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GEOMECHANICAL CLASSIFICATIONS, GEOTECHNICAL INDEXES, AND FRACTURED ROCK MEDIA: THE INFLUENCE OF DISCONTINUITIES ON THE ROCK MASSES DESCRIPTION

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A b s t r a c t

Using geotechnical indexes and geomechanical classifications is crucial in estimating the quality and behaviour of fissured rock masses. These tools play a significant role in large-scale engineering works, particularly in underground projects where the rock mass and its response to excavation are critical for project safety and financial feasibility. The widespread adoption of these classification systems in geoengineering necessitates continuous development and improvement to enhance accuracy and reliability and align them with the evolving construction landscape. Discontinuities, in particular, profoundly impact the strength, deformability, and permeability of the rock mass, therefore defining its behaviour. Given that rock mass assessment forms the basis of geotechnical characterization and evaluation, it is essential to understand and evaluate its characteristics and their influence on the classification systems or indexes.

Keywords: geomechanical classifications, geotechnical indexes, discontinuities, rock mass

1. INTRODUCTION

Bell (2007) highlights that rock mass discontinuities are not just planes of weakness but dynamic structural features ranging in size from small cracks to large faults. These planes introduce a structural discontinuity to the rock material, fundamentally changing its petrophysical properties. According to González de Vallejo and Ferrer (2011), discontinuities transform rock masses into discontinuous and heterogeneous entities, rendering them deformable and weak.

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Discontinuities define the behaviour of the rock mass in response to the stresses caused by excavations. Their geometry, dimensions, and physical characteristics control the way the blocks (from centimetre scale to large dimensions) defined by these structures behave, the strength, deformability, and hydraulic behaviour of rock masses (e.g., Barton and Bieniawski, 2008; González de Vallejo and Ferrer, 2011; Barton and Quadros 2015). In engineering projects, discontinuities and their petrophysical characteristics are fundamental to the behaviour of geostructures. For example, in rocky slopes and underground excavations, the discontinuities influence the stability of the excavation, are essential in the groundwater flow in the rock mass and can condition the stability of structural elements through displacement and rotation. Thus, geo-professionals' role in surveying, mapping, and characterizing these elements in any engineering project is vital and inspiring. They are actively involved in various project stages, either through direct observation and mapping techniques of rock masses such as the scanline sampling technique (e.g., ISRM 1981; Hudson and Priest 1983; Priest 1993, 2004; Smith 2004; Brady and Brown 2007; Hudson 2015; Chaminé et al. 2015) and statistical and stability analysis software such as those provided by the Rocscience package (Dips, Unwedge, Swedge, etc.) or the MGC-RocDesign|Calc software (Pinheiro et al. 2014).

Integrated into the characterization and evaluation of rock masses, geotechnical indexes and geomechanical classifications provide a quantitative approach to classification and framing based on the inherent parameters. These powerful tools are used to approach complex projects, with their genesis dependent on the characteristics of the rock mass and, therefore, of the discontinuities present. This work briefly discusses the importance and influence of discontinuities in rock mass classifications and geotechnical indexes, emphasizing their quantitative nature and practical application. Figure 1 shows an example of geological and geotechnical characterisation of rock discontinuities in a granite slope

Fig. 1. Surveying and characterization of rock discontinuities in a granite slope (photo: C. Santa)

2. EVALUATION OF THE DISCONTINUITIES IN GEOTECHNICAL PRATICES

2.1. Characteristics of discontinuities

Discontinuities have several measurable characteristics that are important to consider when surveying and assessing a rock mass (e.g., ISRM, 1978, 1981; Priest, 1993; CFCFF, 1996; Barton and Quadros 2015). Their careful and objective characterization is fundamental to understanding the rock mass in the different stages of the design of any engineering project and works. Each characteristic directly influences the rock mass's behaviour and response to excavation.

Table 1 summarises these parameters and provides a brief description, as well as the designations given in the evaluation. Geological discontinuities can be grouped into sets, each being defined by the average orientation of that group of discontinuities (parallel and sub-parallel to each other), which may present different characteristics. This type of assembling allows statistical analyses that support excavation stability studies at the project stage and during construction, making possible a better definition of excavation methods (equipment to be used, geotechnical adversities, cost/performance) as well as rock support required for safe excavation, reducing hazards such as rock falling, tunnel collapse, slope sliding, etc.

