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Practical Estimates of Rock Mass Strength and Deformation Modulus: A Case Study of Gattar-V Uranium Occurrence, Arabo-African Shield

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ABSTRACT

The primary objective of this paper is to categorize the quality of the rock mass in the Gattar-V uranium occurrence, which is a part of Gabal Gattar. This has been done by utilizing the Rock Mass Rating (RMR), Rock Mass Quality (Q), and Geological Strength Index (GSI). The results obtained from this classification are used to determine the most accurate estimates for current and future excavation and support systems. The results of the correlations between rock mass classification systems (RMR, Q, and GSI) indicate the followings: First, the support system recommended by the Q system is more effective in ensuring the stability of rock units in future tunnels. Second, the excavation of tunnels suggested by the RMR system is more efficient in ensuring the stability of rock units in future tunnels. Third, the current tunnel is stable and doesn't need supporting with a maximum unsupported tunnel span of 6.2 meters requiring no rock bolts or fiber-reinforced shotcrete. Fourth, for future tunnels with a span greater than 6.2 meters, the excavation and support system recommendations should be based on these rock mass classification results.

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الملخص

تهدف هذه الدراسة إلى تصنيف جودة الصخور في منطقة جتار-5، حيث تصنف الصخور من خلال الدراسات الجيوتقنية المتمثلة في(RMR) ، و (Q)، و (GSI) حيث تستخدم النتائج المستحصلة من هذا التصنيف لتحديد التقديرات الأكثر دقة لنظم شق الأنفاق الحالية والمستقبلية ونظم التدعيم. كما تشير نتائج المقارنة بين أنظمة تصنيف الكتل الصخرية RMR، Q، وGSI إلى ما يلي: أولاً، نظم التدعيم الموصى بها من قبل نظام Q هي أكثر فعالية في ضمان استقرار وحدات الصخور في الأنفاق المستقبلية. ثانياً، يعد شق الأنفاق المقترحة من قبل نظام RMR أكثر كفاءة في ضمان استقرار وحدات الصخور في الأنفاق المستقبلية. ثالثاً، النفق الحالي مستقر ويندرج في فئة الأنفاق التي لا تحتاج إلى تدعيم، يقدر أقصى عرض للنفق بما لا يحتاج إلى تدعيم بحوالي 6.2 أمتار. رابعاً، بالنسبة للأنفاق المستقبلية ذات عرض أكبر من 6.2 متر، يجب أن تكون توصيات شق الأنفاق والتدعيم مستندة إلى نتائج تصنيف كتلة الصخور معتمدة على نتائج هذا البحث.

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Introduction

The Nuclear Materials Authority (NMA) of Egypt has identified Gabal (G.) Gattar's uranium is one of the most significant possibilities in Egypt since its discovery in 1980. The research area "denoted as G-V" encompasses the northern region of G. Gattar granitic batholith, which is found in the Northeastern Desert (NED) of Egypt between latitudes (26° 52' - 27° 08') N and longitudes (33° 13' - 33° 26') E (Fig. 1). G-V rocks are chronologically categorized as post granitic dykes (the youngest), Younger granites, and Hammamat sedimentary rocks (HSR) (the oldest) (Nossair, 1996) (Fig. 2).

The major aims of the present research are: 1) Determination of geotechnical properties of the rock material and rock mass along G-V uranium occurrence providing the geological and structural properties of the study area. 2) Classification of the jointed hard rock masses in the research region according to RMR, Q, and GSI rock classification methods. 3) Providing rock mass classification techniques to acquire the best estimations utilized in current and future excavation and support systems along G-V occurrence.

