Geotechnical mapping of rock masses in natural slopes using geomechanical classifications

ÂNGELO ZENÓBIO[1] & LAZARO ZUQUETTE[2]

[1] *VOGBR - Recursos Hídricos e Geotecnia. (e-mail: azenobio@vogbr.com.br)*
[2] *University of São Paulo. (e-mail: lazarus1@sc.usp.br)*

Abstract: The main objective of this work was to develop zoning charts for the Serra de Ouro Preto slopes and historical centre (Ouro Preto - Minas Gerais), Brazil, to characterize the rock mass in natural slopes in the study area. The main result of these classifications, as a tool for engineering geological mapping, were cartographical maps and charts at a scale of 1:5,000, to forecast gravitational mass movements. The geomechanical classification systems (RMR, Q, SMR) were combined with geotechnical mapping to develop zoning charts. When the RQD ("Rock Quality Designation") was not compatible with field observations, a correction index parameter (RQI - "Rock Quality Index") was proposed. This correction index was obtained from analysis of lithologies that present several geological characteristics such as specific mineralogical bands, weathering grade, mineralogical paragenesis and rock strength values. The results of the corrected RQD parameter were compatible with field observations and agree well with results obtained by Palmstrom's (1975) relationship. The cartographical documents developed were geological-geotechnical maps, mass movement maps, slope charts and zoning charts of the geomechanical classification systems.

Résumé: L'objectif principal de ce travail était développer de la répartition en zones établit un graphique pour le Serra Ouro Preto incline et centre historique (Ouro Preto - Minas Gerais), Brésil, caractériser la masse du roc dans les inclinaisons naturelles dans la région de l'étude. Que le résultat principal de ces classifications, comme un outil pour construire la projection topographique géologique, soit cartes cartographiques et palmarès à une échelle de 1:5,000, prévoir des mouvements de masse gravitationnels. Les systèmes de la classification du géomecanique (RMR, Q, SMR) a été combiné avec géotecnique qui dresse une carte de pour développer des palmarès de la répartition en zones. Quand le RQD (“Rock Quality Designation”) n'était pas compatible avec les observations de champ, un paramètre de l'index de la correction (RQI – “Rock Quality Index”) a été proposé. Cet index de la correction a été obtenu d'analyse de lithologies qui présente plusieurs caractéristiques géologiques tel que bandes minéralogiques spécifiques, niveau désagrégation, moyenne minéralogique, agenesis et valeurs de la force du roc. Les résultats du paramètre RQD corrigé étaient compatibles avec les observations de champ et sont d'accord bien avec résultats obtenus par Palmstrom (1975) rapport. Les documents cartographiques développés étaient le geotechnical géologique dresse une carte de, le mouvement de masse dresse une carte de, palmarès de l'inclinaison et répartissant en zones palmarès des systèmes de la classification du geomechanical.

Keywords: engineering geology, geotechnical maps, rock mechanics, joints, landslides

INTRODUTION

Studies about gravitational mass movements have been carried out for many years by several researchers in geotechnical, geomorphological and water resources fields. These studies have the common objective of understanding the main characteristics of these movements and their main controlling factors.

The occurrence of natural rock slopes in urbanized areas has engendered stability related problems caused mainly by disregard for environmental factors and unplanned development occupation on the slopes, with no respect for the limitations set by components of the environment.

Various techniques have been used for geological/geotechnical evaluation of outcropping rock materials on slopes for design and construction of residences and other related structures. One of the techniques currently in use for slope stability analyses, where rock outcrops predominate, consists of rock mass evaluation based on geomechanical classification. The characterization of a rock mass requires knowledge of its properties and intrinsic characteristics, particularly its discontinuities.

Bearing in mind the issues cited above, the main objective of the work reported in this paper was to develop a rock mass characterization study at a scale of 1:5,000, through the survey and analysis of principal discontinuities in an area of approximately 2.88 km^2, located at an urban site in the city of Ouro Preto, State of Minas Gerais (Brazil).

Geomechanical classifications were applied as tools for geotechnical mapping in order to generate cartographic sheets, which could represent the mapped rock mass behavior in the studied area. Twelve cartographic sheets were generated in this work: topographic maps, geological maps, slope charts, with slope angles, gravitational mass movement feature maps and related processes, and zoning charts for geomechanical classifications.

