Classification of rock masses for dam engineering: A new system – rock condition number

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Since their development, rock mass classification systems have used and manipulated various populations of geomechanical data to allow a rock mass to be divided into different domains or engineering 'masses' with the aim of assisting in the geotechnical design of underground openings, excavations, foundations and ground support systems.

Each of these methods consider different characteristics to generate a material classification; including rock strength, joint weathering, defect spacing, in-situ stress and groundwater. However, none of these systems cater for classification of the rock mass based on whole rock weathering, whole rock strength and incipient defect spacing along a borehole.

This new classification system, the Rock Condition Number (RCN), has been developed to reduce the human factor of variability in interpretation when collecting data to classify the rock mass, as other methods, such as Rock Quality Designation (RQD), are prone to significant variability based on the experience of the person logging the core. RQD provides an indication of rock quality over the length of the cored interval, which varies depending on the drilling equipment and ground conditions. This value may typically be calculated over an interval of 1.0, 1.5 or 3.0 metres. The RQD system does not allow for the rapid identification of thin, though important features in the subsurface.

Using data captured electronically in the field, the RCN calculates an instantaneous classification of the rock mass at any point along the borehole, highlighting variations within the rock mass by assessing a combination of characteristics, allowing rapid identification of potential hazardous zones within the rock mass. This allows for significant improvements in efficiency during the assessment and design process/es. Resolution is greatly improved over RQD, with thin, though important, zones of weak material highlighted using this new process.

Comparison between existing classifications and the RCN using real field data indicates the RCN provides greater resolution when identifying deficient zones within the rock mass.

Keywords: *Rock mass characterisation, RQD, Rock Condition Number, rock quality, dam foundations.*

1. Introduction

Since the development of the first rock mass classification system, numerous classification systems have been developed to allow a rock mass to be divided into different populations to assist with the design of underground openings, excavations, foundations and ground support systems. These classification systems have used and manipulated various populations of geomechanical data to allow a rock mass to be divided into different domains or engineering 'masses' with the aim of assisting the geotechnical design.

Such systems include:

System	Developer/Contributor
• Rock Quality Designation	Deere & Deere
• Rock Mass Rating$_{76\ \&\ 89}$	Bieniawski
• Q-System	Barton
• Geological Strength Index	Marinos, Marinos & Hoek; Cai et al

Each of these systems consider different rock characteristics to generate a material classification, including: rock strength, joint weathering, defect spacing, in-situ stress and groundwater. None of these systems, however, caters for classification of the rock mass based on whole rock weathering, whole rock strength and incipient defect spacing along (for example) a borehole.

In practice, the author has found that Rock Quality Designation (RQD) can be incorrectly determined or evaluated in an inconsistent manner, due to:

- a misunderstanding (even by experienced staff) of the correct field measurement and recording method,

- measurements undertaken post–drilling or post-boxing rather than in the core barrel splits upon immediate exposure of the core,
- calculations based on core run, core lithology or whole core diameter recovery,
- calculation based on core recovery length as opposed to core run length,
- measurement of core length undertaken along the edge / margin of the core rather than the core axis, and
- inclusion of Extremely Weathered and Highly Weathered core in measurements (Bieniawski's suggestion).

Such variations introduce significant ranges in final RQD calculations, especially for investigations where more than one person is logging core. RQD is deficient with respect to the resolution of the system when applied to a borehole in that it assigns one value to a particular cored interval (e.g. 0.0 – 3.0 m: 35 %, 3.0 – 3.5 m: 90 %). Additionally, sticks of core not achieving the required 100 mm length for inclusion, may only fall short by a millimetre, thus significantly reducing the overall assessment of the quality of the rock mass, with core able to be classified as having an RQD of 0 % by this small variation when it is so close to being able to be classified as 100 %.

This newly proposed method; the Rock Condition Number; offers a consistent measurement approach across all field staff with the calculation of a Rock Condition Number (RCN) utilising defect spacing (either intact or not intact), defect interval length, rock strength and weathering. It allows for the graphical representation of important weak zones such as shear zones, alteration zones, voids, inverted weathering and others, which are commonly missed when the RQD method alone is presented on bore logs.

2. Existing classifications

There are several systems available for use to consistently classify rock masses across workers. These systems are well tested and have been utilised in industry over many decades and are appropriate for specific applications, namely tunnelling and slope excavation projects. The majority of the methods utilised in industry today rely upon the RQD as a significant input. A brief summary of the existing systems is provided below.