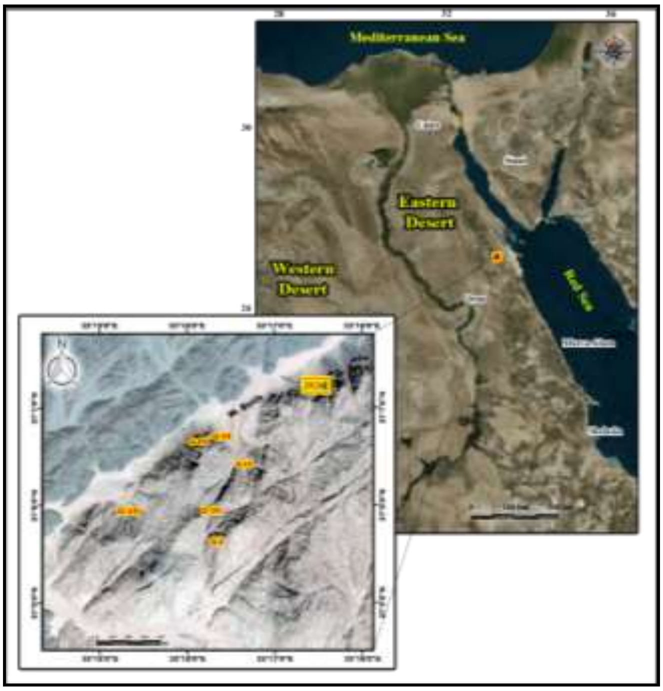


Fig. 1. Location map of (G-V) uranium occurrence (G. Gattar red square), NED, Egypt.

Fig. 2. (a) Intrusive contact between (HSR) and younger granites at (G-V) open-pit, (b) Episyenitized alkali-feldspar granites at (G-V) area.

Materials and Methods

To attain the goals of this work, the following are carried out:

Structural Setting

The structural components (faults, joints, dykes, and veins) in the research region are measured in the field and retrieved from the satellite image (ALOS PALSAR DEM – 12.5 m spatial resolution). Lineament density maps and rose diagrams are built to demonstrate the distribution of the structural features across the research region.

Sampling

Five fresh representative blocks (intact rock) are selected for sampling (Fig. 3) from five stations ($St._{no.1}$, greywackes; $St._{no.3}$, siltstones; $St._{no.2}$ and $St._{no.4}$, fresh alkali-feldspar granites; $St._{no.5}$, altered alkali-feldspar granites ‘episyenite granites’) encompassing the entire investigated area. The samples are manually dug from their host rock with the use of joints as discontinuity planes.

The blocks are carried very carefully to the Cairo laboratory avoiding any extreme jolts or generating expansions of pre-existing ones. The samples are indicated on the map to identify their locations. Regular specimens are utilized for compressive strength and Brazilian testing with extremely smooth and perfectly completed end sides normal to the axis of the specimen and parallel to each other. For the shear strength test, prismatic specimens are produced using the cutting machine, where each two matching faces is parallel to each other and normal to the two neighboring faces.

Geotechnical Properties

The research of physical and mechanical characteristics of the (G-V) occurrence is the significant purpose of this study and constitutes an important contribution to mining activities and to understanding the behavior of such rocks during tectonic events. The physical qualities are density and porosity, whereas the mechanical properties are compressive-, shear-, and tensile strengths.

Rock Mass Classification

A rock mass classification method has been employed in rock mechanics and rock engineering for two purposes: First, characterization of fractured rock masses dependent on their physical and mechanical characteristics, to categorize a given rock mass into groups with comparable behavior. Second, the design that relies on the rock classification systems, and has been effectively implemented for rock engineering works design notably for tunneling and subterranean construction. The most prevalent rock mass classification methods utilized globally nowadays are the Rock Quality Designation index (RQD), Rock Mass Rating (RMR), Rock Mass Quality (Q), and Geological Strength Index (GSI) (e.g., Singh and Goel, 2011; Gong et al., 2021; Adikusuma et al., 2023; Niu et al., 2024).

