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PROPOSAL OF A NEW METHOD FOR CALCULATING GSI

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Abstract: Rock mass classification systems are simple but valuable tools for the qualitative and quantitative classification of rock masses and for the planning of the fortification of mining excavations. Unfortunately, in the prefeasibility phase, not all the information needed for a preliminary project evaluation is always available, and one of the few available information is the RQD, however, although it is very necessary to determine the GSI to analyze the failure criteria, it is difficult to obtain at this stage of the project. Although several correlations between the different classification systems have been identified, the most abundant ones are those relating GSI as a function of RMR and as a function of Barton's Q. As for GSI relationships as a function of RQD, only three recent relationships are available: Hoek et al. (2013), Santa et al. (2019), and Xia et al. (2022). Therefore, this study presents a correlational analysis of the GSI and RQD classification systems, using robust nonparametric statistics, with the aim of determining an expression to estimate GSI in the field. Among the results, it is highlighted that better GSI prediction results are obtained when 25% < RQD ≤ 87%, with a maximum error of ±14 points, improving the estimation accuracy by 62% with respect to current proposals. Despite the above, the difficulty of interpreting more accurately the specific geological characteristics of each rock mass remains.

Keywords: *GSI, geotechnics, RQD, classification of rock mass, correlation*

1. INTRODUCTION

Rock mass classification systems are simple but highly valuable tools for the qualitative and quantitative classification of relevant parameters for rock mass engineering design and excavation fortification planning. These systems are based on tests and field obser-

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vations (Rodríguez et al. 2018; Hassanpour et al. 2022; Sachpazis 1986). This classification is essential for mining engineering and to contributes to the development of geotech-
nical applications, for which the classification systems RMR, MRMR, Q, GSI, among others, have been proposed, and whose purpose has been to contribute to the improvement of the stabilities of natural and anthropic constructions (Garzón-Roca et al. 2021).

Unfortunately, in the early stages of the mining project cycle, such as Profile Engineering and Prefeasibility (or Conceptual Engineering), not all the information necessary for a preliminary evaluation of the project is always available, and it is precisely in these early stages, where information is scarce, that one of the few available information is the Rock Quality Designation (RQD), which is considered elementary information (Zhang 2016; Shen et al. 2014; Huaman et al. 2017).

In many cases the RQD is the only rock mass classification index available at these stages of the project, since other classification methods are more expensive (due to the amount of additional laboratory tests that must be performed) and/or require a lot of experience of the professional who performs the observations (Santa et al. 2019). Such is the case of the RMR, Q, GSI methods. Thus, the use of empirical relationships proposed throughout the history of geomechanical research is resorted to.

Although several correlations between the different classification systems have been identified, the most abundant are those relating GSI as a function of RMR and as a function of Q, which require much more information and precision to determine. As for GSI relationships as a function of RQD, only three recent relationships are available: Hoek et al. (2013), Santa et al. (2019), and Xia et al. (2022).

This study presents an analysis of two of the currently used classification methodologies: Geological Strength Index and Rock Quality Designation, with the objective of determining a mathematical expression that allows quantitative and approximate estimation of GSI in field work, thus contributing to the estimation of rock massif quality classification in the prefeasibility stages of the mining project, since it is an indicator that will be used more and more frequently (Turner 2006).

2. GEOMECHANICAL CLASSIFICATIONS

2.1. GEOLOGICAL STRENGTH INDEX (GSI)

Hoek et al., in 1998, proposed a new geomechanical classification system called the Geological Strength Index, whose objective was to categorize rock masses in the field through geological observations that could be quickly and easily performed by engineers or geologists, to be used in the Hoek and Brown breakage criteria, since the results of the breakage criteria for low-quality massifs, using the Rock Mass Rating (RMR) classification system, did not seem reliable for this type of rock mass. The procedure consisted of the analysis of samples of very delicate materials found in the construction of tunnels in Greece, where they managed to arrive at the current form of GSI (Marinos et al. 2005). From the study, Hoek states that the GSI is determined from geological field observations, comparing the appearance of the massif at the level of structure and surface condition. At the level of structure, the following are considered: the degree of alteration suffered by the rocks; union that exists between them and their cohesion. The surface aspects are alteration; erosion and/or type of texture; type of coating (Priest and Hudson 1976).

