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Assessment of Rock Mass Quality and Deformation Modulus by Empirical Methods along Kandiah River, KPK, Pakistan

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Abstract

The pivotal aim of this study is to evaluate the rock mass characterization and deformation modulus. It is vital for rock mass classification to investigate important parameters of discontinuities. Therefore, Rock Mass Rating (RMR) and Tunneling quality index (Q) classification systems are applied to analyze 22 segments along proposed tunnel routes for hydropower in Kandiah valley, Khyber Pakhtunkhwa, Pakistan. RMR revealed the range of fair to good quality rocks, whereas Q yielded poor to fair quality rocks for investigated segments of the rock mass. Besides, E_m values were acquired by empirical equations and computer-aided program RocLab, and both methods presented almost similar variation trend of their results. Hence, the correlations of E_m with Q and RMR were carried out with higher values of the regression coefficient. This study has scientific significance to initially understand the rock mass conditions of Kandiah valley.

Keywords

Rock Mass Classification, RMR and Q, Deformation Modulus (E_m), Empirical Equations, RocLab, Tunnel

1. Introduction

Geomechanical investigation of the rock mass is an essential part of the feasibility phase of hydropower projects when very little information is available, to ascertain the response of rock behavior under disturbance or excavation. Rock mass characteristics are determined by empirical classification systems to classify the rock mass [1]. Hence, Rock Mass Rating (RMR) and Tunneling quality index (Q) classification systems are pivotal to classify the rock mass. Extensive studies have been conducted by using RMR and Q schemes e.g. [2]-[12]. Among the rock mass parameters, deformation modulus (E_m) has very significance in rock mechanics because it provides the initial idea about mechanical behavior of rock mass before failure. In this regard, there are several direct procedures to determine the deformation modulus in the laboratory, but these methods are costly and time consuming. Therefore, empirical methods have been suggested for indirect estimation of deformation modulus [13] [14]. As a consequence, various researchers [7] [15]-[25] have been proposed different empirical relations for estimation of deformation modulus.

Pakistan is facing a serious shortage of electricity, and Government is trying to develop hydropower, especially in Northern Pakistan to overcome the electricity disorder. In this regard, small hydropower is proposed along Kandiah River in Kandiah valley, KPK, Pakistan. Hence, the present study focuses on preliminary rock mass characterization with an assessment of required support and estimation of deformation modulus along proposed tunnel routes. Therefore, to achieve this goal, field observations including geological mapping, discontinuity surveys and sampling were conducted.

2. Geological Setting of Study Area

The study area is near about 30 Km long V-shaped valley with steep slopes on either side of Kandiah River. Tectonically it is situated in Kohistan Island Arc (KIA) and surrounded by two sutures formed by the collision of Indian plate with Eurasian plate, whereas the first suture is known as northern suture from Eurasian plate and the second suture is between Main Mantel Thrust (MMT) and Indian plate, respectively (**Figure 1**) [26]. Chilas Complex (CC) and Gilgit Complex (GC) are two prevailing major geological units in the study area. The CC dominantly composed of intermediate to basic plutonic rocks such as diorite (**Figure2(a)**), gabbro, anorthosite, pyroxenite and GC comprising metasediments such as psammite (**Figure2(b)**) and protolith of metasediments. Moreover, Pleistocene unconsolidated deposits are also observed in the valley at different places, which are the result of river bed deposits, fan deposits, talus, fluvial deposits, scree and glacial deposits.

3. Data and Methods

3.1. Data

Geological Mapping and Discontinuity Survey

Tunnel routes were divided into segments and various traverses were made to mark geological contacts (**Figure 3**). According to International Society for Rock Mechanics [27], physical parameters (orientation, spacing, persistence, aperture, roughness, the number of joint sets, infilling material and hydraulic conditions)were frequently executed of all those discontinuities that were intersecting the reference line by measuring tape of approx. 10 m during scanline surveys [28].

3.2. Methods

3.2.1. Rock Mass Rating (RMR) and Tunneling Quality Index (Q)

RMR and Q are universal classification systems, and these systems have been applied by many researchers in tunneling and underground excavation. Bieniawski [29] developed RMR system by providing quantitative data for reinforcement of tunnel techniqueslike rock bolts, shotcrete etc. The modifications

