Managing and validating limited borehole geotechnical information for rock mass characterization purposes – experience in Peruvian practice for open pit mine projects

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ABSTRACT

The assessment of rock mass blockiness is fundamental for any geotechnical study, managing and validating geotechnical information is then critical for rock mass characterization purposes, especially when the borehole information is limited or the available cores are disturbed. This work presents cases in Peruvian practice where managing and validation of logging database was successfully undertaken. The validation procedure included an evaluation of the blockiness and the use of a logging database from different projects to confirm/modify theoretical published bounds that correlate RQD and defect spacing, the work also included a comparative analysis of GSI estimation from data collected from cores, well-known approaches have been considered. Moreover, blockiness data consistency as well as typical issues on logging activities and analysis are discussed. Special consideration has been given to weak zones and core loss. Typical issues and shortcomings when using/collecting borehole data for rock mass characterization are also highlighted.

Introduction

Managing and validating geotechnical information from drill core is critical for rock mass characterization purposes in any mining/civil project, especially when the borehole information is limited and/or is the only available source of information (early stages of the project). The importance of this relies on the fact that the rock engineering design is primarily based on rock mass characterization. This work presents cases in Peruvian practice where managing and validation of logging database were undertaken not only for new projects, but also for evaluating optimizations of pit slope designs. The validation procedure included an evaluation of the blockiness and the use of a logging database from 15 projects to confirm/modify theoretical published bounds that correlate RQD and defect spacing such as Bieniawski (1983), Priest and Hudson (1976) and Duran (2014).

It is worth highlighting that the scope of this work is focused to provide practical experience primarily on rock mass characterization rather than classification of rock mass. As suggested by different authors such as Palmstrom et al. (2001) and Potvin (2012), the characterization and classification of rock mass should be treated as two independent procedures. obtained from logging rather than Experience with logging data obtained from core photographs is also described. Guidelines and technical protocols on the assessment of quality of logging and the necessity of re-logging in some cases are highlighted that have been proven useful in practical experience. Finally, a GSI comparative analysis was carried out between values of GSI estimated according to Hoek et al. (2013) and those derived from the relationship between GSI and the RMR’89 (Hoek et al., 1995).

Geological setting

This study analyses logging databases and geotechnical information typically found in Peruvian practice (circum-pacific regions). It primarily includes porphyry-style (copper-gold mining), deposits within sedimentary rocks and epithermal deposits. In all cases, there are deposit-scale geotechnical conditions that control the quality of rock mass, these conditions mainly related to hydrothermal alteration, weathering and structure. Accordingly, it is worth mentioning that the definition of the geotechnical units on each analyzed database has been developed based on not only lithology, but also on alteration and mineralization. not to apply specific protocols and standards

Assessment of rock mass quality

In Peruvian practice, rock mass quality has been typically assessed through the estimation of RMR_{89} (Bieniawski, 1993) and Q (Barton et al., 1974). However, in recent times the use of GSI (Hoek, 2002), GSI_{13} (Hoek et al., 2013) and RMR_{2014} to estimate rock mass quality has become popular in most operating mines. Among the mentioned schemes, the following parameters are common: Intact Rock Strength (IRS), Join Condition (Jc) and blockiness assessment.

Blockiness

As shown in Table I, blockiness can be assigned through the estimation of the Discontinuity Density, guidelines to assess this value have been provided by several authors for each rock mass classification system. Table 1 also shows typical methods to validate the logging data used for assessing blockiness.

Table I Blockiness estimation

Rock Mass classification system	Blockiness Estimation	Typical Validation Process
RMR_{89} (Bieniawski, 1993)	Rating of Discontinuity density. Analyzing plots of RQD vs discontinuity spacing and RQD vs Discontinuity Frequency (FF)	Plotting logging data RQD vs defect spacing including recommended bounds (Bieniawski, 1993 and Priest and Hudson,1976).
Q (Barton et al., 1974)	Assessment of Block size (ratio of RQD and Joint Set Number (Jn)	-
GSI (Hoek, 2002)	Cai et al. (2004) recommends rating using block volume (estimated from Joint density, Jv)	Plotting logging data RQD vs Jv data within bounds Palstrom (2005).
GSI_{13} (Hoek et al., 2013)	Directly from RQD (Y axis of GSI chart)	-

