Statistical Analysis of the Q-system in Different Tunnelling Conditions

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ABSTRACT

Understanding of the quality of a rock mass is essential in determining the expected mode of failure and the support requirement for tunnel and cavern designs. The Q-system quantifies the quality of a rock mass, but due to the complex and varied mechanisms related to ground structure interaction, a single value is unlikely to classify the variety in a rock mass correctly. Statistical methods can account for uncertainty to select the suitable design value for Q instead of a deterministic value, based on estimated Q input parameters. In this study, the Monte Carlo simulation (MCS) method is used to apply statistical analysis to the Q-system. The paper describes the basis and methodology, in conjunction with a case study, to present the use of MCS analysis, of the Q-system, to associate a quantitative level of risk with determining ground support needs for tunnel and cavern excavations.

RÉSUMÉ

La compréhension de la qualité d'une masse rocheuse est essentielle pour déterminer le mode de rupture prévu et les exigences de soutien pour la conception des tunnels et des cavernes. Le système Q quantifie la qualité d'une masse rocheuse, mais en raison des mécanismes complexes et variés liés à l’interaction de la structure du roches, il est peu probable qu'une seule valeur puisse classer correctement la variété dans une masse rocheuse. Les méthodes statistiques peuvent tenir compte de l'incertitude pour choisir la valeur de calcul appropriée pour Q au lieu d'une valeur déterministe, en fonction des paramètres d'entrée Q estimés. Dans cette étude, la méthode de simulation de Monte Carlo (MCS) est utilisée pour appliquer l'analyse statistique au système qualité. Le document décrit la base et la méthodologie, en conjonction avec une étude de cas, pour présenter l'utilisation de l'analyse MCS, du système Q, afin d'associer un niveau quantitatif de risque à la détermination des besoins d'appui au sol pour les excavations en tunnel et en caverne.

1. INTRODUCTION

In tunnel and cavern design, identifying the quality of a rock mass is essential to both determining the dominant mode of failure and adequate ground support to manage it. Empirical classification systems present a quantifiable representation of the rock mass which recommends ground support measures; however, is it advisable to place a single value that classifies the quality of an entire rock mass? Multiple conservative estimations of input parameters to determine rock quality can lead to redundancy, and overestimation of support requirements.

Two of the most widely used empirical classification systems are the Rock Mass Quality Index (Q) (Barton et al. 1974) and Rock Mass Rating (RMR) (Bieniawski, 1989). The Q-system considers multiple parameters, such as joint characteristics and stress regime, to classify the overall quality of a rock mass and provide ground support recommendations. A single Q input parameter, such as joint roughness (J_r), does not wholly define an entire rock mass, but it can significantly affect the overall rating. The Q-system relies on visual observation, instead of an analytical calculation or numerical modelling, which introduces greater potential for human error to affect the estimation. Complex and varied mechanisms related to ground interaction make considering a single value for a Q parameter impractical and can lead to over, or under, evaluation of Q. If a design is believed to be conservative, to decrease the quantity of rock support provides no accurate measurement of its effectiveness. Facilitating the planning process of ground support with statistical analysis reduces the potential to under, or over, estimate the quality of the rock mass.

Ground support recommendations, for Q, are directly correlated to the performance of historical case data, and the majority of the existing data for the Q-system are tunnels from the Scandinavia region. Different conditions can significantly affect the performance of ground support, which can be problematic, leading to the question of how conservative a designer should be (Potvin, 2015). Palmstrom and Broch (2006) performed a detailed review of the limitations of the Q-system, and one major takeaway was that the classification system was most accurate in moderately fractured rock. Specific scenarios can see a substantial alteration in the support installed to recommendations by the Q-system, such as Hawkesbury Sandstone, where Q recommended substantially lower support than what was adopted at five specific sites (Pells, 2002). Overall, empirical analysis is reliant on the capabilities of the investigator. Statistical methods can provide an alternative which can enhance the classification system by allowing a quantifiable level of risk to be estimated instead of relying on judgement alone.

