

Comparative analysis of different calculation methods of the Geological Strength Index (GSI) based on qualitative and quantitative approaches

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Abstract

In this research, the dispersion of the Geological Strength Index (GSI) values obtained with quantitative and qualitative approaches has been evaluated in four rock outcrops of different quality. The subjective component associated with qualitative or visual methods has been studied by conducting a virtual survey in a group of forty participants constituted by civil engineers, geological engineers, and mining engineers from Peru, Spain, and Chile, who were given a data sheet with a photograph and a basic description of each rock mass. The results showed that the GSI values fit a normal distribution characterized by a mean value and a standard deviation, which in some cases could present moderate to high coefficients of variation (COVs). This paper also includes the study of the dispersion of the GSI values obtained with quantitative formulations that have been evaluated and incorporated into regional databases to assess trends, mainly in the GSI-RMR' relationships. The results indicate that the average GSI values reported with both approaches are similar; however, with the quantitative methodologies, COV values were classified as low to moderate, which is better adjusted to the suggested COV values for the GSI. Despite this, quantitative methodologies must be used with caution, taking into account the characteristics of the rock masses on which the relationships have been defined.

Keywords:

GSI; rock mass; rock mechanics; qualitative methods; quantitative methods; sensitivity

1. Introduction

The Geological Strength Index (GSI) (Hoek, 1994; Hoek et al., 1995) was conceived as a rock mass characterization system, originally calculated qualitatively based on the rock mass structure and the joint condition. The calculation procedure was developed under the premise that qualified geologists or geological engineers would carry out the observations of the rock mass characteristics; however, currently in engineering practice, it has been observed that many times the qualitative GSI calculation is carried out by inexperienced personnel or engineers who do not feel comfortable using descriptive methodologies (Hoek et al., 2013), resulting in an index with a high subjective component. Subsequently, to reduce the subjectivity in the GSI calculation, various researchers (e.g. Sonmez and Ulusay, 1999, 2002; Cai et al., 2004; Russo, 2009) proposed quantitative formulations based on specific rock mass parameters, such as RQD (Deere, 1963), joint condition or block volume (V_b), or with approaches based on fuzzy logic (Sonmez et al., 2003), in accordance with Hoek (1999), who indicated that engineers are more comfortable using rock

mass parameters that numbers can express. Despite this, it was observed that in some cases, the application of quantitative formulations could result in very dispersed values of the GSI, so it is necessary to previously evaluate the particular characteristics of the rock masses on which these formulations were defined, such as lithology, range of application, exposure conditions, structure, etc. Hoek (1998) states that it is more realistic to indicate a range of the GSI values instead of a single value, so in engineering calculations, it is suggested to consider the variability of this parameter through statistical distributions.

1.1. Review of GSI versions

Since its appearance, the GSI has undergone various modifications, so after reviewing the extensive technical information available regarding the adaptations of the GSI system and its applications, in this investigation, it has been decided to group the different versions of the GSI into three groups or development lines.

1.1.1. Original approach

It includes the research line carried out under the authorship, co-authorship, or supervision of the developers of the original Hoek-Brown criterion, which began with

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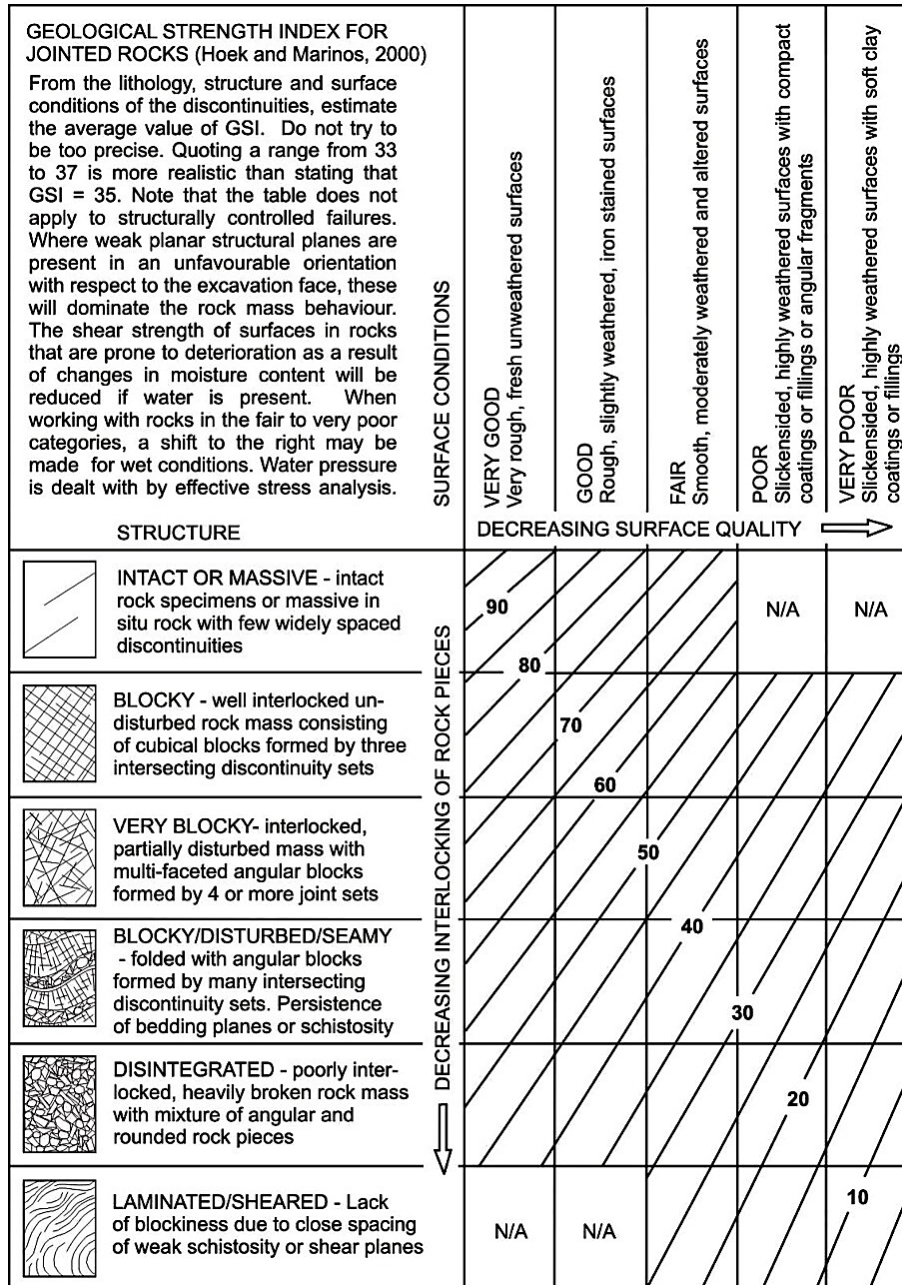


Figure 1: Basic chart for the qualitative calculation of the GSI (from Hoek and Marinos, 2000)

the investigations of Hoek and Brown (1980), incorporating the GSI in the equations of the failure criterion in Hoek et al. (1995), and whose most recent chart version is presented by Hoek et al. (2013). It also includes the development of qualitative charts for application in complex rock masses such as Flysch (Marinos and Hoek, 2001; Marinos, 2017) and molasses (Hoek et al., 2005). The basic chart for calculating the GSI in jointed rock masses is presented in Figure 1, published by Hoek and Marinos (2000).

In this approach, Hoek et al. (2013) propose a quantitative formulation to calculate the GSI, presented in Equation 1.

$$GSI_{2013} = 1.5JCond_{89} + RQD / 2 \tag{1}$$

Where:

- GSI_{2013} – Qualitative GSI (Hoek et al., 2013),
- $JCond_{89}$ – Joint condition (Bieniawski, 1989),
- RQD – Rock Quality Designation (Deere, 1963).