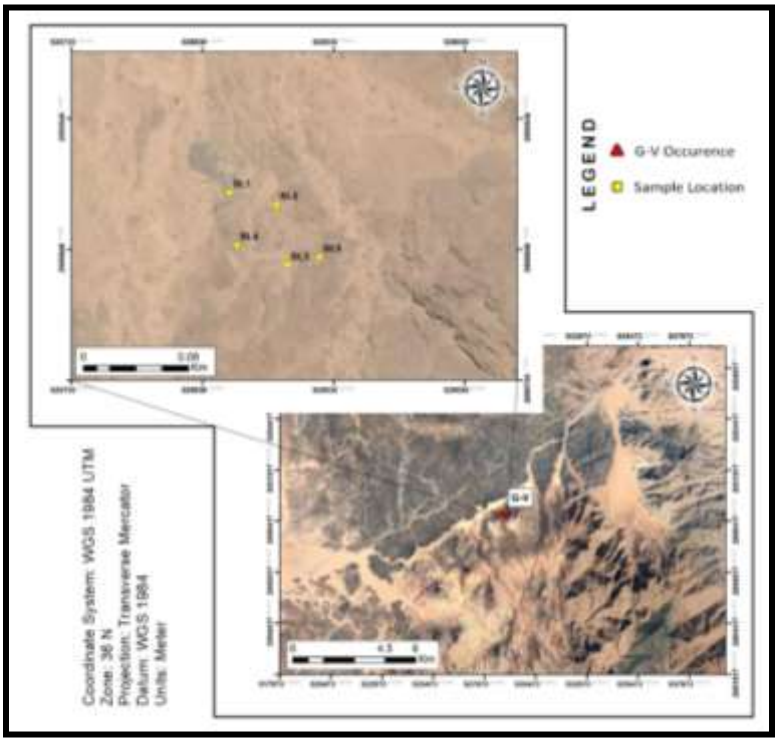


Fig. 3. Sample location map of the study area.

RQD (Rock Quality Designation) Index

It is employed as a fundamental parameter in the (RMR), (Q) and (GSI) equations. When no core is available but discontinuity traces are apparent at surface exposures or exploration audits, the (RQD) may be estimated from the number of discontinuities per unit volume (Palmström, 1982). The recommended connection for clay-free rock masses conforms to the following equation:

$$(RQD) = 115 - 3.3\,(J_v)$$

Where, (Jv) is the sum of the number of joints per unit length for all joint (discontinuity) sets known as the volumetric joint count.

RMR (Rock Mass Rating) System

The Rock Mass Rating (RMR) is discussed in this article according to Bieniawski (1989) categorization. A few fundamental parameters about the geometry and mechanical characteristics of the rock mass are employed. In (RMR) classification, all these parameters are measured in the field (Bieniawski, 2011); uniaxial compressive strength of intact rock material, rock quality designation (RQD), spacing of discontinuities, condition of discontinuities, groundwater conditions, and orientation of discontinuities relative to the engineered structure. The value of (RMR) is derived using the following equation:

$$(RMR) = \sum \text{(classification parameters)} + \text{(discontinuity orientation adjustment)}$$

Q (Rock Mass Quality) System

The (Q) rating is generated by giving values to six characteristics (Barton, 2006); Rock Quality Designation (RQD), number of discontinuities sets, roughness of the “most unfavorable” discontinuity, degree of modification or filling along the weakest discontinuity, water input, and stress state. The (Q) value is defined by the following equation:

$$(Q) = (RQD/J_n) \times (J_r/J_a) \times (J_w/SRF)$$

Where, *(RQD)*: The Rock Quality Designation; (J_n): Ratings for the number of joint sets; (J_r): Ratings for the joint roughness; (J_a): Ratings for the joint alteration, (J_w): Ratings for the joint or groundwater; *(SRF):* Ratings for the rock mass stress condition.

GSI (Geological Strength Index) System

(GSI) system appears to be more practical than the other classification systems such as (RMR) and (Q) when employed in the (Hoek/Brown) failure criteria (Hoek et al., 1995; Hoek and Brown, 1997). So, the (GSI) value becomes a more common input parameter for the (Hoek/Brown) criteria to evaluate the strength and deformation modulus of the jointed rock masses, where (RQD) is categorized from very bad to very excellent according to Hoek et al. (1995) (Table 1).