2.1. Rock Quality Designation

The RQD system was developed to provide a method of classification of core based on the integrity of the material recovered. RQD has allowed for the rock mass to be characterised rapidly, with graphic presentation of RQD commonly presented on bore logs to allow designers to identify potential areas of weakness by rapidly scanning a log.

The system relies on consistent application of the method, being the measurement of those sticks of core ≥ 100 mm when measured along the centre of the long axis of the core.

Through time, different workers have adapted the method to suit their application, including measurement of sticks along the edge of the core as opposed to along the centreline, or dividing the measurement into sections based on lithology as opposed to over the length of the drill run. The 'modified' method applied is seldom recorded on the geological log.

2.2. Rock Mass Rating

Bieniawski's Rock Mass Rating (RMR) systems (Bieniawski; 1976 & 1989) utilise the rock strength, rock quality designation, joint surface condition, joint spacing and groundwater as inputs to the classification, with adjustment [for tunnelling applications] made using the joint orientation.

2.3. Q-System

The Q-System, developed by Barton (1974) utilised RQD, the number of joint sets, the joint roughness, joint alteration and groundwater, in addition to a stress reduction option. Similar to the RMR systems, the Q-System was designed to assist in tunnel support selection during design and construction.

3. Geological Strength Index

The Geological Strength Index is a system first developed by Hoek (1994) and improved upon by Cai et al (2007) [amongst others], utilising block size and the joint [surface] condition factor to allow determination of this index. GSI is also able to be estimated using Bieniawski's RMR_{89} (Bieniawski, 1989) and Barton's (Barton,1974) Joint Alteration and Joint Roughness numbers. All of these methods rely on elements of the overall characteristics of the rock mass, with joint spacing (block size), joint weathering (alteration), joint roughness and RQD.

Although utilised in the estimation of the rock mass strength as part of the Hoek-Brown process, the GSI is not appropriate for use in classifying borehole data.

4. A new alternative

4.1. Why?

The majority of existing classifications systems provide useful classification of the rock mass, however it is up to the user to select the method of employment for each system. These methods may be variably applied depending on the training and experience of the user.

The RCN method attempts to remove the user variability and allows the rock mass to be 'classified' clinically and numerically, without the need for subjective measurement or interpretation.

4.2. What?

The RCN method allows for the rapid identification of weak zones that may be overlooked if applying other methods of classification. Unlike other classifications, the RCN does not rely on RQD, which may be skewed simply by the length of the core run. Additionally, it focusses on using the overall rock mass properties, as opposed to the characteristics of the defects. By applying the RCN, it allows the core [and the rock mass] to be classified, providing a graphical representation of the overall ground conditions based on the contributing characteristics of the rock mass: strength, weathering, defect spacing and defect interval; ignoring RQD.

This value is able to be utilised by designers during the engineering phase, allowing potential weak zones with potential for sliding, settlement, or poor anchor bonding, to be readily highlighted. This process provides an opportunity for more detailed testing and assessment of the rock mass prior to construction.

Additionally, the method can be 'run' on electronic datasets by field staff, allowing them to rapidly check for errors and inconsistencies in field core logging, by highlighting logging errors: e.g. high RCN in poor quality rock suggests a classification error during the logging process.

4.3. How?

The RCN system utilises four (4) inputs from the cored borehole contributing to overall rock mass condition. These values are processed using Equation 1.

Equation 1 Calculation of Rock Condition Number

$$RCN = \left[\frac{D_s}{D_i}\right] \times \left[\frac{\sigma_{ci}}{100}\right] \times \omega$$

Where: D_s = defect spacing (m),

D_i = length of defect spacing interval (m),

σ_{ci} = uniaxial compressive strength (MPa), and

ω = weathering index value.

Using common spread sheet software, the data collected in the field may be processed rapidly to provide the resultant RCN value which may then be presented in graphical form.

4.4. Defect Spacing

Defect spacing is the distance between each defect. When logging rock core, those defects that are visible in the core, be they hairline, intact, incipient, or 'broken' are recorded for engineering use. The distance between each of these defects, be they structural or bedding related, is measured and recorded. Input format: Metres.