As highlighted by Priest and Hudson (1979), to estimate the discontinuity spacing for each identified discontinuity set (and corresponding FF), the perpendicular distance between discontinuities should be considered; in other words, it is recommended to assess the spacing considering the angle between the scanline and the line perpendicular to the discontinuity set. In Peruvian practice, it has been found that FF is typically obtained by just counting the discontinuities that intersect the scanline without considering any correction due to the mentioned angle.

Joint Condition and Geological Strength Index (GSI) estimation

Rock mass assessment is primarily based on geotechnical information from drill core, even for operating mines where access to the pit is constrained due to continued mining practices and safety procedures.

A reliable and simple manner to assess the condition of discontinuities is through the estimation of the Join Condition (JCond89) rating defined by Bieniawski (1989). Joint properties that are considered for this estimation include: persistence, aperture, roughness, infilling and weathering.

As the discussion of typical logging issues related to capturing these parameter from drill cores is out of the scope of this work, the authors have assumed that JCond89 has been appropriately measured so that a comparative analysis from the logging database can be carried out between values of GSI estimated according to Hoek et al. (2013) and those derived from the relationship between GSI and the RMR'89 (Hoek et al., 1995), which has to be set to groundwater conditions to dry. It is worth mentioning that in Peruvian practice, GSI estimation is typically undertaken by using the mentioned approaches which are presented in Table II; moreover, GSI mapping is ultimately utilized to validate the rock mass characterization.

Table II. GSI estimation from rock mas classification

Source	GSI Estimation	Comments
Hoek et al. (1995)	GSI = RMR'89 -5 (where RMR89 >23)	Unreliable for poor quality rock masses (Hoek,2007)
Hoel et al. (2013)	GSI = 0.5*RQD + 1.5*JCon89	-

Managing Blockiness data from drill cores

The types of logging utilized in the data bases to be analyzed were fixed-length style and geotechnically homogenous intervals. The authors believe that these methods are suitable for blocky to massive rock masses. However, it is important highlighting that geotechnical professionals should aware of the potentials differences in outcomes between the methods to be utilized for rock mass assessment before selection the logging style This work points the most frequently issues when logging and analyzing rock mass quality in Peruvian Practice, which includes dealing with blockiness data taken from disturbed cores due to drilling.

Issues on logging activities and analysis

Identification of natural discontinuities, core loss, intervals with no logged defects and weak zones are typically issues found logging activities.

Handling/Drill breaks vs natural discontinuities

In Peruvian practice, logging experience has shown that many times, blockiness can be under/over estimated as sometimes natural discontinuities cannot be differentiated from induced fractures (handling/drill breaks). This error is not only limited to core photographs, but also to logging core boxes on site; in fact, natural fractures are typically considered as induced breaks even with the presence of infilling or microcracks on them (See Figure 1). The review of logging databases shows that this issue appears repeatedly when drilling sedimentary rocks, which can be attributed to well-developed bedding planes (Read and Stacey, 2009). Core disking and stress relief may also cause drill breaks that are perpendicular to the core axis.

Figure 1. Rock with micro-defects (cemented with calcite) where induced breaks were generated by drilling. RQD assessment was underestimated.

Fractured/Decomposed Zones

There is a limited literature on the consideration and inclusion of weak zones into logging databases. In Peruvian practice, when dealing with weak zones, it is common to count four fractures per each 10cm, the total fractures for these zones are then added to the number of fractures considered for the logging interval.

Digital logging

Collected data from core boxes are typically cross-checked against logging data obtained from core photographs. In Peruvian practice, logging of core photographs is carried out when dealing with poor logging quality, which normally are related to logging performed without specific standards or procedure for the geological conditions of project. Moreover, an example showing RQD assessment utilizing different logging styles, including digital logging, is shown in Figure 2. In general, comparison analysis of the data sets may suggest that RQD values estimated from core photographs are typically higher than those from logging core boxes.