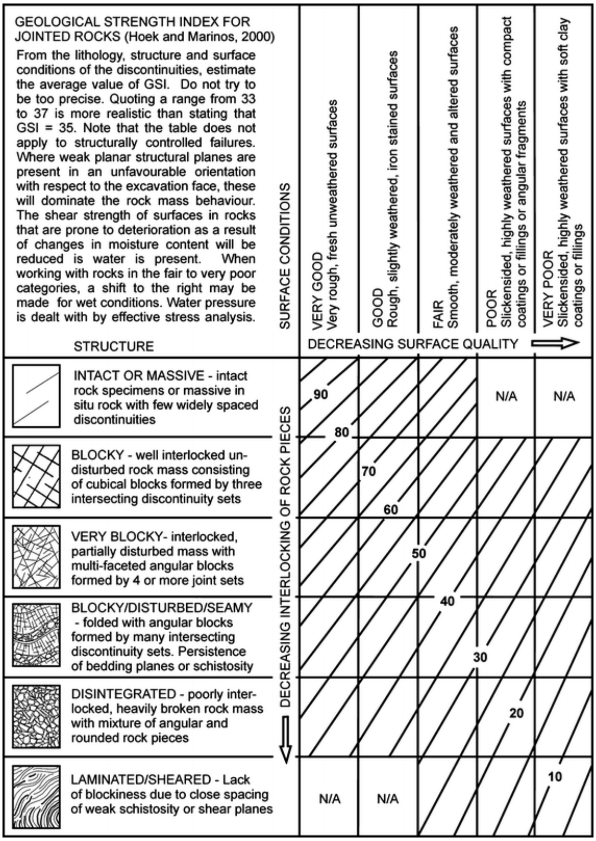

Fig. 1. General chart for GSI estimates from geological observations (Marinos et al. 2005)

Table 1. Description and characterization of rock mass for GSI (González de Vallejo et al. 2002)

Rock mass quality	Class	Score/ranking
Very poor	V	$0 \leq GSI \leq 20$
Poor	IV	$20 < GSI \leq 40$
Fair	III	$40 < GSI \leq 60$

Rock mass quality	Class	Score/ranking
Good	II	60 <GSI ≤ 80
Very good	I	80 <GSI ≤ 100

The results of these aspects are compared with those of Fig. 1 and it is recommended to define a quantitative interval rather than a single value (Bieniawski 2011). The descriptions and scores assigned are shown in Table 1.

2.2. ROCK QUALITY DESIGNATION (RQD)

The procedure used started with the publication "Technical description of rock cores for engineering purposes" (Deere 1963) where he describes and categorizes the characteristics of discontinuities: spacing, orientation, surface and fill, lithology, and hardness. He then drilled and measured the RQD, finally arriving at the expression that is known today, which is presented in Eq. (1).

$$\%RQD = \frac{\Sigma Length\ of\ core\ pieces > 10\,cm}{Total\ length\ of\ core\ run} \cdot 100\,. \tag{1}$$

The 10 cm (4 inches) minimum sample limit was determined by the author (Deere) and his collaborators, who considered it the minimum recovery length for drilling in good quality rock mass, which contains three to four families of faults with moderate spacing (Deere 1963; Deere 1989).

Deere's original proposal is determined by the extraction and the continuity of the diamond core pieces recovered. This is an indicator of the degree of fracturing of the rock mass, through which the quality of the rock mass is classified (Table 2) and can be calculated from the Eq. (1).

Table 2. Description and Characterization of Rock Mass for RQD (González de Vallejo et al. 2002)

Rock Mass Quality	Score/Ranking (%)
Very poor	RQD ≤25
poor	25 < RQD ≤ 50
Fair	50 < RQD ≤ 75
Good	75 < RQD ≤ 90
Very good	90 < RQD ≤ 100

There are three limitations to the RQD:

- Dependence of the RQD value on borehole orientation (Palmstrom 2005);
- The extreme values of the RQD do not consider the joint distribution of the extracted drill cores;
- The minimum recovered length of the core (4 inch ≈ 10 cm).

Despite the limitations described above, the RQD is still widely used in applied geomechanics and is even used as one of several input parameters for other massif classification systems, such as RMR and Q.

