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Rock Mass Quality Analysis of Soko Cave, Temayang District, Bojonegoro Regency, East Java based on Q-System, Rock Mass Rating, and Geological Strength Index Methods

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Abstract

This study aims to analyze the rock mass quality of Soko Cave, located in Temayang District, Bojonegoro Regency, East Java, as a basis for evaluating geotechnical stability for tourism purposes. Three rock mass classification methods were used: Q-System, Rock Mass Rating (RMR), and Geological Strength Index (GSI). Data were obtained through field surveys, geological mapping, cave geometry measurements, and observation of discontinuities using the scanline method at 11 observation stations. The rock mass quality was generally classified as good to very good, with the Q-System method producing the highest score, followed by GSI and RMR. The differences in results were due to the different parameters used by each method. Based on these findings, the rock mass in Soko Cave was considered naturally stable and did not require additional support structures, making it safe for geological tourism development. This study not only compares methods but also emphasizes the importance of using the three systems complementarily to provide a realistic and applicable picture of the stability of rock masses in carbonate caves. The GSI method shows potential as a reliable approach for this environment, although further validation with a broader data coverage is needed.

1. Introduction

Bojonegoro Regency has a vast karst landscape with potential for geotourism. One of the prominent potentials in this area is Soko Cave (Figure 1), located in Soko Village, Temayang District. This cave has ornaments resulting from the carbonatization process such as stalactites, stalagmites and flowstones that are unique and become the main attraction as a geological-based tourist destination. The utilization of karst areas as tourist sites can provide economic benefits while encouraging environmental conservation efforts.

Figure 1. Limestone unit at the entrance of Soko Cave.

As a tourist site open to the public, the safety and stability of the cave structure is very important. Tourism activities within the cave environment risk triggering damage to the rock mass if an adequate geotechnical evaluation is not conducted. Although there are no official reports of collapse in Soko Cave, indications of bridging, fracturing, and the nature of limestone that is susceptible to weathering and dissolution raise the potential for future instability.

The evaluation of cave stability is commonly conducted using rock mass classification approaches, which assesses the physical and mechanical condition of rocks based on discontinuity parameters. Some commonly used classification methods include Q-System (Barton et al., 1974), Rock Mass Rating (RMR) by Bieniawski (1989), and Geological Strength Index (GSI) by (Hoek et al., 2013). These three methods have been widely applied in tunnel and basement design, and are increasingly used in natural cave studies.

Previous studies have demonstrated the effectiveness of rock mass classification methods in analyzing the stability of carbonate caves. Hanif and Indrawan (2021) assessed the stability of Donan Cave in Pangandaran by evaluating variations in Q-system and RMR parameters under complex geological conditions. Their findings indicate the need for local adaptation of the global classification systems. Park et.al (2025) developed a quantitative GSI method that combines the three approaches based on surface conditions and fracture structure. The results show that quantitative GSI values tend to be lower than qualitative approaches but have a strong correlation with RQD and UCS values. These findings indicate that the method is relevant for application in limestone cave systems. Rusydy (2020) further demonstrated the applicability of RMR and GSI in argillaceous limestone terrains in Aceh, where tectonically deformed slopes were shown to be susceptible to plane, wedge, and toppling failures, underscoring the importance of rock mass classification in limestone environments. Additionally, recent research by Bilen et al. (2025) evaluated the weathered limestone and dolomite rock in the Gebze quarry area, Türkiye. This study emphasizes the significant influence of weathering on the strength of carbonate rocks and recommends integrating rock mass classification and laboratory test results (e.g., UCS, Schmidt hammer, and porosity) to produce a more comprehensive assessment of rock quality and stability.

However, comparative studies that simultaneously evaluate Q-System, RMR, and GSI within a single case in East Java's karst setting remain scarce. Therefore, this study aims to assess the rock mass quality and stability of Soko Cave using all three classification methods, with the goal of identifying the most reliable technique for evaluating carbonate caves in tropical environments. The findings will not only support safe tourism development but also contribute methodologically to geotechnical assessments in Indonesia's karst regions.

2. Study Area and Geology Setting

The research was conducted at Soko Cave, Soko Village, Temayang District, Bojonegoro Regency, East Java (Figure 2). Physiographically, this location is located in the eastern Kendeng Zone (Van Bemmelen, 1949), specifically within a karst area that has high geotourism potential. Based on the Regional Geological Map of Bojonegoro Quadrangle, East Java (Pringgoprawiro and Sukido, 2011, Soko Cave is located within the Klitik Formation of Middle Pliocene age. The Klitik Formation is characterized by clastitic limestone lithology interbedded with marl and claystone. This formation contains many planktonic foraminifera and large foraminifera. In general, the structures located in the Kendeng Zone are folds and faults. On the Geological Map of Bojonegoro Quadrangle, East Java by Pringgoprawiro and Sukido (2011) (Figure 3), the geological structure found in the research area is a syncline fold with a west-east orientation, consistent with the characteristics of the Java pattern. This structural configuration reflects the dominant style and orientation of the regional tectonic processes.