Table 1. Main geological and geotechnical parameters of rock mass discontinuities (adapted from ISRM 1978, 1981, 2007, 2015)

Characteristics	Description	Designation
Lithology	Lithological features and heterogeneity.	Igneous, metamorphic, or sedimentary rocks
Orientation	Dip and Dip direction of a discontinuity.	Geological orientation
Weathering degree	Weathered degree of discontinuity wall. Assessment made by visual interpretation and sensitivity to touch.	Fresh (W1) to completely weathered (W5)
Spacing and fracture intercept	Spacing corresponds to the distance between adjacent discontinuities belonging to the same set. Fracture intercept is the average distance between discontinuities independently of the discontinuity set.	Very close spacing (F5) to very wide spacing (F1)
Persistence	Surface length of a discontinuity.	Very low persistence (L1) to very high persistence (L5)
Roughness	Irregularities of the walls of the discontinuities.	Slickensided (planar) to rough (stepped)
Aperture	The perpendicular distance separates the adjacent rock walls of an open discontinuity.	Very tight to cavernous
Wall strength	Uniaxial compressive strength of the walls of the discontinuities.	Very weak rock (S5) to extremely strong rock (S1)
Water inflow	Water seepage through rock walls.	Dry to outflow
Infilling	Material separating the adjacent rock walls of discontinuities.	Various (e.g., clay, quartz, gouge)

2.2. Influence on rock mass behavior

As already mentioned, discontinuities' influence on the rock mass's behaviour is critical, and their analysis is fundamental in designing the response to excavation actions, with this influence being exerted differently by each characteristic. First of all, the structural geological orientation can be favourable or unfavourable to the excavation, as shown in Figure 2, which implies different care in the execution, as well as in the definition and application of rock support. In tunnels excavated in jointed rock masses, the most common types of failure involve wedges falling from the roof or sliding out of the sidewalls of the openings (Hoek, 2007). In the same way, the stability of slopes can be compromised if there is a set of discontinuities with dip and strike close to that of the slope, leading to the need to apply rock support elements. The same applies to channels, wells, etc. The orientation/geometry of the discontinuities directly influences the phenomenon of groundwater percolation, which is fundamental and decisive in dam projects, both in the design of structures and in the treatments of the rock mass with the use of injection curtains.

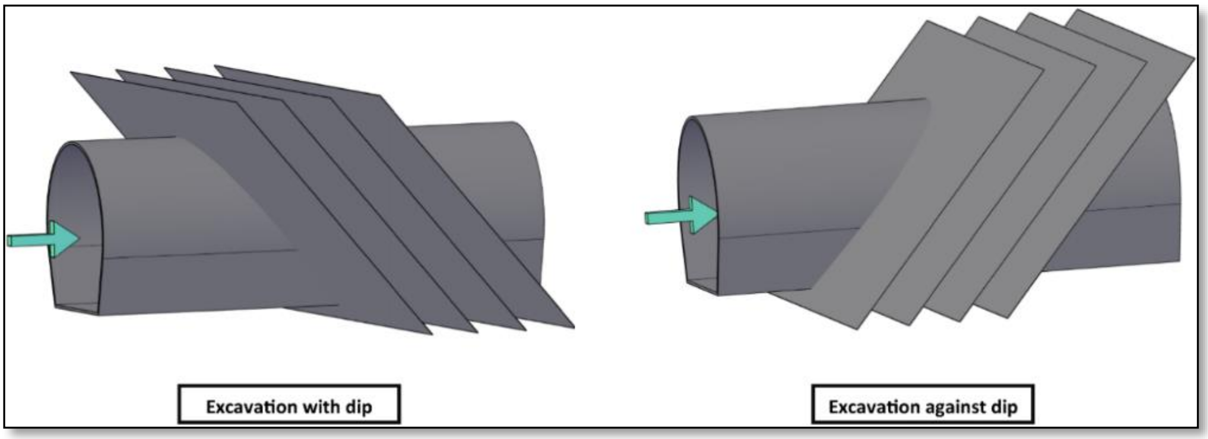

Fig. 2. Tunnel excavation with and against dip (inspired by Hoek, 2007)

The spacing and the length of the discontinuities are (in combination with the geological orientation) the characteristics that control the block size. For lower values of fracture spacing, the smaller the blocks are formed, and the strength of the rock mass decreases. On the other hand, the larger size of the blocks formed (due to higher fracture spacing values) leads to more significant damage in a potential rock fall. Persistence determines the possibility of movement and detachment of blocks, and in quarries, it defines the possible use of the resources.