4.5. Length of Defect Interval

The Defect Interval refers to the length of core that contains defects at a similar spacing. Defects typically cluster in zones of regular spacing. The length of the Defect Interval refers to these zones of regular spacing. An example of this spacing is provided in Table 1. Input Format: Metres.

Table 1 Example of Defect Interval based on Defect Spacing.

Borehole A:

From (m)	To (m)	Defect Spacing (m)	Defect Interval (m)	Number of Defects
0.57 m	0.65 m	0.080 m	0.08 m	1
0.65 m	0.90 m	0.005 m	0.25 m	50
0.90 m	1.15 m	0.010 m	0.25 m	25
1.15 m	1.30 m	0.037 m	0.15 m	4

To provide clarity as to the difference between the Defect Spacing and Defect Interval, and diagram is provided as Figure 1.

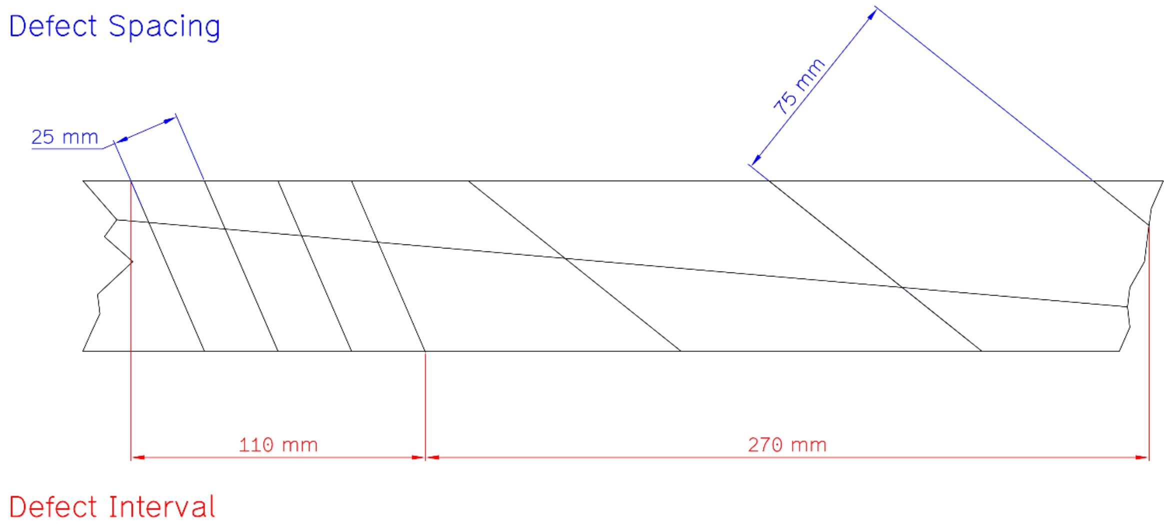

Figure 1 Schematic showing difference between Defect Spacing and Defect Interval.

As the defect spacing is measured over a much smaller interval than would be the case with RQD, bias or variation in judgement caused by the user is considered to have a much greater effect than would be the case in the application of RQD. This is due to the percentage of the overall interval being much less than the length of a core run when compared to the total length of the borehole.

4.6. Strength

The strength input is able to be directly entered by the user, based on the results of tactile field testing, point load testing (when converted) and UCS laboratory testing.

Should laboratory data be unavailable, the strength input values, based on the mean value of the range prescribed by the Australian Standard (AS1726-1993) [when converted to UCS] is provided in Table 2. Input Format: Mega Pascals.

Table 2 Strength Classification and suggested input values.

Indicator	Strength	Strength (MPa)
	Extremely Low: EL	0.700
	Extremely Low – Very Low: EL-VL	1.550
	Very Low: VL	1.550
	Very Low – Low: VL-L	3.175
	Low: L	4.800
	Low – Medium: L-M	10.200
	Medium: M	15.600
	Medium – High: M-H	31.800
	High: H	48.000
	High – Very High: H-VH	102.000
	Very High: VH	156.000
	Very High – Extremely High: VH-EH	198.000
	Extremely High: EH	240.000

Conversion to UCS

Bieniawski (1975) and Broch and Franklin (1972) suggest the relationship between Is_{50} and UCS is defined as:

$$UCS = (K)\ x\ Is_{50}$$

Where: K = 24

Look (2014) suggests K may range between 4 – 25 for weak rocks subjected to axial Point Load Testing, with the following average K values:

- Coarse grained rocks (e.g. sandstone, meta-greywacke, etc.) = 14
- Fine grained rocks (e.g. siltstone, chalk, etc.) = 12, and
- Volcanic rocks (e.g. basalt, rhyolite, etc.) = 17.