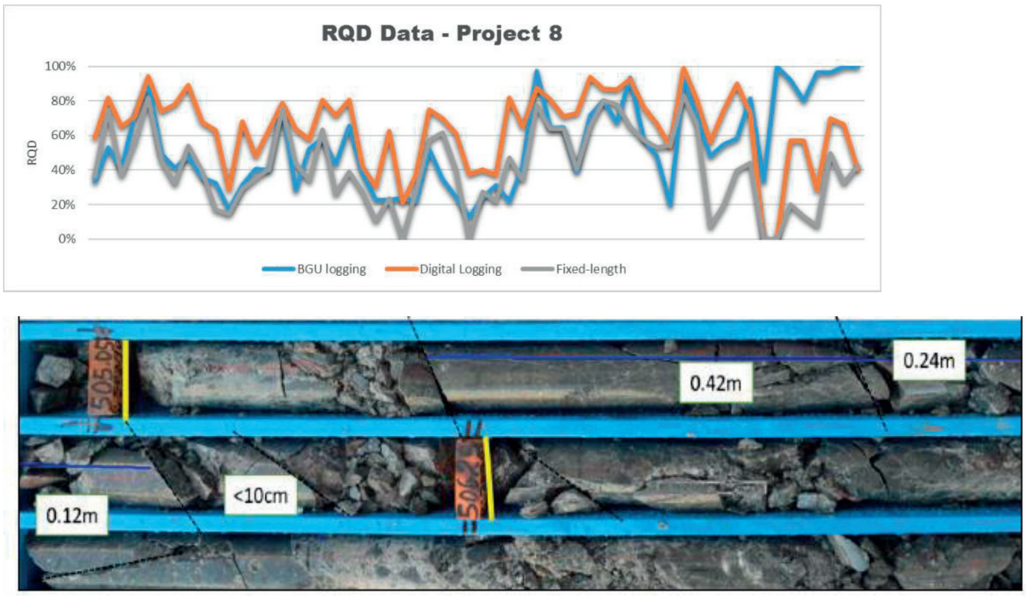

Figure 2 Example of RQD being underestimated on-site and adjusted during digital logging.

Specific logging Protocols and standards

The lack of logging standards for specific geotechnical-geological conditions of a project can result in omissions, ambiguity, issues and therefore assumptions in the rock mass assessment. This likely generates geotechnical models and engineering designs with low confidence. On the other hand, practical experience has shown that successful slope optimization studies can be carried out for open pit projects with logging standards developed specifically for their geological settings.

After analyzing different data sets from different project, some contents that standards/procedures are recommended to contain include the following:

- Definition of weak zones and fracture/decomposed zones: faults, shears, shear zones, decomposed zones, clay seams and fracture zones
- As stated by the Standard ASTM D 6032-02, sound core corresponds to any core which is fresh to moderately weather and which has sufficient strength to resist hand breakage. However, as described by Zuñiga et al. (2014), there are logging protocols in which there is a misunderstanding of the term ‘sound core’. This issue has also been observed in the Peruvian practice where this term is usually related to the sound generated by a hammer blow into the core.
- Protocols should specify the manner in which microcracks information should be collected during logging, that includes a detailed description of the type of microcracks or veinlets that should and should not be included into the RQD assessment. For instance, Laubscher and Jakubec (2001) suggest that cores with veinlets or microcracks healed with hard minerals (hardness above 5 in the Mohs scale) might be considered as intact rock. Accordingly, veinlets with soft infilling with very low to practically no traction resistance such as gouge are recommended to be considered in the RQD assessment.
- The effect of weathering and/or alteration is not judged using the ISRM-based system. Among scientist, there is even a misunderstanding between the terms weathering and alteration.
- Categorization of Joints, definition of typical cemented joint (infill type, width, strength, hardness), definition of micro-defects. A procedure to capture the frequency, strength and other parameters required for the rock mass assessment.
- Procedure to estimate infill resistance; some authors such as Laubscher and Jakubec (2001) recommend the use of the Mohs Hardness scale while others such as Read and Stacey(2009) suggest that the ‘drop test’ can also be used for this purpose

Validating logging database to estimate blockiness

Blockiness

To validate logging data to estimate blockiness, the following parameters are recommended to be reviewed in detail:

- Discontinuity density (RQD vs Defect spacing relationship).
- Missing logging data
- Verify that the core recovery length is not higher than the core run (>100%). As described by Read and Stacey(2009), this may occur when the core slips through the core lifter and is dropped out of the core tube, it would then be recovered crushed at the top of the next run. To overcome this issue,

practitioners in Peru typically make the core recovery length equal to the core run.

