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A robust sampling strategy for UCS using wireline geophysics

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Abstract

Determining where to sample a diamond drillcore and estimating how many Unconfined Compression Strength (UCS) samples would be needed to obtain accurate data are tasks largely based on qualitative knowledge. ISRM suggests taking a minimum of five samples per domain. Prior research has shown that due to the natural heterogeneity in rock better insights with statistically based estimations are usually needed. This hypothesis was confirmed in a recent study at the former Brukunga Mine site, South Australia. Our study in a hard/crystalline rock geology revealed a wider variation than initially anticipated. The UCS results showed a minimum value of 22.9 MPa, a maximum value of 320.2 MPa, and a CoV of 59%. Continuous full wave sonic (FWS), and density logs were extracted to calculate dynamic elastic modulus (E_d) along the length of a single borehole. Robust statistical methods were used to create a measure of variation of rock elastic modulus. This measure is called Relative Median of Absolute Deviation (RMAD) over a 5 m-long moving window. Gaussian Mixture Modelling identified a threshold of 3% RMAD that separates the geological record exposed in the borehole into mechanically homogeneous and anomalous zones. A sampling strategy was developed by combination of fuzzy c-means clustering domaining on continuous X-ray fluorescence geochemistry data as well as RMAD zones. The outcome of the study is a sampling strategy guided with RMAD that provides a measurable and quantitative means to take samples, based on the mechanical and geological conditions of the sampled medium.

Keywords

Wireline Logging, Dynamic Elastic Modulus, Mechanical Heterogeneity, RMAD, Sampling Strategy.

1 Introduction

Rock mass shows three-dimensional variability in its mechanical properties. The ever-present question in geotechnical and mining engineering is: what is the reliability and representativeness of the samples we extract from the rock, relative to the bulk volume? Even if we assume that testing procedures involve limited bias, which is itself unrealistic in most cases, two key questions remain: 1- from where should samples be taken, and 2- how many are enough to adequately cover the uncertainty? Working

in such a complex geological and mechanical medium (whether for development, stabilisation, or blasting) requires either the use and development of key diagnostic tools or the acceptance of conservative designs based on large safety margin. Managing risk and optimising costs remains a fundamental aspect of mining operations. An improper or unrealistic mechanical picture of the rock mass can affect multiple aspects of mine engineering. In blasting, it can cause undesirable particle size distribution, dilution, and over or under break which extend to downstream mineral processing, where undesirable particle size distributions increase comminution energy and cost (Jackson and Sellers 2017). In stability and support design, it results in overly conservative support systems. In surface mining it causes unrealistic stripping ratios and low slope angles, while in underground mining it can urges engineers to consider unnecessarily conservative stope designs (Stacey 2015). Growing concerns around the deviation of mine performance from what had been planned during the early phases of study further highlight the need for not only provision of datasets rich in variety (downhole geophysical, seismic tomography, core scanning, optical logging, etc.) but also increase of data reliability and less reliance on untested assumptions. While one may criticise the costs of conducting additional studies or drilling, economically there is no justification for such oversight, given the potentially disastrous consequences of ignoring the reliability and variability of these geotechnical variables (van As 2020). Addressing the issues, authors have criticised the shortcomings of existing characterisation methods and highlighted a need for a paradigm shift in rock engineering (Elmo et al. 2022).

Geophysical methods have strengthened rock mechanics through in characterisation, monitoring, and measurement applications (Hatherly 2013; Kieu et al. 2024; Takahashi et al. 2006). Deere et al. (1966) proposed that wave velocity can provide estimations for Rock Quality Designation (RQD), and Barton (2006) explained the potential of seismic waves for characterising rock mechanics properties. Seismic waves induce small elastic strains in rock and are therefore sensitive to the mechanical properties of the medium(Barton 2006). Apart from prediction, mapping the variability of mechanical properties is also achievable using continuous wireline log data. Wireline tools provide continuous measurements along the entire borehole. Design practice in rock engineering could be improved with a better picture of variation in mechanical properties that wireline log data analysis could provide.

In this study, we present a method for measuring variation in mechanical properties along the length of a diamond borehole using dynamic elastic modulus obtained from full-wave sonic and density logging, and we test whether this indicates UCS level, likely failure mechanism, and finally suggests how it can be combined with geochemical domains to guide sampling strategy.

