Joint surface characterization using manual and multi-sensor core logging systems

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ABSTRACT: The shear behavior of a discontinuity can be significantly influenced by its surface characteristics. This paper compares manual and sensor-based geotechnical core logging methods for joint surface characterization. More than 500 m of core samples were logged, in which 367 joints were both digitally and manually characterized. Manual logging was carried out by visually assessing joint surface roughness and alteration indices. Sensor-based logging includes creating 2D and 3D joint roughness profiles using a handheld 3D scanner and measuring joint wall hardness and alteration type using Equotip Leeb hardness and pXRF analyzer. The collected data were statistically analyzed. A comparison between manual and multi-sensor joint surface characterization was made to demonstrate the discrepancy between the manual and digital logging techniques regarding joint surface roughness, joint wall strength and joint alteration.

Keywords: Joint surface characterization, Multi-sensor core logging, Leeb hardness test, Joint alteration, Joint roughness, 3D handheld scanner.

1 INTRODUCTION

Geomechanical characterization and classification are essential to predict the behaviour of a jointed rock mass. This requires a detailed characterization of rock mass discontinuities using reliable, accurate, and fast measurement techniques. Structural characteristics of a jointed rock mass can be described by measuring orientation, spacing, persistence, and joint surface characteristics. These characteristics have been incorporated into the most popular rock mass classification systems, such as the Q classification system (Barton et al., 1974).

Joint surface characteristics (e.g. roughness and alteration) can significantly influence the shear behavior of discontinuity and, subsequently, the geomechanical design of a surface and underground excavation developed in the jointed rock mass. Uncertainties and inconsistencies in joint surface characterization can lead to unreliable geomechanical design and, consequently, the risk of failure and the ultimate economic repercussions of an engineering project (Esmaeili, 2019; Read & Stacey, 2009). Thus, rock structural defects should be characterized and classified based on consistent and objective measurements.

To characterize a joint surface, roughness, wall strength, aperture, alteration, and infill materials must be measured, described, and logged. Despite technological improvements, the data collection process for the geotechnical characterization of joint surfaces still contains subjectivity because the process is based on observation or assessments, not measurements (Hadjigeorgiou, 2012). This could be critical as important design decisions are made based on the collected data.

Core logging is one of the fundamental methods commonly used to obtain geological and geotechnical data. The manual core logging method is subjective, inconsistent, and time-consuming and requires experienced experts to log and characterize the rock samples (Esmaeili, 2019; Ewan et al., 1983). A core logger can manually assess joint surface characteristics by comparing the joint roughness to reference profiles and visually evaluating surface alteration. Recent advances in multi-sensor core logging (MSCL) systems allow the measurement of joint surface characteristics, including 3D joint surface roughness and the identification and measurement of joint surface alteration (Bhuiyan & Esmaeili 2018; Fifer-Bizjak 2010).

This study will focus on the characterization of joint surfaces in core samples, including roughness and the degree and type of surface alteration. Despite the advances in joint surface data acquisition, limited studies have compared the measured vs. assessed joint surface data in terms of accuracy and precision. In addition, the characterization of geomechanical rock properties, particularly the shear behaviour of joints, using digital core logging data has received limited attention.

2 METHODOLOGY

For this study, 564 m of BQ-size core samples were obtained from nine different boreholes of an underground Ni-Cu mine in the Sudbury region. The core samples are not oriented and are placed into 100 core boxes. Six different lithologies were identified in the core samples: Metasediment, Metabasalt, Metagabbro, Mafic Norite, Felsic Norite and Subx (a lithology showing metasedimentary and metabasalt attributes). All core samples were logged both manually and using a sensor-based approach. The logging process started by identifying natural discontinuities. Overall, 367 natural joints were recorded from these core samples. Figure 1 illustrates the data collection and core logging process flow diagram.