APPLICATION OF GEOMECHANICAL CLASSIFICATIONS ON THE ROCKY SLOPES OF SERRA DE OURO PRETO

The overall area in question is situated in the south central State of Minas Gerais, within the municipality of Ouro Preto. The actual mapped area, located within urban limits of Ouro Preto city, extends over a total of 2.88 km^2.

The surveyed field data for the area were mapped to a scale of 1:5,000. The contacts, alignments and main orientations of the lithological units were traced with the aid of 1:8,000 scale aerial photographs. The area, which is regionally within the southeastern portion of the *Quadrilátero Ferrífero*, contains a diversity of lithologies (see Table 1) that were classified, subsequent to the field survey phase, according to the stratigraphy defined by Endo (1977).

Table 1. Stratigraphical column adopted for the surveyed area.

Super-Group	Group	Formation	Lithology
Minas	Piracicaba	Cercadinho	Quartzites and phyllites
	Itabira	Cauê	Itabirite
	Caraça	Batatal	Phyllite
		Moeda	Sericitic quartzite
Rio das Velhas	Nova Lima	Undividable	Sericite-schist- quartz

The rocks mapped within the area generally strike NW/SE, with high dips towards the SW. Based on aerial photographs it was observed that these present a characteristic pattern within the overall *Quadrilátero Ferrífero* NNW/SE, NNE/SW and N/S alignments.

METHODOLOGY

The methodology used in the fieldwork and analysis of its results comprised three phases and are described in this section.

Phase I

A desk study stage comprised a literature review of the studied themes: gravitational mass movements, discontinuities, geomechanical classifications and its usage. During this literature review the methodology was evaluated. It should be noted that there is not a great deal of the literature reporting this line of research, that is, the use of geomechanical classification as tool for geotechnical mapping.

Regarding discontinuities surveys, the adopted methodology was the one proposed by ISRM (1978). The Rock Quality Designation (RQD) survey was a key issue.. In the survey of this parameter in the study area the Palmstrom (1975) proposal was adopted, which suggested an equation for RQD based on a calculation of discontinuity density per volume (Jv) when drill cores are not available. The geomechanical classifications used were those of Bieniawski (1989), Barton et al. (1974) and Romana (1985).

In a second stage, the area to be studied was selected. All aspects that would support a successful survey were evaluated and taken into account; including a history of slope-related accidents and the disorderly urban expansion in the proposed study area.

Phase II

This phase was divided into two stages. The first related to the geological survey and the second to the survey of the actual discontinuities of the rock masses. Based on these surveys cartographic sheets were generated, according to the methodology proposed by Zuquette (1987,1993).

In the geological survey stage, besides observing all the actual characteristics in the rock of the area, scanlines were carried out in order to evaluate target areas for geomechanical classifications. After the field works were carried out, the data were analyzed which made possible the generation of two cartographic sheets: documentation map I (auxiliary map) and the geological map (fundamental base map).

In this stage the gravitational mass movements feature map and related processes was generated (optional basic map), where the mass movements classification, proposed by Zuquette (1987, 1993), was adopted. In this second phase the actual discontinuities of rock mass was surveyed. At the end of the fieldwork and data analysis two other cartographic maps were generated: documentation map II (auxiliary map) and a slope chart (fundamental base map).

Phase III

In this phase all the analyses were carried out using data from the fieldwork and information management. After the first geomechanical classification results, it was found that the derived RQD values were incompatible with the field observations, and that some modifications were necessary. Therefore a correction index was proposed in order to evaluate the RQD parameter. Once these corrections were made new geomechanical classifications were generated. At the end of phase III, six cartographic sheets were prepared following analysis of the results. These were zoning charts (derivative or interpretative) for each one of the classification systems, with and without corrections. They were the result of correlating the geological map, slope chart and geomechanical classification results. Once the zoning was carried out, their families could be used to classify the actual rock masses in the area.

RESULTS AND ANALYSES

The results obtained and respective analyses are discussed in this section. The cartographic sheets presented in a first stage were generated using the previously described methodology. These were the base for geotechnical zoning utilizing geomechanical classification. In a second stage, the RQD parameter correction was adopted, once it was concluded that this parameter needed some modification following the first analyses of the field data.

The parameter correction index and its results are presented, followed by a comparative analysis between the geomechanical classification before and after application of the corrections index. Finally, discussion of the zoning charts is presented.

Cartographic Documents

After a first analysis, the cartographic sheets generated using the field data were documentation map I and II topographic and geologic maps, slope charts and gravitational mass movement features map.