2 Site, Data, and Methodology

2.1 Site and data collection

As part of a research programme at the Brukunga mine site, north of Adelaide, South Australia, we conducted comprehensive geophysical wireline logging and collected a large number of UCS samples from core acquired at two adjacent boreholes(Each with a depth of 300m and only 5 m apart).They were depth-matched using natural gamma log correlation. Our total dataset contains 162 UCS test results, done based on standards (ASTM 2019, 2023), and various geophysical logs including FWS and density logs, as well as detailed XRF geochemical data came from XRF core scanning (By Veracio) using a proprietary tool (TruScan).

Table 1 represents the statistical results of UCS tests and shows a wide variability in results. Each UCS sample was classified into foliation controlled (FC) and non-foliation controlled (NFC) failure. Failure mode was recorded (Szwedzicki 2007) and the dominant mode of failure in FC was seen to be single shear (SS) while in NFC it was observed to be multiple fracturing (MF).

Table 1. UCS summary statistics.

Group	n	Mean	Std	CoV	Min	Median	Max
All data	162	12.7	74.6	0.59	22.5	99.8	320.2
No foliation Controlled failure	77	184.6	62.6	0.33	29.3	195.4	320.2
Foliation Controlled failure	85	70.4	29.1	0.41	22.5	60.2	168.7

2.2 Dynamic elastic modulus and RMAD

After velocity analysis, intact rock P-wave (V_p) and S-wave (V_s) velocities were extracted from the full-wave sonic logs (By RoqSense). Dynamic Elastic Modulus, E_d, was calculated using elasticity relations (Eq.1). Due to the non-normal distribution of E_d along the borehole, Relative Median Absolute Deviation (RMAD) of E_d over a 5m-sized moving window was adopted as a robust statistical method for quantifying variability (Eq. 2).

$$E_d = \rho V_s^2 \frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2} \quad (1)$$

$$RMAD_w(z) = \frac{MAD(E_d\left[z - \frac{w}{2} : z + \frac{w}{2}\right])}{median(E_d\left[z - \frac{w}{2} : z + \frac{w}{2}\right])} \times 100\% \quad (2)$$

Where ρ Density

z Centre value

w Window size

Gaussian Mixture Modelling (GMM) was applied to the full RMAD to identify three mechanical zones (homogeneous, relatively heterogeneous, heterogeneous). It was decided to use the first threshold (3%) as a divider between Homogenous and (relatively or globally) heterogeneous zones (Fig 1):

a) Zone 1(RMAD ≤ 3%) Homogeneous: Representing mechanically uniform rock covering 48.3% of the total borehole length.
b) Zone 2 (RMAD >3%) Heterogeneous: Representing mechanically variable rock covering 51.7% of the total borehole length.

2.3 Geochemical domain

To domain the borehole, continuous XRF data was used, and fuzzy c-means clustering were utilised. Fuzzy c-means (FCM) is an unsupervised soft clustering algorithm in which each data point is assigned a degree of membership to multiple clusters, and cluster centres are iteratively updated by minimising an objective function (Bezdek et al. 1984). 4 main clusters were identified (Fig 1) (Kieu et al. 2024; Shakib et al. 2025). XRF core scanning provides high-resolution geochemical data along boreholes(Harris et al. 2024)and can be used for domaining as the mechanical properties of rock are controlled by bulk composition, mineralogy, and fabric(s) (Barton 2006).

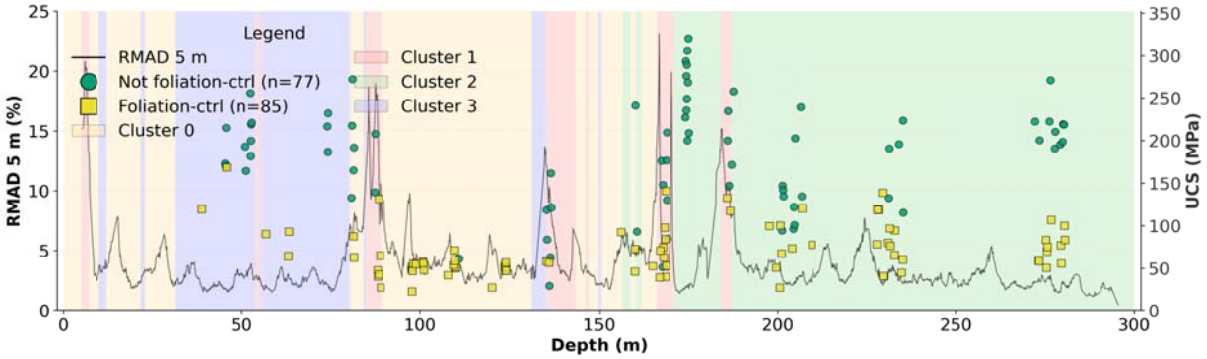


Fig. 1 Borehole profile showing RMAD_5m (upper chart), UCS samples (lower panel), and XRF geochemical domains in background.

