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A quantitative approach to predict tunnel overbreak based on the Q-system

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A quantitative approach to predict tunnel overbreak based on the Q-system

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Abstract. Overbreak can be a significant challenge in tunnelling and is usually assessed on a project-by-project basis. This paper attempts to quantify tunnel overbreak in jointed rock masses by producing a predictive model that practitioners can utilize at the preliminary design stage. Discontinuum numerical analysis of a circular-shaped tunnel is performed using the combined finite difference – discrete element method to generate a database of rock masses prone to overbreak. The Q-system, rock mass quality index, is used to classify the rock masses that are expected to overbreak in various tunnelling environments. The results are scrutinized to identify trends between overbreak and: i) Q, ii) average joint spacing and, iii) in-situ stress conditions. It is observed that overbreak increases when $Q \leq 4$ and is uniform when $Q > 4$. A predictive model is generated through multiple regression analysis and can be used to identify and highlight the maximum likely overbreak or scenarios where overbreak is expected to occur.

1. Introduction

The need to understand and quantify overbreak in tunnels and underground excavations is of significant importance to engineering projects. Overbreak has been seen to pose a substantial problem during the excavation of hard rock tunnels and caverns, leading to unsound designs at the preliminary stages of the design primarily due to the heightened likelihood of cost overruns, increased construction times, reduced safety and stability, and poorer performance [1]. Hence, it is becoming increasingly important to quantify the overbreak expected during the construction of an underground excavation to account for this during design. Although there have been numerous studies considering the formation, causes, and effects of tunnel overbreak, there has yet to be much significant focus on the relationship between overbreak and a commonly used and relatively simple classification system, such as the Q-system.

Understanding the rock mass behaviour is particularly important in tunnel design to confirm that the parameters that define the rock and the discontinuities are appropriate while ensuring sufficient support requirements. A rock mass behaviour is typically described by the behaviour of the intact rock and the discontinuities. Geological descriptions describing the rock mass behaviour are commonly qualitative; however, for design and support, quantitative data must be input into numerical models.

Nevertheless, although it is possible to predict and describe rock mass behaviour, geological uncertainty is significant in tunnelling projects. The sub-surface nature of underground excavations means that ground conditions, including the geological and geotechnical parameters, may remain unknown until the point of excavation. Hence, rock mass behaviour is often required to be predicted based upon knowledge and experience to make sensible assumptions and interpretations. To manage this, empirical classification systems are commonly implemented to assess the ground conditions and apply appropriate support measures quickly.

The overall aim of this research is to quantify the overbreak expected when excavating a tunnel using numerical analysis methods while utilising the Q-system to define and classify the quality of rock masses. Thus, this work aims to quantitatively understand the effect of rock mass quality on the overbreak of various stress conditions.

2. Background

2.1. Rock Tunnelling Quality Index

Rock mass classification systems aim to describe rock masses using parameters obtained through field and lab investigations. These classification systems are typically based upon empirical relationships of rock mass parameters with data from real-world case studies, ranking the rock mass's quality on a specified scale or within quality classes (groups). They also provide quantitative data and guidelines on support requirements. Unfortunately, due to their simplicity, these systems are often misused and applied in rock masses or environments they are not designed for, leading to false conclusions and design errors. In this research work, the Q-system [2] is used to capture all the critical parameters that can describe the rock's overall quality and behaviour and the discontinuities.

The Rock Tunnelling Quality Index (Q-system), developed by [2], was initially based on 200 case studies, consisting primarily of Scandinavian drill and blast tunnels, with 24 metamorphic, 13 igneous, and 9 sedimentary examples. It was updated in 1994 when a further 1,050 case studies were added and were expanded again in 2013, with approximately 900 supplementary case studies.

The Q-system is based on six parameters: the RQD, the number of joint sets (Jn), the joint roughness number (defined as the degree of roughness along the joints) (Jr), the joint alteration number (defined as the degree of alteration or filling along the joints) (Ja), the joint water reduction number (defined as the water inflow) (Jw), and the Stress Reduction Factor (defined as the ratio of rock stress to rock strength) (SRF). The parameters defining Q were chosen partly due to the ease with which they can be recovered from field observations apart from SRF, which is harder to determine. The Q-value is calculated using Equation (1), where RQD/Jn is a measure of the block size and considers the overall structure of the rock mass, Jr/Ja considers the inter-block shear strength and Jw/SRF is a measure of the active stresses. The final Q-value may range from exceptionally poor to exceptionally good rock, with nine categories available to describe the rock mass quality.

