

A Statistical Review of Rock Mass Classification With Some Surprising Results

Wellman, E.C. and Kemeny, J.

University of Arizona, Tucson, AZ, USA

Copyright 2024 ARMA, American Rock Mechanics Association

This paper was prepared for presentation at the 58th US Rock Mechanics/Geomechanics Symposium held in Golden, Colorado, USA, 23-26 June 2024. This paper was selected for presentation at the symposium by an ARMA Technical Program Committee based on a technical and critical review of the paper by a minimum of two technical reviewers. The material, as presented, does not necessarily reflect any position of ARMA, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper for commercial purposes without the written consent of ARMA is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 200 words; illustrations may not be copied. The abstract must acknowledge where and by whom the paper was presented.

ABSTRACT: The main classification systems that estimate rock mass properties include variants of the Rock Mass Rating (RMR) System, Rock Quality Designation (RQD), the Norwegian Tunneling Index (Q) (Barton), and the Geological Strength Index (GSI). The RMR system is based on intact strength, Rock quality designation, fracture frequency, and discontinuity condition. Typical distributions for these parameters may be approximated by normal, lognormal, or Weibull distributions and discrete distributions for fracture conditions. Water and pore pressure are sometimes included but should generally be treated as a boundary condition. RQD is a single-parameter system describing the percentage of sound rock core with a length greater than 10 cm. The Barton system has three main terms to describe a relative measure of the block size, an indicator of the inter-block shear strength, and a third quotient to describe "active stresses."

One of the primary findings of the statistical study is that two parameter systems, such as blockiness and joint condition, are better differentiators between rock mass classes; however, these systems still smear parameters. For example, a GSI range of 25-55 each indicates anything from blocky to disintegrated rock mass conditions. As a result, strength estimators based on GSI are not reliable for estimating rock mass strength and, in turn, the factor of safety. RMR and GSI results result in values on a normal distribution scaled from 0-100, typically centered on 50. The models are insufficient to describe the tail end of the distribution where rock mass failure typically occurs. The Q system significantly improves when the terms are derived independently but suffers from the same normalization issue when calculated from an RMR value.

The surprising finding is that single-parameter systems, including Fracture Frequency and Volumetric joint count, are better estimators (and differentiators) or properties across the range of rock mass conditions when looked at individually. Always understand the range of the rock mass parameters used and how that can impact the design. The paper will evaluate the need to develop strength estimators based on fracture frequency and volumetric joint count. Rock mass strength estimates should be developed from the underlying input data for classification rather than from normalized sums of multiple parameters.

1. INTRODUCTION

Rock Mass classification systems are useful and essential tools – they provide a framework for effective communication across geomechanics disciplines. Don Deere's development of the RQD in the 1960s and rapid advancement in Rock Engineering by Barton, Bienawski, and many other contributors allow discussion of commonalities and major differences in rock mass quality worldwide. They provide a common framework and language for practitioners.

More importantly, the classification system is a critical checklist if all important criteria for assessing a rock mass have been collected. Is there sufficient data about the intact strength and, more importantly, the discontinuities that control the strength of the rock mass? This paper uses the term 'discontinuity' as a general term encompassing defects, micro-cracks, fissures, joints, bedding planes, and faults adopted after Goodman (1991) and Priest and Hudson (1976).

Our Paper presents a statistical analysis of the systems and indicates potential bias by normalizing the results. Strength and rock engineering analysis approaches should be developed based on the input data and distributions from the classification systems rather than relying on the numeric results of a rock mass classification. We should develop ways to use the wealth of data collected in rock mass classification and tools to use the whole range of information in rock engineering analysis.

2. ROCK MASS CLASSIFICATION FRAMEWORK

Rock mass classification systems are essential tools in geomechanics and rock engineering. They provide a systematic approach for assessing geological and engineering material properties, including discontinuities. There are four widely recognized rock mass classification systems, including:

- Rock Quality Designation (RQD) (Deere, 1969, 1989)
- Norwegian Tunneling Index (Q) (Barton, 1974)
- Rock Mass Rating System (RMR) (Bieniawski, 1989)
- Geological Strength Index (GSI) (Marinos and Hoek, 2000)

Each system has variants and modifications adopted based on local and regional geology and mining methods used to extract ores. They each also have a set of companion engineering tools to assess rock mass strength and deformability to aid in the design of slope or underground openings.

Table 1 lists the primary inputs and factors in determining the numerical value of the rock mass classification. RMR has five primary inputs: fracture frequency (FF), RQD, Joint Condition, Joint Water, and Uniaxial Compressive Strength. The Joint Condition rating is calculated from 5 additional inputs described below in section 2.3. The Q system has three main terms to describe a relative measure of the block size,- shear strength and "active stresses." The GSI is calculated by assessing volumetric joint count or equivalent fracture spacing, which is plotted in a chart against the assessment of the joint condition. RQD is a function of fracture frequency.

Table 1. Rating System Factors

System	RMR	Q	GSI	RQD
Disc. Meas	F RQD	RQD/Jn	Joint Count	FF>10c m
Disc Rating	Joint Cond.	Jr/Ja	Joint Cond.	-
Boundary Conds.	Ground-water	Jw/SRF	-	-
Intact Strength	UCS	-	-	-

In summary, RMR has 5 main terms, Q has 3 terms, GSI has two, and RQD is a single parameter. The following sections describe the calculation of each input and resultant classification value. Please refer to the original publications for detailed instructions and methods to determine the classification. This general description and the formulas used to define the classification are here to inform the review of the statistics in section 3 of this paper.