The roughness and the aperture of discontinuities regulate the friction angle and the shear strength mainly due to the relationship between filling and water percolation. The roughness of the surface walls makes it difficult for blocks to move (González de Vallejo and Ferrer, 2011). In addition, the direction of the displacement depends on roughness since this can favour or hinder it. Also, the discontinuity aperture allows rock mass movement when stresses are applied. Also, it promotes the accumulation of fills that, by their nature, can contribute to the reduction of shear strength (as is the case of damp clay fills) (details in Bieniawski, 1989) such as the water percolation that also has the particularity of promoting physical and (possibly) chemical weathering of the walls.

2.3. Influence of discontinuities on rock mass classification

2.3.1. RMR, SMR, SRC

Rock Mass Rating (RMR) (Bieniawski, 1989) is one of the most widely used classifications for rock mass characterization and rock support estimation (e.g., Serafim and Pereira, 1983; Celada et al., 2014; Celada and Bieniawski, 2020; Mateus et al., 2023), and its application depends on the direct observation of the excavated surfaces considering the state of the rock mass and its discontinuities defined by a sum of values assigned to different characteristics. This classification system integrates in its structure all the characteristics of the discontinuities mentioned in Tabel 1. They influence the behaviour of the rock mass, adding the strength of intact rock material, which often corresponds to the strength of the walls of the discontinuities and the value of RQD (Deere, 1988). The basic RMR is the value obtained without considering the discontinuities' orientation. This factor is added for the type of project to be worked on (tunnels, slopes, and foundations), varying from very favourable to very unfavourable. Figure 3 shows the table where it is possible to check the classification parameters and the respective weights.

Romana (1985, 1995) and Romana et al. (2003) presented an adaptation of the RMR applicable to slopes, adding adjustment factors related to discontinuity orientation concerning slope orientation, the orientation of the rupture plane, and the excavation method. Thus, a classification value directed to slopes and focused on discontinuities was obtained.

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values						
1	Strength of intact rock material	Point-load strength index	>10 MPa	4 - 10 MPa	2 - 4 MPa	1 - 2 MPa	For this low range - uniaxial compressive test is preferred		
		Uniaxial comp. strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	< 1 MPa
	Rating		15	12	7	4	2	1	0
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		> 2 m	0.6 - 2 . m	200 - 600 mm	60 - 200 mm	< 60 mm		
	Rating		20	15	10	8	5		
4	Condition of discontinuities (See E)		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge >5 mm thick or Separation > 5 mm Continuous		
	Rating		30	25	20	10	0		
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 - 125	> 125		
		(Joint water press)/ (Major principal)	0	< 0.1	0.1, - 0.2	0.2 - 0.5	> 0.5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very favourable	Favourable	Fair	Unfavourable	Very Unfavourable
Ratings	Tunnels & mines	0	-2	-5	-10	-12
	Foundations	0	-2	-7	-15	-25
	Slopes	0	-5	-25	-50	

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 – 81	80 – 61	60 – 41	40 – 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 yrs for 15 m span	1 year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 min for 1 m span
Cohesion of rock mass (kPa)	> 400	300 - 400	200 - 300	100 - 200	< 100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY conditions