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \tag{1}$$

The Q-value is plotted against the ratio of the tunnel span or wall height and the Excavation Support Ratio (ESR), considering the excavation method, in order to provide guidelines for support requirements. In general, the Q-system should not be used in soft ground tunnelling conditions as it applies to jointed rock masses; however, there are some exceptions to this rule, which are beyond the scope of this paper.

2.2. Tunnel Overbreak

Tunnels and caverns in hard rock environments can exhibit overbreak. Overbreak can result from any excavation method adopted, and it is observed that many studies are focused on investigating the overbreak and excavation induced-damage on tunnelling scenarios where the drill & blast method has been employed, and it is often related when investigating deep underground openings for nuclear waste storage. However, understanding excavation induced damage is important to avoid cost over-runs due to additional support requirements, increased construction times, and unsafe excavations or excavations with poor performance (due to reduced stand-up times). Quantifying excavation-induced damage can also allow for optimisation towards a more economical design to be developed before construction.

The Excavation Damage Zone (EDZ) is considered to be any damage that takes place around an underground excavation. EDZ can be categorized into three main sub-zones: i) Highly Damaged Zone (HDZ), the damaged zone or inner EDZi; and iii) the disturbed or outer EDZo. Beyond the EDZ is the Excavation Influence Zone (EIZ). This paper focuses on the HDZ, where overbreak can occur. This is the zone that has been excavated beyond the original design line [3], and where blocks and slabs are separated from the rock mass.

According to [4] besides poor excavation practice (i.e. blasting quality), geological and geotechnical factors can be also critical, leading to an overbreak development; for example, the intact rock strength, the in-situ conditions, depth, jointing (orientation, spacing etc.). [3] examined the damage distance in drill & blast tunnels in various rock masses rated with the Q-system. They found that when Q<4, the damage increases significantly. Such studies consider the blasting parameters that have often been found to be more significant than the rock mass quality. Consequently, there has been little focus on overbreak arising through other excavation sequences, where the impact of rock mass quality may be more significant, for instance in the case of a TBM excavation or an excellent quality controlled blasting with minimal or no disturbance in the surrounding rock mass.

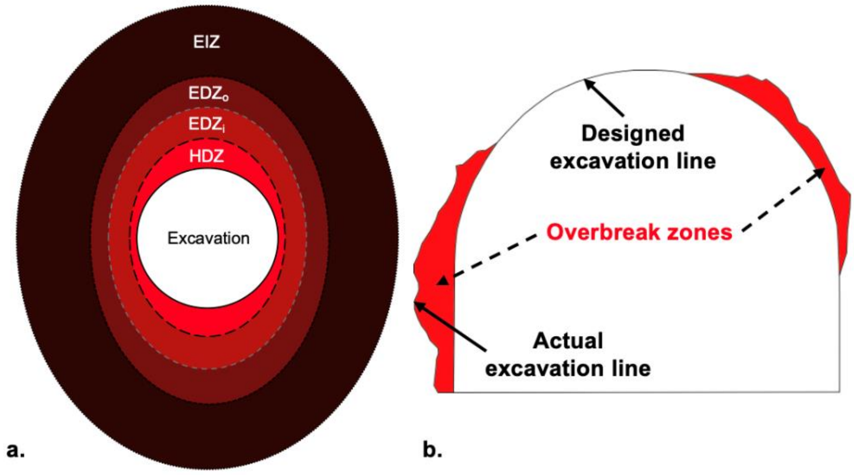

Figure 1. a. Excavation Damage Zones and b. Overbreak around tunnel.

Structurally-driven failure was considered by [5] who found that overbreak arises primarily due to joint set structure and joint roughness. Hence, when correlating overbreak with Q, the most important parameters are J_n and J_r, with overbreak expected to occur when $J_n/J_r \geq 6$ [5]. Although this is one condition expected to result in overbreak, overbreak may be achieved without meeting this criterion, in the case of slabbing or bursting.