The value of K varies depending on the terrane within which the work is being undertaken, however for the purposes of this classification and field applications, this multiplier (K = 24) is considered appropriate for the RCN.

4.7. Weathering

The variability in weathering along the length of a borehole has a significant impact on rock mass quality and, unlike rock strength, there is no measurable value to input into the equation. A dimensionless number has been defined for each of the different weathering categories, including alteration, to allow the impact of weathering to be accounted for in the calculation.

These values range between 0.143 and 1.000, as detailed in Table 3. Input Format: [Dimensionless Value]

Table 3 Weathering Classification and input values.

Indicator	Weathering State	ω
	Altered: AX	0.360
	Residual Soil: RS	0.143
	Extremely Weathered: EW	0.286
	Distinctly Weathered: DW	0.429
	- Highly Weathered: HW	0.571
	- Moderately Weathered: MW	0.714
	Slightly Weathered: SW	0.857
	Fresh: FR	1.000

4.8. Missing core

Missing core is excluded from the calculation. When presented in the spreadsheet, the section lost or missing is not plotted and appears blank.

5. Range

The typical upper and lower limits for the RCN are provided in Table 4, as are the input data used to define the limits of the system.

Table 4 Typical Scale Limits: Rock Condition Number.

Input Value	Typical Lower Boundary	Typical Upper Boundary
Defect Spacing	0.001 m	1.0 m
Interval	1.0 m	1.0 m
Rock Strength	0.7 (Extremely Low)	240 (Extremely High)
Weathering	0.286 (Extremely Weathered)	1.00 (Fresh)
Common Operating Range for RCN	**2.0×10^{-6}**	**2.400**

The results of the calculation are then plotted on the sections and bore logs on a Logarithmic Scale, which allows an approximate comparison to RQD.

Using data from 4,271 intervals for which the RCN and RQD have been calculated, comparison has made between the two classification systems. As shown in Figure 2, it is noted that there is very limited correlation between RQD and RCN (Logarithmic Fit $R^2 = 0.11$, Linear Fit $R^2 = 0.15$). This suggests the two methods are resolving different horizons within the rock mass.

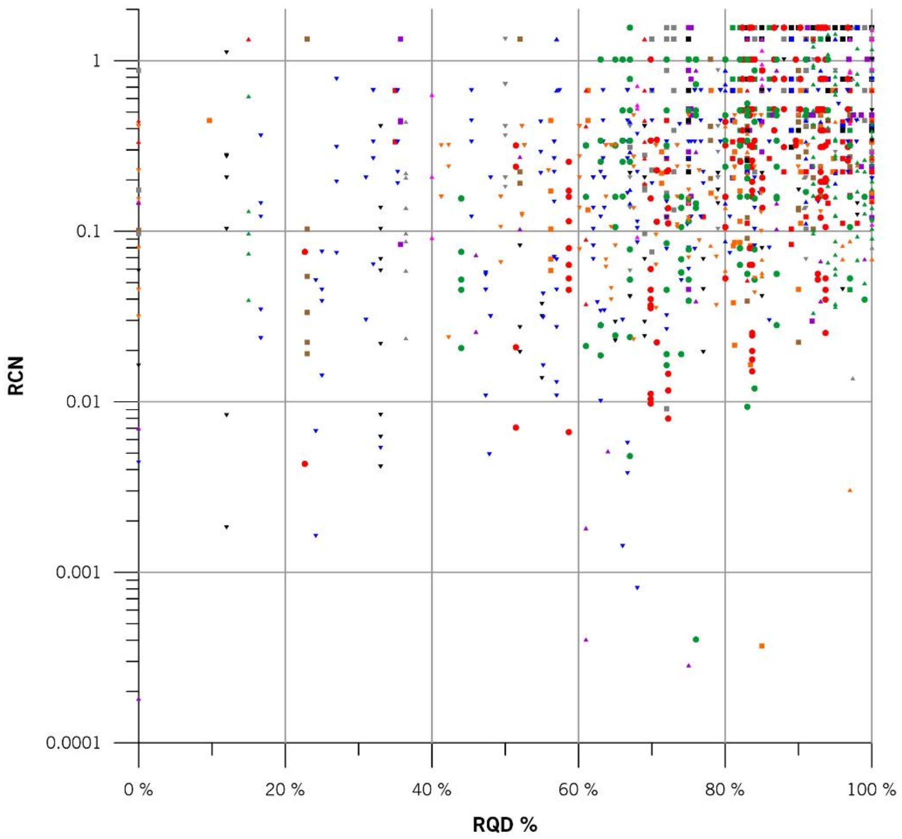

Figure 2 Plot showing relationship between RQD and RCN.