Discontinuity length (persistence) Rating	< 1 m 6	1 - 3 m 4	3 - 10 m 2	10 - 20 m 1	> 20 m 0
Separation (aperture) Rating	None 6	< 0.1 mm 5	0.1 - 1.0 mm 4	1 - 5 mm 1	> 5 mm 0
Roughness Rating	Very rough 6	Rough 5	Slightly rough 3	Smooth 1	Slickensided 0
Infilling (gouge) Rating	None 6	Hard filling < 5 mm 4	Hard filling > 5 mm 2	Soft filling < 5 mm 2	Soft filling > 5 mm 0
Weathering Ratings	Unweathered 6	Slightly weathered 5	Moderately weathered 3	Highly weathered 1	Decomposed 0

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 - 90_	Drive with dip - Dip 20 - 45_	Dip 45 - 90_	Dip 20 - 45_
Very favourable	Favourable	Very unfavourable	Fair
Drive against dip - Dip 45-90	Drive against dip - Dip 20-45	Dip 0-20 - Irrespective of strike	
Fair	Unfavourable	Fair	

Fig. 3. Rock Mass Rating chart (Bieniawski, 1989)

Surface Rock classification System (SRC) (Gonzalez de Vallejo, 1983, 1985) is based on RMR coupled with correction factors to take into account the situ stress, data from outcrops, and tunnel construction conditions (Gonzalez de Vallejo, 2003). The SRC includes all the characteristics of discontinuities in its definition (RMR), adding the rock mass's correction factors and tectonic stress.

2.3.2.Q- System

Rock Tunnelling Index—Q-system (Barton et al., 1974, 1977; NGI, 2015) is a classification system that uses six parameters to classify the observed rock mass, assigning a value on an exponential scale ranging from 0.001 to 1000. In addition to the RQD and the stress reduction factor, the number of discontinuity sets, the roughness of the walls, joint alteration, and groundwater are considered.

$$Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF} \tag{2.1}$$

Where:

- RQD – Rock Quality Designation (Deere, 1988).
- Jn - Joint set number.
- Jr - Joint roughness number.
- Ja - Joint alteration number.
- Jw - Joint water reduction.
- SRF – Stress reduction factor.

As shown, the orientation and dimensional characteristics of the discontinuities are not considered. However, it is essential to highlight the consideration given to the number of sets of discontinuities (intensified in areas of crossings and tunnel entrances) and the stress factor. The support to apply is defined by the diameter of the excavation but also depends on its finality.

2.3.3.RMi

Developed by Palmström (1995), the Rock Mass index (RMi) is a geological-geotechnical index that allows the characterization of the rock mass strength based on its characteristics and was designed to calculate rock support and tunnel boring machine penetration rates in underground works (Palmström, 1996). Its calculation factors include the uniaxial compressive strength of the intact rock and a parameter relating to discontinuities (Equation 2.2), which considers the blocks' volume and the discontinuities' characteristics.

$$RMi = \sigma_c + \text{J.P.} \tag{2.2}$$

Where:

- σ_c - uniaxial compressive strength of intact rock measured on 50 mm samples
- J.P. – jointing parameter, i.e. the reduction factor from jointing

Where the jointing parameter is expressed as:

$$JP = 0{,}2 \times \sqrt{jC} \times Vb^{D} \tag{2.3}$$

Where:

- jC – Joint condition factor
- Vb – block volume
- D = 0,37 $jC^{-0,2}$

The joint condition factor is given by:

$$jC = jL \times \frac{jR}{jA} \tag{2.4}$$

Where:

- jL – Joint size and continuity factor
- jR – Joint roughness factor
- jA – Joint alteration factor

RMi includes the characteristics of the discontinuities, considering most of them, such as persistence, spacing, alteration, and roughness, when defining the joint condition. The orientation of the discontinuities indirectly influences the block volume factor, although it is not valued, while groundwater is not considered a penalizing factor in the RMi.

2.3.4. GSI

The Geological Strength Index (GSI) was introduced by Hoek (1994) — with further developments, among other works, in Hoek and Brown (1997, 1998), Hoek et al. (1998), Hoek and Marinos (2000), Marinos and Hoek (2000, 2001), Hoek et al. (2013) — and allows to practically estimate rock mass strength based on geological and geotechnical field observations. For this purpose, charts have been developed for fractured crystalline and metasedimentary rock masses. The vertical axis defines classification charts that refer to the block size of the excavated rock mass, and the conditions of the discontinuities define the horizontal axis. The discontinuities' orientation, size, and spacing define the block sizing. However, the valorization of these parameters is not direct and depends on the user’s experience. The characteristics of the discontinuities evaluate the roughness, weathered degree of walls, and the infilling material type.

