The use of geomechanical classifications, especially RMR, GSI and Barton Q, applied to underground civil works is very common in Andean areas where important infrastructures are being built in recent times and many others projected related to tunnels and hydroelectric projects. The use of different classifications is needed to characterize the rock masses, but their individual use reveals inconsistencies between the results of these classifications implying a deficit in the characterization of rock masses affected. In this paper new criteria of correlation between these geomechanical classifications, RMR, GSI, and Barton Q, associated with Andean contexts are presented, in order to obtain an optimum characterization of the rock mass affected by the infrastructure.

Keywords: Andean environments, Geomechanical classification, RMR, GSI, Q.

1. Introduction

Nowadays geomechanical classifications are very much used in practical Rocks Mechanics, especially in the Andean region where, at this moment, a wide development of infrastructures are taken place.

The engineer usually uses different geomechanical indices, in combination with data of 'in situ' and laboratory tests, to obtain engineering calculation parameters. However, there is a risk of making inaccuracies or obtaining results which can differ in some order of magnitude.

Therefore this study deepens on correlations GSI-RMR and Q-RMR indices, which are commonly used in almost every geological engineering study. This study is an update of previous results obtained by the authors [12].

2. Geomechanical classifications

Geomechanical classifications allow the characterization of rock masses from simple tests and field observations. There are many geomechanical indices in use today, among which are: RMR, Q, GSI SMR, RQD, RSR, RMi and so on.

The present study focuses its analysis on Andean rock masses which have been characterized by Rock Mass Rating (RMR), Geological Strength Index (GSI) and Tunneling Quality Index (Q).

2.1. Rock Mass Rating (RMR)

Rock Mass Rating (RMR) index was developed by Bieniawski (1976) [3]. It is one of the most used geomechanical classifications for the characterization and description of rock masses.

The RMR, value from 0 to 100, is obtained as the total sum of parameters related with strength of material, rock fracturing, discontinuities and groundwater conditions. In the specialized bibliography two different versions can be found, depending on the scoring ranges assigned to each of the parameters previously defined (RMR76, RMR89) as shown in Table 1.
2.2. Geological Strength Index (GSI)

Geological Strength Index (GSI) was developed by Hoek et al. in 1995 [6]. Unlike RMR and Q, it is an index that is obtained in a more simplified and visual way from two parameters: the structure and the superficial state of the rock mass. GSI considers a final score within the range 0-100, having the two parameters considered on it the same importance or weight. Table 1 summarizes the main ideas showing the differences between RMR\textsubscript{76}, RMR\textsubscript{89} and GSI.

As it is extracted from the previous paragraphs, GSI introduces a greater empiricism in an empirical classification by itself. However, it is the nexus of union between the visual description made in the field works and the constitutive model of non-linear failure developed by its authors and implemented in a wide range of software used in the design of engineering works.

Table 1. Differences between RMR\textsubscript{76}, RMR\textsubscript{89} and GSI.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RMR\textsubscript{76}</th>
<th>RMR\textsubscript{89}</th>
<th>GSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniaxial compressive strength of rock material</td>
<td>15</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>RQD and Spacing of discontinuities</td>
<td>50</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Condition of discontinuities</td>
<td>25</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Groundwater conditions</td>
<td>10</td>
<td>15</td>
<td>0</td>
</tr>
</tbody>
</table>

2.3. Tunneling Quality Index (Q)

Tunneling Quality Index (Q) was proposed by Barton et al. (1974) [1] with the aim of determinate rock mass characteristics and tunnel support requirements based on a large number of case histories of underground excavations. Index Q varies on a logarithmic scale from 0.001 to 1000 and its numerical value is the product of only three parameters:

- Block size \( \frac{RQD}{J_n} \),
- Inter-block shear strength \( \frac{J_f}{J_a} \) and
- Active stress \( \frac{J_w}{SRF} \).

Equation (1) shown below represents Index Q proposed by Barton et al. in 1974 [1]:

\[
Q = \left( \frac{RQD}{J_n} \right) \cdot \left( \frac{J_f}{J_a} \right) \cdot \left( \frac{J_w}{SRF} \right)
\]  

(1)

Where \( RQD \) is the Rock Quality Designation, \( J_f \) is the joint roughness number, \( J_a \) is the joint alteration number, \( J_w \) is the joint water reduction factor and SRF is the stress reduction factor.

2.4. Existing correlations between RMR, GSI and Q

Authors consider further studies on RMR-Q-GSI correlations are of high interest. Some reasons are:

- RMR and Q classifications have been used in studies of geological engineering for a long time. In consequence, there are remarkable empirical knowledge, large bibliographical references related to correlations between other parameters and great of data collected during the development of engineering projects existing.
• GSI classification, despite being more recent, has a nonlinear failure criterion associated with it, that it is implemented in many rock engineering softwares.