Topographic Map:

The topographic map is considered a fundamental base item. It was constructed to 1:2,000 scale and was based on the 1;2000 topographic sheets of CEMIG (Centrais Elétricas de Minas Gerais), with contour lines at 2 meter intervals.

Documentation Map I:

The documentation map I is a secondary or auxiliary item. Constructed to a scale of 1:5,000, it contains the main access roads and structures, inactive gold mines, drainage system and geological observation points, as well as the main surface water divide.

Documentation Map II:

The documentation map II shows at a scale of 1:5,000, the observation points relating to the geomechanical classifications (125 points), presents the main access roads and structures, inactive gold mines, drainage system and geological observation points, as well as the main surface water divide. All the parameters necessary for the geomechanical classification evaluation were described at the observation points.

Geological Map:

The geological map was generated for the area to a scale of 1:5,000. The lithologies, the main features and structural aspects encountered in the area surveyed are included.

Slope Chart:

The slope chart, generated to a scale of 1:5,000, is a fundamental base document. The construction of this chart was carried out in two stages. Firstly, actual topographic variation of the area was analyzed through preferential slope directions, which were plotted in the chart. At the same time, delimiting bulbs of main slope directions and angles were analyzed considering a minimum variability. Secondly, calculations were carried out and logged on the chart, for dip slope angles and directions relative to true North (Zuquette & Gandolfi 2004).

Map of Gravitational Mass Movement Features and Correlated Processes:

The map of gravitational mass movement features and correlated processes show information related to gravitational mass movement and erosion to a scale of 1:5,000. Drainage present in the area as well as surface water divides were also registered in this map. The feature analyses were carried out in two stages. In the first stage, developed in the office, 1:8,000 aerial photographs were utilized. In the second stage, ancient and recent features were mapped in the field. In this map 64 gravitational mass movements were classified according to Varnes (1978). Types of slope failures, rock falls and complex movements involving were identified in the area.

Geomechanical Classifications Versus RQD Parameter

Considering that the RQD. is important in all three geomechanical classifications that have been adopted, the determination of a reliable RQD value is of fundamental importance. Initially RQD parameters were determined on the basis of rotary drill core samples (Deere et al. 1967). Later, empirical relationships, such as those of Palmstrom (1975) and Priest & Hudson (1976) were proposed to determine the RQD values on the basis information obtained in field surveys.

Empirical relationships are very useful in a region where the topography is very irregular and steep and rotary drilling becomes difficult and hence expensive to obtain core samples.

R.Q.D. Parameter Results and Correction Proposal

A survey was conducted within the area at 125 locations. For each location all the necessary parameters to determine the geomechanical classifications were evaluated, described and measured.

26 of the above total number of locations were in itabirites, 4 in phyllites, 36 in quartzites and 59 in schists. Regarding tectonic related discontinuities, 6 families were diagnosed in the itabirites, 4 in the phyllites, quartzites and schists. One of the families present in all the lithologies refers to foliation (schistosity) and the others refer to fractures.

The values obtained for the first analyses of the RQD parameter for the majority of the 125 sets of data obtained for the area, were high when considering the other characteristics of the rock mass in the field. These RQDs varied from 90% to 100%, which, in the case of some of the rocks within the area in question, is practically impossible to obtain especially for the schists and phyllites of low mechanical strength and a high degree of weathering. Another issue was that when the above RQDs are combined with other parameters of the rock masses, they increase the values of the geomechanical classifications (Zenóbio & Zuquette 2004).

A parameter correction index (RQI.) was therefore proposed in the light of the above-determined incompatible values, in order to obtain values that would be compatible with actual geological/geotechnical characteristics. The evaluation of the lithologies was based on the following aspects:

- discontinuities of genetic and structural origin;
- intact rock strength;
- mappable weathering degree;
- mineralogical paragenesis of sound rock;
- specific mineralogical lineations, that behave as discontinuities;
- rock fragmentation and disintegration degree when struck.

Based on the above aspects, it was considered that:

- due to the laminar characteristics of the micaceous minerals, schists and phyllites were found to be very breakable, easily disintegrated, have low mechanical strengths and feature mineralogical paragenesis that favours the breakage of the rock into smaller pieces;
- interbedded quartzite and phyllite presented, in general, more favourable conditions than phyllite and schist intercalations. This occurs, because, even if the phyllites are in a weathered condition, the quartzites are in good condition. Samples of quartzites with dimensions greater than 10 cm could frequently be obtained;
- itabirites present a mineralogical paragenesis from slightly cemented quartz rich through to compacted layers of hematite;
- quartzites are characterized by blocks delimited by structural discontinuities and specific mineralogical levels, or discontinuities of genetic origin.