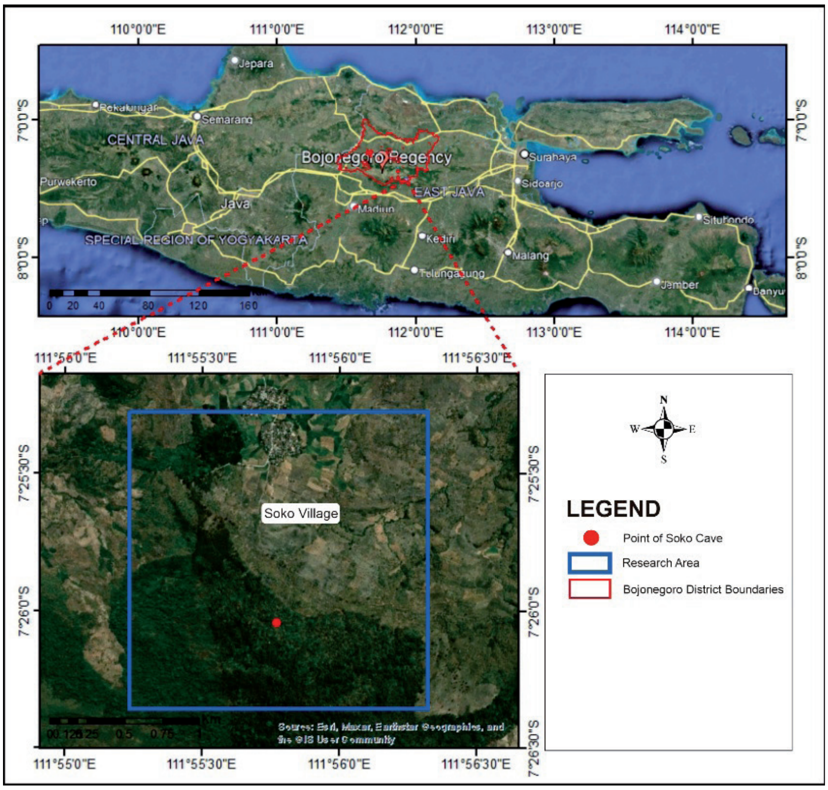

Figure 2. Map of research area in Soko Village, Temayang Sub-district, Bojonegoro Regency, East Java, showing the boundaries of Bojonegoro Regency and Soko Cave location.

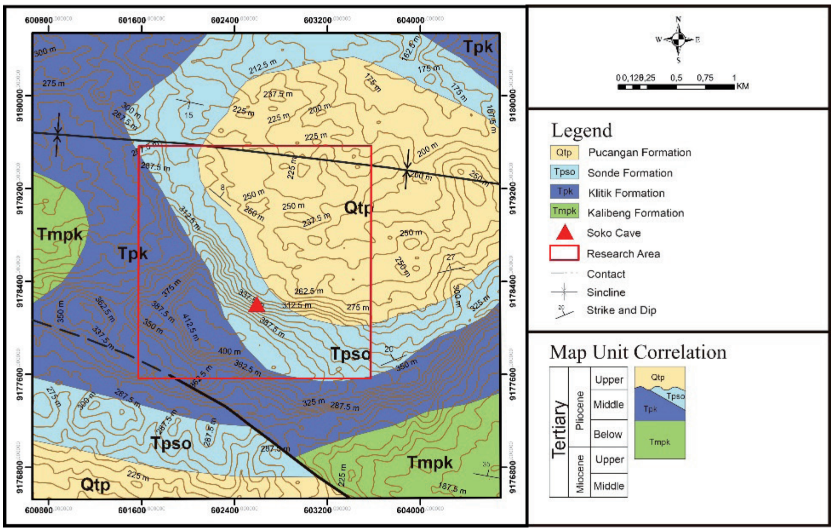

Figure 3. Regional geology of the study area and its surroundings, adapted from Geological Map of Bojonegoro Quadrangle, East Java (Pringgoprawiro and Sukido, 2011).

3. Data and Methods

The rock mass quality analysis was carried out using data collected from field investigations. The field investigations included geological mapping, lateral (top view) and vertical (side view) cave geometry mapping, and rock mass quality mapping. In addition, the research was supported by secondary data in the form of regional geologic maps, Indonesian landform map, a digital elevation model, and previous research.

Field observations were conducted to identify geological structures such as kinks and faults, and determine the lithology forming the cave. Mapping was carried out at a detailed scale to produce data on the position and orientation of the faults. Cave mapping was performed at a scale of 1:200, recording the coordinates of the cave mouth and variations in cave morphology and ornamentation. Mapping of distance, azimuth, and slope between stations, passage width, cave roof height, and sketching were carried out with reference to the system established by the British Cave Research Association (BCRA) and by applying the 5D method.

The rock mass quality mapping was carried out by investigating parameters for rock mass classification according to the Q-System (Barton et al., 1974), Geological Strength Index (Hoek et al., 2013), and Rock Mass Rating (Bieniaswski, 1989). Each classification has a weighting value for each parameter and has its own rock mass quality value. The parameters for each classification were collected through mapping using the scanline method to measure the orientation of the joints and the mechanical properties of the rock. Along the path in the five caves in Soko Cave, 11 stations were obtained. In addition, at this stage, lithological sampling of the cave wall was also carried out based on different physical appearances and can represent all parts of the cave for compressive strength testing. Rock mass classification analysis was carried out to identify the rock mass quality and stability of Soko Cave based on the Q-System, GSI, and RMR system scores. Rock Quality Designation (RQD) was used to assess the quality of the rock mass and is a component of the Rock Mass Rating (RMR),Q-system, and GSI scores.