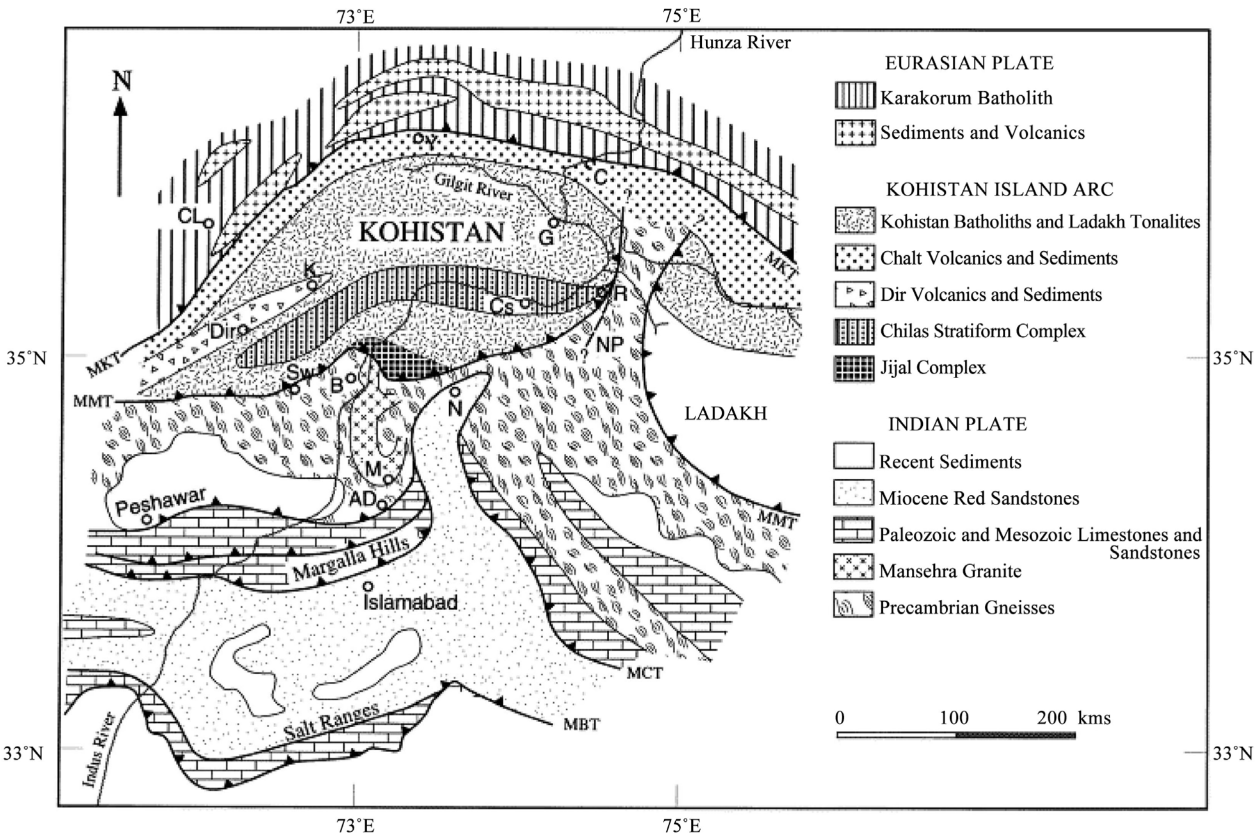


Figure 1. Regional tectonic map of study area (Modified after Tahirkheli and Jan [26]).

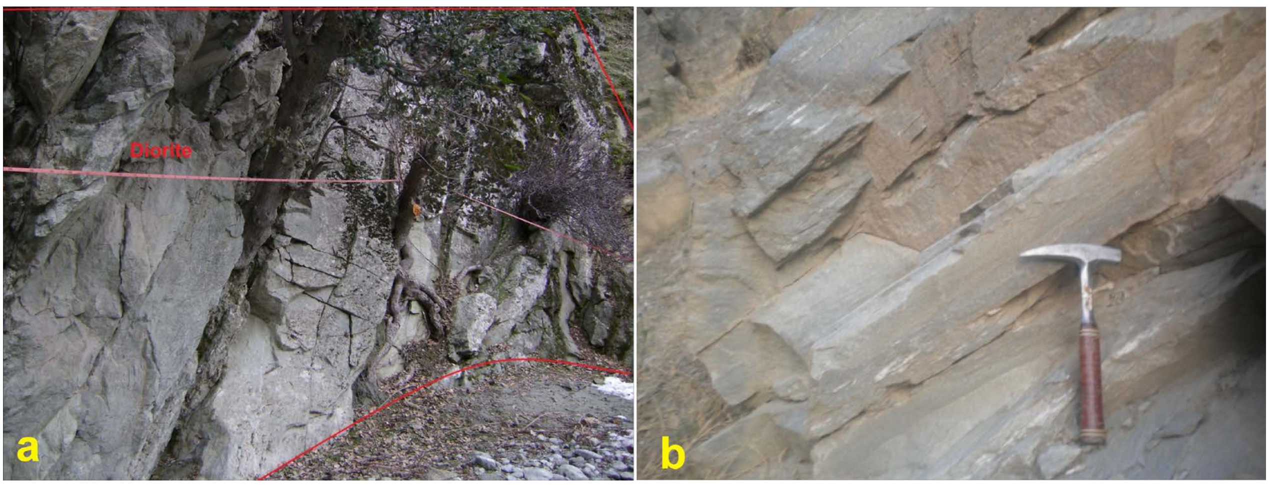


Figure 2. Exposed Rocks Unit of (a) Diorite belonging to Chilas Complex; (b) Psammite belonging to Gilgit Complex in study area.