2.1. Fracture Frequency (FF)

One of the most basic and essential measures is quantifying the number of discontinuities in a rock mass. In its simplest terms, it is described in equation 1 as the

number of fractures divided by the length of the scanline (Unit length) that the fractures are measured across.

$$FF = \frac{\# \text{ of fractures}}{\text{unit length (m)}} \quad (1)$$

The scanline should be normal to the orientation of the discontinuity. If the scanline is not normal, the values of fracture frequency can be corrected based on the apparent orientation of the discontinuity set (Hudson and Priest, 1983).

2.2. Fracture Spacing

The fracture spacing is the inverse of fracture frequency, where:

$$\text{spacing (s)} = 1/FF \quad (2)$$

2.3. Volumetric Joint Count

The volumetric joint count concept was developed to account for at least three discontinuity sets with known spacing values of S1, S2, and S3. The number of discontinuities intersecting a unit rock mass, defined as the volumetric count, will then be:

$$Jv = \frac{1}{s_1} + \frac{1}{s_2} + \frac{1}{s_3} \quad (3)$$

The definition of volumetric joint count was developed by Palmstrom (2005) to account for all discontinuities in multiple orientations for a rock mass.

2.4. Rock Quality Designation (RQD)

RQD was the first classification system based on core recovery from drilling (Deere, 1966). RQD is calculated as the percentage of intact core pieces greater than 10 cm, as shown in Equation 4.

$$RQD = \sum_{i=1}^N \frac{(\text{Sound Core pieces} > 10 \text{ cm})_i}{L = \text{Length of Core Run}} * 100 \quad (4)$$

There has been continuing debate in the industry about the utility of this measure, and some practitioners will state that it is subjective and only measures the quality of core drilling (Elmo and Stead, 2021; Heuze, 1971; Pells, 2017). This indicates that the factor was used in developing rating systems but is not a critical component. We note that the measure of RQD can also be expressed as a function of the fracture frequency shown in Equation 5 by Priest and Hudson, 1976.

$$RQD = 100e^{-0.11FF}(0.1FF + 1) \quad (5)$$

RQD is a relative indicator of the degree of fracturing, and it is probably the easiest measure to explain and quantify rock quality to a wide audience.

2.5. Rock Mass Rating (RMR)

The RMR system was originally developed in 1973 and underwent several modifications and updates. The most common and widely adopted ratings are based on the Bieniawski 1989 revision. Equation 6 has five primary components: UCS, RQD, fracture spacing, joint condition, and groundwater.

$$RMR = f_1(UCS) + f_2(RQD) + f_3(spacing) + f_4(Joint\ condition) + f_5(groundwater) \quad (6)$$

The five parameters sum to a maximum of 100. This is the only rating system that explicitly considers intact strength. Fracture frequency is included in both the RQD and spacing terms. Factors including Waviness, Persistence, Roughness, Infilling, and Weathering are all included in the Joint Condition score with a maximum of 25. Groundwater is included in this classification, even though it can be considered a boundary condition in rock engineering analysis.

2.6. Q-system (Q)

The Norwegian Tunneling Index, more commonly referred to as the Q-system, was originally developed in 1974. A major update was published in 2002. The Q system has three main quotients, as shown in Equation 5. The first term measures the block size (RQD divided by the number of joint sets), an indicator of the inter-block shear strength (Joint roughness divided by alteration), and a third quotient to describe "active stresses" where a factor for water conditions is divided by a stress reduction factor (SRF).

$$Q = \left(\frac{RQD}{J_n} \right) \left(\frac{J_r}{J_a} \right) \left(\frac{J_w}{SRF} \right) \quad (7)$$

In addition to RQD, major parameters in Q include the number of Joint sets (J_n), Joint Roughness Factor (J_r), Joint Alteration (J_a), Water Conditions (J_w), and Stress Reduction Factor (SRF). The Q-System is particularly useful for tunneling and mining projects, aiding in the design of support systems.

2.7. Geological Strength Index (GSI)

GSI was originally proposed by Hoek and Marinos in 1997. Significant contributions to quantifying the joint dimensions and structure ratings were developed by Sonmez and Ulusay 1999; two factors were developed: a surface condition rating (SCR) and a structure rating (SR) on the y-axis. The SCR is the sum of the roughness, weathering, and infill ratings. The SR is a function of the volumetric joint count, which can be related to fracture frequency. The GSI can be calculated using the chart solution in Figure 1 with these two factors.

Cai et al., 2004, also modified the GSI approach to estimating the strength of jointed and a 2007 paper to estimate the residual strength of rock masses. The Cai et al. approach is similar to Sonmez and Ulusay's, except the structure rating is explicitly defined as a block size – or joint spacing value, which can be calculated from the volumetric joint count and discontinuity set orientations. A separate Joint Condition Value J_c is used in place of the SCR. The J_c value is calculated in the system by the following relationship:

$$J_c = \frac{J_w J_s}{J_a} \quad (8)$$

where J_w is a large-scale waviness value, J_s is a small-scale smoothness, and J_a is a joint alteration factor.

Both approaches use two parameters: one for relative block size and the second for a discrete assessment of the discontinuity conditions, including surface roughness and alteration.