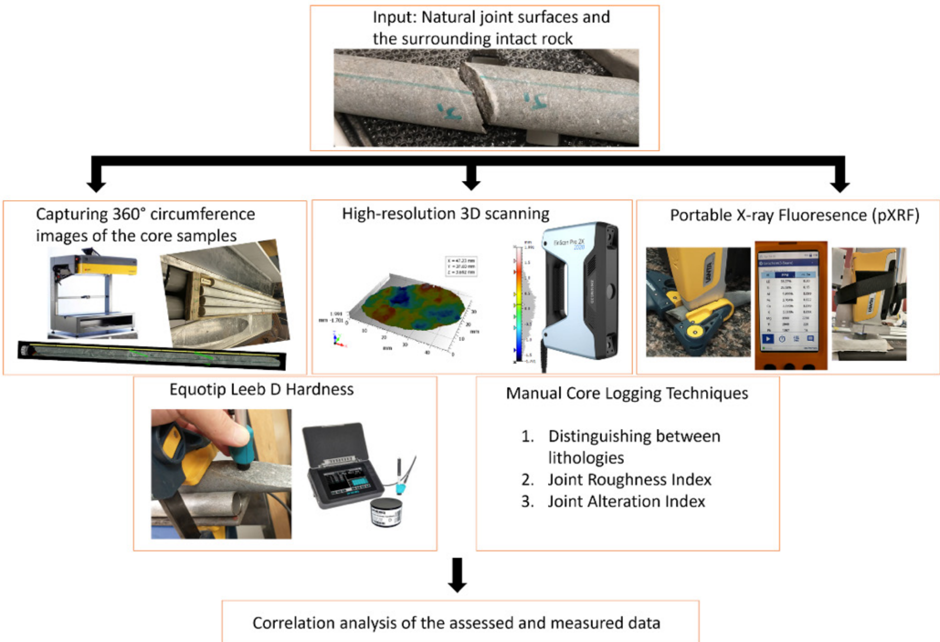


Figure 1. The flow diagram of the data collection and analysis.

In the manual core logging approach, for each natural joint, the joint roughness index (Jr) and joint alteration index (Ja) were assessed based on the reference tables from the Q classification system.

The joint alteration index ranges from 0.75, associated with tightly healed and hard joint surfaces, to 20, where the infill material introduces a slippery surface, e.g. swelling clay. Figure 2 presents the assigned Ja values for some joint samples. Where mineralization was observed on the joints based on the thickness of mineralization, the Ja values were assigned as 2 for mineral coating and 4 for thin mineral filling.

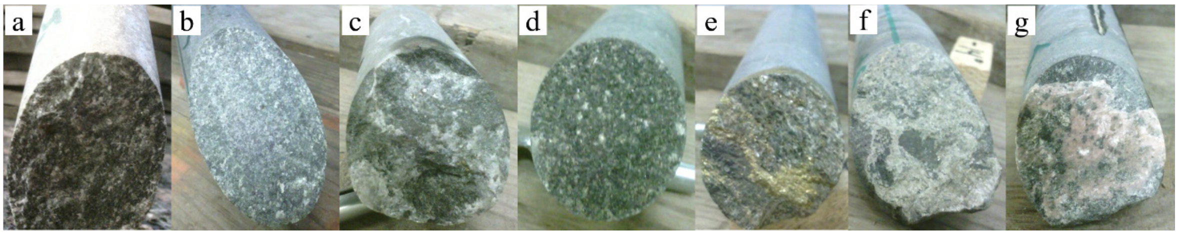


Figure 2. Reference joint surface images and their assigned Ja values: (a) Ja=0.75 (Tightly healed); (b) Ja=1 (staining only); (c) Ja=2 (mineral coating); (d) Ja=3 (clay-traction); (e) Ja=4 (disintegrated rock); (f) Ja=6 (non-softening clay); (g) Ja=8 (softening clay).

The joint roughness index (Jr) is used to describe the unevenness of the discontinuity surface as numbers. Jr ranges from 0.5 to 4, and higher Jr values are desired for the rough joint surfaces. This study used the guidance table from the Q classification system to assess joint roughness (Barton et al., 1974). Figure 3 shows the shapes and roughness profiles assigned to some joint samples.

Figure 3. Assessed joint shape (left) and roughness (right) examples.

In sensor-based core logging, EinScan Pro 2X Plus Handheld 3D Scanner was used to scan the discontinuity surfaces. The best scan accuracy of up to 0.08mm was obtained on handheld HD scan mode. The device was calibrated before scanning natural joints from each core box. For transparent, highly reflective, and dark joint surfaces, spraying powder was applied to avoid having holes and gaps in the scanned images. Once the natural joints were scanned, 3D surface images were created as STL (Standard Triangle Language) files (stored point clouds as sets of vertices joined by edges to make triangular faces). Post-processing operations (deleting unnecessary parts of the joint images and auto hole filling only for less than 10mm perimeter holes using Tangent filling type) were done to treat noises and fill holes and improve the morphology of the image. Not to change the roughness profile significantly, the 3D scanning process was repeated after spraying powder to the surfaces with holes bigger than 10mm perimeter. The actual and nominal joint surface areas were calculated for each joint, and the ratio of actual surface area to nominal joint surface area (Rs) (El-Soudani, 1978) was estimated as Joint Roughness. Using Mountains 9 Premium software, 2D sections were drawn on the 3D joint profile to analyze surface morphology. These 2D sections were then visually compared with the ten standard profiles of the Joint Roughness Coefficient (Barton & Choubey, 1977) to assign JRC values to the joint surfaces. Figure 4 presents the digital elevation model of a joint, and the 2D section along the joint's shear direction, which was used for JRC estimation.