1.1.2. Complementary approach

It includes the development of new charts for the GSI calculation carried out by independent researchers. In some of these publications, the scores associated with the rock mass structure and the joint condition have been quantified, indicating them directly on the chart axes

Table 1: GSI – Original approach

Reference	Description	Calculation parameters	
		Structure	Joint condition
Hoek (1994), Hoek et al. (1995)	These publications introduce the concept of GSI as a replacement for RMR in the Hoek-Brown criterion equations. Unique GSI values are associated with each category of rock masses ($5 < \text{GSI} < 85$).	Visual	Visual
Hoek and Brown (1997)	The chart for calculating the GSI is presented for the first time as a series of continuous lines that define the GSI values based on the rock mass structure and the condition of the discontinuities, so it is possible to define a range of values of GSI instead of a single value ($5 < \text{GSI} < 85$).	Visual	Visual
Hoek et al. (1998)	To include rock masses of very poor quality, such as the schists found in the excavation of the Athens Metro, the range of GSI values is extended below 5.	Visual	Visual
Marinos and Hoek (2001)	A new chart is presented to calculate GSI in weak and tectonically disturbed rock masses, such as Flysch.	Visual	Visual
Hoek et al. (2002)	A new set of relationships between GSI, m_p , s , and a is introduced to give a smoother transition between very poor quality rock masses ($\text{GSI} < 25$) and stronger rocks.	Visual	Visual
Hoek et al. (2005)	A new GSI chart is presented for the calculation in tectonically undisturbed sedimentary rocks deposited in a shallow marine environment (molasses).	Visual	Visual
Marinos (2017)	An update of the chart published by Marinos and Hoek (2001) is presented to calculate the GSI in heterogeneous rock masses, such as Flysch.	Visual	Visual
Hoek et al. (2013)	It presents a quantitative formulation for the calculation of the GSI in rock masses with a blocky structure.	RQD	JCond ₈₉

(e.g. Sonmez and Ulusay, 1999, 2002), or suggesting quantitative formulations depending on the rock mass parameters (e.g. Cai et al., 2004; Russo, 2009). This approach also includes evaluating exceptional cases, such as rock masses with an intrablock structure (Day et al., 2019) or the GSI in cores from drilling (Shang et al., 2011; Lin et al., 2014).

1.1.3. Specific application approach

Although the GSI system was developed for its exclusive application with the Hoek-Brown failure criterion, it has been found in engineering practice that it can be used successfully in other areas of rock mechanics. The specific application approach includes the development of GSI charts for the study of any particular problem; for example, qualitative charts have been developed to design support systems for tunnels in Peruvian mines (Mejía and Chacón, 2009), the study of rock mass excavability (Tsiambaos and Saraglou, 2009), the study of rock mass permeability (Kayabasi, 2017) or the evaluation of vibrations in the rock mass (Mesec et al., 2016).

Previous research studies published by Hoek et al. (1998), Marinos and Hoek (2000), Hoek et al. (2002), Marinos et al. (2005), Hoek et al. (2013), Marinos and Carter (2018), and Hoek and Brown (2019), provide essential recommendations on the application of the GSI, which refer to conditions of alteration, lithology, moisture, the opening of joints, filling and depth.

Tables 1, 2, and 3 summarize the different versions of the GSI chart according to the classification mentioned previously.

1.2. Review of previous researches

Hoek et al. (2013), to verify its quantitative formulation, compared the values estimated visually and with the proposed formula in 75 rock outcrops, concluding that there is an acceptable correspondence between the observed and calculated GSI and that the majority of values do not exceed 5 points of difference concerning the GSI evaluated in-situ.

Winn and Wong (2018) carried out a comparison study on sedimentary rocks located in Singapore, using the formulations of Russo (2009), Sonmez and Ulusay (1999), Cai et al. (2004), and Hoek et al. (2013), concluding that the calculated GSI values are in a range limited by ± 10 points concerning the GSI values estimated visually, being the results of Russo (2009) those that present a greater dispersion, and the results of Sonmez and Ulusay (1999) those that offer a better fit.

Bertuzzi et al. (2016) compared the GSI values obtained visually in four different rock masses, observing that many of the calculated values differ by more than 10 points for the values estimated visually, which indicates that there is a considerable uncertainty; however, in approximately half of the data there is a reasonable correlation. For this reason, Bertuzzi et al. (2016) recommend

Table 2: GSI – Complementary approach

Reference	Description	Lithology	Site	Calculation parameters	
				Structure	Joint Condition
Sonmez and Ulusay (1999, 2002)	A quantitative formulation for its exclusive application in slope stability analysis	Marl, barite, coal	Turkey	Structure Rating (SR)	Surface Condition Rating (SCR)
Sonmez et al. (2003)	Application of fuzzy set theory to the GSI system. The original and modified GSI charts published by Sonmez and Ulusay (1999, 2002) were defined by fuzzy sets, using 22 „if-then“ rules.	General	-	Structure Rating (SR) based on fuzzy sets	Surface Condition Rating (SCR) based on fuzzy sets
Cai et al. (2004)	A quantitative formulation for jointed hard rock masses.	Granite, siltstone, andesite, basalt	Japan	Block Volume (V_b)	Joint Condition Factor (J_c)
Russo (2009)	A quantitative formulation based on the conceptual affinity of the GSI with the Joint Parameter (JP) used in the RMI index of Palmström (1996)	General	-	Block Volume (V_b)	Joint Condition Factor (J_c)
Day et al. (2019)	Definition of the Composite GSI (CGSI) for the study of rock masses with intrablock structure	Rock masses with hydrothermal veins, veinlets, and stockwork	Chile	Block Volume (V_b)	Joint Condition ($J_{cond_{99}}$)
Russo et al. (2020)	Definition of the GSI in hypogenic environments (IGSI), based on the spacing of welded veins and the hardness of their infill	Used only for a hypogene environment and cannot be used in a weathered and jointed rock mass	Chile	Rating Spacing (R_{sp})	Weighted Mohs hardness (R_{WHd})
Baczynsky (2020)	Introduces the concept of directional GSI	Rock masses with step-path failure	-	Visual	Visual
Lin et al. (2014)	Calculation of the GSI in cores from drilling	Granite	China	Rock Core Length (RCL)	Joint Conditions and Rock Mineral Conditions (V)
Shang et al. (2011)	Calculation of the GSI in cores from drilling	Gneiss	China	Rock Core Length (RCL)	Joint Condition Factor (J_c)
Truzman (2009)	Calculation of the GSI in metamorphic rocks	Metamorphic rocks	Venezuela	Visual	Visual
Schlotfeldt and Carter (2018)	Definition of the Volumetric Geological Strength Index (V-GSI)	Jointed rock masses	-	VFC (fractures/ m^3), RQD, V_b , P_{32} , RQD/ J_n	Joint Condition ($J_{cond_{99}}$), J_r/J_a

that the quantified GSI should be used as a complementary calculation and that the visual analysis must necessarily be carried out in-situ.

Win (2019) compared the in-situ GSI and those calculated quantitatively using the formulations of **Hoek et al. (1995)**, **Hoek et al. (2013)**, and a formulation depending on the parameters of the Q index (**Barton et al., 1974**) in stratified sedimentary rocks in Singapore, observed differences in the order of 10 to 30 points. It was indicated that the main reason for these differences is the variability of the parameters referring to the discontinuities, such as the RQD, J_n , J_r , and J_a in the sedimentary

rocks, for this reason, it was proposed to modify the coefficients of the indicated formulations to adjust the values calculated with the values explicitly observed in the rock masses.

Vásárhelyi et al. (2016) evaluated the GSI with various formulations along 70 m of a tunnel in Hungary, indicating that the GSI values calculated with the different methodologies are between 15 and 38 points, which suggests a considerable dispersion between the results when applying the different calculation methodologies. It is also observed that the results of **Russo (2009)** present a more significant difference concerning the rest.

Table 3: GSI – Specific applications approach

Reference	Description	Lithology	Site	Calculation parameters	
				Structure	Joint Condition
Cai et al. (2007)	GSI and rock mass residual strength parameters	Conglomerate, sandstone, mudstone, porphyrite, slate, schist	Japan, Spain	Residual Block Volume ($V_{b,r}$)	Residual Joint Condition Factor ($J_{c,r}$)
Mejía and Chacón (2009)	GSI and support in tunnels	Not specified	Peru	Visual	Visual
Tsiambaos and Saraglou (2009)	GSI and the rock mass excavability	Gneiss, weathered gneiss, schist, limestone, sandstone, marble, siltstone	Greece	Visual	Visual
Kayabasi (2017)	GSI and rock mass permeability	Volcanic breccia, granite, quartzdiorite, andesite, agglomerate	Turkey	Visual	Visual
Mesec et al. (2016)	GSI and vibration level characterization	Sandstone, limestone, dolomite limestone, marbleized limestone	Croatia	Visual	Visual
Špago and Jovanovsky (2019)	GSI and the karsticity of the rock mass	Carbonate rock (limestone, dolomite, marble)	Bosnia and Herzegovina and Macedonia.	Thickness of strata	Uniaxial Compressive Strength (UCS)