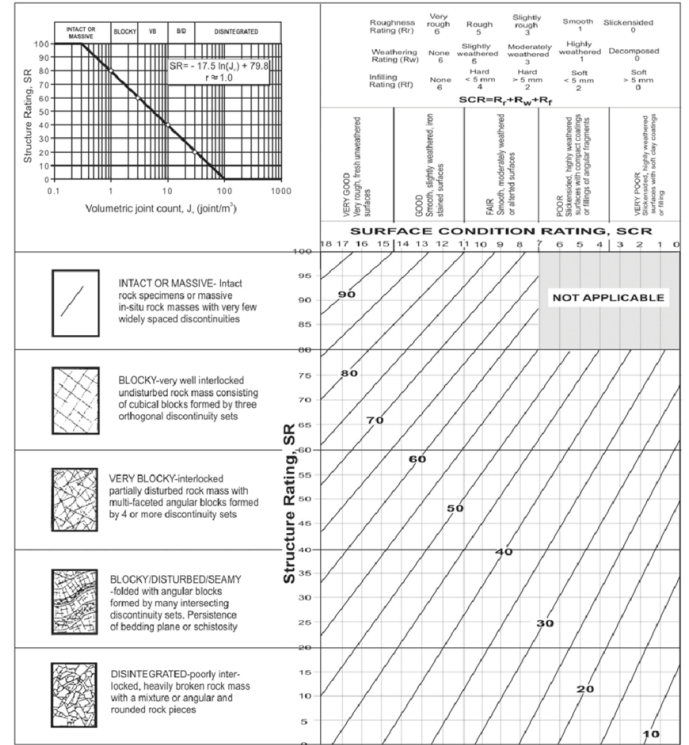


Fig 1. Geological Strength Index with structure and surface condition rating modifications (Sonmez and Ulusay, 1999).

3. STATISTICAL DISTRIBUTIONS

This section of this paper will evaluate the rock mass factors as statistical distributions. Over the last 50 years, numerous geomechanics studies have been undertaken to understand the inputs to the classifications. We will first start with parameters, including the UCS. A normal or Gaussian distribution for a similar rock sample can define that. We will then move on to fracture spacing and length characteristics that log-normal parameters or exponential statistics can estimate. We will finish the statistics with the joint conditions, which typically are descriptive terms that are quantified. In this paper, we will treat these descriptive terms as discrete distributions.

Several boundary conditions, including the influence of groundwater and stress factors, find their way into the rating systems. These are important modeling boundaries but should typically be evaluated as sensitivities in rock engineering design rather than lumped in the classification.

3.1. Unconfined Compressive Strength

The use of cylindrical samples to evaluate the UCS dates back to civil engineering research on the strength of concrete in the 1920s and 30s (Talbot and Richard, 1923; Blanks and McNamara, 1935). Cylinders were formed easily in mining rock mechanics from the 1930s to the '70s. Research focused on the strength of pillars in underground mines (Martin and Maybee, (2000). Once rock drill core was more commonly available, the cylindrical test was adopted to measure intact strength Bieniawski, (1967).

UCS is a function of grain size, and most natural rock samples have small discontinuities as part of the natural variability. Additional factors include mineral composition and porosity. As a result, in practice, the ISRM and ASTM guidelines for testing suggest minimum height-to-width ratios of 2:1, and the diameter of the sample should be a minimum of 10 times the minimum grain size. Some practitioners (Bewick et al., 2015) maintain that the UCS is not a true measure of intact rock strength due to the “defects” natural discontinuities.

Bewick et al. (2015) evaluated the statistical distribution from Franklin and Hoek (1970), Perras et al. (2012), and Amann et al. (2013) and the rock masses. Figure 2 below illustrates the normally distributed UCS results from Bewick.

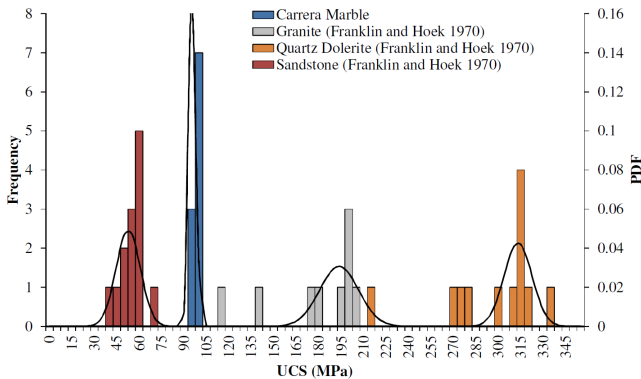


Fig. 2. Examples of Normally distributed UCS results (Bewick, 2015).

Ruffolo and Shakoor (2009). A systematic approach to estimating the right number of samples Confirmatory work of Coates and Parsons (1966), Yamaguchi(1970), and ASTM(1993). Coates and Parsons (1966) also indicate that the UCS is normally distributed and recommend testing at least 5 samples from each rock mass. ISRM (Bieniawski, 1979) suggests a minimum of 5 samples.

The authors interpret that due to the inherent variability in any rock mass, any single rock mass UCS can be modeled as a normal distribution where the mean is μ ,

and the variance is σ^2 . The probability density function (pdf) of a normal distribution is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad (9)$$

3.2. Fracture Frequency

Several studies starting in the 1970s have provided evidence to support modeling fracture frequency as a log-normal distribution. Priest and Hudson are among the key studies that evaluated these relationships in various conditions in rock quarries and the soft rock masses of channel tunnel excavations. Call, Savely, and Nicholas (1976) also independently developed this relationship from surface mapping in porphyry copper deposits in Arizona. Sen and Kazi (1984) also developed this relationship from scanline data in civil rock sites. Since 2010, Annavarapu et al. (2012) have also observed the log-normal distribution of fracture frequency at 1-2 kilometers depths in the drill core for a deep underground mine. Figure 3 illustrates the log-normal fits of the spacing data.

