

Geoengineering Characterization of the Rock Masses of Northern Face of Jabal Sabir, Taiz City, Yemen

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ABSTRACT

This paper is aimed at the description and the geotechnical characterization of the Tertiary granitic rock masses of the northern face of Sabir Mountain, Taiz city, Yemen, for the first time. For accomplishing this task, direct and indirect approaches are adopted. The direct approach is represented by field and laboratory investigations. Field investigations include discontinuity (joints) measurements/evaluation, applied Rock Mass Rating (RMR) system and Geological Strength Index (GSI) system, in addition to field tests, while laboratory investigations encompass physico-mechanical tests carried out on granitic rock materials. Indirect approach for the estimation of shear strength parameters (c , ϕ), compressive strength (σ_{cm}), tensile strength (σ_{tm}) and deformation modulus (E_{rm}) of these rock masses was made by applying the generalized Hoek–Brown failure criterion using geotechnical Roc-Lab software. The laboratory results indicate that the Tertiary granitic rock masses show wide range of variations in their physico-mechanical characteristics owing to degree of weathering /alteration and microfractures. The intact samples of Sabir granitic (Tg) rocks show "Moderate" to "High" density, "Low" to "Medium" porosity, "Good" to "Marginal" water absorption capacity and "Weak" to "Very Strong" strength. Stereographically, three main sets of discontinuities (joints) are identified at each station; however, the fourth joint set occurs, in addition to random joint sets. The discontinuities (joints) trend predominately in NE-SW and NW-SE directions in conformity with the regional structures or faults. According to J_v j/m^3 values, the degree of jointing of these rock masses are varied from "Moderate" to "High" jointing. These rocks are categorized as "Fair" to "Excellent" quality, "Fair" to "Good/Very Good" quality and "Poor" to "Very Good" quality classes according to RQD, RMR_{b89} and GSI respectively. Values of the shear strength parameters (c and ϕ) and the other rock mass parameters (σ_{tm} , σ_c , σ_{cm} and E_{rm}) show variations depending on the rock mass quality and properties of intact rock. However, in general the values of the rock mass parameters are found to increase with increase in the quality of rock mass and intact rock properties.

Keywords - Geoengineering characterization, GSI, RMR, Rock mass parameters, Sabir granite

I. INTRODUCTION

The Miocene Sabir granitic body forms one of the Tertiary intrusive bodies exposed in various locations, especially in the south and along the western escarpment slopes of Yemen highlands, running nearly parallel to the general trend of the Red Sea. It has occupied the southern part of Taiz city, located far southwestern part of Yemen Republic and is bounded approximately by longitudes 387862 E and 402165 E and latitudes 1488685 N and 1499862N (Fig.1). The contents of each section may be provided to understand easily about the paper. Jabal Sabir granitic rock masses form the dominant morphological feature (Sabir Mountain) overlooking the city of Taiz from south (Figs.1 & 2) and has been emplaced as a laccolithic body inside the older stratified Tertiary Yemen volcanic rocks. It occupies about 96 km² of the total Taiz area with elevation reaching up 3070 m above mean sea level and is characterized by high lands, steep slopes and deep valleys. Physical weathering

of varying intensities has produced different sizes of granitic blocks and boulders along the slope sides. Infrastructural development in these regions is a formidable task with considerable geotechnical problems such as steep slopes, presence of different sizes of unstable granitic blocks and boulders, joints, weathering /alteration and excavations implemented by human.

Planning and designing of infrastructure without due consideration to these problems may pose the infrastructure as well as the environment at risk. The geoengineering characterization of rock masses during, before and after the construction of any project in this area is essential. In this study, the northern face of Jabal Sabir covering an area of 21.40 km² was selected for geotechnical investigation because relatively significant part of Taiz city is built on foot hills and slope regions of this Mountain.

Geologically (including petrogenesis), the Sabir granitic masses have been studied by [1, 2, 3,

4, 5 & 6]. Sabir granitic masses are represented by alkaline or peralkaline granites. They are white to greyish white, massive, medium to coarse-grained rocks at places grading up to granite porphyry and consist almost < 5 % of melanocratic minerals (dark). These rocks essentially consist of k-feldspar, quartz, hornblende and biotite. The thin sections studied by Al-Qadhi [6] indicated that Sabir granitic rocks largely consist of k-feldspar (orthoclase, perthite, and perthitic microcline), quartz, hornblende and biotite with zircon and opaques as accessory minerals. The spheroidal and cavernous weathering is one of characteristic features of Sabir granitic rocks. The caverns of various sizes and

shapes were observed in different locations. Sabir granitic rock masses are cut by different shapes and sizes of mafic and felsic dykes.

From the geotechnical point of view, the knowledge about the Sabir granitic rocks or engineering geology is very scarce. The only research work to be mentioned is the work of Al-Qadhi [6] who has carried out geo-engineering assessment of some of the rocky outcrops. The present situation warrants the geotechnical assessment of Sabir granitic rock masses of Taiz area as the city is witnessing rapid growth owing to urbanization.