- Blockiness data (RQD and spacing) for the following zones.
    - Zones identified with higher IV weathering
    - Zones with resistance lower than R1 (IRS)
    - Zones with RQD values higher than 100
    - Intervals where induced fractures have been considered as limits of the logging interval.
- Zones identified with a RQD values between 0 and 20 should be reviewed as induced fractures sometimes are considered into the assessment, especially when drilling sedimentary rocks.

In Peruvian practice, theoretical recommended bounds by Bieniawski (1993) and Priest and Hudson (1976) are typically used to validate RQD values and/or discontinuity. spacing. The amount of data sets captured by the mentioned bounds and the data tendency are parameters taken into consideration not only to validate logging data, but also to classify the logging quality.

As shown in Figure XX and Figure XX, an important amount of the different data sets analyzed generally falls outside the existing bounds; in fact, Bieniawski's bounds approximately captured 25 to 70% of the data whilst Priest and Hudson limits captured 30 to 80% of the data. In general, it can be stated that significant data sets plots below bounds.

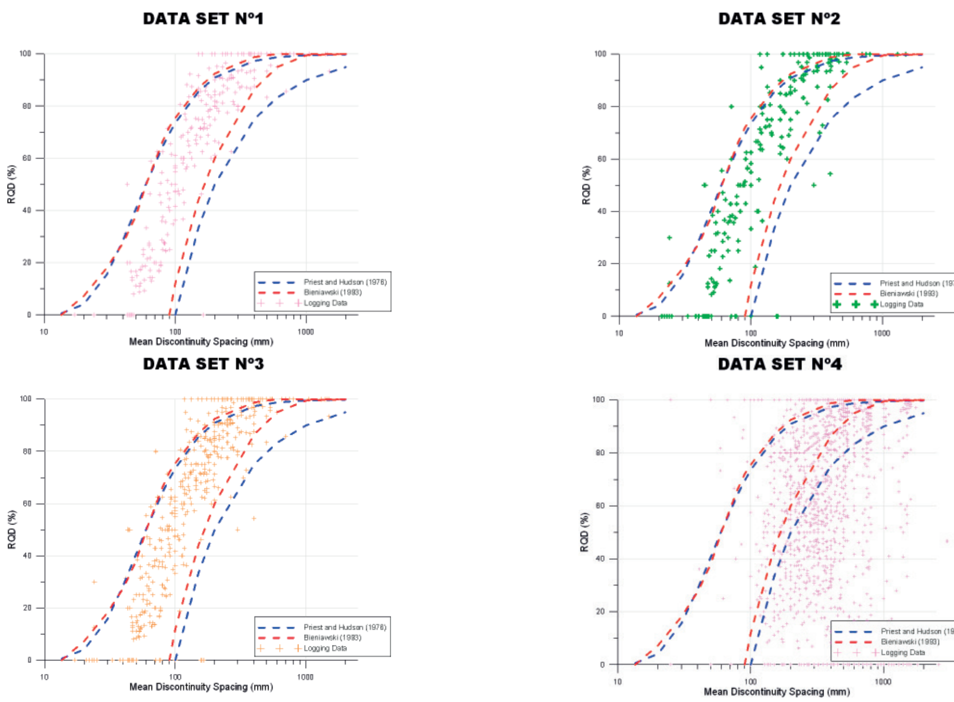

Figure 3- RQD vs Discontinuity spacing for analyzed data sets, bounds recommended by Bieniawski (1993) and Priest and Hudson (1976) are also shown. (1 of 3)

