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Physical stability of iron ore caves: geomechanical studies of a shallow underground cave in SE Brazil

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Abstract

Caves hosted in iron formations are attracting considerable interest due to their scientific and environmental value. Some of these caves are located in or near iron ore mine sites, which represent an important source of income to Brazil. However, the Brazilian legislation requires speleological studies that currently have an impact upon ore reserves and environmental licensing processes.

The aim of this study was to apply conventional geotechnical empirical approaches to a cave located within the grounds of an iron ore mine in the Iron Quadrangle and validate it with numerical modelling, to ensure the method's applicability to natural caves under mining activity influence.

These studies comprised the mapping of structural, geotechnical and geomechanical features of rocks hosting and surrounding the cave and to propose geotechnical domains. Field data collection covered the geotechnical parameters necessary to calculate the characteristic Mining Rock Mass Rating (MRMR) for each geotechnical domain, and to evaluate the stability conditions using the stability index or hydraulic radius of the cave. These geotechnical parameters were then used to calculate the physical parameters used in two-dimensional numerical simulations to verify the good stability conditions of the cave, corroborating the adequacy of Laubscher's diagram.

The results of this study, although comprising only one cave, suggest that Laubscher's diagram is applicable for assessing the geotechnical behavior of iron ore caves.

Keywords: natural caves; canga; laterite crust; geotechnics; conservation.

1. Introduction

Natural caves hosted in iron-rich lithologies (iron ore caves – IOCs) have been identified in several iron-rich formations in the world (Grimes & Spate, 2008). For some reasons still not fully understood, they appear to be more common in Brazil than in other iron-producing provinces in the world (Parker *et al*., 2013a). They are not as scenic and rich in speleothems as carbonate caves, but some of them have attributes that deserve to be studied and preserved. The troglobitic fauna is little known, with new species currently being discovered and described (e.g. Iniesta & Ferreira, 2013; Pellegrini & Ferreira, 2017). Some of these caves are palaeoburrows of giant sloths or armadillos, and some contain vestiges of primitive human usage or occupation. On the other hand, as they are hosted in or near high-grade iron ore mines that are important sources of wealth for the country, criteria have been proposed in order to determine which caves may be suppressed during the mining operations and which ones should to be preserved (e.g. Donato *et al*., 2014; Auler *et al*., 2017). Brazilian environmental laws are quite strict, although they leave room for compensation for destruction of low, medium and highly relevant caves. The maximum relevance caves must be preserved at all costs, though less relevant ones may be suppressed, subject to permitting processes from the local authorities (BRASIL, 2008).

There are still discussions concerning the speleogenesis processes of the IOCs. Many authors consider their origin to be a result of differential erosion in the interface between the hard cap "canga" and friable material underneath (Grimes & Spate, 2008), while others believe the origin is hypogenic, originating from the decrease of volume created by the same processes that dissolved the siliceous materials and concentrated the iron oxides that formed the high-grade ore (Auler *et al*., 2014). Iron-reducing bacteria are also being studied as possibly having played a role in the cave formation (e.g. Parker *et al*. 2013a, 2013b and 2017).

The understanding of the geomechanical behavior of the rock mass where these natural caves have been developed is essential for iron mining, since its knowledge and characterization are key determinants for defining the iron project forecast with regards to the need for maintenance of the physical integrity of some of the caves. Geomechanical studies provide sources for understanding the relationship between open-pit mining and physical impacts generated in natural caves and allow the design of physical stability monitoring projects for caves during mining operations. Thereby, the key drivers for defining operational procedures can be outlined to allow the coexistence between mining activity and conservation of cave integrity.

Geomechanical studies in caves and mining environment have been conducted in many areas of the world (e.g. Klimchouk & Andrejchuk, 2002; Waltham & Park, 2002; Geniş & Çolak, 2015). Barton (1976) considers limestone cave spans in his empirical graph with satisfactory results. Waltham & Fookes (2005) applied graphical methods to natural caves and have presented the cave concentration trend in the Q-system's stability chart, specifically concerning limestone caves. In addition, Jordá-Bordehore *et al*. (2016) and Jordá-Bordehore (2017) have applied the Q-system's support graph to natural caves and came to the conclusion, considering 137 caves, among which the ones that have the largest spans in the world, that a new empirical limit for evaluating the stability of natural caves could be proposed, having done so. However, the published results refer mostly to caves hosted in limestone or other soluble rock types. Pires *et al*. (2017) have applied Laubscher's diagram to IOCs in Carajás, Brazil, and have obtained promising results. De Paula *et al*. (2018) have, complementarily, compared the graphical approach from the MRMR and the Q systems to IOCs, having Laubscher's approach shown to be closer to the expectation considering the cave's spans.