Once the joint samples were scanned, the Equotip Leeb Hardness test and portable XRF test were conducted on the joint surfaces to measure the joint wall strength and alteration type. The ASTM standard was followed for the Leeb hardness test (ASTM International, 2012). Core samples were fixed to avoid vibration or movement during the hardness test. Hardness tests were applied on natural joint surfaces and their surrounding intact rock. Ten measurements were taken on the intact rock, and ten different spots were measured on the joint. Hardness Leeb D (unit for the Hardness variable) HLD (Δ) was calculated by subtracting the mean HLD of the joint from the mean HLD of intact rock ($\Delta = IR_{hardness} - J_{hardness}$).

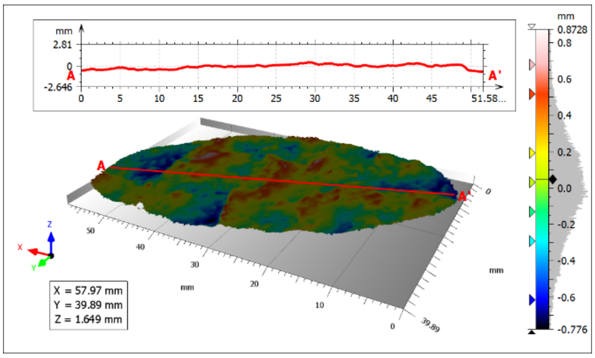


Figure 4. 3D digital elevation model of a joint and 2D section of the joint along the shear direction (A-A').

The multi-element geochemical data were collected using Olympus Vanta pXRF, an X-ray fluorescence spectrometer with a 3mm measuring window that allows relatively non-destructive chemical analyses, on the joint and the surrounding intact rock. The pXRF recalibrated after four repeated tests, and the measuring window was cleaned with a cloth before each test. Portable XRF was mounted on an MSCL device controlled by the logging device's software (Esmaeili, 2019), and its position was adjusted to reduce air between the surface and the measuring window. The device can detect 39 elements; however, all the elemental compositions cannot be used for the analysis because they are not present on most joint surfaces, and some of the elements measured are under the detection limit of the device. A data cleaning was performed to remove undetected elements. To determine the type of alteration on each joint surface, the multi-element geochemical measurements (pXRF measurements) on the joint surface were compared to those measured on the adjacent intact rock (beside every joint). Delta (Δ) concentration values were calculated by subtracting elemental composition on the intact rock from the joint surface ($\Delta = IR_{concentration} - J_{concentration}$). When the delta concentration percentage is equal to or near 0, there is no difference between the joint surface and intact rock. Negative values in the y-axis explain that the elements tend to have a higher concentration on the joint surface based on alteration degree.

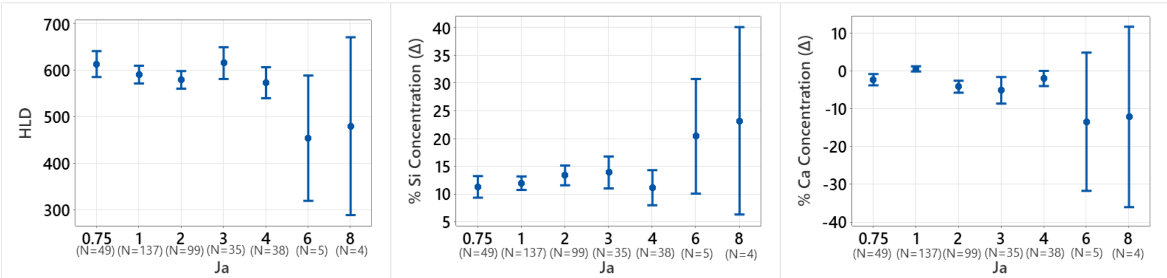
3 RESULTS

The joint surface characterization tests consist of a raw dataset containing manually collected Ja and Jr and measured data, including HLD (Δ), elemental compositions (Δ), JRC, and Rs. Using the collected data, a correlation analysis was carried out to find relationships between different assessed and measured joint surface characteristics. Joint wall strength significantly influences the shear behaviour of a joint surface. Previous studies pointed out a positive correlation between Si composition in intact rocks and rock hardness measured by the Leeb hardness test (Esmaeili 2019).