Table 2, presents anticipated RQD ranges associated with rock types, assessed on the basis of the above evaluations.

Table 2. Relationship between rock types and the expected R.Q.D. ranges.

Rock	Range of expected R.Q.D. ranges (%)
Schists/Phyllites	0 – 25
Quartzites/ Phyllites (Weathered)	25 – 50
Itabirites	50 – 60
Quartzites	60 – 80

Considering the observations described above, the expected RQD ranges together with geological aspects, it was considered that the four geological/geotechnical aspects that most affect the RQD values are: rock strength, degree of weathering, mineralogy and specific mineralogical laminations.

An analysis was undertaken involving the classification used for each geological/geotechnical factor which resulted in a index to adjust the RQD to a final (RQD^f.) value

The partial indexes were defined on the basis of the on the following RQD related aspects:

- rock material weaknesses having a direct influence on RQD
- repetition or frequency of the above within the rock material;
- discontinuities of tectonic origin.

The partial indices were defined considering that the theoretical expected values of RQD could vary from 0 to 80%. Considering this, the total minimum correction could range from 20% to 100%.

The following expression was proposed to simplify the development of the work:

$$\text{Rock Quality Index (RQI.)} = \text{IpnI} + \text{IpnII} + \text{IpnIII} + \text{IpnIV}$$

Where: Ip is the partial index for each geological/geotechnical factor
n (I,II, III, IV) is the factor number;
RQI should always be greater than 1.0.

To aid in the definition of the partial indices it was determined that the mechanical strength of the rock and the weathering degree should have the same level of importance followed by mineralogical paragenesis and specific mineralogical lamnations, respectively. Furthermore, the partial indices should decrease in value depending on the intensity of the class or degree over the final RQD value.

Based on these conditions, it was determined that the partial correction indexes should vary between 0 to 2.0, and that their distribution among the 4 factors and the relationships of the classes or degrees should comply with the relative importance of the RQD parameter.

Table 3 for RQD correction was drafted based on the partial correction indexes obtained for the 125 locations, with the objective of attaining a corrected RQD^f. parameter value that would be of better use in the geomechanical classifications.

Table 3. Partial indices and RQI. ranges ("Rock Quality Index").

I-Rock Strength (MPa)	II-Degree of Weathering	III-Mineralogy	IV-Mineralogical Laminations	R.Q.I.
1 - 5 [2.0]	W5/ W 4 [2.0]	Micas (Sericite, biotite, muscovite) [1.5]	Sericític [1.0]	6.5 (Max.)
5 - 25 [1.5]	W 3 [1.5]	Quartz [1.0]	Sandy [0.75]	4.75
25 - 50 [0.70]	W 2 [0.70]	Hematite/ Quartz [0.30]	Hematite and Quartz [0.30]	2.0
50 - 100 [0.5]	W 1 [0.5]	Cemented Quartz [0.0]	Quartz (Fractures) [0.25]	1.25 (Min.)

[ ] – Partial correction indexes

Accordingly analyses and calculations of the RQD parameter were carried out for each of the 125 sets of data based on the four geological/geotechnical factors considered for RQI. Table 4 presents the results of the analyses expressed in minimum and maximum values that represent the variations of the factors in the rocks throughout the area.

Table 4. Results for the calculated RQD (*), the R.Q.I. and the corrected RQD^f

Lithology	Calculated RQD. (**)	RQI. (**)	Corrected RQD^f. (**)
Schist	100	6.50-5.25	15.39-19.05
Phyllite	100	5.00-4.75	20.0-21.05
Itabirite	96.06-100	4.35-2.00	22.98-50.0
Quartzite	58.43-100	2.00-1.25	29.21-80.0

(*) – Palmstrom (1975) expression
(**) – Minimum and maximum values

Comparative analyses of geomechanical classifications before and after corrections:

In view of the results that were obtained, it can be said with respect to geomechanical classification, the best results were the ones from the Bieniawski (RMR System) and the Barton. (Q) system. It should be noted, although, that even with these results, they needed adaptations for weak rocks, because even with the corrections of the RQD parameter there was a need for evaluation of other parameters within the geomechanical classifications and also for the weighting of values obtained in the field.