Presently, with the need for conservation of the most relevant IOCs, as the mining fronts get closer to their radius of protection, it has become increasingly important to define simple and feasible criteria and parameters to assess their stability. In this study, the aim was to establish a preliminary way of investigating the influence of mining operations in the stability of adjoining natural caves, by using the results from geomechanical studies developed in a natural cave occurring near two iron mines. The study comprised field mapping and numerical stability analyses, considered as a more robust method to assess the applicability of the essayed empirical method.

Location

The MP-07 cave is located in the Itabirito (SE Brazil), in a very important mining district of Brazil, the Iron Quadrangle. It is in the grounds of an iron ore extraction site operated by the Brazilian mining company VALE, between the Pico and Galinheiro open-pit iron mines (Figure 1).

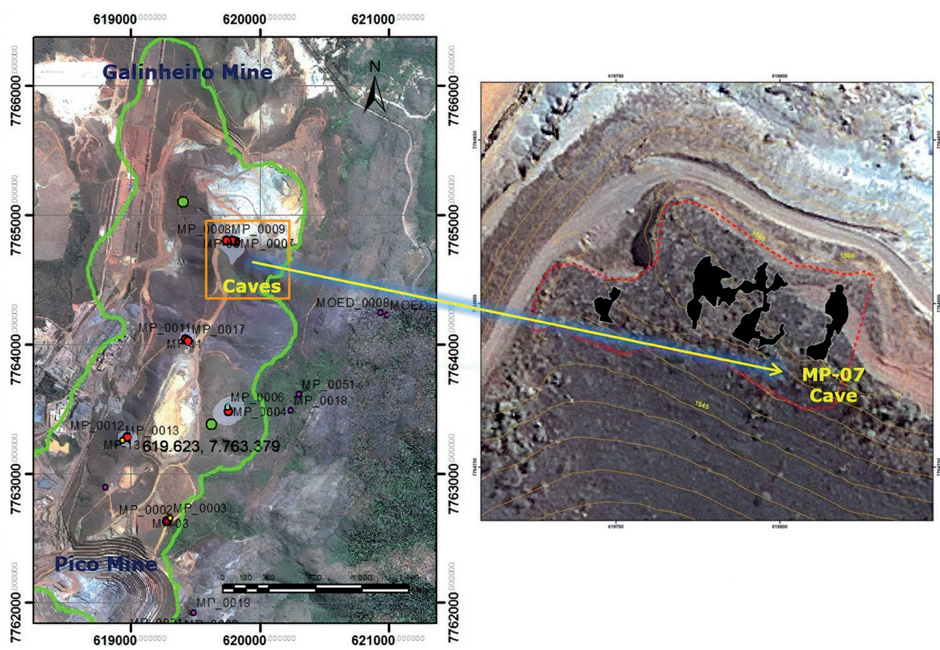

Figure 1
Location of the MP-07 cave.

Geological characterization

The MP-07 cave is inserted in the contact zone between the iron formation and the hardened crust, termed 'canga' in Brazil. The predominant rock type observed in the interior of the cave is the iron formation, consisting of leached itabirite (Figure 2a). It can be observed in the whole northern room and in the basal part of the southern room walls. The detrital canga emerges in the southern room ceiling (Figure 2b). A third rock type, locally called hematitite, can be observed in the central part of the cave (Figure 2c). This rock type consists of high-grade compact ore. It is usually located in fold axes and stands out as projected massive nucleus on the mine slopes. Where the hematitite rock type outcrops, its greater strength prevents further development of the erosive process of the cave, forming passages that are narrower than the others found in other parts of the cave.

Figure 2
MP-07 cave lithologies:
(a) iron formation (leached itabirite),
(b) detrital canga and (c) – hematitite

2. Methodology

Field mapping

The geomechanical studies developed for the MP-07 cave started with a detailed scale mapping of the structural, geotechnical and geomechanical features of the rocks hosting in the cave and surrounding areas. These studies allowed the identification of the geotechnical variables, necessary to assist the evaluation of the physical stability conditions of the cave.

