic-based certainty score and to identify potential errors associated with these scores. To ensure a robust and unbiased evaluation, 10 participants were involved in the analysis. Each participant was briefed on the concept of the Kaiser point and the various methods for its selection before being tasked to independently identify the Kaiser points for the provided curves.

The results of this analysis are visualized in Fig. 1 (a), which presents a box-and-whisker plot of the selected Kaiser points. The plot demonstrates a significant range of selected values for curves with low certainty scores, highlighting the high degree of subjectivity associated with these scores.

To quantify the potential error introduced by subjectivity, the average of the Kaiser points selected by the participants was used to calculate the principal stress. These calculated principal stress values were then compared to the stress values reported by the testing contractors. The differences were organized according to the certainty scores, and the possible indicative errors in principal stress measurements were derived based on Fig. 1(b) which shows the relationship between the certainty scores and the associated indicative errors in principal stress values. The summarised range of these possible errors for each certainty score is provided in Table 3.

The identification of sub-curves in the analysis follows a systematic naming convention. The naming begins with the mine site identifier (Mine Site A (MA) or Mine Site B (MB)), followed by the supplier identifier (Supplier 1 or 2 (S1 or S2)), the sub-core number (C1 to C6), and the sub-curve number (1 to 6). For example, the nomenclature "MA-S1-C5-1" refers to a sub-curve from Mine Site A, tested by Supplier 1, at the fifth core measurement point, with the first sub-curve from that core.

This analysis underscores the significant influence of subjectivity in selecting the Kaiser point, particularly for data with lower certainty scores. The results validate the fuzzy certainty scoring system as an effective tool for identifying and mitigating the variability introduced by subjective interpretations of AE data.



(a) (b)

Fig. 1 (a) Distribution of the selected Kaiser point for the fifteen selected curves from the subjectivity study for mines A and B, (b) Coefficient of variation between the reported Kaiser point and the average Kaiser point selected in the subjectivity study arranged according to the respective certainty score.

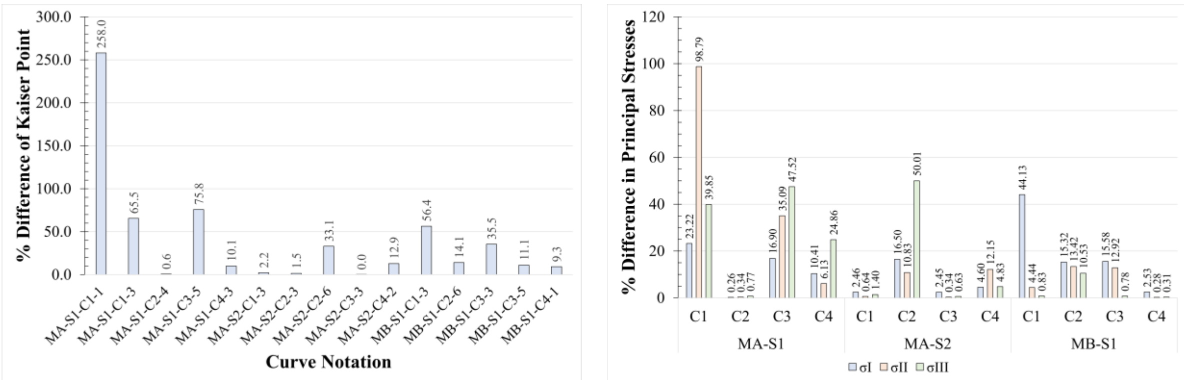
Table 3 Associated possible indicative error assigned for the certainty score based on the subjectivity analysis.

Certainty Score	Remarks	Associated possible indicative error
≥4.5	Excellent	~ 5-10%
4 to 4.49	Good	Up to ~15%

3 to 3.9	Moderate	Up to ~35%
2.51 to 2.9	Poor	Up to ~50%
≤2.5	Very Poor	More than 50%

It is important to note that the simple average of the Kaiser points selected by participants does not necessarily reflect any physical meaning. To address this, outliers were discarded, and a modified average of the selected Kaiser points was calculated. This modified average was then used to compute the principal stresses, allowing for an evaluation of how variations in the selection of the Kaiser point could affect stress measurements.

As shown in Fig. 1(b), even a 10% deviation between the Kaiser point reported by the testing contractor and the perceived Kaiser point significantly influences the principal stress estimation, often resulting in errors greater than 10%. This highlights the critical impact of subjectivity in selecting the Kaiser point, particularly for low-certainty curves. Based on these findings, we recommend the evaluation especially when checking the variation in Kaiser point selection is within 10% of the reported value.



(a)

(b)

Fig. 2 (a) Results from the subjectivity analysis (a) percentage difference between average of the participants selected and reported values (b) percentage difference of principal stress between the calculated value (based on the average participants selected Kaiser point) and reported.

