Evaluating the correlation of rock mass classification systems in volcanic lithologies: a case study in a vein-shaped mining district at central Chile

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Abstract. Defining engineering behavior of rock masses is strongly dependent on observations made in situ and the following rock mass geotechnical classification. Nowadays, the most widely used classifications are rock mass rating (RMR) and the rock mass quality (Q). Because the rock mass characterization is normally done in terms of one (or rarely more than one) of these systems, and because different mechanical assessment tools used in this and later stages of mining design are typically expressed in any of the systems, it is important to be able to properly correlate rock mass classification ratings in at least the most used rock mass classification systems. In this paper new relationships for correlation of mentioned ratings are proposed. Data used was collected from active mines at Chépica mining district, located in the Maule region of central Chile. Results are compared with similar proposals from various authors and statistically evaluated to show that the proposed correlation equation is accurate and useful when applied to volcanic lithologies with rock masses in the range of fair to good.

1. Introduction

The study of rock masses geotechnical conditions is one of the most important tasks when digging and maintaining underground infrastructure. For this, different classification systems are used, where Rock Mass Rating RMR [1] and Rock Mass Quality Q [2] stand out due to their accuracy. Although these index ratings are methodical and systematic, the experience of the professional in charge of data collection plays a significant role in the final results and interpretations, adding a subjective factor to the process, especially in Q system, which can be relatively difficult to apply for inexperienced users [3,4]. In addition to this, those inputs needed to evaluate the quality of the rock mass using both classification systems are not always collected due to a lack of time or resources, especially in small and medium scale mining operations.

Bieniawski [1,5] indicates that for better results and decision making in an underground project, at least two rock mass classification systems should be used, which could be simplified by employing only one and using a correlation between this and another classification system to calculate the second, if the situation allows it. Since the first correlation of RMR and Q values presented by [6] there has been a misguided tendency to rely in excess on it [7]. For this, it is useful to establish original correlation equations between classification systems during the early stages of tunnel advancement of each project. Well formulated correlations allow the establishment of a guideline for the local project and serve as a reference for others with similar rock mass characteristics where geotechnical data has still not been collected.
Diverse empirical correlations have been published between different rock mass classification systems based on data extracted mainly from window mapping and core logging. A compilation of some of these with several characteristics and observations is presented below (Table 1). 34 correlations between RMR and Q were considered for this study, but due to the information available from each one and its representability, only some of them have been selected as shown in the equations (1) to (15) in table 1.

### Table 1. Compilation of correlations between Q and RMR indexes selected for this study.

| Correlation equation | $R^2 / R$ | Lithology | Observation | Author |
|----------------------|-----------|-----------|-------------|--------|
| (1) $\text{RMR} = 9 \cdot \ln Q + 44$ | $R^2 = 0.59$  
$R = 0.77$ | Diverse | 111 RMR and Q input data from Europe, Australia, North America and Africa | [6] |
| (2) $\text{RMR} = 5.9 \cdot \ln Q + 43$ | $R^2 = 0.66$  
$R = 0.81$ | - | Data collected from 9 tunnels located in New Zealand | [8] |
| (3) $\text{RMR} = 5.97 \cdot \ln Q + 49.5$ | $R^2 = 0.79$  
$R = 0.89$ | Diverse | Data collected in South Korea | [9] |
| (4) $\text{RMR} = 4.52 \cdot \ln Q + 43.6$ | $R^2 = 0.74$  
$R = 0.86$ | - | Data collected in India | [10] |
| (5) $\text{RMR} = 7.5 \cdot \ln Q + 41.8$ | $R^2 = 0.87$  
$R = 0.93$ | Mainly subvolcanic, volcanic and volcaniclastic | Copper porphyry and gold epithermal deposits. 135,000 m of drill core. Data collected in Chile | [11] |
| (6) $\text{RMR} = 5.4 \cdot \ln Q + 55.2$ | $R^2 = 0.30$  
$R = 0.55$ | - | Data collected from 4 tunnels in Spain | [12] |
| (7) $\text{RMR} = 10.5 \cdot \ln Q + 41.8$ | $R^2 = 0.44$  
$R = 0.66$ | Diverse sedimentary | Data collected from coal mines | [13] |
| (8) $\text{RMR} = 5.614 \cdot \ln Q + 49.395$ | $R^2 = 0.70$  
$R = 0.83$ | Sedimentary and volcanic intruded by igneous bodies | Data collected in Morocco | [14] |
| (9) $\text{RMR} = 5.3 \cdot \ln Q + 50.81$ | - | Altered igneous rocks, some affected by metamorphism | Data Collected in Quebec, Canada | [15] (A) |
| (10) $\text{RMR} = 12.5 \cdot \log Q + 50.81$ | $R^2 = 0.55$  
$R = 0.74$ | Altered igneous rocks, some affected by metamorphism | Data Collected in Quebec, Canada | [15] (B) |
| (11) $\text{RMR} = 6.3 \cdot \ln Q + 41.6$ | $R^2 = 0.61$  
$R = 0.78$ | Limestones and mudstones | Data collected in Canada | [16] |
| (12) $\text{RMR} = 6.4 \cdot \ln Q + 49.6$ | $R^2 = 0.72$  
$R = 0.85$ | Metamorphic, mainly schist and gneiss | SRF values valid for moderately jointed rocks. Data collected in India | [17] |
| (13) $\text{RMR} = 7 \cdot \ln Q + 36$ | - | Limestones | Data collected in Turkey | [18] |
| (14) $\text{RMR} = 6.4 \cdot \ln Q + 45.4$ | $R^2 = 0.77$  
$R = 0.88$ | Diabases or micro gabbros | Data collected in Colombia | [19] (A) |
| (15) $\text{RMR} = 5.7 \cdot \ln Q + 43.6$ | $R^2 = 0.71$  
$R = 0.82$ | Sedimentary clastic and subvolcanic, some affected by metamorphism | Data collected in Colombia | [19] (B) |