Rock Quality Designation (RQD)

Rock Quality Designation (RQD) was introduced by Deere et al. (1967) as a quantitative rock quality assessment index (Table 1). In the absence of core log data, the RQD can be estimated using an indirect method, namely the volumetric joint number method developed by Palmstorm (1982). RQD can be estimated from the number of joint (discontinuities) per unit volume (Jv) using a formula proposed by Palmstorm (2005), as follows.

$$\text{RQD} = 110 - 2{,}5\text{Jv}$$

$$\text{Jv} = \sum_{i=1}^{j} \frac{1}{Si}$$

$$\text{Jv} = \frac{1}{S1} + \frac{1}{S2} + \frac{1}{S3} + \cdots + \frac{1}{Sn}$$

where S1, S2 and S3 are the average spacings for the joint sets.

Table 1. Correlation between RQD values and rock quality (Deere and Deere, 1989).

RQD (%)	Rock Quality
<25	Very Poor
25-50	Poor
50-75	Fair
75-90	Good
90-100	Very Good

Q-System (Barton et al., 1974)

The Q-System value provides a description of the stability of the rock mass in the underground opening where high Q values indicate rocks that have good stability and low values indicate poor stability (Table 2). In the classification using the Q-System method, there are six parameters that are taken into account, namely RQD, joint set number (Jn), joint roughness number (Jr), joint alteration number (Ja), joint water reduction factor (Jw), and stress reduction factor (SRF) (Barton et al., 1974). Determination of rock mass quality based on these six parameters is obtained from the following equation:

$$\mathbf{Q} = \frac{RQD}{Jn} \ x \ \frac{Jr}{Ja} \ x \ \frac{Jw}{SRF}$$

Table 2. Q-System rock mass quality class (NGI, 2015).

Class	Quality	Q Value
A	Exceptionally good	>400
	Extremely good	100-400
	Very good	40-100
B	Good	10-40
C	Fair	4-10
D	Poor	1-4
E	Very poor	0.1-1
F	Extremely poor	0.01-0.1
G	Exceptionally poor	0.001-0.01

Rock Mass Rating (Bieniawski, 1989)

In RMR, Bieniawski (1989) proposed several parameters to assess the quality of rock masses, including: RQD (rock quality designation), uniaxial compressive strength of rock material, spacing of discontinuities, condition of discontinuities, and groundwater conditions. The RMR value is obtained by summing the weighted values of the five parameters to indicate the rock mass quality as described in Table 3.

Table 3. Rock mass quality class based on Rock Mass Rating (RMR) (Bieniawski, 1989).

RMR	<20	21-40	41-60	61-80	81-100
Class	V	IV	III	II	I
Rock Mass Classification	Very Poor	Poor	Fair	Good	Very Good

Geological Strength Index (Hoek dkk., 2013)

The GSI classification system was introduced by Hoek (1994) to analyze the quality of hard and soft rock masses. In the GSI measurement of subsurface rocks, Hoek et al. (2013) developed a quantification chart that refers to two parameters, namely the join condition (Jcond) assessment by Bieniawski (1989) and the RQD value (Fig 4).

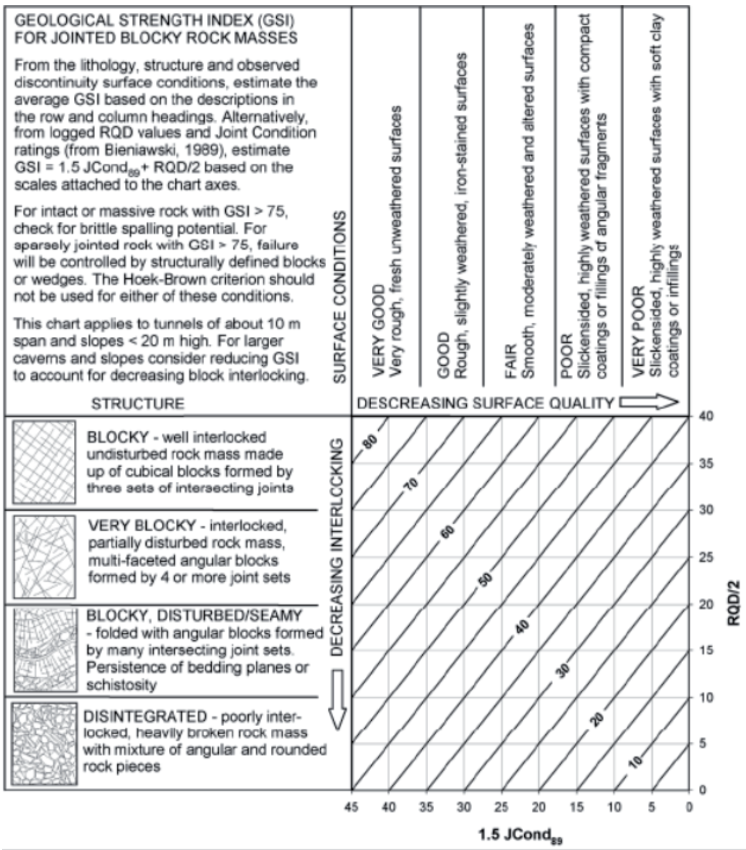

Figure 4. Quantification of GSI with JCond and RQD (Hoek et al., 2013).

The GSI value can be obtained from the combination of the two parameters, resulting in the following equation:

$$GSI = 1{,}5\ JCond + RQD/2$$

However, GSI is not a rock mass classification system; its primary function is to estimate rock mass properties. Therefore, it is necessary to correlate the results with RMR to obtain rock mass classification results.

The parameters for each classification were collected through mapping using the scanline method to measure the orientation of discontinuities and the mechanical properties of the rocks. Along the survey path in the five sections of Soko Cave, 11 stations were established. In addition, lithological samples were collected from the cave walls based on distinct physical characteristics to represent all parts of the cave for compressive strength testing. Rock mass classification analysis was then conducted to assess the rock mass quality and stability of Soko Cave based on the Q, GSI, and RMR system scores.