Hoek, Carter, and Diederichs, in their research "Quantification of the Geological Resistivity Index chart" (Hoek et al. 2013) present a proposal for the quantification of the GSI based on other parameters, in this case, they associate it with the Joint Condition ($J_{cond.89}$) and the RQD. The research process consisted of generating a GSI graph associating the 5 divisions of surface quality to the Joint Condition of the RMR rock mass classification system of 1989 by Bieniawski; and then, associating the 5 divisions of the block structure scale the RQD parameter of Deere (1964). This process enabled the authors to conclude a new empirical relationship, Eq. (2) (Hoek et al. 2013).

$$GSI = 1.5 \cdot J_{cond.89} + \frac{\%RQD}{2}\,. \tag{2}$$

Based on Hoek, researchers Xia, Chen, Wang, Pang, and Liu perform a numerical estimation of the GSI values and the D parameter of the Hoek and Brown breakage criterion, using the RQD and the discontinuous surface condition (SCR) that depends on the infill, weathering, and roughness classifications of the rock to give correction and bring it closer to the original definition of GSI (Xia et al. 2022). The described and corrective relationship is the one expressed in Eq. (3).

$$GSI = 2.5 \cdot SCR + \frac{\%RQD}{2}\,. \tag{3}$$

Santa, Gonçalves and Chaminé, set out to contribute to the understanding of the GSI (version Hoek et al. 2013), for which they mapped and geotechnically analyzed the discontinuities of 300 m of subway gallery, in Portugal (Santa et al. 2019).

They concluded that the GSI in its 2013 version tends to be more conservative than that of its original 1998 version. They also determined that RQD is more influential than Jcond.89 due to its magnitude, along with which they determined an empirical relationship between RQD and GSI in its 2013 version, which is observed in Eq. (4) and whose statistical correlation is high, and has no associated error in its estimation.

$$\mathrm{GSI}_{2013} = 0.5886 \cdot \%\mathrm{RQD} + 21.119. \tag{4}$$

3. DESCRIPTION

3.1. DATABASE

The sampling units on which the database is composed correspond to diamond drilling drilled in rocks, where it has been possible to determine the RQD, mineralogy, structures, elastic properties, resistivity properties, and GSI. This type of sampling is with non-probabilistic classes of secondary origin (targeted sampling). In this way, we have completed the construction of the database with more than 5000 m diamond holes drilled.

3.2. SCOPE OF WORK

The research presented has a correlational scope and evaluates the type of empirical correlation GSI and RQD applied in mining, with the significant benefit of reducing economic costs and time of the first estimation.

3.3. WORK METHODOLOGY

The working methodology corresponds to the non-experimental quantitative type (Hernández 2018) through the creation of the inventory or data bank, for its classification and measurement of relevant parameters from the perspective of geotechnical quality classification (Fig. 2) here it is visible that the drilling collected with their RQD and GSI measurement.

For those investigations where GSI was not determined by traditional methods, the expressions proposed by Zhang and Einstein (2004) and Gokceoglu et al. (2003), which relate both RQD and GSI to the modulus of elasticity of the rock mass, are used.

The research is of an exploratory type, since it is a topic that is little investigated when there is little field information, a complex and common situation in the early stages of a mining project (Zhang 2016; Shen et al. 2014; Huaman et al. 2017).

The direct deductive method is used to test the hypothesis stated in the research problem: is it possible to reliably estimate the GSI from the RQD measurement? To prove or disprove this hypothesis, a descriptive statistical study of the database was conducted to determine the best correlation and data processing adjustment (Fig. 2).

By means of the Shapiro-Wilk test (Table 3) and graphic analysis (Fig. 2) it is determined that none of the study variables behaves in a Gaussian way, given that the p-value is less than the critical value 0.05; this allows rejecting the null hypothesis of the test, and, therefore, there is sufficient evidence to say that the RQD and GSI variables are not normally distributed.

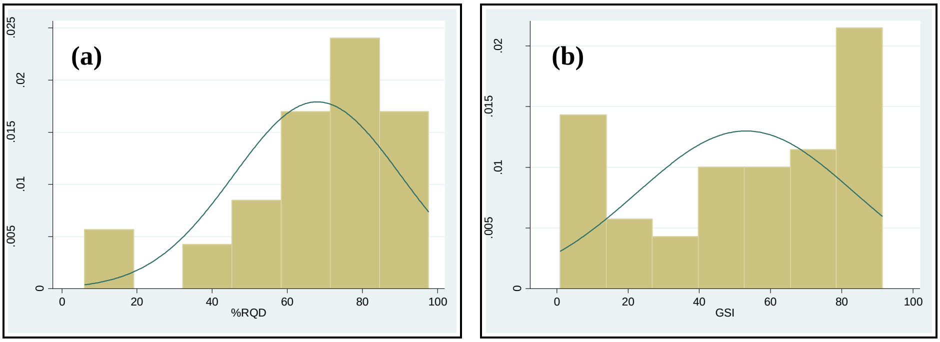

Fig. 1. Data distribution densities for variables (a) %RQD and (b) GSI. Own elaboration. Note: Software Stata 14.2 Windows software, College Station, Texas 77845 USA, StataCorp.