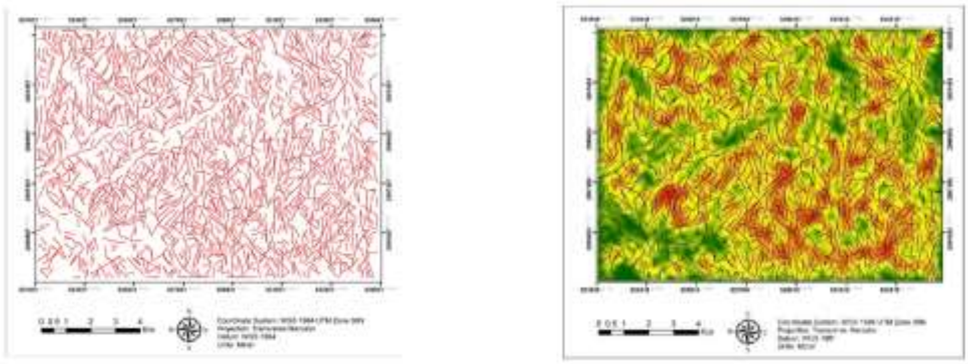
Table 1: Rock mass quality classification based on (GSI) values (Hoek et al., 1995).

GSI	(RQD)
< 20	Very Poor
21 - 40	Poor
41 - 55	Fair
56 - 75	Good
76 – 95	Very Good

Results

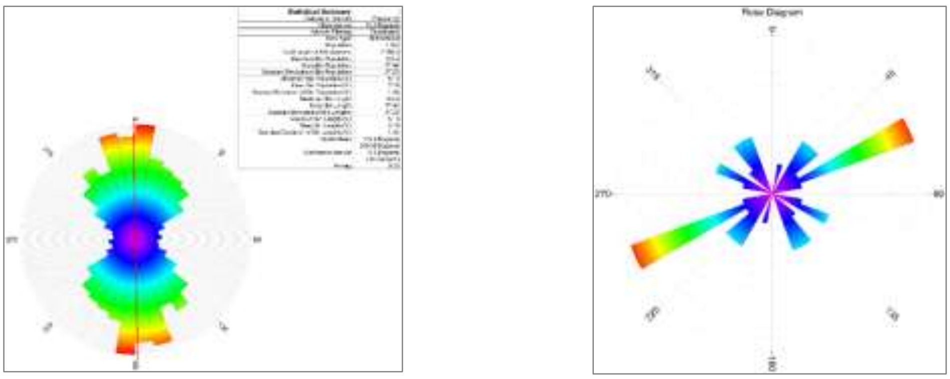
Structural Setting

A lineament density map was constructed (Fig. 4.a and b) and rose diagrams of orientation data (1394 lineaments) have been built based on frequency (Fig. 5.a and b), demonstrating that the most prevalent lineament trends are N-S, NNW-SSE to NW-SE and NE-SW.



(a) (b)

Fig. 4. **(a) Automated lineament extraction map, (b) Lineament density map of the study area.**



(a) (b)

Fig. 5. **Rose diagrams of lineaments frequencies (N %) (a) Extracted from DEM, (b) Joints measured in the study area.**

Geotechnical Properties

In the current study, extensive structural and geotechnical evaluations were carried out to categorize the researched units according to (RMR), (Q), and (GSI) systems. The rock mass quality and support components for the (G-V) occurrence are determined based on the physical parameters (density/and/porosity) and mechanical properties (compressive strength, tensile strength, and shear strength) of the collected samples, and also the (RQD) is calculated (Table 2).

Table 2: Physical and mechanical properties, and (RQD) of obtained samples of (G-V) occurrence.