The internal mapping of the MP-07 cave and surrounding areas comprised the following activities: (1) identification of the lithologies in and around the cave; (2) estimation of the parameters of weathering and resistance of the involved masses through tactile-visual tests (Barton, 1978); (3) identification and measurement of discontinuity sets and their attitudes, frequency and distribution; (4) characterization of the discontinuities that define anisotropy and influence the geomechanical behavior of the rock masses (spacing, aperture, roughness, filling, walls weathering, frequency and persistence); (5) characterization of the degree of weathering and water presence, and (6) photographic record of the relevant joints.

In addition, the relationship between the physical conditions of the rock masses in the MP-07 cave and the progress of the mining in the surroundings of the cave were evaluated, especially where it was possible to make observations from the exposures in the cuts of the mine pit slopes.

Data were compiled using a spreadsheet form elaborated to collect the geomechanical parameters necessary for rock mass classification considering Laubscher's proposed approach (1990).

Rock mass classification

The process contemplated assessing values to the considered parameters for Laubscher's Rock Mass Rating (RMR). Namely, that is: (1) intact rock strength (IRS), (2) spacing of fractured and joints and (3) joint condition and water. The IRS is the unconfined uniaxial compressive strength of the rock between fractures and joints. Spacing is the measurement of all the discontinuities and partings and does not include cemented features, which affect the IRS and as such must be included in that determination. It could be indicated by the Rock Quality Designation (RQD) (Deere & Miller, 1966), joint spacing (given by a chart) or by the fracture frequency per meter. Finally, the factor for joint condition takes into consideration both large and small-scale expressions of the feature, if there is a distinct difference between the hardness of the host rock and that of the joint wall and joint filling.

Considering the Brazilian legislation regarding natural caves (BRASIL, 2008), there shall be no impacts to caves without previous authorization from environmental agencies. Therefore, the parameters IRS and RQD were estimated via tactile-visual inspection (Barton, 1978) and Priest & Hudson's equation (1976), respectively, aiming to replicate the methodology in any cave. The other parameters were obtained conventionally, as proposed by the author.

In addition, Laubscher proposes correction factors concerning the mining influence on the excavation and to this corrected index the author entitles the Mining Rock Mass Rating (MRMR). The author indicates four factors: (1) weathering, (2) joint orientation, (3) mining induced stresses and (4) blasting effects.

The data collected in the field were submitted to the CLASROCK 32 software (Geo&Soft, 2005), designed to evaluate the geomechanical behavior of the rock mass and to estimate the MRMR values for the identified lithologies. Results obtained from these calculations made it possible to distinguish among geomechanical classes in the cave and surrounding area, favoring the definition of different geotechnical domains.

This parameter was used, together with the stability index (Laubscher, 1990), for self-supporting conditions assessment for an underground cave.

Empirical method

There are mainly three conventional empirical methods for excavation stability – Bieniawski's stand-up time chart (1973, 1989), NGI's support graph (Barton *et al.*, 1974; Barton & Grimstad, 1994) and Laubscher's diagram (1990). The literature review hasn't uncovered any application of Bieniawski's approach to caves. Barton's support graph, on the other hand, has been tested by a few authors (Waltham & Fookes, 2005; Renó, 2016; Lacerda *et al.*, 2017; Jordá-Bordehore, 2017), being suggested as conservative. So much that Jordá-Bordehore (2017) has, in fact, proposed a new boundary line for the stability assessment interpretations for caves. Finally, Laubscher's diagram has been successfully employed to natural ferriferous caves by Pires *et al.*, (2017) and de Paula *et al.*, (2018) presenting promising results. Therefore, Laubscher's diagram was chosen as the empirical method to have their results compared to numerical modelling simulations.

2D finite element stress analysis

The geomechanical parameters were also processed using the RocLab program (Rocscience, 2002) to obtain the physical parameters adopted in the two-dimensional elasto-plastic finite element simulations performed to validate the stability conditions resulted from empirical methods. The software employed to perform these two-dimensional simulations was the PHASE2 version 7.0 program (Rocscience, 2008). This program uses a plane strain analysis assuming the two principal in-situ stresses are in the plane of the excavation and the third principal stress is out of plane. It is also assumed that the cross-section of the excavation is constant, and the excavation has infinite out-of-plane length and that there are no shear stresses or strains in the out-of-plane direction.

