Proposed Methodology for Utilising Automated Core Logging Technology to Extract Geotechnical Index Parameters

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ABSTRACT

In the past decade, increased processing capacity combined with precision robotics in high resolution spectrometers has resulted in a new generation of high-speed hyperspectral core logging systems. The application of these multisensor automated platforms provides a key advancement in the characterisation of metal resources. The development of this technology has allowed for comprehensive, drill core-based, mine-scale rock mass characterisation studies. Here we propose a new method for the extraction of parameters that seek to more accurately quantify ground conditions, including quantified rock mass rating (RMR) and the Rock Tunnelling Quality (Q) Index. Data inputs include rock quality designation (RQD), number of joint sets, joint roughness, joint alteration and joint spacing. Geologists and geotechnical engineers have historically collected these inputs by manually logging drill core. With automated core scanning technologies, these parameters can be estimated from the acquired image data and used to objectively calculate RMR and Q-index values for oriented core.

Corescan is an automated hyperspectral core scanner that uses a 3D laser profiling system to measure the height of the surface of drill core. This technology allows for rapid core analysis to produce detailed fracture and rock condition data. Through an integrated geometallurgical approach, the proposed methodology will test the accuracy of joint measurement using the height profile Corescan data from oriented drill core. This will be combined with joint roughness and alteration mineralogy measured from the hyperspectral images to calculate the RMR and the Q-index continuously downhole. The values obtained can then be compared to the traditional, manual geotechnical log data. If the precision is sufficient, these techniques can then be applied site-wide to automate the collection and modelling of key ground condition classification indices across an entire deposit. Compared to the laborious manual geotechnical logging procedures that currently form the industry standard, utilisation of core laser profile data and high resolution red-green-blue (RGB) images provide an opportunity to collect large volumes of consistent geotechnical data, which can increase the efficiency and accuracy of deposit scale geotechnical models.

INTRODUCTION

The careful assessment and modelling of geotechnical characteristics within an ore deposit are vital to both the mineability and profitability of a mining operation (Hoek, Kaiser and Bawden, 2000). The geotechnical characteristics of rocks are a function of the geological processes that formed both the host rocks and associated mineralisation. Typically, a geotechnical model is completed by combining manually collected geotechnical measurements from drill core with other geologic observations and characteristics of the ore deposit. Here we propose a methodology that seeks to enhance and streamline the current, manual data collection techniques with the automated extraction of geotechnical parameters using automated core logging technology.

The application of downhole imagery to perform fracture analysis has been applied in the oil and gas industry since the 1960s (Prensky, 1999). In mining, acoustic televiewer data acquired from borehole logging is often used to measure the orientation of fractures and joints downhole (Trofimczyk and du Pisani, 2009; Shigematsu *et al*, 2014). While this data is accurate and measures orientations *in situ* downhole, it is expensive and is often difficult to acquire in areas with poor ground conditions. The high resolution core logging system used here (via Corescan) provides a unique opportunity to capture and record continuous, downhole fracture data over large volumes of core.

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The present industry standard method for geotechnical data acquisition and ground condition modelling in hard rock environments is manual logging of drill core by geologists and geotechnical engineers (Holcombe, 2013). While this approach has been successfully applied to mining in the past, it is often laborious and inconsistent. Automation of geotechnical data collection using automated core loggers would allow for consistent, rapid assessment of key parameters as they relate to ground conditions.

GEOTECHNICAL ASSESSMENT CALCULATIONS

Consistent, quantitative rock classification is required to understand both the cavability of an orebody as well as the ground support required for the installation of underground development and extraction infrastructure (Brady and Brown, 2013; Hoek, Kaiser and Bawden, 2000). Rock quality designation (RQD) is a common calculation used to estimate the rock conditions from drill core (Deere *et al*, 1967). The RQD value is calculated by measuring the percentage of core that is considered to be unbroken (>10 cm in length) as shown by the following equation:

$$RQD\,(\%) = \frac{(\Sigma\ length\ core > 10\ cm)}{(total\ length\ core\ run)} \times 100\%$$

The RQD can act as a rock quality description alone, but is also a key component in both the rock mass rating (RMR) and Q-index calculations.

The RMR classification system was originally developed for civil engineering applications, but has since been modified to account for underground mining conditions (Bieniawski, 1989). RMR is calculated by categorising six parameters:

1. uniaxial compressive strength (UCS)
2. RQD
3. spacing of discontinuities
4. condition of discontinuities
5. groundwater conditions
6. orientation of discontinuities.