In this paper, the idea of statistical analysis methods to facilitate the planning process of ground support will be discussed. Monte Carlo Simulation (MCS), considering all measured Q input parameters as independent variables, was implemented to develop probability (PDF) and cumulative distribution function (CDF) curves of Q, creating an intuitive method for determining the rock mass quality. A case study on the Norwegian Underground

Olympic Stadium (NUOS) demonstrates the process, illustrating how a designer can use the statistical curves. Through this method, the raw measured data provides a means to allocate an acceptable level of risk when determining support requirements for underground excavations.

2. REVIEW OF THE Q-SYSTEM

The Q rating consists of three terms which provide a generalisation of the block interaction and stress condition for tunnelling projects (NGI, 2015), measuring the:

- Block Size (RQD/J_n)
- Joint Condition (J_r/J_a)
- Effective Stress (J_w/SRF)

By calculating the product of the three subgroups, the six rock parameters produce a single value that represents the overall quality of the rock mass as seen in the equation below.

$$Q = (RQD/J_n) * (J_r/J_a) * (J_w/SRF) \qquad (1)$$

2.1 Block Size (RQD/J_n)

The quotient of the Rock Quality Designation (RQD) and the joint number (J_n) represents the relative size of the blocks in the rock mass. Understanding the size of the blocks, corresponding to the excavation span, provides insight into the potential failure modes and effects the type of ground support required.

RQD provides a rough estimate of the frequency of jointing occurring in a rock mass, but it is also important to understand whether these joints are random or have a general spatial trend. J_n is a measurement of the number of occurrences where joints trend in a similar orientation, with systematic spacing, yet if a very large spacing exists between the joints they should be considered random. The values for block size can range by a magnitude of 400, with the potential for a massive rock mass to be measured as high as 100/0.5 or as low as 10/20 for crushed rock (Palmstrom and Brock, 2006).

2.2 Joint Condition (J_r /J_a)

The size of the blocks provides a fundamental understanding of the expected mode of failure, but one must also understand the condition of the joint's surface, which affects block interaction. The surface structure (e.g. joint aperture, roughness, wall strength and infilling material) has a significant effect on the frictional interaction and overall, the shear strength between joint contacts. Reducing shear movement along the joints, due to increased friction, improves the compression arch in the block network, and overall stability of an excavation. Based on this, joints with rock-wall contact and a light coating of material on the surface of the discontinuity improve the quality with a joint condition value as high as 4/0.75, while joints with no contact and thick bands of clay can have a joint condition of 1/20.

2.3 Effective Stress (J_w/SRF)

The block size and condition play a significant role in determining the potential mode of failure; however, the stability of an excavation is directly related to the effective stress acting on the rock mass. Block network and stress conditions provide a framework to estimate the potential mode of failure that exists in a rock mass (Martin et al. 1999). The existence of high and low-stress conditions in connection with pore pressure can have a positive or negative effect on stability, making it impossible to allocate inter-block effective stress (Hoek, 2004); on the other hand, a general estimation of the stress condition can be made.

The inflow of water has two significant effects on the stability of a rock mass, (1) inflow can reduce the normal stress by pushing the joints apart, and (2) removal of infill material which provides frictional resistance. On the other hand, SRF is a relative measure between the stresses acting on the rock mass and the rock strength (NGI, 2015). The stress condition is classified into one of four categories, weak zones, competent rock with stress issues, squeezing rock and swelling rock. In cases, such as competent rock and squeezing rock, the uniaxial compressive strength (σ_c) and the major principle stress (σ_1) or the maximum tangential stress (σ_{max}), provide a framework to estimate the SRF. For weak zones, visual evaluation of the size and frequency of problematic zones provides a means to quantify the effects on the overall rock quality, while swelling rock considers the magnitude of the reaction related to the addition of water within the rock structure.

2.4 Support Recommendation Chart

By comparing the Q to the Equivalent Dimension (D_e), Figure 1 illustrates how a designer can recommend bolt spacing, bolt length and shotcrete for a specific tunnel or cavern. The D_e is the quotient of the span or height of the excavation, in meters, and the Excavation Support Ratio (ESR), a generalised safety factor which accounts for the longevity/importance of the excavation.