Figure 3 illustrates the variation in RCN that may be achieved by adjusting the defect spacing only. All other values are preserved.

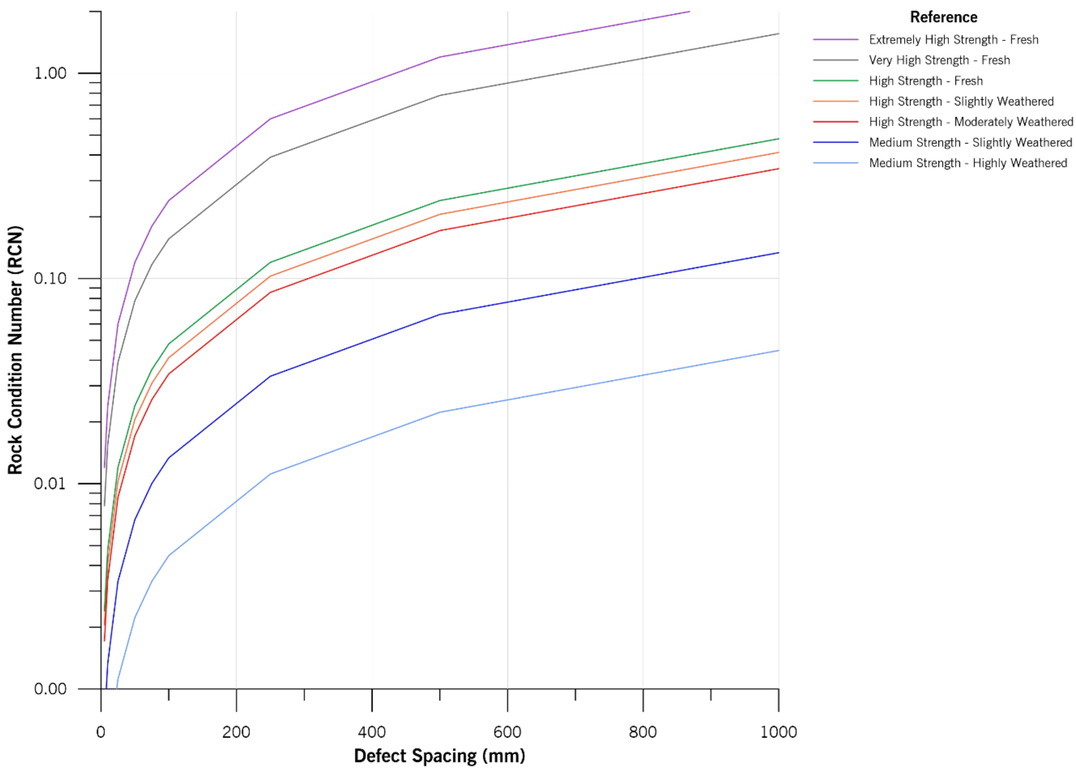

Figure 3 Comparison of rock condition number vs defect spacing

6. Data capture, processing and presentation.

Prior to the development of the RCN, Géologique developed iGloo, an electronic data collection application to capture geological and geotechnical data in the field. iGloo captures various forms of geotechnical data in a complex database allowing consistency and efficiencies to be achieved across different logging personnel whilst in the field. When exported, the data file is able to be processed within a matter of minutes through a spreadsheet to calculate the RCN along the length of the borehole. The spreadsheet uses a series of lookup scripts to apply the correct weathering and strength value to the relevant defect interval.

In practice, Golden Software's Grapher package has been successfully used to present the RCN data, although this information is also be displayed on the borelog, using Golden Software's Strater.

7. Example boreholes

To provide a comparison between traditionally collected RQD, using Deere & Deere's method, two (2) example boreholes are provided as Figure 7. For each of the holes, real field data has been utilised to calculate both the RQD and the RCN, the latter calculated using the method described herein. Both examples highlight the improved resolution available when using the RCN, allowing field staff and designers to identify risk zones rapidly.