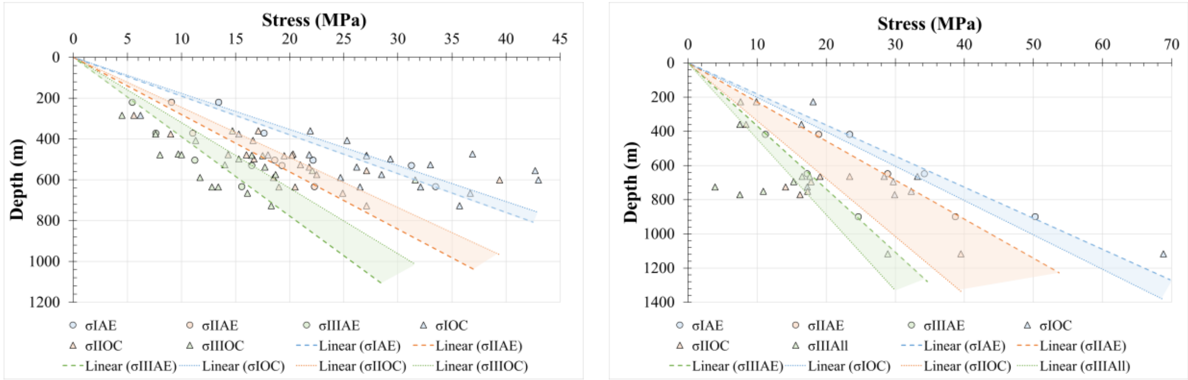
3.3 Comparison of AE and overcoring in-situ stress measurements

A comparison between OC and AE stress measurements was conducted for Mine Sites C and D based on the available data. Poor-quality data reported by either method was filtered out to ensure the reliability of the comparison. The relationship between depth and the principal stress values calculated by these methods is shown in Fig. 3(a) for Mine Site C and Fig. 3(b) for Mine Site D.

When plotting the best-fit linear lines through the data points for both OC and AE measurements, a range of principal stress values emerges, represented by the shaded regions on the curves. For Mine Site C, the OC measurements produced a higher range of principal stresses compared to AE. Conversely, for Mine Site D, the AE measurements yielded higher principal stress ranges than those from OC. These variations suggest that considering the range of stress values, rather than relying on a single set of measurements, could facilitate sensitivity analyses. This approach allows for optimised designs and ensures safe operational practices by accounting for possible stress variability.

To further analyse the consistency of the measurement methods, the coefficient of variation (CoV%) of the gradients of the linear fits was calculated. For Mine Site C, the CoV(%) for major, intermediate, and minor principal stresses was 3.56, 6.71, and 9.55, respectively. For Mine Site D, the CoV(%) for the same principal stress categories was 5.02, 19.34, and 9.18, respectively. These CoV(%) values highlight the variability between the two methods in capturing stress trends at different depths.

The gradient values of the linear fit, along with the coefficients of determination (R^2), for the principal stresses measured at Mine Sites C and D are provided in Table 4. This comparison shows that using both measurement techniques can capture a comprehensive range of stress values, which can be particularly beneficial in applications requiring a detailed understanding of stress distributions.



(a) (b)

Fig. 3 Stress estimates of AE and OC to form the range of principal stresses for (a) Mine site C and (b) Mine site B

Table 4 Data from AE and OC principal stress estimation plots for mine sites C and D

Description	**Mine**	**σ_IAE**	**σ_IOC**	**σ_{II}AE**	**σ_{II}OC**	**σ_{III}AE**	**σ_{III}OC**
Gradient of curve, m	Mine C	18.985	17.681	28.069	24.537	38.869	32.091
	Mine D	18.191	20.115	22.857	33.815	36.927	44.394
R^2	Mine C	0.9879	0.9546	0.9950	0.9467	0.979	9.033
	Mine D	0.9993	0.9349	0.9996	0.9488	0.9998	0.8599

4 Conclusion and Recommendations

This study identifies key limitations and opportunities for improving the reliability of Acoustic Emission (AE) measurements in estimating in-situ stresses. One major limitation is the reliance on Kaiser points derived from a single cycle, which may not fully capture stress conditions; thus, providing data for all three cycles is recommended. Variations of ≥10% between the reported and perceived accurate Kaiser points can significantly affect principal stress calculations, necessitating independent verification for low-certainty curves. The comparison of OC and AE measurements indicates that their agreement is context-dependent, and incorporating a range of values from both methods is essential for robust stress analysis. During the preliminary investigation stages, it is recommended that both OC and AE measurements be carried out. The comparison of OC and AE can be carried out as described in 3.3. If the coefficient of variation between the principal stresses obtained from OC and AE shows a maximum difference of 5% in their gradients, there is statistical justification to consider the methods in agreement. Alternatively, a range of values from both methods should be considered, and a sensitivity analysis conducted to determine the most critical condition, with the designer adopting the conservative value for design purposes. Finally, a systematic review of AE-based stress estimation methods is recommended to ensure data quality, assess site-specific suitability, and refine testing methodologies.

In cases where clear Kaiser points cannot be obtained from a single AE parameter, testing parties are encouraged to take the following actions to enhance data quality:

1. Parameter selection: Use parameters that exhibit clear inflexion points, such as cumulative AE hit rate, cumulative AE energy, or cumulative AE energy rate, instead of solely relying on one single parameter such as AE hits/events.
2. Alternative curve analysis: Plot the square of the cumulative hit rate against the stress curve if the cumulative hit rate alone does not provide a distinct inflexion point.
3. Overlay cycles for comparison: Overlay the AE cumulative hits/events rate for the first and second cycles to identify the deflection point and obtain a more reliable Kaiser point.
4. Felicity ratio analysis: Plot the Felicity ratio against the stress curve to identify the inflexion point, which can then be used as the in-situ stress value.

These recommendations aim to refine AE testing methodologies, ensure the reliability of in-situ stress estimations and support safer and more efficient mining operations.

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