3. STATISTICAL VARIABILITY AND DESIGN CONSIDERATIONS FOR THE Q-SYSTEM

The support recommendation chart is based on historical case history data to predict the most suitable ground support. As new data is collected, a more accurate estimation for ground support exists, although inherent variability is present, since an individual can estimate the quality of a rock mass differently than another. Because of this, understanding the standard deviation (SD), and distribution of the data is crucial since a larger SD indicates a substantially higher spread of potential outcomes.

The general trend of the data plays a significant role in any statistical analysis. While a normal distribution is a symmetrical shape, where the vast majority of data lies within two SD, this is not the case for all statistical distributions. Any distribution has the potential to have extreme data points, which can cause an abnormally large SD, raising the question: should the probability of exceedance be considered?

3.1 Variability of Q Parameters

The significant factors that determine the quality of the rock mass are the product of the block size and joint condition, known as Q'. Effective stress, due to the effects of pore pressure, is an essential factor to consider, but it can be challenging to define, and often is regarded as a constant value.

The presence of an aquifer or surface water over specific spans in a longer reach of a tunnel can cause variability in the groundwater condition, although J_w is generally a constant value. Similarly, in most cases for the SRF, unless the rock type drastically changes or water causes swelling, the reduction value is kept constant. At the same time, anisotropic stress conditions present the potential for variability to exist in the maximum tangential stress which is directly related to the orientation of the excavation and the principle stresses, which have been seen to typically follow a normal distribution (Kaiser and Maloney, 2005).

3.2 Monte Carlo Simulation (MCS)

MCS has been implemented in numerous engineering disciplines, presenting a useful approach to analyse distributions with random data inputs. When the statistical data and its distribution of input values are known, and the random variables have a direct relation to the solution, MCS is a viable option.

The geotechnical assessment of a particular site provides valuable statistical data which can be used in conjunction with the mathematical software MATLAB[1] to develop PDF and CDF curves. Each Q input parameter has an absolute lower limit (LL) and upper limit (UL) that cannot be exceeded; therefore, all random variables are truncated to the values in Table 1, dependent on the existing conditions for the rock mass in question. Truncating the data has the potential to distort the PDF of each Q parameter somewhat; however, to ensure that the LL and UL were not exceeded this was considered valid until alternative methods can be applied.

4. EXAMPLE APPLICATION OF METHOD

Field data from the Norway Underground Olympic Stadium (NUOS) was used to demonstrate the statistical design method for the Q-system. The NUOS is a vast cavern, with a span of 64 m; therefore, all data is experienced on the extremities of the recommendation chart (Bhasin et al. 1993). Instead of directly analysing the existing excavation a theoretical excavation of a 10 m wide roadway, ESR = 1, was considered instead of the actual dimensions of the stadium. An excavation of this size will see the simulated PDF of Q occur in a more central location of the support recommendation chart, providing a better illustration of the statistical analysis of the Q-system.

4.1 Location and Geotechnical Investigation

The NUOS is located in Gjovik city, 25 km south of Lillehammer, Norway. Nearby caverns and access tunnels in the hillsides were investigated as they were expected to have the same geology, and mapping was performed on the Precambrian gneiss. The frequency of jointing in the Precambrian gneiss was determined to have large variability (Bhasin et al. 1993). Overall, the initial investigation determined the rock mass would have lower quality, and the high horizontal stress of 3.5 – 4 MPa at a shallow depth of 45 m presented the potential for stability issues.

Table 1. Lower and upper limits for Q-system rock parameters

Q Parameter	Cat.	Description	LL	UL
RQD	-	-	10	100
J_n	-	-	0.5	20
J_r	a	Rock-wall contact (no mineral fillings, only coatings)	0.5	4
	b	Rock-wall contact before 10 cm shear (thin mineral fillings)	0.5	4
	c	No rock-wall contact when sheared (thick mineral fillings)	1	1
J_a	a	Rock-wall contact (no mineral fillings, only coatings)	0.75	4
	b	Rock-wall contact before 10 cm shear (thin mineral fillings)	4	12
	c	No rock-wall contact when sheared (thick mineral fillings)	6	20
J_w	-		0.05	1
SRF	a	Weak zones	2.5	10
	b	Competent rock with stress issues	0.5	400
	c	Squeezing Rock	5	20
	d	Swelling Rock	5	15