For each parameter, a range of measured or observed values defines the rating number. These numbers are then summed to obtain the final RMR value for the examined interval. Bieniawski (1989) defines the excavation type and ground support requirements based on the range of RMR values calculated.

The Norwegian Geotechnical Institute's Q-index was developed after examining numerous case studies of rock behaviour in underground mines (Barton, Lein and Lunde, 1974). The Q-index is defined as a numerical value on a logarithmic scale from 0.001 to 1000 with the following geotechnical inputs:

1. RQD
2. number of joint sets (J_n)
3. joint roughness (J_r)
4. joint alteration number (J_a)
5. joint water reduction factor (J_w)
6. stress reduction factor (SRF).

The relationship between these six parameters is given by the following Q-index formula:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$

where:

RQD/J_n	is an approximation of block size
J_r/J_a	is an estimate of the inner block shear strength
J_w/SRF	represents a total active stress indicator (Barton, Lein and Lunde, 1974)

While the RQD, RMR and Q-index calculations refer specifically to 'joints', it should be noted that joints are simply one type of discontinuity observed in drill core. The general term 'fracture' will be used here to reference all types of naturally occurring breaks in the drill core including joints, faults, cracks, fractures and other discontinuities of unknown geologic origin.

PROPOSED AUTOMATED METHODOLOGY

The Corescan system utilises the Hyperspectral Core Imager Mark-III (HCI-3) logging technology that collects high resolution red-green-blue (RGB) visible wavelength imagery, 3D laser height profiles and high resolution VNIR-SWIR (visible near-infrared and short wave infrared) spectra. The RGB imagery is collected at a pixel resolution of 60 µm. The laser data is collected at a resolution of 200 µm horizontally and a vertical precision of 15 µm. The scanning capabilities and sensor array of the Corescan system allows for the rapid, non-destructive analysis of drill core to produce high resolution 3D laser maps representing a digital profile model of the surface of the drill core (Figure 1). By utilising the three image types collected, it is proposed that the Corescan data can be applied to extract key geotechnical input parameters as they relate to ground conditions within the deposit of interest.

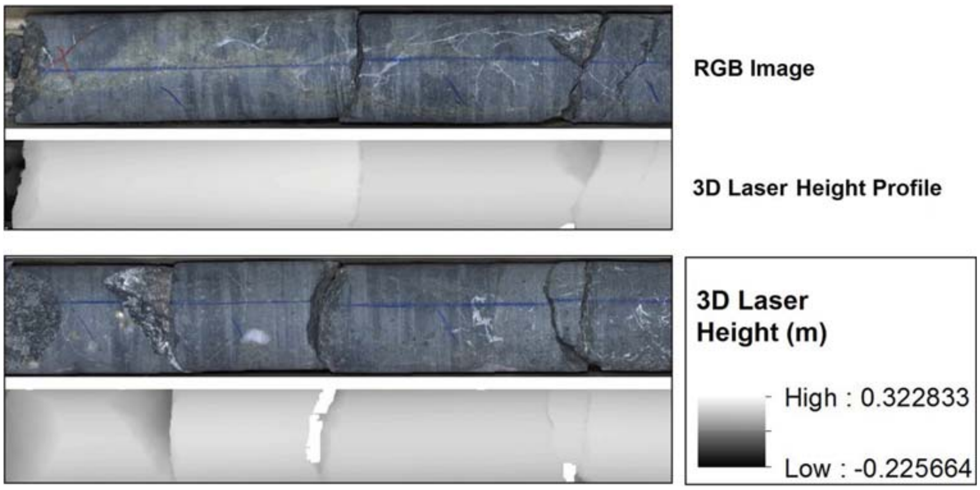

FIG 1 – Examples of the red-green-blue (RGB) imagery and 3D laser data produced from Corescan analysis.

In order to extract the parameters required to calculate the RMR and the Q-index from Corescan data, the location, orientation, morphology and mineralogy of fractures need to be recognised and measured. When considering the automation of this type of analysis, the mode of data collection should also be carefully considered. Usually Corescan imaging is conducted on halved core as it provides a flat surface (constant core height), which ensures that the focal length of the RGB sensor and hyperspectral scanner is continuous for a given run of core. However, since the cutting and sampling process induces rock breaks not related to natural fracture patterns, Corescan analysis of whole, uncut core will be required for geotechnical data calculation. Additionally, the location of the orientation mark on the surface of the drill core is lost when the core is cut, so imaging of whole core ensures that the orientation line can be observed for oriented fracture measurements.