These were the main reasons why in recent years several authors have invested great efforts in developing relationships between these geotechnical classifications. Among which are:

• Hoek et al. (1995) [6] proposed the following general mathematical expression is:

\[
GSI = \begin{cases} 
RMR' - 5 & \text{if } RMR' > 23 \\
(\ast) & \text{if } RMR' < 23
\end{cases}
\]

Where RMR' is the value of RMR in dry conditions (with 15 points for groundwater condition) and uncorrected by orientation of the joints

(\ast) The RMR' should not be used as an indirect parameter in obtaining the GSI.

• Bieniawski (1976) [3] correlated RMR and Q with the well-known general proposal:

\[
RMR = 9 \cdot \ln(Q) + 44
\]

RMR value is uncorrected for the orientation of the joints.

3. Study for Andean environments

3.1. Goals of the study

Currently a very important part of the global investment on civil and construction works is located in Latin American countries.

Consequently, this study aims to obtain correlations between the Rock Mass Rating (RMR), Geological Strength Index (GSI) and Quality Index (Q), depending on the different types of rocks existing in the Andean environment. Secondly, correlations obtained shall be compared with results obtained previously by other authors, such as Hoek et al. (1995) [6], Bieniawski (1976) [3] and so on.

All of this with the ultimate goal of being able to use, with the best accuracy, all the tools, applications and correlations associated with the different geomechanical classifications regardless the indices obtained during field investigation.

3.2. Description of the database

The characterization and description of Andean rock masses is based on 298 outcrop mapping measurements and 61 tunnel face mapping results, which were executed in 10 projects located in 4 Latin American countries where the authors of this publication participated recently (Bolivia, Ecuador, Colombia and Peru).

All of the outcrop mapping and tunnel face mapping have been classified according to the type of rock. In addition, pairs of RMR-GSI and Q-RMR values have been obtained in all of them.

3.3. Working methodology

The first step of this study consisted on compilation of data and its classification based on the lithology, type of measurement (tunnel face or outcrop) and geomechanical index used.

Basic information regarding the compiled data is shown in Table 2. As can be seen, a total of 359 pairs of RMR-GSI for 6 types of rocks were considered, whilst the number of RMR-Q values were 136.
Table 2. Number of pair data RMR-GSI and RMR-Q depending on the type of rock

<table>
<thead>
<tr>
<th>Type of rock</th>
<th>RMR-GSI</th>
<th>RMR-Q</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outcrop Mapping</td>
<td>Face Mapping</td>
</tr>
<tr>
<td>Coarse grained sedimentary rocks</td>
<td>105</td>
<td>31</td>
</tr>
<tr>
<td>Fine grained sedimentary rocks</td>
<td>51</td>
<td>11</td>
</tr>
<tr>
<td>Chemical sedimentary rocks</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Metamorphic rocks</td>
<td>69</td>
<td>12</td>
</tr>
<tr>
<td>Plutonic rocks</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>Volcanic rocks</td>
<td>51</td>
<td>0</td>
</tr>
<tr>
<td>Entire of database rocks</td>
<td>298</td>
<td>61</td>
</tr>
</tbody>
</table>

Secondly, a statistical study of the data series described above and based on the type of rock was carried out. The main target of this was obtaining the best fit using the least squares method.

3.4. Results obtained

3.4.1. Correlations RMR’-GSI and RMR-Q

The results obtained from this study are shown below. After analyzing different mathematical expressions, it was confirmed that the best statistical fit that correlates the RMR’ and GSI is the linear. RMR’ is the uncorrected value for dry conditions.

Figure 1 shows the correlation obtained for the entire sample data considered regardless of lithology, correlating the GSI index compared to RMR’, i.e., the RMR uncorrected and with the highest score for water condition.

In further analysis, RMR-GSI has been correlated to different lithologies of the rock masses studied, including: sedimentary rocks of coarse grain (sandstone and conglomerates), fine-grained sedimentary rocks (siltstones, shales), metamorphic rocks (schists, slates), plutonic rocks (granites, granodiorites) and volcanic rocks (andesites, basalts). Results obtained are shown in Table 3.

Table 3. Correlations GSI = GSI (RMR’) depending on the type of rock.