3 Results and Hypothesis Testing

According to Table 2, three hypotheses were developed and non-parametric tests were selected to cover the non-normal, multimodal nature of the UCS distributions. The specific test statistic was chosen to match the nature of each hypothesis. Rank-based tests were used to test H1, while contingency-based tests were utilised to test H2 and H3.H1 is supported, as the median UCS in homogeneous zones (169 MPa) is notably higher than in the heterogeneous zone (77 MPa) (Table 2 and Fig 2a). H2 was supported emphasizing that 65.6% of the failures in homogeneous zone were NFC and 64.3% in heterogeneous zone were FC (Table 2 and Fig 2b). Lastly, H3 was supported with

MF occurring 54.7% in the homogeneous zone and SS happening 54.1% in heterogeneous zone (Table 2 and Fig 2c).

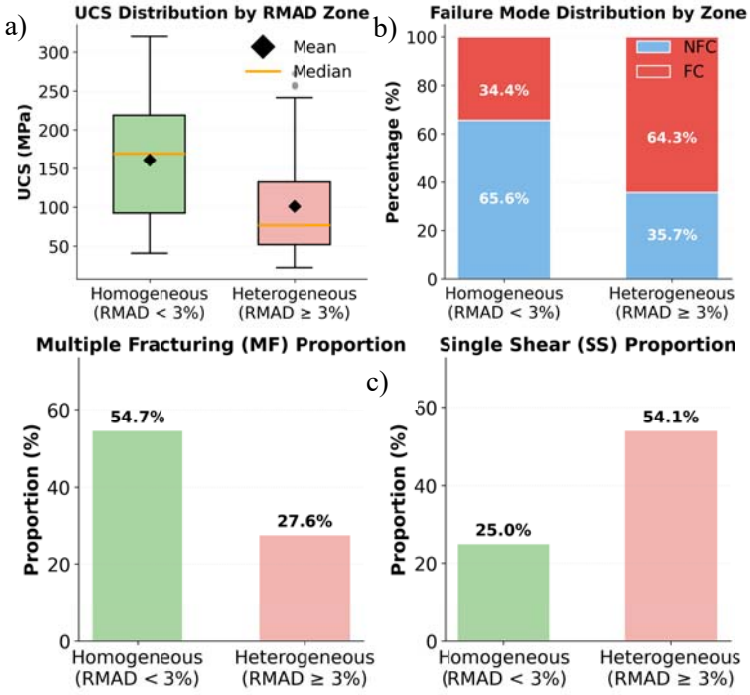


Fig. 2 Distribution by RMAD Zone (a) UCS (b) Failure mode and (c) geometry of failure.

Table 2. Summary of hypothesis testing results.

H	Hypothesis	Test	Statistic	Result	State
H1	The UCS level differs between RMAD zones	Mann–Whitney U	$U = 4621$, $p = 3.7 \times 10^{-7}$	Median: 169 vs 77 MPa [44, 129] at 95% CI	Supported
H2	Foliation-controlled failure is associated with RMAD zone	Chi-squared	$\chi^2 = 12.7$, $p = 3.6 \times 10^{-4}$	FC rate: 34% in homogeneous and 64% heterogeneous zone	Supported
H3	Higher RMAD shows SS failure; lower RMAD shows MF failure	Chi-squared	$\chi^2 = 27.0$, $p < 0.001$	Homogeneous: MF (55%), Heterogenous: SS (54%)	Supported

3.1 Interpretation

Results suggest that RMAD of elastic modulus, as a measure of spatial mechanical heterogeneity, can be indicative of low and high UCS values. However, it must be clearly stated that a direct point-to-point linear relationship between individual UCS values and their corresponding RMAD values cannot be established. There are two principal reasons for this. Firstly, the wireline logging process involved limitations around modifications and adjustments during the campaign and data clipping which affected the resolution of velocity analysis (measurement issue). Secondly, a UCS sample is approximately 15 cm in height, while the RMAD window in our case is 5 m. The RMAD value at a given depth reflects the heterogeneity of a wider section compared to the sample (scale issue).Both issues could be addressed to some extent if we had access to higher-resolution sonic logging (intervals of less than 5 cm and/or slower logging speeds).