Sample	**Physical Prop.**		**Mechanical Prop.**			**RQD% = (115 - 3.3Jv)**
	Density (D) g/cm^3	Porosity (P) %	Compressive Strength (σ_C) kg/cm^2	Tensile Strength (σ_T) kg/cm^2	Shear Strength (S) kg/cm^2	
St$_{no.1}$	3.66	5.29	105.5	123.04	87.88	12.7
St$_{no.2}$	2.73	2.32	2,214.70	59.76	70.3	72.1
St$_{no.3}$	4.22	1.64	316.4	52.73	35.15	22.6
St$_{no.4}$	2.37	1.85	1,933.40	49.21	59.76	62.2
St$_{no.5}$	2.32	3.27	808.5	80.85	70.3	55.6

(RMR) and (Q) Systems

The rock mass classification systems (RMR) and (Q) estimations are calculated using the rating adjustment for discontinuities orientations, which is observed from the relations between the attitude of the discontinuity (strike, direction of dip, and amount of dip) and a mine axis (Tables 3 and 4).

Table 3: The (RMR_{1989}) system results (By Bieniawski, 1989).

P parameters	$St_{no.1}$		$St_{no.2}$		$St_{no.3}$		$St_{no.4}$		$St_{no.5}$	
	Value	**Rating**	**Value**	**Rating**	**Value**	**Rating**	**Value**	**Rating**	**Value**	**Rating**
Uniaxial compressive str. (MPa)	10.3	2	217.2	12	31	4	189.6	12	79.3	7
RQD (%)	12.7	3	72.1	13	22.6	3	62.2	13	55.6	13
Discontinuity spacing (mm)	32	5	77	8	36	5	63	8	56	5
Discontinuity condition	Smooth UnW.	11	Rough UnW.	17	Smooth UnW.	11	V. Rough UnW.	16	Rough Sli. W.	14
Groundwater condition	$Dry_{co.}$	15	$Dry_{co.}$	15	$Dry_{co.}$	15	$Dry_{co.}$	15	$Dry_{co.}$	15
Discontinuity orientation adjustment	V. Fav.	0	V. Fav	0	V. Fav.	0	V. Fav.	0	V. Fav	0
TOTAL RATINGS	36		65		38		64		54	
Class number	IV		II		IV		II		III	
Description	$Poor_{Rock}$		$Good_{Rock}$		$Poor_{Rock}$		$Good_{Rock}$		$Fair_{Rock}$	
Average $stand_{up}$ $_{time}$	span=2.5 m 10h.		span=10 m 1y.		span=2.5 m 10h.		span=10 m 1y.		span=5 m 1w.	
Cohesion of RM (kPa)	100 - 200		300 – 400		100 - 200		300 – 400		200 - 300	
Friction angle of RM (deg)	15 - 25		35 – 45		15 - 25		35 – 45		25 - 35	

UnW. = Unweathered; Sli.W. = Slightly Weathered; V. Fav. = Very Favorable

Table 4: The (Q_{2006}) system results (By Barton, 2006).

P parameters	$St_{no.1}$		$St_{no.2}$		$St_{no.3}$		$St_{no.4}$		St_{no5}	
	Value	**Rating**	**Value**	**Rating**	**Value**	**Rating**	**Value**	**Rating**	**Value**	**Rating**
RQD%	12.7	3	72.1	13	22.6	3	62.2	13	55.6	13
(J_n)Joint set number	A	15	B	4	A	15	A	15	A	15
(J_r)Joint roughness number	C	4	C	4	C	4	C	4	C	4
(J_a)Joint alteration number	D	4	E	1	D	4	F	2	E	1
(J_w) Joint water reduction factor	G	0.66	H	1	G	0.66	H	1	H	1
(SRF) Stress reduction factor	I	10	J	2.5	I	10	K	5	K	5
$Q = RQD/J_n \times J_r/J_a \times J_w/SRF$	0.013		5.2		0.013		0.35		0.69	
$Description_{station}$	Extremely Poor		Fair		Extremely Poor		Very Poor		Very Poor	

A: Joint sets(random, heavily jointed, 'sugar cube', etc) ≥4; B: Two Joint sets =2; C: Discontinuous joints; D: Softening or low-friction mineral coatings (kaolinite); E: Unaltered joints wall, surface staining only; F: Joint walls Slightly altered, non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.; G: Medium inflow or pressure, joint fillings occasional outwash; H: Dry excavation or minor inflow i.e., < 5/m locally; I: Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock at any depth); J: Single shear zone in competent rock (clay-free). (Depth of excavation > 50 m); K: Loose open joints, heavily jointed or 'sugar cube', (any depth).

