A review of the application of empirical methodologies for preliminary analysis of natural caves

Abdelmadjid Benrabah
Technical University of Madrid (Universidad Politécnica de Madrid), Madrid, Spain

Luis Jorda-Bordehore
Technical University of Madrid (Universidad Politécnica de Madrid), Madrid, Spain

Salvador Senent
Technical University of Madrid (Universidad Politécnica de Madrid), Madrid, Spain

ABSTRACT: Geomechanical classifications have been used for the analysis of tunnels and mines since the 1970's. The database generated is huge: all types of lithologies, countries and works. However, there are few studies on its application to caves. The geotechnical stability of natural and anthropic caves (troglodytes) is a very little studied subject and of vital importance from the point of view of safety: there are thousands of caves that can be visited in the world, as well as cave houses, cellars and underground hotels and restaurants. We propose a review of the application of empirical methodologies for analysis of natural and anthropic caves. Both rock mass classifications CGI and Q index are too conservative, even in some cases alarmist. Stable caves appear as transitional or even unstable in graphs (Q) and rock classes (CGI).

Keywords: Cave Geomechanical Index (CGI), Scaled Span, Q index, Rock Mass Classification, troglodyte.

1 INTRODUCTION AND SCOPE

Rock Mass classifications have been used since the 1970s for the pre-design and construction supervision of mines, tunnels and caverns. However, there are very few references to its use to ensure the stability of caves. It is worth noting the works of Waltham (2002) and Waltham et al (2005) on the analysis of the stability of caves using the RMR and Q. However, these authors used, in the case of the Q index, graphs originally developed for tunnels. Jorda compiles his own work on the stability of caves in Spain, lava tubes in Galapagos and data from various caves (Jorda et al 2016, Jorda & Toulkeridis 2016) to prepare the first specific graph of application of the Q index in caves and empirical evaluation of its stability (Jorda, 2017).

A recent major milestone is the publication in 2021 of the first cave-specific geomechanical – rock mass - classification, developed by Brandi and collaborators in the iron caves of Brazil (Brandi et al, 2021). In this work, a series of caves in very different lithologies have been chosen lava tubes in basalts, karstic caves in limestone and shelters in limestone and sandstone, comparing pros and cons of each of the geomechanical classifications in these particular cases. The idea is to obtain some first conclusions to establish the path to follow in future investigations.

2 STUDY SITES

We have selected some caves among various that our research team has been studying the past decade, while analysing some other recent projects. Mirador cave is a lava tube in basalts located in Santa Cruz island (Galapagos) the rock mass properties and geometry comes from our published articles of Bastidas et al. (2022) and Rodriguez et al (2023). We have selected two paleolithic shelters, Abrigo del Molino in Segovia and Reguerillo cave (Madrid) in limestones and a cave in Lugo (Spain) in sandstones which results are still unpublished. The information of Castañar cave was obtained from our publication from Jorda et al (2016). We have selected very different shapes of caves and lithologies: basalt, limestone and sandstones and big caves rooms as well as shallow rock shelters. Images of some of the caves are shown below these lines (Figure 1).