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[1] https://www.mathworks.com

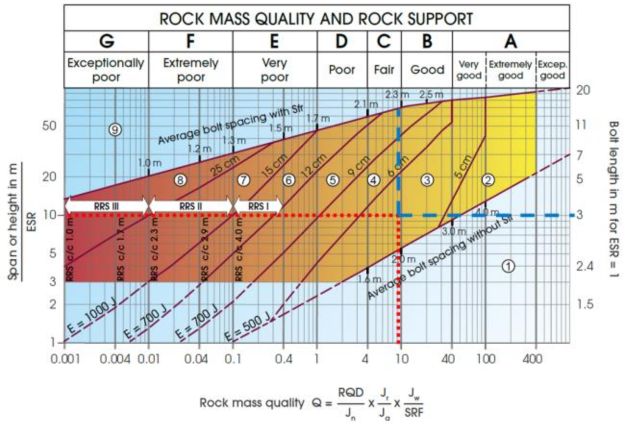


Figure 1. Q-system Support Recommendation Chart with an example, the dotted line is measured values and dashed shows recommended support (revised from NGI, 2015)

4.2 Statistical Data Collection

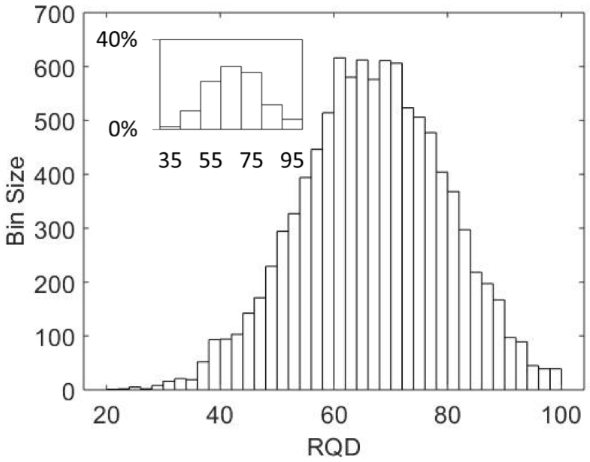
Based on the geotechnical investigation, histograms of the measured data were developed to estimate the Q for the rock mass. The original geotechnical study analysed the extreme low and high values, plus the weighted average for Q, determining the rock mass had a range of 1.1, 9.4 and 30. These values were based on differing block sizes and joint condition; however, the effective stress was considered to be constant with a value of 1. Before implementing MCS the statistical μ and SD for each parameter were calculated from the field data, presented in Table 2.

Table 2. Statistical parameters determined from measured data during the geotechnical investigation of NUOS

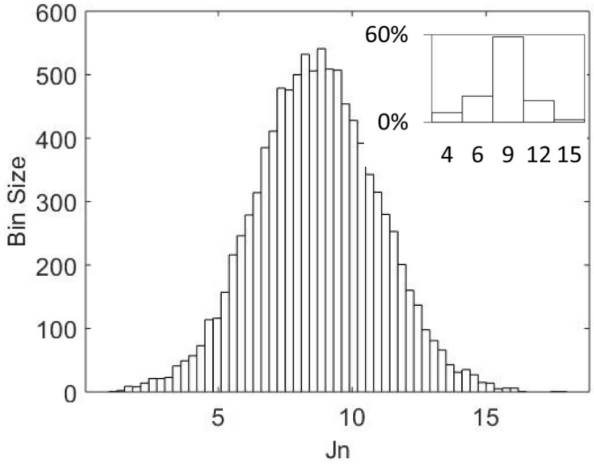
Q Parameter	μ	SD	LL	UL
RQD	67.0	13.2	10	100
J_n	8.7	2.3	0.5	20
J_r	2.3	0.6	0.5	4
J_a	1.9	1.4	0.75	4

4.3 Monte Carlo Simulation Analysis

The statistical distribution of all rock parameters was considered to be normally distributed, and histograms were simulated with the program MATLAB. The input parameters for the MCS can be seen in Table 2, which include the μ and SD from the measured data for each Q input parameter, and LL and UL determined to be in category (a) for the J_r and J_a based on the statistical data. Due to the effective stress being considered a constant value of 1, histograms of the RQD, J_n, J_r and J_a were only developed. Figures 2 and 3 illustrate these simulations, and it can be seen all parameters, except J_r, match almost identically with the measured field data. While the idea of J_r being normally distributed has validity to it, there is the potential for any parameter not to have a perfectly normal distribution and be skewed.