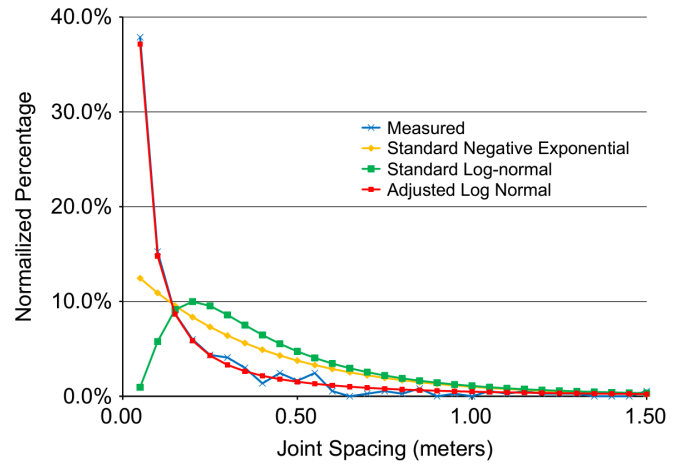


Fig. 2. Log-normal fits to spacing data Annavarapu, (2012).

There is a sufficient database of rock masses worldwide to demonstrate the log-normal distribution of fracture frequency. The probability density function (pdf) of a log-normal distribution is:

$$f(x) = \lambda e^{-\lambda x} \quad (10)$$

The derivative of fracture frequency, specifically joint spacing and volumetric joint count, can also be modeled using the log-normal distribution.

3.3. RQD

In its simplest terms, RQD is the percentage of core greater than 10 cm in any drill run. This is expressed in eq. 3. Additionally, Priest and Hudson's relationship for eq. 4 indicates that it can be linked to fracture frequency. Based on the substantial work completed, we assume that RQD can be modeled as a lognormal distribution.

3.4. Joint Condition

The qualitative assessment of joint conditions, including Waviness, Persistence, Roughness, Infilling, and Weathering, can be effectively modeled as a discrete statistical function by assigning numerical values to the conditions observed on the rock mass discontinuities. These discrete numerical values represent a quantitative scale that captures the inherent variability. Discrete variables or statistics represent distinct or separate conditions and do not necessarily represent a continuous range. The results of these data, including counts and frequencies, are much more of a qualitative value used in classification.

These discrete descriptions of joint conditions are useful in developing written classification and can also be used to develop discontinuity strength (e.g., Barton-Bandis or Patton's Law). Therefore, the five main parameters of the joint conditions represent a discrete variable.

3.5. Boundary Conditions

Boundary Condition factors such as the state of water and stress conditions get factored into RMR and Q. The range of water conditions in rock masses spans from saturated and wet conditions, characterized by high pore water pressures and potential for groundwater flow, to dry conditions with minimal or no water presence. Water is almost always treated as a potentially adverse input.

Joint Water and the Stress Reduction Factors represent discrete states in the statistical analysis. Water is included in RMR, and the ratio of Joint water to SRF is a key factor for determining Q.

3.6. Summary of Typical Distributions Used in RMR

Table 2 shows the RMR Parameter, Typical Distribution, and the minimum and maximum range in the RMR89 system.

Table 2. RMR Parameter, Distribution, and Range.

Parameter	Typical Distribution	RMR89 (Min, Max)
$f_1(UCS)$	Normal	(0,15)
$f_2(RQD)$	Lognormal	(0,20)
$f_3(spacing)$	Lognormal	(5,20)
$f_4(Joint\ condition)$	Discrete	(0,25)
$f_5(groundwater)$	Discrete	(0,15)
RMR	Normal	(5,100)

The RMR rating approach forces the lognormal and discrete variables into a normal distribution centered on 50.

3.7. Q-System

The Q system has 3 main quotients to describe the rock mass as a function of blockiness, joint condition, and stress reduction factor. The Q system significantly

improves estimates of the range of rock mass quality when the terms are derived independently. However, it suffers from the same normalization issue when it is calculated from an RMR value using the mathematical relationship established by Bieniawski, 1976 and 1989 where:

$$Q = 9\ln(RMR) + 44 \quad (11)$$

The blockiness Factor (RQD/J_n) yields a numeric value similar to the fracture frequency in the RMR system or the volumetric joint count used in the GSI. It is used as a representative factor for quantifying the intact block dimension in the Q approach.

Joint Condition Factor (J_r/J_a) estimates fracture conditions. It is a function of joint roughness and describes the typical joint alteration of the rock mass.

The stress reduction term (J_w/SRF) combines the boundary conditions of water conditions and stress from RMR. When the SRF term is omitted, the resultant Q' value is used only when evaluating rock mass. The full Q is typically calculated for ground support estimates or evaluating the stability of large openings (Barton et al., 1974)

Q values range from exceptionally poor 0.001 to strong and massive 1000. The approach typically gives a wide range of values depending on rock mass quality.

3.8. Geological Strength Index

The GSI represents a numerical index ranging from 0 to 100, where higher values indicate more competent and stable rock masses. It incorporates a fracture spacing or a volumetric joint count plotted against a structure or joint condition rating.

The volumetric joint count measures the density of fractures within the rock mass. The process involves obtaining joint measurements in three orthogonal directions and calculating the volumetric joint count as the sum of joint intersections per unit volume. It is essentially a fracture spacing or frequency term.

GSI accounts for joint conditions and evaluates the character of discontinuities on the blocks. Parameters such as joint surface conditions, roughness, and aperture are considered, and numerical values are assigned to represent the discontinuities of the overall condition.

GSI is sometimes approximated by the RMR value, lending itself to being a normalized value. Also, each numerical value has a wide range, typically over three rock mass classes. For example, a GSI range of 25-55 each indicates anything from blocky to disintegrated rock mass conditions. As a result, strength estimators based on GSI are not reliable for estimating rock mass strength and, in turn, the factor of safety.