In Hole A, for example, traditionally measured RQD (presented in red) is presented with the new method (RCN) (provided in green). If using RQD alone, it is easy to assume that the rock between 7 - 9 m is generally competent, however the RCN indicates that there is a decrease in overall quality within this zone. Similar zones also occur between 12 – 14 m and 17 – 19 m. Significant variation in overall rock mass condition is identifiable by 'assessing' weathering and strength in addition to defect spacing over each interval.

Holes B also shows the comparison between RQD and RCN, highlighting potentially poor ground conditions that may not be readily identifiable using RQD.

8. Application to dam foundations

An example of the application of the RCN is provided to illustrate the effectiveness of the system in the assessment of spillway chute foundations. A known zone of geological weakness [associated with the intrusion of a dyke] was identified during historic geological mapping of the spillway. As part of an upgrade investigation, the location of this feature required definition to assist with more focussed, feature specific, investigation of the foundation materials.

Data was captured in the field electronically using iGloo, processed and modelled in three dimensions using Golden Software's Voxler 4 software. The boreholes utilised in the modelling are shown in Figure 4 with the RCN shown by varying colour. The blue end of the spectrum represents a higher quality rock mass, whereas the red end of the spectrum suggests a lower quality rock mass.

As part of the data processing, the inclination of the boreholes required consideration, with captured data adjusted for orientation and depth to allow the model to be processed correctly. This was completed using a bespoke spreadsheet.

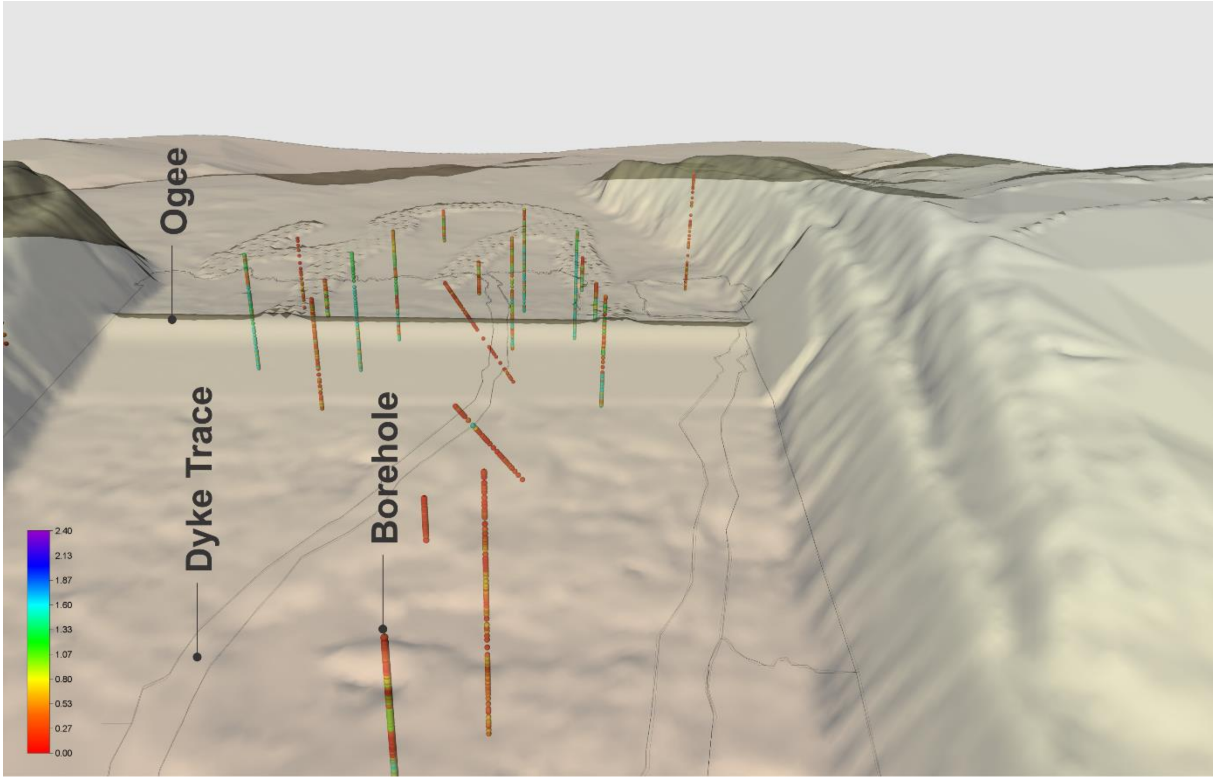

Figure 4 Location of boreholes, coloured to show RCN.