Laboratory Test

Laboratory tests were conducted to measure the compressive strength of intact rock using the point load method in accordance with ISRM (1985) standards by applying load to specimens through two opposing pressure points until failure occurrs. This test was performed on five representative samples from eleven observation stations, as the lithological and structural conditions at several stations showed uniformity. Therefore, the selected samples were considered to represent other stations with similar rock characteristics.

Geospatial Analysis

In this research, Survex software was used to visualize the results of cave mapping, producing two-dimensional top and side views of the cave. This visualization provides an overview of passage orientation, rock sampling locations, and discontinuity observation points. In addition, ArcGIS software was used to generate and analyze spatial data layers, offering insights into the topographic and geological aspects of Soko Cave and its surroundings.

4. Results

Cave mapping was conducted to produce a cave map, which served as the basis for zoning the quality of the cave rock mass. Soko Cave has five entrances, each with a different name: from east to west, these are Lowo Cave, Susu Cave, Pertapan Cave, Bale Cave, and Gogor Cave, as shown in Figure 5. The caves range from approximately 10 to 35 m in length, with subsurface thickness that cannot be determined (marked with '?'). The lowest point is found in Lowo Cave at an elevation of 339 m above sea level, while the highest point is in Bale Cave at 355 m above sea level. Pertapan Cave is the longest, with a length of about 30 m and a maximum height of 8 m.

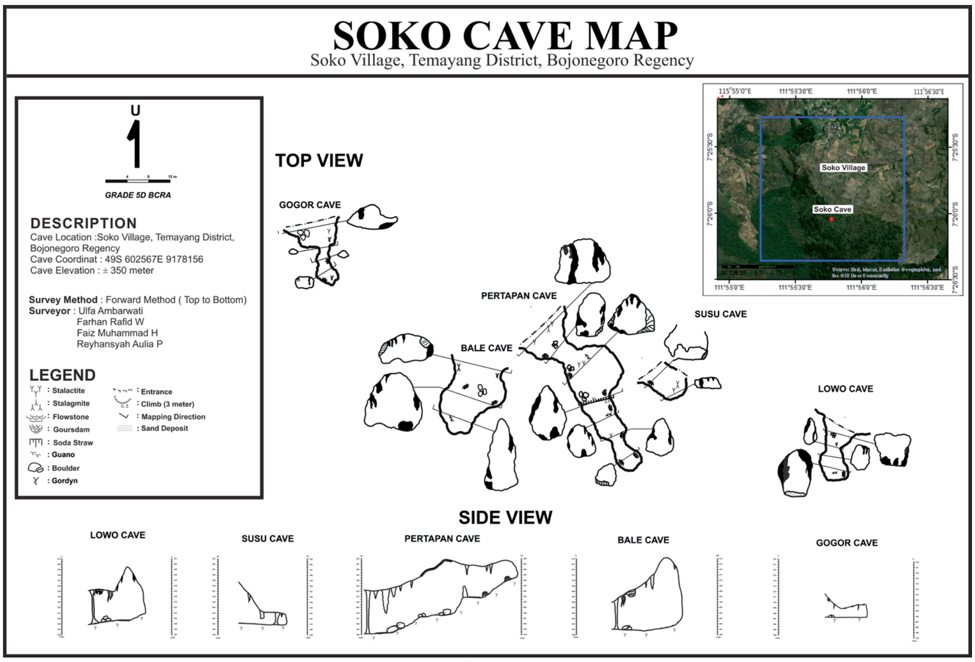

Figure 5. Map of Soko Cave that includes lateral and vertical sections of the cave.

Physiographically, Soko Cave is part of the eastern Kendeng Zone. This area is characterized by hills with a general elevation of less than 400 m above sea level and a karst topography. Geological mapping results showed that Soko Cave and its surroundings were composed of limestone, andesite breccia, and marl. The limestone units in Soko Cave were classified according to Embry & Klovan (1971) into two types: wackestone and floatstone, based on samples collected from several STA points within the cave. Furthermore, no fault structures were identified cutting through Soko Cave.

Rock mass quality analysis utilized three classification systems: the Q system (Barton et al., 1974), RMR (Bieniawski, 1989), and GSI (Hoek and Brown, 1997) with modifications by Hoek et al. (2013). Based on scanline measurements at 11 observation stations (STAs) in Soko Cave, the Q-system results showed that rock mass quality values ranged from 11 to 38 (Table 4) (Figure 6), indicating a good class (Class B). This quality was identified in 10 STAs. In addition, 1 STA yielded a value of 66, indicating an excellent class (Class A) (Figure 7). In the good rock mass class, the number of joints was relatively high, although the rock surfaces were very rough and fresh. In contrast, in the excellent rock mass class, the joints were relatively few and the joint walls tended not to be laminated, resulting in better rock mass conditions than in other parts of the cave of medium rock mass quality (Figure 8). Overall, it was concluded that the rock mass of Soko Cave had good quality. The results were then grouped into zones according to rock mass quality, as visualized in Figure 9. Based on the zoning results, the area with excellent quality was located in the eastern part of the cave.

Table 4. Quantification of rock mass quality (Q-System, Barton et al., 1974).