Figure 5a presents the mean and standard deviation (Std.) of HLD for different Ja values assigned to the joint surfaces. The mean and Std. of HLD for joint surfaces with lower alteration index (0.75-Ja-4) remain almost constant (HLD 550-650). As the joint alteration index increases (Ja 6 and 8), the mean joint wall strength (HLD) decreases and the range of HLD increases (HLD ~300-650).

Figures 5b and 5c show the relationship between the joint alteration index (Ja) and the ΔSi and ΔCa concentrations. The results indicate that as the joint alteration index increases (higher alteration degree), the Si composition on the joint surfaces decreases. This can be attributed to the presence of softer infill minerals (e.g. clay, silt) or coatings on the joint surfaces with higher Ja. An inverse relationship is observed between the Ja and the ΔCa; the composition of Ca on the joint surfaces, with a higher alteration index, increases, implying the presence of softer infill minerals on the joint surface, containing high Ca. Different compositions of Ca and Si were obtained in 6 different rock types due to their inherent geochemical nature. However, the calculation of delta values eliminated the influence of lithology on this interpretation. Thus, Si and Ca compositions can be used as a proxy to indicate the degree of joint surface alteration, like joint wall strength.

Figure 6 presents the relationship between the assigned Ja values and the Δ composition for Ni, Cu and S. The graphs show a relatively high negative delta elemental concentration when the Ja increases. This can be attributed to the joint surfaces' alterations as these samples come from a Ni-Cu deposit. The presence of these elements (Ni, Cu, S) on the joint surface can reduce joint wall strength. As mentioned earlier, when mineralization was observed on joints, based on the thickness of mineralization, the Ja values were assigned as 2 and 4. These Ja values indicate mineralization on the joint surface as staining, coatings or disintegrated rock. This explains why Ni and Cu elements show their highest concentrations when Ja values equal 2 or 4. The high Sulfur composition indicates Sulfide or Pyrite-Millerite-Chalcopyrite alteration types. In addition, clay (such as Ca-montmorillonite) can easily absorb this element, as reported by (Fang et al., 2022). This may explain why higher S was observed on the joint surfaces with a high alteration index of 4, 6 and 8.



a) b) c)

Figure 5. Interval plots of mean and Std. of a) HLD (Joint), b) % Si (Δ), and c) % Ca (Δ) against Ja.

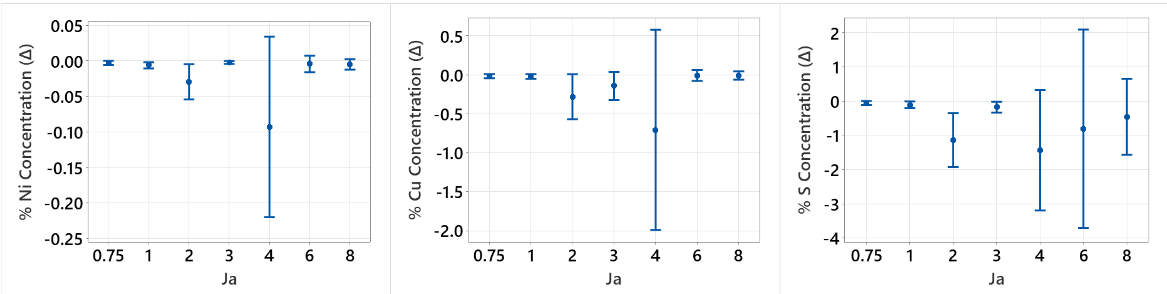
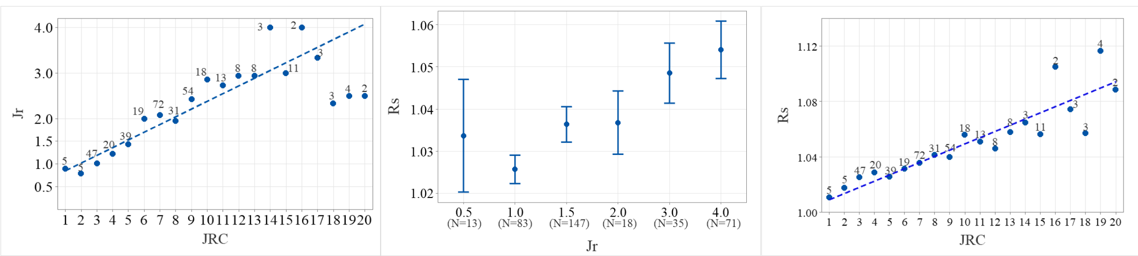


Figure 6. Interval plots of mean % Ni (Δ), % Cu (Δ), and % S (Δ) against Ja.



a) b) c)

Figure 7. Correlation between a) Jr and JRC, b) Rs and Jr and c) Rs and JRC. The dots represent the mean values, and the numbers above show the samples in each category.