The geotechnical properties and stability conditions of the best station are explained as follows:

Station $_{no.2}$ (Tunnel Excavation and Support Designation)

Tunnel Excavation: According to Bieniawski (1989) excavation and support guidelines of a 10 m span rock tunnel, the tunnel with the rate of excellent rock at (RMR) classification (St.no.2 = 65) may be dug by full face, 1-1.5 m advance, full support 20 m from the face. The support should be situated at a maximum distance of 20 m from the face. Locally, bolts in/crown/3 m long, spaced/2.5 m/ with occasional wire/mesh is preferred. Wire/mesh with/50/mm of shotcrete for the crown is needed, and no steel sets.

Support Designation: Excavation Equivalent Dimension (D_e) is defined as a function of the size and nature of the excavation, and assumed from the following equation (Barton et al., 1974):

$$(D_e) = \text{Excavation span diameter or height (m) / Excavation support ratio (ESR)}$$

Where, (ESR) is estimated from guidelines support categories for the present tunnel based on the (Q) index (Palmstrom and Broch, 2006).

The (D_e) plotted against the (Q) value, is used to offer 38 support categories in a graphic provided in the original publication by Barton et al. (1974). This chart has been revised by Palmström and Broch (2006). For the present tunnel with excavation span diameter/of/2/m, the estimated support categories from Figure (6) are (updated chart for Palmström and Broch, 2006) with a value of (D_e) of/1.25/m/at excavation support ratio (ESR)/of/1.6 and a value of/(Q)/of/5.2 places this crusher excavation in category (1) (unsupported) which requires no rock bolts and no fiber reinforced shotcrete.

The maximum unsupported span for the tunnel with 5.2 (Q) value (St.2) may be determined from the equation:

$$Span_{Max.}\ (unsupported) = 2\ ESR\ Q^{0.4}$$

which is equivalent to 6.2 m. In addition, the link between the (Q) value and the permanent roof support pressure (P_{roof}) is found in the equation (Grimstad and Barton, 1993):

$$P_{roof} = (2\sqrt{J_n}) / (3\ J_r) \times Q^{⅓}$$

So, (P_{roof}) above the tube of 5.2 (Q) is equal to 0.577 Kpa.

GSI values (Supporting Results)

In the earliest efforts to characterize rock mass geological conditions, RMR1989 was employed in the Hoek-Brown failure criterion equation. It is also important to build the link between RMR and GSI described (Hoek et al., 1995):

$$GSI_1=RMR-5 = (R_1+R_2+R_3+R_4+R_5) - 5 \quad \ldots\ldots \text{(eq. 1)}$$

Where, the parameters and their values vary in distinct situations. R_1: Uniaxial Compressive Strength, R_2: RQD, R_3: average joint space. R_4: joint wall conditions, and R_5: water. R_5 must be specified as dry (In the original criteria).

Hoek et al. (2013) constructed the following simple formula for GSI calculation:

$$GSI_2=1.5\ R_4 + 0.5\ RQD \quad \ldots\ldots\ldots \text{(eq. 2)}$$

Using the above equations, it can be said that (GSI) is one of the most used methods to determine rocks' strength in creating the empirical tunnel, where the rock mass quality is classified from very poor to very good according to Hoek et al. (1995) (Table 1) and the Quantification of (GSI) using a relation between joint condition and (RQD) (Hoek et al., 2013) (Fig. 7).

Discussion

In the current investigation, besides RMR, the Q and GSI values are established by measuring the distinct rock mass features. GSI determination that follows equations (1) and (2) and considering field data and the GSI chart released by Hoek et al. (2013) is utilized for visualizing the findings.

According to the GSI estimates, sample (1) rating of Hammamat sediments ($St._{no.1}$) varies between 22.8 and 31 which corresponds to weak rock class in both Hoek categories. The GSI value of the first granitic sample ($St._{no.2}$) displays quality fluctuations within a wide range shifting between 60 and 61.55, which corresponds to excellent rock based on the classification by Hoek et al. (1995) and fair to good rock based on the classification by Hoek et al. (2013).