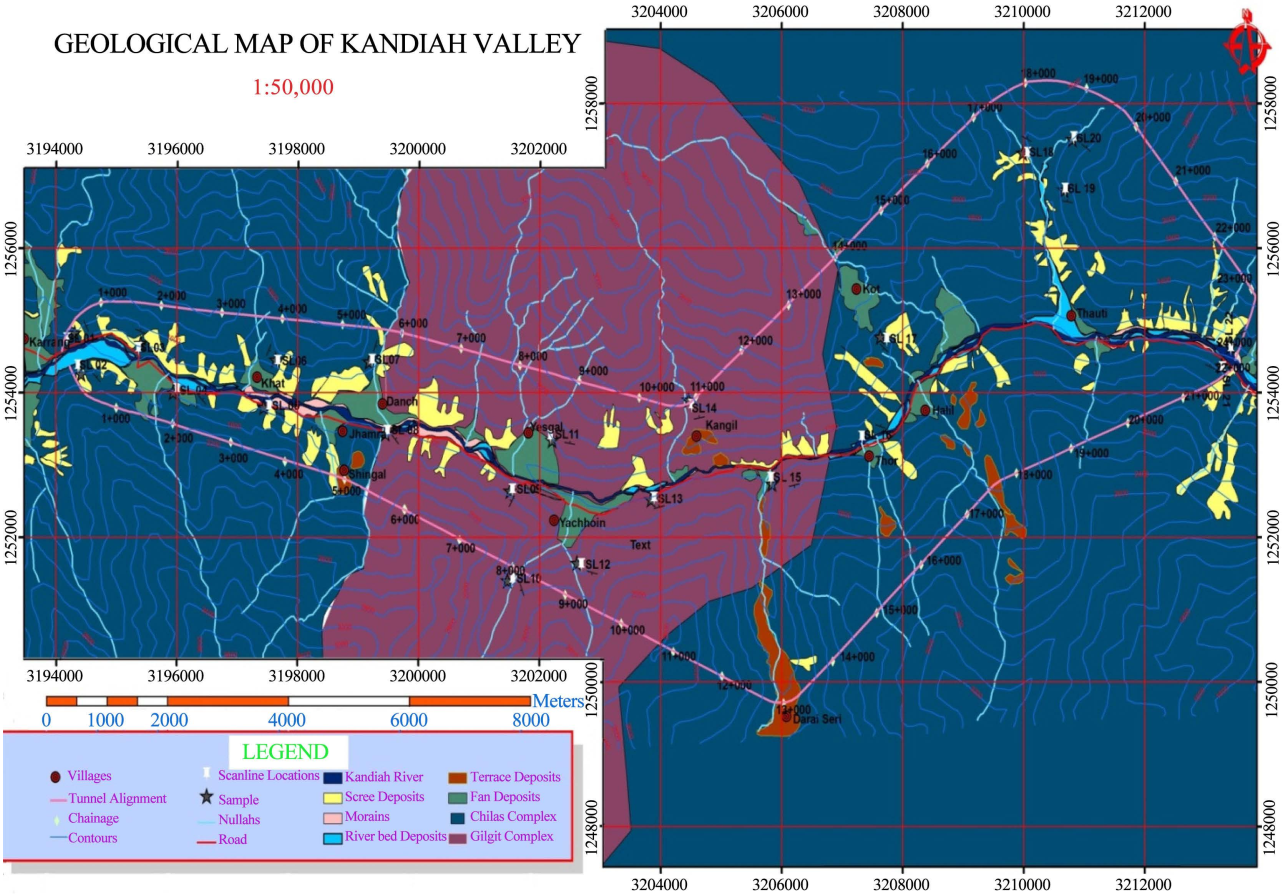


Figure 3. Geological map of study area.

had made over the many years e.g. [29] [30] [31] [32] [33]. In beginning, the system was established for only tunnels but with the passage of time, this system is also used for foundations, rock slopes, and mining problems. The following parameters were investigated during field work to calculate the RMR values: Uniaxial compressive strength (UCS), spacing, rock quality designation (RQD), ground water conditions, discontinuity conditions and orientation of discontinuities [3] [8] [10]. The RMR values are estimated by following equation [29]:

$$RMR = R_1 + R_2 + R_3 + R_4 + R_5 + R_6 \tag{1}$$

where, $R_1 - R_6$ are the above mentioned parameters of discontinuities.

Barton *et al.* [34] proposed Q system that was used to determine rock mass quality and required support estimation for tunnels. The overall Q values ranged between 0.001 (exceptionally poor) to 1000 (exceptionally good) and can be estimated by using this expression:

$$Q = (RQD/Jn) \times (Jr/Ja) \times (Jw/SRF) \tag{2}$$

RQD is rock quality designation, J_n is the joint set number, J_r and J_a are the ratings of roughness and alteration number, J_w is for water inflow and pressure effects, and SRF is the stress reduction factor. Moreover, terms Jr/Ja represents peak strength, RQD/Jn indicates the relative block size and Jw/SRF related to the effective strength of the rock mass. It is noticed by the Equation (1) and Equation (2) that RMR values are calculated by summation of all assigned ratings, whereas Q values are calculated by divisions and products of assigned ratings to parameters.

3.2.2. Estimation of Deformation Modulus Based on RMR and Q

There are several equations proposed by different researchers to estimate deformation modulus (E_m) based on Geomechanical classification systems e.g. [4] [15] [17] [18] [19] [20] [24] [35] [36] [37] [38] [39]. Most widely used equations by different researchers were plotted in **Figure 4** by Hoek and Diederichs [7] and relevant equations are listed in **Table 1**.

In order to calculate the deformation modulus of rock mass, at least rating value of one rock mass classification system is required because joint's properties (e.g. roughness, weathering, infilling material, aperture, persistence, etc.) have significant effect on rock mass deformation [24] [40]. Hence, equations proposed by different researchers (**Table 2**) in which RMR and Q values considered as input parameters to estimate E_m.

4. Results and Discussions

4.1. Rock Mass Classification

This paper highlights the characterization of rock mass by RMR and Q schemes. Furthermore, discontinuity surveys were conducted at various locations to collect the required parameters for the estimation of RMR and Q values. The orientation data of discontinuities were analysed by computer program DIPS (version 5.1) that show mostly 2 to 3 joints sets were prevailing in the study area. The field surveys revealed that discontinuity's trend was mostly dipping towards the tunnel axis but at some points, the trend was away from tunnel axis, as well as at few locations strike was parallel to the tunnel axis.

The RMR values vary from 53 (fair) to 65 (good) with a mean of 57 (**Table 3**) on left route and values ranged between 51 (fair) to 62 (good) with average 56 (**Table 4**) for the right route of the tunnel. Moreover, Q values of rock mass ranged between 1.60 (poor) to 6.13 (fair) with an average of 3.22 along left tunnel route and 1.60 (poor) to 4.27 (fair) with an average of 2.81 along right tunnel alignment. The detail ratings of all required parameters with Q values are listed in **Table 5** and **Table 6**.

The comparisons of RMR and Q values were analyzed by using the results of input parameters to calculate the empirical ratings for tunnel alignments. Along left tunnel route, RMR designated ten segments as a fair rock and only one segment (20+000 - 22+000) show good rock but according to Q system, same segments were designated as a poor rock except for three segments (3+000 - 5+000, 17+000 - 19+000, 20+000 - 22+000) that revealed a fair quality rock. Similarly, values of RMR along different segments of right tunnel route gave fair rock quality except for one segment (12+000 - 15+000) that designated as good quality of rock and Q system designated various segments as poor quality except for one segment (15+000 - 20+000) that presented fair quality of rock mass. The calculated ratings suggest that Q system provided a more conservative approach as compare to RMR system for rock mass classification. The variation in values of RMR and Q plotted in **Figure 5** and estimated support for specific rock class is summarized in **Table 7**.

Table 1. Empirical equations and field data of different researchers plotted in **Figure 4** (after Hoek and Diederichs [7]).