With regard to Bieniawski classification (RMR System) it can be said that the results were satisfactory for schist and phyllite rocks, mainly after corrections. As regards itabirite and quartzite the results were not compatible with the rock mass field observations.

The Barton classification (Q System) had satisfactory results, mainly regarding schist phyllite and quartzite. Regarding quartzite it should be noted that after the corrections were made there was a class change. At some localities the quartzite was found in direct contact with other rock types, but in general it was found in a distinct mass.

The Romana classification (SMR System) presented results incompatible with field observations, mainly with respect to schists, phyllites and itabirites. The results were satisfactory only for quartzite. However after corrections, there was a decrease of values when changing classes for rock mass classification.

ZONING CHARTS

The zoning charts were generated based on results obtained by geomechanical classifications and were derived from base and auxiliary sheets that were aimed at mapping objectives and area characteristics. The Zuquette (1987,1993) methodology was used in the construction of these charts at a scale of 1:5,000. The cartographic documents utilized for information evaluation and end result analysis were;: topographic map, documentation map II, geological map and slope charts.

The basic division used for zoning was the slope chart with values of maximum slope angle and direction. Thus, by combining relative classes of geomechanical classifications, lithologies and topography it was possible to obtain the units and their characteristics. For a better presentation of the results, two charts were constructed for each classification system (Figure 1). The first chart shows the results of geomechanical classifications obtained for each discontinuity family observed in each lithology, without the correction index adopted for RQD parameters. The second chart shows the results obtained with the corrections, using RGQ[f].

These charts have contour lines with 10 m and contain all the mapped lithologies in the area as well as their contact with the slope influence area referring to the east part of the area, where geomechanical observation points were surveyed. Regarding the presentation of the results in the zoning charts, a legend was developed, according Figure 1, an informative form of presentation for ease of chart users. This table was inserted in each slope influence area for all lithologies with respect to geomechanical classification results for each discontinuity family.