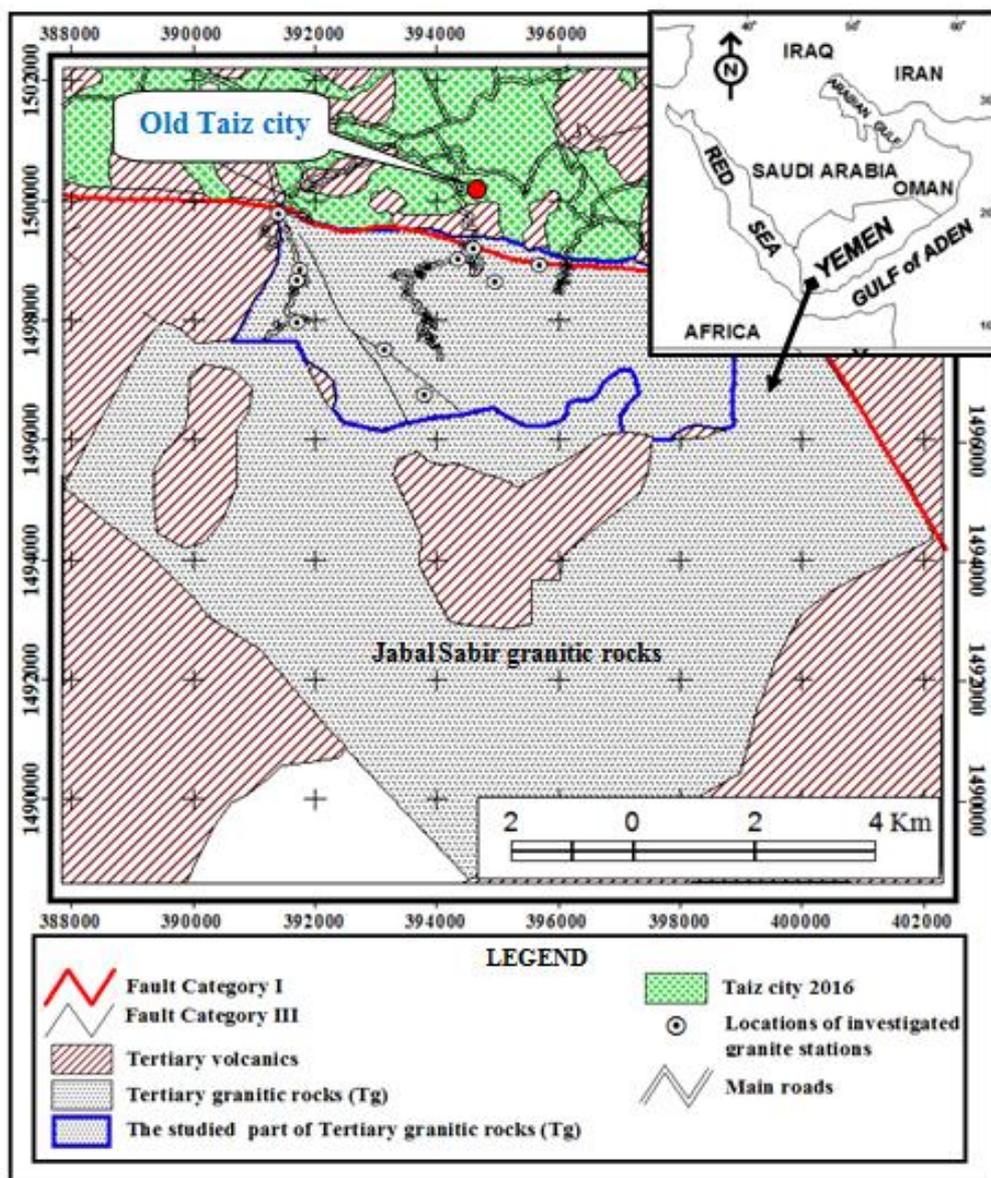


Figure 1 Geological map of the study area (modified after [7, 8, 9 & 10] showing locations of the investigated stations

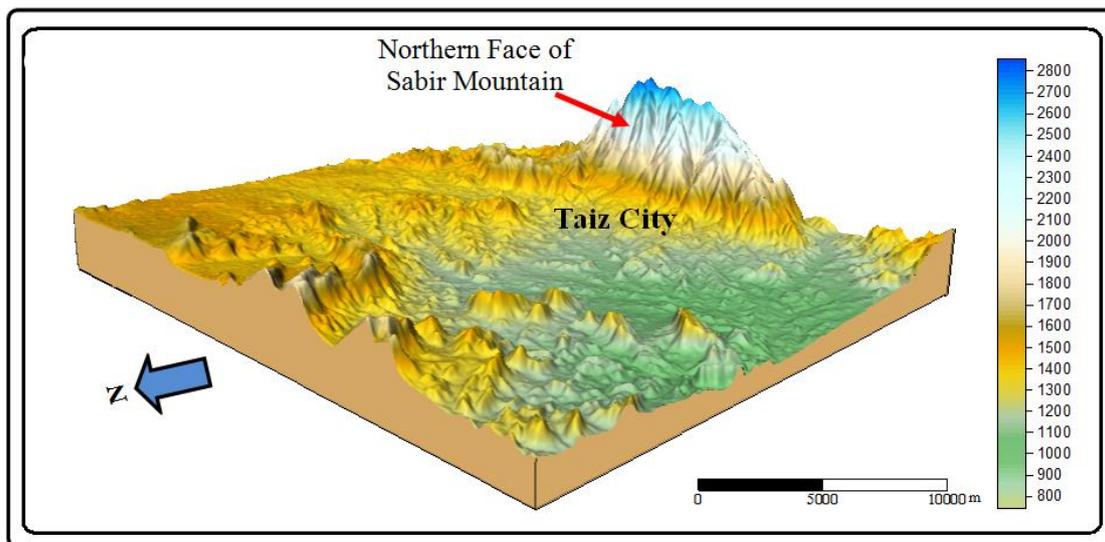


Figure 2 3D Model (DEM) illustrates the northern face of Sabir Mountain and its features

II. METHODOLOGY

2.1 Field Procedures

Site investigations were carried out on exposures of Sabir granitic rock masses along road cuts and on the natural rock outcrops at 16 locations; 10 of them were chosen to be representative field stations or sites (Fig.1). At each representative site, the rock mass was divided into a number of rock mass units or zones based on change in lithology and rock mass structural properties and according to the guidelines prescribed by Bieniawski [11]. Field scanline (tape) surveys [12] were carried out to record discontinuity in three dimensions (as possible) and the following characteristics [13] were recorded: orientation or attitude of discontinuity (dip/dip direction (deg.)), persistence (m), aperture (mm), roughness, state and thickness of filling material, water flow and wall weathering (Table1). The discontinuity orientations data was plotted stereographically (equal-area stereographic projection) using RockWorks/14 (Rock- Ware) [14], and the joint sets were distinguished for all scanline data and then the pole concentrations were contoured. The maximum density points or average density on the contour diagram were selected as the best representation of the orientation of each discontinuity set (Table 1). The mean discontinuity spacing was calculated for each recognized

discontinuity set. Occurrence of more than one set of discontinuity and the existence of more complicated jointing patterns prompted the present investigators to give the lowest (minimum) rating for spacing [15]. Where the measurements are possible on the rock exposures in three dimensions, the volumetric joint count (J_v j/m^3) is measured. It was measured from the joint set spacings within a volume of rock mass [16, 17, 18, 19 & 20]. Random joints are included because they represent a significant part of the number of measured discontinuities, neglecting them would lead to erroneous quantifications of the discontinuity nature of rock mass [21]. As suggested by Palmström [16], the spacing of 5m for each random joint was taken, thus, the volumetric joint count (J_v) can be generally expressed as:

$$J_v = 1/S_1 + 1/S_2 + \dots + 1/S_n + N_r / (5\sqrt{A}) \quad (1)$$

where S_1, S_2 and S_3 are the average spacings for the joint sets, N_r is the number of random joints in the actual location and A is the area in m^2 .

In this study, the obtained values of J_v index were used to determine the Rock Quality Designation (RQD) [22] (Table 2) based on the following Equation:

$$RQD = 110 - 2.5 J_v \quad (2)$$

where $RQD = 0$ for $J_v > 44$ and $RQD = 100$ for $J_v < 4$.