Plots and curved	Equations	Equation No.	Researcher (s)
○	Field Data		[17]
◇	Field Data		[15]
□	Field Data		[35]
1	$E_m = 2RMR - 100$ for $RMR > 50$	3	[15]
2	$E_m = 10^{(RMR-10)/40}$	4	[17]
3	$E_m = E_i/100\left(0.0028RMR^2 + 0.9\exp\left(RMR/22.82\right)\right), E_i = 50\text{Gpa}$	5	[18]
4	$E_m = E_i\left(0.5\left(1-\cos\left(\pi RMR/100\right)\right)\right), E_i = 50\text{Gpa}$	6	[19]
5	$E_m = 0.1\left(RMR/10\right)^3$	7	[20]
6	$E_m = 10Q_c^{1/3}$ where $Q_c = Q\sigma_{ci}/100$	8	[4]
7	$E_m = \left(1-\frac{d}{2}\right)\sqrt{\frac{\sigma_{ci}}{100}} \times 10^{(RMR-10)/40}$	9	[38]
8	$E_m = E_i\left(S^a\right)^{0.4} E_i = 50\text{GPa}, s = \exp\left(\left(GSI-100\right)/9\right)$	10	[24]
9	$E_m = E_i S^{1/4} E_i = 50\text{GPa}, s = \exp\left(\left(GSI-100\right)/9\right)$	11	[37]
10	$E_m = 7(\pm 3)\sqrt{Q'} Q' = 10\left(\left(RMR-44\right)/21\right)$	12	[36]

Table 2. Empirical equations for estimation of deformation modulus (E_m) by using RMR and Q values.

Empirical Equation	Equation No.	Required Parameter	Reference
$E_m\left(GPa\right) = 40\log Q\left(Avg.\right)$	13	Q	[41]
$E_m\left(GPa\right) = 8Q^{0.4}$	14	Q	[21]
$E_m\left(GPa\right) = 2RMR - 100$ for $RMR > 50$	3	RMR	[15]
$E_m\left(GPa\right) = 0.1\left(RMR/10\right)^3$	7	RMR	[20]
$E_m\left(GPa\right) = 5.6\left(RMR\right)^{0.375}$	15	RMR	[42]
$E_m\left(GPa\right) = 0.0736e^{0.0755RMR}$	16	RMR	[22]

Table 3. Geomechanical classificationby RMR along left tunnel alignment (After [31]).

Chainage		Uniaxial compressive strength (Avg.)	Rock Quality Designation (Avg.)	Spacing (Avg.)	Discontinuity Condition	Water Condition	RMR Value	Description	Rock Class	GSI (RMR-5)
From	To									
0+00	1+000	7	8	10	Persistence > 10 - 15 m, aperture > 1 - 5 mm, slightly rough to rough, slightly to moderately weathered	Approx. Damp to completely dry	57	Fair	III	52
1+000	3+000	12	8	8			56	Fair	III	51
3+000	5+000	12	13	10			59	Fair	III	54
5+000	7+000	7	13	10			55	Fair	III	50
7+000	10+000	7	17	10			58	Fair	III	53
10+000	14+000	7	13	10			57	Fair	III	52
14+000	17+000	7	13	5			53	Fair	III	48
17+000	19+000	12	8	15			59	Fair	III	54
19+000	20+000	7	8	15			57	Fair	III	52
20+000	22+000	7	13	15			65	Good	II	60
22+000	24+000	7	13	15			57	Fair	III	52

Table 4. Geomechanical classification by RMR along right tunnel alignment (After [31]).

Chainage		Uniaxial compressive strength (Avg.)	Rock Quality Designation (Avg.)	Spacing (Avg.)	Discontinuity Condition	Water Condition	RMR Value	Description	Rock Class	GSI (RMR-5)
From	To									
0+00	2+000	7	13	10	Persistence > 10 - 15 m, aperture > 15 mm, slightly rough to rough, slightly to moderately weathered	Approx. damp to completely dry	59	Fair	III	54
2+000	3+000	7	13	10			58	Fair	III	53
3+000	5+000	7	8	10			51	Fair	III	46
5+000	6+000	7	13	10			58	Fair	III	53
6+000	8+000	7	8	10			55	Fair	III	50
8+000	9+000	7	17	10			53	Fair	III	48
9+000	10+000	12	13	10			53	Fair	III	48
10+000	12+000	7	13	10			57	Fair	III	52
12+000	15+000	12	13	10			62	Good	II	57
15+000	20+000	7	13	8			57	Fair	III	52
20+000	22+000	4	13	15			51	Fair	III	46

Table 5. Estimated Q values along left tunnel alignment of KandiahRiver (After [34]).

Chainage		RQD (Avg.)	J_N	J_R (Avg.)	J_A (Avg.)	J_W (Avg.)	SRF (Avg.)	Q-Value	Description
From	To								
0+00	1+000	48	9	1.5	2	1	2.5	1.60	Poor
1+000	3+000	50	9	3	2	1	2.5	3.33	Poor
3+000	5+000	64	9	1.5	1	1	2.5	4.27	Fair
5+000	7+000	64	9	1.5	2	1	2.5	2.13	Poor
7+000	10+000	76	9	1.5	2	1	2.5	2.53	Poor
10+000	14+000	60	9	1.5	2	1	2.5	2.00	Poor
14+000	17+000	59	9	1.5	1	1	2.5	3.93	Poor

Continued

17+000	19+000	46	9	3	1	1	2.5	6.13	Fair
19+000	20+000	48	9	3	2	1	2.5	3.20	Poor
20+000	22+000	62	9	3	2	1	2.5	4.13	Fair
22+000	24+000	64	9	1.5	2	1	2.5	2.13	Poor

Table 6. Estimated Q values along right tunnel alignment of KandiahRiver (After [34]).

Chainage		RQD (Avg.)	J_N	J_R (Avg.)	J_A (Avg.)	J_W (Avg.)	SRF (Avg.)	Q-Value	Description
From	To								
0+00	2+000	56	9	3	2	1	2.5	3.73	Poor
2+000	3+000	58	9	1.5	2	1	2.5	1.93	Poor
3+000	5+000	48	9	1.5	2	1	2.5	1.60	Poor
5+000	6+000	54	9	1.5	2	1	2.5	1.80	Poor
6+000	8+000	48	9	1.5	1	1	2.5	3.20	Poor
8+000	9+000	76	9	1.5	2	1	2.5	2.53	Poor
9+000	10+000	56	9	3	2	1	2.5	3.73	Poor
10+000	12+000	60	9	1.5	2	1	2.5	2.00	Poor
12+000	15+000	68	9	1.5	2	1	2.5	2.27	Poor
15+000	20+000	64	9	1.5	1	1	2.5	4.27	Fair
20+000	22+000	58	9	3	2	1	2.5	3.87	Poor

Table 7. Estimated support categories of rock mass according to RMR and Q (after [29] [41]).