Therefore, there are limitations to applying this software to natural caves, which are underground voids with varying sections throughout its extension. However, it is effective to simulating stress versus deformation analysis in critical sections, selected for its ceiling shapes and thickness.

3. Results

Geomechanical classification

The geomechanical classes for the lithotypes observed inside the cave were defined by field mapping using the Laubscher's method (1990). The field data were processed using CLASROCK 32 software. Results obtained from the characterization and geomechanical classification allowed the definition of three geotechnical domains (Table 1).

Parameter	Canga cap		Compact hematite		Leached itabirite	
	Characterization	Factor	Characterization	Factor	Characterization	Factor
UCS	100-250 Mpa	18	100-250 Mpa	18	50-100 Mpa	8
RQD	25-50%	5	50-75%	5	25-50%	5
Spacing of discontinuities	0.06-0.2m	6	0.06-0.2m	10	0.06-0.2m	6
Conditions of discontinuities	Slightly rough surface, separation < 1 mm, highly weathered wall	21	Slightly rough surface, separation < 1 mm, highly weathered wall	21	Slightly rough surface, separation < 1 mm, highly weathered wall	21
Laubscher's RMR	-	50	-	54	-	40
Weathering	Fresh	100%	Fresh	100%	Fresh	100%
Joint orientation	5 joints defining the block with 2 faces inclined away from vertical	85%	5 joints defining the block with 1 face inclined away from vertical	90%	5 joints defining the block with 1 face inclined away from vertical	90%
Mining induced stresses	Average rating 30-40 with plunge degree >50	90%	Average rating 30-40 with plunge degree >50	90%	Average rating 30-40 with plunge degree >50	90%
Blasting effects	Boring technique	100%	Boring technique	100%	Boring technique	100%
MRMR	-	38	-	43	-	32

Table 1
Geomechanical classification of the rock types observed in the MP-07 cave showing the higher values of the compact hematite.

The first proposed domain was the canga rock type, which forms a very rigid crust. The main characteristics of the canga were its high values of mechanical strength, with estimated values for uniaxial compressive strength of about 120 MPa. Concerning the fracturing system, the canga has a massive appearance, with fracture spacing ranging from centimeters to decimeters. An average spacing from 0.06 m to 0.2 m was considered. The cave is located very close to the surface, where a very strong canga crust prevails, providing good conditions of self-support to the ceiling.

The second proposed domain was the prevailing compact hematite (hematitite). The main feature was its higher values of mechanical strength, with estimated value reaching over 200 MPa. As the studied cave presents weathering features, a value of 160 MPa was adopted for the purpose of its geomechanical characterization and classification.

This domain presented a less accentuated fracture pattern, massive aspect, and fracture spacing typically higher than 0.20 m. An average spacing between 0.015 m and 0.25 m was considered. Due to its high mechanical strength, the cave pillars and, in some instances, its ceilings were developed in this rock type. It was observed that this type of rock has a limited presence in the studied cave.

The third proposed domain was that of compact, leached, hardened itabirite, a laminated, metamorphosed oxide-facies iron formation. The key feature of this domain was its mechanical strength values lower than those of the two other rock types, with estimated values averaging 80 MPa. In relation to the fractures, this rock type presented a highly accentuated fracture pattern, banded aspect, and a fracture spacing typically lower than 0.010 m. An average spacing of 0.006 m to 0.01 m was adopted. Due to its high degree of fracturing and consequent deterioration of the strength parameters, it is very susceptible to erosive processes, indicating the cave might have developed through alteration processes in this rock type.

Stability conditions evaluation

The MRMR values were used to check the stability of the current cave span through correlation between MRMR and span size, given by the hydraulic radius or stability index, which consists of the span area divided by its perimeter. The ceiling of the MP-07 cave consists predominantly of canga or compact hematite, with MRMR values ranging from 38 to 43. To be conservative in the evaluation, considering the Precautionary Principle, a value of 38 was assumed. For this MRMR value, it can be estimated from the abacus in Figure 5 that the cave's stability conditions are suitable for hydraulic ranges below 8.0 m, and that a hydraulic radius from 8.0 m and 17.0 m is transitional between stability and roof collapse (caving).