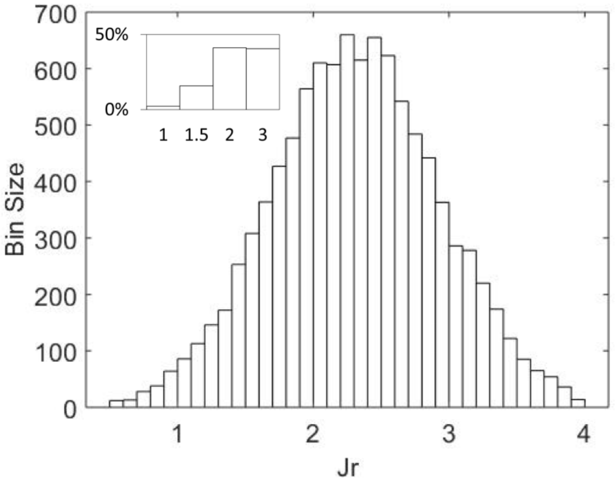
a) Distribution of Measured and Simulated RQD



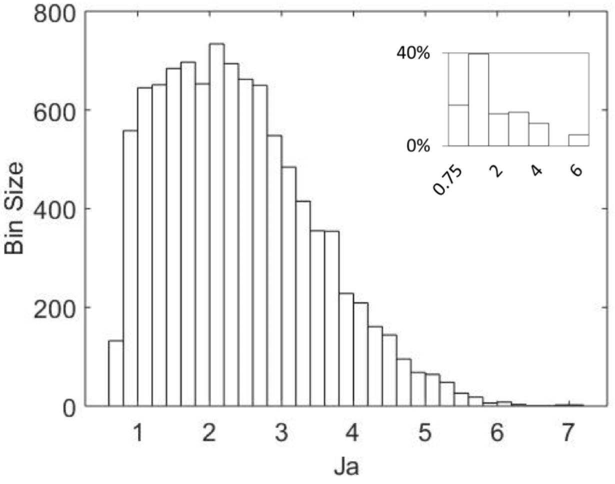
b) Distribution of Measured and Simulated J_n

Figure 2. Distribution of block size parameters using MCS compared to actual measured data (inset figures).

In the MCS, 10,000 iterations were performed with MATLAB to develop the PDF and CDF curves illustrated in Figure 4. An “if” statement was developed to determine UL and LL, considering a single type of rock contact and SRF for the simulation. With the limits set, the “makedist”, “truncate” and “random” commands were implemented, creating an individual value for each Q input parameter in a single iteration. The “makedist” function set the shape of the distribution, e.g. normal, log-normal, etc., while “truncate” ensures no data is generated outside the UL and LL. Based on the shape of the distribution, considering the μ, SD, UL and LL, the “random” command will generate a value for each Q input parameter. In cases where the data generated is outside the UL and LL, the iteration repeats until all conditions are met, which can slightly distort the PDF of a specific Q input parameter. Truncating the data raises the question of whether the simulation causes slight deviation from the intended distribution; however, the number of data points that have the potential to exist outside the UL and LL are negligible compared to the sample size and do not affect the validity of the analysis. At the end of each iteration, Q is calculated with equation 1, overall producing 10,000 Q data points based on the statistical data from each input parameter. For design purposes, the PDF can be compared to either the mean Q (Q_μ) or plus/minus one SD denoted as the lower bound (Q_{LB}) and upper bound (Q_{UB}). Additionally, using the CDF, an acceptable level of risk can be applied as a design parameter.



a) Distribution of Measured and Simulated J_r



b) Distribution of Measured and Simulated J_a

Figure 3. Distribution of joint conditions parameters using Monte Carlo simulation compared to actual measured data (inset figures)