Once gridded in three dimensions using Voxler 4, the quality of the rock mass can be viewed by constructing slices through the model in any plane required. Figure 5 shows a vertical and horizontal slice through the RCN model of the chute. The rockmass within the chute is generally faulted, sheared and intruded by dykes, however upstream of the ogee, the faulting and shearing is reduced. This is reflected in the model, showing an improvement in ground conditions (i.e. the cooler colours) across the majority of the upstream section, with the exception of the intruded zone (hot colours). It is important to recognise the limitations of the gridding process. Unlike two dimensional gridding software, such as Golden Software's Surfer, the three dimensional grid is only able to be 'clipped' by way of adjusting the bounding box, rather than constraining the grid using an isosurface. As such, where no data exists, the interpolation of the grid becomes uncontrolled. This must be considered when utilising the model for foundation analysis.

In addition to 'slicing' the model, an isosurface may be applied to the model, effectively creating a cloud separating zones of RCN as being either inside or outside the surface. In this model, a surface value of 1.0 has been adopted. Figure 6 shows the higher quality material upstream of the ogee and contained within the cloud, with the exception of the intruded zone. The isosurface allows the orientation of the zone weakened by the intrusion of the dyke to be observed. This information may assist in the improved targeting of additional boreholes or other investigations to understand the intruded zone.

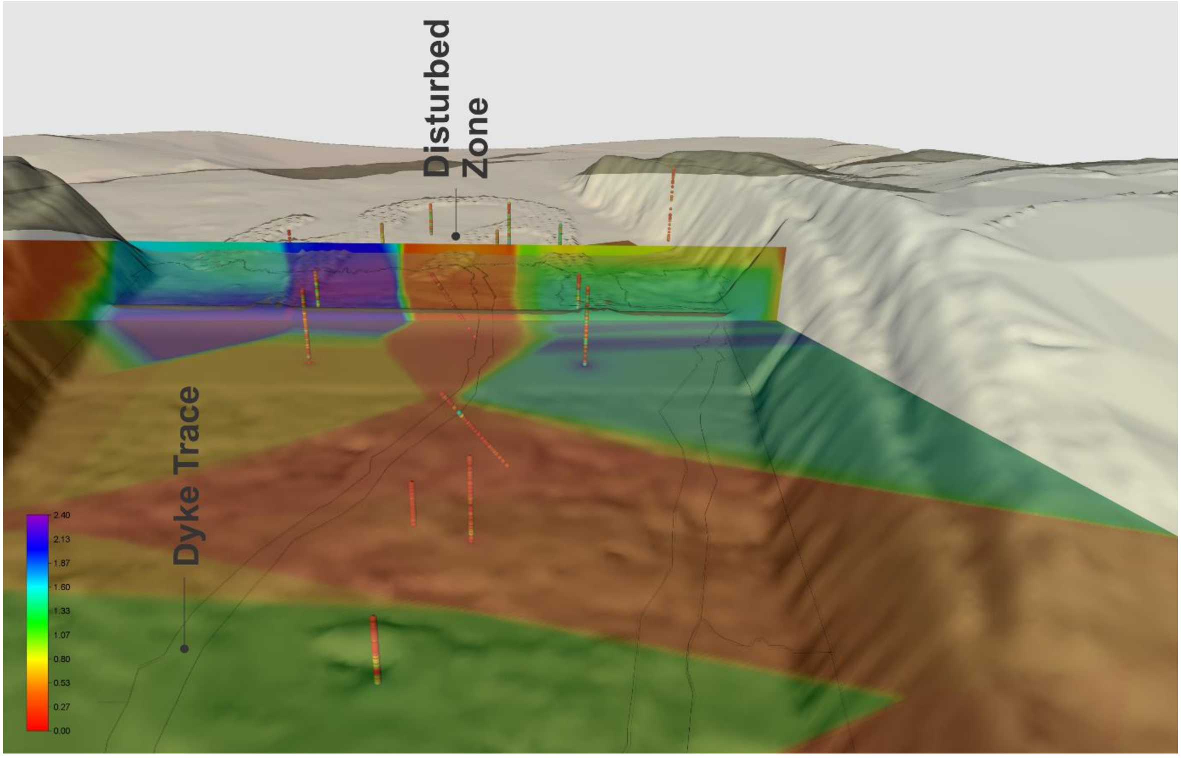

Figure 5 Sliced model showing trace of dyke and corresponding disturbed zone in vertical and horizontal slices.