In terms of stress-driven failures which may result in overbreak, there have been numerous attempts to estimate the depths of EDZs and develop criteria defining the stress threshold for overbreak.
This was further developed by [6] who estimated that under high stress, brittle failure (i.e. spalling) and overbreak occur when the ratio of the maximum tangential stress to the uniaxial compressive strength (σ_{max}/σ_c) exceeds 0.4. [7] show that failure initiates as extension strain induces when the stress/strength ratio is higher than 0.4UCS ≈ σ_t/v (σ_t – tensile strength, v – Poisson's ratio).

3. Numerical Analysis

A two-dimensional (2D) discontinuum analysis is performed in this work. Eight main cases are built and modelled, representing different rock mass and stress conditions. The combined discrete element - finite difference method is used and implemented using the commercial code, UDEC. This allows for the accurate modelling of jointed rock masses.

Mohr-Coulomb failure criteria is utilised in this analysis. The Mohr-Coulomb criterion represents the blocks or intact rock, and the is also applied to the joints. It should be highlighted that it is suggested that the Barton-Bandis criterion for the joints accounts for the non-linear shear behaviour through

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asperity roughness and strength (i.e. JRC and JCS, respectively) should be also considered. However, this is beyond the scope of this paper and the equivalent Mohr-Coulomb jointing model, which is only appropriate for smooth and non-dilatant joints is used herein. Nevertheless, this research considers yield primarily occurring through the joints; the failure criterion used to define the intact rock should not be as significant as that used to define the joints, provided that the joints yield prior to the intact rock (which is expected). Table 2 shows the geotechnical parameters used as input in the numerical analysis.

Table 1. Q parameters values for the 8 cases investigated.

Reference	[8]					[9]		
	Case 1 (Limestone)	Case 2 (Sandstone)	Case 3 (Diorite)	Case 4 (Amphibolite)	Case 5 (Sandstone)	Case 6	Case 7	Case 8
RQD	55	70	90	55	40	100	90	60
J_n	9	12	12	6	15	2	9	12
J_r	2	1.5	1.5	1.5	1	2	1	1.5
J_a	2	3	1	4	3	1	1	2
J_w	1	1	1	1	1*	1	1	1**
SRF	5	2.5	10	3	0.5	1	1	1
Q	1.22	1.17	1.13	1.15	1.78†	100	10	3.75††
S_a **(m)**	0.3	2.22	2.3	0.25	0.4	0.73	0.44	0.2
K-ratio	1	1.5	2	1.7	0.75	0.43	0.43	0.43
Overbreak expected? $J_n/J_r \geq 6$	No	Yes	Yes	No	Yes	No	Yes	Yes

* J_w for Case 5 altered from 0.7 to 1 so that all excavations are modelled as dry.

† Q for Case 5 not representative of an "equivalent material" and not consistent with Case 1 – 4 as altered J_w.

** J_w for Case 8 altered from 0.66 to 1 so all excavations are modelled as dry.

†† Q for Case 8 differs from [9] data due to alteration in J_w.

An 8m diameter circular tunnel is considered in this analysis with full-face excavation. The extent of overbreak (R) is normalised to the radius (r) to account for the scale effect of the excavation on overbreak, measured from the centre of the excavation as shown in figure 2 and expressed as a percentage increase.

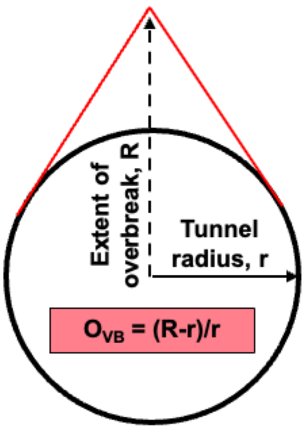

Figure 2. Geometrical characteristics to quantify overbreak O_{VB}=(R-r)/r, R-Extent of overbreak and r-tunnel radius.

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Table 2. Geotechnical parameters used in the numerical analysis for the 8 cases.