Numerous correlations have been proposed for different lithologies and rock mass characteristics. Two main disadvantages stand out: first, usually two or more lithologies with contrasting characteristics are grouped in the same correlation without considering different behaviors, which might lead to a higher uncertainty and error. Second, most of published correlations are proposed for calcareous and/or metamorphic lithologies, with very few cases for volcanic and volcaniclastic rock masses. These are both common lithologies in zones associated with subduction processes and therefore the presence of ore deposits, such as the area of the present case study and many others, where small and medium scale...
mines are exploited and usually struggle with limited budgets and are unable to collect all the geotechnical data they would intend.

This study has been proposed to evaluate the geotechnical relationship between RMR and Q classification systems for the previously mentioned lithology, using data collected by window mapping on underground advances of two active mines. The obtained correlation model is statistically compared with previously proposed correlations in terms of prediction accuracy.

2. Case study description
The studied area is found in the Chépica mining district, located in the Maule region of central Chile. It is part of an underdeveloped copper-gold belt that runs along the Eastern margin of the Coastal mountain range between 35°- 35.5° S latitude, where veins systems are associated to a structural heading control NNW and installed in a Jurassic volcanic arc that is configured by massive volcanic, hypabyssal sequences and pyroclastic levels.

There are currently two active mines in the district: Chépica I and Colin. While on a regional scale, several exploration campaigns and prospective studies are being conducted to promote the development of small and medium scale mining projects.

2.1 Geological setting
The Chépica mining district is located in a section of the volcanic sequences belonging to the Middle - Late Jurassic Alto de Hualmapu Formation defined by Morel [20] and Bravo [21] as a volcanic series with a minimum thickness of 3,680 m, lithologically composed by: andesitic volcanic breccias, subordinated andesitic and dacitic lavas, intercalations of tuffs and restricted levels of marine sedimentary rocks.

Locally, the lithologies recognized in drillings on the Chépica I and Colin mines have been correlated by Rivas [22] to the upper members of the Alto de Hualmapu Formation. These consider mainly a sequence of lapilli tuff, tuff breccia, porphyritic andesites and microdiorites.

3. Methodology
Geotechnical characterizations on window mapping of the Chepica I mine from internal reports have been used. For Colin mine a new window mapping was carried out, executing a survey based on both RMR\textsubscript{89} and Q\textsubscript{93} simultaneously. Data was collected every ten meters through the main tunnel level, which presents a total length of about 450 m.