3.9. Summary

There are three main takeaways from the review of statistics of classification inputs. The rock mass rating approach will result in normally distributed values as a function of the rating. This approach may introduce subjective bias and oversimplify the inherent variability in rock masses.

Several variables within the classification systems are descriptive and receive numerical values modeled as discrete parameters. These discrete descriptions of joint conditions are useful in developing written classification and can also be used to develop discontinuity strength (e.g., Barton-Bandis or Patton's Law). Therefore, the five main parameters of the joint conditions represent a discrete variable.

Finally, boundary conditions are incorporated into the Q and RMR classification systems. These boundary conditions can be explicitly modeled later in the rock engineering design process. Introduced early, they can also bias later results.

4. STATISTICAL ANALYSIS

The approach in the last section was subjective concerning the normal resultant distributions in Table 2. This is an inherent subjective bias of the classification process, as discussed by Elmo and Stead (2021).

Let us now evaluate the underlying distributions with a more rigorous statistical approach. The following section illustrates how the values of each of the systems can be estimated using inferential statistical methods.

4.1. Central Limit Theorem and RMR

The central limit theorem says that the sampling distribution of the mean will always be normally distributed as long as the sample size is large enough. Regardless of whether the population has a normal, lognormal, Poisson, binomial, or any other distribution, the sampling distribution of the mean will be normal (Casella and Berger, 2021).

The Central Limit Theorem (CLT) states that the sum (or average) of many independent and identically distributed random variables will be approximately normally distributed regardless of their original distribution. This is true under certain conditions, such as finite variance.

Consider the sum of one normal distribution (UCS), two log-normal distributions (RQD and FF), and 2 discrete distributions. The resulting distribution can be approximated to a normal distribution by the Central Limit Theorem.

Let f_1 , f_2 , f_3 , f_4 , and f_5 be the variables representing the UCS, RQD, FF, JC, and Groundwater, respectively. Let Y be the sum of these random variables.

$$Y = f_1 + f_2 + f_3 + f_4 + f_5 \quad (12)$$

If the distributions have a mean μ and variance σ^2 , then the mean and variance of Y can be calculated as follows:

$$\text{Mean of } Y = \mu_1 + \mu_2 + \mu_3 + \mu_4 + \mu_5 \quad (13)$$

$$\text{Variance of } Y = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2 + \sigma_5^2 \quad (14)$$

The Central Limit Theorem states that the distribution of Y will be approximately normal with the above mean and variance. The resulting PDF of the normal distribution can be expressed as:

$$f(y) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{y-\mu_Y}{\sigma_Y}\right)^2} \quad (15)$$

where y is the mean of (RMR) and μ_Y is the population mean and σ_Y is the population variance.

4.2. Statistical Evaluation of Q

Given equation 6 and that RQD follows a log-normal distribution and the remaining parameters J_n , J_r , J_a , J_w , and SRF are discrete, determining the resultant distribution of Q and PDF involves considering the properties of the individual distribution and their operations.

Given that RQD follows a log-normal distribution, and the remaining variables are discrete, the resulting distribution for Q may not follow a specific well-known distribution due to the interaction of discrete variables and a log-normal one. However, it is possible to approximate the distribution of a product of variables as log-normal when at least one of the variables is log-normally distributed, assuming independence.

The PDF for the product of the discrete variables is challenging to derive analytically. However, when considering the log-normal approximate, the PDF for Q can be expressed in terms of the log-normal distribution of RQD and the individual probability masses of the discrete variables:

$$f_Q(q) = \int_{-\infty}^{\infty} f_{RQD}(\ln x) \cdot P_{J_n}(x) \cdot P_{J_r}(x) \cdot P_{J_a}(x) \cdot P_{J_w}(x) \cdot P_{SRF}(x) \quad (16)$$

Where:

$f_{RQD}(\ln x)$ is the log-normal distribution function for RQD; and $P_{J_n}(x)$, $P_{J_r}(x)$, $P_{J_a}(x)$, $P_{J_w}(x)$, $P_{SRF}(x)$ are the probability masses for the discrete variables.

It is important to note that this is an approximation, and the accuracy depends on the characteristics and interactions of the discrete variables and the lognormal distribution of RQD. Additionally, the independence assumption among the variables is crucial for this approximation. There may be an opportunity for meta-analysis, numerical analysis, or simulation to approximate this function better.

4.3. Statistical Evaluation of GSI

To evaluate the GSI as a function of a log-normal distribution for volumetric joint count and a discrete surface condition rating (SCR), we must consider the joint distribution of the two components. Let X represent the log-normal distribution for volumetric joint count, and Y represent the SCR.

The GSI is a function of both X and Y ; we can express it as $G(X, Y)$. The distribution of GSI will depend on the joint distribution of X and Y . Given that X follows a log-normal distribution and Y is discrete, the approach may not be valid and may need empirical or simulation approaches.

The joint PDF of X and Y as $F_{X,Y}(x,y)$, the PDF of GSI, denoted as $f_G(g)$, can be expressed as:

$$f_G(g) = \int_{-\infty}^{\infty} f_{X,Y}(x,y) dx \quad (17)$$

This integral involves evaluating the possible ranges of volumetric joint count to an upper limit, and the form $F_{X,Y}(x,y)$ is a function of the joint distribution assumptions.

A data or meta-analysis may be more practical due to the nature of the joint condition rating and the discrete distributions.