Table 1 Characteristics of the discontinuities and calculation of GSI parameters for Sabir granitic rock masses in the study area

Station no.	74	76	77	80	81	85	86	88	90	91	Remark	
Zone	I	I	I	I	I	I	I	I	I	I	From field observations	
Zone thickness (m)	>20	38	6.4	>6.3	>11.7	>60	6.5	>10.80	>9	>4.9	From field measurements	
Orientation (dip/dip dir) and Average Spacing (m) of Discontinuities	Main Joint Sets	Set1	83/284 (1.16)	55/047 (0.24)	63/213 (0.22)	55/172 (0.90)	30/218 (0.62)	59/160 (0.98)	26/173 (0.13)	67/349 (0.62)	51/310 (1.13)	47/153 (0.29)
		Set2	23/175 (0.31)	62/218 (0.28)	47/342 (0.33)	69/079 (0.64)	81/124 (0.59)	56/329 (1.08)	81/008 (0.26)	75/134 (1.11)	68/107 (0.71)	70/281 (0.32)
		Set3	81/013 (1.20)	77/113 (0.60)	84/091 (0.16)	58/307 (1.15)	75/039 (1.27)	81/237 (0.62)	41/244 (0.23)	41/222 (0.55)	81/190 (0.62)	74/056 (0.56)
		Set4	-	69/312 (0.54)	-	-	-	-	-	-	-	-
		Set 4/5(random)	5/2=2.5	5/2=2.5	5/4=1.25	-	5/2=2.5	-	5/4=1.25	-	5/2=2.5	5/2=2.5
	Min. Spacing	0.31	0.24	0.16	0.64	0.59	0.62	0.13	0.55	0.62	0.29	
Ground water condition	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	From field observations	
Discontinuities Condition and ratings (as average)	Persistence (m)	<1-10	<1->20	<1-3	<1-10	<1-3	<1->20	<1	<1-10	<1-10	<1-10	
	[Rating]	[4]	[3]	[5]	[4]	[5]	[3]	[6]	[4]	[4]		
	Aperture (mm)	1-5	>5	>5	1-5	>5	>5	>5	1-5	>5	>5	
	[Rating]	[1]	[0]	[0]	[1]	[0]	[0]	[0]	[1]	[0]	[0]	
	Roughness	Rough	S. rough	Smooth	Rough	Rough	Rough	Smooth	Rough	Rough	S. rough	
	[Rating]	[5]	[3]	[1]	[5]	[5]	[5]	[1]	[5]	[5]	[3]	
Infilling	Sf	Sf	Hd	No	Sf	Hd	Sf	Hd	Sf	Hd		
[Rating]	<5mm	<5mm	<5mm	>5mm	<5mm	<5mm	<5mm	<5mm	<5mm	>5mm		
Weathering	Fresh	Slightly	Md-Hw	Fresh	Fresh	Fresh	Md	Fresh	Slightly	Slightly		
[Rating]	[6]	[5]	[2]	[6]	[6]	[6]	[3]	[6]	[5]	[5]		
GSI Parameters	(Rr)	4	2	0	4	4	4	0	4	4	2	
	(Rw)	5	4	1	5	5	5	2	5	4	4	
	(Rf)	1	1	3	5	0	3	1	3	1	1	
	(SCR)	10	7	4	14	9	12	3	12	9	7	
	(SR)	70.70	56.94	52.97	77.84	73.63	77.74	50.65	74.30	74.39	61.95	
(GSI)	64.61	46.67	35	81.67	62.46	75.20	31.10	73	63.35	49.17		
(Jv)(J/m ²)	5.32	11.66	14.63	3.54	4.5	3.56	16.69	4.33	4.31	8.76		
Degree of Jointing	Md	High	High	Md	Md	High	Md	Md	Md	Md		
RQD (%)	96.70	80.86	73.44	100 ⁽¹⁾	98.76	100 ⁽¹⁾	68.28	99.18	99.23	88.10		
Classification based on GSI	Good	Fair	Poor	V. Good	Good	Good	Poor	Good	Good	Fair		

Where: S: Slightly, SF: Soft, Hd: hard, Hw: High weathered, Md: Moderately, V: Very, Ave: Average, Jv = volumetric joint count= 1/S1+1/S2...1/Sn + Nr(5/4) (Palstrom, 1982) (Table 2), RQD = Rock Quality Designation= 110-2.5Jv (Palstrom, 2005). Rr, Rw and Rf values are estimated from conditions of discontinuities. SCR = (surface condition rating) = Σ Rr+Rw+Rf. GSI is estimated depending on GSI chart modified by Hamasur, (2009) after Hoek, (1999); Marinos and Hoek, (2000); Sommez and Ulusay, (2002). SR (structure rating) = 100-17.5322lnJv (Hamasur, 2009), Degree of Jointing is estimated depending on Jv values and according to Palmstrom, (2005)⁽¹⁾; because Jv <4 (Palstrom, 2005).

Table 2 Volumetric joint count (Jv) and Rock Quality Designation (RQD) measurements from average spacings of the main joint sets measured on the rock surface exposures of Sabir granitic rock mass in Taiz city, Yemen

Station No.	74	76	77	80	81	85	86	88	90	91	Remarks	
Average set spacing (s) of disc. (joint) (m) and Average frequency (A. Fr.)	Joint set1 (J1)	1.16 (A.Fr.) 0.86	0.24 4.17	0.22 4.55	0.9 1.11	0.62 1.61	0.98 1.02	0.13 7.69	0.55 1.82	1.13 0.88	0.29 3.45	Field measurements
	Joint set2 (J2)	0.31 (A.Fr.) 3.23	0.28 3.57	0.33 3.03	0.64 1.56	0.59 1.69	1.08 0.93	0.26 3.85	1.11 0.90	0.71 1.41	0.32 3.13	Field measurements
	Joint set3 (J3)	1.2 (A.Fr.) 0.83	0.6 1.67	0.16 6.25	1.15 0.87	1.27 0.79	0.62 1.61	0.23 4.35	0.62 1.61	0.62 1.61	0.56 1.79	Field measurements
	Joint set4 (J4)	-	0.54	-	-	-	-	-	-	-	-	Field measurements
	(S)*	5	5	5	5	5	5	5	5	5	5	A.Fr. :=1/Average spacing
	Rm (S)	2/5=0.4	2/5=0.4	4/5=0.8	-	2/5=0.4	-	4/5=0.8	-	2/5=0.4	2/5=0.4	Field observations
Jv (j/m ²) (ave.) =Σ frequencies (Fr.s)	5.32	11.66	14.63	3.54	4.5	3.56	16.69	4.33	4.31	8.76	Based on Equation (1)	
Rock Quality Designation (RQD) (%)	96.70	80.86	73.44	100 ⁽¹⁾	98.76	100 ⁽¹⁾	68.28	99.18	99.23	88.10	Based on Equation (2)	
Classification based on RQD %	Exc.	Good	Exc.	Exc.	Exc.	Exc.	Fair	Exc.	Exc.	Good	Deer, (1968)	

Where: Jv= Volumetric joint count (j/m²), A.Fr.: Average frequency=1/Average spacing (S)..... (Palstrom, 2005), Bold number = Average spacing (s) of a joint set (J), *For random joints, a spacing of 5m for each random joint is used in the Jv calculation; 2/5 means 2 random joints in 1 m² surface divided by spacing of 5 m, and so on, ⁽¹⁾: RQD = 100 because Jv < 4 Palstrom (2005), Exc.: Excellent.