Sr. No.	RMR values	Q values	Estimated support by RMR	Estimated support by Q
1	41 - 60	1 - 4	Systematic bolts 4.0 m long, 1.5 - 2.0 m spaced in crown and walls with wire mesh in the crown. 50 - 100 mm shotcrete in crown and 30 mm.	Systematic bolting with 40 - 100 mm unreinforced shotcrete.
2	61 - 80	4 - 10	Locally, bolts in crown 3 m long, spaced 2.5 m with occasional wire mesh. Shotcrete 50 mm in crown where required.	Systematic bolting

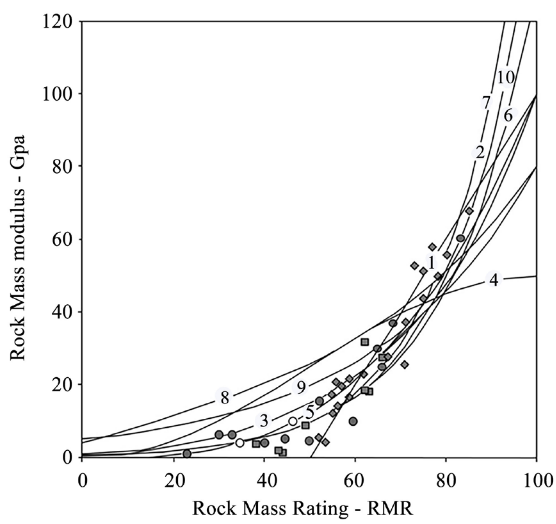


Figure 4. Comparison of rock mass deformation modulus by using different empirical equations with data from in situ measurements (after Hoek and Diederichs [7]).

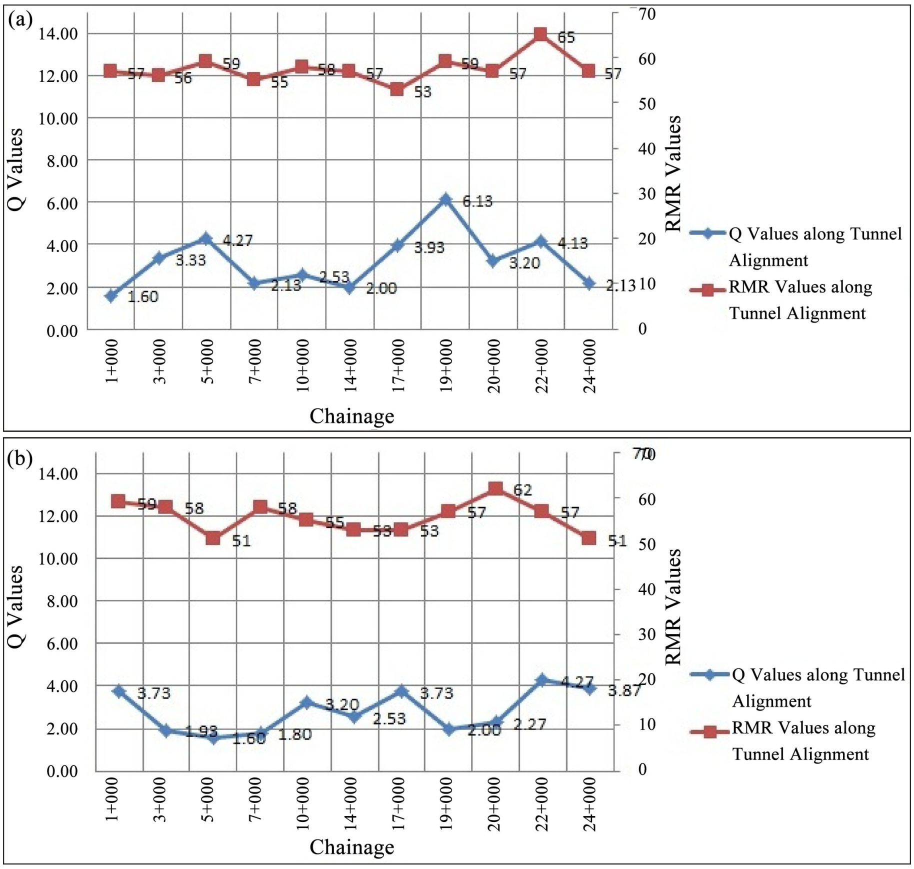


Figure 5. Comparison of RMR and Q values for (a) left tunnel alignment (b) right tunnel alignment.

4.2. Estimation of Rock Mass Deformation Modulus

In this study, E_m values were calculated for total 22 segments along tunnel alignments by widely accepted empirical equations and presented in Table 8 and Table 9. E_m values of left tunnel alignment obtained from Palmstrom and Singh [21] (9.65 - 16.53 GPa, Avg. 12.54 GPa) are on the lower side as compare to Grimstad and Barton [41] ranged between 8.16 - 31.51 GPa with an average of 19 GPa by using Q values. However, the range of E_m values calculated with RMR values by Bieniawski [15] is 6 - 30 GPa with average 15.09 GPa and by Read *et al.* [20] values range between 14.89 - 27.46 GPa (average 19.20 GPa). Similarly, E_m values vary between 4.02 - 9.96 GPa with an average of 5.82 GPa by Gokceoglu *et al.* [22] and the equation of Palmstrom [42] provides the values range of 24.82 - 26.79 GPa with average 25.59 GPa. The E_m values of right tunnel alignment calculated from Palmstrom and Singh [21] vary within the range of 9.65 - 14.29 GPa with an average of 11.94 GPa and values by Grimstad and Barton [41] ranged between 8.16 - 25.20 GPa with an average of 16.99 GPa by using Q values. Likewise, calculated values of E_m using RMR values by Bieniawski [15] vary between 2 - 24 GPa with average 11.64 GPa and by Read *et al.* [20] values range between 13.27 - 23.83 GPa with average 17.58. Likewise, E_m values vary between 3.46 - 7.94 GPa with average 5.14 GPa by Gokceoglu *et al.* [22], and values calculated by Palmstrom [42] vary between 24.46 - 26.32 GPa with average 25.30 GPa.