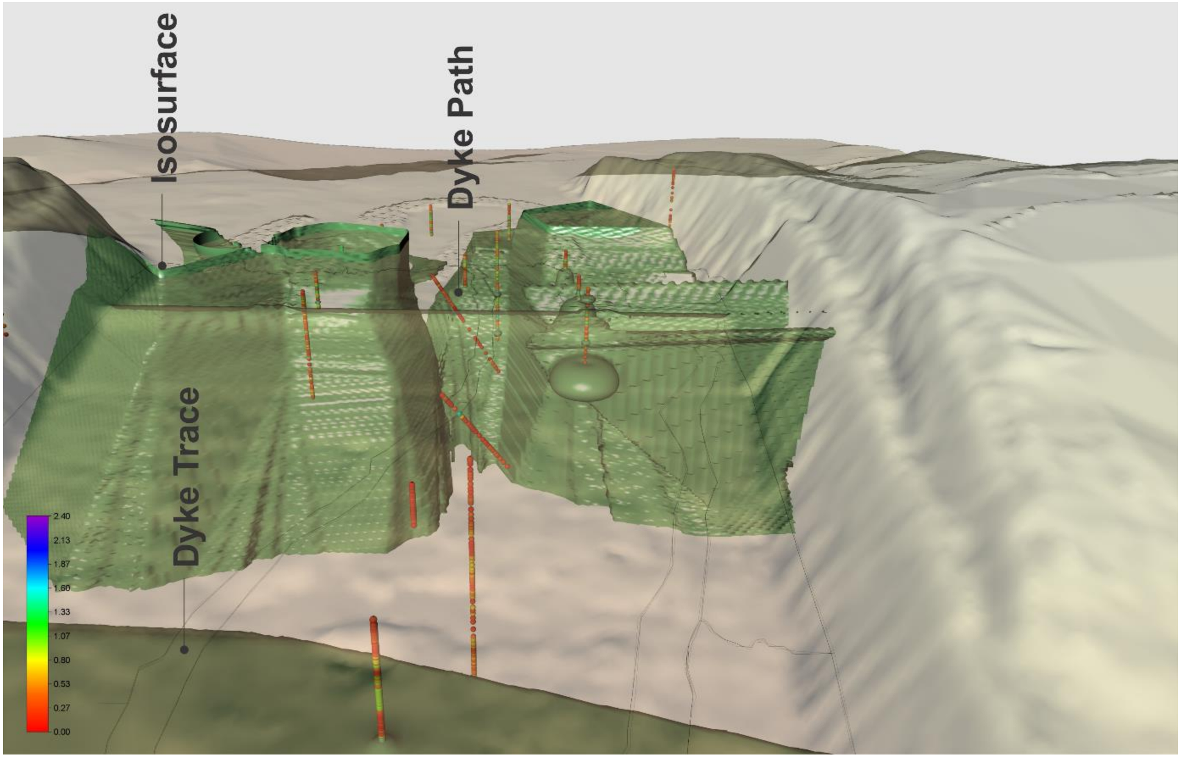

Figure 6 Isosurface model set at RCN = 1.0 showing path of dyke between higher quality rock upstream of the ogee.

9. Conclusions

Since the development of rock mass classification systems, different workers have proposed methods to classify the rock masses, with the majority of these typically relying upon the use of the joint strength and weathering characteristics and the rock quality designation.

This method allows the rock mass to be classified based on the defect spacing within each defect interval, using rock strength and weathering characteristics as opposed to those of the joints. By removing the influence of the length of the core run and including defect spacing and interval to be considered together, it allows a greater resolution of characterisation to be achieved.

This method will continue to be refined as time progresses, with incorporation into field logging systems to provide the logger a real-time indication of overall rock mass conditions.

This new process will be trialled by workers for projects and applications requiring the identification of specific ground conditions across a site.

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Figure 7 Example borehole showing comparison between RCN and RQD