STA	RQD		Jn	Jr	Ja	Jw	SRF	Q		
	Jv	Value						Value	Class	Desc.
1	1.250	100	2	2	4	1	1	25.00	B	Good
2	7.667	90.83	9	3	2	1	1	15.14	B	Good
3	1.493	100	2	2	6	1	1	16.67	B	Good
4	4.115	99.71	2	2	1	0.66	5	13.16	B	Good
5	1.938	100	2	2	1	0.66	1	66.00	A	Very Good
6	3.770	100	4	1.5	1	0.66	1	24.75	B	Good
7	3.766	100	4	2	2	1	1	25.00	B	Good
8	1.238	100	2	3	1	1	5	30.00	B	Good
9	2.712	100	4	1.5	1	1	1	37.50	B	Good
10	3.514	100	4	3	4	1	1	18.75	B	Good
11	7.849	90.37	4	2	4	1	1	11.30	B	Good

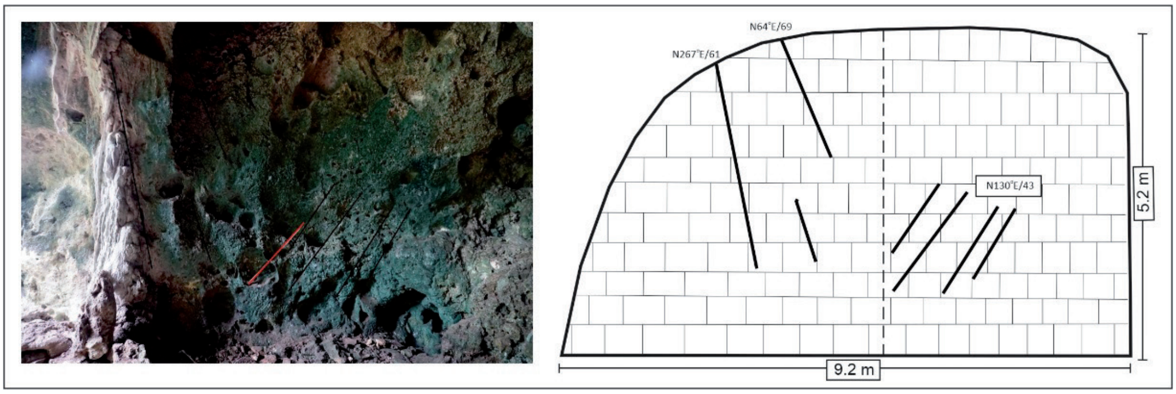

Figure 6. Documentation and sketches of rock mass appearance at one of the STAs.

Figure 7. Documentation of rock mass appearance: (1) very good quality rock mass appearance (2) good quality rock mass appearance.

Figure 8. Documentation of the appearance of medium quality rock masses.

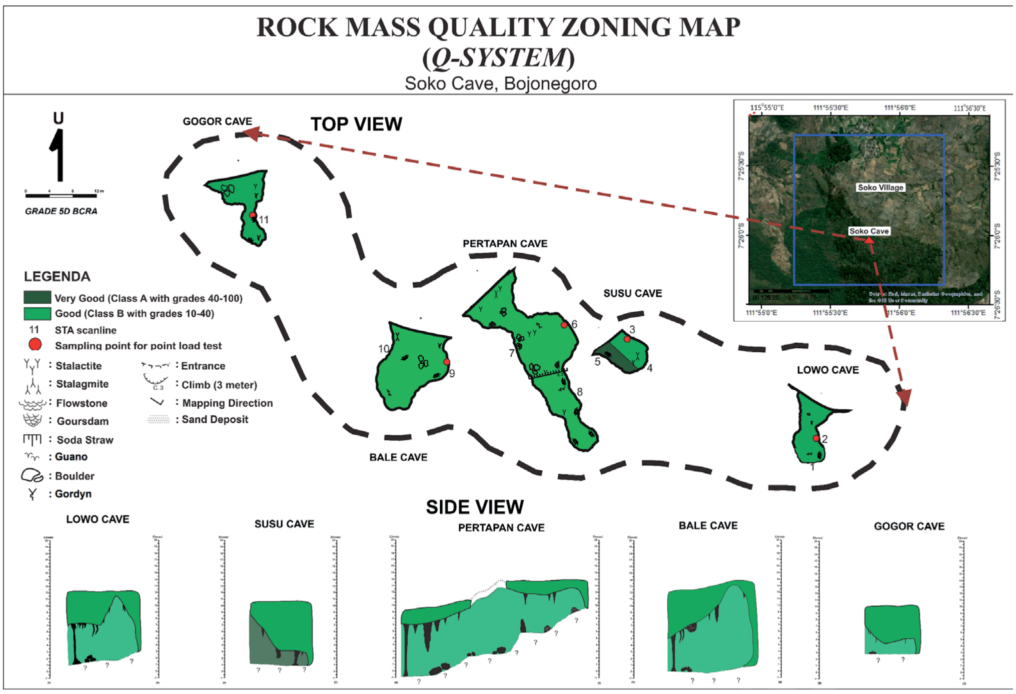

Figure 9. Rock mass quality zoning map of Soko Cave based on Q-System classification.

In the Rock Mass Rating classification, compressive strength was assessed through laboratory testing. Five samples were tested based on the identified rock types and field-estimated strengths, representing each cave. The test results and the corresponding STAs of the sampling sites are presented in Table 5. The point load test yielded representative results, with point load index values ranging from 1.04 to 2.66 MPa (Table 5). When converted to Unconfined Compressive Strength (UCS), these values corresponded to 30–100 MPa, which is consistent with the compressive strength of limestone (Waltham and Fookes, 2003), except at STA 1, where the sample was classified as weak limestone with low compressive strength.