Hoek et al. (2013) presented a proposal for a new version of GSI. It is intended to assign an exact value for the GSI through an expression (Equation 2.5) that considers the conditions of the discontinuities defined in the RMR (namely, weathered degree, fracture spacing, persistence, roughness, aperture, infilling) and the RQD. Although it gives greater emphasis to the conditions of the discontinuities, it still does not consider the influence of water on the behavior of rock mass.

$$GSI = 1.5JCond89 + RQD/2 \tag{2.5}$$

Where:

- JCond89 - Joint conditions defined in Bieniawski (1989)
- RQD – Rock Quality Designation (Deere, 1988).

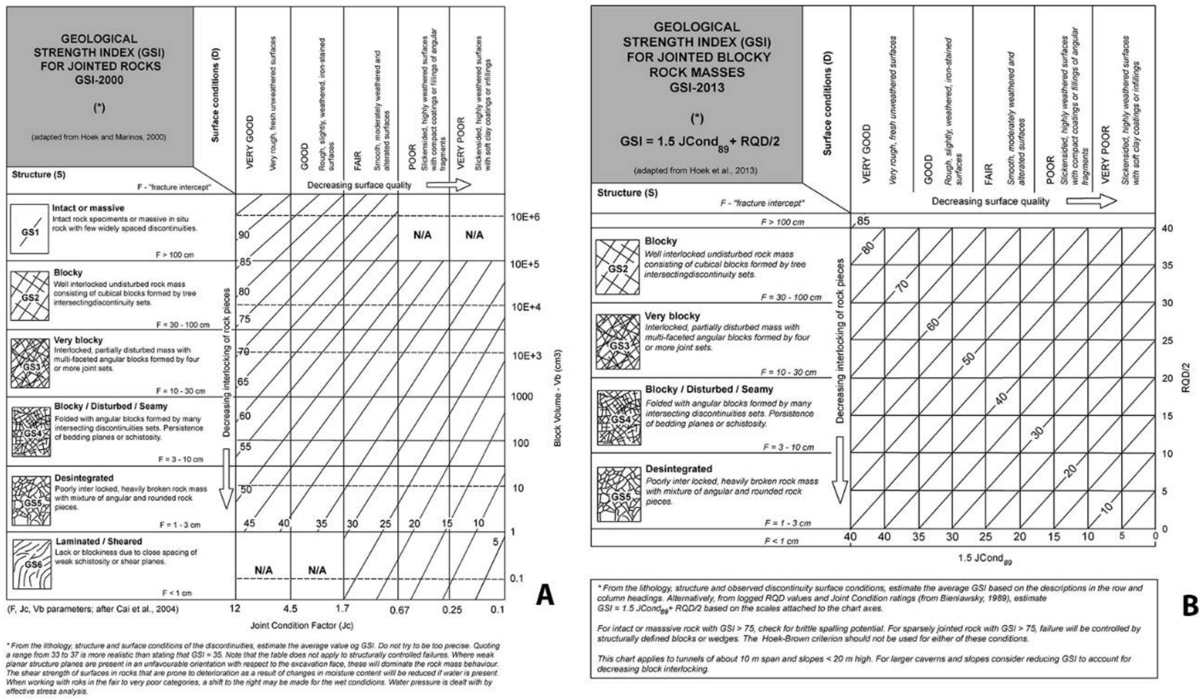

Fig. 4. GSI classification abacus (Adapted: A) Hoek et al., 1998 and Hoek and Marinos 2000; B) Hoek et al., 2013)

3. DISCUSSION

Geomechanical classifications or geotechnical indexes are widely recognized when working on engineering projects. They are fundamental in defining the rock support at the design stage and the type and quantity to be applied during excavation to stabilize the rock mass. The classifications and indexes analysed depend heavily on the characteristics of the discontinuities; each one considers them differently and with different importance.