Table 4: Quantitative formulations GSI-RMR' (from Sanchez et al., 2016 and Ceballos et al., 2014)

Lithology	Quantitative formulation (Ceballos et al., 2014)	Quantitative formulation (Sánchez et al., 2016)
All data	$GSI = 1.17RMR' - 11.36$	$GSI = RMR' - 6$
Coarse-grained sedimentary rocks	$GSI = 1.30RMR' - 20.19$	$GSI = RMR' - 7$
Fine-grained sedimentary rocks		$GSI = 1.1RMR' - 12.5$
Metamorphic rocks	$GSI = 0.95RMR' - 10.44$	$GSI = RMR' - 4$
Plutonic rocks	$GSI = 1.08RMR' - 10.44$	$GSI = 1.15RMR' - 15$
Volcanic rocks		$GSI = 0.95RMR'$

Table 5: Quantitative formulations of the form $GSI = aJCond_{89} + bRQD$ (from Sanchez et al., 2016)

Lithology	Quantitative formulation
Various	$GSI = 1.28JCond_{89} + 0.48RQD$
Medium grained sedimentary rocks	$GSI = 0.76JCond_{89} + 0.53RQD$
Fine-grained sedimentary rocks	$GSI = 0.81JCond_{89} + 0.59RQD$
Metamorphic rocks	$GSI = 1.99JCond_{89} + 0.41RQD$
Plutonic rocks	$GSI = 1.47JCond_{89} + 0.45RQD$
Volcanic rocks	$GSI = 0.62JCond_{89} + 0.57RQD$

Some formulations that relate the GSI with the RMR (Bieniawski, 1976, 1989) can also be found in the technical literature; the most widespread was published by Hoek et al. (1995), presented in Equation 2.

$$\text{If } RMR' > 23, GSI = RMR' - 5 \quad (2)$$

Where:

RMR' – RMR in dry conditions and without correction for fracture orientation,

GSI – Geological Strength Index.

Ceballos et al. (2014) compared the values of the RMR' and the qualitative GSI in a database of 59 rock

Table 6: Quantitative formulations of the form $GSI = aRMR' + b$ (from Somodi et al., 2021)

Reference	Lithology	Empirical formulation
Hoek et al. (1995)	Various	$GSI = RMR' - 5$
Irvani et al. (2013)	Sandstones	$GSI = 0.739RMR' + 12.097$
Singh and Tamrakar (2013)	Metamorphic	$GSI = 0.7393RMR' - 4.3349$
Cosar (2004)	Schists and sedimentary rocks	$GSI = 0.42RMR' + 23.08$
Ali et al. (2014)	Gabbro, ultrabasic rocks	$GSI = 0.9932RMR' - 4.913$
Zhang et al. (2019)	Various	$GSI = 1.2092RMR' - 18.6143$
Siddique and Khan (2019)	Various	$GSI = 1.265RMR' - 21.49$

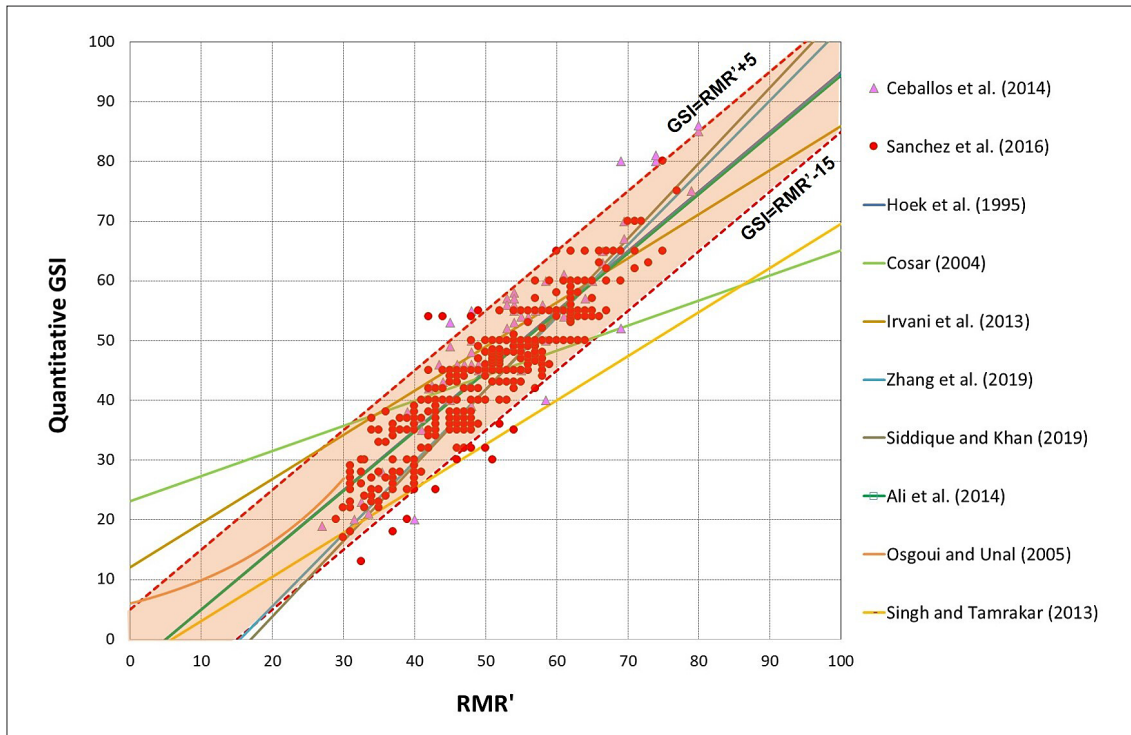


Figure 2: Compilation of GSI - RMR' relationships

outcrops located in Spain, concluding that most of the GSI values were in the range defined by $GSI=RMR'+5$ and $GSI=RMR'-15$. Similarly, Sánchez et al. (2016), to obtain correlations between the different geomechanical classifications, carried out studies in rock masses located in the Andes Mountains, a total of 298 rock outcrops and 61 tunnel faces were mapped corresponding to projects developed in Bolivia, Ecuador, Colombia, and Peru.

The formulas that relate the RMR' and GSI values according to Ceballos et al. (2014) and Sánchez et al. (2016) are summarized in Table 4.

Additionally, Sánchez et al. (2016) estimated the GSI for various rock types, modifying the coefficients of the relationship of Hoek et al. (2013). The proposed relationships are presented in Table 5, valid for their application in rock masses belonging to the Andes Mountains.

Similarly, several authors have recommended estimating the GSI value from the RMR', using a linear equation of the form:

$$GSI = aRMR' + b \tag{3}$$

Where:

RMR' – RMR in dry conditions and without correction for fracture orientation,

a, b – constants that depend on the lithology.

Somodi et al. (2021) compiled quantitative formulations in the form described previously, these are summarized in Table 6.

Most of the data considered in the formulations presented in Table 6 have been defined in rock masses with

GSI values between 30 and 80 points, so its application in rock masses of poor and very poor quality must be carried out with care. In this sense, for poor and very poor rock masses ($RMR' < 30$), Osgoui and Unal (2005) suggest an exponential relationship, which is presented in Equation 4.

$$GSI = 6e^{0.05RMR'} \tag{4}$$

Where:

RMR' – RMR in dry conditions and without correction for fracture orientation,

GSI – Geological Strength Index.

Figure 2 presents all the GSI - RMR' values from the database reported by Ceballos et al. (2014), Sánchez et al. (2016), and the GSI - RMR' formulations shown in Table 6. It is observed that the data from Ceballos et al. (2014), Sánchez et al. (2016), and the majority of GSI - RMR' formulations are found within the shaded area, which is delimited by the $GSI=RMR'+5$ and $GSI=RMR'-15$ relationships, defined by Ceballos et al. (2014).

In addition, it is observed that the formulation of Cosar (2004), defined for its specific application in schists and sedimentary rocks, provides more conservative GSI values for high RMR', and very optimistic values for low RMR', so its application must be made with care in these ranges. However, this correlation is within the shaded area for RMR's values between 30 and 70, which corresponds to most of the rock masses found.