Table 2. Shapiro-Wilk test. Own elaboration

Variable	Prob > z
RQD	0.00012
GSI	0.00012

Note: Software Stata 14.2 Windows software. College Station, Texas 77845 USA, StataCorp.

Thus, it is established that the appropriate correlation test to analyze the data is Spearman's test (nonparametric) for the analysis of the relationship between the variables presented (Flores-Ruiz et al. 2017; Martínez et al. 2009; Ramalle and Andrés de Llano 2003; Loureiro 2011; Hesse et al. 2017; Restrepo and González 2007; Conover 1999; Altman 1990).

4. RESULTS OBTAINED

4.1. CORRELATIONS RQD-GSI

Spearman's Rho coefficient shows that the type of correlation between the RQD and GSI variables is direct with a moderate-to-strong association (Martínez et al. 2009) with a coefficient of 0.6593, therefore, it can be assured that there is a relationship between the two variables.

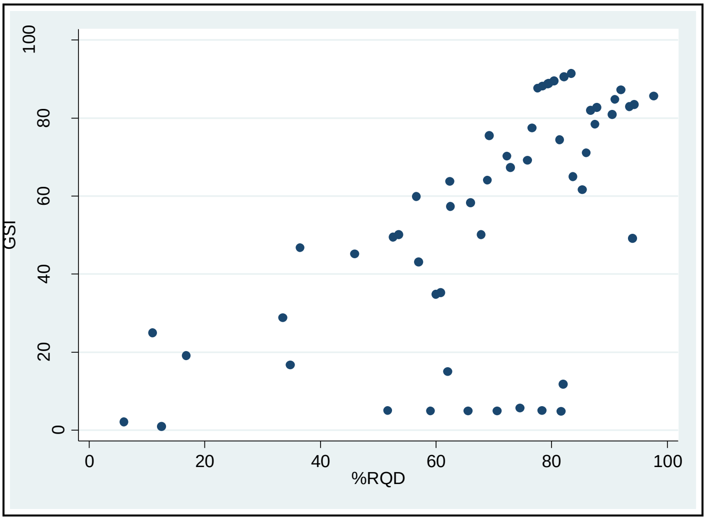

Fig. 2. Scatter plot %RQD vs. GSI. Own elaboration.
Note: Software Stata 14.2 Windows software, College Station, Texas 77845 USA, StataCorp.

It is also possible to observe, from the same figure, that there is a clear direct linear trend in most of the data distribution; however, it is striking that there is a small cloud of data, which, a priori, does not show the correlation when the estimated values of GSI are very low, in the case of the presented graph, observing a certain density of data when the GSI values are below 20 points (Fig. 3).

When GSI values are very low, the rock mass is very fractured, which from the geomechanical perspective, is a soil type structure (Bieniawski 2011), where the construction of subway galleries and slope stability is difficult to achieve using self-supporting methods.

A separate analysis between the data where GSI > 20 and GSI ≤ 20 shows that:

- when GSI > 20. Spearman's Rho coefficient is 0.7012, therefore, there is still a direct type correlation with a high association;
- when GSI ≤ 20. No clear correlation is observed, in the Spearman correlation analysis it is obtained that Rho is 0.1429, which indicates little or no correlation.

4.2. SPEARMAN HYPOTHESIS TEST

Although it was shown that data whose GSI below 20 points are not correlated, Spearman is a nonparametric and robust method (especially for the presence of outliers), so Spearman's hypothesis test is performed with the totality of the data.

According to the analysis, a value Rho = 0.6593 is obtained; with 95% confidence interval, it can be determined that Spearman's correlation coefficient is statistically significant because p = 0.00 which is less than α = 0.05 (required critical value). Thus, since $p < \alpha$, then it can be indicated that the results are not the product of chance, so the null hypothesis is rejected and the RQD measurements of the diamond drillings do present a positive correlation with the GSI geotechnical quality estimation of the rock mass where these drillings were drilled (Conover 1999).