Geomechanic classification system known as Rock Mass Rating (RMR) [23, 11] was employed in this study for geotechnical characterization of Sabir granitic rock masses in the field. The input basic parameters of Rock Mass Rating (RMR) [11] are six. They are: Uniaxial compressive strength of intact rock (UCS) (A1), Rock quality designation (RQD) (A2), Spacing of discontinuities (A3), condition of discontinuities (A4), groundwater condition (A5) and orientation of discontinuities (A6). These parameters (excluding the sixth parameter-A6) were obtained numerically/descriptively for the various investigated zones. Only the first five parameters ratings (with no adjustment for discontinuity orientation) are calculated for basic RMRb89 (Table 3); based on the

Table given by Bieniawski [11]. Here, the accurate ratings of A1 (uniaxial compressive strength) and A2 (RQD) were determined using the charts suggested by Bieniawski [11] (Figs. 3a and 3b). These charts are helpful for borderline cases and also remove an impression that abrupt changes in ratings occur between categories. The sum ratings of five parameters (A1+A2+A3+A4+A5) yield the RMR values (C: RMR) (Table 3).

The Geological Strength Index (GSI) system was also applied in this study for characterization of Tertiary granitic rock masses. A quantitative numerical basis to estimate more precise values was provided by Hamasur [24]. This quantitative rock mass classification was modified after [25, 26, 27 & 28].

Table 3 Calculation of the RMR parameters for the Sabir granitic rock mass in Taiz city, Yemen

St. no.	Geotechnical sub-unit	Zone	A1		A2		A3		A4		A5		C: RMR _{dry} = A1+A2+A3+A4+A5				
			Values	Rating	Values	Rating	Values (m/min.)	Rating	Values	Rating	Values (desc.)	Rating	Rating	RMC	RMD		
74	Sabir granitic rock masses (Tig.)	I	96.16	9.2	96.7	19.3	0.31	10	Discontinuities Condition (as average)	18	C. dry	15	71.5	II	Good		
76		I	47.66	5.4	80.86	15.8	0.24	10		13	C. dry	15	59.2	III	Fair		
77		I	31.44	3.8	73.44	14.4	0.16	8		12	C. dry	15	53.2	III	Fair		
80		I	47.04	5.3	100	20	0.64	15		22	C. dry	15	77.3	II	Good		
81		I	132.3	11.4	98.76	19.7	0.59	10		16	C. dry	15	72.1	II	Good		
85		I	149.1	12.3	100 ⁽¹⁾	20	0.62	15		18	C. dry	15	80.3	II/I	Good/V.G		
86		I	18.94	2.8	68.28	13.6	0.13	8		12	C. dry	15	51.4	III	Fair		
88		I	34.06	4.1	99.18	19.8	0.55	10		20	C. dry	15	68.9	II	Good		
90		I	64.34	6.6	99.23	19.9	0.62	15		16	C. dry	15	72.5	II	Good		
91		I	52.92	5.8	88.1	17.6	0.29	10		14	C. dry	15	62.4	II	Good		
Remarks			From Lab.	Fig. 3.a	Table 2	Fig. 3.b	Table 1	Table of Bieniawski, (1989), section (A3)		Table 1	2[Rating] from Table 1	Table 1	Table of Bieniawski, (1989), section (A5)	E Ratings A1...A5	From Table of Bieniawski, (1989), section (C)		

RMR_{dry} = Basic RMR_{dry} with no adjusting factor for joint orientation. St. no.: Station number. A1: ratings for the uniaxial compressive strength of the intact material (MPa). A2: ratings for the Rock Quality Designation (RQD %). A3: ratings for the spacing of discontinuities (average minimum spacing is taken from Table 4.16, according to Edlboro (2003)). A4: ratings for the condition of discontinuities obtained from Table of Bieniawski, (1989). A5: ratings for the groundwater condition. C. dry: Completely dry. (desc.): descriptive term. C: Rock mass rating deduced from total ratings. RMC: Rock mass class. RMD: Rock mass description. ⁽¹⁾: RQD = 110 - 2.5 Jv = 100 because Jv < 4 (Palmstrom, 2005). V.G: Very Good.

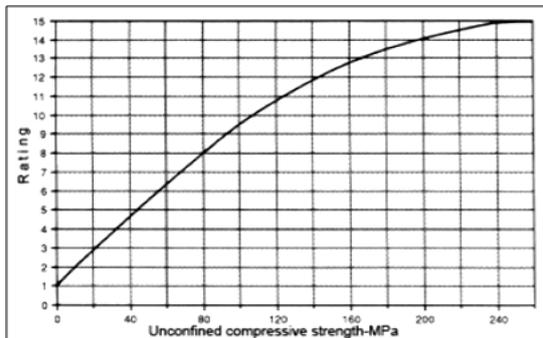


Figure 3a Variation of rating for the Uniaxial Compressive Strength (after Bieniawski, 1989)

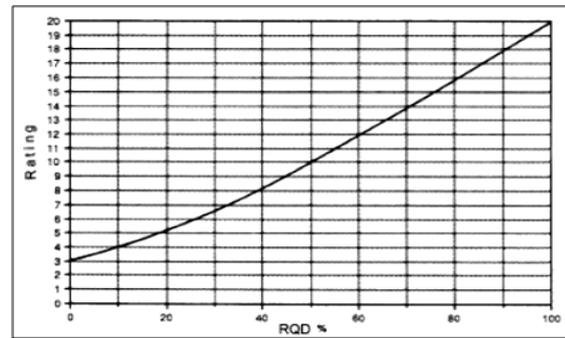


Figure 3b Variation of rating for the RQD (after Bieniawski, 1989)

The main components of this modified quantitative rock mass classification are the structure rating (SR) and surface condition rating (SCR). The structure rating (SR) is determined from volumetric joint count (Jv) and according to the following Equation:

$$SR = 100 - 17.5322 \ln J_v \dots\dots\dots (3)$$

where Jv is volumetric joint count (J/m³).

Surface condition rating (SCR) is estimated from sum of the roughness (Rr), weathering (Rw) and infilling (Rf) materials ratings; which are assessed visually in the field. Because the GSI is based on the RMR₇₆ [25], the roughness, weathering and infilling ratings (SCR) are also based on the RMR₇₆, in which the sum of these three parameters ranges from 0 to 15 [24]. The intersection of these ratings (SCR and SR) on the modified quantitative GSI chart gives precise value of GSI (Table 4). The derived values from the GSI chart for the various investigated sites are shown in the Table 1. Finally, at representative sites, rock block samples also were selected for the geotechnical laboratory tests.