Table 2 summarises the characteristics considered in the different classifications, noting that weathered degree and roughness are the most common characteristics of the various classification systems. On the other hand, orientation, wall strength, and water inflow are the least important characteristics. RMR (and the adapted SMR and SRC) is the most inclusive classification, directly considering all the characteristics of the discontinuities, while the Q-System and GSI98 are those in which the characteristics of the discontinuities have the least direct influence.

It is important to note that the presence of water is not considered in some classifications; and it is only included in RMR (and its derivatives) and Q-System. However, it has a significant influence on the behaviour of the rock mass, reducing the friction angle and the shear resistance (González de Vallejo and Ferrer, 2011), washing the infill and weathering the walls, influencing the rock support by causing additional pressure on the shotcrete and influencing the sealing of rock bolts.

Table 2. Summary of the characteristics of the rock discontinuities in the classifications and indexes

Features	Rock Classification Systems and Indexes				
	RMR/SMR/SRC	Q-System	RMi	GSI|98	GSI|2013
Orientation	✓	✗	○	✗	✗
Weathered degree	✓	✓	✓	✓	✓
Fracture Spacing	✓	○	○	○	○
Persistence	✓	○	✓	○	✓
Roughness	✓	✓	✓	✓	✓
Aperture	✓	✗	✓	✗	✓
Wall strength	✓	○	○	✗	✗
Infilling	✓	○	✓	✓	✓
Water inflow	✓	✓	✗	✗	✗

✓ - Considered

✗ - Not considered

○ - Indirectly considered

4. FINAL REMARKS

- Aiming at the constant search for innovation and the adaptation of the rock classification systems to the broadest possible range of realities, there is the need for these classifications and indexes to be increasingly accurate, reliable, and transversal to all areas of geoengineering.
- This work is part of an ongoing study that aims to contribute to the development of the characterization of rock masses in engineering projects, with a focus on GSI and the possibility of developing and adapting the index to be more inclusive regarding the characteristics of the rock mass, particularly the presence of groundwater based on the use of data collected in underground excavation works in different geological and geotechnical contexts.
- Analysing the influence of the characteristics of the discontinuities proved to be fundamental for better compression of the weighting considered in each classification and the need to introduce groundwater into GSI.
- The main challenge ahead is the quantification of underground percolation, given that flow values in the excavation phase are rarely measured. Flow quantification is usually obtained from permeability/water injection tests carried out during the investigation and testing phase, before excavation work. It is recognized that permeability closely depends on the degree of fracturing and the occurrence of intersections between the various discontinuities sets, ain this reinforces the importance of taking account of the different characteristics of discontinuities in geotechnical classification and characterization.
- The current study, as mentioned, aims to test the inclusion of groundwater in the GSI, having studied data from an underground excavation based on the values obtained for RMR89 and GSI1998, while also analysing the data previously presented by the author (Santa et al., 2019). It is expected that a proposal will be presented to add a penalizing factor to the expression for GSI 2013 (Equation 2.5) to take into consideration the presence of groundwater.