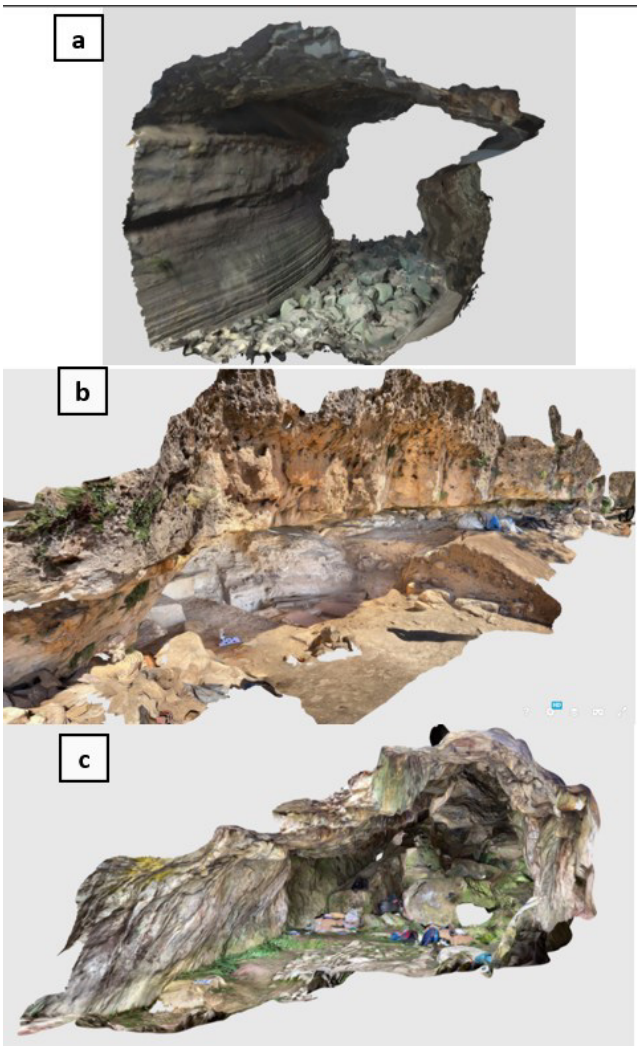

Figure 1. Images of some of the caves analysed: a) Mirador lava tube (Galapagos, b) Segovia shelter in limestones, c) Cueva de Lugo in sandstones and quarzite, a shelter.

3 MATERIALS AND METHODS

In each cave or shelter we have carried out the same methodology, we have gathered the geotechnical data through geomechanical stations, which consists of a series of observations and data collection through non-destructive techniques, for example, use of the compass to take orientation data of fractures, sclerometer for the resistance of the rock matrix and analysis of the properties of the joints: roughness, filling, persistence, etc. In addition, each cave has been scanned using Structure From Motion photogrammetry to be able to analyze in detail some geometric aspects and make a census of discontinuities.

Once all the geomechanical parameters have been obtained, we have carried out the empirical analysis of the stability of the cave using three geomechanical – rock mass - classifications, we refer the reader to the bibliography to know the ratings of each of the parameters of these classifications: Rock Mass Rating – RMR (Bieniawski , 1989), Q index for caves (Jordá, 2017) and the Cave Geomechanical Index CGI (Brandi et al, 2021).

4 RESULTS

The results of the investigation are shown in the following tables. Table 1 illustrates the RMR - Rock Mass Rating values for each cave. Once obtained the RMR and other geometric parameter of the cave it is possible to obtain the CGI – Cave Geomechanical Index as in table 2. Table 3 shows the input parameter and results of the Q index of each cave.

Table 1. Rock Mass Rating values for each cave.

Site #	location	Type	RMR1 UCS	RMR 2 RQD	RMR 3 spacing	RMR4 j.conditions	RMR 5 water	RMR_{89}
1	Galapagos Mirador cave	LT	3	16	8	15	15	57
2	Galapagos Mirador cave	LT	12	10	8	19	15	64
3	Galapagos Mirador cave	LT	4	18	10	20	15	67
4	Galapagos Mirador cave	LT	4	16	9	18	15	62
5	Segovia Molino shelter Spain	S	2	8	15	21	15	61
6	Reguerillo cave Spain	C	7	15	15	19	15	71
7	Lugo cave Spain	S	4	8	8	9	7	36
8	Castañar entrance Spain	C	3	14	7	13	10	47
9	Castañar Nevada room Spain	C	3	14	20	12	7	56

Table 2. Cave Geomechanical Index (CGI) values. In “type” column LT indicates Lava Tube, S Shelter and C Cave.

Site #	Width (m)	Length (m)	Area (m2)	Perimeter (m)	Hydraulic Radius HR (m)	Ceiling shape CS	Ceiling thickness (m) CT	RMR	αRMR	βHR	γCS	δCT	CGI
1	6,4	19	122	51	2,4	planar	1	57	30	0	4	0	34
2	6,3	19	120	51	2,4	Planar	3,6	64	45	0	4	2	51
3	8,4	25	208	66	3,1	Arch	1,5	67	45	0	10	0	55
4	7	48	336	110	3	planar	1	62	45	0	4	0	49
5	5,5	3	16,5	17	1	Arch	1,5	61	45	15	10	0	70
6	3,4	5	17	17	1	Planar	4	71	45	15	4	2	66
7	6	20	120	52	2,3	Arch	3,5	36	15	0	10	2	27
8	20	20	400	80	5	Arch	12	47	30	0	10	5	45
9	16	40	640	112	5,7	planar	12	56	30	0	4	5	39

Colors on the right side indicate the category of the CGI

Table 3. Q index values for each cave.