The connection between RMAD and failure mechanism provides information regarding heterogeneity of the medium as in our case, the major source of heterogeneity was foliation. On one hand, high RMAD also reflected zones where foliation was controlling the failure mainly through SS failure. On the other hand, Low RMAD values indicated more mechanically uniform rock, where failure occurred through matrix fracturing at higher strengths through multiple fracture failure.

4 Quantitative Sampling Strategy

4.1 Suggested allocation strategy

RMAD-based zonation in conjunction with XRF fuzzy clusters can be used to develop a quantitative sampling strategy for taking UCS samples from drillcore as follow:

1. Acquire full-wave sonic and density logs and compute E_d and RMAD over a desired moving window.
2. Apply the GMM threshold to classify zones.
3. Run Fuzzy C-means clustering on continuous geochemical data.
4. Take at least 3 samples for the smallest cluster and use its length proportion to determine the total required sample (Eq. 3).
5. Allocate UCS samples proportionally to cluster length and RMAD zone fractions as follows:

Allocate n_k samples to cluster k (Eq.3) based on the relative length of each XRF cluster.

$$n_k = round\left(N \times \frac{L_k}{L_{Total}}\right); \sum_{k=0}^{K-1} n_k = N\,; N \geq \frac{3 \times L_{Total}}{L_{k,min}} \tag{3}$$

Within each k cluster, determine the proportional length of the RMAD zones and sample accordingly (Eq.4).

$$n_k^{Heterogeneous} = \max\left(1, round(n_k \times (1 - h_k)\right)$$
$$n_k^{Homogeneous} = n_k - n_k^{Heterogeneous} \tag{4}$$

Where N Total number of samples based on constraints
k XRF clusters (k = 0,1, …, K-1)
L_k Length of cluster k along the borehole
$L_{k,min}$ Length of the shortest XRF cluster
L_{Total} Total logged borehole length
h_k Fraction of cluster k where RMAD ≤ GMM threshold (homogeneous)
$(1-h_k)$ Fraction of cluster k where RMAD >GMM threshold (heterogeneous)

This sampling strategy was tested against UCS data from the Brukunga site. Based on Table 3, the minimum number of samples required by the proposed methodology is 36. According to Fig. 3, at N=36, the probability of exceeding 30% bias in the estimated median UCS (based on 5,000 bootstrapping simulations) is 5% for the proposed methodology versus 19% for the equal-allocation method (taking samples equally across each XRF domain).

Table 3. XRF cluster proportions and RMAD heterogeneous fractions.

Cluster	L_k / L_{Total} (%)	1- h_k
0	30.1	0.24
1	8.5	0.12
2	41.3	0.63
3	20.1	0.7

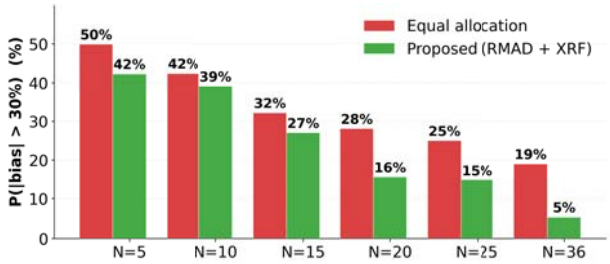


Fig. 3 Probability of more than 30% bias in estimated median UCS vs. sample budget N for equal-allocation and proposed (RMAD + XRF) strategies (10,000 simulations, n=162).

We acknowledge that this framework is presented as a preliminary method. However, the methodology using variability index (RMAD) on continuous geophysical data and using fuzzy c-means clustering on geochemical logs can be useful in formulating a sampling strategy.

5 Discussion

Results of the study shows that RMAD of dynamic elastic modulus, derived from full-wave sonic and density wireline logs, provides a continuous, robust measure of mechanical heterogeneity along the borehole. RMAD can be considered as a spatial heterogeneity indicator. It was shown that a GMM zonation can be considered to separate the borehole into homogeneous and heterogeneous zones.

Based on our statistical observations, homogeneous zones show higher median UCS (169 MPa) and mainly cover NFC and MF failure. Heterogeneous zones exhibit lower median UCS (77MPa) and mainly cover FC and SS failure. RMAD-based zonation when combined with domaining, provides a quantitative approach for informing UCS sampling strategy. Despite the observations presented in this study, careful geophysical data collection, combined with the development of accurate tools, remain as a key topic. There is a need to encourage the mining and rock engineering community to bridge the existing gap between rock mechanics and geophysics at a time when inadequate and/or unreliable data can result in significant economic costs to the client. The paradigm shift that rock engineers strive for may be achieved by the routine integration of geophysical approaches into contemporary rock mechanics frameworks.

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