The Singh and Tamrakar (2013) correlation, defined for metamorphic rocks in Nepal, provides more conserv-



Figure 3: View of rock mass 1



Figure 5: View of rock mass 3



Figure 4: View of rock mass 2 (from Jordá and Tomás, 2014)

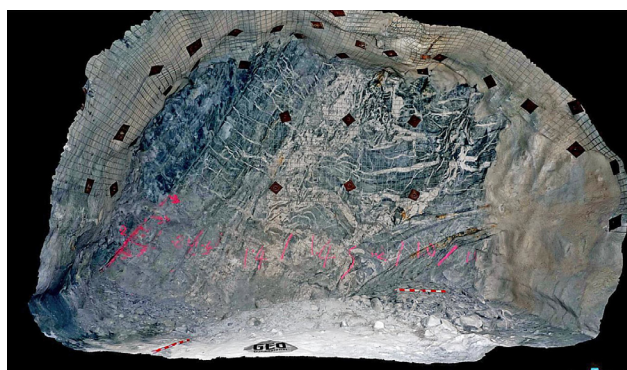


Figure 6: View of rock mass 4 (from <https://sketchfab.com/3d-models/underground-blast-face-3659ecc6bd684eazad45bdd561f2ac64>)

ative GSI values for RMR' values greater than 40. For lower values, it is within the expected range; however, this correlation has been defined with a base of rock masses with RMR' between 36 and 82, so its application must be done with care or avoided since it corresponds to a correlation for particular rock masses.

It is also observed that the nonlinear relationship of Osgoui and Ünal (2005) is within the shaded area. Hence, its application is valid for poor and very poor rock masses.

2. Methods

First, the dispersion of the GSI values calculated through qualitative methodologies has been studied. A virtual survey has been conducted on a group of geological engineers, mining engineers, and civil engineers from Peru, Spain, and Chile (40 participants). The purpose of this survey is to define the mean values, the standard deviation, and the coefficients of variation (COVs) of the GSI values and to verify if these values are similar to the reference values suggested by Hoek (1998) and Harr (1987). The survey presents a general photograph with the basic description of the four rock masses evaluated in this investigation and was conducted during August 2021 on the Google Surveys platform.

Table 7: RMR' of the rock masses evaluated

Rock mass	Lithology	RMR'
Rock mass 1	Diorite	71
Rock mass 2	Slate	45
Rock mass 3	Shale	31
Rock mass 4	Sandstone, shale, schist	55

Subsequently, the values of the GSI have been obtained through the quantitative formulations proposed by Somnez and Ulusay (2002), Cai et al. (2004), Russo (2009), Hoek et al. (2013), Ceballos et al. (2014), Sánchez et al. (2016) and the GSI - RMR' relationships; the results have been compared with the qualitative GSI, allowing to identify which is the formulation that best adjusts to the value estimated visually. Finally, the data reported in previous studies and the data obtained in this research have been integrated into a unique graph, concluding that the new data show the same trend observed in previous studies.

2.1. Rock masses evaluated

2.1.1. Rock mass 1

Outcrop of intrusive rock (diorite) located in a cut for the construction of a highway (Ramiro Prialé highway – Lima – Peru), hard rock mass (UCS = 60 MPa), with a

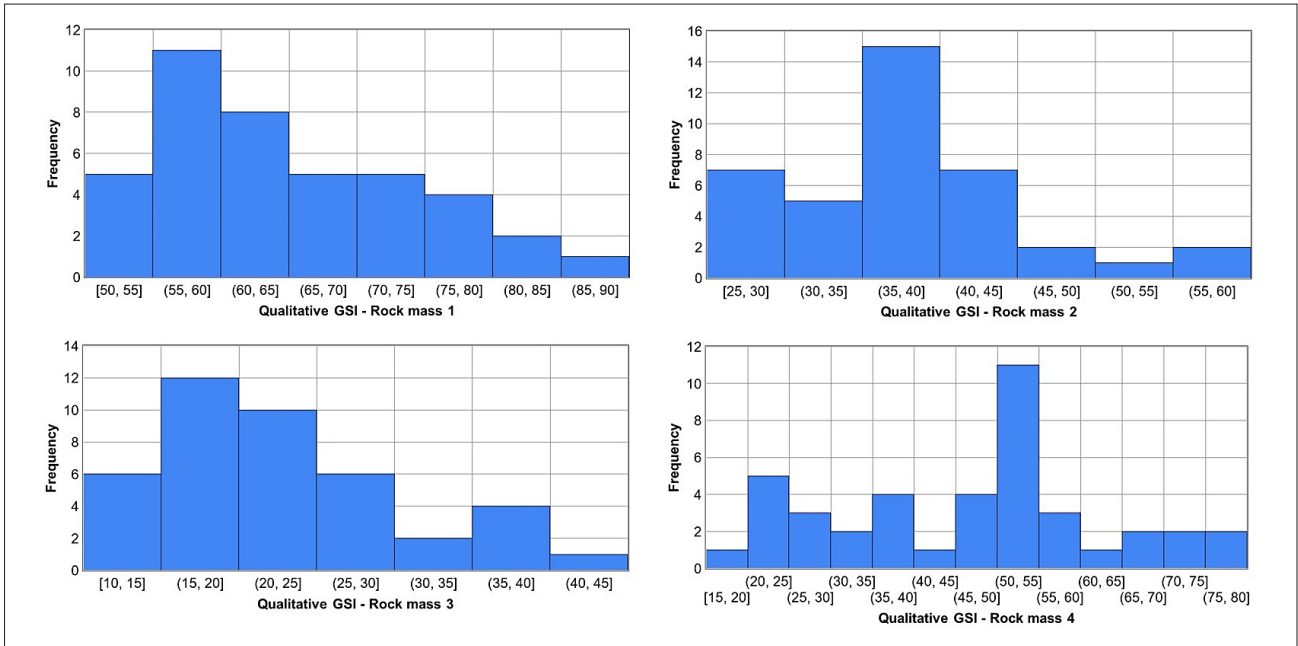


Figure 7: Dispersion of qualitative GSI values

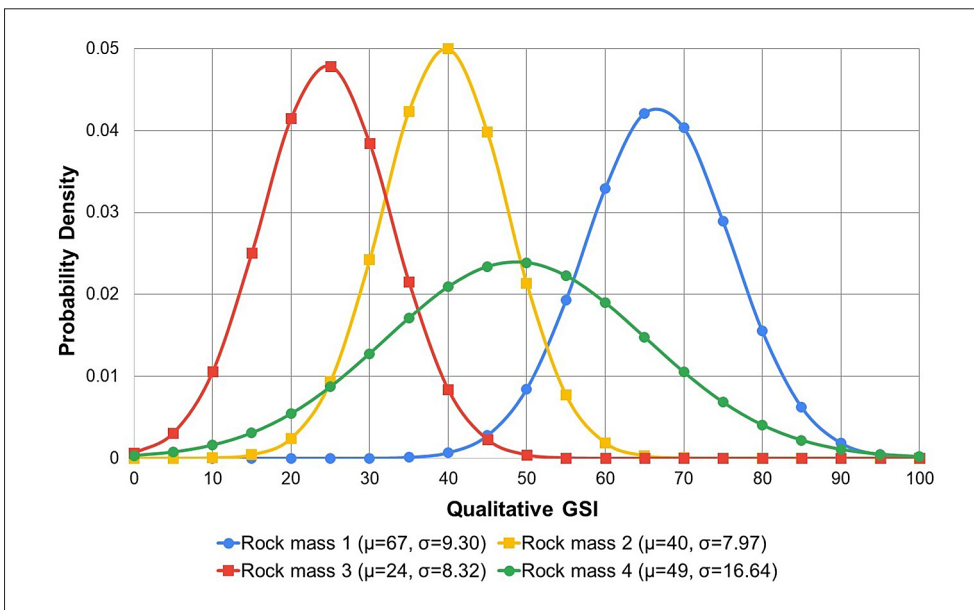


Figure 8: Normal distribution fit - qualitative GSI values

blocky structure, three main fracture systems, with spacing between 0.60 and 2.00 m, rough, planar, clean discontinuities, with some clayey fill, slightly altered and dry, $RMR' = 71$. (see **Figure 3**).

2.1.2. Rock mass 2

Slate rock outcrop located on the Izcuchaca - Quichuas Highway (Huancavelica - Peru), whose description and analysis are presented in **Jordá and Tomás (2014)**. The rock mass has an average UCS of 25 MPa, joint spacing 60 - 200 mm, persistence greater than 20 m, undulating/smooth discontinuities, opening greater than 5 mm, slight to moderate alteration, with hard fill, $RQD = 45\%$, $RMR' = 45$ (see **Figure 4**).

2.1.3. Rock mass 3

Pseudo-metamorphized rock mass (slate shale) located on the campus of the National University of Engineering (Lima - Peru), intensely fractured, with an average spacing between fractures of 0.05 m, low resistance to simple compression ($UCS < 5MPa$), the discontinuities are persistent and have an opening of up to 5 mm, partially with hard fill, the rock mass is wet and altered, $RMR' = 31$. (see **Figure 5**).