2.2 Laboratory Procedures

The physical characteristics of the Tertiary granitic rocks were determined in the laboratory on rock specimens prepared from rock block samples collected from the investigated representative sites.

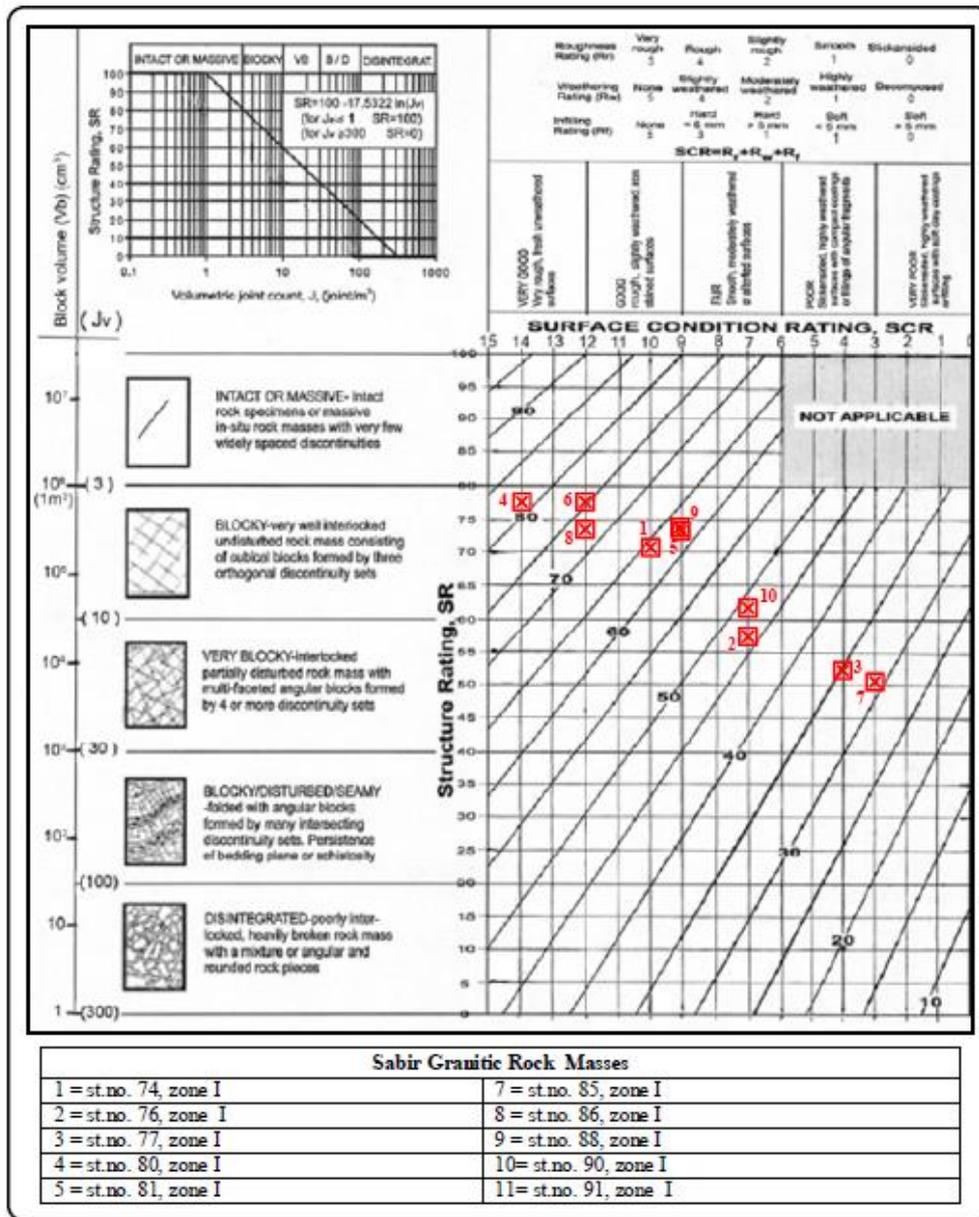
Determination of water content (Wc), unit weight (γ), dry density (ρ_d), porosity, water absorption (W. Ab), bulk specific gravity (Gs) and apparent specific gravity (A.Gs) were made according to the methods suggested by the ISRM [29]. The results of all the physical properties of granitic rock samples are provided in Table 5. The mechanical characteristics include uniaxial compressive strength (UCS), Point load test (PLT) and Schmidt Hammer rebound test, (SH) (in the field and lab.). These tests were performed as per the procedures provided by many researchers and organizations [13, 30, 31, 32 & 33]. All these geotechnical tests were performed in the materials laboratory of Sheba General Contracting Co. Ltd, main branch, Taiz, and in Technical institute, Al-Hassib, Taiz, Yemen.

The point load strength (PLS) test was used as cheaper and effective alternative to the UCS test when the rock specimen for UCS tests could not be obtained from rock exposures. This test was carried out on geometrical form rock samples (regular specimens) and/or irregular lumps in the laboratory and according to Brook [32] and ISRM [33]. The following relationship between the PLS and UCS and suggested by Rusnak and Mark [34] was used:

$$UCS = 21 * I_s(50) \dots\dots\dots (4)$$

where I_s(50) is Point load strength index of a specimen of 50 mm diameter.

Table 4 Plot of the GSI values based on SR and SCR ratings for Sabir granitic rock mass, Taiz city, Yemen



Schmidt hammer tests using an N-type hammer were undertaken on some of exposed rock faces (7 zones) as suggested by Barton and Choubey [31]. The N-type rebound data obtained were converted to L-type data using the following empirical correlation developed by Ayday and Grktan [35]: $R_n(N) = 7.124 + 1.249R_n(L)$, ($r^2 = 0.882$) (5), where $R_n(L)$ and $R_n(N)$ are respectively the L-type and N-type Schmidt hammer rebound numbers; and r^2 is the determination coefficient. To get Schmidt hammer rebound number, initially ten impact readings were undertaken in each case, and the average of the 5 highest readings taken to represent a mean rebound value (r) [13]. Conversion

to equivalent uniaxial compressive strength values was undertaken using the equation and chart of Miller presented by Deere and Miller [36]. The study of the physico-mechanical properties of the Tertiary granitic rock masses is based on the block samples weighting between 30 to 50 kg and with a minimum thickness of 10 cm to allow cubing of samples. On pieces of these block samples; the physical characteristic tests were performed in the laboratory. Before tests, the rock samples prepared as definite geometrical forms were immersed in water for 48 hours for the purpose of testing their strengths in the worst situation. The results of the all mechanical properties of granitic rock samples are provided in Table 5.