The calculated values of E_m from empirical equations were compared with rock mass quality (**Figure 6** and **Figure 7**) to understand the similarity or inconsistency emanating. However, the pattern of E_m with rock mass quality was observed significantly for all equations. According to Kayabasi *et al.* [23] and Panthee *et al.* [43], significant results between E_m calculated by using empirical equations and rock mass class were not observed but Hoek and Diederichs [7] revealed that E_m values increases with an increase in rock mass class (**Figure 4**) by using exponentially or power function (**Table 1**). In this study, E_m values were calculated by different equations where few equations gave high values, and several equations provided E_m values of the lower range.

The relationships of E_m with Q and RMR were derived and presented in **Figure 8** and **Figure 9**. The E_m values show significant positive correlation with Q and RMR. The E_m values for left tunnel alignment calculated by Grimstad and Barton [41] & Palmstrom and Singh [21] show apositive correlation with Q values (R^2 = 0.96 and 0.98) as shown in **Figure 8**. Likewise, the calculated values of E_m with equations suggested by Bieniawski [15], Read *et al.* [20], Gokceoglu *et al.* [22], Palmstrom [42] have been plotted against RMR values (**Figure 9**) that presented direct correlation (R^2 = 1, 0.99, 0.97 and 0.99). Similarly, E_m values for right tunnel alignment calculated by Grimstad and Barton [41] & Palmstrom and Singh [21] provides positive correlation with Q values (R^2 = 0.98 and 0.99) as shown in **Figure 8** and likewise, E_m values obtained from Bieniawski [15], Read *et al.* [20], Gokceoglu *et al.* [22], Palmstrom [42] were plotted against RMR values of right tunnel alignment and displays significant positive direct relationship (R^2 = 1, 0.99, 0.98 and 0.99) (**Figure 9**). In the light of above discussion, relations provided in **Table 10** can be used to predict E_m by Q and RMR values with an accuracy of R^2 = 0.96 - 1.00 for similar properties of the rock mass and rock type of this study.

The E_m values were also determined by the computer-aided program RocLab by using various required parameters of rock mass like Geological strength index (GSI), UCS, etc. and listed in **Table 8** and **Table 9**. Estimated E_m values for left tunnel alignment vary between 7.76 - 16.22 GPaby RocLab and E_m values (Avg.) of each segment acquired by all stated empirical equations ranged between 13.40 - 22.38 GPa. Similarly, for right tunnel alignment, RocLab provides the E_m values range of 7.14 - 14.99 GPa and E_m values (Avg.) by all empirical equations along each segment ranged between 10.23 - 18.19 GPa. It can be observed in **Figure 10** that fluctuation of obtained E_m values by both ways has the more or less similar trend. On the other hand, it should be noted that provided values by RocLab are on the lower side as compare to average values obtained by empirical equations (**Figure 10**). However, the present research is based on the data of few locations devoid of detail observation of rock mass. Therefore, results can be improved by conducting more discontinuity data in detail by following the same approach.

Table 8. Calculated values of deformation modulus along left tunnel alignment.

Chainage		E_m by using Q values		E_m by using RMR values				E_m by Using RocLab GPa
		Grimstad and Barton [41] GPa	Palmstrom and Singh [21] GPa	Bieniawski [15] GPa	Read *et al.* [20] GPa	Palmstrom [42] GPa	Gokceoglu *et al.* [22] GPa	
		(Equation (13))	(Equation (14))	(Equation (3))	(Equation (7))	(Equation (15))	(Equation (16))	
0+00	1+000	8.16	9.65	14.00	18.52	25.51	5.44	10.68
1+000	3+000	20.92	12.95	12.00	17.56	25.34	5.05	11.66
3+000	5+000	25.20	14.29	18.00	20.54	25.84	6.33	13.20
5+000	7+000	13.16	10.83	10.00	16.64	25.17	4.68	9.18
7+000	10+000	16.15	11.60	16.00	19.51	25.67	5.87	13.84
10+000	14+000	12.04	10.56	14.00	18.52	25.51	5.44	12.14
14+000	17+000	23.79	13.84	6.00	14.89	24.82	4.02	7.76
17+000	19+000	31.51	16.53	18.00	20.54	25.84	6.33	14.08
19+000	20+000	20.21	12.74	14.00	18.52	25.51	5.44	10.34
20+000	22+000	24.65	14.11	30.00	27.46	26.79	9.96	16.22
22+000	24+000	13.16	10.83	14.00	18.52	25.51	5.44	10.11

Table 9. Calculated values of deformation modulus along right tunnel alignment.

Chainage		E_m by using Q values		E_m by using RMR values				E_m by Using RocLab GPa
		Grimstad and Barton [41] GPa	Palmstrom and Singh [21] GPa	Bieniawski [15] GPa	Read *et al.* [20] GPa	Palmstrom [42] GPa	Gokceoglu *et al.* [22] GPa	
		(Equation (13))	(Equation (14))	(Equation (3))	(Equation (7))	(Equation (15))	(Equation (16))	
0+00	2+000	22.88	13.55	18.00	20.54	25.84	6.33	11.32
2+000	3+000	11.45	10.41	16.00	19.51	25.67	5.87	11.42
3+000	5+000	8.16	9.65	2.00	13.27	24.46	3.46	7.14
5+000	6+000	10.21	10.12	16.00	19.51	25.67	5.87	13.34
6+000	8+000	20.21	12.74	10.00	16.64	25.17	4.68	10.78
8+000	9+000	16.15	11.60	6.00	14.89	24.82	4.02	10.26
9+000	10+000	22.88	13.55	6.00	14.89	24.82	4.02	10.63
10+000	12+000	12.04	10.56	14.00	18.52	25.51	5.44	12.14
12+000	15+000	14.22	11.10	24.00	23.83	26.32	7.94	14.99
15+000	20+000	25.20	14.29	14.00	18.52	25.51	5.44	9.89
20+000	22+000	23.49	13.74	2.00	13.27	24.46	3.46	7.30

Table 10. Correlations of E_m with RMR and Q values for present study area.