2.1.4. Rock mass 4

Unlike the three previous cases found on slopes, in case 4, there is a rock mass corresponding to an underground excavation (see **Figure 6**). The rock mass corre-

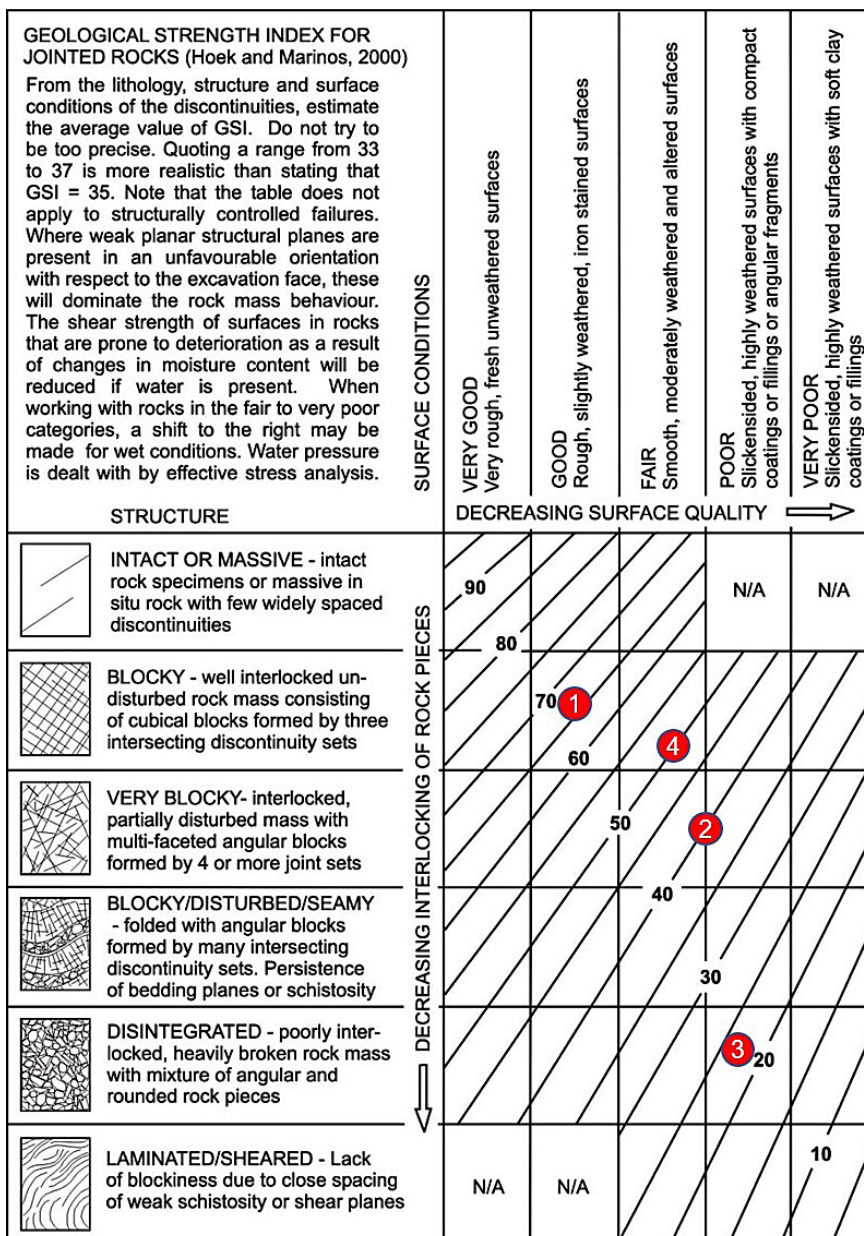


Figure 9: Summary of qualitative GSI (mean values)

sponds to a gold-bearing quartz vein gallery embedded in sandstones, lutites, and folded schists, with an approximate width of 7 m and RMR' = 55. This rock mass is available in the sketchfab repository, where the rock mass can be viewed in 3D at the link <https://sketchfab.com/3d-models/underground-blast-face-3659ecc6b-d684ea2ad45bdd561f2ac64>.

The summary of the RMR' values defined for each rock mass is presented in Table 7.

3. Results

3.1. Qualitative analysis

The survey results are presented graphically in Figure 7, considering GSI intervals every five points; these data

have been statistically processed, adjusting to a normal distribution curve, defined by the mean value (μ) and by the deviation standard (σ). Figure 8 shows the normal distribution curves of the four evaluated rock masses.

Figure 8 shows that rock masses 1, 2, and 3 have standard deviation values close to 10 points, which indicates that 68.2% of the data is in the confidence interval defined by $\mu \pm \sigma$ or $GSI \pm 10$, which is consistent with the studies by Hoek et al. (2013) and Winn and Wong (2018). It is also observed that unlike rock masses 1, 2, and 3, the normal density function of rock mass 4 presents a more flattened and elongated shape, due to the pronounced dispersion of the GSI values reported in the survey, this is reflected in a higher value of the standard deviation ($\sigma=16.64$), greater than 10 points. The expla-

Table 8: Statistical parameters – qualitative GSI

Rock mass	Mean value (μ)	Standard Deviation (σ)	Coefficient of Variation (COV)	COV Classification
rock mass 1	67	9.30	0.14	Low - moderate
rock mass 2	40	7.97	0.20	Moderate
rock mass 3	24	8.32	0.35	High
rock mass 4	49	16.64	0.34	High

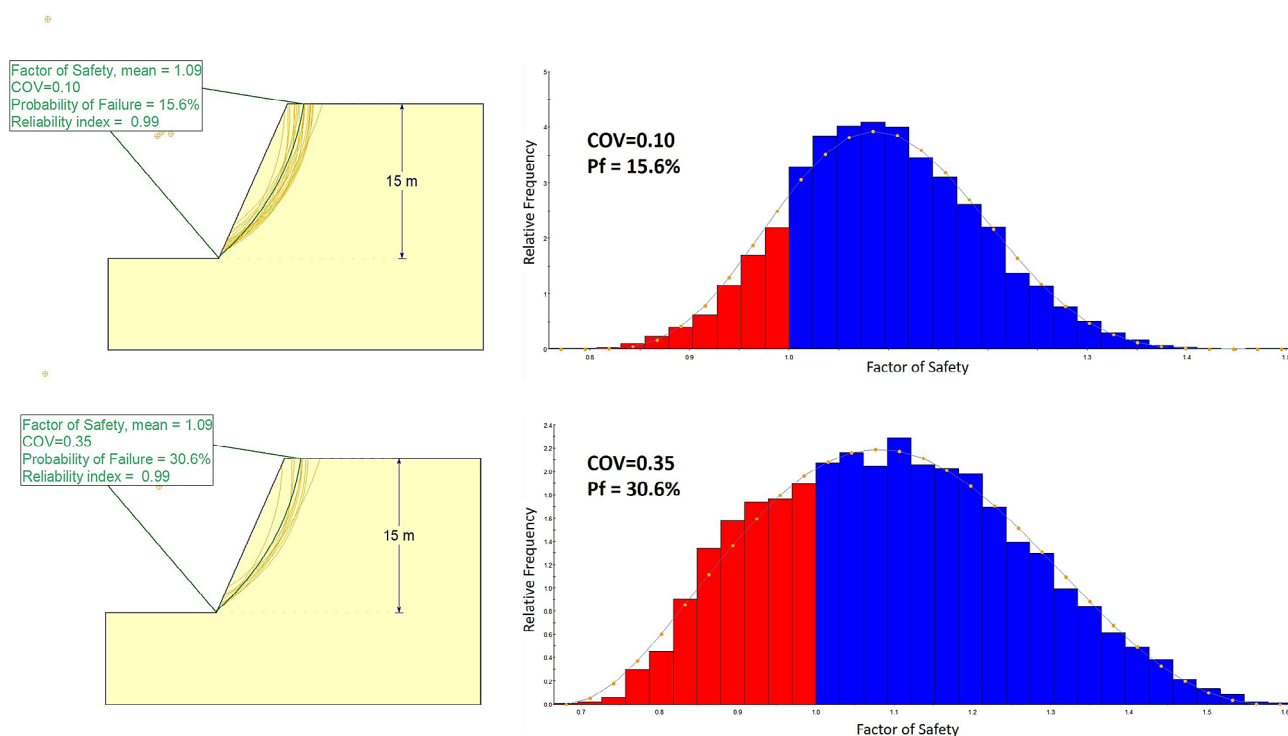


Figure 10: Results of the probabilistic analysis of the trial slope

nation for this behaviour in rock mass 4 is attributable to the presence of quartz veinlets; according to what has been observed in engineering practice, this tends to confuse many field evaluators, as they erroneously consider that the presence of any discontinuity is necessarily equivalent to a decrease in the rock mass quality. Therefore, although the discontinuities present a gold-bearing quartz fill, with resistance even greater than the host rock, it is common for this type of rock mass to be reported with low GSI values.