4.4. Normalization example

Figure 3 shows an exponential distribution of a population of fracture spacing. One thousand fractures were simulated using an exponential distribution. The fracture spacing was estimated using a negative exponential distribution, as shown in Figure 3. This distribution was taken from the GSI Chart, ranging from 1 mm to 1.5 m. The spacing and structure ratings were then sampled in groups of 5, 10, and 20. The resultant sampled values, shown in Figure 4, show a normal distribution centered on the mean of 0.5 m, as shown in Figure 4. The standard deviation gets smaller with the higher sample values; however, the mean remains the same. -

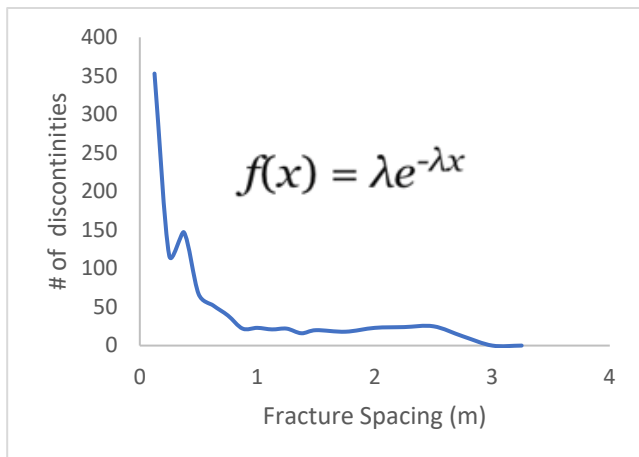


Fig. 3. Example of exponential distribution of fracture spacing.

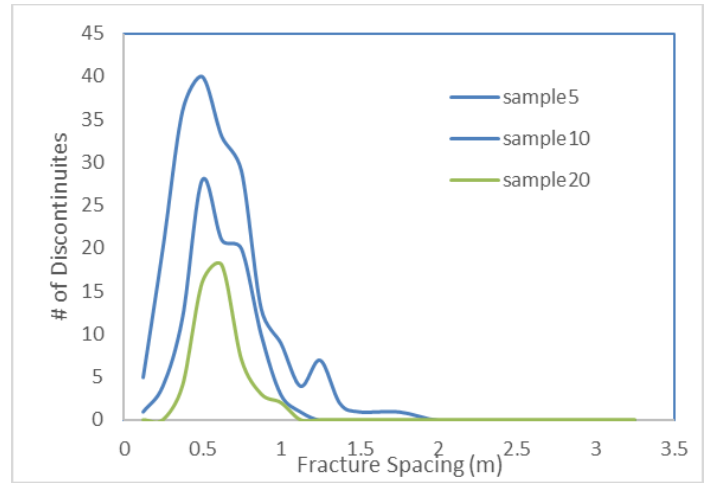


Fig. 4. Normalization based on sampling 5, 10, or 20 discontinuities.

When fracture spacing is used as a proxy for the block size or structure rating in the GSI, one parameter indicates that the structure rating in the evaluation will be normalized. When combined with a discrete description of the block, the GSI values rarely depart from the range of 50-60.

4.5. Summary of the Statistical Evaluations

A probability density function (PDF) can be developed for each rock mass classification system. Based on the Central Limit Theorem, the 5-parameter RMR system analysis, and the analysis of the GSI, the output will typically be normally distributed.

PDFs can also be developed for both Q and GSI . However, the number of discrete variables makes statistical quantification difficult, and either meta-analysis, additional empirical approaches, or simulation is recommended to understand the normalization further.

Several empirical methods use RQD as an input. RQD is valuable when your design project's critical engineering dimension is 10 cm. Measure and use a fracture spacing or fracture frequency value, where possible. The values can become normalized even in one parameter system modeled as exponential or lognormal distributions such as fracture spacing. Understand the distribution for the parameter you are modeling and how changes may impact your rock mass design. Run sensitivity analyses to the maximum and minimum or percentile cut-offs. Do not base a design on the mean or average values.

5. COMPARISON OF ROCK MASS STRENGTH APPROACHES

A full discussion and outline of rock mass strength approaches are outside the scope of this paper. However, the next logical step is understanding how classification inputs and normalization can affect the resultant rock mass strength development. We comment on how the

statistical data from rock mass classification will flow through to a rock engineering design.

In addition to the rock mass classification numeric value, The big lever arm to approximate rock mass strengths for design has been the HB Disturbance Factor (range 0-1) and the Cohesion Reduction Factor (C_{rf}) (range 0.25-0.5) in the CNI Criterion.

5.1. Hoek-Brown

The Hoek-Brown strength criterion was originally developed in 1980. Hoek-Brown has consistently overestimated strength, and adjustments have been made to reduce the envelope to match failures observed in case histories. The most notable development was the Damage or Disturbance Factor Adjustment D in the mid-1990s to account for damage due to blasting and stress changes due to excavation.