Parameters	Relation	R^2	Equation No.
Q	$E_m = 6.3036Q - 0.7354$	0.98	16
	$E_m = 1.7308Q + 7.071$	0.99	17
	$E_m = 5.1659Q + 2.371$	0.96	18
	$E_m = 1.5264Q + 7.6272$	0.98	19
RMR	$E_m = 2RMR - 100$	1.00	20
	$E_m = 1.0556RMR - 41.541$	0.99	21
	$E_m = 0.5008xRMR - 22.998$	0.97	22
	$E_m = 0.1641RMR + 16.148$	0.99	23
	$E_m = 0.9402RMR - 34.899$	0.99	24
	$E_m = 0.387RMR - 16.461$	0.98	25
	$E_m = 0.17RMR + 15.804$	0.99	26

*y is for E_m and x for RMR & Q.

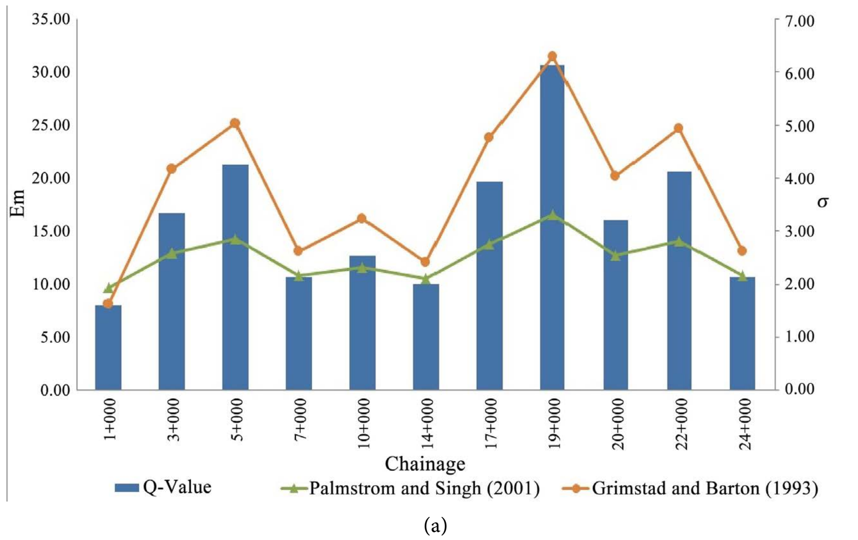
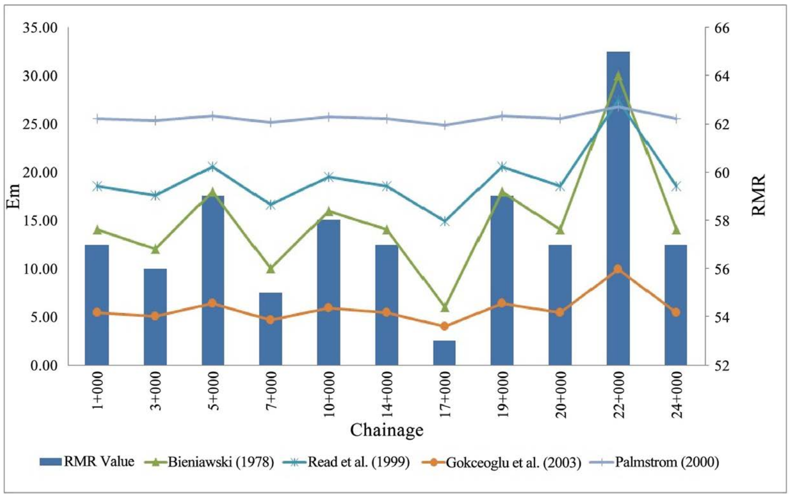
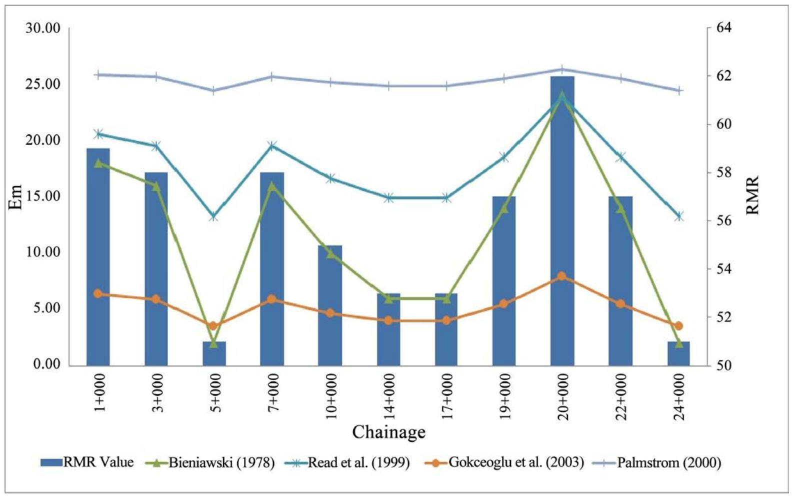


Figure 6. Comparison of E_m values with Q ratings for (a) left; (b) right tunnel alignment.



(a)



(b)

Figure 7. Comparison of E_m values with Q ratings for (a) left; (b) right tunnel alignment.

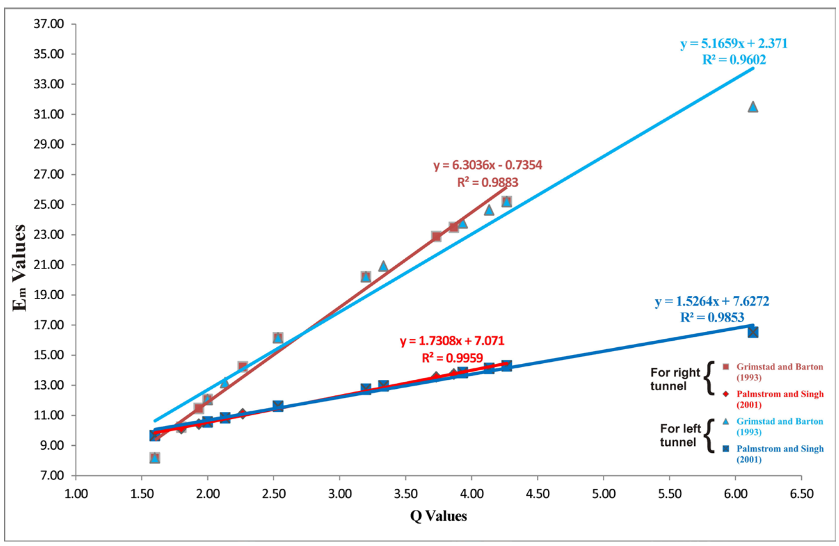


Figure 8. Relationship between estimated E_m values and Q values.