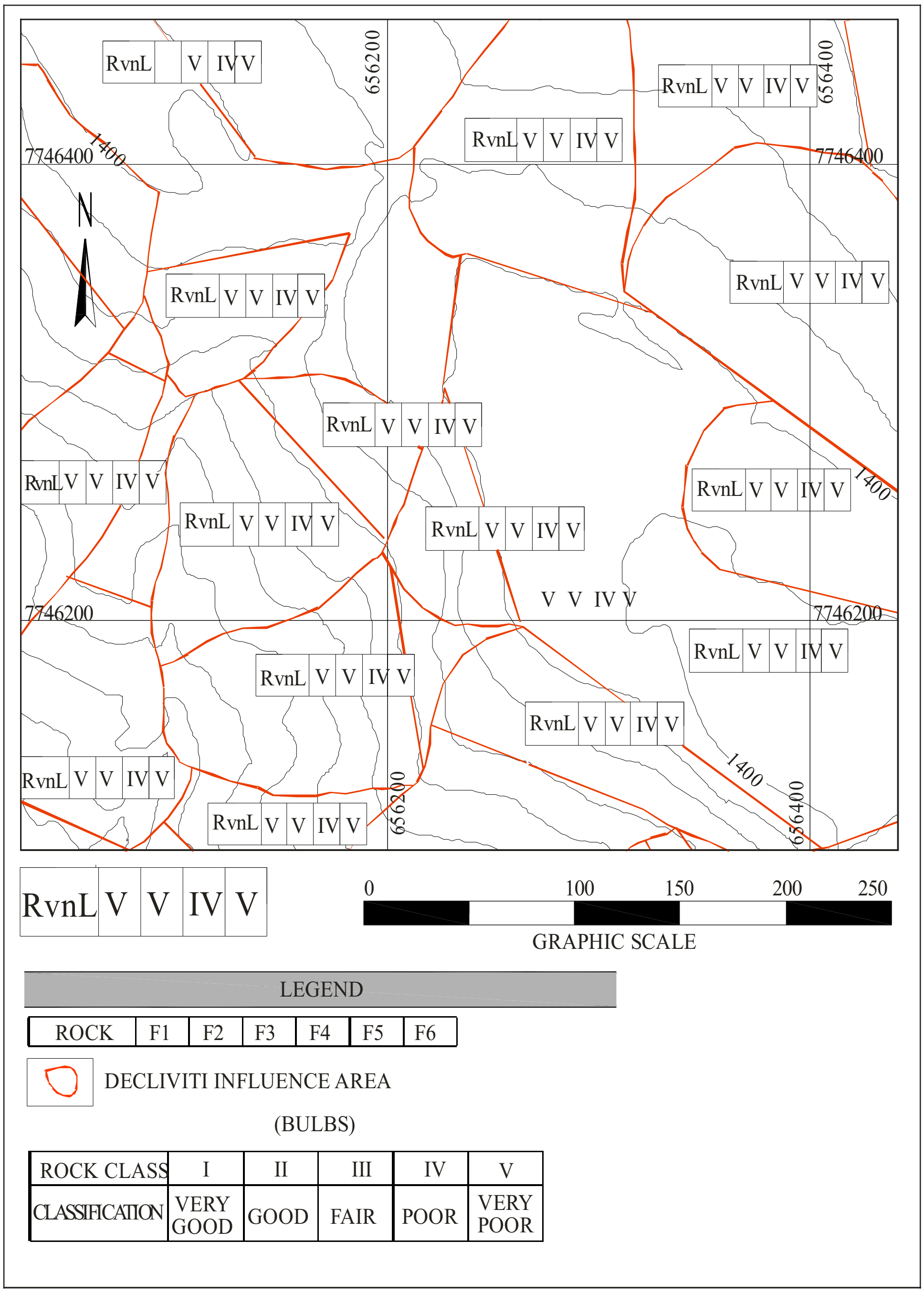

Figure 1. A Typical Zoning Chart – RMR (Zenóbio 2000)

Table 5. Legend of geomechanical classification results for each family of discontinuity used in the zoning charts.

ROCK	F1	F2	F3	F4	F5	F6

Where: **ROCK –** actual lithology found in the area of influence of the analyzed declivity.
Fn – geomechanical classification results for the each discontinuity family

CONCLUSIONS

In general, the geomechanical classifications with best application results were the Bieniawski (RMR System) and the Barton (Q System) classifications based on the results of the zoning charts. The Romana classification (SMR System) presented results that were incompatible with field observations, mainly with respect to schist, phyllite and itabirite.

Even with the obtained results it should be noted that geomechanical classifications could be a tool of great utility in geotechnical mapping, when classifying rock slopes, if the systems are modified in the case of weak rocks, in order to gain better rock mass characterization.. In the case of corrections made to the RQD parameter it was necessary to analyze other parameters within the geomechanical classifications and its relative weights in the light of the field data.

Regarding the geomechanical classification systems some aspects should be noted that tend to hinder a satisfactory classification rock mass behavior.

- In relation to the RMR system it can be conclude that the factor summation can be a little limited for rock mass evaluation, leading to conservative results.
- In Q system, firstly joint spacing is not considered directly in estimating Q index, although it is considered in the RQD. Secondly the intact rock resistance and degree of weathering are not taken into account directly in the system and it also does not consider discontinuity orientation with respect to the civil works to be constructed.
- With respect to the SMR system, although the system proposes some corrections, no changes in the classification are included as regards actual dip orientations in the slope rock masses.

With relation to corrected RQD^f, for the rock masses that were mapped, the observed results were compatible with the observed field behavior. It can be concluded that the correction index RQI proposed in this paper was satisfactory for the rock masses in the area and was an important tool to evaluate the RQD because the corrected values were within the expected range.

This index can be applied to areas that have the same lithologies within the Quadrilátero Ferrífero as well as regions with similar characteristics. The four attributes that comprise the correction can be determined in field surveys.

However, other necessary parameters besides the RQD are necessary for rock mass classification, and need to be evaluated and analyzed in detail. To evaluate the rock mass parameters for rock mass classification it is necessary to assess if corrections are necessary in order to obtain results that are compatible with the rock mass classification.

With regard to the collection of data for the Jv Index (volumetric joint counter) it is important that all the discontinuities within a rock mass be observed in detail and identified; not only foliations or fractures, but also all those that present discontinuity behavior. This is because, in some cases, planar structures that behave as discontinuities and when not identified can lead to errors in the collection of data for the Jv Index and consequently in the evaluation of the behavior of the rock mass.

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Corresponding author: Mr Ângelo Zenóbio, VOGBR - Recursos Hídricos e Geotecnia, Alameda do Ingá nº 89., Vale do Sereno - Nova Lima - MG, Minas Gerais, CEP 34.000-000, Brazil. Tel: +55 31 3071 7114. Email: azenobio@vogbr.com.br.

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