Table 5 Laboratory test results of the physico-mechanical characteristics of intact rock samples of Sabir granitic rock mass (Tg) in the study area

Characteristic	Property	Results	No. of Tests (N/Ft)
Physical characteristics	Range /(ave.) of Wc %	0.269-0.91/ (0.628)	N=9
	Range /(ave.) of (γ) (KN/m ³)	23.806-26.117/ (24.827)	N=9
	Range of ave.pd (gm/cm ³)	2.415-2.656	N =75
	Range of ave. n (%)	2.099-6.976	
	Range of ave.W.Ab. (%)	0.792-3.123	
	Range of ave.Gs (Ssd)	2.484-2.677	
	Range of ave. A. Gs	2.589-2.713	
Mechanical characteristics	σ _{ci} (UCS) (in lab.) (MPa), range /(ave.)	12.12-74.57/(35.892)	N =13
	σ _{ci} (PLT) (MPa), range /(ave.)	52.92-184.8/(122.14)	N =7
	σ _{ci} (SH)(MPa), in field, (range /(ave.))	27.3-45.2/(35.21)	Ft = 7
	Average of σ _{ci} (UCS)(MPa) (as range)*	25.71- 119.38	N+ Ft =27

Where: Wc: Water content, ave.: average, γ: Unit weight, pd: Dry density, n : Porosity, W. Ab.: Water Absorption, Gs(Ssd): Bulk Specific gravity (Saturated-surface-dry mass) , A.Gs = Apparent Specific gravity, UCS: Uniaxial compressive test in the laboratory conditions, PLT: Point Load Test, SH: Schmidt Hammer, GH: Geological Hammer,* the ranges of averaged results from all strength tests, N: number of the tested specimens, Ft: Number of field tests.

Based on the field measurements and laboratory tests data, the generalized Hoek–Brown failure criterion [37] is applied for estimating the strength and deformability of the Tertiary jointed granitic rock masses, employing RocLab software program [38]. In applying the Hoek and Brown criterion to achieve this task, three parameters are required (as input parameters). These are: uniaxial compressive strength (σ_{ci}) of the intact rock pieces, value of the Hoek-Brown constant (mi) for these intact rock pieces, and value of the Geological Strength Index (GSI). The σ_{ci} is obtained from laboratory and/or field tests. The quantified geological strength index (GSI) values were obtained as mentioned before. The intact rock constant (mi) was estimated according to rock type and then quoted from the Table proposed by Hoek and Brown [39] and Hoek [40]. Accordingly, the intact granitic constant (mi) is 32. The disturbance factor (D) which depends upon amount of stress relaxation, weathering, and blast damage associated with the method of excavation has been taken into

account in the 2002 version of the Hoek-Brown criterion. The value of D ranges from 0 to 1 and represents a progressive transition between the criteria for disturbed and undisturbed rock masses. Here, based on the guidelines recommended by [37, 40], the estimated D values used in generalized Hoek– Brown failure criterion are 0 (undisturbed in situ rock masses), 0.7 (partially disturbed in situ rock masses) and 1 (highly disturbed in situ rock masses). Also the intact rock deformation modulus (Ei) is required as input value for the determination of the rock mass deformation modulus. In this study, no direct value of the intact modulus (Ei) is available so this value was also estimated using average values of modulus ratio MR of intact rock which are obtained from the Table modified by Hoek and Diederichs [41], based on Deere [42] and Palmstrom and Singh [43]. Accordingly the MR value for intact granite is 425. This value was entered into RocLab software program (2013) for the calculation of the rock modulus of elasticity (Ei).

Table 6 Input data used in RocLab software for the determination of rock mass parameters for Sabir granitic rock mass in the study area

Geotechnical sub-unit and abbreviation	No. investigated zones	σ _{ci} (MPa)	GSI	mi	D	MR
Sabir granitic rock mass (Tg)	10	From Table (3)	From Table (1)	32	0 0.7 1	(425)

Where, σ_{ci} (MPa): Uniaxial compressive strength (UCS) of intact rock, GSI: Geological Strength Index obtained as precise values, mi = Intact rock constant estimated according to rock type (Hoek and Brown,1997 and Hoek, 2007), Average MR value is 425 (Hoek and Diederichs, 2006, based on Deere, 1968 and Palmstrom and Singh 2001), D: disturbance factor; here, D = 0 for undisturbed in situ rock mass, 0.7 for partially disturbed in situ rock mass, and 1 for highly disturbed in situ rock mass, based on Hoek, et al. (2002) and Hoek (2007).

The parameters (input parameters; σ_{ci} , GSI, m_i , D and MR) (Table 6) related to granitic geotechnical unit were entered into RocLab software

to compute the values of the rock mass properties (c , ϕ , σ_{tm} , σ_c , σ_{cm} and E_{rm}) (as output parameters) (Table 7).

Table 7 Results of the estimated Sabir granitic rock mass properties in the study area following the GH-B failure criterion

St. No.	Geotechnical sub-unit	Zone	Hoek-Brown classification			Mohr-Coulomb fit		Rock mass parameters(MPa)			
			mb	s	a	C (MPa)	ϕ (deg)	σ_{tm}	σ_c	σ_{cm}	E_{rm}
74	Sabir granitic rock mass (Tg)	I	9.041	0.0196	0.502	5.901	44.927	-0.15	9.605	28.441	18319.6
76		I	1.708	0.0004	0.507	2.305	30.741	-0.012	0.945	8.104	1758.74
77		I	0.9	0.0008	0.516	1.169	25.411	-0.003	0.244	3.7	598.6
80		I	11.689	0.0702	0.501	4.582	46.898	-0.282	12.446	23.206	9939.14
81		I	4.068	0.0043	0.502	8.718	38.127	-0.141	8.6	35.851	13002.4
85		I	13.197	0.0636	0.501	14.786	47.949	-0.718	37.501	76.935	51915.9
86		I	0.233	0.00001	0.521	0.409	15.702	-0.0008	0.048	1.079	234.03
88		I	7.259	0.02	0.501	2.757	43.02	-0.094	4.8	12.688	5532.9
90		I	2.335	0.0022	0.502	3.551	33.352	-0.061	2.993	13.178	4067.3
91		I	1.96	0.0006	0.506	2.693	31.901	-0.017	1.272	9.698	2288.15

GH-B: Generalized Hoek-Brown failure criterion, m_i , mb , s and a =Material Constants, C and ϕ = Cohesion (MPa) and Friction Angle (deg.) respectively, σ_{tm} = Tensile Strength (MPa), σ_c = Uniaxial Compressive Strength (MPa), σ_{cm} = Global Strength (MPa), E_{rm} = Deformation Modulus.

III. RESULTS AND DISCUSSION

3.1 Geotechnical characterization of Sabir granitic rock masses (Tg)

The geomechanical behavior of rock mass is governed by characteristics of both intact rock material and discontinuities crossed the rock masses.