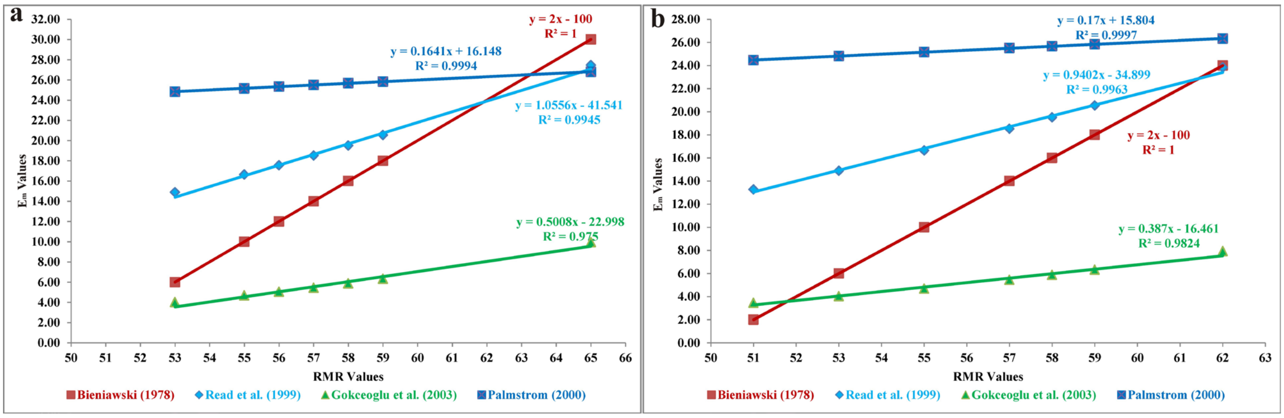


Figure 9. Relationship between estimated E_m values and RMR values for (a) left; (b) right tunnel alignment.

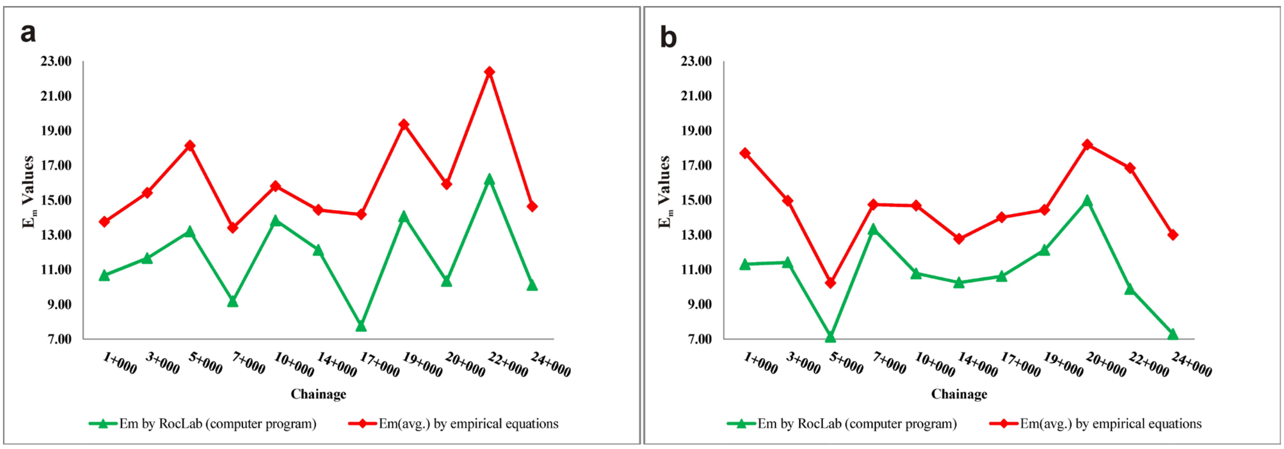


Figure 10. Variation of E_m values obtained by RocLab and empirical equations (avg.) along (a) left; (b) right proposed tunnel alignments.

5. Conclusions

Rock mass classification and deformation modulus were studied by RMR and Q schemes on the basis of field studies, laboratory studies, computation work, and graphical representation. RMR yielded fair to good quality rocks with values from 53 to 65 along left tunnel alignment and 51 to 62 along right tunnel alignment. While Q values vary between 1.60 to 6.13 for left tunnel alignment and 1.60 to 4.27 for right tunnel alignment with covering a range of poor to fair quality rocks. This study has predicted that segments of left tunnel alignment have fair rocks except for one segment (20+000 - 22+000) of good quality rocks, but Q values for the same segments presented poor rock quality except for three segments (3+000 - 5+000, 17+000 - 19+000, 20+000 - 22+000) that designated fair rock quality. Similarly, for right tunnel alignment, RMR values revealed fair rocks except for one segment (12+000 - 15+000) of good quality rocks, but Q yielded poor rock quality except for one segment (15+000 - 20+000) of fair rock quality. The estimated values of E_m by various equations have the more or less similar trend of variation with respect to rock quality of study area, respectively. The plots of E_m with RMR and Q indicated significant correlations (R^2 = 0.96 -

1). Furthermore, this study revealed that E_m values obtained by RocLab are on the lower side as compare to E_m (Avg.) values obtained by empirical equations and both methods have witnessed their results with the almost similar trend of variation. Moreover, it is recommended that detail investigation of joints, weak zones and laboratory analyses for assessment of appropriate support along tunnel alignments would be necessary.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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