Table 5. Point load test values on 5 samples.

STA	*Point Load Index* (MPa)	UCS (MPa)
2	1.04	25.06
5	2.66	63.95
7	2.34	56.14
10	1.66	39.73
11	1.43	34.41

Table 6. Quantification of rock mass quality using Rock Mass Rating (RMR) (Bieniawski, 1989).

STA	Strength of intact rock material		RQD			Joint Spacing		Condition of Joints		Groundwater		RMR		
	UCS	Rating	Jv	RQD	Rating	Desc.	Rating	Desc.	Rating	Condition	Rating	Value	Class	Desc.
1	1.04	4	1.250	100	20	Wide	15	Slightly rough	13	Dry	15	67	II	Good
2	1.04	4	7.667	90.83	20	Moderate	10	Slightly rough	13	Damp	10	57	III	Fair
3	2.66	7	1.493	100	20	Wide	15	Slightly rough	14	Damp	10	66	II	Good
4	2.66	7	4.115	99.71	20	Moderate	10	Smooth	11	Damp	10	58	III	Fair
5	2.66	7	1.938	100	20	Moderate	10	Slightly rough	18	Damp	10	65	II	Good
6	2.34	7	3.770	100	20	Moderate	10	Slightly rough	13	Damp	10	60	III	Fair
7	2.34	7	3.766	100	20	Moderate	10	Slightly rough	15	Damp	10	62	II	Good
8	2.34	7	1.238	100	20	Wide	15	Slightly rough	17	Damp	10	69	II	Good
9	1.66	4	2.712	100	20	Wide	15	Rough	15	Damp	10	64	II	Good
10	1.66	4	3.514	100	20	Wide	15	Rough	16	Damp	10	65	II	Good
11	1.43	4	7.849	90.37	20	Moderate	10	Slightly rough	17	Damp	10	61	II	Good

Based on the Rock Mass Rating classification, obtained by summing the values of all parameters including the compressive strength test (Table 6), the rock mass quality values ranged from 57 to 60. According to Bieniawski (1989), these values correspond to a medium rock mass class (Class III), which was identified at 3 STAs, as in Figure 8 and occurred in the eastern part of Soko Cave (Figure 10). The remaining 8 STAs had values of 61 to 69, classified as a good rock mass class (Class II), which was dominant in the Soko Cave area as depicted in Figure 7. The results showed that STAs with medium rock mass classes had discontinuities that were smoother than those in good rock mass classes. In addition, the degree of weathering in medium-grade rock masses tended to be higher, resulting in lower quality compared to good-grade rock masses, which exhibited less weathering.

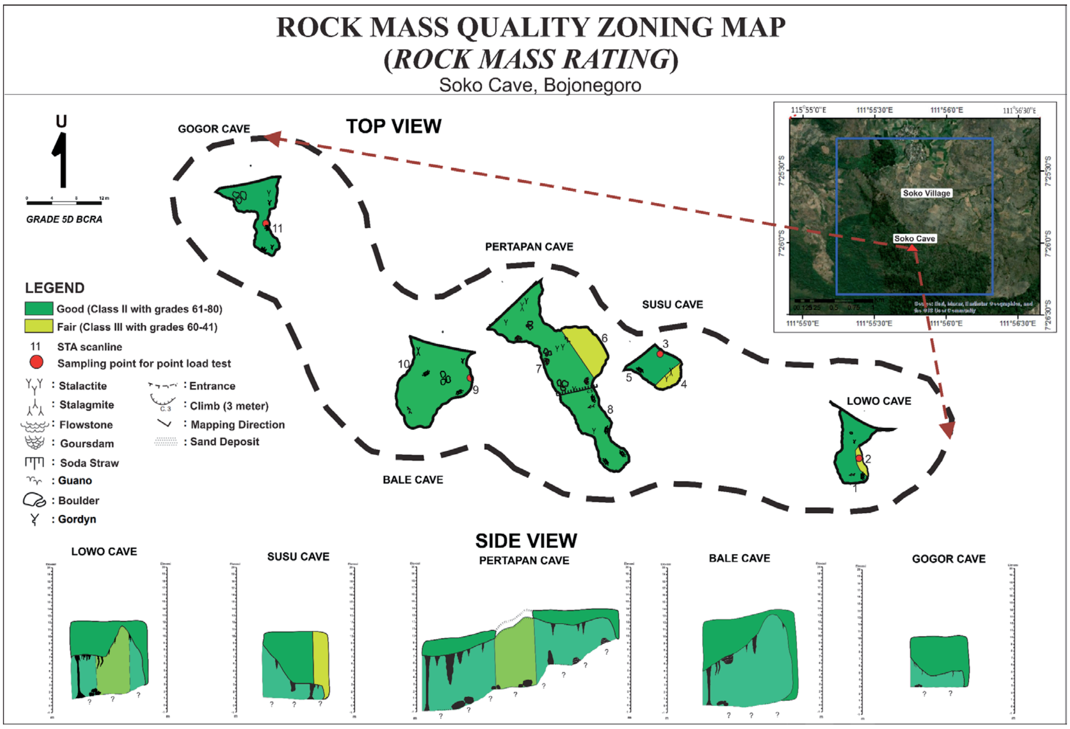

Figure 10. Zoning map of rock mass quality in Soko Cave based on Rock Mass Rating classification.