3.1 Data grouping
Both data samples (Colin and Chépica mines) have been statistically compared to determine if they can be treated as the same population. Basic statistics have been conducted for all data to provide an overview about key parameters that affect rock mass quality directly [14] such as intact rock strength (IRS), RQD, joint separation, condition and water presence (Js, Jc and Jw respectively) considering both mines separately.

Bar charts (figure 1) show an acceptable similarity in the variables analyzed, the greatest differences are found in some maximum values. Basic statistics are presented in table 2 to show the behavior of the data when samples are combined. Further analysis is performed below to confirm the error remains low when combining both data samples with equations (16), (17) and (18).

### Table 2. Basic descriptive statistics for combined Chépica and Colin mines parameters.

| Parameter | Max | Min | Standard Deviation | Median | Average | Variance | Skeweness | Kurtosis |
|-----------|-----|-----|--------------------|--------|---------|----------|-----------|----------|
| IRS       | 12  | 1   | 3.06               | 7      | 8.05    | 9.38     | 0.09      | -1.01    |
| RQD (%)   | 100 | 30  | 12.44              | 84     | 81.30   | 154.65   | -1.64     | 4.01     |
| Js        | 20  | 8   | 2.54               | 10     | 11.58   | 6.45     | 1.14      | 0.79     |
| Jc        | 27  | 2   | 6.12               | 15     | 16.09   | 37.49    | 0.08      | -1.02    |
When considering Colin and Chépica mines together, RMR data is evaluated with the following parameters to visualize the amount of error acquired when using the correlation equation presented for this study, where \( F_t \) means the predicted value and \( A_t \) the real value:

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (A_t - F_t)^2} \tag{16}
\]

\[
\text{RSS} = \sum_{i=1}^{n} (A_t - F_t)^2 \tag{17}
\]

\[
\text{MAPE} = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{A_t - F_t}{A_t} \right| \tag{18}
\]
The following results are obtained regarding real and obtained values of RMR:

| Table 3. Calculated parameters for RMR error. |
|---------------------------------------------|
|                | Chépica | Colin | Total  |
| RMSE           | 4.70    | 3.54  | 4.56   |
| RSS            | 728.01  | 575.31| 1644.16|
| MAPE (%)       | 5.6     | 4.8   | 6.1    |

The root mean square error (RMSE) and mean absolute percentage error (MAPE) values remain low, which indicates that treating the two samples independently is correct, as it is to treat both mines as one. The residual sum of squares (RSS) values tend to be higher due to the characteristic of the parameter, which should be evaluated when calculating the correlation between RMR and Q for each mine separately and together. The correlation and its determination coefficients were taken into account when deciding the feasibility of grouping data.

3.2 Data assessment

Correlations between RMR$_{89}$ and Q$_{93}$ are conducted for both mines together, with a total of 79 data inputs, of which 46 come from Colín mine and 33 from Chépica mine. A logarithmic correlation is proposed due to better results in terms of correlation and determination coefficients ($R$ and $R^2$ respectively). Logarithmic linear regressions have been used by most authors (table 1) for presenting the best correlation coefficients in a large spectrum of rock mass quality, nevertheless differences between these models are accentuated at extreme values of the curve (very poor and very good rock qualities).

As the studied tunnels present rock quality values between the range from fair to good, the logarithmic regression fits the model well and allows a direct comparison with other published correlations. Additionally, experimental RMR$_{e}$ and Q$_{e}$ values (estimated RMR and Q values from published correlation equations including that of this study case) will be calculated from the theoretical RMR, and Q$_{p}$ (known RMR and Q values obtained from field observations in situ). Then, a linear correlation between these variables (RMR$_{e}$ vs RMR; and Q$_{e}$ vs Q$_{p}$) will be determined to compare their correlation, determination coefficient and mean absolute error values to verify the similarity of the values obtained from the equations with the original value observed in each window mapping.

4. Results

After processing the data (figure 2), the correlation and determination coefficient values for this case study are $R=0.8476$ and $R^2=0.7185$ respectively, with a mean absolute error MAE=3.589%, indicating a moderately strong relationship between the variables RMR and Q for the studied volcanic rock mass corresponding to Colín and Chépica I mines. In addition, the standardized residuals have been graphically represented (figure 3). As observed, the points are distributed mainly over the straight line, except for the slightly sigmoidal shapes in the tails. This is enough to show that, in general, the error terms are normally distributed except for some outliers. The following proposed equation (19) uses lnQ$_{93}$ as independent variable:

$$RMR_{89} = 49.0972 + 10.3387*lnQ_{93}$$  (19)
Figure 2. Logarithmic correlation between $Q_{93}$ and $RMR_{89}$.