Parameters	Case 1	Case 2	Case 3 [8]	Case 4	Case 5	Case 6	Case 7 [9]	Case 8
Material Properties								
γ (MN/m^3)	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027
Poisson's Ratio, v	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Young's Mod., E (GPa)	41.3	52.5	40.6	78.8	20.6	52.44	41.94	33.23
Stress Conditions								
K-Ratio	1	1.5	2	1.7	0.75	0.43	0.43	0.43
σ_H (MPa)	19	7.5	35	10	6	5.79	5.79	5.79
σ_V (MPa)	19	5	70	16	8	13.5	13.5	13.5
Intact Rock Parameters								
σ_{ci} (MPa)	75	75	125	175	75	100	100	50
σ_{Ti} (MPa)	5.36	3.79	5.12	7	3.79	4.91	4.91	3.3
Bulk Mod., K_i (GPa)	29.92	46.18	56	61.94	35.75	43.7	34.95	27.69
Shear Mod., G_i (GPa)	22.44	21.32	25.84	28.59	16.5	20.17	16.13	12.78
Joint Conditions								
No. Joint Sets	3	3	3	2	4	1	3	3
φr (^{o})	30	25	35	12	25	30	30	30
k_n (GPa/m)	36.4	4.9	5.58	57.5	28.8	556	102	80.5
k_s (GPa/m)	15.2	1.89	2.15	22.1	11.1	214	39.1	30.9
c (MPa)	0.917	1.75	0.938	5.35	4	50	10	2.5
φ (^{o})	45	26.6	56.3	20.6	18.4	63.4	45	36.9
Conditions for Overbreak met?								
$J_n/J_r \geq 6$	No	Yes	Yes	No	Yes	No	Yes	Yes

3.1. Model Setup

Figure 4 shows the model with excavation located in the centre. For each model examined, the boundary conditions are defined by fixed velocity boundaries and three regions with different mesh densities define the mesh setup. The coarsest mesh defines the region furthest from the excavation. The subsequent region has a reduced coarseness and the region closest to the excavation having the tightest mesh to show the greatest detail in the area closest to the excavation. The purpose of the outermost region will be to replicate placing equivalent continuum properties at a sufficient distance from the excavation to dissipate stresses while not affecting the results. This region is represented by the rock mass parameters only. Figure 3 shows the model setup, mesh and boundary conditions for the circular geometry, using Case 2 as an example.

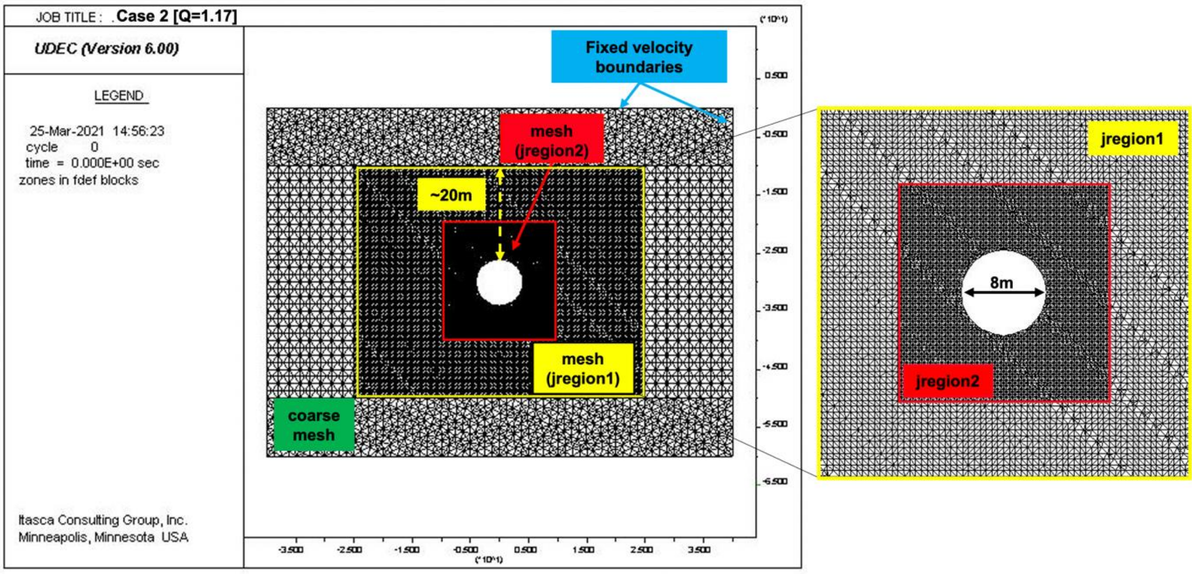

Figure 3. Model set-up showing the mesh and boundaries conditions.