3.1.1 Characteristics of Intact Rock Material

The physical tests carried out for granitic rock samples involve the determination of water content (%), unit weight (γ) (KN/m³), dry density (ρ_d g/cm³), porosity (n %), water absorption (W. Ab %), bulk specific gravity (Gs) and apparent specific gravity (A.Gs). The ranges of average values of these properties are presented in Table 5. The values of water content and unit weights range from 0.269 to 0.91% and from 23.806 to 26.117 KN/m³ respectively. The ranges of average minimum and maximum values of other five parameters are 2.415-2.656 g/cm³, 2.099-6.976 %, 0.792-3.123 %, 2.484-2.677 and 2.589-2.713 respectively. According to the obtained values of dry density, porosity and water absorption, the granitic rocks belong to the class of "Moderate to High" density "Low to Medium" porosity [44] and "Good to Marginal" water absorption respectively [45]. The strength values obtained from the uniaxial compressive strength (UCS-lab) and point load (PLT-lab) tests vary from 2.12 MPa to 74.57 MPa and from 52.92 MPa to 184.84 MPa respectively while the rock strength obtained from Schmidt hammer (SH-in

field) tests range between 27.3 MPa and 45.2 MPa with an average of 35.21 MPa (Table 5).The average values from all strength tests vary from 25.71 MPa to 119.38 MPa indicating that Sabir granitic rock masses are "Medium Strong" to "Very Strong"

3. 1.2 Discontinuities Characteristics of Sabir Granitic Rock Masses (Tg)

Ten representative field stations of granitic outcrops were studied for the purpose of characterization of discontinuities (totally 305) and geotechnical classification of these rock masses. The surveys were carried out as detailed in the methodology section. Stereographically, three main sets of discontinuities are identified at each station; however, the fourth joint set occurs, in addition to random joint sets (Fig.4 & Table 1). Figure 5 shows the variation in the strike directions of discontinuities which are predominately NE-SW and NW-SE running parallel to the strike directions of regional structures or faults. The averages of spacing of discontinuities vary from 0.13m (close spacing) to 1.27m (wide spacing). The averages of spacing which range from 0.22 m to 0.6 m and from 0.62m to 1.27m more frequency indicate "Moderate" to "Wide" spacing respectively [13]. These spacing would provide in-situ block size distribution that can give commercial value [46].

The discontinuity persistence varies from < 1m to more 20 m ("Very Low" to "Very High" persistence). The surfaces of joints are generally rough, fresh to slightly and moderately weathered. Highly weathered surfaces stained with iron oxides, and dry surfaces with no evidence of water flow are also encountered. The width of the aperture varies from 1mm (Open) to more than 5 mm (Moderately Wide). The joints are either open with no infilling or filled with hard or soft materials of varying thickness.

Volumetric joint count (Jv) index values for granitic rock masses calculated from averages of the main joint sets (Table 2) vary from 3.54 j/ m³ (Moderate jointing) to 16.69 j/ m³ (High jointing) with average 7.73 j/ m³ (Moderate jointing) (Tables 1& 2). For the "Blocky (B)" structure the Jv values range from 3.54 j/ m³ to 8.76 j/ m³ and the same for "Very Blocky (VB)" structure range from 11.66 j/ m³ to 16.69 j/ m³ (Table 4).

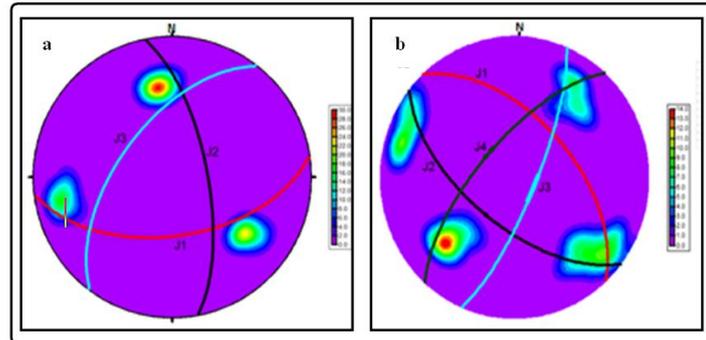


Figure 4 Two examples for equal- area stereographic projection of the main joint/ discontinuity sets in Tertiary Sabir granitic rock mass (Tg); **a)** Three joint sets at station No. 80; three sets are almost diagonal, **b)** Four joint sets at station No. 76; all sets also are almost diagonal

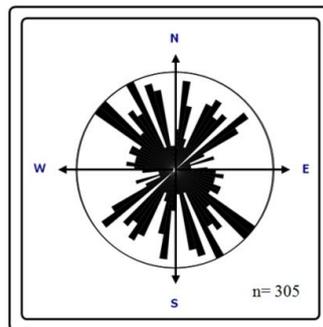


Figure 5 Rose Diagram showing the local variations in the strike directions of surveyed joints in the different stations of the Tertiary Sabir granitic rock mass (Tg)

3.3 Geotechnical Classification of Sabir Granitic Rock Masses (Tg)

Geotechnical classification of the granitic rock masses was carried out according to RQD, RMR and GSI and details of which are provided below.

3.3.1 Rock Quality Designation (RQD) index

For assessing rock quality quantitatively, Rock Quality Designation (RQD) index calculated from Jv was used (Table 2). The RQD values of granite range from 68.28 % to 100 % indicating "Fair to Excellent" quality rock class, with an average of 90.46 % corresponding to "Good/Excellent" quality rocks [42], however; the "Poor" and "Very Poor" rock qualities were also observed in the field (Fig. 6).

3.3.2 Rock Mass Rating (RMR)

The basic RMR₈₉ rating values for the Sabir granitic rock mass vary from 51.4 to 80.3 indicating "Fair" to "Good/Very Good" quality rocks and belong to classes III and II of Bieniawski [23, 11]. The basic RMR_{b89} values suggest that 30 % of the rock belongs to "Fair" class and the remaining 70 % of the granite belongs to "Good/Very Good" class of rocks (Table 3), however, the poor and very poor rock qualities were also observed in the field (Fig. 6).

3.3.3 Geological Strength Index (GSI)

The average values and ratings of the parameters required for the calculation of SR and SCR components and for the estimation of the quantified GSI values of the granitic rock masses are

provided in the Table 1. The obtained values of SR and SCR were plotted on GIS chart (Table 4) to derive GSI values. The obtained GSI values range from 31.1 to 81.67 (poor to very good) with an average of 58.22 (Table 1). The GSI values for the

rocks showing "Blocky (B)" structure vary from 62.46 to 81.67 with an average of 67.07 and for "Very Blocky (VB)" structure, the values range from 31.1 to 46.67 with an average of 37.59.