This correlation result makes sense, because if the percentage degree of jointing or fracturing of drilled diamond drill holes (RQD) is high, it indicates that the rock mass is considered to be of good to high competence, so it is expected that a structure and surface analysis (GSI) will find results of high scores as well.

4.3. NEW PROPOSAL FOR GSI ESTIMATION BASED ON RQD

The predictive analysis to be used is a robust linear regression adjustment since the distributions are not normal and there is evidence of outliers (Fig. 3) (Loureiro, 2011; Hesse et al. 2017)

Given the above, a scatter plot with linear fit is made (Fig. 4), where the distribution of the data of the variables under study is observed: the fit without robustness (segmented line); and the robust fit (continuous line), the latter presents an excellent correlation with most of the data, with a goodness of fit of 0.69, this is due to a special treatment of lower weighting with the outliers. The equation representing the data with the recommended fit corresponds to (5) with an error of ±14.1 (unbiased estimate of error variance or Root MSE in Stata).

$$GSI' = (0.9422985 \cdot \%RQD - 1.612585) \pm 14.1. \quad (5)$$

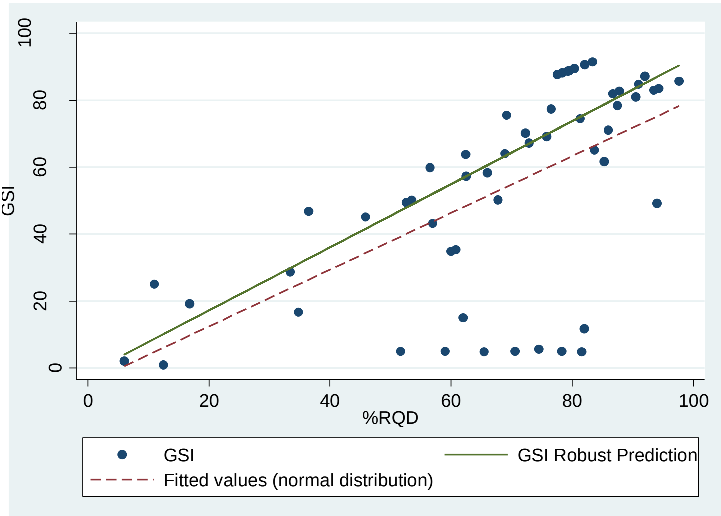

Fig. 3. Robust Linear Regression presented for %RQD vs. GSI. Own elaboration.
Note: Software Stata 14.2 Windows, College Station, Texas 77845 USA, StataCorp.

4.4. VALIDATION PROCESS

The validation of the nonparametric mathematical model has been performed by hypothesis testing, indicating that there is sufficient evidence to reject the null hypothesis, determining that indeed the model of Eq. (5) is adequate for the data presented.

Similarly, the correlation determined in Eq. (5) was evaluated by contrasting the results with those presented by He, et al. (2019). In this sample, the RQD values are presented, which vary between 37% and 92% while the GSI sample varies between 53 and 63 points. When evaluating the GSI′ prediction adjusted by the proposed (5) it is obtained that it varies between 33 and 85 points, showing in general an overestimation whose average is 6.6 points; but which always remains below the 14.1 points indicated as error in the prediction.

Another case used to compare the proposed fit for GSI′ is based on the data published by Kayabasi and Gokceoglu, C. (2019). In this sample, the RQD values are presented, which vary between 10% and 100% while the GSI′ sample varies between 26 and 56 points. When evaluating the prediction of GSI′ adjusted by the proposed (5) it varies between 7.8 and 92.6 points, whose average error is ≈8 points.

In this case, where there are several RQD magnitude dispersions, it is interesting to analyze the behavior of the GSI′ prediction when RQD is low, medium and high. In this way, it is observed that:

- when GSI < 20 points, it is equivalent to an RQD < 23% (soil type structure). Here, the values taken by the GSI′ setting vary between 7.8 and 18 points, magnitudes that are almost entirely within the margin of error of the prediction setting;
- when GSI > 80 points, it is equivalent to an RQD > 87% (good to very good quality). In this case, the values taken by the GSI′ fit average ≈93 points, notoriously overestimating the measured GSI, which presents constant values of 55 points;
- when GSI varies between 20 and 80 (class II, III, IV massifs), the RQD varies between 23% and 87%. Here, the values taken by the GSI′ adjustment vary between 21 and 63 presenting an average of 38 points, very close to the average of the magnitudes of the measured GSI, which range between 35 and 48 points, whose average is 42 points.