The average qualitative GSI values of the four rock masses analyzed have been plotted on a **Hoek and Marinos (2000)** chart, presented in **Figure 9**.

Hoek (1998) suggests reference values of the coefficients of variation (COV) of the parameters involved in the Hoek-Brown criterion. It is indicated that the values of UCS, m_i , and GSI fit a normal distribution with coefficients of variation of 0.25, 0.125, and 0.10, respectively. **Harr (1987)** classifies the coefficients of variation as low ($COV < 0.10$), moderate ($0.15 < COV < 0.30$), and high ($COV > 0.30$), indicating that the values suggested by **Hoek (1998)** are among the low ranges. and moderate. However, the values presented in **Table 8**, calculat-

ed as a result of statistical analysis, indicate COV values classified as moderate in the case of rock masses 1 and 2 and high in the case of rock masses 3 and 4.

To evaluate the influence of COV on the behaviour of the rock mass, a probabilistic stability analysis of a 15 m-high slope excavated in rock mass 3 has been carried out. For the UCS and m_i parameters, the suggested COV values by **Hoek (1998)** have been considered, and for the GSI, both, the COV values proposed by **Hoek (1998)** and the one obtained in the survey were considered.

The probabilistic analysis results presented in **Figure 10** indicate that although the average safety factors do not vary since the mean value of GSI in both cases is the same, the value of the probability of failure (Pf) of the slope has practically doubled, increasing from 15.6% to 30.6%.

3.2. Quantitative analysis

The GSI value of the four rock masses studied has been estimated using the quantitative formulations of **Hoek et al. (2013)**, **Cai et al. (2004)**, **Russo (2009)**, **Sonmez and Ulusay (2002)**, and the GSI - RMR³ rela-

Table 9: Geomechanical parameters of rock masses

Parameter	Rock mass 1	Rock mass 2	Rock mass 3	Rock mass 4
UCS (MPa)	60	25	1-5	40
RQD (%)	88	25	22	70
Spacing of discontinuities (m)	0.60-2.00	0.06-0.20	0.05	0.20
Persistence (m)	3-10	>20	10-20	3-10
Aperture (mm)	1-5	>5	1-5	1-5
Roughness	Rough	Undulating/smooth	Undulating	Undulating, rough
Infilling	None	None	Hard filling < 5mm	Hard filling < 5mm
Weathering	Slightly	Slightly to moderate	Decomposed	Slightly
Groundwater conditions	Dry	Dry	Damp	Dry
JCond ₈₉	17	11	7	15
J _w (undulation)	1	1.5	1.5	2
J _s (roughness)	2	1	1	2
J _A (alteration)	1	2	6	1
J _C (joint condition factor)	1	0.75	19	4
V _b (block volume)	0.68 m ³	720 cm ³	125 cm ³	8000 cm ³
J _v (disc/m ³)	3.8	38	60	15
SR (structure rating)	56.4	16	8.1	32.4
R _r (roughness)	5	1	1	3
R _w (alteration)	5	4	0	5
R _f (infill)	4	6	4	4
SCR (surface condition rating)	14	11	5	12
Structure	Blocky	Very blocky	Disintegrated	Blocky
Joint Condition	Good	Fair-Poor	Poor	Fair

Table 10: GSI values calculated with a qualitative approach

Reference	Rock mass 1	Rock mass 2	Rock mass 3	Rock mass 4
Hoek et al. (1995)	66	40	26	50
Sonmez and Ulusay (2002)	61	36	19	46
Cai et al. (2004)	58	36	22	59
Russo (2009)	69	22	8	58
Hoek et al. (2013)	70	29	22	58
Ceballos et al. (2014)*	72	41	25	53
Ceballos et al. (2014)**	66	32	19	51
Sanchez et al. (2016)*	65	39	25	49
Sanchez et al. (2016)**	67	41	27	48
Sanchez et al. (2016)***	65	32	23	49
Zhang et al. (2018)	67	36	19	48
Siddique and Khan (2019)	68	35	18	48
Singh and Tamrakar (2013)	NA	29	19	NA
Cosar (2004)	NA	NA	NA	46
Osgoui and Ünal (2005)	NA	NA	19	NA
Quantitative GSI (average)	66	35	22	50

Notes:

(*) GSI calculated from the RMR' (with the general correlation)

(**) GSI calculated from RMR' (depending on lithology)

(***) GSI calculated based on RQD and JCond₈₉

NA: This does not apply to the lithology or the rock mass quality

Table 11: Comparison of results – qualitative and quantitative approaches

Rock mass	Mean value (μ)		Standard deviation (σ)		Coefficient of Variation (COV)	
	Qualitative	Quantitative*	Qualitative	Quantitative*	Qualitative	Quantitative*
Rock mass 1	67	66	9.30	3.86	0.14 (Low – moderate)	0.06 (Low)
Rock mass 2	40	35	7.97	4.30	0.20 (Moderate)	0.12 (Low-moderate)
Rock mass 3	24	22	8.32	3.17	0.35 (High)	0.15 (Low-moderate)
Rock mass 4	49	50	16.64	4.25	0.34 (High)	0.09 (Low)

Notes:

(*) Russo’s (2009) formulation is not considered because it presents discrepant values compared to the other approaches.

tionships. The calculation parameters involved in these formulations are presented in **Table 9**, obtained from the field characterization, and **Table 10** shows the summary of the GSI values calculated quantitatively.

The **Sing and Tamrakar (2013)** relationship has been developed for metamorphic rocks, so it has only been applied to rock masses 2 and 3. The **Cosar (2004)** relationship has only been used to rock mass 4, corresponding to schists and sedimentary rocks. The nonlinear relationship of **Osgoui and Ünal (2005)** is only applicable to rock mass 3 corresponds to a poor-quality rock mass ($RMR=23$).

4. Discussion

In the calculation of the quantitative GSI, no significant variation is observed using the general formulation

of **Sánchez et al. (2016)** and the formulation of the same author considering the lithology; the maximum difference observed varies between 1 and 2 points, which increases up to 7 points if the formulation in terms of RQD and $JCon_{80}$ is used. Regarding the formulations of **Hoek et al. (2013)**, **Cai et al. (2004)**, **Russo (2009)**, and **Sonmez and Ulusay (2002)**; it is observed that the **Russo (2009)** formulation provides lower GSI values compared to the others, especially in the case of rock masses 2 and 3, which have regular and poor quality. This trend had already been observed in the works of **Vásárhelyi et al. (2016)** and **Wing and Wong (2018)**.

In terms of the statistical parameters, in the quantitative approach, the dispersion of the results is lower compared to the qualitative approach; the results are presented in **Table 11**, where the average values do not suffer a significant variation; however, the standard deviation