The D factor adjusts the m_b , s , and factors in the most recently adopted 2018 Hoek-Brown strength in equation 18:

$$\sigma_1 = \sigma_3 + \sigma_{ci} \left(m_b \frac{\sigma_3}{\sigma_{ci}} + s \right)^a \quad (18)$$

Practitioners commonly use an RMR (possibly adjusted by -5 as the GSI value in this relationship (Read and Stacey, 2009)). Where m_b , s , and a are the material constants as a function of the GSI, given by:

$$m_b = m_b \exp\left(\frac{GSI-100}{28-14D}\right) \quad (19)$$

$$s = \exp\left(\frac{GSI-100}{9-3D}\right) \quad (20)$$

$$a = \frac{1}{2} + \frac{1}{6} \left(e^{-GSI/15} - e^{-20/3} \right) \quad (21)$$

The latest in a series of approaches Hoek Brown 2018 (incorporating modification of prior iterations)

5.2. CNI Criterion

The Call and Nicholas Criterion (Call et al., 2001; Read and Stacey, 2009; Cylwik et al., 2022) uses RQD. They published a linear strength relationship using the cohesion and friction angle from intact rock and a linear mohr-coulomb fracture strength, and they related this to the RQD for fracture frequency. The intact and fracture strengths are combined with the following equations to estimate a rock mass strength where:

$$c_{mass} = C_{rf} [r c_{intact} + (1-r) c_{fracture}] \quad (22)$$

$$\phi_{mass} = \text{atan} [r^{2/3} \tan \phi_{intact} + (1-r^{2/3}) \tan \phi_{fracture}] \quad (23)$$

$$r = \alpha e^{\beta \cdot RQD} \quad (24)$$

r also be expressed in terms of fracture frequency, where:

$$r = \alpha e^{(3-0.15\lambda^{0.85})} \quad (25)$$

Table 3 lists the empirical factors used to adjust the rock mass strength as a function of the RQD of the rock mass Call (2001); Read and Stacey (2009). They have been modified based on additional research by Cylwik et al., (2022)

Table 3. CNI Criterion CRF empirical rock adjustment factors.

	α	β
2009 (RQD>50-60)	0.225	0.3
2009 (RQD 40-50)	0.475	0.007
2022	0.05	0.026

5.3. Closure

Reasonable rock mass strength tools are available; they must be detached from a normalized “rock mass” characterization or rating value. The authors recommend sensitivity analysis using distributions of all the inputs for analyzing rock mass strength rather than just the mean rock mass rating.

6. CONCLUSIONS AND RECOMMENDATIONS

Rock Mass classification systems are useful and essential tools – they provide a framework for effective communication across geomechanics disciplines. They provide a common framework and language for practitioners. They also are a useful checklist to ensure pertinent data is collected.

RMR results in values on a normal distribution scaled from 0 to 100, typically centered on 50. The RMR rating approach forces the lognormal and discrete variables into a normal distribution. The Central Limit Theorem states that the distribution of RMR will be approximately normal.

Q should be developed independently. If calculated using common relationships (eq Eq. 9), it will be normalized and less useful than if derived from the procedure outlined by Barton.

Statistical analysis PDFs can also be developed for both Q and GSI. However, the number of discrete variables makes statistical quantification difficult, and either meta-analysis, additional empirical approaches, or simulation requires additional analysis.

The surprising finding is that single-parameter systems, including RQD, Fracture Frequency, and Volumetric joint count, are better estimators (and differentiators) of properties across the range of rock mass conditions. It is critical to understand the full range of the parameters and their modeled distribution. These parameters and their full distribution should be stored, recorded, and used in forward rock engineering analyses. What is most critical is understanding how variation in these parameters can

influence the rock mass properties used in design analysis. Understanding the design impacts is critical.

Rock mass strength estimates should be developed from the underlying input data for classification rather than from normalized sums of multiple parameters. Based on these distributions, our path forward should involve approaches to using model inputs across the range of conditions.

7. PATH FORWARD

Rock Mass Model Development - Prioritize the advancement of rock mass model development by emphasizing domain modeling techniques. Focus on capturing rock mass behavior by recording full distributions of key parameters such as intact strength, fracture frequency, and joint conditions.

In the course of the literature review for this paper – research by Snow – not explicitly listed previously, but in the late 1960s and 70s, developed a novel approach for assessing rock mass parameters by looking at flow and permeability through fractured rock masses. This interdisciplinary approach, along with the recent advancements in subsurface geophysics and monitoring, has the potential to be used better to identify the damage zones around large rock slopes.

One of the biggest challenges in mining is the change in stress and rock mass conditions due to mass mining activities. A basic research goal is to monitor the actual change of rock mass input parameters over time and mining development. Measuring and monitoring the changes to fracture spacing, density, and characteristics over time would help develop empirical strength criteria for mining projects.

8. ACKNOWLEDGEMENTS

We gratefully acknowledge Kray Luxbacher, the head of the University of Arizona's Department of Mining and Geological Engineering, for support of this research project.