The (GSI) value of the second HSR ($St._{no.3}$) is found to be ranging from 27.8 to 33. This relates to bad rock based on the two classes. The (GSI) value of the second granitic sample ($St._{no.4}$) fluctuates between 55.1 and 59. This corresponds to excellent rock based on the classification by Hoek et al. (1995) and mediocre rock based on the classification by Hoek et al. (2013). The findings of GSI of the third granitic sample (St.$_{no.5}$) indicate quality fluctuations within a fair range ranging between 48.8 and 49, which corresponds to good rock quality based on both categories by Hoek et al. (1995 and 2013). The findings of GSI measurements for each sample site in the research region are reported in Table (5).

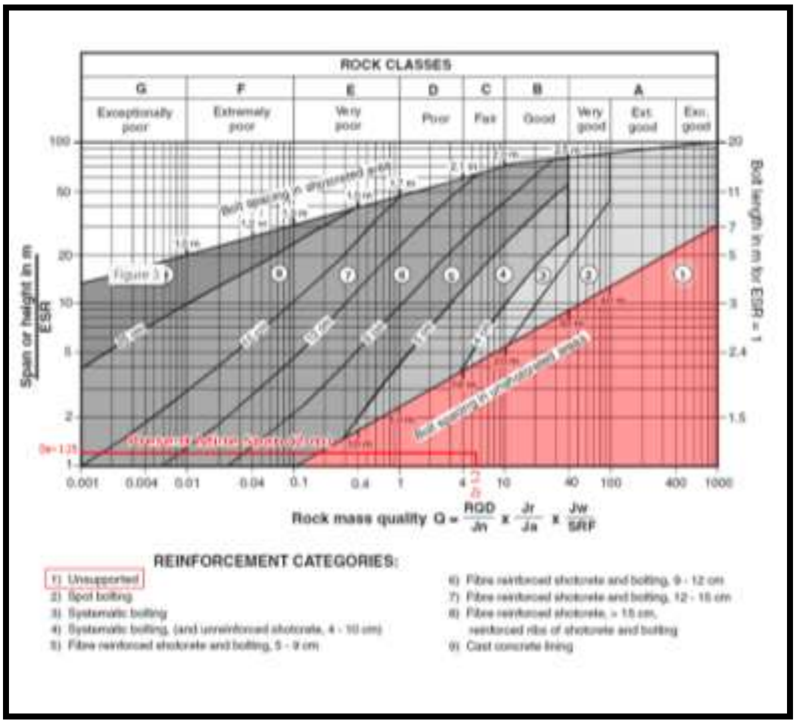


Fig. 6. Estimated support categories for the present tunnel based on the tunneling quality index (Q) (Palmstrom and Broch, 2006).