The GSI assessment was conducted using two main parameters, namely Rock Quality Designation (RQD) and joint condition (Jcond). The analysis results indicate that the rock mass quality across the STAs is characterized as *blocky to very blocky*, with joints in *good* conditions (Table 7). These conditions suggest that the discontinuities exhibit coarse to very coarse textures and a relatively low degree of weathering. The GSI classification results for the rock mass quality zoning map were derived from an equation based on the correlation between the quantified GSI value and RMR′, where the RMR value was calculated by assigning the groundwater condition parameter a fixed value of 15 (dry). The regression equation is presented in Figure 11. Based on this correlation between GSI and RMR values, it can be concluded that the rock mass condition of Soko Cave falls into the *good* category (Figure 12).

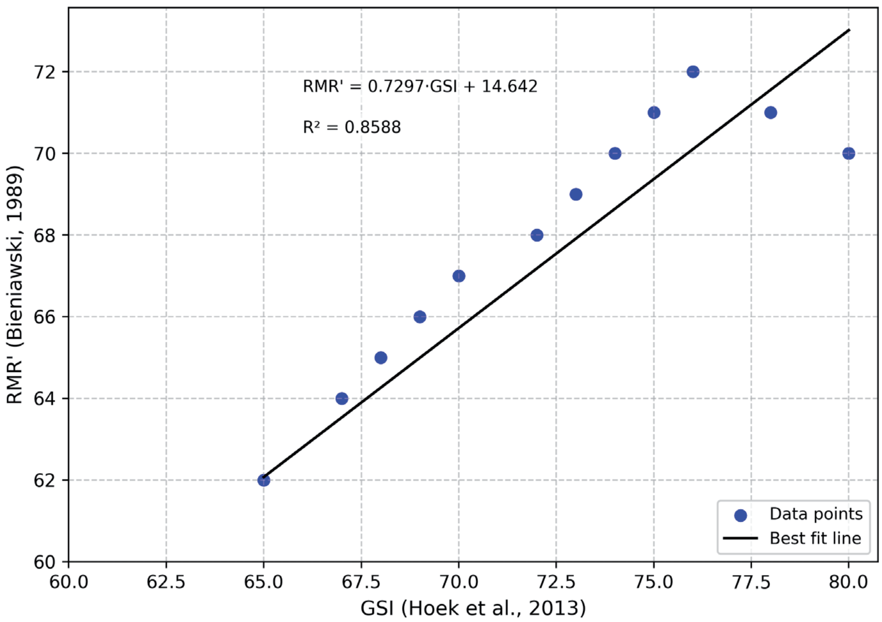

Figure 11. Relationship between RMR' and GSI classification for Soko Cave.

Table 7. Quantification of rock mass quality based on the Geological Strength Index (Hoek et al., 2013).

STA	Discontinuity Condition		RQD		1,5 JC	RQD/2	GSI (Hoek et al., 2013)	
	Desc.	Value	Jv	Value			Value	Desc.
1	Slightly rough	13	1.250	100	19,5	50.00	69.50	Good
2	Slightly rough	13	7.667	90.83	19,5	45.42	64.92	Good
3	Slightly rough	14	1.493	100	21	50.00	71.00	Good
4	Smooth	11	4.115	99.71	16,5	49.86	66.36	Good
5	Slightly rough	18	1.938	100	27	50.00	77.00	Good
6	Smooth	13	3.770	100	19,5	50.00	69.50	Good
7	Slightly rough	15	3.766	100	22,5	50.00	72.50	Good
8	Slightly rough	17	1.238	100	25,5	50.00	75.50	Good
9	Slightly rough	15	2.712	100	22,5	50.00	72.50	Good
10	Rough	16	3.514	100	24	50.00	74.00	Good
11	Slightly rough	17	7.849	90.37	25,5	45.19	70.69	Good