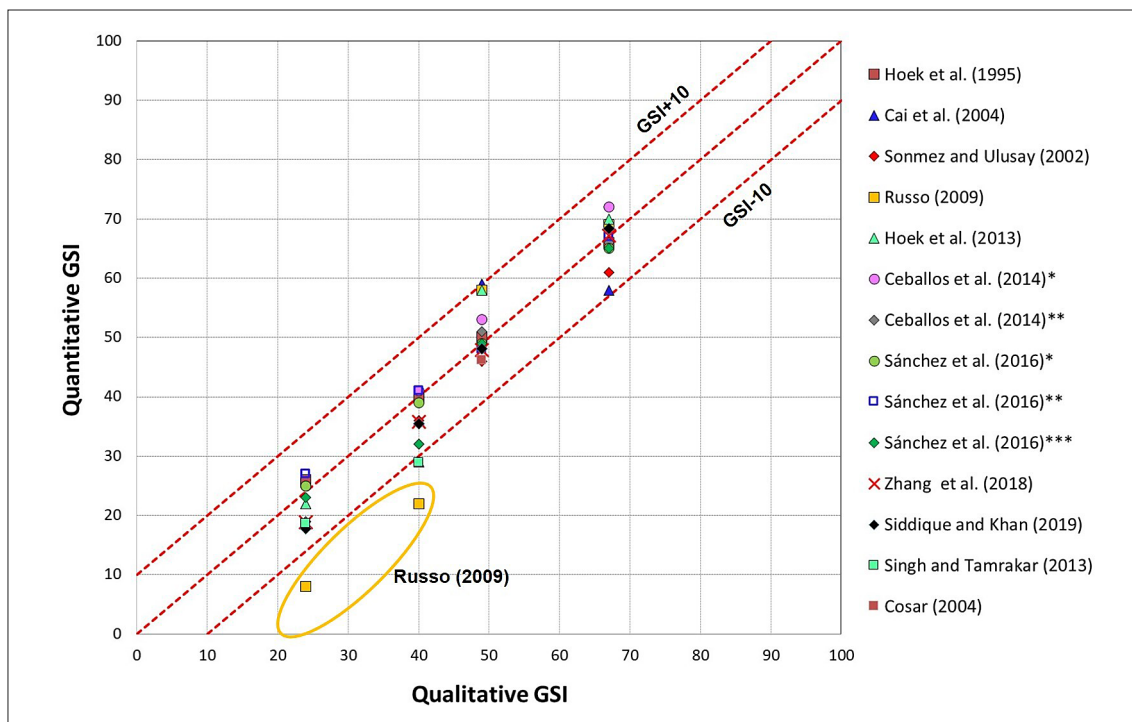


Figure 11: Dispersion of GSI values calculated with quantitative approaches

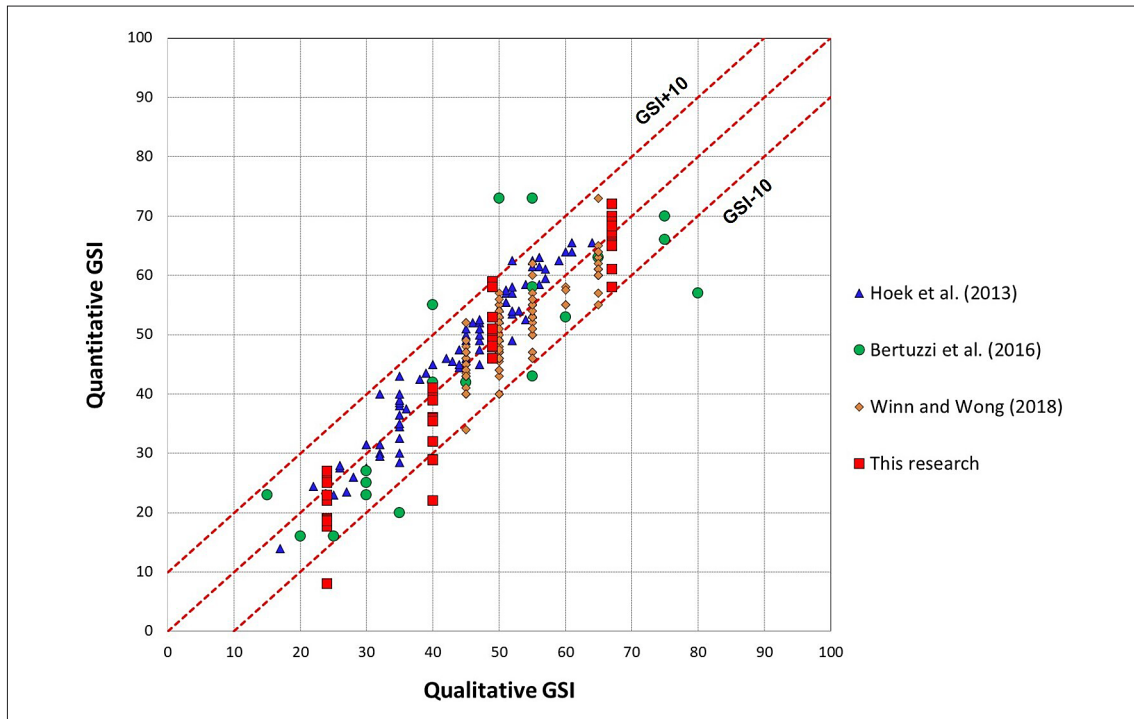


Figure 12: Compilation of own data and data reported by others

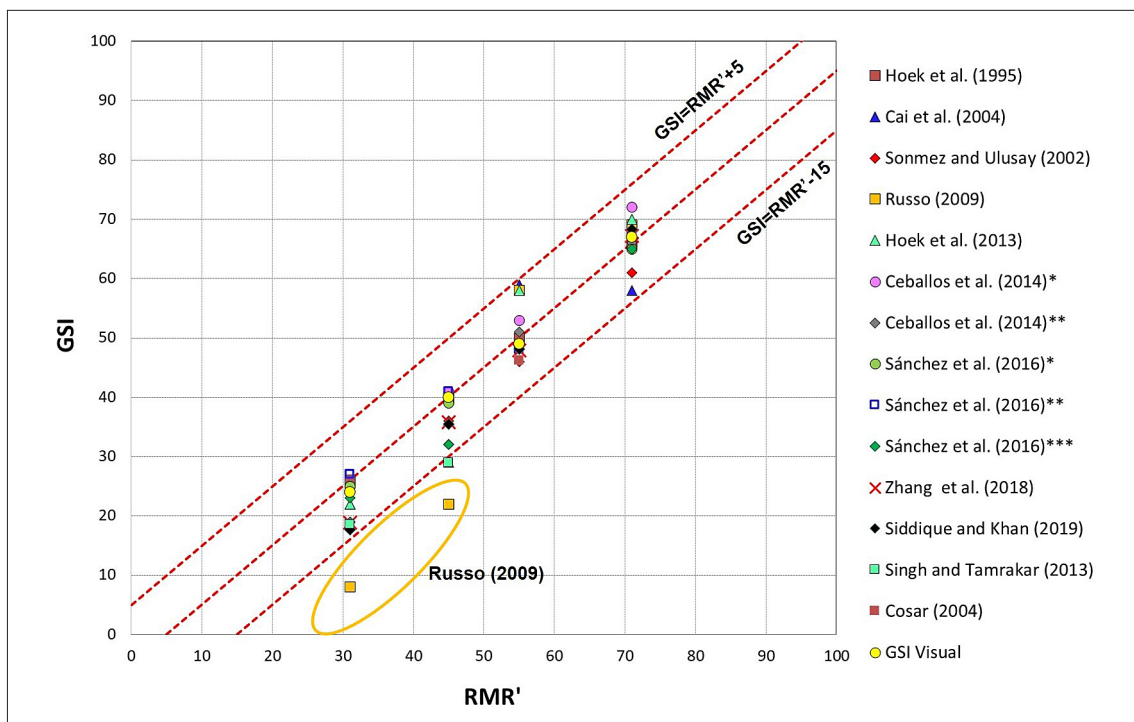


Figure 13: Comparison of RMR' – GSI results in the four rock masses evaluated

values have been reduced between 46 and 74%, resulting in a reduction in the coefficients of variation, which are between 0.06 and 0.15. These results are similar to the values by **Hoek (1998)**, who suggests a COV of 0.10 for the GSI. The smaller dispersion of the results with the quantitative approach is because the formulations are

presented in terms of known rock mass parameters with which field engineers are more comfortable, such as the RQD, J_v , $J_{Cond_{89}}$, or RMR'.

Figure 11 graphically presents the dispersion of the results, where a tendency of the GSI values to be within the range that defines a variation of $GSI \pm 10$ points is observed.