Functionally, the geotechnical parameters contributing to the RMR and Q-index that will be extractable from Corescan data are: RQD, fracture spacing, fracture orientation, number of fracture sets, fracture roughness and fracture alteration. Other parameters such as UCS, groundwater conditions and SRF will need to be evaluated separately from the Corescan data. By applying an integrated geometallurgical approach, the automated extraction of geotechnical parameters from Corescan data can be achieved by developing a series of protocols applied to the Corescan data in post-processing. The proposed methodology and specific outputs are outlined here:

- automatically recognise fractures
- determine the orientation of selected fractures
- determine the fracture roughness
- filter out mechanical breaks
- enhance the current RQD calculations
- determine the number of fracture sets
- measure fracture spacing
- determine fracture condition and alteration
- methodology verification and integration.

The general process is illustrated in Figure 2. The details of each of the individual procedures are outlined in the following sections.

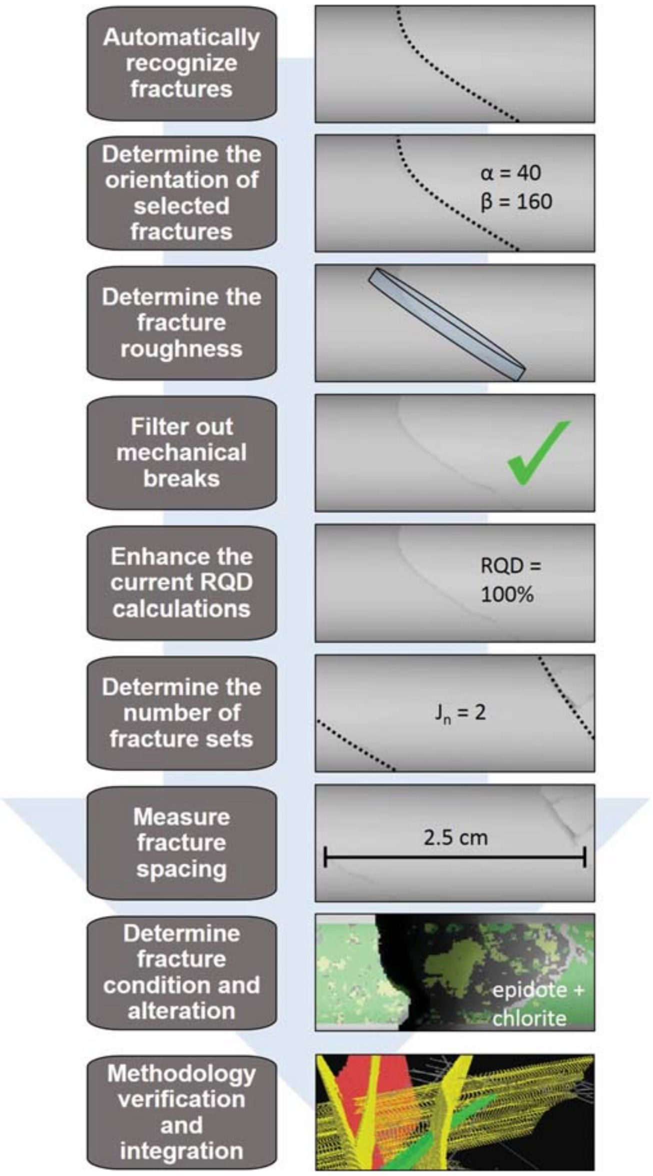

FIG 2 – The proposed methodology to automate the extraction of key geotechnical parameters required to calculate rock mass rating and Q-indices.

Automatically recognise fractures

Since the fractures in the drill core represent discontinuities in what should be a relatively consistent cylinder shape, any deviation from the typical cylinder represents a potential fracture. Using the 3D laser profiler data, slope values can be calculated across the surface of the drill core. Any abrupt changes in slope likely represent discontinuities in the core. Since the core is cylindrical and has steep slopes on the rounded edges, it will be necessary to filter changes in slope related to the cylindrical shape of the core. This can be achieved by applying derivative functions to determine the rate of change in the slope values, thus differentiating between the gradual slope changes resulting from the shape of the core and the abrupt slope changes resulting from breaks in the core. The output of this stage of the processing will be a series of individual fractures labelled by depth downhole. These features will be used in further processing steps.