Site #	Width or span (m)	RQD	Jn	Jr	Ja	Jw	SRF	Q
1	6,4	78	2x9	3	2	1	5	1,3
2	6,3	50	2x9	3	2	1	5	0,83
3	8,4	90	2x9	3	2	1	5	1,5
4	7	80	2x9	3	3	1	5	1,78
5	5,5	35	2x15	3	3	1	5	0,23
6	3,4	80	2x15	3	3	1	5	0,53
7	6	30	2x15	3	2	1	5	0,3
8	20	66	12	2	2	1	1	5,5
9	10	66	12	2	3	1	1	3,7

5 DISCUSSION

We have used the Rock Mass Rating to obtain one of the ratings of the CGI, no observations strictly about the RMR will be done. In this section we summarize and relate the findings of the empirical stability assessment approach using the Q index and CGI values. Figure 2 shows the “dots” of each cave represented as its Q value and width or span. All the caves appear in the “transition” zone: sites 1,4 and 9 in the limit line to “stable”.

Visually the caves are either stable or slightly unstable (some unstable slabs). Since they all appear in the transition zone of the Q-span graph (figure 2), we can say that there is a good correlation between the Q index and the observations. The Q index being slightly conservative.

Regarding the CGI index, we can make some observations depending on the type of cave and the lithology. In the case of volcanic caves (sites 1,2,3,4) the correlation is correct except for 4 which is somewhat conservative, indicating that the cave is unstable when in reality it is not. in caves 5 and 6 it is stable, just the same observed and that nevertheless appears in transition in the Q index, here the CGI is more realistic than the Q. In sites 7, 8 and 9 the indications of "unstable" of the CGI is not realistic, and excessively conservative (in some cases almost alarmist).

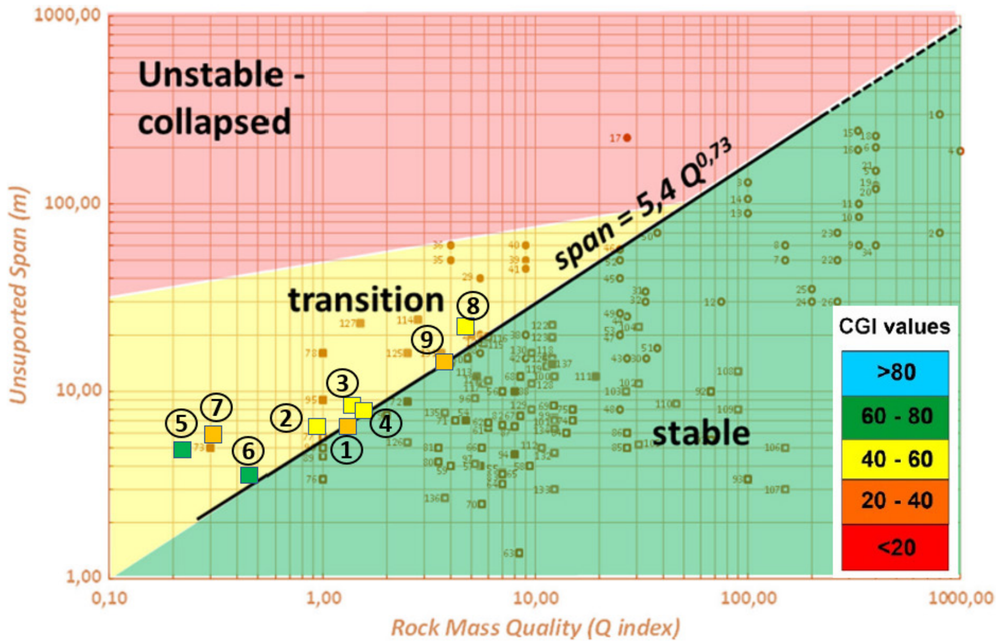

Figure 2. Use the label 'Figure' as caption. Separate the caption text from the numbering by a period (point). Image modified over original from Jorda (2017).

Table 4 shows the stability assessment using the visual approach (if "we see" any rock fall, slabs, failure), the Q – span graph (Figure 1) and the values of the CGI. Note that the CGI considers stable values >60 (blue and green colors), transition from 40 – 60 (yellow) and unstable <20 (orange and red).

Table 4. Stability assessment of the caves analyzed in the comparative research.