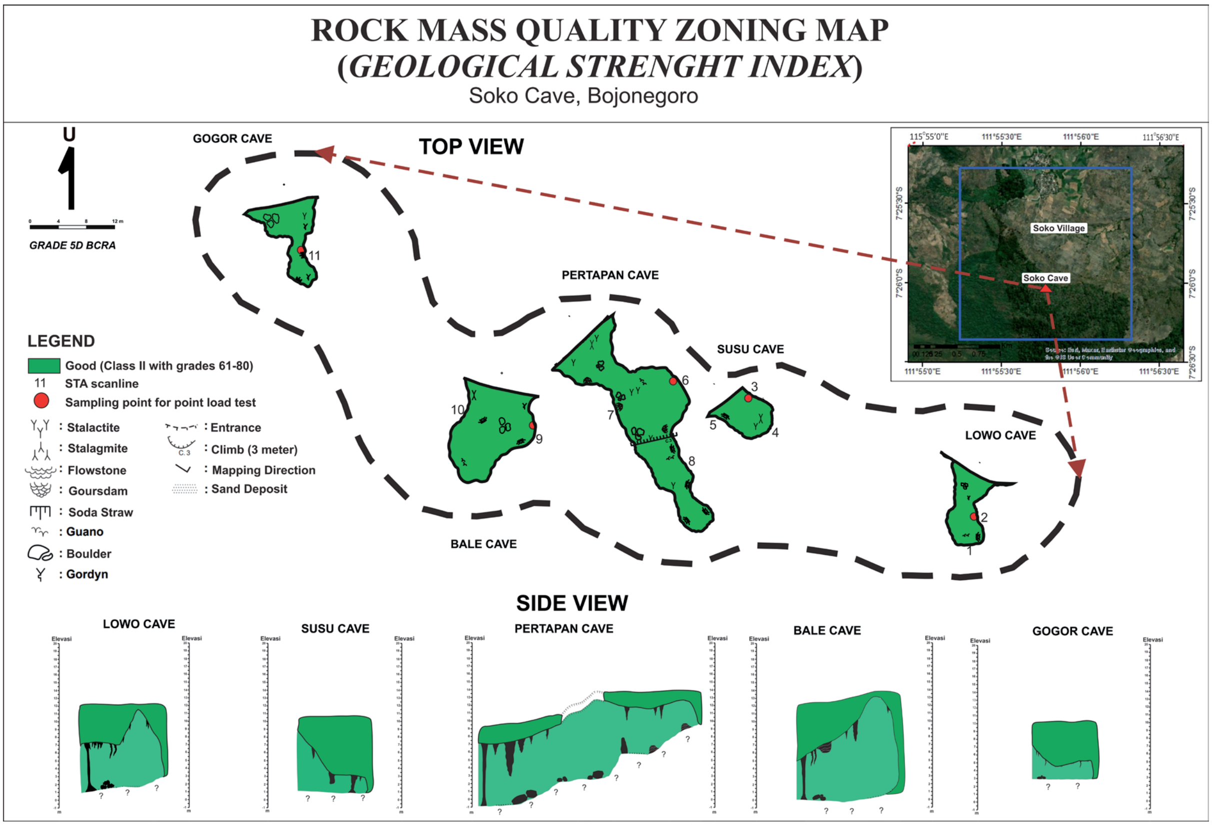

Figure 12. Zoning map of Soko Cave rock mass quality based on Geological Strength Index (GSI) classification.

5. Discussion

The results of the rock mass quality analysis of Soko Cave using the Q-System, RMR, and GSI methods generally indicate that the cave is in a stable condition. These three classification methods are sufficiently representative to provide an initial assessment of the cave's stability, particularly in the context of natural carbonate caves that have formed geologically over a long period of time. Field observation revealed no indications of collapse or significant structural deformation on the cave walls or ceiling. Therefore, in this study, no further evaluation was conducted regarding the need for supports or support system design, as all indicators suggest the cave is naturally stable.

Each classification method produced varying values. The Q-System yielded the highest score, likely influenced by the subjective Stress Reduction Factor (SRF), which may not adequately represent the actual conditions of natural caves. The RMR method produced lower values due to its sensitivity to groundwater conditions and the limited number of compressive strength test samples. In contrast, the GSI method provides fairly stable values because it is based on visual observations of fractures and rock block shapes, but does not explicitly consider the influence of groundwater.

In karst environments, dissolution generally weakens rock masses by enlarging fractures, forming cavities, and increasing porosity, thereby reducing rock strength and quality. Consequently, the presence of groundwater generally lowers classification scores in systems such as RMR and Q-System. If high values are obtained in areas showing dissolution, this may reflect sampling bias or the presence of local reinforcements, such as calcite crusts, which cannot be generalized.

On the other hand, secondary cementation, which is the deposition of minerals such as calcite into fractures or pores, can increase the strength of rocks locally by reducing porosity and increasing cohesion. In some parts of Soko Cave, the presence of features such as stalactites, stalagmites, and flowstone indicates the presence of active cementation processes. However, it is important to understand that cementation and dissolution processes often occur simultaneously. While secondary cementation can strengthen specific zones, this process can also mask structural weaknesses, especially if the calcite crust is thin and covers areas that are actually hollow or weathered. Therefore, interpretation of RMR values and other classification systems in karst environments must be done with caution. High values may not fully reflect subsurface conditions due to the presence of hidden cavities or irregular dissolution patterns.

Considering the results obtained, the urgency of this study is not only limited to comparing methods, but more importantly to assess the extent to which the three methods are able to describe the stability of rock masses in carbonate caves in a realistic and applicable manner. This is important given the limited number of similar studies in Indonesia, especially in karst areas with tourism potential. It is recommended that future assessments of rock mass in karst caves be supplemented with additional methods, such as ground-penetrating radar (GPR) or microseismic monitoring, to detect hidden cavities and water flows. The combination of conventional classification systems (RMR, GSI, Q-System) with modern geophysical or geotechnical technologies will provide a more comprehensive understanding of cave stability.

6. Conclusions

This study aimed to evaluate the quality and stability of the rock mass in Soko Cave as part of efforts to ensure safe and sustainable management of karst areas. Analysis using three rock mass classification systems, Q-System, Rock Mass Rating (RMR), and Geological Strength Index (GSI) indicates that the geotechnical condition of the cave is generally stable, with the rock mass quality ranging from good to very good. All the three methods produced relatively consistent results, although some variations in scores were observed due to differences in assessment parameters. The Q-System yielded the highest scores, likely due to the subjectivity in determining the Stress Reduction Factor (SRF). The RMR method tended to be more conservative, being sensitive to groundwater conditions and limited laboratory data. Meanwhile, the GSI method produced more stable results, as it is based on visual observation, though it does not explicitly account for groundwater influence.

Rather than aiming to identify the most suitable method, this study focused on assessing how well the three classification systems could realistically and practically represent the stability conditions of carbonate caves. In the context of Soko Cave, which formed naturally and shows no signs of major collapse, the use of rock mass classification methods is considered a sufficient preliminary approach to stability assessment.

In future research, it is recommended that stability evaluations in karst caves be supported not only by conventional classification systems but also by additional techniques such as ground-penetrating radar (GPR) and micro-seismic monitoring. The combination of traditional rock mass classification with modern geophysical approaches will offer a more comprehensive understanding of cave stability and potential hazards.

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