It should be stated that in UDEC, it is possible to observe blocks 'dropping out' of the models, with these representing failure around the excavation and beyond the designed excavation line. The latter is, therefore, directly indicative of overbreak. Hence, the extent of these yielded blocks is deemed to be the best indicator of overbreak in UDEC. Alongside the yielded blocks, total displacement contours are plotted; however, it is implied that displacement contours are not a good indicator of overbreak. Yielded elements and joints are also included, with yielded joints indicating the EDZo limit and yielded elements being consistent with the zones where blocks have 'dropped out' of the models. Furthermore, σ_3 contours are not used as an indicator of overbreak in UDEC as it was decided that the ability to observe the zones where blocks have been removed from the excavation boundaries is a better indicator of overbreak.

4. Numerical Results and Discussion

The numerical analysis results are shown in table 3. Figure 4.a shows the velocity vectors (direction of the tunnel deformability) for Case 2 with the yielded blocks outlined to define overbreak. It should be stated that the numerical analysis is enriched with results from a parametric analysis of three main scenarios that are examined with $Q \leq 10$. The results in table 3 show that, with the exception of Case 1 and Case 4, the observed overbreak (or lack of observed overbreak) is consistent with [4] criteria to generate overbreak due to structurally-driven failures. Most notably, for Case 6, no overbreak is observed. Thus, it appears that this supports previous research stating that discontinuum methods such as UDEC provide a more accurate analysis of jointed rock masses in comparison to continuum methods. Case 1 and Case 4 appear to generate overbreak due to the stress conditions as opposed to due to the structural conditions, explaining why the results are not consistent with overbreak not being expected due to the defined criteria.

Figure 4.b shows the overbreak plotted against the corresponding Q-value. A non-linear, negative correlation between Q and overbreak can be seen, with overbreak increasing most notably for $Q \leq 4$. Overbreak is predicted to reduce to zero at a Q-value of 40, although this is an extrapolation, with more data being required between Q of 10 and 100 to accurately determine this point. The R-squared value, although appearing very poor, is considered to show a good fit for the type, quality and quantity of data; however, a significant degree of error is associated with the trends observed from figure 4.b.

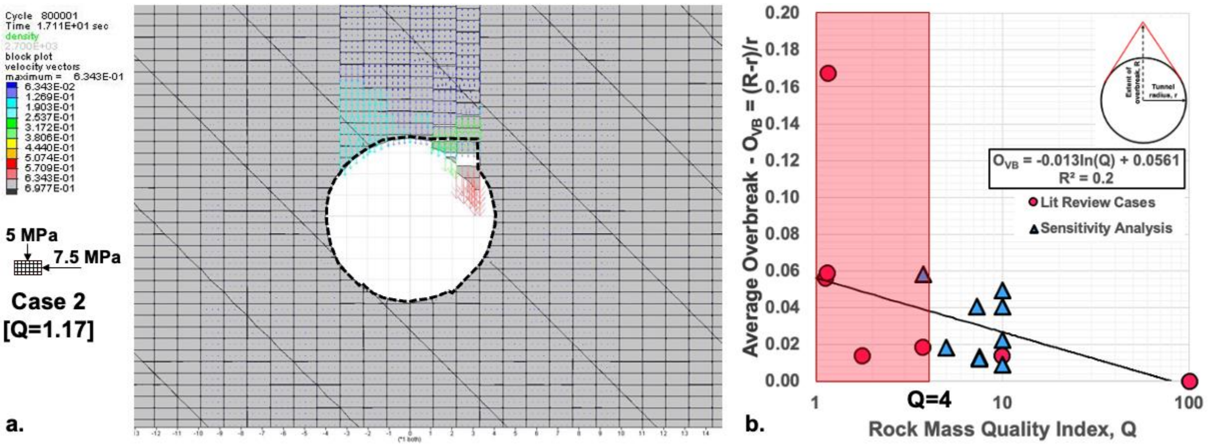

Figure 4. a. Numerical results from UDEC analysis of Case 2, and b. Relationship between Average Overbreak and Q.

Table 3. Observed and predicted Overbreak from numerical and sensitivity analysis.