As Figure 3 indicates, the MP-07 cave dimensions are approximately 24.0 length and 8.0 m average width. Based on these values, the conservative hydraulic radius presented for the present ceiling exposure will be as follows:

$$HR = \text{area} / \text{perimeter} = 24 \times 8 / (24 \times 2 + 8 \times 2) = 3.0 \text{ m} \quad (1)$$

The found value of 3.0 m for MP-07 hydraulic radius is much lower than the limit of 8.0 m for self-supporting conditions, therefore, the cave was in a safe situation with regards to overall stability conditions.

It can also be observed from Figure 3 that the maximum ceiling exposure in the largest chamber of the cave is limited to 11.0 m long and approximately 6.0 m wide, providing the following maximum hydraulic radius:

$$HR = \text{area} / \text{perimeter} = 11 \times 6 / (2 \times 11 + 2 \times 6) = 1.94 \text{ m} \quad (2)$$

For this value, it is obtained from the abacus that the stability conditions are very good in this span, as the maximum hydraulic radius found is less than 50% of the self-supporting threshold.

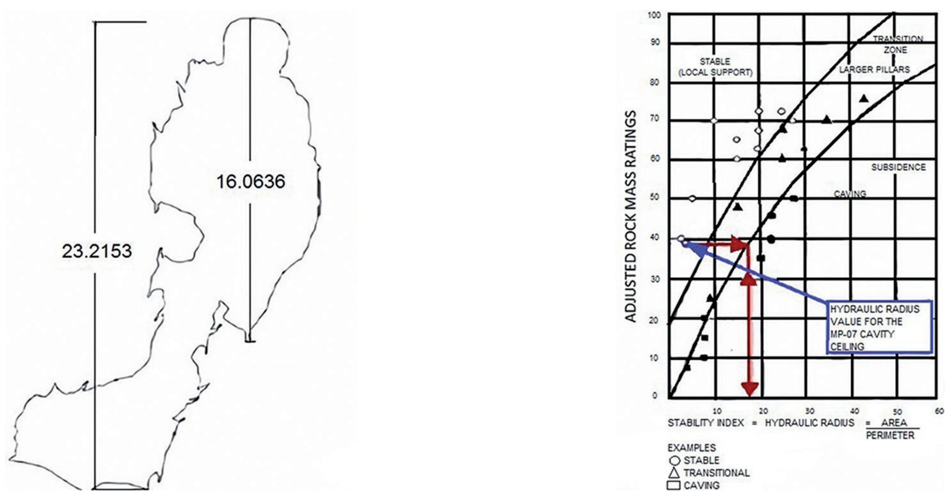

Figure 3
Dimensions (m) and Hydraulic Radius Abacus – MP-07 cave (abacus modified from Laubscher, 1990)

Tensile stress and deformation analysis

The tensile stress and deformation analysis to verify the stability conditions of MP-07 cave was carried out using a 2D finite element stress analysis program, PHASE 2 version 7.0 (Rocscience, 2008), based on strength parameters of geomechanical classifications and also geotechnical values obtained through RocLab (Rocscience, 2002), a computer software that performs rock mass strength analysis using the generalized Hoek-Brown failure criterion (Hoek *et al.*, 2002). The parameters input into Roclab were considered given the tactile-visual assessment (Barton, 1978) and the characteristic properties of each lithotype, considering the software inner property tables. Table 2 indicates the Roclab parameters for the three geomechanical domains proposed for MP-07.

	Compact hematite	Canga cap	Leached itabirite
Hoek-Brown Classification			
intact uniaxial comp. Strength-sigc (MPa)	160	120	80
GSI	63	58	53
mi	19	19	16
Disturbance Factor (D)	0	0	0
Intact modulus-Ei (MPa)	80000	60000	20000
Modulus ratio (MR)	500	500	250
Hoek-Brown criterion			
mb (reduced material constant)	5.068	4.239	2.986
s (rock mass constant)	0.0164	0.0094	0.0054
a (rock mass constant)	0.502	0.503	0.505
Mohr-Coulomb fit			
cohesion	2.053	1.229	0.746
friction angle	65.41	64.04	60.24
Rock Mass Parameters			
tensile strength	-0.517	-0.266	-0.145
uniaxial compressive strength	20.292	11.460	5.735
global strength	49.833	33.641	18.612
deformation modulus	47020.99	28480.22	7321.38

Table 2
Geotechnical ratings for the three geotechnical domains in cave MP-07.