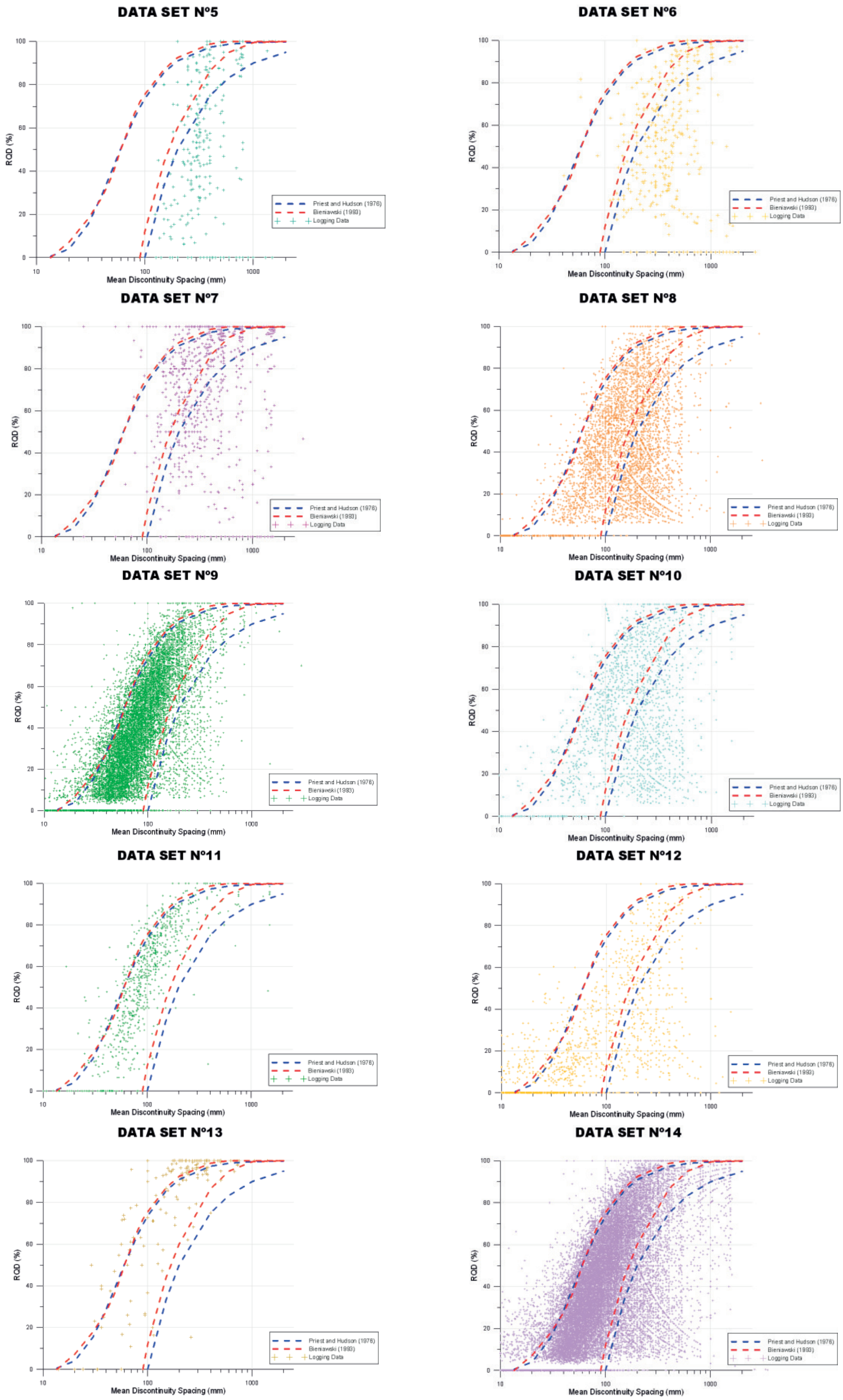

Figure 4- RQD vs Discontinuity spacing for analyzed data sets, bounds recommended by Bieniawski (1993) and Priest and Hudson (1976) are also shown. (2 of 3)