Determine the orientation of selected fractures

Using 3D laser data, the orientation of the fractures can be determined by fitting a three-dimensional plane through the fracture (Quiniou *et al*, 2007; Olson, 2013). This can be accomplished by using the x, y and z pixel values along the fracture and applying a linear least squares regression to find the best-fit plane. The apparent strike and dip of the plane can then be calculated. Based on the location of the orientation line from the RGB image, the apparent orientation can then be rotated to account for the trend and plunge of the drill hole using a series of two-dimensional linear transformations. The final output of this process is a true strike and dip for each fracture previously identified (Figure 3). These orientations can then be used in the RMR calculation, as well as in future processing steps.

Determine fracture roughness

The relative roughness of a particular fracture can be measured by assuming that fractures should be planar. Since the plane fitting through the fracture was determined in the previous step, a simple calculation quantifying the deviation of the actual fracture surface in the 3D laser data from the calculated flat plane will result in an estimation of the roughness. Only the Q-index requires this parameter, and the input value for roughness when calculating the Q-index uses a qualitative system (irregular, smooth, undulating etc), so broad ranges for the assignment of roughness values should determine threshold values. The fracture roughness description can then be assigned and used in Q-index calculations.

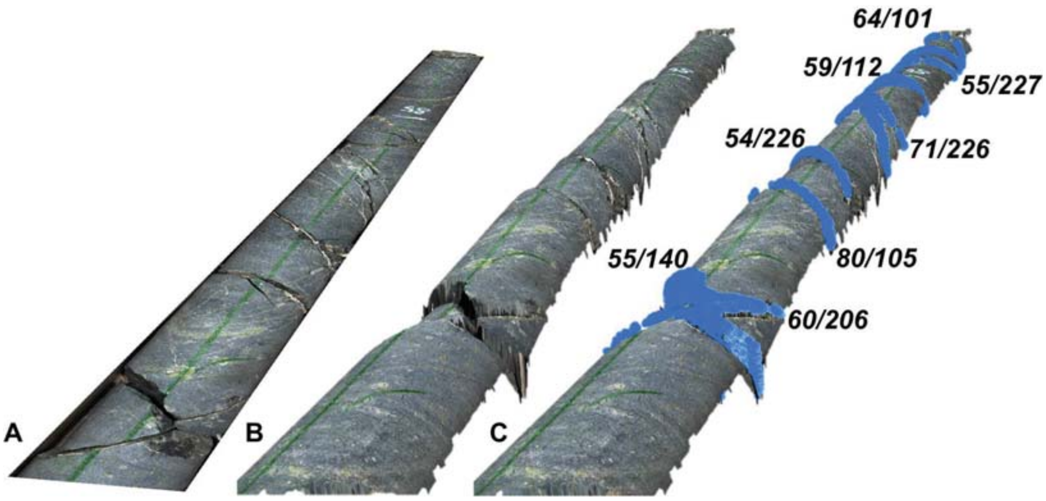

FIG 3 – (A) Two-dimensional red-green-blue (RGB) image of a 1 m interval of drill core. (B) RGB image draped over the 3D laser profile data and rotated to accentuate the fractures. (C) Calculated fracture orientation planes (blue shading) with true orientation values listed as dip/strike.

Filter out mechanical breaks

In order to exclude mechanically induced fractures, a two-step process can be applied. First, the presence of driller's marks (typically a coloured 'x') on the core from the RGB image would automatically designate the fracture as a mechanical break. Second, a set of specific rule sets applied to the 3D laser data will define the parameters for mechanical breaks based on fracture roughness and orientation. These rule sets will include expected threshold values for natural fracture roughness and expected site-specific structural orientation. Once these parameters are established, any previously identified fracture that does not meet the established criteria will be marked as a mechanical break and will be excluded from further geotechnical calculations. It is sensible at this stage to allow a geologist or geotechnical engineer to interact with the designation of each fracture and flag any fractures that have been incorrectly labelled by the automated procedures. This ensures that site knowledge and human expertise is integrated into the fracture interpretation process.

Enhance current rock quality designation calculations

RQD is a current data output from the Corescan 3D laser data, but does not discriminate between natural discontinuities (fractures) and mechanically induced breaks from the drilling process. Including these mechanical breaks greatly decreases the RQD values and falsely degrades the overall RMR and Q-index values. By filtering out the mechanical breaks before determining the RQD, the RQD calculations will be a more robust indicator of the overall rock quality. Since both the RMR and Q-index calculations require this input, these values can be used directly in the calculation of these two indices.