Overall, Figure 4 provides useful insight into the classification of the quality of the rock mass, but the primary reason for the study is to relate this statistical analysis to recommendations for ground support directly. Figure 5 illustrates the PDF and CDF curves superimposed on top of the recommendation chart to allow for statistical analysis to be implemented to determine ground support requirements for an excavation. Based on the simulation a Q_μ was found to be 10, and the Q_{LB} was 2.5. Both statistical points suggest a bolt length of 3 m; in contrast the significant difference is related to spacing and shotcrete requirements, where a change was experienced for the shotcrete requirements from zone 3 (5-6 cm fibre reinforced shotcrete) to zone 4 (6-9 cm fibre reinforced shotcrete) and a decrease in bolt spacing of 0.3 m.

D_e has a significant effect on the shotcrete requirements, and if the 10 m tunnel were increased to a 20 m cavern the range from the μ_Q to Q_{LB} would increase drastically, ranging from zone 3 to zone 5 (which is 9-12 cm of shotcrete). The Q_μ and Q_{LB} provide a reasonable estimate for a practical Q; however, comparing the probability of exceedance is another option which could be better due to the fact in many cases the SD of the distribution is quite large compared to the Q_μ.

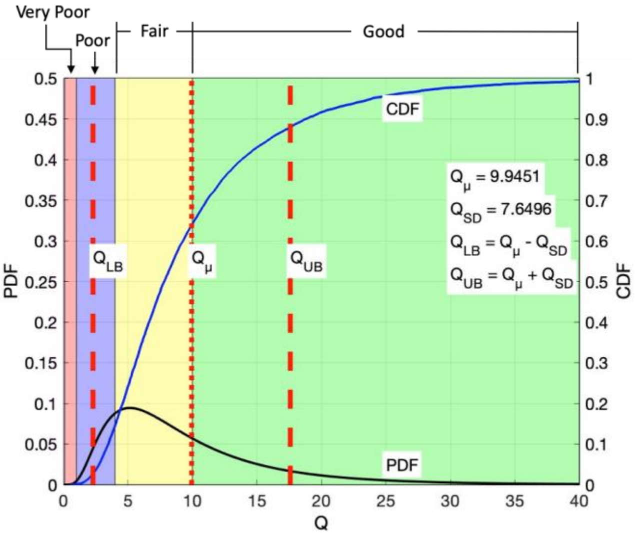


Figure 4. PDF and CDF of Q compared to statistical values Q_μ, Q_{LB} and Q_{UB}, plus the shade rock classification zones