ADDITIONAL INFORMATION

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REFERENCES

1. Barton, N and Bieniawski, ZT 2008. RMR and Q-setting records are straight. *Tunnels and Tunnelling International*, 26–29.
2. Barton, N, Lien, R and Lunde, J 1974. Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics*, **6 (4),** 189-239.
3. Barton, N, Lien, R and Lunde, J 1977. *Estimation of support requirements for underground excavations.* Proceedings of 16th Symposium on Design Methods in Rock Mechanics Rock Mechanics, Minnesota, ASCE, NY, 163-177.
4. Barton, N and Quadros, E 2015. Anisotropy is everywhere, to see, to measure, and to model. *Rock Mech Rock Eng,* **48**, 1323–1339.
5. Bell, FG 2007. *Engineering geology.* Amsterdam: Butterworth-Heinemann.
6. Bieniawski, R 1989. *Engineering rock mass classifications: a complete manual for engineers and geologists in mining, civil, and petroleum engineering.* New York: Interscience, John Wiley & Sons.
7. Brady, BHG, Brown, ET 2007. *Rock mechanics for underground mining*. 3rd edn. Dordrecht: Springer.
8. Celada, B, Bieniawski, ZT 2020. *Ground characterisation and structural analyses for tunnel design*. Boca Raton: CRC Press, Taylor & Francis Group.
9. Celada, B, Tardáguila, I, Varona, P, Rodríguez, A and Bieniawski, Z 2014. *Innovating Tunnel Design by an Improved Experience-Based RMR System.* Proceedings of the World Tunnel Congress, Foz do Iguaçu, Brazil, 9–15.
10. CFCFF—Committee on Fracture Characterization and Fluid Flow 1996. *Rock fractures and fluid flow: contemporary understanding and applications.* Washington DC: National Research Council, National Academy Press.
11. Chaminé HI, Afonso MJ, Ramos L and Pinheiro, R 2015. Scanline sampling techniques for rock engineering surveys: insights from intrinsic geologic variability and uncertainty. *In D Giordan, K Thuro, C Carranza-Torres, F Wu, P Marinos, C Delgado (eds.), Engineering Geology for Society and Territory – Applied Geology for Major Engineering Projects, IAEG, Springer*, **6**, 357–361.
12. Chaminé, HI, Afonso MJ, Teixeira J, Ramos L, Fonseca L, Pinheiro R and Galiza, AC 2013. Using engineering geosciences mapping and GISbased tools for georesources management: lessons learned from rock quarrying. *Eur Geol Journal,* **36**, 7–33.
13. Deere, DU, Deere, DW 1988. The Rock quality designation (RQD) Index in practice. *L, Kirkaldie, Ed., Rock classification systems for engineering purposes, ASTM STP 984, American Society for Testing and Materials, Philadelphia,* 91 -101.
14. González de Vallejo, LI, Ferrer, M 2011. *Geological engineering.* London: CRC Press, Taylor-Francis group.

15. González de Vallejo, LI 1983. *A new classification system for underground assessment using surface data.* IAEG Symp. On Eng. Geol. and Underground Construction, Lisboa 2. Balkema, Rotterdam, 85–94.
16. González de Vallejo, LI 1985. *Tunnelling evaluation using the Surface Rock Mass Classification System SRC.* ISMR Symp. The Role of Rock Mechanics in Excavations for Mining and Civil Works, Zacatecas, México, vol. 1. Soc. Mexicana de Mec. de Rocas, Mexico, D.F., 458–466.
17. González de Vallejo, LI 2003. SRC rock mass classification of tunnels under high tectonic stress excavated in Weak Rocks, *Engineering Geology*, **69(3–4)**, 273–285.
18. Hoek, E 2007. *Practical rock engineering.* Toronto: RocScience: Hoek's Corner.
19. Hoek, E, Carter T, G, Diederichs, M, S 2013. *Quantification of the geological strength index chart.* Proceedings geomechanics symposium 47th U.S. rock mechanics, San Francisco, CA, ARMA 13-672, 1–8.
20. Hoek, E 1994. Strength of rock and rock masses. *News Journal of ISRM*, **2(2)**, 4-16.
21. Hoek, E 1998. Reliability of Hoek-Brown estimates of rock mass properties and their impact on design. *International Journal of Rock Mechanics & Mining Sciences*, **35(1)**, 63-68.
22. Hoek, E and Brown, ET 1997. Practical estimates of rock mass strength. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, **34(8)**, 1165-1186.
23. Hoek, E and Marinos, P 2000. Predicting tunnel squeezing problems in weak heterogeneous rock masses: Part 1 (estimating rock mass strength); Part 2 (potential squeezing problems in deep tunnels). *Tunnels and Tunnelling International*, **132(12)**,1-21.
24. Hoek, E, Marinos, P and 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)**, 151–160.
25. Hudson JA, Priest SD (1983) Discontinuity frequency in rock mass. *Int J Rock Mech Min Sci Geom Abstr*, **20(2)**,75–89.
26. ISRM – International Society for Rock Mechanics 1978. Suggested methods for the quantitative description of discontinuities in rock masses. *Int. J. Rock Mech. Min. Sci. & Geom. Abstr.*, **15, 6**, 319-368.
27. ISRM – International Society for Rock Mechanics 1981. Basic geotechnical description of rock masses. *Int. J. Rock Mech. Min. Sci. & Geom. Abstr.*, **18**, 85-110.
28. ISRM – International Society for Rock Mechanics 2007. *The complete ISRM suggested methods for characterisation, testing and monitoring: 1974-2006.* Ankara: Ulusay R. & Hudson J.A., eds., suggested methods prepared by the commission on testing methods, ISRM.
29. ISRM – International Society for Rock Mechanics (2015). *The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007–2014.* Cham, Heidelberg: Ulusay R., ed., suggested methods prepared by the commission on testing methods, ISRM, Springer.
30. Marinos, P, Hoek, E 2000. *GSI: a geologically friendly tool for rock mass strength estimation.* Proceedings GeoEng2000 on Geotechnical and Geological Engineering. Melbourne, Victoria, Australia. Technomic Publishers, Lancaster, PA. 1422-1442.
31. Marinos, P and Hoek, E 2001. Estimating the geotechnical properties of heterogeneous rock masses such as flysch. *Bull. Eng. Geol. Env.*, **60**, 85-92.
32. Mateus, S, Afonso, MJ, Fernandes, I and Chaminé, HI 2023. RMR|14 Versus RMR|89: A Methodological Approach for Rock Mass Excavations (N Portugal). *Chaminé, H.I., Fernandes, J.A. (eds) Advances in Geoengineering, Geotechnologies, and Geoenvironment for Earth Systems and Sustainable Georesources Management. Advances in Science, Technology & Innovation. Springer, Cham.*, 187–192.