<table>
<thead>
<tr>
<th>Type of rock</th>
<th>Equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>All data rocks</td>
<td>GSI = RMR’ - 6</td>
<td>0.82</td>
</tr>
<tr>
<td>Coarse grained sedimentary rocks</td>
<td>GSI = RMR’-7</td>
<td>0.81</td>
</tr>
<tr>
<td>Fine grained sedimentary rocks</td>
<td>GSI = 1.1 RMR’ - 12.5</td>
<td>0.87</td>
</tr>
<tr>
<td>Metamorphic rocks</td>
<td>GSI = RMR’ - 4</td>
<td>0.68</td>
</tr>
<tr>
<td>Plutonic rocks</td>
<td>GSI = 1.15 RMR’ - 15</td>
<td>0.76</td>
</tr>
<tr>
<td>Volcanic rocks</td>
<td>GSI = 0.95 RMR’</td>
<td>0.87</td>
</tr>
</tbody>
</table>

As can be seen, correlation is based on a range of RMR’ data between 30-80 points, and provides a reasonable correlation coefficient of 0.82, for the expression of GSI = RMR’-6, which is close to the proposal of Hoek et al. (1995) [6].

Fig. 1. Statistical fit RMR’-GSI for the entire simple of data considered in the study.
However, depending on the type of material or lithology this study has shown discrepancies or differences above 5 points of GSI depending on the nature of the rocks. For example, one of these cases is related with fine grained sedimentary rocks, which can be clearly unconservative in case of weak rocks masses.

The same analysis was made with pairs of RMR-Q values. Figure 2 and Table 4 show the results obtained along with some of the traditional correlations proposed in specialized bibliography. A general conclusion of this study is that results were consistent with those proposed by several authors.

### Table 4. Correlations RMR = RMR (Q) depending on the type of rock.

<table>
<thead>
<tr>
<th>Type of rock</th>
<th>Equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>All data rocks</td>
<td>RMR=5·LnQ +49</td>
<td>0.55</td>
</tr>
<tr>
<td>Coarse grained sedimentary rocks</td>
<td>RMR=7·LnQ +50</td>
<td>0.93</td>
</tr>
<tr>
<td>Fine grained sedimentary rocks</td>
<td>RMR=5·LnQ +54</td>
<td>0.88</td>
</tr>
<tr>
<td>Metamorphic rocks</td>
<td>RMR=4·LnQ +47</td>
<td>0.48</td>
</tr>
<tr>
<td>Plutonic rocks</td>
<td>RMR=9·LnQ +48</td>
<td>0.78</td>
</tr>
</tbody>
</table>

3.4.2. New proposal for GSI estimation based on RQD and Jcond

Similarly to Hoek et al. (2013) [7], it has been obtained an expression for estimating the GSI as a function of the RQD and the $J_{cond}$. Subsequently, GSI values obtained by this new expression and GSI mapped data available have been compared, showing that obtained results differ from the ones deduced by the use of Hoek’s proposal. Additionally, dependency on lithology has been proved as can been seen in the figure below.

### Table 5. Correlations depending on the type of rock of GSI Estimated = a·$J_{cond}$ +b·RQD

<table>
<thead>
<tr>
<th>Type of rock</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>All data rocks</td>
<td>GSI=1.28·$J_{cond}$ +0.48·RQD</td>
</tr>
<tr>
<td>Coarse grained</td>
<td>GSI=0.76·$J_{cond}$ +0.53·RQD</td>
</tr>
<tr>
<td>Fine grained</td>
<td>GSI=0.81·$J_{cond}$ +0.59·RQD</td>
</tr>
<tr>
<td>Metamorphic</td>
<td>GSI=1.99·$J_{cond}$ +0.41·RQD</td>
</tr>
<tr>
<td>Plutonic</td>
<td>GSI=1.47·$J_{cond}$ +0.45·RQD</td>
</tr>
<tr>
<td>Volcanic</td>
<td>GSI=0.62·$J_{cond}$ +0.57·RQD</td>
</tr>
</tbody>
</table>
4. Conclusions

This study analyzed large number of pairs of data GSI - RMR corresponding to different projects and works located in the Andean region. These have been studied in order to shed light on the correlation between these two indices so frequently used in Rock Mechanics. The main conclusion of this study refers to the goodness of the generally used correlation proposed by Hoek.

However, depending on the type of material or lithology, it is strongly recommended to obtain site specific correlations for each case or project; especially in the case of detailed studies, since this study has shown discrepancies or differences above 5 points of GSI depending on the nature of the rocks.

Here, a new expression to obtain GSI from RQD and J\_cond has also been proposed. This provides a best fit with available data visually measured on site by the authors.

Finally, a new correlation between RMR and Q was also obtained, although this should be improved with more data in the range of Q<1.

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References