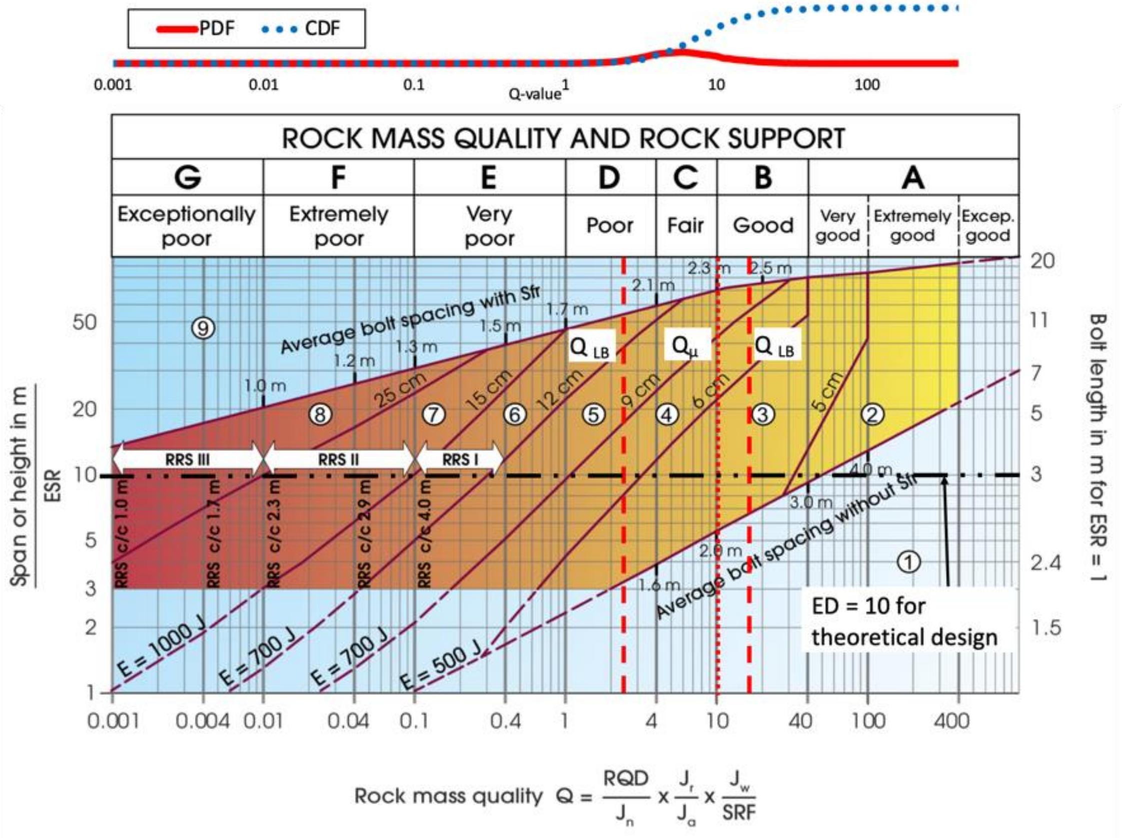


Figure 5. Support recommendation chart for Q with the MCS superimposed on top (revision of NGI, 2015).

5. FUTURE DISCUSSION

The results of MCS are only as reliable as the input parameters, and as shown in Figure 3a, it may not always be normally distributed. Different types of distributions for each Q parameter should be considered to ensure a close match with the measured field data. Further, by forcing all Q parameters to lie within the LL and UL the PDFs can be somewhat distorted, putting into question the validity of the simulation. Instead, placing the data in log-normal space, to ensure no negative values exist, and running the simulation may be a better option.

The Q-system works best in the moderately jointed rock mass, and time-dependent failure such as squeezing or swelling can be challenging to predict ground support measures. Instead, comparing the magnitude of potential tunnel deformation to the estimated Q value, and support recommendation could be beneficial. By correlating tunnel deformation and the Q, support recommendations can be compared to bolt and shotcrete response through numerical modelling to determine if the suggested ground support has the capabilities to manage the expected tunnel deformation.

6. CONCLUSION

Deterministic methods place a significant emphasis on the abilities of the engineer to accurately estimate Q as a single value that defines the entire rock mass. Alternatively, by considering the variability in each Q input parameter, a statistical design approach provides the ability to analyse all likely rock conditions.

This paper illustrated the use of statistical analysis on the Q-system to design ground support for tunnels and caverns. The Q was calculated using MCS with the program MATLAB to develop PDF and CDF curves. The method was applied to a jointed rock mass at the NUOS, considering the geotechnical data with a theoretical tunnel design. Before Q was calculated histograms of each Q parameters were developed with MCS, and it was found the simulated data almost perfectly matched the shape of the measured data, except J_r, validating the assumptions, but presenting the idea of considering different distributions for each specific Q parameters. Figure 5 illustrated by superimposing the PDF and CDF curves on the support recommendation chart substantially difference in support requirements are suggested considering the $Q_μ$ and Q_{LB}. A difference in bolt spacing of 0.3 m and 1-3 cm thicker shotcrete for the $Q_μ$ and Q_{LB} of a 10 m roadway tunnel was determined, while a 20 m cavern saw an increase of 4-7 cm of shotcrete, in the NUOS rock mass.

Instead of merely making an assumption all Q input parameters are a single estimated value, the $Q_μ$ and Q_{LB} considered the dispersion Q. A designer can now review all potential rock conditions and the likelihood that best suits the project in question, to make a sound judgement for the ground support design. The tool provides a new approach to improve an existing system potentially. While this may be correct, empirical methods are based on the judgement of the geologist or engineer, and experience of the individual will be a driving factor to determine how risk-averse the project will be.

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