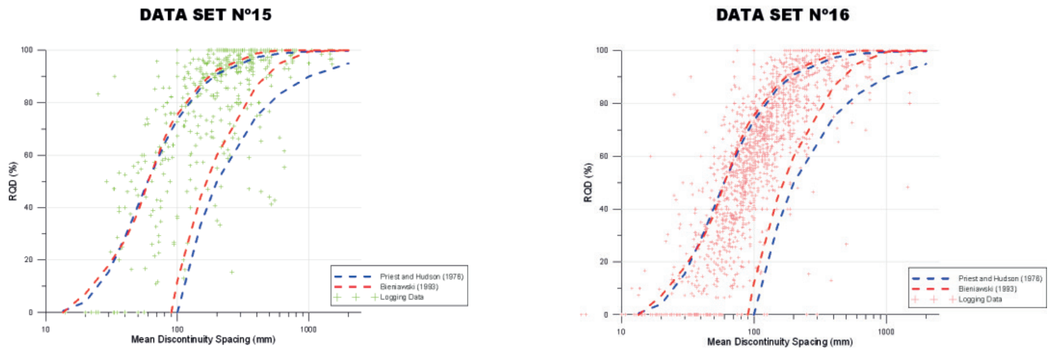

Figure 5- RQD vs Discontinuity spacing for analyzed data sets, bounds recommended by Bieniawski (1993) and Priest and Hudson (1976) are also shown. (3 of 3)

Results indicate that for many projects, especially those with good quality rock masses, RQD might have been underestimated due to different issues as discussed above. On the other hand, data sets from poor quality rock masses (disintegrated) or those presenting many weak zones have shown that discontinuity spacing might have been overestimated as number of defects were not adequately registered, primarily on the very blocky intervals.

As theoretical bounds poorly to fairly captured the analyzed data sets, these authors suggest the use of empirical alternative bounds so that good logging practices could be associated to them as shown in Figure 6.

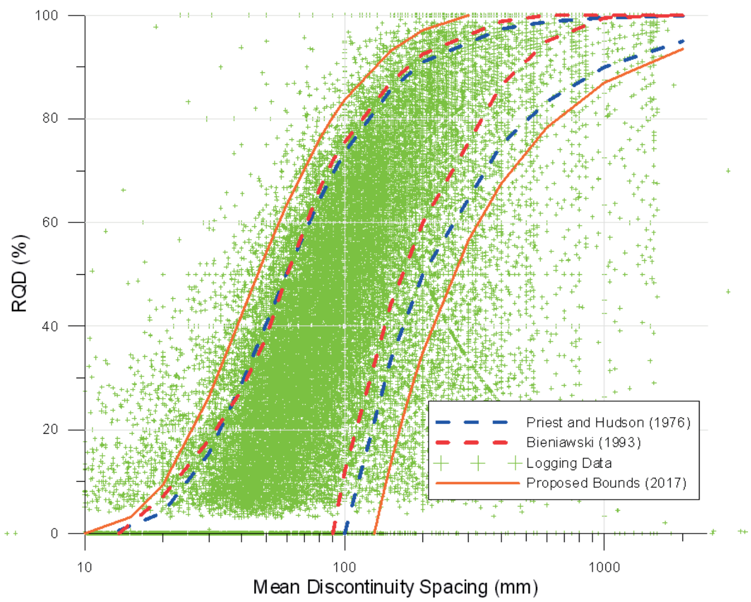

Figure 6- Proposed empirical bounds.

Confidence of Logging Quality

Finally, a criterion to qualitatively assess the confidence on logging quality considering the proposed bounds is suggested as illustrated in Table III.

Table III. Proposed criteria to assess confidence on logging quality.

Specific standards and procedures (1)	% Data captured by proposed bounds			
	< 50 %	50 - 70 %	70 - 90 %	> 90 %
Yes.	Very Low	Medium	Medium	High
No	Low	Medium	High	Very High

(1) logging standards and procedure developed for specific geotechnical-geological conditions of the project

GSI comparative analysis

For the previously presented data sets, a GSI comparative analysis was carried out between values of GSI estimated according to Hoek et al. (2013) and those derived from the relationship between GSI and the RMR'89 (Hoek et al., 1995). GSI was then calculated for each logged interval, Figure XX shows typical relationships found between the two considered approaches.