Figure 6 Field Photograph of high to moderately weathered Sabir granitic rock masses exposed to the east of Dar Al-Nasr, Sabir area; where quality of rock masses are poor (black arrow) and very poor (red arrow)

3.4 Indirect Estimation of the Sabir Granitic Rock Masses Properties

The strength and deformability of the Tertiary jointed Sabir granitic rock masses were estimated based on the generalized Hoek–Brown failure criterion [37] and Geological Strength Index (GSI) and employing RocLab software program (Rocscience, 2013). The input parameters required in this program for calculation of rock mass parameters for each granitic station are shown in Table 6. The obtained output parameters (Table 7) include: Hoek-brown classification parameters (mb,

s and a), Mohr-Coulomb Fit (shear strength parameters; c, ϕ) and rock mass parameters given in terms of compressive strength (σ_c), tensile strength (σ_{tm}), deformation modulus (E_{rm}) and global strength (σ_{cm}). The averages of the obtained values of mb, s, a, c, ϕ , σ_c , σ_{tm} , E_{rm} and σ_{cm} for Sabir granitic rock masses are: 5.239, 0.0182, 0.506, 4.69 MPa, 35.80°, -0.148 MPa, 7.85 MPa, 21.29 MPa and 10765.68 MPa respectively (Table 7). Note that the RMR value and the strength of intact rock sample are function of these properties as shown in the Figures 7a and 7b.

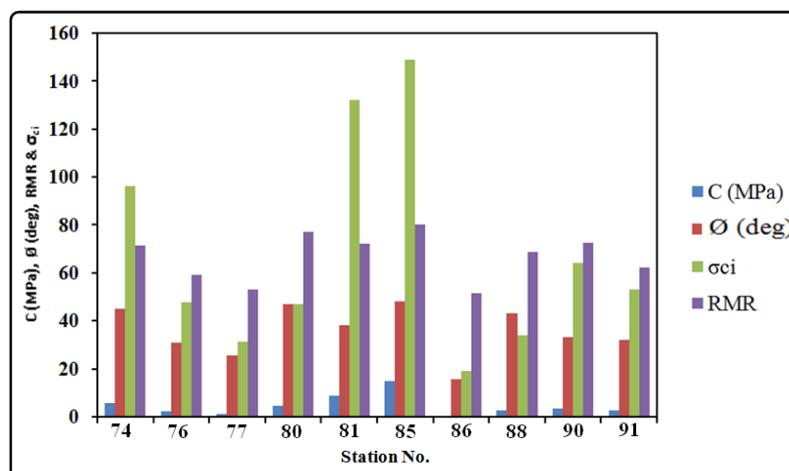


Figure7a Shows the proportional increase for strength parameters (C, ϕ) with that of RMR ratings of granitic rock mass and the strength values of intact rock granitic material; UCS (σ_{ci}) (MPa) at the different investigated granite stations

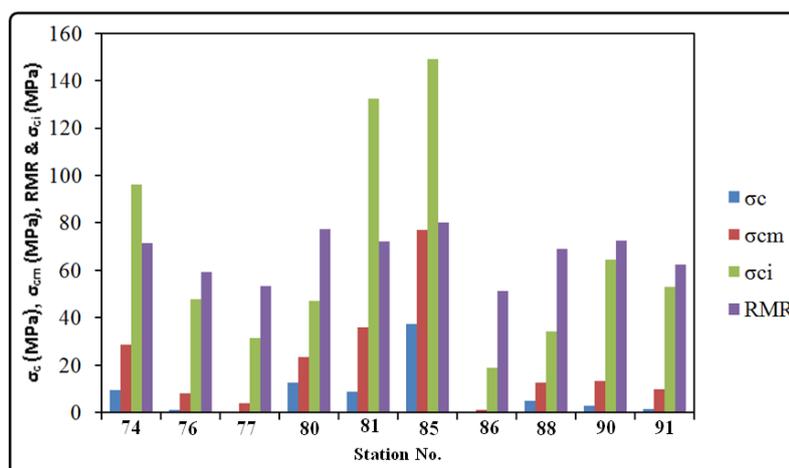


Figure 7b Shows the proportional increase of the UCS (σ_c) (MPa) and Global strength (σ_{cm}) (MPa) values of rock masses with that of the UCS (MPa) of intact granitic rock material (σ_{ci}) and RMR ratings for granitic rock masses at the different investigated granite stations

IV. CONCLUSIONS

The present study, first of its kind in the study area, deals with characterization and evaluation of geo-engineering parameters of Tertiary granitic rock masses by direct and indirect methods. The direct approach includes the field measurements and tests (at 10 representative field stations) and the laboratory tests of physico-mechanical characteristics for samples collected from different field stations. Indirect approach for rock mass characterization is through two rock mass classification systems, namely Rock Mass Rating (RMR) and Geological Strength Index (GSI). The data obtained on Sabir granitic rock materials from laboratory and field investigations demonstrate that the geomechanical characteristics and behavior markedly vary between the rock masses of volcanic and non-volcanic origins which may be attributed to their volcanic nature, petrographic variety and structural complexity. The Tertiary granitic rock masses are found to be affected by the development of the intense fracturing systems which can pose instability problems when excavation for road cuts or construction purpose is made.

The physico-mechanical characteristics of these rocks showed range of variations in their dry densities, porosities, water absorption tendencies, bulk and apparent specific gravities and uniaxial compressive strengths (UCS) as the rocks contain microfractures and are affected by various degree of weathering and alteration. The UCS of these rocks are expected to be more because the tests were carried out on submerged rock samples in water for 24 hours (so they may lose their strength by average of 30 %). The lower strength ranges from Schmidt hammer (SH) compared with strength ranges taken by PLT for these rocks probably reflect the sensitivity of the Schmidt hammer to surface

alteration of the materials in the field and size of the rock sample in the laboratory. According to the obtained values of dry density, porosity and water absorption, the granitic rocks belong to the class of "Moderate" to "High" density, "Low" to "Medium" porosity. The average values from all strength tests vary from 25.71 MPa to 119.38 MPa indicating that Sabir granitic rock masses are "Medium Strong" to "Very Strong".

The characterization of the geotechnical granitic rock masses based on RQD, RMR₈₉ and GSI systems showed that these rocks have range of variations in their qualities and they are categorized as "Fair" to "Excellent" quality, "Fair" to "Good/Very Good" quality and "Poor" to "Very Good" quality classes. Values of shear strength parameters (c and ϕ) and the other rock mass parameters (σ_{tm} , σ_c , σ_{cm} and E_{rm}) of these rocks are varied, depending on rock mass quality and properties of intact rock. In general, the values of the rock mass parameters increase with increase in the quality of rock mass and intact rock properties.

The modified quantitative GSI system applied here has provided useful information about rock mass characteristics and can be used at all stages of any engineering project, especially at the preliminary design stage where only limited information is available.

ACKNOWLEDGMENT

The authors are deeply grateful to the manager of Sheba General Contracting Co. Ltd, main branch, Taiz and its technical staff at the materials laboratory as well as to technical staff at Technical institute, Al-Hassib, Taiz, Yemen who gave us the opportunity to carry out physical-mechanical tests.

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