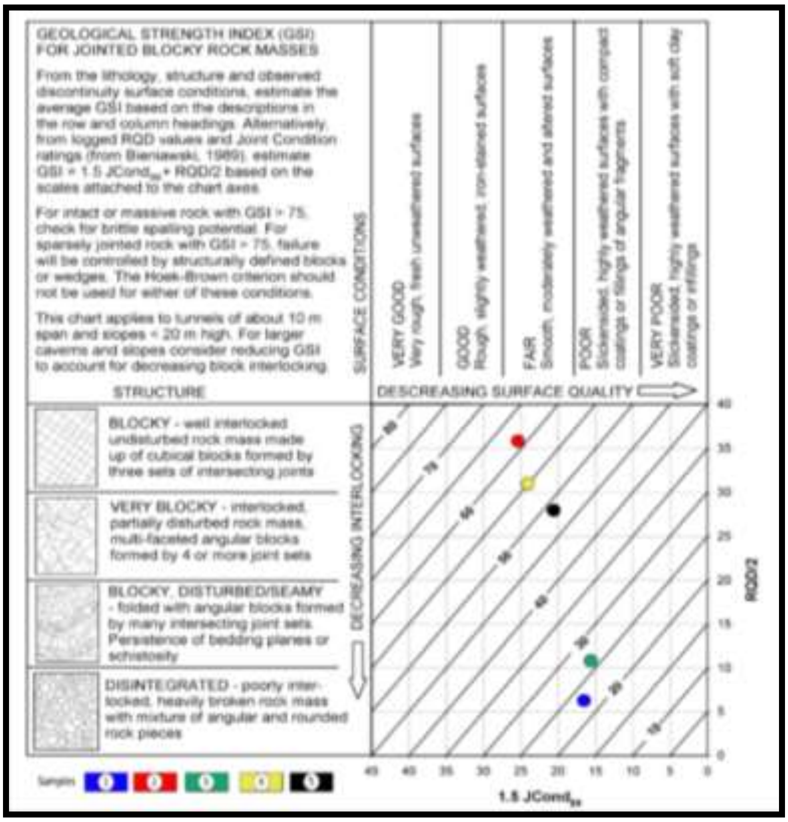


Fig. 7. Quantitative GSI of rock mass (Hoek et al., 2013).

Table 5: (GSI) results in determinations of each sample site in the research region.

Pparameters	**St.no.1**	**St.no.2**	**St.no.3**	**St.no.4**	**St.no.5**
RMR_{1989}	36	65	38	64	54
GSI_1 (Hoek et al. 1995)	31	60	33	59	49
J_{cond}	11	17	11	16	14
RQD	12.7	72.1	22.6	62.2	55.6
GSI_2 (Hoek et al. 2013)	22.85	61.55	27.8	55.1	48.8

Conclusion

The current study investigates the consequences of geotechnical features of the G-V occurrence of G. Gattar on underground mining in the Arabian-Nubian Shield (ANS). Calculations of the rock mass quality and support components for the existing and future mining operations are accomplished. The findings of rock mass categorization systems for the (G-V) occurrence are compared, and the correlations between (RMR), (Q) sand (GSI) are created by carrying out statistics, where:

- $St._{no.1}$ of (HSR-greywackes) is classified as ‘poor rock of class IV’ (In the RMR system), ‘very poor rock’ (In the Q system), and ‘very poor to poor rock’ (In both Hoek categories GSI system).
- $St._{no.2}$ of fresh alkali-feldspar granites is classified as ‘excellent rock of class II’ (In the RMR system), ‘fair rock’ (In the Q system), and ‘fair to good rock’ (In both Hoek categories GSI system).
- $St._{no.3}$ of (HSR-siltstones) is classified as ‘poor rock of class IV’ (In the RMR system), ‘very poor rock’ (In the Q system), and ‘poor rock’ (In both Hoek categories GSI system).
- $St._{no.4}$ of fresh alkali-feldspar granites is classified as ‘excellent rock of class II’ (In the RMR system), ‘very bad rock’ (In the Q system), and ‘fair to good rock’ (In both Hoek categories GSI system).
- $St._{no.5}$ of altered alkali-feldspar granites (episyenite granites) is classifed as ‘fair rock of class III’ (In the RMR system), ‘very bad rock’ (In Q system), and ‘fair rock’ (In both Hoek categories GSI system).

Recommendations

- The support system indicated by the Q system is more competent than RMR to guarantee the stability of rock units in future tunnels, while the excavation of tunnels suggested by the RMR system is more capable than Q to ensure the stability of rock units in future tunnels.
- Rock mass classification systems lead to consider the present tunnels as stable and classified as the unsupported category which requires no rock bolts no fiber-reinforced shotcrete, and the span $_{max.}$ unsupported in the future tunnel is 6.2 meters and (P_{roof}) over this tunnel is 0.577 Kpa.
- Future tunnels with a span higher than 6.2 m, strength parameters, and excavation and support suggestions should be discovered based on these classifications with other empirical techniques and numerical research.

Conflict of Interest

"The authors declare that there are no conflicts of interest regarding the publication of this manuscript".

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