Figure 3. Normal probability plot of residuals.

For a better visualization and a quick comparison of the proposed model with other correlations with the highest $R^2$, a schematic graph (figure 4) is presented to contrast their curves.

The correlation and determination coefficients of theoretical and experimental known data for $Q$ values show that the proposed equation behaves very similarly to equations (12), (13) and (1) as well as most other models which have slightly lower results, even when these models work with different lithologies and rock mass characteristics. When analyzing the $R$ and $R^2$ for RMR, the correlation in the present study makes a huge improvement, outperforming all other models, proving that the correlations are much more sensitive to variations in $Q$ values obtained in situ (table 4) and that the proposed correlation works better in this geological environment.

Table 4. Determination coefficient for correlations between theoretical and experimental index values.

| Author | $Q_t$ vs $Q_e$ | $RMR_t$ vs $RMR_e$ |
|--------|----------------|-------------------|
|        | $R^2$  | $R$   | MAE | $R^2$ | $R$   | MAE |
| [1]    | 68.89  | 0.829 | 4.71 | 55.16 | 0.742 | 3.20 |
| [8]    | 67.37  | 0.820 | 42.12 | 53.34 | 0.730 | 2.08 |
| [15] (A) | 66.06  | 0.812 | 19.33 | 54.85 | 0.740 | 1.89 |
| [15] (B) | 67.30  | 0.820 | 0.97 | 54.69 | 0.739 | 1.94 |
| [16]   | 67.97  | 0.824 | 35.71 | 55.08 | 0.742 | 2.25 |
| [18]   | 68.63  | 0.828 | 43.92 | 53.93 | 0.734 | 2.45 |
| [9]    | 67.49  | 0.821 | 13.2 | 53.92 | 0.734 | 2.18 |
| [17]   | 68.09  | 0.825 | 9.32 | 54.41 | 0.737 | 2.31 |
| [19] (A) | 68.09  | 0.825 | 17.97 | 55.48 | 0.744 | 2.27 |
| [19] (B) | 66.99  | 0.818 | 46.99 | 53.51 | 0.731 | 2.05 |
| [10]   | 63.38  | 0.796 | 240.74 | 52.81 | 0.726 | 1.66 |
| [14]   | 66.81  | 0.817 | 18.41 | 53.20 | 0.729 | 2.02 |
| [11]   | 68.87  | 0.829 | 5.82 | 52.72 | 0.726 | 2.71 |
| Proposed model | 71.98  | 0.84 | 1.62 | 65.95 | 0.81 | 3.41 |
5. Conclusions

This geotechnical study was carried out in the exploratory tunnels of the Chépica mining district and made it possible to establish a new correlation model between the most used rock mass classification systems (RMR and Q). It has been proven that active mines in the district (Colin and Chépica I) share not only their geology but similar mechanical properties from the statistical viewpoint, so it has been possible to treat the collected data as a single population. This can be used as a precedent of the ability to extrapolate the model to other mines in the studied area that could start operating in the future.

This exercise has proven to be important, especially at the mining district level, since the proposed model has shown a better correlation coefficient ($R^2=0.7185$) than most of the equations published for volcanic or igneous rock masses. Additionally, the existing correlations obtained by several authors were reviewed as well as their behavior with the raw data collected, revealing that the locally generated model is better when RMR values are calculated from Q taken in situ and vice versa.

Many published correlations have been proposed from rock masses with different types of lithologies which may have diverse behaviors at different scale for various reasons; for example, their inherent rock’s fabrics, that can control the presence of anisotropies having an effect on the behavior of the rock such as its resistance and differences in the orientation of fractures against the same stresses. Bibliography that characterizes rock masses both geotechnically and geologically is hard to find, instead it tends to omit this last parameter. Therefore, the scope of the proposed model could be cautiously extended from the district level to the regional prospective belt and even up to other projects installed in similar volcanic arches. It is encouraged to replicate the methodologies of this work for future projects in their early stages of development with their original raw data.

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