Determine the number of fracture sets

A comparison of the automated fracture orientation calculations over selected intervals will be used to group the data into distinct fracture sets. Since the orientation of fractures was previously determined, a statistical grouping will identify the primary fracture sets present (Figure 4). The calculated number can then be compared to the expected number of fracture sets for each geotechnical domain within the deposit (based on previous site knowledge) to determine if it is reasonable. This calculated value can then be used in the Q-index calculation.

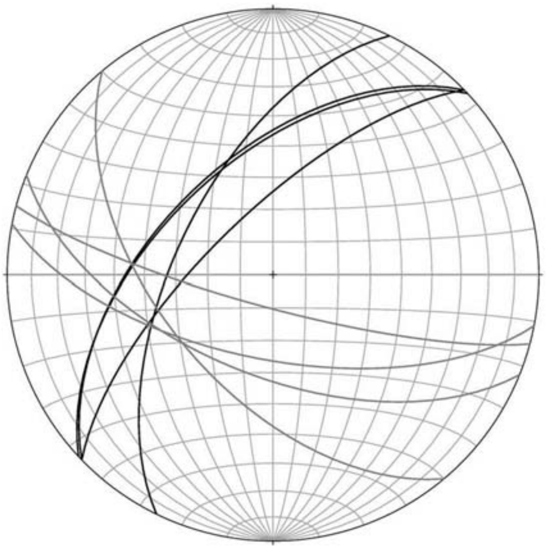

FIG 4 – Stereonet plot of calculated fracture orientations from core interval in Figure 3. Two distinct fracture sets are present: one displayed in black and one displayed in grey. Using the orientations calculated in a previous step, the individual fracture sets can be quickly identified.

Measure fracture spacing

Using the locations of the fractures, the fracture spacing can easily be calculated by determining the average distance between fractures for a given interval. This parameter is required for the calculation of RMR.

Determine fracture condition and alteration

The extraction of parameters such as fracture condition and fracture alteration will require the integration of the fracture locations extracted from the 3D laser data and the hyperspectral mineralogical data to determine the minerals present in and around the fracture. The RMR and Q-index input parameters list specific minerals in the classification schemes; however, the general grain size of these minerals is also required. Using the SWIR hyperspectral mineralogical data, the general categories for the fracture condition and alteration as they relate to the RMR and Q-index calculations can be established. By generating a series of threshold values on mineral type and abundance, the fracture condition and alteration values can be automatically calculated.

Methodology verification and integration

Once the uncut core has been scanned and processed using the Corescan system, the workflow and calculation methodology proposed here will need to be applied to a subset of data in order to calibrate threshold values (as required) and to establish the methodology on a test data set. These results will then be used to calculate RMR and Q-index values that will be compared to the current modelled values for the subset. Once each of the steps of the proposed process is verified on the subset of data, the workflow and extraction methodology can be built into the automated core logging processing software for automatic feature extraction. This process will then need to be tested again at a larger scale by comparing the RMR and Q-index values calculated through automated analysis to the modelled values from the site geotechnical model.

If the precision of the automated methodology proves to be sufficient, algorithms to calculate the partial RMR and Q-index can then be built into the software to be included as data deliverables associated with the Corescan output. The values for UCS, groundwater and SRF would need to be measured separately in order to fully calculate RMR and Q-index values. This approach can then be applied to the site-wide geotechnical database and used for detailed modelling of the key ground condition indices throughout the deposit being scanned.

CONCLUSIONS

Underground mining operations require huge data sets that constrain geotechnical indices, including RMR and Q-index, in order to estimate the ground conditions. These parameters are traditionally based on manual geotechnical logging procedures which can be time-consuming and inconsistent. By utilising the 3D laser data in conjunction with the RGB imagery and hyperspectral mineralogical data collected by Corescan, large volumes of consistent, continuous downhole geotechnical data can be automatically collected. The geotechnical parameters contributing to the RMR and Q-index that could be extracted from Corescan data are the RQD, fracture spacing, fracture orientation, number of fracture sets, fracture roughness, fracture condition and fracture alteration. Other parameters such as UCS, groundwater conditions and SRF will need to be evaluated separately, outside of the Corescan data and added to the geotechnical index calculations later. The automation of this type of data collection would allow for the consistent collection of geotechnical data, increasing both the efficiency and overall accuracy of a deposit scale geotechnical model. This novel approach to geotechnical assessment could not only provide rapid, reliable, continuous downhole geotechnical data, but could provide a key development in the approach to underground mining.

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