5. DISCUSSION

When comparing the proposed adjustment with the one made by Santa et al. (2019), it is observed that their work presents lower estimation error if all the data are analyzed, however, in a more detailed review, it is observed that when using the new GSI′ (5) adjustment in the suggested rock mass quality interval (between 20 and 80 points), the error of Santa et. al increases to |–5.5| and the one proposed by this research decreases to |2.1| indicating that GSI′ improves the prediction by 62% with respect to the one made by Santa et. al.

This change is because the relationship proposed by Santa et al. is parametric, which makes it sensitive to extreme values, in addition to not having an estimate of the error committed in each estimate, therefore, it is recommended to analyze the GSI predictions that are within the set of natural numbers [20; 80] ± 14.

However, it is still difficult to estimate more accurately the influence of the specific geological characteristics of each rock mass and its effect on its quality, in agreement with Hassanpour's proposal in 2022 (Hassanpour et al. 2022) therefore, it is recommended to expand the data and classify it according to the type of rock, looking for

a geological similarity that allows greater accuracy in the prediction. This may be because the GSI depends both on the structures (analyzed through RQD) and the different characteristics of the discontinuities (surface condition), as stated by Xia (Xia et al. 2022).

6. CONCLUSIONS AND RECOMMENDATIONS

1. To mathematically predict the GSI value from the RQD, we recommend the use of Eq. (5) considering an estimation error of ±14.1
2. Do not use the prediction result when GSI is less than 20, or when available RQD is equal to or less than 25%, in both cases the rock mass is expected to be of very poor quality.
3. It is suggested that GSI estimates are in intervals, for which the use of the estimation error ±14.1 is proposed.
4. While equation (5) is statistically valid on a larger scale, better predictions (62%) were observed when the RQD ranged between 25% and 87%.
5. It is still difficult to interpret more accurately the specific geological characteristics of each rock mass, in agreement with Hassanpour et al. (2022), therefore, it is recommended to expand the data and classify it according to the type of rock, looking for a geological similarity that allows greater accuracy in the prediction.
6. It is recommended to analyze how this prediction affects fracture criteria and

failure predictions in geomechanics applied to metro mining.

REFERENCES

ALTMAN D.G., 1990, *Practical statistics for medical research*, En: s.l.:CRC Press, p. 611.

BIENIAWSKI Z.T., 2011, *Errores en la aplicación de las clasificaciones geomecánicas y su corrección. Ingeopres*, Actualidad técnica de ingeniería civil, minería, geología y medio ambiente, Issue 208, pp. 10–21.

CONOVER W., 1999, *Practical nonparametric statistical*, En: s.l., John Wiley & Sons, p. 578.

DEERE D.U., 1963, *Technical description of rock cores for engineering purposes*, Rock Mechanics and Engineering Geology, 18(1).

DEERE D.U., 1989, *Rock Quality Designation (RQD) after Twenty Years*. DEERE (DON U) CONSULTANT GAINESVILLE FL.

FLORES-RUIZ E., MIRANDA-NOVALES M.G., VILLASÍS-KEEVER M.A., 2017, *El protocolo de investigación VI: cómo elegir la prueba estadística adecuada*, Estadística inferencial. Revista alergia México, Jul., 64(3).

GARZÓN-ROCA J., TORRIJO F.J., COBOS G., 2021, *Geomechanical characterization and analysis of the Upper Cretaceous flysch materials found in the Basque Arc Alpine region*, Bulletin of Engineering Geology and the Environment, 80(10), pp. 7831–7846.

GOKCEOGLU C., SONMEZ H., KAYABASI A., 2003, *Predicting the deformation moduli of rock masses*, International Journal of Rock Mechanics and Mining Sciences, 40(5), pp. 701–710.

GONZÁLEZ de VALLEJO L., ORTUÑO-ABAD L., FERRER GUIJÓN M., OTEO MAZO C., 2002, Ingeniería Geológica, s. l, Pearson.

HASSANPOUR J., KHOSHKAR A.S., FARASANI M.G., HASHEMNEJAD A., 2022, *Investigating the relationships between rock mass classification systems based on data from mechanized tunneling projects in Iran*, Bulletin of Engineering Geology and the Environment, 147(8), pp. 1–19.

HE M. et al., 2019, *An empirical method for determining the mechanical properties of jointed rock mass using drilling energy*, International journal of rock mechanics and mining sciences, Vol. 116, pp. 64–74.