Figures 4 to 6 show the results of tensile stress x deformation analysis for the cave in question. The selected section was chosen where the most demanding conditions were expected.

Figure 4 shows the redistribution of tensile stress before and after the the cave opening. A stress relief system can be observed on the ceiling and floor and moderate stress concentration on the sides. These data confirm the expectation of predominance of tensile stresses acting on the rock mass neighboring the cave.

Figure 5 shows the deformations model for the area surrounding the cave. The ceiling deformation is small, ranging from 0.003 m to 0.006 m. The values calculated for the cave floor, on the other hand, were high, showing a trend for floor uplift, which would be unlikely to happen in practice. A possible explanation for this is the contact of compact hematite and canga (ceiling) and leached itabirite (lower walls and floor). The strength factor values calculated and displayed in Figure 6 confirm the previous statement. It can be noticed that, for the floor, the calculated values were around 4.4, whilst, for the cave ceiling, these values fluctuate around 6.0. The strength factor is given by the ratio of the rock strength and the induced stress at every mesh point. This is the reason why the factor became greater in the ceiling, reflecting its greater rock strength with the proximity to the compact hematite, indicating that the strength values obtained are consistent with the geotechnical domains proposed.

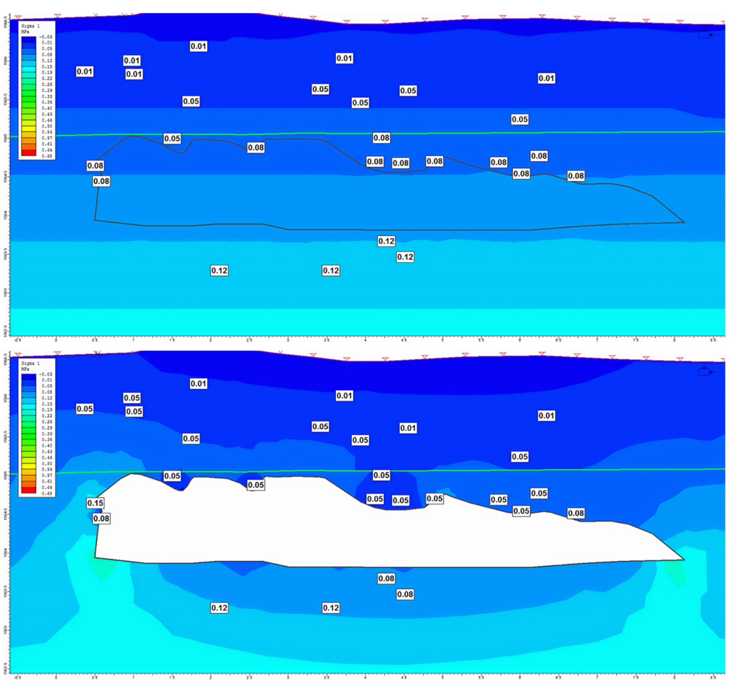

Figure 4
Distribution of stress before (top) and after (bottom) the MP-07 cave opening.

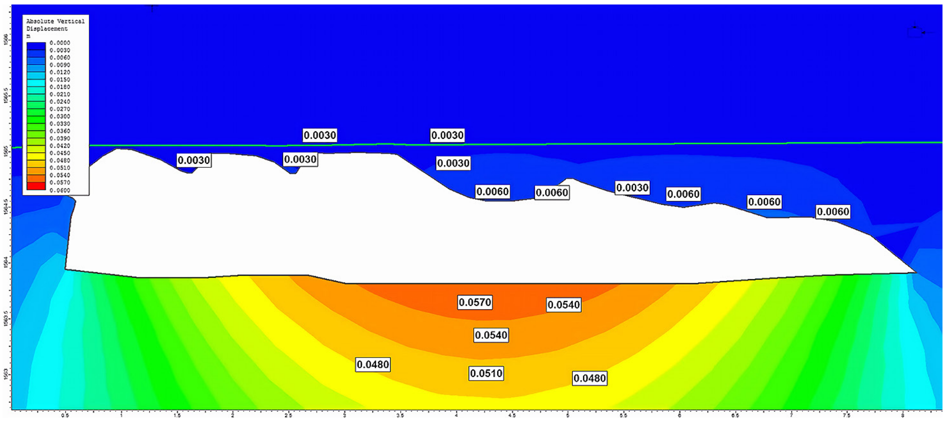

Figure 5
MP-07 cave deformation.