Site #	location	Type	lithology	Visual assessment	Q – span graph	CGI values
1	Galapagos Mirador cave	LT	Basalt	Minor unstabilities	Stable	unstable
2	Galapagos Mirador cave	LT	Basalt	Minor unstabilities	Transition	Transition
3	Galapagos Mirador cave	LT	Basalt	Minor unstabilities	Transition	Transition
4	Galapagos Mirador cave	LT	Basalt	Minor unstabilities	Transition	Transition
5	Segovia Molino shelter Spain	S	Limestone	Stable	Transition	Stable
6	Reguerillo cave Spain	C	Limestone	Stable	Transition	Stable
7	Lugo cave Spain	S	Sandstone	Minor usntabilities	Transition	Unstable
8	Castañar entrance Spain	C	Limestone	Stable	Transition	Transition
9	Castañar Nevada room Spain	C	limestone	stable	transition	unstable

We believe that the future line of work regarding these geomechanical classifications in caves (Q index and CGI) consists in "refining" them. The CGI has been created in a very particular type of cave, extremely delicate and very shallow in iron rocks, normally with small openings. It would be interesting to increase the database of this CGI classification to caves in all types of lithologies and especially volcanic and limestone ones as we point out here.

On the other hand, the Q-span graph of Jorda (2017), which serves as the basis for the application of the tunneling Q index to caves, has a transition zone that is too wide. It could be necessary to delimit the border line (Q-span equation) with more data from stable and collapsed caves in the low ranges: quality (Q<2) and span (width <20m).

REFERENCES

Barton, N.; Grimstad, E. Q-System—An Illustrated Guide following Forty Years in Tunneling. 2014. Available online: www.nickbarton.com (accessed on 20 May 2022).

Barton, N.; Bieniawski, Z. RMR and Q-setting records straight. Tunn. Tunn. Int. 2008, 2, 26–29.

Bastidas, G.; Soria, O.; Mulas, M.; Loaiza, S.; Bordehore, L.J. Stability Analysis of Lava Tunnels on Santa Cruz Island (Galapagos Islands, Ecuador) Using Rock Mass Classifications: Empirical Approach and Numerical Modeling. Geosciences 2022, 12, 380. https://doi.org/10.3390/geosciences12100380

Bieniawski, Z.T. Engineering Rock Mass Classification; John Wiley & Sons: Hoboken, NJ, USA, 1989. https://doi.org/10.1016/C2010-0-64994-7.

Brandi, I.V.; Barbosa, M.R.; Barata, A.; de Paula, R.G.; Correa, T.; Mota, H.; Lima, D.; Osborne, R.A.; Vale, S.A.; Lima, N.; et al. Cave Geomechanical Index (CGI). Classification and Contribution to the Conservation of Natural Caves in the Iron Mines. Geoconserv. Res. 2021, 3, 134–161. https://doi.org/10.30486/gcr.2021.1908888.1033.

Jordà-Bordehore, L. Stability Assessment of Natural Caves Using Empirical Approaches and Rock Mass Classifications. Rock Mech. Rock Eng. 2017, 50, 2143–2154. https://doi.org/10.1007/s00603-017-1216-0.

Jordà-Bordehore, L.; García, R.; Alonso-Zarza, A.; Romero, C. Stability assessment of shallow limestone caves through an empirical approach: Application of the stability graph method to the Castañar Cave study site (Spain). Bull. Eng. Geol. Environ. 2016, 75, 1469–1483.

Jordà-Bordehore, L.; Toulkeridis, T. Stability assessment of volcanic natural caves—Lava tunnels—Using both empirical and numerical approach, case studies of Galapagos Islands (Ecuador) and Lanzarote Island (Canary—Spain). In Proceedings of the ISRM International Symposium—EUROCK, Ürgüp, Turkey, 29–31 August 2016; pp. 835–839.

Rodríguez, G.; Mulas, M.; Loaiza, S.; Del Pilar Villalta Echeverria, M.; Yanez Vinueza, A.A.; Larreta, E.; Jordá Bordehore, L. Stability Analysis of the Volcanic Cave El Mirador (Galápagos Islands, Ecuador) Combining Numerical, Empirical and Remote Techniques. Remote Sens. 2023, 15, 732. https://doi.org/10.3390/rs15030732

Waltham, A.C.; Park, H.D. Roads over lava tubes in Cheju Island, South Korea. Eng. Geol. 2002, 66, 53–64.

Waltham T. The engineering classification of karst with respect of the role and influence of caves. Int J Speleol. 2002, 31(1/4):19–35

Waltham, T.; Bell, F.; Culshaw M. Sinkholes and Subsidence: karst and cavernous rocks in engineering and construction. 2005, Springer, Berlin, p 382.