This study employed three different approaches to assess/measure joint surface roughness (Jr, JRC and Rs). Figure 7 presents the relationship between these parameters. Figures 7a and 7c show a positive association between JRC (measured along the joint's shear direction) and Jr and Rs, except for the higher JRC values. The discrepancy for higher JRC values can be attributed to the wrong estimation of Jr or the wrong approximation of JRC profiles. Figure 7b shows the relationship between Jr and Rs. While a positive correlation can be observed, a larger discrepancy can be seen for the Jr value of 0.5. This value was assigned to both the slickensided and planar joints, where wider Rs values were recorded; an indicator of wrong interpretation while assigning Jr value.

4 CONCLUSION

This paper describes manual and sensor-based core logging for joint surface characterization. There is a discrepancy between these two core logging techniques when it comes to joint surface roughness, joint wall strength, and joint alteration type. A visual assessment, a 2D measurement, and a 3D measurement were used to characterize joint surface roughness. The correlation between these parameters was positive despite some discrepancies. In order to quantify joint alteration, we measured the hardness and geochemical composition of joint surfaces and their adjacent intact rocks. Joint wall strength was lower when Ca was infilled or stained on the joint surface. Harder elements, such as Si, on the joint surface, gave higher joint wall strength. Joint surfaces with higher Si and lower Ca concentrations have lower Ja values.

One person logged the core samples in this study. This has substantially reduced the inconsistency between the measured and assessed joint surface parameters. It is recognized that in a real geotechnical core logging process, different core loggers can be involved in the process. Depending on the experience of the core loggers, the complexity of rock mass and the pace of work in a core shake, two loggers can produce different results for the same core sample, increasing the inconsistency of the assessed core logging data.

ACKNOWLEDGEMENTS

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REFERENCES

ASTM International. 2012. A956-12, *Standard Test Method for Leeb Hardness Testing of Steel Products*. https://doi.org/10.1520/A0956-12

Barton, N., & Choubey, V. 1977. *The Shear Strength of Rock Joints in Theory and Practice*. *Rock Mechanics*, 10, 1–54. https://doi.org/10.1007/BF01261801

Barton, N., Lien, R., & Lunde, J. 1974. *Engineering Classification of Rock Masses for the Design of Tunnel Support*. Rock Mechanics 6, 189–236. https://doi.org/10.1007/BF01239496

Bhuiyan, M., & Esmaeili, K. 2018. Comparison between conventional and multi-sensor geotechnical core logging methods. *In Proceedings of the EUROCK 2018, Geomechanics and Geodynamics of Rock Masses*, Saite-Petersburg, Russia, 212–217, CRC Press.

El-Soudani, S. M. 1978. *Profilometric Analysis of Fractures*. *Metallography* 11(3), pp: 247-336.

Esmaeili, K. 2019. Improving the quality and quantity of geotechnical core logging data. In: *Proceedings of the 14th International Congress on Rock Mechanics and Rock Engineering (ISRM 2019),* Foz do Iguassu, Brazil, September 13-18, 2019.

Ewan, VJ., West, G., & Temporal, J. 1983. Variation in measuring rock joints for tunnelling. *Tunnels & Tunnelling International*, 15(4), pp.15–18.

Fang, Z. J., Song, C. H., Liu, M. L., Li, B., Lin, S. K., Lin, X. S., Zhou, X., He, Q. Z., & Mo, M. 2022. *First-principle calculations of sulfur dioxide adsorption on the Ca-montmorillonite*. Scientific Reports, 12(1). https://doi.org/10.1038/s41598-022-24737-x

Fifer-Bizjak, K. 2010. *Determining the surface roughness coefficient by 3D Scanner*. Geologjia, 53(2), 147–152. doi:10.5474/geologija.2010.012

Hadjigeorgiou, J. 2012. *Where do the data come from?* Mining Technology, 121(4), pp. 236–247. https://doi.org/10.1179/1743286312Y.0000000026

Read, J., & Stacey, P. 2009. *Guidelines for Open Pit Slope Design (J. Read & P. Stacey, Eds.).* CSIRO.