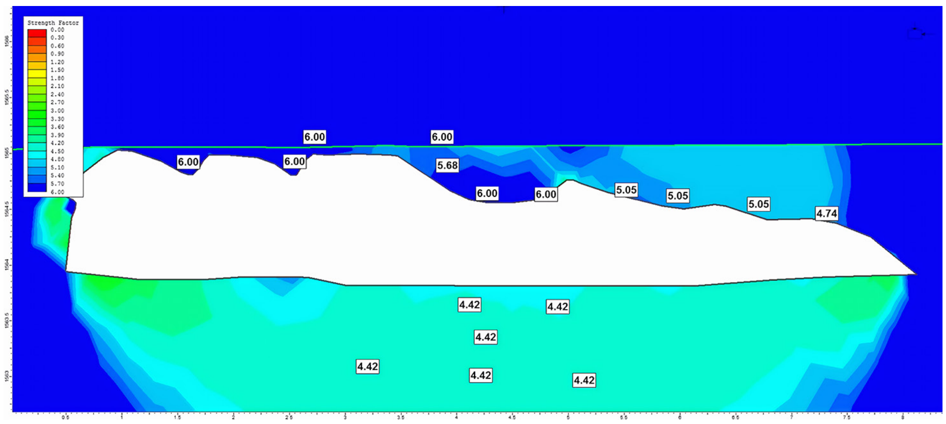

Figure 6
Strength Factor in MP-07 cave.

4. Discussion

The three geotechnical domains defined by the detailed mapping of the MP-07 correlated very well with the numerical simulations, suggesting that the same classification methodology can be extended to other caves mapping in similar geological environments.

As regards the stress state of a rock mass, it is well known that it is a function of the weight of the overlying rock types and the tectonic stresses acting on the mass, being the deformations, thereof, result of the interaction of the state of stress with the geomechanical characteristics of the rock types which constitute the rock mass. An underground excavation or the development of a cave induces a rearrangement in the distribution of stress and, eventually, a stress accumulation according to the geometry of the cave that can surpass the rock resistance and provoke instability. Regardless, a tensile stress and deformation analysis demands much more effort than employing empirical methods.

The results suggest the simulations carried out using the hydraulic radius theory for estimating the geomechanical stability of underground excavations are applicable to estimate the stability of iron ore caves, given the two-dimensional numerical simulations for MP-07 cave corroborated the outcome.

Both Laubscher's diagram and the numerical modelling presented high degrees of safety for the studied span, given by the rate of actual hydraulic radius compared to the threshold value from the diagram and by the strength factors numerically obtained, respectively.

In general, the results of the numerical simulations for the MP-07 cave confirmed the expected good stability conditions obtained by applying the hydraulic radius theory, therefore suggesting that simple empirical methods, based upon careful field mapping of the involved rock mass parameters, can be employed to assess the geotechnical stability of caves with much less effort.

Thus, it is understood that although the method has been applied to one cave only in this study, and the given results indicate the sequence of traditional mapping and empirical approaches can be easily replicated to other caves, which will bring more credibility and maturity with time and usage.

5. Concluding remarks

When a reasonable amount of data for several IOCs is available, a modified abacus should be proposed and its applicability tested for a number of caves, using for validation, similarity to the work of Waltham & Fookes (2005) and the adapted graph proposed by Jordá-Bordehore (2017), which considered a large number of natural caves inserted in limestone and other lithologies.

In further studies, other simulations could be done by varying the strength parameters and physical indexes, as well as to simulate other geotechnical situations for other caves sections. It is suggested that an adequate instrumentation and monitoring program for the caves in iron ore mines would allow for the quantification and analysis of cause and effect phenomena, in order to subsidize the definition of operational and control parameters to determine the safe distances for mining operations in regions with natural caves, and/or to refine the operational procedures related to blasting operations, aiming to guarantee their physical integrity.

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