HERNÁNDEZ SAMPIERI R., 2018, *Metodología de la investigación*, DF, McGraw-Hill, Interamericana.

HESSE C.A., OFOSU J., NORTEY E., 2017, *Introduction to nonparametric statistical methods*, Akrong Publications, Ltd., Accra.

HOEK E., CARTER T.G., DIEDERICHS M.S., 2013, *Quantification of the Geological Strength Index Chart*. 47th US rock mechanics/geomechanics symposium.

HOEK E., MARINOS P., BENISSI M., 1998, *Applicability of the Geological Strength Index (GSI) classification for very weak and sheared rock masses. The case of the Athens Schist Formation*, Bulletin of Engineering Geology and the Environment, 57(2), pp. 151–160.

HUAMAN A., ARDILES R., MENDIETA H., ARÍAS F., SALAS W., NIKAIDO E., CURI N., 2017, *Guía de criterios geomecánicos para diseño, construcción, supervisión y cierre de labores subterráneas*, Primera ed. Lima: Osinergmin.

KAYABASI A., GOKCEOGLU C., 2019, *An Assessment on Permeability and Grout Take of Limestone: A Case Study at Mut Dam*, Karaman, Turkey, Water, 11(12).

LOUREIRO PÉREZ E., 2011, *Estadística no paramétrica: un modo de introducción*, Buenos Aires, s.n.

MARINOS V., MARINOS P., HOEK E., 2005, *The geological strength index: applications and limitations*, Bull. Eng. Geol. Environ., Issue 65, p. 55–65.

MARINOS V., MARINOS P., HOEK E., 2005, *The geological strength index: applications and limitations*, Bulletin of Engineering Geology and the Environment, 64(1), pp. 55–65.

MARTÍNEZ ORTEGA R.M. et al., 2009, *El coeficiente de correlación de los rangos de Spearman ca-*

racterización, Revista Habanera de Ciencias Médicas, 8(2).

PALMSTROM A., 2005, *Measurements of and correlations between block size and rock quality designation (RQD),* Tunn. Undergr. Sp. Tech., 20(4), pp. 362–377.

PRIEST S., HUDSON J., 1976, *Discontinuity spacings in rock,* International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 13(5), pp. 135–148.

RAMALLE-GÓMARA E., ANDRÉS de LLANO J., 2003, *Use of robust methods in inferential statistics*, Atención Primaria, 32(3), pp. 177–182.

RESTREPO L., GONZÁLEZ J., 2007, *De Pearson a Spearman,* Revista Colombiana de Ciencias Pecuarias, 20(2), pp. 183–192.

RODRÍGUEZ S.S., VALERO J.D.L., GÓMEZ C.L., 2018, *Correlations of geomechanical indices for Andean environments*, ISRM European Rock Mechanics Symposium – EUROCK 2018.

SACHPAZIS C., 1986, En: *Geotechnical Description, Classification and Properties of Carbonate and Calcareous Rock Masses. Their Recording Procedure,* s.l, s.n.

SANTA C., GONÇALVES L., CHAMINÉ H.I., 2019, *A comparative study of GSI chart versions in a heterogeneous rock mass media (Marão tunnel, North Portugal): a reliable index in geotechnical surveys and rock engineering design,* Bulletin of Engineering Geology and the Environment, 78(8), pp. 5889–5903.

SHEN J., JIMENEZ R., KARAKUS M., XU C., 2014, *A Simplified Failure Criterion for Intact Rocks Based on Rock Type and Uniaxial Compressive Strength*, Rock Mechanics and Rock Engineering, 47(2), pp. 357–369.

TURNER J., 2006, *Rock Socketed Shafts for Highway*, Transportation Research Board, WA, USA.

XIA K. et al., 2022, *Quantification of the GSI and D values in the Hoek–Brown criterion using the rock quality designation (RQD) and discontinuity surface condition rating (SCR)*, Bulletin of Engineering Geology and the Environment, 81(1), pp. 1–21.

ZHANG L., 2016, *Determination and applications of rock quality designation (RQD),* Journal of Rock Mechanics and Geotechnical Engineering, 8(3), pp. 389–397.

ZHANG L., EINSTEIN H., 2004, *Using RQD to estimate the deformation modulus of rock masses,* International Journal of Rock Mechanics and Mining Sciences, Vol. 41, pp. 337–341.