33. NGI [Norwegian Geotechnical Institute] 2015. *Using the Q-system: Rock mass classification and support design.* Oslo: NGI.
34. Palmström, A 1995. RMi - *A rock mass characterisation system for rock engineering purposes. PhD Thesis.* Norway: The University of Oslo.
35. Palmström, A 1996. RMi - A system for characterising rock mass strength for use in rock engineering. *Journal of Rock Mechanics and Tunneling Technology*, **1**, 69-108.
36. Pinheiro R, Ramos L, Teixeira J, Afonso MJ, Chaminé HI 2014. MGC– RocDesign|CALC: a geomechanical calculator tool for rock design. *Alejano LR, Perucho A, Olalla C, Jiménez R (eds) Proceedings of Eurock 2014, rock engineering and rock mechanics: structures in and on rock masses (ISRM European regional symposium, Vigo, Spain). CRC, London*, pp 655–660.
37. Priest, SD 1993. *Discontinuity analysis for rock engineering.* London: Chapman and Hall.
38. Priest, SD 2004. Determination of discontinuity size distributions from scanline data. *Rock Mech Rock Eng,* **37(5)**, 347–36.
39. Romana, M 1985. New adjustment ratings for application of Bieniawski classification to slopes. *Int. Symp. On the role of rock mechanics ISRM. Zacatecas*, 49-53.
40. Romana, M 1993. A geomechanics classification for slopes: Slope Mass Rating. *Comprehensive Rock Engineering. Ed. J. Hudson. Pergamon*, **Vol 3**, 575-600.
41. Romana, M, Serón, JB, Montalar, E 2003. SMR Geomechanics classification: Application, experience, and validation, *ISRM 2003–Technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy*.
42. Romana, M, Tomás, R and Serón, JB 2015. Slope Mass Rating (SMR) geomechanics classification: thirty years review. *Hadjigeorgiou, J., Archibald, J. (eds.), Proceedings of the 13th International Symposium on Rock Mechanics, ISRM, Quebec*, 1-9.
43. Santa, C, Gonçalves, L and Chaminé, HI 2019. 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. *Bull Eng Geol Environ,* **78**, 5889-5903.
44. Serafim, JL and Pereira, JP 1983. *Consideration of the geomechanics classification of Bieniawski*. Proceedings of the international symposium on engineering geology and underground constructions, Lisbon, 1,1133–1144.
45. Singh, B, Goel, RK 2011. *Engineering Rock Mass Classification.* Amsterdam: Elsevier Inc. Publication.
46. Smith, JV 2004. Determining the size and shape of blocks from linear sampling for geotechnical rock mass classification and assessment. *J Struct Geol,* **26(6–7),** 1317–1339.