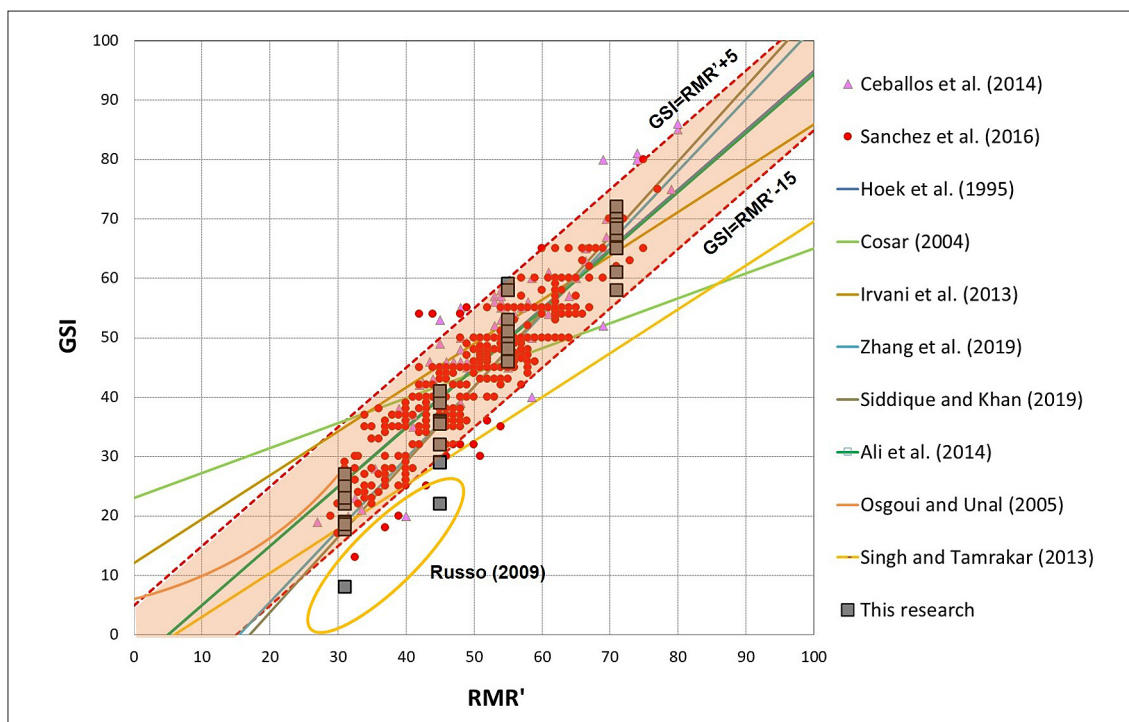


Figure 14: Compilation of own data and reported by others, GSI – RMR' relationships

Figure 12 includes the results obtained in this research and the results of previous studies carried out by Hoek et al. (2013), Bertuzzi et al. (2016), Winn and Wong (2018), and Winn et al. (2019); the tendency of the GSI values calculated with quantitative approaches to be in the region defined by $GSI_{\text{qualitative}} \pm 10$ points is clearly observed.

On the other hand, if the comparison graph between the RMR' and the GSI (see Figure 13) is considered, similarly to what was reported by Ceballos et al. (2014) and Sánchez et al. (2016), it is observed that most of the data is within the range suggested by Ceballos et al. (2014), defined between the lines $GSI = RMR' + 5$ and $GSI = RMR' - 15$. Therefore, it is verified that this is the confidence interval of the GSI calculated from the RMR'. This graph also shows that the values of Russo et al. (2009) are outside the indicated confidence interval, providing very conservative values.

Figure 13 also shows that the average GSI values estimated visually (qualitative approach) fit the line defined by the relationship $GSI = RMR' - 5$, so that, in general, and because of the results, they constitute a reasonably reliable and straightforward approximation for the calculation of the GSI from the RMR'.

Finally, by combining the data from Ceballos et al. (2014), Sánchez et al. (2016), and those originated in this research (see Figure 14), it is observed that the trend of all the data is similar. Therefore, it is confirmed that the confidence range to calculate the GSI from the RMR' is between $GSI = RMR' + 5$ and $GSI = RMR' - 15$, as indicated by Ceballos et al. (2014).

5. Conclusions

Although the GSI system was developed to be used exclusively with the Hoek-Brown criterion in rock mass strength and deformability estimation, this system continues to evolve. It has been successfully applied for other purposes, such as rock mass evaluation, excavability, karsticity, permeability, residual resistance parameters, and support in tunnels.

The qualitative or visual methodologies provide a high subjective component, which has been observed even considering that in the survey conducted in this research, all the participants had experience in characterizing rock masses. The high variability of the GSI values obtained with the qualitative approach is reflected in the coefficients of variation (COVs) of the rock masses evaluated in this investigation, which are classified as low to moderate in the case of rock masses 1 and 2, and high in the case of rock masses 3 and 4, exceeding the values suggested by Hoek (1998) and Harr (1987). They assign low COV values for the GSI.

In the particular case of rock mass 4, there is a more elongated and flattened normal distribution curve than the other three cases, with variable GSI values between 15 and 80 points. The explanation given for this behaviour is attributable to the presence of quartz veinlets, which tends to confuse some of the rock mass quality evaluators because, in general, the presence of filler in the joints reduces the quality of the rock mass; however, in this case, the fill material has a higher resistance to the encasing rock.

The GSI values calculated with the quantitative formulations present a lower dispersion concerning those evaluated qualitatively, which is reflected in the values of the COVs observed in the four rock masses evaluated. With the qualitative approach, the COV values are between 0.14 and 0.35 (moderate to high); however, with the quantitative approach, the COV values are between 0.06 and 0.15 (low to moderate), getting closer to the value of 0.10 suggested by **Hoek (1998)** and **Harr (1987)**. Of all the quantitative formulations analyzed, **Russo (2009)** is the one that provides the most conservative values, especially for GSI values less than 50; this trend has already been observed in previous studies. The average values obtained with both methodologies show differences of less than 5 points.

Quantitative formulations should be used with caution, taking into account the characteristics of the rock masses on which the relationships have been defined.

Although the database of **Ceballos et al. (2014)** and **Sánchez et al. (2016)** correspond to rock masses located in Spain and the Andes Mountains respectively, it is observed that in both cases, the majority of data are within the range bound by the relationships $GSI=RMR^2+5$ and $GSI=RMR^2-15$, this trend is also observed in the four rock masses evaluated in this investigation, so this range can be considered as the confidence interval to obtain the GSI value from RMR^2 . However, GSI - RMR^2 relationships have generally been defined in rock masses with GSI values between 30 and 80 points, so their application in rock masses of poor and very poor quality must be made with care.

Recommendations

It is recommended to expand the number of rock masses evaluated and include complex rock masses, such as volcanic rocks.

In the survey conducted to estimate the qualitative GSI, 90% of the participants assigned a single GSI value to each rock mass evaluated, only 10% indicated a range of values. However, the majority of the GSI charts suggest that one should not try to be too precise in its determination and that it is more realistic to establish a range of values. For this reason, it is necessary to emphasize this point prior to the execution and supervision of the field data collection.

In the geotechnical analyzes of slopes or other structures that involve rock masses, it is advisable to consider the variability of the GSI through probabilistic analyses to define the safety factor and the probability of failure, which according to the results obtained in this investigation can be increased by up to 50%.

The development of virtual reality is a tool that has begun to be used successfully for training in mining and civil geomechanics. It could be incorporated into the study of rock masses and the estimation of the GSI.

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SAŽETAK

Analiza osjetljivosti procjene geološkoga indeksa čvrstoće (GSI) na temelju kvalitativnih i kvantitativnih metoda

U ovome istraživanju evaluirana je disperzija vrijednosti geološkoga indeksa čvrstoće (GSI) koje su određene kvantitativnim i kvalitativnim metodološkim pristupima na četiri stijenska izdanka različite geomehaničke kvalitete. Subjektivna komponenta povezana s kvalitativnim ili vizualnim metodama proučavana je provođenjem virtualnoga istraživanja u skupini od četrdeset sudionika koju su činili inženjeri građevinarstva, geologije i rudarstva iz Perua, Španjolske i Čilea. Oni su analizirali obrazac s fotografijom i osnovnim opisom svake stijenske mase. Rezultati su pokazali kako vrijednosti GSI-ja imaju normalnu razdiobu koju karakterizira srednja vrijednost i standardna devijacija, koje su u nekim slučajevima imale umjerene do visoke koeficijente varijacije (COV). Ovaj rad također uključuje proučavanje disperzije vrijednosti GSI-ja dobivenih kvantitativnim oblikovanjem, a koje su ocijenjene i ugrađene u regionalne baze podataka kako bi se procijenili trendovi, uglavnom u odnosima GSI-ja i RMR-a. Rezultati pokazuju da su prosječne vrijednosti GSI-ja određene obama pristupima slične. Međutim, vrijednosti COV-a kod kvantitativnih metodologija klasificirane su kao niske do umjerene, a to je bolje prilagođeno predloženim vrijednostima COV-a za GSI. Unatoč tome kvantitativne metodologije moraju se primjenjivati pažljivo, uzimajući u obzir na koji su način definirani parametri kojima se utvrđuju karakteristike stijenskih masa.

Ključne riječi:

GSI, stijenska masa, mehanika stijena, kvalitativne metode, kvantitativne metode, osjetljivost

Author's contribution

The author prepared the whole work.