REFERENCES

1. Amann, F., Ündül, Ö., and Kaiser, P. K. (2014). Crack initiation and crack propagation in heterogeneous sulfate-rich clay rocks. *Rock mechanics and rock engineering*, 47, 1849-1865.
2. Annavarapu, S., Kemeny, J., and Dessureault, S. (2012). Joint spacing distributions from oriented core data. *International Journal of Rock Mechanics and Mining Sciences*, 52, 40-45.
3. Barton, N., Lien, R., and Lunde, J. J. R. M. (1974). Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics*, 6, 189-236.
4. Barton, N., 2002. Some new Q-value correlations to assist in site characterization and tunnel design. *Int. J. Rock Mech. Min. Sci.* Nr. 39, 185–216.
5. Bewick, Robert P., et al. "Interpretation of UCS test results for engineering design." *ISRM Congress*. ISRM, 2015.
6. Bieniawski, Z. T. (1967). Mechanism of brittle fracture of rock: part I—theory of the fracture process. In *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts* (Vol. 4, No. 4, pp. 395-406). Pergamon.
7. Bieniawski, Z. T. (1989). *Engineering rock mass classifications: a complete manual for engineers and geologists in mining, civil, and petroleum engineering*. John Wiley and Sons.
8. Blanks, R. F., and McNamara, C. C. (1935, January). Mass concrete tests in large cylinders. In *Journal Proceedings* (Vol. 31, No. 1, pp. 280-303).
9. Cai, M., Kaiser, P. K., Uno, H., Tasaka, Y., and Minami, M. (2004). Estimating rock mass deformation modulus and strength of jointed hard rock masses using the GSI system. *International Journal of Rock Mechanics and Mining Sciences*, 41(1), 3-19.
10. Cai, M., Kaiser, P. K., Tasaka, Y., and Minami, M. (2007). Determination of residual strength parameters of jointed rock masses using the GSI system. *International Journal of Rock Mechanics and Mining Sciences*, 44(2), 247-265.
11. Call, R. D., Cicchini, P. F., Ryan, T. M., and Barkley, R. C. (2000). Managing and analyzing overall pit slopes. *Slope stability in surface mining*, 39-46.
12. Call, R. D., Savely, J. P., and Nicholas, D. E. (1976, August). Estimation of joint set characteristics from surface mapping data. In *ARMA US Rock Mechanics/Geomechanics Symposium* (pp. ARMA-76). ARMA.
13. Casella, G., and Berger, R. L. (2021). *Statistical inference*. Cengage Learning.
14. Coates, D. F., and Parsons, R. C. (1966, July). Experimental criteria for classification of rock substances. In *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts* (Vol. 3, No. 3, pp. 181-189). Pergamon.
15. Cylwik, S. D., Killian, J. R., and Cicchini, P. F. A practical strength criterion for rock masses based on quantitative input parameters. *Proceedings, Slope Stability 2022*, Tucson, AZ.
16. Casella, G., and Berger, R. L. (2021). *Statistical inference*. Cengage Learning.
17. Deere, D. U., and Miller, R. P. (1966). Engineering classification and index properties for intact rock (pp. 6-10). Springfield, VA, USA: National Technical Information Service.
18. Deere, D. U., Merritt, A. H., and Coon, R. F. (1969). Engineering classification of in-situ rock (Vol. 67). Montgomery County, OH, USA: Air Force Weapons Laboratory, Air Force Systems Command, Kirtland Air Force Base.
19. Deere, D. U., and Deere, D. W. (1989). Rock quality designation (RQD) after twenty years (No. 89). US Army Engineer Waterways Experiment Station.
20. Elmo, D., and Stead, D. (2021). The role of behavioural factors and cognitive biases in rock engineering. *Rock Mechanics and Rock Engineering*, 54, 2109-2128.

21. Franklin, J.A., Hoek, E. (1970) Developments in triaxial testing equipment. *Rock Mech.* 2, 223-228.
22. Goodman, R. E. (1991). *Introduction to rock mechanics*. John Wiley and Sons.
23. Heuzé, F. (1971, July). Sources of errors in rock mechanics field measurements, and related solutions. In *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts* (Vol. 8, No. 4, pp. 297-310). Pergamon.
24. Hoek, E., Brown, E.T. (2019). The Hoek–Brown failure criterion and GSI–2018 edition. *J Rock Mech Geotech Eng.* 2019; 11(3): 445- 463.
25. Hudson, J. A., and Priest, S. D. (1983, April). Discontinuity frequency in rock masses. In *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts* (Vol. 20, No. 2, pp. 73-89). Pergamon.
26. Marinos, P., and Hoek, E. (2000, November). GSI: a geologically friendly tool for rock mass strength estimation. In *ISRM international symposium* (pp. ISRM-IS). ISRM.
27. Martin, C. D., and Maybee, W. G. (2000). The strength of hard-rock pillars. *International Journal of Rock Mechanics and Mining Sciences*, 37(8), 1239-1246.
28. Palmstrom, A. (2005). Measurements of and correlations between block size and rock quality designation (RQD). *Tunnelling and Underground Space Technology*, 20(4), 362-377.
29. Pells, P. J., Bieniawski, Z. T., Hencher, S. R., and Pells, S. E. (2017). Rock quality designation (RQD): time to rest in peace. *Canadian Geotechnical Journal*, 54(6), 825-834.
30. Perras, M. A., Diederichs, M. S., and Amann, F. (2012, June). Fracture initiation and propagation in the Quintner Limestone. In *ARMA US Rock Mechanics/Geomechanics Symposium* (pp. ARMA-2012). ARMA.
31. Priest, S. D., and Hudson, J. A. (1976, May). Discontinuity spacings in rock. In *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts* (Vol. 13, No. 5, pp. 135-148). Pergamon.
32. Read, J., and Stacey, P. (2009). *Guidelines for open pit slope design*. CSIRO, Australia.
33. Ruffolo, R. M., and Shakoor, A. (2009). Variability of unconfined compressive strength in relation to number of test samples. *Engineering Geology*, 108(1-2), 16-23.
34. Sonmez, H., and Ulusay, R. (1999). Modifications to the geological strength index (GSI) and their applicability to stability of slopes. *International Journal of Rock Mechanics and Mining Sciences*, 36(6), 743-760.
35. Sen, Z., and Kazi, A. (1984, August). Discontinuity spacing and RQD estimates from finite length scanlines. In *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts* (Vol. 21, No. 4, pp. 203-212). Pergamon.
36. Snow, D. T. (1970, January). The frequency and apertures of fractures in rock. In *International journal of Rock mechanics and Mining sciences and Geomechanics Abstracts* (Vol. 7, No. 1, pp. 23-40). Pergamon.
36. Talbot, A. N., and Richart, F. E. (1923). *The strength of concrete, its relation to the cement aggregates and water*. University of Illinois. Engineering Experiment Station. Bulletin; no. 137.