Q	S_a (m)	K-Ratio	Overbreak Observed (R/r)	Predicted Overbreak (R/r)
		Initial Literature Cases		
1.22	0.3	1	0.03	0.06
1.17	2.22	1.5	0.17	0.11
1.13	2.3	2	0.06	0.12
1.15	0.25	1.7	0.06	0.07
1.78	0.4	0.75	0.01	0.05
100	0.73	0.43	0	0
10	0.44	0.43	0.01	0.03
3.75	0.2	0.43	0.02	0.04
		Scenario 1 (parametric study)		
5	0.44	0.43	0.02	0.04
7.5	0.44	0.43	0.01	0.03
3.75	0.44	0.43	0.06	0.04
7.5	0.44	0.43	0.01	0.03
		Scenario 2 (parametric study)		
7.27	0.22	0.43	0.04	0.03
		Scenario 3 (parametric study)		
10	0.44	1	0.01	0.04
10	0.44	2	0.02	0.05
10	0.44	0.75	0.04	0.03
10	0.44	1.5	0.05	0.04

The results in table 3, as well as further analyses based on the cases in table 1 and 2, were analysed with multiple linear regression to give Equation (2). This gives a simplistic method of predicting overbreak, with a simple look up chart for a K-ratio of 1 given in figure 5 as an example. This plot can be used as a primary tool to assess overbreak for a circular opening at initial design stages; however, further analysis should be undertaken for verification as overbreak is project-specific.

$$Overbreak: (R-r)/r = 0.0388 - 0.0210\,log\,Q + 0.0130S_a^2 + 0.00316K \qquad (2)$$

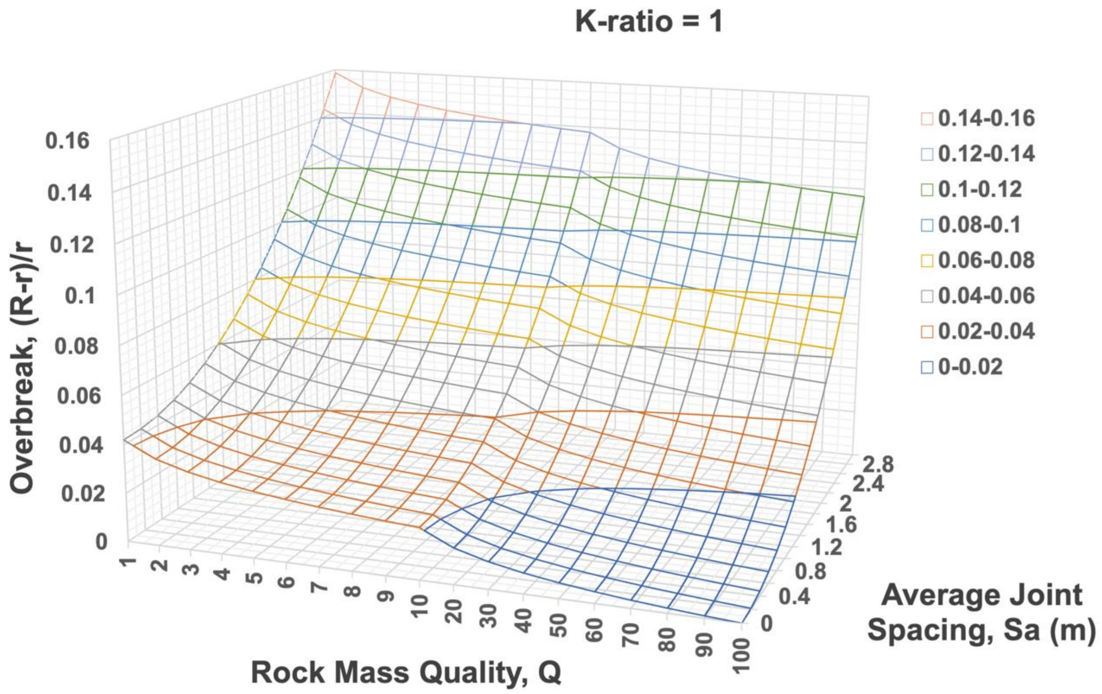

Figure 5. Contour plots to predict overbreak, using predictive model, where K-ratio = 1.

5. Conclusions

This research work shows that the rock mass quality does impact overbreak, with these having a negative relationship. Hence, as the rock mass quality (Q-system) decreases, overbreak increases, with this increase in overbreak being most significant when Q ≤ 4 when the condition of $J_n/J_r \geq 6$ is also met. It can be seen that the rock mass quality is not the sole factor influencing overbreak, with other important factors being the joint spacings and the in-situ stress conditions. The predictive model provides a good basis and can be used in the preliminary stages of design and could be utilised to highlight the maximum likely overbreak or possible scenarios where overbreak may occur.

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