In general, results may suggest that for poor to fair quality rock mass, GSI values derived from Hoek et al. (2013) are slightly higher than those obtained based on RMR89. On the other hand, for good to very good quality rocks, GSI from RMR89 is apparently underestimating the GSI parameter. It is worth highlighting that the GSI value of 50 appears to be limit from which the data tendency changes. Considering this, caution needs to be utilized when selecting the GSI value for rock mas assessment and that this will ultimately affect slope design.

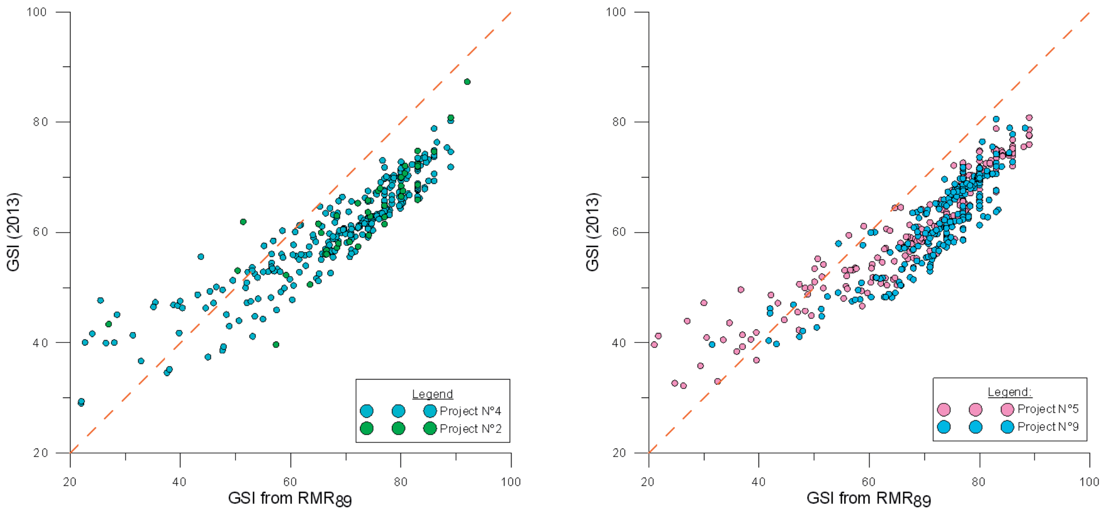

Figure XX GSI (2013) vs GSI from RMR89.

It was noted to be at the upper range of that observed in the limited window mapping. (potential deterioration of the exposed material)

Conclusions

Logging data sets from 15 projects were used to estimate blockiness; in general, it was observed that theoretical bounds recommended by Bieniawski (1993) and Priest and Hudson (1976) poorly captured the data. Alternative bounds based on empirical assessment were recommended by the authors so that confidence in logging can be classified. The necessity of re-logging in some cases are highlighted that have been proven useful in practical experience. Logging of core photographs is typically carried out when dealing with poor logging quality as more data can be captured for validation purposes.

Discussion regarding the typical managing and validation procedures of logging databases was also presented, from which it was observed that the quality of logging practices was notably improved when logging standards for specific geotechnical-geological conditions of the project are available.

Results also shown that for the reviewed data, typically RQD values were underestimated as induced fractures were included into the RQD estimation. It is worth highlighting that the scope of this work is focused to provide practical experience primarily on rock mass characterization rather than classification of rock mass. With respect to the GSI comparative analysis between values of GSI estimated according to Hoek et al. (2013) and those derived from the relationship between GSI and the RMR'89 (Hoek et al., 1995), results have suggested poor agreement of the GSI values for poor to fair quality rock mass. For good to very good quality rocks, GSI from RMR89 is apparently underestimating the GSI parameter. It also was observed that a GSI value of 50 appears to be limit from which the data tendency changes. Considering this, caution needs to be utilized when selecting the GSI value for rock mas assessment and that this will ultimately affect slope design.

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